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Heat transfer – a review of 1999 literature

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1. Introduction

The present review is intended to encompass the English language heat transfer papers published in 1999. The papers have been placed into a number of subject categories. While being exhaustive, some selection is necessary. 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 1999, and books on heat transfer published during the year.

The 15th Fluidized Bed Combustion Conference was held in Savannah, USA on 16–19 March. Topics covered included atmospheric and pressurized fluidized bed combustors, environmental issues, and operation. The Fifth ASME/JSME Thermal Engineering Joint Conference was held on 14–19 March in San Diego, USA. The Second International Symposium on Heat and Mass Transfer Under Plasma Conditions held on 18–23 April in Tekirova, Turkey discussed plasma torches and physics, transport and radiative properties flow modeling. The Second International Symposium on Two-Phase Flow Modeling and Experimentation was held in Pisa, Italy on 23–26 May. Sessions included turbulence in two-phase flow, pool boiling, flow boiling, and interfacial phenomena. The 1999 Turbo Expo organized by the International Gas Turbine Institute on 7–10 June in Indianapolis, USA held sessions on external heat transfer, film cooling, blade internal heat transfer, and combustor development and cooling. The first Mediterranean Combustion Symposium was held on 20–25 June in Antalya, Turkey. Topics covered stationary sprays and gas combustion systems, fire and explosions, solid fuels, and flame dynamics and turbulence. The 1999 National Heat Transfer Conference organized jointly by the ASME, AIChE and AIAA was held on 15–17 August in Albuquerque, USA. Sessions included enhanced heat transfer, combustion instrumentation and diagnostics, and natural and mixed convection heat transfer. The Fourteenth International Symposium on Air-Breathing Engines held in Florence, Italy on 5–10 September discussed aero-thermo-elasticity, engine diagnostics and cooling, and combustion. A Conference on Microgravity Fluid Physics and Heat Transfer held in Kona, Hawaii, USA on 19–24 September covered capillarity and two-phase flows, bubble dynamics and boiling heat transfer in microgravity. The annual International Mechanical Engineering Congress and Exposition (IMECE) was held in Nashville, USA on 14–19 November. The Heat Transfer Division of the ASME held sessions on modeling issues in bio heat and mass transfer, thermal hydraulics of advanced nuclear reactors, microscale and mesoscale energy systems, and direct energy conversion.

Awards presented during the year include:

The Max Jakob award for 1998 was presented to Alexander Leontiev for his fundamental contributions to convective heat transfer, as exemplified by his application of the limiting laws to heat and mass transfer in turbulent boundary layers. The Donald Q. Kern award instituted by the AIChE was awarded to Dr. Peter Wayner for his work on thin films and two-phase flows. The Heat Transfer Memorial Awards were presented to Dr. Soung M. Cho (Art) for technical contributions in the design of advanced heat exchangers and steam generators, Dr. Avram Bar-Cohen (General) for his scholarly work contributing to a greater understanding of immersion cooling and cooling of electronic devices, and to Dr. Sanjoy

Bannerjee (Science) for definitive experimental studies and numerical simulations in multi-phase processes and turbulence at gas–liquid interfaces.

Books published during the year include:

1. J.P. Hartnett, T.F. Irvine, G.A. Greene (Eds.), Advances in Heat Transfer, Vol. 33, Academic Press, New York.
2. M. Lehner, D. Mewes (Eds.), Applied Optical Measurements, Heat and Mass Transfer, Springer, Berlin.
3. Arthur T. Johnson, Biological process engineering: an analogical approach to fluid flow, Heat Transfer, and Mass Transfer Applied to Biological Systems, Wiley, New York.
4. R.F. Barron, Cryogenic Heat Transfer, Taylor & Francis, London.
5. G. Comini (Ed.), Computational Analysis of Convection Heat Transfer, Computational Mechanics.
6. J.M. Coulson, J.F. Richardson, J.R. Backhurst, J.H. Harker, Coulson and Richardson's Chemical Engineering: Fluid Flow, Heat Transfer and Mass Transfer, Butterworth-Heinemann, London.
7. W. Roetzel, Y. Xuan, Y. Xuan, Dynamic Behaviour of Heat Exchangers, Developments in Heat Transfer, Computational Mechanics, vol. 3.
8. J. Vilemas, P. Poskas, A.A. Zhukauskas, Effect of Body Forces on Turbulent Heat Transfer in Channels, Begell House.
9. W.S. Janna, Engineering Heat Transfer, CRC Press, Boca Raton, FL.
10. Je-C. Han, S. Dutta, S. Ekkad, Gas Turbine Heat Transfer and Cooling Technology, Taylor & Francis, London.
11. K.C. Rolle, Heat and Mass Transfer, Prentice-Hall, Englewood Cliffs, NJ.
12. P. Fauchais, J. Van Der Mullen, J.V.R. Heberlein, Heat and Mass Transfer Under Plasma Conditions, Academy of Sciences, New York.
13. J.S. Lee (Ed.), Heat Transfer 1998: Proceedings of the 11th International Heat Transfer Conference, Taylor & Francis, London.
14. S. Kakac (Ed.), Heat Transfer Enhancement of Heat Exchangers, Kluwer Academic Publishers, Dordrecht.
15. J.C. Heinrich, D.W. Pepper, Intermediate Finite Element Method: Fluid Flow and Heat Transfer Applications, Taylor & Francis, London.
16. M.N. Ozisik, H.R. Orlande, Inverse Heat Transfer: Fundamentals and Applications, Taylor & Francis, London.
17. M. Iguchi, W. Wahnsiedler, O.J. Ilegbusi, Mathematical and Physical Modeling of Materials Processing Operations, CRC Press, Boca Raton, FL.
18. B. Sunden, M. Faghri, Modelling of Engineering Heat Transfer Phenomena, Computational Mechanics.
19. D. Kessler, R. Greenkorn, Momentum, Heat and Mass Transfer Fundamentals, Marcel Dekker, New York.
20. B. Sunden, P. Heggs (Eds.), Recent Advances in Analysis of Heat Transfer for Fin Type Surfaces, Computational Mechanics.
21. C. Clauser, Thermal Signatures of Heat Transfer Processes in the Earth's Crust, Springer, Berlin.
22. J.W. Van Heuven, W.J. Beek, K.M.K. Muttzall, Transport Phenomena, Wiley, New York.

2. Conduction

Various aspects of conduction heat transfer are overviewed in this section. The sub-topics are categorized as: contact conduction/contact resistance; composites or heterogeneous media and materials processing; microscale heat transfer aspects and laser/pulse heating and heat waves; heat conduction in solids; modeling and simulation/experimental studies; thermomechanical problems; inverse problems and applications; conduction–convection and flow effects; microelectronic heat transfer and applications; and specialized and miscellaneous applications involving heat conduction.

2.1. Contact conduction/contact resistance

Contact conduction and contact resistance papers appear in this sub-category. The aspects of thermal constriction resistance between two solids for random distribution of contacts appear in [1A]. The thermal conduction of cylindrical joints is described in [2A]. The thermal contact conductance of sintered copper coatings on ferro-alloy [3A], effects of contact and spreading resistance dealing with heat sink cooling performance [4A], interfacial contact resistance of single crystal ceramics for solar concentrators [5A], the thermal spreading resistance in multi-layered contacts with applications to contact resistance [6A], that deal with silicone rubber to AISI 304 contacts [7A], and computer simulations of the effect of thermal contact resistance on cooling time in applications such as injection molding [8A] appear in this sub-category.

2.2. Composites or heterogeneous media and materials processing

A model dealing with heat transfer in grinding is described in [9A]. The comparison of the effective thermal conductivity and contact conductance of fibrous composite media is studied in [10A]. From another application viewpoint, the determination of the thermal conductivity and diffusivity of materials such as wood was studied in [11A].

2.3. Microscale heat transfer, laser/pulse heating, and heat waves

As in the previous years, there appears to be a continued interest in these topic areas. The range of problems is varied with applications focused on thin films subjected to short pulse lasers and the determination of their thermal behaviors or thermophysical characteristics; heat conduction due to phonon waves in thin films and superlattices and superconductors; heat waves and propagation and prediction; development of constitutive heat conduction models with/without features for characterizing finite/infinite propagation speeds; and alternate approaches employing developments emanating from Boltzmann Transport Equations (BTE), molecular dynamics simulations, kinetic theory-based approaches and the like. These and related developments have been studied and appear in [12A–31A].

2.4. Heat conduction in solids of arbitrary geometries

A study on conduction of heat in spheriods appears in [32A]. That dealing with conduction trees with spacing at the tips appears in [33A]. The influence of order–disorder transition on thernal conductivity and thermal conduction through a molecule appears in [34A,35A]. Studies involving fins of different shapes such as circular and annular disc fins [36A,37A,39A,40A], and other geometries involving arrays of thin strips [38A] also appear in the literature.

2.5. Modeling and numerical simulations and/or experimental studies

As in most years, this sub-category always enjoys continued interest and is widely popular in a variety of problems encountered in heat conduction. The range of approaches employed include finite difference, finite element, boundary element and finite volume techniques and the like. The range of issues encompass development of new techniques and approaches for more effectively and accurately simulating existing or new problems involving heat conduction; or the simple use of existing techniques to help shed insight into heat conduction problems. Also available are studies involving experimental and/or comparative results for specific applications to heat conduction problems. The aforementioned studies are described in [41A–64A].

2.6. Thermomechanical problems

Thermal effects on materials and structures are an important aspect and few papers appear in this sub-category. Thermoelasticity with contact [65A], models for textile composites at high temperatures [66A], simulation of residual stresses and distortion in stepped cylinders [67A], stress distribution in thermally tempered glass panes [68A], analysis of thermal stresses in a boiler drum during start-up [69A], and the application of a hybrid method for predicting transient thermal stresses in isotropic annular fins [70A] appear in the literature.

2.7. Inverse problems and applications

The papers appearing in this sub-category included three-dimensional boundary value inverse heat conduction [71A], determination of time-dependent heat transfer coefficient [72A], a sequential gradient method [73A], application of a conjugate gradient method for three-dimensional heat conduction problem [74A], estimation of initial temperature profile and its evolution in polymer processing [75A], and the determination of two heat sources in an inverse heat conduction problem [76A].

2.8. Convection and flow effects

A study dealing with the control of Marangoni–Benard convection [77A], heat transfer from catalysts via CFD [78A], a gas-kinetic scheme for the Euler equations with heat transfer [79A], and a study describing heat and momentum transfer in fluids heated in tubes with turbulence generators at moderate Prandtl and Reynolds numbers [80A] appear in this sub-category.

2.9. Microelectronic heat transfer and related applications

The dynamic in situ measurements of head-to-disc spacing [81A] and a heat transfer model for thermal fluctuations in a thin slider/disk air bearing [82A] are described in the literature.

2.10. Miscellaneous studies and applications

A variety of miscellaneous studies and specialized applications dealing with heat conduction have been investigated and appear in [83A–93A].

3. Boundary layers and external flows

Papers on boundary layers and external flows for 1999 have been categorized as follows: flows influenced externally, flows with special geometric effects, compressible and high-speed flows, analysis and modeling techniques, unsteady flow effects, flows with film and interfacial effects, flows with special fluid types and property effects and flows with reactions.

3.1. External effects

Papers which focus on external effects document the influence of flow conditions imposed upon the boundary layer [1B–3B,6B,9B–12B,14B,16B–18B,21B–23B], flow instability effects [15B], heat generation effects [4B], electric effects [7B,8B] and magnetic fields [5B,19B]. The effects of wakes from a cylinder adjacent to the boundary layer were characterized with a quadrant splitting method [17B], the influence of elevated free-stream turbulence on turbine blade flow was experimentally documented [21B] and the effects of turbulence from a co-current stream on heat transfer to a wall jet were quantified [14B]. The effects of agitation with a double disc turbine were described and related to single disk behavior [12B]. Strong augmentation due to swirl was documented [22B] as was the influence of putting vortex generators on the surface to introduce vorticity within the boundary layer [16B] or having the vorticity develop naturally in the form of Goertler cells [15B]. The effects of introducing a streamwise pressure gradient to a boundary layer were computed [11B] and the effects of having streamwise curvature on turbulent boundary layer transport were measured [10B]. For a laminar boundary layer, the effects of blowing and suction were computed and compared with analysis [1B], blowing effects were numerically analyzed for hypersonic flow past a sphere [23B], integral analysis was used to describe the effects of injection and blowing on turbulent boundary layer flow [18B] and effects of suction and injection through a sheet moving in a flowing fluid were analytically described [6B]. A new approach to computation of blowing effects on turbulent boundary layers was presented [2B] and applied [3B] and heat transfer of a compressible gas with alternating blowing and suction was described [20B]. The effects of Schmidt number on turbulent mixing with a jet in cross-flow were discussed [9B]. Emphasis was on the appropriateness of assuming constant Schmidt number in the analysis. The influences of an oblique electric field on flow stability were documented [7B] and the enhancement of heat transfer by an electric field on an emulsion droplet was quantified theoretically [8B]. The influences of magnetic fields were evaluated for a vertical stretching surface under natural convection flow [4B] and under mixed convection [5B] while the effects of a magnetic field on the stagnation-point region of a three-dimensional body were described by analysis [13B]. The effect of Prandtl number was noted for a flow with an aligned magnetic field [19B].

3.2. Geometric effects

Papers in this category could be categorized as those with roughness effects [31B,28B,40B], large features on the surface [26B,45B,25B,52B], fins and louvers [50B,48B,47B,38B,43B,34B,46B], geometric effects that affect the thermal conditions [49B,24B,36B,27B,32B], stretching sheets [35B,51B,39B,37B], particular body shapes [30B,33B] and those with conjugate heat transfer effects [44B,29B,42B,41B]. Papers which dealt with roughness included one on the effects of roughness length [31B], another regarding wing icing effects [28B] and a third on the effects of soil and plant communities on atmospheric boundary layer heat transfer [40B]. The section on surface mounted obstacles included one paper on laminar flow over a square micro-obstacle [26B], another was a transient simulation of flow over an electronic module [45B], a third was for transitional flow over an array of heated blocks [25B] and the last was an experimental and numerical study of flow over channel-mounted, two-dimensional obstacles [52B].

Several papers dealt with heat exchanger geometries, including louvered fins with fully developed and developing flow [50B] and flow within the finned entry region [48B], extended fins on two-rows of tubes [47B], horizontal ribs on a rectangular plate [38B], longitudinal ribs in an internal flow passage [43B], winglet vortex generators in a compact fin and tube heat exchanger [34B] and spirally indented tubes [46B].

For some papers, the geometry affected the boundary conditions: the nocturnal cooling in urban parks [49B], heat transfer from patchy urban surfaces [27B], open waters around thin ice and thick ice [24B], urban street canyons [36B] or leaf canopies [32B].

Several papers dealt with stretching surfaces. In one, the fluid was electrically conductive [35B], another was influenced by a magnetic field [37B], a third was with a second-grade fluid [51B] and in a fourth, the surface was exponentially stretching [39B].

A couple of papers dealt with body shape effects. One was a general study of body shape and position [30B] and another was with compressible flow over a sphere [33B].

Studies with conjugate effects include flows through a circular fracture of a rock [44B], flow over a body with anisotropic conduction properties [29B], the thermal striping effect experienced in liquid metal flows in a fast breeder reactor [42B] and heat transfer through a wall with natural convection on one side and forced convection on the other [41B].

3.3. Compressibility and high-speed flow effects

In this category, there was a study of aerodynamic heating of a plate [57B], another investigated the effects of airfoil shape on aerodynamic heating [58B]. Several were with non-equilibrium effects; one on the influence of molecular vibration and transport modeling [60B], another on the non-equilibrium kinetics of a re-entering body [53B] and a third in a supersonic air nozzle flow [55B]. An artificial viscosity model applied to the analysis of a strong shock was shown to have excellent shock-capturing capabilities [54B]. One paper presented a numerical simulation of flow over a long thin moving cylinder [59B] and another presented a coupled thermal model for panel flutter at high Mach number [56B].

3.4. Analysis and modeling

A review of turbulent heat transfer modeling was presented in the Annual Review [73B] and the conceptual models of turbulence developed over the years were used to discuss the correlation of experimental data and recent DNS results [63B]. Fractal modeling was applied to turbulent mixing of reactants [74B] where the analytical expressions were used to study turbulent combustion. A statistical model of particle transport was applied to two-phase flow with emphasis on the near-wall flow behavior [76B]. Variational theory of relaxation of the Onsager type was shown in one paper to be compatible with the engineering approach to heat and mass transfer [71B]. Various turbulent Prandtl number closure models were evaluated [72B]. The effects of thermal stress induced by temperature gradients were described while the applicability of the Burnett equation was discussed [67B]. The law of the wall was modified for application to swirling flows so that perturbation analysis could be applied [66B]. Application of the technique to other non-linear problems was discussed. Asymptotic methods based upon geometrical optics were applied to flows of high Peclet number [62B]. The temperature away from the body could be expressed as a sum of contributions from each stagnation point, in some instances. Conjugate heat transfer with laminar flow over a flat plate was analyzed with an integral technique [69B]. The results were discussed in terms of the local Brun number. A spreadsheet simulation was applied to laminar-free convection [68B]. A method for rapid computation of the temperature of hot combustion gases flowing inside of a chimney was presented [64B]. Results are used for the estimation of air pollution in the vicinity of the stack and the possibility of acid condensation on the inner liner. The computation of boundary layer-forced convection with high free-stream turbulence was addressed while various k–ϵ models were evaluated [65B]. Weaknesses were noted and physical reasons were presented. The k–ϵ model of closure was applied to the flow and turbulent mixing in a non-compressing piston engine-like geometry [61B]. The results were compared against experiments. Direct numerical simulation was applied to high-Prandtl number flows where the pressure-temperature-gradient correlation is dominant [75B]. The low-wave number components of velocity fluctuations were solely responsible for the cascade of temperature fluctuations. Finally, an analysis with modified boundary conditions applied to the non-penetrative convection boundary condition problem was evaluated for application to planetary boundary layers [70B].

3.5. Unsteady effects

Flows in this category include five in which the unsteadiness is imposed [79B,86B,78B,83B,80B], four in which the flow is naturally unstable, and one in which the thermal boundary conditions are varied. In the first sub-category, temperature fluctuations are computed for the unsteady flow of a driven cavity [79B] and experiments [86B] and analysis [78B] were performed with unsteadiness due to an upstream moving wake on the heat transfer from a curved wall. In the latter, a boundary layer transition model was presented. Two papers were on unsteadiness due to a cylinder adjacent to the boundary layer, one investigated the departure from Reynolds analogy [83B] and another searched for coherent structures [80B]. In the latter, a multi-point, hot-wire rake was employed to look for correlations in velocities. The effects of stability of a laminar wall jet on heat transfer were evaluated experimentally and analytically [84B] and the effects of large injection rates on unsteady mixed convection in a three-dimensional stagnation point region were numerically evaluated [81B]. Mass transfer enhancement of chaotic laminar flow within a droplet translating by buoyancy through an entraining flow was described [77B] and experiments and theory were applied to laminar spray diffusion flames which show oscillatory behavior, the genesis of which is from the heat and mass transfer mechanisms [82B]. Finally, a numerical solution is presented for convective heat transfer on a plate which was impulsively cooled or heated [85B].

3.6. Films and interfacial effects

Only three papers fell into this sub-category, a significant decrease from last year's review. The first is an experimental study of thin suspension films where the enhancement of heat transfer due to putting PVC particles in the flow was shown [89B]. In the second, a numerical study was performed on a falling liquid film. The means by which the interfacial waves enhance heat transfer were described [87B]. The third showed the results of an analysis of gravity-driven flow of a power-law fluid. A critical Prandtl number was defined and applied to the analysis [88B].

3.7. Effects of fluid type or fluid properties

Several papers in this category dealt with power-law fluids. In one, an approximate analytical solution was applied to a laminar boundary layer [92B]. In another, the heat transfer problem was with arbitrary injection and suction at a moving wall [101B]. Results of a study of the coupling of heat and momentum transfer were discussed for a flow of a drag-reducing polymer and surfactant solution [90B]. The data showed that no decoupling of momentum and heat transfer was seen at the onset of drag reduction, this is contrary to some earlier literature. Heat transfer in a mixed flow of a highly viscous fluid was computed [95B]. Wall heat transfer coefficients were presented. The effects of variable properties were described in the case of heat transfer on a continuous flat surface moving in a parallel free stream [93B]. The assumption of constant properties was shown to lead to significant error. Modeling of heat and mass transfer rates for deposition of sodium sulfate in a heated flow of supercritical water was presented [102B]. The model results matched the experimental values for salt deposition rate. Several papers dealt with micropolar fluids. One was an analysis of laminar flow past a wedge [96B]. The heat transfer rate for a micropolar fluid was shown to be lower than that of a Newtonian fluid. Two others were for a micropolar fluid flow on a continuous moving surface [94B,97B]. The micropolar fluid displayed drag and heat transfer reduction characteristics. Several papers investigated particle-laden flow. In one, stochastic simulation was conducted in isotropic turbulent flow [98B]. The importance of several effects not captured by this model was discussed, using comparisons to DNS. The heat transfer from an obstruction with a dilute gas particle suspension flow was computed [99B]. Both the particle size and concentration were shown to affect heat transfer. The effects of particle-phase diffusivity and viscosity on compressible boundary layer heat transfer were computed [91B]. Wall heat transfer rates were given. Field test data for sublimation in turbulent flow laden with snow were presented [100B]. It was concluded that blowing snow physics must be incorporated in land surface and hydrological models.

3.8. Flows with reactions

The sub-category of flows with reaction continues to be an active one with most of the papers presenting analyses of combustion flows. In an exception, a system for developing a liquid phase agitated reactor was presented [112B]. Knowledge of reaction and mixing at various length scales was applied. Also, a numerical simulation of non-isothermal gas–liquid adsorption in chemical reaction of a laminar film was presented [113B]. It was applied to absorption of phosgene. A combustion paper focused on carbonized semi-coke particles [110B] while another was a study of unsteady burning of *n*-heptane droplets [104B]. Several papers were on plate geometries; one was for laminar flow along a semi-infinite horizontal plate [103B], another was with microgravity [114B] while another was with fuel injection [115B]. The movement of the three-dimensional cellular flame at low Lewis numbers was numerically investigated [105B]; the conditions on Lewis number under which hydrodynamic effects were important were identified. Time-dependent computations of turbulent bluff-body diffusion flames close to extinction were computed with a combination of computational tools, depending on the region of the flame being analyzed [106B]. A numerical simulation of a two-dimensional, jet premixed, CH_4/air flame was presented [116B]. Emphasis was put on the influence of detailed chemical kinetics on flame temperature and species distributions. A Monte Carlo PDF computation was applied to spray flames to show the value of applied parallel computing techniques [111B]. The application to confined, swirl-stabilized spray flames was shown to be reasonable. The effects of combustion on turbulence in a premixed, supersonic, diffusion flame were investigated using DNS [109B]. A simple mechanism for describing this effect was presented. Two papers were more focused on combustion systems; one was a simulation of the combustion in a W-Shaped boiler furnace [108B] and another discussed the application of flamelet profiles to flame structures in practical burners [107B].

4. Channel flows

4.1. Straight-walled ducts

A considerable number of numerical modeling studies were conducted in straight-walled ducts with a variety of boundary and initial conditions. The turbulent-forced convective heat transfer at low Reynolds numbers was modeled using the non-linear k–ϵ model, combined with the LamBremhorst and Abe–Kondoh–Nagano damping functions [23C]. The RNG model was applied to a turbulent flow in a straight-walled duct [24C]; arbitrary three-dimensional ducts were also modeled using four different Reynolds stress models [25C]. A numerical study was carried out to determine the uncertainties of fluid properties on the heat transfer characteristics of a heated smooth tube [27C]. The thermally developing Poiseuille flow was modeled to evaluate the impact of radiation [1C]. The CONTAIN computer code was used to study the heat and mass transfer to asymmetrically heated vertical channels [31C]. The SIMPLER method was employed to study the absorption process on a horizontal tube with surface-tension effects [18C]. An error assessment was conducted for flow fields in draft tubes to determine the potential for overall efficiency improvements in hydro power applications [6C]. A perturbation method was used to examine the fully developed flow and viscous heating in a vertical channel [4C]. The k–ϵ model with variable Prandtl number was used to study heat transfer in air flows [26C]. Direct numerical simulations (DNS) in fully developed channel flows were used to assess the effects of Prandtl number on the temperature fields [21C]. DNS was also used in the study of passive scalar transport in a free-shear boundary of an open channel flow [11C]. Prandtl and Reynolds number effects were studied in a turbulent channel flow using DNS [15C]. DNS studies of channel flows up to $Re_\tau = 590$ were reported [20C]. Temperature-dependent viscosity was examined numerically for laminar mixed convection in a horizontal duct [22C]. Laminar viscous dissipation in rectangular ducts was analytically determined [19C]. A numerical analysis of a strongly heated gas flow was conducted in circular tubes [10C]. The impact of reference temperature on the fully developed mixed convection in vertical channels was studied [5C]. Buoyancy and viscous dissipation were considered in the vertical flow in a circular duct [3C]; isoflux boundary conditions were studied as well [2C]. The dual reciprocity boundary element method was used to study laminar heat convection in a concentric annulus with constant heat flux boundary conditions [7C]. The general turbulent heat transfer correlation of Maciejewski and Anderson was tested experimentally [8C]. Experiments on ternary distillation were made for a nitrogen–argon–oxygen system in a wetted-wall column [9C]. The influence of recycle on double-pass parallel-plate heat and mass exchangers with uniform wall temperature was studied analytically [12C]. The turbulent convective heat transfer was modelled for water near the critical point [13C]. Transient flow conditions and heat transfer were studied in turbulent pipe flow [14C]. Buoyancy effects on plane Poiseuille flow heated isothermally from below were analyzed [16C]. The analytical solution of the Graetz problem with axial conduction was studied [17C]. Similarity laws for heat and momentum turbulent transport from low-Prandtl number fluids were considered [29C]. Coupled temperature and density are considered in rarefied-gas dynamics using the discrete ordinates method [28C]. One study considered the numerical solution of unsteady conjugated mixed-convection heat transfer in a vertical plate channel [30C]. Radiation effects were considered on the heat transfer of laminar mixed convection flow in an inclined square duct [32C].

4.2. Microchannel flow

Microchannel heat transfer was examined to determine the enhancement of forced convection heat transfer due to the release of dissolved non-condensibles [34C]. Experimental results were presented for single-phase forced convection from deep rectangular microchannels [36C]. Microtubes of fused silica and stainless steel were studied experimentally using water flow and tube dimensions from 50 to 254 μm [39C]. A two-layered microchannel heat sink was considered in a countercurrent flow arrangement; the arrangement was proposed for electronic cooling [40C]. The effect of microgrooves on the flow characteristics in coupled liquid and vapor flow in miniature passages was considered [38C]. Flat miniature heat pipes were studied and found to be promising in the area of the cooling of electronic components [37C]. Traditional turbulent heat transfer was studied in non-circular microchannels [33C]. Viscous-dominated flow in a micro-channel was studied; the phenomenon called "mathematical choking" was examined [35C].

4.3. Irregular geometries

A wide variety of geometries were considered in the literature. Laminar flow and heat transfer in square serpentine channels with right angles was simulated [46C]. Heat transfer augmentation in a channel was examined using concavities in contrast to the more common approach of using protruding elements [47C]. The complex-variable boundary element method was used to analyze forced convection in cooling passages with general convex cross-sections [50C]. The heat and mass transfer characteristics in a two-pass smooth channel with a 180° turn were examined experimentally [52C]; a 180° turn was also studied with different divider thicknesses [56C]. Straight and 90° turn trapezoidal ducts were studied using a transient liquid crystal method [54C]. A numerical study of the laminar mixed-convection heat transfer of air in concave and convex channels was conducted; a large parametric space was considered [58C]. Flow and heat transfer characteristics in a sinusoidal wavy passage were studied experimentally [61C]. Trapezoidal and hexagonal ducts were studied under fully developed conditions using finite difference methods [62C]. Elliptic and rectangular cross-sectioned ducts were examined for incompressible laminar flow with constant properties; finite difference methods were used [63C]. Localized heat sources were modeled in a channel using fibrous materials [41C]. Experiments were conducted to determine local heat transfer coefficients at the junctions of rectangular channels [43C]. The general expression for the spreading resistance of an isoflux, rectangular heat source on a two-layer rectangular Bur channel was presented [69C]. The vortex shedding by an oblique plate was used to enhance the heat transfer of mixed convection flow [67C,68C]. Correlation of fully developed heat transfer and pressure drop in a symmetrical grooved channel was provided [66C]. The symmetrically coupled Gauss–Seidel-based multi-grid method was investigated by applying it to three-dimensional conjugate heat transfer [65C]. The developing flow and heat transfer in a wavy passage were studied numerically [64C]. A finite element solution of the flow and heat tranfer in a cross-flow tube-fin compact heat exchanger was presented [60C]. A numerical study of conjugate heat transfer in an inclined tube was conducted [59C]. An experimental study of heat transfer from a vertical tube in a gas–solid spouted bed was used to assess several parametric effects [57C]. The heat transfer in gas turbines blades was studied experimentally by studying a pin–fin trapezoidal duct [53C]. One paper considered the influence of rib-roughness on the turbulent flow in gas turbine passages [55C]. The numerical solution of laminar and transitional flow was provided to evaluate the heat transfer in cross-corrugated ducts [42C]. A joint experimental and numerical study of fully developed forced convection in large rectangular ducts was presented [48C]. Buoyancy-assisted and buoyancy-opposed flow in inclined semicircular ducts was studied numerically [44C]. A concentric annulus with peripherally varying and axially constant heat flux was investigated theoretically [45C]. Tapered capillaries were modeled [49C] as was the cavity outflow from a nearly horizontal pipe [51C].

4.4. Finned and profiled ducts

The heat transfer in a turbulent square channel with v-shaped broken ribs was investigated experimentally and numerically [70C]. Turbulent heat transfer and pressure drop in annular regions with rectangular fins were studied experimentally [72C]. The influence of periodically arranged rib-roughness elements was studied experimentally and numerically [73C]. One study considered the optimisation of the geometry of tubes with internally asymmetrical fins under laminar flow conditions [78C]. The heat transfer and fluid flow in rib-roughened rectangular ducts was experimentally investigated [83C]. DNS simulation was used to study the flow in a rib-roughened channel [84C]. A numerical study was conducted on the turbulent flow and heat transfer in internally finned tubes [86C]. Local heat transfer measurements were made in a rig-roughened serpentine passage with a 180° sharp bend [88C]. Turbulent heat transfer was studied in inner heated annuli with artificially roughened outer walls [89C]. Symmetric and asymmetric rough walls were investigated for fully developed turbulent flow in ducts [91C]. The experimental and numerical study of rib angle, rib pitch, rib height and rib configuration were addressed in one study [95C]. Periodically mounted transverse vortex generators were studied numerically in a Reynolds number range from laminar to oscillatory transitional [101C]. Internally wave-like longitudinal fins were studied experimentally; pressure drop and heat transfer characteristics were considered [105C]. An experimental study of heat transfer in a reciprocating square-sectioned duct fitted with transverse ribs was conducted [76C,77C]. The heat transfer and pressure loss characteristics of flow in channels with flush-mounted and protruding heat sources were examined experimentally [102C]. A spirally finned tube was studied numerically for fully developed flow conditions [106C]. The absorption process of water vapor into lithium bromide solution was reported; experimental heat and mass transfer results were presented [104C]. The influence of flow velocity and fin spacing on the heat transfer characteristics from an annular-finned tube was found in the literature [103C]. The forced convection heat transfer from flush-mounted discrete heat sources was studied experimentally [99C]. Alternate attached-detached rib-arrays in rectangular ducts were studied experimentally [98C]. A three-dimensional computational study of conjugate heat exchangers was conducted for wavy fin surfaces [97C]. A rib-roughened square channel experiencing a 45°turning was studied [96C,71C]. Experimental work described the heat transfer from a rough-smooth annulus where small regions with ribbing had been removed [93C]. The placement of a cylinder of various aspect ratios in a channel was studied experimentally [90C]. Rectangular fin-tube arrangements were investigated; thermal and geometrical parametrics were considered [75C]. The influence of streamwise vorticity on frost growth was studied in steady, laminar flow in a channel [94C]. A three-dimensional computational method was used to study the flow and heat transfer in internally finned tubes with multilobe vortex generators [100C]. A numerical study considered laminar natural convection in horizonal annuli with radial fins [92C]. The heat transfer efficiency of fine metal honeycombs was studied [87C]. The impact of imbedded longitudinal vortices was examined in a turbulent channel flow [85C]. The turbulent heat transfer in internally finned tubes was experimentally studied [82C]. Temperature fields in turbulent channel flows were studied for smooth and rough walls [81C]. The effect of sinusoidal protuberances on the natural convection in a vertical concentric annulus was considered [80C]. Experiments were conducted to determine local flow and heat transfer characteristics within the finned region of a cowled, annularly finned cylinder [79C]. A channel flow perturbed by turbulent flow separation was studied [74C].

4.5. Channel flows with periodic motion and secondary flow

Laminar-forced convection in a circular duct was studied for the case of sinusoidal variation of the axial heat flux [107C]. Mass transfer enhancement caused by pulsatile laminar flow in an axisymmetric wavy channel was examined numerically [113C]. A swirl chamber with and without inlet forcing due to vortex generators was investigated [119C]. Temperature measurements were made in pulse tube flow using Rayleigh scattering [111C]. Pulsation due to resonance and the concomitant impact on heat transfer was studied in a turbulent pipe flow [120C,121C]. Pulsatile turbulent flow was also studied at various frequencies, amplitudes and Reynolds numbers [110C]. A numerical study was undertaken to better understand the swirling flow in a sudden-expansion dump combustor configuration; the SIMPLER algorithm was employed [108C]. Secondary flow and the associated heat transfer characteristics were studied in horizontal parallel-plate and convergent channels heated from below [109C]. A numerical solution was presented on the laminar swirling flow between two fixed cones having the same apex angle [115C]. Thermal design correlations for turbulent flow in helically enhanced tubes was found in the literature [116C]. The role of inlet turbulence on the development of flow and heat transfer in a helically coiled pipe was studied numerically [114C]. The swirling flow and heat transfer phenomena relevant to internal turbine blade cooling were studied [112C]. Entropy generation, heat transfer and irreversibility were investigated for swirling flow in a circular duct with restriction [122C]. A rectangular channel subject to concave heating was investigated experimentally [117C]. The local heat transfer characteristics along narrow channels was investigated by holographic interferometry [118C].

4.6. Multi-phase channel flow

Fluid-to-particle heat transfer coefficients were examined using a calorimetric approach under tube-flow conditions [131C]. Local measurements were made at high pressure and low temperatures in a droplet-laden vapor core in upward R-134a annular flow of a vertical duct [129C]. Heat transfer results were presented for two-phase He II flow in a horizontal duct [128C]. Comparisons were made of 20 two-phase heat transfer correlations; seven sets of data were used including flow pattern and tube inclination effects [127C]. Two-phase flow patterns were studied in small diameter round and rectangular tubes [125C]. Heat transfer enhancement due to slug bubbles passing through a capillary channel submerged in a liquid was modeled [124C]. The flow and heat transfer characteristics of a slurry containing microencapsulated phase-charge materials were investigated experimentally [130C]. A theoretical model was developed to analyze the thermal storage and heat transfer characteristics in a phase change material outside a circular tube with heat transfer fluid inside the tube [132C]. The oil–air–water three-phase flow through a helically coiled pipe was studied experimentally; the goal of the work is to develop new flow separation technology [123C]. Computational results are presented for the heat dissipation rate per unit area in a sheared granular flow [126C].

4.7. Non-Newtonian flow

A theoretical study was conducted to evaluate the heat transfer characteristics of a power-law fluid in a porous channel with constant wall heat flux and constant temperature [133C]. The heat transfer behavior of a non-Newtonian fluid was studied in a 2:1 rectangular channel; the Reiner–Rivlin constitutive relation was used to model the fluid [138C]. The steady heat transfer to water and purely viscous non-Newtonian fluid films falling down a vertical tube was measured for uniform wall heat flux of a power-law fluid [137C]. A theoretical model of laminar flow of non-Newtonian fluids is presented; heat transfer characteristics were the primary focus of the study [134C]. The heat transfer reduction parameters were quantified [135C]. The steady-state heat transfer associated with mixed lubrication involving significant frictional heating was studied [140C]. The entrance region of viscoplastic materials inside tubes was analyzed; the material viscosity was modeled by the Herschel–Bulkley equation [139C]. The laminar flow of a Bingham plastic in a circular tube with uniform wall heat flux was studied [136C].

4.8. Miscellaneous channel flow

The three-dimensional flow and heat transfer in the Sulzer SMX static mixer was computed; both Newtonian and non-Newtonian power-law fluids were considered [146C]. Drag reduction and the corresponding heat transfer reductions were examined in internally grooved rough tubes; a surfactant solution of Ethoquad O/12 was used [143C]. The fully developed, laminar, steady, free- and forced-convection heat transfer in an electrically conducting fluid was studied numerically [141C]. Experiments were carried out to determine the effect of air extraction on the flow uniformity in a combustor [147C]. Unsteady heat transfer to compressible fluids though the acoustic-heat release coupling was studied [145C]. The concept of a time-invariant turbulent flame speed is used to develop a kinematic model of the response of a flame to flow disturbances [144C]. The combustion process in a channel with supersonic inlet conditions was investigated [142C].

5. Separated flows

Flows experiencing abrupt changes in geometry are often plagued by separation and reattachment. The general category of separated flows considers a variety of geometries including: sudden expansions; flows past bluff objects; flows experiencing shock interactions; and the myriad of tube bundle configurations common in heat exchangers. The three-dimensional flow and heat transfer over a backward-facing step was examined using the SIMPLER method [28D]. A numerical study was also conducted of the transient mixed convection on a backward facing step [15D]. The laminar flow of a non-linear viscoplastic fluid was studied in a combined experimental and numerical study; the axisymmetric sudden expansion was considered [13D]. The average Nusselt number is computed for laminar-mixed convection from an isothermal cylinder in crossflow [1D]. The thermal-fluid behavior behind a heated horizontal cylinder is studied experimentally using two-dimensional particle tracking velocimetry [18D]. Overall heat transfer coefficients were determined experimentally for U-bends in crossflow [14D]. The flow over a rectangular solid body with constant heat flux was investigated; entropy analysis was presented using a numerical control volume approach [30D]. Similarity solutions of unsteady laminar flow of compressible two-dimensional and axisymmetric boundary layers were presented [32D]. Analytical solutions for the transient analysis of two-dimensional cylindrical pin fins with tip convection were provided [31D]. The study of transition and turbulence in hypersonic blunt-body wake flows indicated that transition was the result of the instability of the free shear layer emanating from the shoulder [27D]. Prandtl number effects were examined in convective turbulence [33D]. Non-equilibrium chemistry models were studied by comparison to experiments conducted in a shock tunnel; the double-wedge flow was considered [29D]. Experimental results were presented of the local heat transfer on a wall-mounted cube placed in a developing turbulent channel flow [25D]. Spatially periodic cubes placed on one wall of a plane channel were studied; both vortex structure and heat transfer characteristics were considered [24D]. The heat transfer and fluid flow past large horizontal cylinders were studied experimentally in water; the cylinder was held at uniform heat flux [19D]. Numerical studies of blunted leading-edged airfoils were used to create analytical models for peak heat transfer rates [12D]. Experiments were performed to investigate the heat transfer over a heated oscillating cylinder; local heat transfer measurements were complimented by flow visualisation studies [10D]. Local and surface-averaged heat transfer measurements were made in convex-louvered fin arrays [9D]. The effects of thermal boundary conditions on the modeling of heat transfer from pins and endwalls were considered [7D]. A subgrid-scale model was used to study the two-dimensional time-dependent subcritical flow in a staggered tube bundle [5D]. A parametric investigation of supersonic flow of a viscous gas considered angles of incidence and slip [4D]. A numerical approach was used to analyze the transient flow through in-line and staggered tube banks [3D]. A numerical approach based on the adjoint formulation of forced convection heat transfer was proposed [26D]. The exact analytical solution was given for the separating boundary layer flow induced by a continuously stretching surface [23D]. The temperature field in the near wake region of a heated ribbon in air and water was obtained experimentally [21D]. The hypersonic thermochemical non-equilibrium air flow over blunt bodies was examined numerically [22D]. Scale and pressure effects on the performance of combustors were considered using new experimental data [11D]. The classical Leveque solution of heat transfer induced by a small step change in the surface temperature in a shear flow is revisited [20D]. Heat transfer measurements were made to better understand the thermal-fluid characteristics in the leading edge region of a stator vane endwall [17D]. The heat transfer rates from large droplets of a monodisperse spray onto a high temperature surface were measured [8D]. The heat transfer in a bluff-body methane–air combustor was modeled using the probability density function [6D]. A numerical study of the heat convection from a sphere in an oscillating stream was considered in the forced and mixed convection regimes [2D]. The heat transfer from a liquid drop in a liquid environment was studied under creeping flow and moderate Reynolds number conditions [16D].

6. Porous media

6.1. Highlights

6.1.1. Fundamental advances

Basic work continues to seek generality in the description of transport properties, but few experimental studies were reported. There appears to be a rising level of interest in extending the Dary–Brinkman–Forcheimer formulation to the equations of change to systems in which the porous matrix deforms as a result of heating and species transfer. Modeling isotropy near a solid boundary and its effects on heat transfer motivated experimental and analytical studies that appear to have potential for future contributions.

6.1.2. Property determinations

Although no major breakthroughs were reported on predicting the effective thermal conductivity of a saturated porous medium, the literature keeps growing. The majority of research seeks to apply various analytical techniques to the problem. Definitive experiments are yet to have been conceived and realized.

6.1.3. External flow and heat transfer

Most papers published dealt with the heat and mass transfer associated with immersed surfaces. The effects of a variety of thermal and concentration boundary conditions were investigated.

6.1.4. Packed and fluidized beds

This sub-field continues to produce a large number of articles because of the difficulty in generalizing the behavior of packed and fluidized beds. Fluidisation in a confined volume was investigated numerically, and various studies sought to determine wall boundary condition effects on over-bed performance.

6.1.5. Porous layers and enclosures

Studies in this area treated a variety of systems that model those encountered in environmental heat and mass transfer problem. Modeling flow and heat transfer in micromachined channel systems was approached via a volume-averaged porous media model.

6.1.6. Coupled heat and mass transfer

The equations describing coupled heat and mass transfer in porous media remain the subject of much research owing to the difficulty in modeling the physics at whatever length scale intended. Porous and fractured systems received attention largely because of environmental heat and mass transfer problems, and some modeling efforts were extended to multi-component, three-phase systems.

6.2. Fundamental advances

The departure from local thermal equilibrium in conduction transients in a saturated porous medium was characterized by a new dimensionless group, the Sparrow number, that includes the length scales of the pore and system, the interstitial heat transfer coefficient, and the thermophysical properties [6DP]. Another study presented the criteria for local thermal equilibrium in terms of the thermal conductivity ratio [4DP]. Luikov's equations for coupled heat and mass transfer were analyzed to reveal the quantitative basis for the cross-effects of heat and mass transfer in capillary porous media [2DP,11DP].

Two- and three-scale mixture theories were developed to describe hydration and swelling in smectic clays as an advance beyond the classical thermo-consolidation model of non-swelling media [7DP,8DP]. A notable result of the modeling and homogenisation procedures employed is a general inter-phase mass transfer equation. The equations for Darcy flow in a poroelastic medium of low permeability were developed and solved for range flow rates and temperature fields [14DP]. A similar study presented a numerical solution for large Rayleigh number free convection in layers heated from below [16DP]. Wetting phenomena within porous coatings was investigated to gain insight on the changes that such surfaces bring to heat transfer laws and values of the critical heat flux [1DP]. The origin of the Forchheimer term was investigated within a framework set by the momentum and energy balance equations and applied to saturated thermo-eleastic media and multi-phase porous systems; verification with a one-dimensional laboratory model was obtained [5DP]. The effect of either a magnetic field or rotation added to the momentum equation for flow in a porous medium was shown to require a porosity term that is linked to pressure in Darcy's law [10DP].

The effects of isotropy on flow and heat transfer in a porous medium were analyzed via models of viscous flow past a triangular array of cylinders. Isotropy was modeled via the inclination of the cylinder array [15DP], and a boundary perturbation technique determined that the velocity distribution was third-order [13DP]. Turbulence in a porous medium was modeled with a two-equation model and volume-averaged transport [9DP]. The long-standing problem of heat transfer between the fluid and solid phases of a porous medium was modeled by obtaining the local interface Nusselt number numerically and then extracting volumetric Nusselt numbers via integral measurements [3DP]. Related work was presented on the effects of matrix morphology on coupled transport for which a parallel pore model was employed to obtain analytical solutions for permeability and dispersion coefficients [12DP].

6.2.1. Property determinations

Most work on the properties of porous media centered on the effective thermal conductivity, and a comprehensive review of effective thermal conductivity was presented in connection with heat transfer in highly porous chars [26DP]. Studies of specific thermophysical properties included permeability in reactive systems [31DP,34DP], dispersion coefficients [27DP], effects of pressure in defomable media [36DP], and acoustic velocity in aerogels [20DP]. Interesting work on laser attenuation in fluid-saturated porous media was presented [21DP].

Experimental data were obtained on effective thermal conductivity in the form of equations applicable to building bricks [37DP], ammonium chloride [17DP], graphite-calcium chloride composites [22DP], and dry sand [35DP]. An experimental technique was developed for systems in which coupled conductive and radiative heat transfer take place [28DP].

The effective thermal conductivity tensor was predicted by a variety of methods that embraced specific structural models of the matrix, unit cells, cell arrays, and interfacial heat transfer models. Deterministic structural models include a periodic array coupled to the volume-averaged conservation equations [24DP]. A moving reference frame that converts the convection problem to conduction and the unit cell concept were applied to fibrous porous media [23DP]. Fractal theory was applied in another modeling study for high-porosity metal foams [18DP,33DP]. For transient conduction, a closure model that embodies geometrical factors and interfacial heat transfer was applied to periodically packed cubes to determine the effective thermal conductivity [25DP]. Particle-to-particle heat transfer and particle connectivity were the crucial factors in determining the effective conductivity of a packed bed of mono-sized spheres [19DP]. When particles exhibit microasperity gaps and deformed contacts, the effective conductivity was found to be strongly affected by interstitial fluid, contact diameter, and fluid and solid conductivities [32DP].

Material with microcracks was modeled as porous medium to take into account the contact area and average crack opening between grains [30DP]. For high-temperature applications, radiation within gas cavities alters both the local equivalent and the effective conductivities [29DP].

6.2.2. External flow and heat transfer

The majority of studies for the past year concerned transport from very simple impermeable surfaces imbedded in saturated porous media. One of them generalized the transport problem via exact, asymptotic and numerical solutions for convection over sources of various shape, including those at the pore-network scale [48DP]. Another reports experimental data and a correlation for buoyancy-driven mass transfer from spheres embedded in a saturated medium [54DP]. A related analytical study revealed the time and length scales of unsteady mass transport from an immersed sphere at finite Peclet number [40DP].

Mixed and free convection for vertical immersed surfaces were analyzed largely by similarity methods for variable surface heat flux [42DP], variable surface temperature [44DP,46DP,55DP], suction and injection [50DP,60DP,62DP,63DP], temperature-dependent viscosity [45DP], non-Newtonian fluids [43DP], variable porosity [38DP,56DP], convective effects on melting from an imbedded vertical surface [45DP], and thermally stratified media [39DP,47DP]. Heat transfer from horizontal flat plate immersed in a porous medium was analyzed for asymptotic behavior for laminar-forced flow [59DP], and for parameterized regimes of free convection on a horizontal plate [58DP]. For heat and mass transfer from bodies of arbitrary shape imbedded in a porous medium, such as a truncated cone, the governing equations were first transformed by the Keller box method [61DP]. Some interesting work appeared on the effects of inertial and a spanwise pressure gradient on three-dimensional but self-similar free convection on a vertical plate [57DP]. The time-dependent migration of species from a leaking, heat source within a porous medium was calculated for Darcy flow and buoyant convection [51DP].

Several studies investigated various aspects of flow and heat transfer on porous plates. Forced convection from a flat plate enhanced by a porous substrate was numerically investigated by the fully extended Darcy equations [49DP]. The effect of random porosity on the heat transfer performance of a porous boundary was studied under impinging flow conditions [41DP,52DP,53DP].

6.2.3. Packed and fluidized beds

Research on packed beds focused on local and overall descriptions of heat and mass transfer. Wall heat transfer coefficients were of particular interest, and the determining of the overall effective heat and mass transfer coefficients for the bed was addressed theoretically and experimentally [65DP,86DP,102DP]. Local quantities of interest in fixed bed systems included the particle-to-fluid heat transfer coefficient [88DP] and interstitial fluid dispersion [82DP]. Transient fixed beds were modeled for optimisation of heat transfer and to test models of wall heat and mass transfer coefficients [84DP,90DP,91DP]. A moving fixed bed was analyzed in the same context for heat recovery applications [68DP]. The yield from a fixed bed reactor via injection of a ballast gas to control oxidation was addressed with a one-dimensional model [94DP]. An experimental study was reported on use of a combination of plasma discharge and adsorption in a fixed bed reactor to reduce production of nitrous oxide in the oxidation of benzene [93DP]. Combined conduction and radiation with variable porosity was investigated numerically for several porosity distributions and effective thermal conductivity [105DP].

Three reviews presented a broad picture of heat and mass transfer in fluidized beds and cover heat transfer characteristics of mechanically stimulated particle beds [98DP], measurement techniques [104DP], and the phenomenology of fast fluidisation [70DP].

Fundamental advances on flow and transport in fluidized beds were reported in a number of areas. A comprehensive numerical and experimental study on fluidisation in a confined volume revealed new fluidisation regimes and regions of stability [101DP]. Generalized models were developed to describe two- and three-component beds [64DP,77DP,79DP], and similarity variables were established for circulating and bubble-fluidized beds [99DP,100DP]. Modeling and experimentation on total and radiative heat transfer in a circulating bed showed good agreement when independent scattering theory for the radiative transfer was applied [87DP]. Measurement and prediction of heat transfer to immersed tubes were addressed in a number of studies, and heat transfer coefficients were more precisely related to the characteristics of the flow regime and bed type, e.g., fluid–solid–solid [71DP,80DP, 107DP]. One study employed an Eulerian formulation of the particulate enthalpy equation via the kinetic theory of granular flow to predict enhanced heat transfer to a single immersed tube [95DP]. A gas–solid–solid circulating bed was conceptualized as combination of the packed and fluidized bed, and experiments on the effect of the fluidized solid phase on conversion and heat transfer rate in a reacting bed were reported [78DP]. Entropy generation in a rectangular packed bed as a result of heating at the wall and frictional effects was shown to be discontinuous across the bed [72DP].

Measurements of various operational characteristics and transport phenomena of fluidized beds continued to expand the literature. A fast response heat transfer probe was developed for instantaneous heat transfer coefficients in slurry bubble column [85DP]. The dynamics of heat transfer between a hot wire probe and gas fluidized beds was reported for an air–silica powder bed [66DP]. A rapid measurement technique and model of particle-to-liquid heat transfer was reported for liquid–solid and gas–solid beds [67DP]. Momentum dissipation of jet dispersion in a gas–solid bed was measured using a pitot tube [103DP]. A pilot plant study of a 100 kW graphite bed melter was run to test design assumptions for a high-frequency induction power generator [89DP].

A new correlation for the wall-to-fluid mass transfer in liquid–solid beds was developed [96DP]. Measurements were reported on emission and heat transfer in pressurized fluid bed coal combustion [75DP]. Data on ignition and degradation times for loosely packed straw beds revealed the effects of swelling and leaching of the straw [73DP]. Thermal imaging was used to visualize the motion of clusters of particles near the wall of a circulating bed [92DP], and bed to wall transfer coefficients were reported [69DP,81DP]. A time series analysis of local voids revealed the correlation dimension and Komogorov entropy of void fluctuation in a liquid–solid bed [83DP]. Particle concentration profiles and correlations for local voids were presented for a circulating bed [106DP].

Coupled fluid bed reactors were employed in a conceptual study that demonstrated oxygen production and carbon dioxide liquefaction [97DP]. The burning of clinkers associated with cement manufacture via fluid bed combustion successfully demonstrated the viability of low-grade fuels and the reduction of NO_x emissions [76DP]. New technology and detailed measurements were presented on decontamination of fluidized catalyst-absorbent beds [74DP].

6.2.4. Layers and enclosures

The criterion for stability presented by the Horton–Rogers–Lapwood problem was experimentally verified [118DP]. The linear and finite amplitude stability problems for a water-saturated system near the density maximum yielded the possibility of sub-critical convection and multiple solutions [131DP]. Critical Rayleigh numbers were determined for a saturated layer overlying a solid layer [149DP]. The effects of through-flow on thermo-convective stability in layers containing micropolar fluids showed that the addition of Coriolis forces enhanced stabilizing and destabilizing effects of the through-flow [134DP]. For a tilted cavity filled with a binary fluid, the onset of double-diffusive convection exhibited Hopf bifurcations that depend on the layer aspect ratio and a Lewis number [123DP]. When solidification takes place in the porous-layer extension of the Rayleigh–Benard problem, the onset of convection is significantly affected by the presence of the solid, degree of solidification, and the thermal boundary conditions [130DP]. A stability analysis for a system comprising liquid and vapor layers was applied to the development of plausible structures for geothermal systems [141DP]. Random walk methods were applied to heat transfer and energy storage in porous aquifer systems by neglecting free convection effects and defining local velocities by the analytical solution at a single source or sink [112DP,113DP].

Natural convection in layers and cavities was analyzed for a fluid layer overlying a porous layer saturated with the same fluid [147DP], non-Darcy flow [138DP,139DP], horizontal temperature gradients and a non-Newtonian fluid [135DP,146DP]. Experiments were reported that identified the Rayleigh-regimes of two- and three-dimensional flows [114DP]. Boundary layers under double-diffusive free convection in a square cavity were demonstrated to change their overall character under opposing flow conditions, and Rayleigh-regimes were identified where temperature and concentration boundary layers vanished [108DP,109DP]. The propagation of an intruding plume in a double layer system with contrasting permeability was determined via numerical analysis [144DP,145DP]. Numerical methods were presented for the general cavity problem by which computation time can be significantly reduced [117DP]. Transient free convection in layers bounded from below by a segment of sphere showed almost no effects of buoyancy in the early stages of the transient, and only the recirculating flow in the central region of the layer exhibited a dependence on the conductivity ratio [153DP].

Free convection in a porous annulus was numerically analyzed under conditions where the wall is thermally coupled to the flow [116DP] and confocal elliptical boundaries [143DP]. One study demonstrated that heat transfer enhancement can be obtained by inserting a porous perturbation, or plug, in the gap of an otherwise open annulus [119DP].

Convection in a vertical porous layer comprising a flowing granular material was analyzed numerically, and key regimes of heat transfer identified [133DP]. An analysis was presented for a fixed matrix that showed that a higher temperature difference is needed to achieve the similar flow when a couple stress fluid is present [148DP]. An extensive numerical study of free convection in a vertical porous cylinder with volumetric heat generation reported effects of Darcy number variation on average Nusselt numbers [122DP]. Double-diffusive free convection in a vertical driven by constant heat and mass fluxes at the boundaries was determined for a fairly large range of Rayleigh and Lewis numbers [132DP]. Free convection effects on solidification of a superheated fluid were determined numerically via a freeze-front tracking method, and several regimes of convection were identified [152DP].

Experiments on mixed convection in a vertical porous channel under asymmetric heating demonstrated the existence of secondary lows and identified limits of the free, mixed and forced convection flow regimes [142DP]. Studies of mixed convection in bottom-heated layers and channels considered the effects of rotation [150DP] and the effects of sudden expansion of the flow cross-section [151DP]. For the latter, average Nusselt numbers were found to be very close to those for the bottom-heated channel. Flow and heat transfer in unsteady mixed convection with volumetric heating in an enclosure driven by a moving upper surface was determined via finite difference solutions [124DP].

Forced convection in porous channels was modeled with a two-equation formulation, including transverse conduction, and analytical results were compared with those due to the one-equation formulation [129DP]. Other one-equation formulations determined average Nusselt numbers and the effects of property variations, non-Darcy effects, and pulsating flow [110DP,111DP, 115DP,126DP,140DP]. The effects of a temperature-dependent viscosity on Nusselt numbers were determined experimentally [137DP]. Fluid flow and heat transfer between a fluid and porous interface in channel flow were analyzed using boundary-layer approximations [128DP]. Local thermal equilibrium effects and thermal coupling to the wall were analyzed for forced convection, and a new solid-to-fluid exchange parameter and dispersion model were [120DP,121DP,136DP]. An assembly of microchannels was modeled as a porous medium, and its heat transfer capabilities were determined for various aspect ratios and effective thermal conductivity [125DP].

Experiments on buoyancy effects of boiling in vertical tube with a constant wall heat flux revealed a critical heat flux criterion for mass flux [154DP]. Heat transfer results were also reported on flow with boiling in a channel with metallic porous inserts and a cryogenic fluid [127DP].

6.2.5. Coupled heat and mass transfer

Fundamental work on the equations that describe coupled heat and mass transfer in porous media focused on saturated and unsaturated systems that arise in a wide range of engineering and environmental problems. One basic study concerned moisture and heat transfer between a capillary porous body and a gas–vapor environment without bulk flow [170DP]. A general thermodynamic theory was developed on the constitutive equations of an elastic, incompressible porous solid, filled with an incompressible liquid and compressible gas [162DP]. A derivation of the basic conservation equations via an approach based on continuum mechanics was shown to produce the same equations as are obtained via volume averaging [193DP]. Closed form solutions of the Luikov equations for capillary porous bodies were developed using a periodic solutions and Laplace transforms [167DP, 188DP]. Thermodynamic cross-effects in a two-component diffusion substitution process were uncoupled using the eigenstates of the diffusivity matrix [174DP]. Non-similar solutions for heat and mass transfer from a wedge embedded in a saturated porous medium were obtained for the entire range of flow from forced to free convection [214DP]. Crystal growth in hydrothermal systems was successfully modeled as a coupled heat and mass transfer process in a porous medium [159DP,160DP]. An analysis was presented on deposition with polymorphic transformation of gallium oxide on a porous matrix [155DP].

Modeling convective diffusion and the fate of the volatile gases in non-isothermal soil systems focused on inter-phase transport and degradation of the volatile component [184DP,200DP] and on effects of a deformable solid phase [201DP,202DP,220DP]. When toxic compounds are convected with sorption–desorption and decay in underground systems, a set of coupled equations describing the flow and concentration fields was solved to determine regions of pollution [171DP]. Analysis of multi-component adsorption-based separation processes in particle-bed systems showed that a single energy equation for macroscopic temperature in the bed is sufficient for most practical applications [195DP]. For an unsaturated system exposed to a large surface heat flux, a three-phase model was developed to describe the movement of the evaporation zone and determine the intrapore pressure distribution [215DP]. A three-dimensional model of transport in unsaturated media in which the matrix exhibits moisture diffusion and a heat of respiration, such as exists in the storage of foodstuffs, was developed using empirical data on temperature for heat of respiration [161DP,212DP]. The prediction of moisture distribution in a porous annulus was solved via an inverse method involving the temperature history at any point in the body [158DP].

A multi-component, multi-phase model of baking was developed and validated with experimental data obtained in baking potatoes [186DP]. The coupled moisture and heat transport problem in intense microwave heating of biological materials identified the criterion by which high-moisture loss rates will exist by liquid flow at the surface [187DP]. Energy recovery using porous hydrophyllic membranes was modeled as a coupled heat and mass transfer problem in a porous medium, and the structure of the temperature and moisture fields internal to a cross-flow type of mass exchanger were identified [216DP]. Three-dimensional numerical solutions for the coupled transport processes present during resin transfer molding were developed and exercised for thick molds [163DP,179DP]. A site-scale model to simulate moisture, gas, and heat flows in fractured, low permeability rock was developed and exercised for the geology of Yucca Mountain, Nevada [211DP]. The effect of non-condensable gases on heat transfer in porous rock structures such as found in hydrothermal systems was determined for a water–sodium chloride–carbon dioxide system [177DP].

Experimental studies of coupled heat and mass transfer continued to build a database on transport mechanisms, to verify ad hoc modeling hypotheses, and to test predictions for specific problem types. The heat of absorption of toluene on microporous carbons was measured by gas–vapor microcalorimetry [194DP]. Transport of heat and moisture around a heated cylinder in an unsaturated soil were measured under steady and cyclic heating [182DP]. Evaporative transfer rates in a vertical capillary structure heated at the top revealed that the heat transfer coefficient exhibits a maximum as heating flux is increased [173DP]. New data were presented on heat and mass transfer between a liquid desiccant and air in a packed bed regenerator using high-liquid flow rates [176DP]. Salinity and compaction effects on soil–water evaporation were measured in open soil columns [183DP]. The transport and fate of benzene in non-isothermal salty solids was shown to depend on the temperature and temperature gradient [185DP].

Basic processes of multi-phase flow and heat transfer in a porous medium under a variety of thermal boundary conditions were the subject of a good number of theoretical papers. The temperature distribution during boiling under conditions of percolation of liquid and when vaporisation of liquid occurs inside the matrix was determined via the solution of boundary value problem with mixed boundary conditions [192DP]. When percolation patterns and capillary forces are dominant during drying, a three-dimensional network simulation of the pore system is found to adequately describe the liquid phase structure and the formation of isolated liquid clusters [172DP]. A multi-space scale, single time-scale model of moisture and heat transfer in a swelling porous medium was developed that generalizes several existing theories and models applicable on a restricted space scale [156DP]. The enhancement of boiling heat transfer via vapor channeling in porous layers was demonstrated analytically [198DP]. When phase change takes place at a heated side-wall of an enclosure, a decrease of permeability leads to an increase in the conversion of liquid to vapor [204DP]. Effects of liquid vapor coupling and non-Darcian transport in heat pipes were determined via a closed form solution [221DP]. Flow boiling in a vertical capillary structure was characterized for aiding and opposing flows [218DP]. Evaporation of a liquid from a wetted surface in natural convection was shown to affect the overall heat transfer coefficient [166DP]. When the wetted surface partially covers the upper surface of a cavity, vaporisation produces a liquid–vapor front that penetrates into the porous medium [165DP]. An analytical solution was obtained for coupled heat and mass transfer in the stagnation region of air-flow in a heated porous bed with liquid film evaporation [217DP]. Condensation and adsorption processes occurring during mass transfer in a highly porous system were solved via direct statistical simulation to reveal velocity fields and the existence of non-condensable admixtures [197DP]. Natural convection in a porous medium coupled to condensation on an impermeable vertical boundary was numerically analyzed, and overall heat transfer coefficients were determined in terms of coupling parameters [181DP].

Applied and fundamental research on drying addressed a variety of industrially important problems. The hygro-thermal behavior and damage of concrete at high temperature was investigated numerically [168DP], and experiments were run on drying with superheated steam [203DP]. Drying of granular foodstuffs with thermal coupling at the wall was the subject of theoretical and experimental work aimed at the time–space evolution of temperature and water content distributions [157DP, 178DP,222DP]. The effective diffusivity of foodstuffs under low temperature drying was found to exhibit significant effects of temperature in the evaporation–condensation regions [207DP]. A model of drying in a fixed bed reactor containing moist particles was developed and included intra-particle pressure effects and conjugate effects between the gas phase and the fixed bed [208DP]. Measurements of moisture removal from a saturated layer by convective diffusion into an overlying sub-layer in which dry air is flowing were reported and compared to a conceptual model [180DP]. A transformation of the flow domain in a dryer was used to simplify the solution for flow field and thus obtain a practical comparison among potential dryer shapes [189DP–191DP]. A parametric experimental study of microwave freeze drying of beef indicated that the effect of vacuum pressure on drying time is negligible [209DP].

Phase change and pyrolysis of the porous matrix due to impulsive surface heating showed the existence of delayed secondary impulses of intrapore pressure [164DP]. A diffusion model was developed for the oxidation kinetics of zirconium alloy under stress at a porous oxide metal interface [219DP]. The transient performance of a porous matrix combustor-heat exchanger was determined numerically for the coupled transport processes within the system. [213DP]. Reaction in single polypropylene particle was studied experimentally, and reaction kinetics, monomer absorption and microscale morphology were measured [210DP].

Experiments were reported on the influence of non-combustible coating material on flame propagation over a solid fuel [206DP]. Measurements of heat and mass transfer in a smoldering combustible solid in a microgravity environment revealed little effect of gravity on kinetics and no self-sustained smolder propagation [205DP]. Porous burners with an embedded heat exchanger were modeled as a two-region system with a coupling via a convective heat transfer coefficient [175DP]. Ignition of porous energetic materials was analyzed for large activation energy and shown to exhibit three reactive–diffusive regions near the ignition surface [199DP]. Heat transfer and combustion in dense porous ceramic blends were investigated numerically for heating at a constant rate [196DP]. Experiments and analysis of combustion with cyclic flow in a porous system established criteria for maximizing flame temperature [169DP].

7. Experimental methods

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

7.1. Heat flux measurements

A comprehensive review of various heat flux measurement techniques applied to fluid mechanics and heat transfer was published [1E]. Several optical methods have been used to measure surface heat flux or the heat transfer coefficient including infrared radiation [7E], a fluoroptic method [15E], shearing interferometry [10E], thin layer thermography [4E] and the reflection of visible light from a drying surface [9E]. Thin film techniques have been used to study thermal contact conductance [8E] and to measure the local heat transfer coefficient [11E]. Transient heat transfer measurements were made using a CO_2 laser [2E] and liquid crystals [6E]. Enthalpy changes were determined with several types of calorimeters [3E,5E,12E].

7.2. Temperature measurements

Nearly all the methods described for temperature measurement were non-invasive. Measurement techniques included the use of an atomic force microscope [14E], a fluoroptic method for particles [15E], a resonant acoustic cell [16E] and coherent anti-Stokes Raman spectrometry [17E]. Other remote sensing techniques include the use of liquid crystals [13E] and infrared imaging [18E]. The reconstruction of a three-dimensional temperature field using a Mach–Zehnder interferometer and tomography was described [19E]. Thermocouples were applied to measure the temperature of a satellite mesh reflector [20E].

7.3. Velocity and single-phase flow measurements

A micromachined shear stress sensor was developed to measure fluid velocity [25E]. Investigations were made to quantify the effects of non-isothermal flows [21E] and the presence of a nearby wall [24E] on hot wire anemometers. Particle Image Velocimetry (PIV) methods were applied to the measurement of gas–solid two-phase spiral flows [26E] and flows in the cylinder of an internal combustion engine [27E]. Several authors discussed the advantages and limitations of flowmeters [22E,23E,28E].

7.4. Two-phase flow measurements

Several papers describe the measurement of local void fraction, interfacial area and local velocity in two-phase liquid–vapor/gas flows [30E–34E]. Space- and time-resolved heat transfer variations during nucleate pool boiling were measured using a high-speed charge-coupled device [29E].

7.5. Miscellaneous

Methods of measuring the thermal conductivity of fluids containing nanoparticles [35E] and the thermal diffusivity of thin films [40E] were described. Several papers addressed the issue of measurement uncertainty [36E,37E,38E,39E].

8. Natural convection – internal flows

8.1. Highlights

Mostly theoretical work on stability of the conduction solution and of supercritical flows, including transitions to chaotic motion. DNS techniques continue to gain favor for both laminar and turbulent free convection in all geometries. Transient free convection is receiving a lot of attention in all areas of application. Flow structures in cavity flow and mixed convection in a variety of geometries received both experimental and theoretical treatment; and there appears to be continuing interest in the fundamental fluid dynamic processes even though local and overall heat transfer has been quantitatively determined and reduced to engineering correlations.

8.1.1. Fundamental studies

Two fundamental studies of internal free convection appearing are worthy of note in that they provide experimental data for future theoretical work. One study [11F] established the Nusselt-vs.-Rayleigh number relation for fluids with a mean Prandtl number of $O(10^4)$ to $O(10^5)$ in a test cell with aspect ratios from ~ 4 to 20. Another [7F] investigated the influence of viscosity stratification on the interaction between thermal convection and a stable viscosity discontinuity. Both experiments and numerical simulations were carried out on the onset of finger-like convection in a stratified layer produced by thermal and capillary motion [4F].

Various aspects of the stability of the conduction and convection regimes continue to occupy theorists. The onset of convection in an initially stably stratified layer [13F] and in bottom-heated layers where surface tension effects are important [2F,10F,18F,19F] received a good deal of attention. Mass transfer and temperature-dependent viscosity as factors in the onset of motion were also considered [9F,17F,22F]. The effect of micropolar fluids on the stability of the conduction regime was determined for spherical layers [5F]. Buoyancy-driven instability in a layer of electrically conducting fluid in the presence of a vertical magnetic field and heated from below was investigated via a collocation method [21F]. A review of the onset of motion near the liquid-vapor critical point included a discussion of piston effect on predictions of linear stability theory [3F].

Time-dependent Rayleigh–Benard convection was computed in fluid layers via very large eddy simulation [12F] and by direct numerical simulation [20F]. The transitions to chaos in three-dimensional cavities at a fixed Prandtl number were also computed by direct numerical simulation and two mechanisms for transition to non-periodic motion were identified [1F,23F]. For long inclined cavities heated at the ends, oscillatory and stationary modes of instability were identified as a function of Prandtl number [8F].

An interesting theoretical paper appeared in which functions and lines used for visualisation of the flow can be unified from physical and numerical viewpoints [6F]. The inverse natural convection problem of determining the heat flux, or the strength of a heat source, from temperature measurement in the domain was solved using a single sensor and a minimisation technique [15F,16F]. A real-time phase-shift interferometer was developed to measure diffusion fields without the effects of double-diffusive convection, and testing of the device was done in a microgravity environment [14F].

8.1.2. Thermocapillary flows

Droplets in which thermocapillary effects drive fluid motion were studied from several aspects. When a droplet is heated with a short-duration energy pulse, the resulting flow structure was shown to be totally different in the case of negative surface-tension temperature coefficient fluids [30F]. Another study reported Prandtl number effects on buoyancy-driven flow for similar temperature coefficients [29F]. Droplets with internal thermocapillary circulation were shown to have an impact on the local ambient temperature distribution and thus the migration speed of the droplet [26F].

Experiments and analysis on oscillatory thermocapillary flow were conducted in microgravity. Results point to the necessity of a deformable surface for the onset of flow [25F]. When either thermocapillary or buoyancy-driven flow is induced by a hot wire beneath the free surface of a horizontal layer, the shape of the free surface above the wire is found to depend on the mechanism driving the flow [27F]. Thermocapillary flows in a cavity with a free upper surface were investigated numerically to show that horizontal temperature and concentration differences make opposing contributions to the cavity flow and the conditions at the free surface [24F].

A stability analysis of thermocapillary convection in cylindrical liquid bridges under an axial magnetic field established the form of the most dangerous disturbance and the effects of properties and geometry on the flow and heat transfer [28F].

8.1.3. Enclosure heat transfer

Experimental studies addressed the effects of thermal radiation in an air-filled enclosure [57F] and the effects of partitions [46F,58F]. The latter study resulted in correlations for Nusselt numbers that validated already existing numerical predictions. Some interesting experiments with complementary numerical analysis report heat transfer coefficients for tiled cavities that are either partially or fully open at one end [37F,38F]. Nusselt numbers of the benchmark problem for the cubical cavity were measured for various angles of inclination and Rayleigh numbers up to 10^5 [48F].

Density inversions, such as exist for water near 4°C, were considered for rectangular cavities ranging from a nearly flat layer to a narrow vertical slot. Correlations for the mean Nusselt number were developed to emphasize the aspect ratio effect [64F]. Magneto-convection for two- and three-dimensional and axisymmetric cavities was analyzed to expose the details of both flow and magnetic fields [45F,52F,63F]. Oscillatory flow and heat transfer in a tall cavity in water near the density maximum revealed a Hopf-type bifurcation followed by a traveling wave along the maximum density contour [43F]. Numerical results for flow patterns and heat transfer in a three-dimensional cavity were also presented with the temperature dependence of thermophysical properties taken into account [59F]. Convection in a tall cylinder heated from below with arbitrary thermal boundary conditions was analyzed to reveal fundamental frequencies of instability [44F].

The effects of property variations on heat transfer coefficients in square cavities received a good deal of attention for square and rectangular enclosures and a fairly wide range of Prandtl numbers [35F]. A notable result was that at low Prandtl number, Nusselt numbers are well represented via a correlation of usual form when properties are evaluated at the average temperature [39F]. Other studies investigated the effects of inclination, non-uniform thermal boundary conditions, layering, and Prandtl number on flow structure and heat transfer [33F,34F,54F,55F].

Grid sensitivity in computations of low Rayleigh number turbulent convection was eliminated by introducing a damping function into the buoyancy source term [56F]. A comparison of direct numerical simulation to large eddy simulation of high Rayleigh number flow was carried out for a fluid layer with internal heating [41F]. Buoyancy effects on turbulent convection were successfully computed with a four-equation turbulence model and a return-to-isotropy concept for the pressure vs. strain relation [50F]. A second law analysis of the flow and heat transfer in a rectangular cavity has revealed that the flow pattern is dependent on the distribution of entropy generation [53F].

Enclosures in which buoyant convection is driven by a localized source either within the enclosure or on its boundary were the subject of numerical studies for laminar and turbulent flows. With the heat source located within the enclosure, heat transfer from the source was found to depend on ratio of the temperature differences across the cavity and that between the source and the walls [42F]. A three-dimensional analysis of free convection from a heater array flush mounted in one wall of a rectangular enclosure was carried out for cooling liquids over a range of Prandtl numbers; results include detailed thermal maps and overall Nusselt numbers [62F].

Asymmetric heating via a heated side wall and a cooled top in a two-dimensional cavity was most influenced by geometry when the cavity is very shallow [32F,33F]. Uniform magnetic fields were found to move the flow to a higher transition Rayleigh number and enhance the heat transfer [65F]. Heat transfer was also computed for a cavity with non-vertical insulating sidewalls [47F].

Oscillatory convection in a square cavity under opposing temperature and concentration gradients was found to exist for certain values of the thermal and solutal Grashof numbers. The structure of the flow was demonstrated to depend on the Lewis number [40F]. The well-studied problem of the stability of convective motion in a differentially heated vertical slot was enriched by results for heat transfer, temperature fields and flow fields for moderate to large aspect ratio and Prandtl numbers spanning four orders of magnitude [51F]. Stratification that develops on the cooling-down of an intially constant temperature fluid in a tall cylinder was described numerically, as well as by scaling analysis [49F]. Transient heat transfer at low Prandtl number was computed for a square cavity in which the horizontal sidewalks were heated [60F].

Transient flow and heat transfer in a square enclosure in which the horizontal walls are submitted to periodic temperatures exhibited either enhancement or reduction of the heat transfer coefficient depending on the choice of the variable heating mode, the parameters related to the periodic temperatures, and the Rayleigh number [31F].

A fluid layer with large Prandtl number and heating from within and from below was considered as the model geometry for earth mantle convection. Results for moderate Rayleigh number indicated that the heat transfer relation is nearly the same as for the case of heating from within [61F]. Time-dependent heat transfer from base of lithosphere was modeled as a two-dimensional non-Newtonian flow, and results were used to propose a mechanism for the development of the oceanic lithosphere [36F].

8.1.4. Vertical ducts and annuli

Buoyant flows in vertical annuli were numerically investigated to determine heat transfer coefficients for developing flow [69F] and a type of conjugate problem in which the inner tube experiences axial wall conduction [70F,71F]. Heat transfer enhancement in an annulus using surface perturbations was determined numerically [72F].

A direct numerical simulation of convection between two walls of different temperature was carried out for moderate large Rayleigh numbers. Results for heat transfer and derived scaling laws were found to be in agreement with the previously published results [78F]. A similar study using a general integral transform was reported for the case of variable thermophysical properties [75F]. When the plates were partially heated in the axial direction, heat and mass transfer coefficients were dramatically affected by the fraction of the channel that was unheated [74F]. Transient flow and heat transfer in air between isothermal plates reveals the existence of time-dependent solutions at $Gr > 10^7$ [67F]. In systems of vertical channels, the chimney effect was found to enhance heat transfer coefficients [77F].

The effect on wall temperature and heat transfer of adding an insulated extension at either the inlet or outlet of a vertical duct was determined numerically [68F]. In tilted channels, the effects of asymmetric thermal boundary conditions and channel width were via an overall correlation for heat transfer coefficient [67F,76F]. Fully developed laminar mass and heat transfer coefficients in vertical rectangular ducts were determined analytically via a vorticity–velocity formulation [73F].

8.1.5. Horizontal cylinders and annuli

Experiments on the unsteady temperature fluctuations in the plume region of a differentially heated horizontal annulus were reported, along with power spectral density estimates when plume breakdown occurred at high Rayleigh number [80F]. Thermal stratification effects in a horizontal cylinder were shown to be reduced with external heating [81F].

A numerical analysis of the coupled thermal and hydrodynamic instability for $Pr < 1$ in a narrow annulus yielded complex cellular flows with a Grashof number uniquely tied from multi- to mono-cellular transitions [82F,83F]. For a numerical and experimental study for large and moderate gap annuli provided quantitative three-dimensional descriptions of spiral convection in air for the small gap, flow structures preceding oscillation in air for the large gap, and unicellular flow development at $Pr = 100$ for the large gap [79F].

8.1.6. Mixed convection

The alteration of forced convection by buoyancy generated by fluid density variations near the critical point was analyzed for tube flows. A full range of mixed-to-forced convection results was reported for developing flow and heat transfer [88F]. Several types of flow instability resulting from the co-linear flow of unstably stratified fluids in a channel were identified via flow visualisation [85F]. Bifuration in steady, fully developed laminar convection in uniformly heated inclined tubes was characterized by two- and four-vortex secondary flows [90F].

Combined free and forced convections for a finite size heat source in an enclosure was studied numerically for various dynamical, geometrical and flow parameters pertinent to industrial or electronic equipment. [87F]. Mixed convection resulting from the injection of a cold flow into a warm cavity was determined numerically for a variety of inlet–outlet combinations [89F]. The flow generated by two non-isothermal plane wall jets was investigated numerically and experimentally to test several k–ϵ turbulence models [84F]. Buoyancy effects on flow in a curved square channel with conjugated thermal boundary conditions are shown to weaken the secondary flow field and thus reduce Nusselt numbers [86F].

8.1.7. Complex geometries

The coupling between human thermo-regulation and an enclosure was developedusing a k–ϵ turbulence model for the flow field and a nodal-physiological model for the human response system [97F]. A zonal model using coarse grids for natural and mixed convection was demonstrated for two- and three-dimensional rooms [96F].

An experimental study of buoyancy-opposed mixed convection in upward air flow in a pipe with a cooled surface reported heat transfer correlations from the free convection to the forced convection regimes [92F]. Bifurcation to oscillatory flow in free convection around a vertical channel in a rectangular enclosure exhibited both symmetrical and asymmetrical flows depending on Rayleigh number [93F].

Nusselt numbers for a heated cylinder in a rectangular cavity in natural convection have been determined numerically [91F]. Free convection in a non-ventilated electronic system has been investigated numerically to link component-level analysis to system-level analysis [94F].

Free convection in a micropolar fluid in a partially divided enclosure was computed to reveal the effects of fluid type and height of the divider [95F].

8.1.8. Fires

A review of the literature on fires was prepared that broadly integrates the literature on fundamentals, industrial fires, ignition, fire development, and fully developed fires [100F]. Fundamental data on velocity, temperature and concentration have been obtained via optical techniques on transient two-dimensional spreading flames on liquid fuels [99F].

The self-extinction of enclosure fires was explained via a thermal theory in which spontaneous changes in heat transfer produce reductions in temperature or pressure [102F]. Three-dimensional heat transfer from turbulent diffusion flames between vertical walls was determined numerically via a buoyancy-modified k–ϵ method [103F]. Experiments on fires in vertical enclosures of the type encountered in buildings produced data on velocity and temperature fields, as well as general description of wall plumes and recirculation [101F]. The movement of smoke and species transport through enclosure openings has been studied via experiments on a full-scale multi-zone building [98F].

8.1.9. Miscellaneous

The coupling of thermal convection and thermoacoustic heat transfer near the critical point in a thermal plume of a van der Waals fluid was found to lead to a quasi-thermal equilibrium situation with no steady state [107F]. An analysis of field experiments on heat transfer in large-scale heavy-gas dispersions showed that the limited heat capacity of the ground contributes to a decrease of the surface heat flux during plume releases [106F].

New experiments on electro-convection were reported on a system comprising a colloid suspension of akgeneite particles in distilled water. Electroconvective heat transfer coefficients were reported in terms of electric field intensity, colloidal charge, convection and orientation [104F].

Heat transfer effects on flow transition in a Taylor–Couette flow were determined numerically for a range of Grashof numbers. Transitions in flow and heat transfer were noted, as well as a hysteresis loop and a limit cycle for local heat transfer and radial velocity [105F].

9. Natural convection – external flows

9.1. Vertical plate

A number of investigators considered various aspects of heat transfer for buoyancy-driven convection around a vertical plate. Experiments were performed with a constant heat flux boundary condition on a vertical surface immersed in both Newtonian and non-Newtonian fluids over a large range of viscosities [8FF]. Another study considered convection in thermomicropolar fluids [3FF]. The influence of thermophoresis has been examined [5FF] with a finite difference model. Convection in a porous medium surrounding a vertical plate has been studied analytically [6FF]. A study of a stretching vertical surface immersed in a conducting fluid provides interesting effects on free convection including influence of magnetic fields and stretching speed [2FF]. Combined heat and mass transfer from a vertical wavy surface [4FF] has been studied analytically. The attachment of poorly conducting ribs on a vertical surface can substantially reduce the heat transfer from a surface [9FF]. Studies on transient convection include the influence of various heat and mass fluxes on an impulsively started vertical plate [7FF] and flow on a vertical plate with periodically varying temperature [1FF].

9.2. Horizontal and inclined plates

A study [13FF] shows the effects of natural convection and conduction on the temperature distribution within a thin horizontal strip. Convection above a surface slightly inclined from the horizontal has been analyzed for heat transfer to a surrounding thermomicropolar fluid [12FF]. A study of the flow and heat transfer in an inclined slab shows the influence of an array of horizontal circular channels within the slab [11FF]. An analysis of the influence of the Marangoni effect on mass transfer from a surface includes the influence of chemical reactions [10FF].

9.3. Cylinders and blunt bodies

Experiments on convection from a horizontal cylinder to liquid sodium [16FF] have been followed by a numerical solution [17FF] which is well able to predict the experimental results. The presence of a ceiling above a horizontal cylinder increases the heat transfer from the cylinder at low spacings, but has little effect when the ceiling is a diameter or more above the cylinder [19FF]. Numerical models predict convection from a point source or small sphere at small Grashof numbers [18FF] and combined heat and mass transfer from a horizontal line source [15FF]. Convection in CO_2 near its critical point [14FF] has been studied. Convection from isothermal conical surfaces at different inclinations has been examined theoretically [20FF] while a boundary layer analysis includes the influence of radiation on the natural convection in a surrounding optically dense fluid [21FF].

9.4. Thermal plumes

A two-equation turbulent model improves the prediction of the influence of buoyancy on turbulent transport [24FF]. Visualisation of a plume above a line source shows large-scale vortices related to the laminar swaying motion of the plume [22FF]. Experiments with a turbulent adiabatic wall plume of helium–air mixtures include measurements of the fluctuating mixture fractions [23FF].

9.5. Mixed convection

A numerical study shows the influence of a plane jet on natural convection from a heated isothermal vertical surface including the detachment of the jet flow from the surface under some conditions [25FF]. Equations for the turbulent transport of heat and species under mixed convection stress the importance of the turbulent transport coefficient [27FF]. An analysis [26FF] predicts the mixed convection from a vertical plate embodied in a porous medium when the plate is suddenly heated. Equations for the natural convection flow of a particulate to suspension over a permeable inclined plate have been solved numerically using an implicit finite difference method [28FF].

9.6. Applications and miscellaneous

Studies on natural convection in buildings show the effects of venetian blinds on heat transfer from windows and convection from internal walls [38FF,30FF]. Studies on natural convection cooling of micro-electronic circuits indicate the effects of annular heat sinks [40FF] and predict the mixed convection flow between parallel plates simulating integrated circuit boards [35FF].

Natural convection is an important process in heating and cooling of food. Recent studies include optimisation of a finite difference scheme for simultaneous heat and mass transfer [29FF] and development of experiments and correlations for relevant thermophysical properties of various foods needed in predicting convection from fruit layers [32FF].

Heat and mass transfer issues in shallow lakes have been described [34FF] and the importance of buoyancy effects in a chemical vapor deposition process has been demonstrated [31FF]. Key issues studied recently include heat transfer with crust formation in molten metal pools [37FF], heat transfer from rubber to air using a finite element analysis [39FF] and heat transfer to transformer oil flowing past a sphere and a packing layer [36FF]. The influence of heat transfer and thermal accommodation coefficients on the apparent mass of materials has been examined [33FF].

10. Rotating surfaces

10.1. Rotating disks

Heat transfer from a single, horizontal, rotating silicon wafer containing chips was studied experimentally [6G]. Heat and mass transfer from a liquid film on a rotating disk [1G] and freezing of a liquid impinging on a disk [7G] have been investigated. Flow and heat transfer between two corotating [2G,4G,5G] and two counter rotating disks [3G] have been studied.

10.2. Rotating channels

An analogy between flow and heat transfer in curved pipes and in orthogonally rotating pipes was presented [16G,17G]. The majority of papers on rotating channels consider ducts of square or rectangular cross-section. Several single duct and pipe flows and heat transfer was investigated [9G,20G,23G–25G,28G,30G,32G]. Several authors reported studies on U-bends [14G,15G, 26G,29G,31G] or two-pass ducts joined with a 180° bend [10G,21G,22G]. Heat transfer in a coiled pipe that rotates about its axis [18G] and in a rotating four-pass channel [12G] was reported. The effects of leading wall blowing or suction [13G] and jet impingement [8G,11G] were described. Experimental [19G] and numerical [27G] studies of flow in annular channels were reported.

10.3. Enclosures

An experimental study of double-diffusive convection in a rotating annulus with lateral heating was described [34G]. The flow in a vertical cylindrical container with a rotating lid was studied numerically [33G].

10.4. Cylinders and bodies of revolution

Numerical studies of heat transfer from a rotating, heated horizontal cylinder were presented [36G–38G]. Entropy generation from a horizontal rotating cylinder in mixed convection was computed [35G]. A finite element method was used to simulate the heat transfer and strain in continuously quenched rotating axisymmetric bodies [39G].

10.5. Miscellaneous

Various applications of rotating heat pipes are described [41G–43G]. Other investigations of heat transfer in rotating environments include corotating jets [45G], a fluidized bed drier [46G], a rotary kiln [47G], cooling of rotating electrical machines [44G] and heat transport in geostrophic flows [40G].

11. Combined heat and mass transfer

11.1. Ablation

A number of studies consider the thermal response of ablating materials. Researchers considered the ablation of dental hard tissue [10H] the epidermis [6H] and the directional effects of cooling on the ablation of bovine liver and other biological tissue [1H]. Researchers utilized computational techniques to study the viscous shock-layer of airflow past an ablating blunt body [8H], to obtain the solution to the single-phase Stefan problem with external heat flux [7H], to study thermal damage on thin Cr films undergoing excimer laser irradiation [3H], and to model the complex flow and plasma properties of cutting plasma torches [2H] and the heat transfer in the melt layer under steady, hypersonic conditions [9H]. In addition, experimental studies considered the ablation of zinc sulphide films on silicon [5H], and the energy coupling during laser ablation and drilling of solids with varying reflectivity [4H].

11.2. Film cooling

Film cooling is an effective method of heat transfer and very useful in protecting surfaces from the effects of thermal stress. Several studies considered the film cooling of turbine blades. The effects of the number, and arrangement, of rows of cooling holes have been considered [15H,16H,20H,18H,24H]. Investigators also considered aerothermal effects, including the blowing ratio, freestream velocity, and pulsation frequency [11H], molecular properties [17H], and the effects of unsteady wake with coolant ejection [14H]. Researchers proposed a general correlation for the effectiveness of film cooling which takes into account non-isothermality, compressibility, surface roughness, and swirl [19H]. Several numerical studies were also performed. Numerical simulations were carried out to investigate the influence of the inlet Mach number and the inlet turbulence intensity [12H], to the study of geometric parametric variation was conducted to optimize film cooling design [23H], and to isolate the flow physics responsible for hot cross-flow ingestion [21H]. The leading edge region of a high-pressure turbine blade with slot cooling was investigated [13H]. Researchers also used multi-disciplinary design optimisation in conjunction with a quasi-three-dimensional Navier–Stokes solver to reduce turbine blade temperatures [22H].

11.3. Jet impingement heat transfer – submerged jet

A number of studies involved heat transfer in submerged jets (air issuing into air, liquid issuing into liquid) impinging on an opposite wall. Several numerical studies illustrating the effect that variation of the Reynolds number and nozzle-to-target spacing have on heat transfer were performed [49H,41H,25H,26H]. A three-dimensional Monte Carlo simulation of plume impingement was performed [34H]. Simulations of both laminar and turbulent, conical and round, impinging jets have been performed using three-dimensional and axisymmetric simulations [45H,42H,40H,32H]. Other numerical studies considered the effect of Schmidt and Prandtl numbers [28H], the performance of Reynolds stress and k–ϵ models [47H], impinging jets with and without a moving surfaces [52H,31H]. Experimental investigations provided flowfield visualization during jet impingement heat transfer using smoke wire methods and laser-doppler anemometry [37H,38H,29H]. Steady periodic surface pressure distributions were obtained for a pulsed radial jet reattachment nozzle [33H]. The surface shear stress was measured for a round submerged jet [53H]. Heat transfer characteristics in the stagnation region were investigated [36H]. A comparative investigation of jet impingement and microchannel cooling was performed [35H]. Heat transfer enhancement via jet pulsation was considered [44H]. Heat sink performance was studied for a range of Reynolds numbers and nozzle-to-sink distances [39H]. The heat transfer due to impinging gas jets on liquid and concave surfaces was considered [43H,50H,51H]. The effects of pulsation on turbulence intensity and heat transfer performance of jet arrays were studied [46H]. An experimental investigation provided detail heat transfer distributions for an array of jets impinging on plate with a staggered array of film cooling holes [30H]. Researchers also focused on the cooling of pistons using jet impingement and ribbed duct flow [27H], and obtained circumferential heat transfer distribution as well as axial Nusselt number in a circular cylinder exposed to an impinging air jet [48H].

11.4. Jet impingement heat transfer – liquid jets

A jet in which the issuing stream has a density significantly higher than that of the ambient fluid is said to be a liquid jet. Due to their relatively high-thermal conductivity liquid jets are often used for jet impingement heat transfer. Researchers considered heat transfer characteristics of single and dual-exit drainage configurations for arrays of liquid jets [54H]. An experimental investigation was performed to determine heat transfer rates for a range of Prandtl numbers and viscosity ratios [55H]. Researchers utlized numerical methods to investigate the influence of parameters such as the jet velocity, heat flux, plate thickness, nozzle height, and plate material, on heat transfer [56H].

11.5. Spray cooling

Spray cooling consists of a stream of fluid droplets impacting on a surface and thus providing a highly effective means of local heat transfer. The spreading of liquid films produced by drop impaction was studied [57H]. A configuration utilizing four full cole, swirl spray nozzles was investigated [58H]. Numerical simulations were performed to study droplet formation, detachment and impingement in gas metal welding [59H]. In addition, a new model for the description of particle wetting, and temperature and concentration distribution in the spraying of fluidized beds was developed [60H].

11.6. Drying

Heat and mass transfer are integral to drying. Recent investigations include the drying of various foods. Studies of microwave, convective, and freeze drying of fruits and vegetables [63H,65H,68H,73H,78H,79H,87H,89H,96H,98H,101H,107H,112H]. Superheated steam was utilized for the removal of moisture in fishmeal and tortilla chips [67H,86H]. Numerical studies have been extremely useful in the modeling and simulation of the drying process. The k–ϵ approach was applied in both two- and three-dimensional calculations [83H,102H]. Researchers also used computer modeling to predict the drying and crystallisation during processing of thin sugar films [66H], the drying of wet PVC particles in large scale pneumatic dryers [85H], and also to predict spray drying using both air and superheated steam [69H]. The drying of wood was studied extensively. Diffusion and mass transfer coefficients in the drying of hard and soft woods were investigated [76H,106H]. The relationship between heat and mass transfer on a wooden surface was investigated, producing a correction factor for the mass transfer coefficient predicted by boundary layer theory [77H]. The validation of a model for a wood dryer kiln was performed [104H,105H]. Simulations were used to study both the effect of air velocity [91H], and microwave drying in an over-sized waveguide [90H]. Researchers utilized computer-tomography to measure moisture flux during drying [109H]. Boundary layer conductance and transpiration were studied over a range of wind speeds [88H]. The drying of films including multi-component and multi-layer, was investigated [61H,62H,80H,64H]. Fluidized bed dryers were also considered. These include the drying of polypropylene powder [70H] and a computational investigation of solid material drying via finite elements [111H]. A modified three-phase model for the drying of fine powders was developed [84H], and models for the prediction of the heat transfer coefficient were validated via comparison with data obtained experimentally [108H,72H]. Several investigators considered the drying of paper, and paper products. These include the development of an impedance method to measure moisture content [110H], the development of models which simulates the drying of a paper [97H,94H], and through drying of paper and fabrics [74H,93H]. Researchers also considered such physical effects as shrinkage, blistering, and induced strain–stress during the drying process [75H,99H, 81H,92H]. A variety of dryers, and drying mechanisms, have been considered [100H,103H, 71H,95H,82H].

11.7. Miscellaneous

A variety of studies in which heat and mass transfer occurs in combination have been performed. These include the modeling and measurement of heat and mass transfer in soil–plant–atmosphere systems [135H,124H,143H,127H]. The effect of sea-spray droplets on transfer between the air and the sea was considered [142H]. Researchers modeled water and heat transfer in soils [153H,131H,123H,132H]. The effect of increased atmospheric carbon dioxide on water efficiency in plants was investigated [138H]. The characteristics of a summer monsoon were examined using a global analysis-forecast system [145H]. Biomass fast pyrolysis processes were studied [117H, 118H]. Combined heat and mass transfer was studied during material synthesis [130H,133H]. Several models were developed and evaluated via numerical simulation [139H,128H,137H,119H,152H,148H,151H,136H, 129H,146H,144H,126H,150H,121H]. Among these were the simulation of an anti-icing system[139H], a low Reynolds number model for the prediction of thermal fields [128H], a two-dimensional model for the cooking of regularly shaped chicken patties [119H] and the simulation of a shallow lid-driven cavity [114H]. Analytical models were developed to obtain first- and second-order quantities [115H,125H], and the removal of acetone from aqueous streams [113H]. Researchers also developed a model to study the heat transfer across an epoxy coating subject to an impinging flame [116H]. Experimental investigations include the study of reactive flow systems [140H,141H], air dehumidification [134H], potato frying [120H], the cooling of film blown bubbles [147H], the effect of gas absorption on a rising bubble [122H], and the effect of wrapping very low birth weight infants in polyethylene on preventing heat loss [149H].

12. Bioheat transfer

This section is composed of papers obtained through searching current contents in the general area of bioheat transfer. It should be emphasized that this is only a subset of the total papers available in this area and should not be taken as comprehensive.

12.1. Thermal engineering

Several studies on heat transfer from the human body included: heat and mass exchange between the surface of the human body and ambient air at various altitudes [8I]; CFD analysis of wind environment around a human body [10I]; and a new approach to assessment of an accurate wind chill factor [2I].

Heat transfer through clothing was investigated by a number of groups. Their work included: heat strain in workers wearing personal protective clothing [5I]; wind and human movement on heat and vapor transfer properties of clothing [11I]; an improved representation of clothing evaporative resistance [6I]; thermal characteristics of clothing ensembles for use in heat stress analysis [1I]; efficacy of air and liquid cooling during light and heavy exercise while wearing special NBC clothing [9I]; proposed improvements in modeling of clothing convective heat exchange [7I]; and a description of a cooling suit to reduce heat sensitivity in multiple sclerosis patients [4I].

Heat transfer in birds was studied. This work included: heat transfer from starlings Sturnus vulgaris during flight [12I] and heat transfer through penguin feathers [3I].

12.2. Thermoregulation

Studies in this area included: a computer model of human thermoregulation for a wide range of environmental conditions [14I]; metabolic and thermodynamic responses to dehydration-induced reductions in muscle blood flow in exercising humans [16I]; the failure of negative pressure rewarming to accelerate recovery from mild hypothermia in post-operative surgical patients [22I]; the effect of dialysate temperature on energy balance during hemodialysis [24I]; and the introduction of a bronchial thermodilution method to estimate cardiac output [17I].

Thermoregulation studies in animals focused on: thermoregulation and physiology during swimming and diving in bottlenose dolphins [18I,25I]; the role of hyperthermia in the water economy of desert birds [23I]; the relationship between the thermal environment and activity of Piute ground squirrels [21I]; behavioral thermoregulation effects on the rate of body temperature change in wild freshwater crocodiles [19I]; and how thermoregulatory mechanisms create a high and stable body temperature in crocodiles [20I].

Thermoregulation is intimately tied to blood flow. Studies in the area of blood flow included effects of flow on control of heat exchange in reptiles [13I]; and a new blood flow measurement technique based on Lagrange multipliers [15I].

12.3. Thermal therapy

Thermal therapies generally require the use of an energy source to induce thermocoagulation in the tissue of interest. Studies using Ultrasound, Laser and RF are presented here. Studies in Ultrasound focused on: a dual-frequency ultrasonic system for breast cancer treatment [34I]; an angular directivity of thermal coagulation using an air-cooled direct-coupled interstitial ultrasound applicator [27I]; and the relationship between acoustic aperture size and tumor conditions for external ultrasound hyperthermic treatment [32I]. Laser studies included work on: dynamic modeling of interstitial laser photocoagulation [43I]; long exposure growth of in vivo interstitial laser photocoagulation lesions [37I]; modeling of laser treatment of port wine stains [36I]; and optical thermal modeling of laser tissue soldering [35I]. In radiofrequency, one study performed an evaluation of the effectiveness of transurethral radio frequency hyperthermia in the canine prostate [44I].

Several studies investigated thermal changes in tissues in response to thermal therapeutics. This work included: microvascular thermal equilibration in rat spinotrapezius muscle [42I]; countercurrent vessel heat transfer formulations [41I]; flow dependence of temperature gradients near large vessels during tissue heating [29I]; modeling the thermal impact of a discrete vessel tree [30I]; and modeling the effects of metabolic heat generation and blood perfusion in tissues supplied by a blood vessel [38I,39I]. In addition, the effect of nonlinear heat transfer on temperature control in regional hyperthermia [31I]; and a computational evaluation of temperature distribution during hyperthermic treatment in biliary tumors were presented [40I].

Related studies showed that heat treatment of human sera reveals antibodies to bactericidal protein [26I]; changes are induced in MR properties of tissues after heat treatment [28I]; and finally the thermal wave aspects of instantaneous heating in skin were evaluated [33I].

12.4. Cryopreservation

An "Open Pulled Straw" method for vitrification of porcine blastocysts was presented [45I] along with a numerical model of continuous hybrid heating of cryopreserved tissue [46I]. In addition, sperm collection from shot red deer stags was frozen and successfully used in in vitro fertilization [47I].

12.5. Dental/biomaterial

These studies investigated: the thermal effects on long-term performance of UHMWPE failure in artificial knee joints [50I]; the use of Gelfoam as a barrier to prevent polymethylmethacrylate induced thermal injury of the spinal cord during vertebral reconstruction [49I]; and the use of heat-treated cortical bone for use as a bone substitute [48I].

13. Change of phase – boiling

Thermal transport phenomena associated with liquid-to-vapor phase change are addressed in the publications reviewed in this section and classified into five major categories: droplet and film evaporation (21 papers), bubble characteristics and boiling incipience (17 papers), pool boiling (39 papers), flow boiling (31 papers), and two-phase thermohydraulics (24 papers). In addition to these 132 papers, the interested reader will find reference to studies of evaporative and ebullient heat transfer among the papers included in: change of phase – condensation (JJ), heat transfer applications – heat pipes and heat exchangers (Q), and heat transfer applications – general (S).

13.1. Droplet and film evaporation

The 1999 archival literature provides several fundamental studies of droplet evaporation, including three numerical studies which focused on the effects of temporal pressure variations [16J], continuous variation in the free stream velocity past the drop [4J], and use of a non-gray gas radiation model for modeling of a combusting/evaporating droplet [2J], respectively. The surface temperature variation of a hydrocarbon droplet is the subject of [7J]. In [18J] a population balance model is used to predict volumetric heat transfer coefficients in a direct-contact evaporation column, while [19J] compares extensive high-pressure experimental data for freely falling droplets with the conduction limit and diffusion limit models.

Evaporation of liquid films is described in [1J] – dealing with a thin falling water film inside an electrically heated tube, [17J] – providing numerical predictions of a falling water film on a tilted plate subjected to radiant heating, and [10J] – focusing on the use of enhanced copper tubes to improve heat transfer to a falling film of lithium bromide. The evaporation of multi-component hydrocarbon fuel compounds was described in [8J], the design and simulation of multi-effect evaporators in [21J], and use of a non-isothermal microscale model to explore the characteristics of the three-phase contact zone in liquid rewetting of hot surfaces in [3J]. Thome [20J] provides a review of falling film evaporation on single tubes and tube bundles, with emphasis on studies of alternative refrigerants and ammonia.

The role of evaporation in methanol liquid pool fires was described in [14J] – presenting the development of a comprehensive numerical model, and in [13J] – focusing on the suppression of such fires using water mist. Thermal transport associated with the pre-boilover burning of an oil slick is examined in detail in [9J]. Pool evaporation of decane, in the presence of convecion, and the development of an analytic procedure for investigating evaporation from a saline solution subject to transients are described in [5J,11J], respectively.

Evaporating liquid sprays in gas turbine combustors are modeled numerically in [15J], while experimental studies of spray cooling on horizontal staggered tubes are reported in [6J] and on a disk-shaped surface in [12J].

13.2. Bubble characteristics and boiling incipience

Homogeneous nucleation of vapor bubbles is well represented in the 1999 heat transfer literature, including a study of boiling incipience along a cavity-free microheater [33J] and in surfactant solutions [37J], of aluminum slurry droplets experiencing a microexplosion [22J], of the initiation of "boilover" in liquid fuel spills [24J], of flashing under rapid depressurisation in small non-adiabatic vessels [32J], and in the development of a mathematical model describing the growth of an internal vapor bubble in a superheated liquid [34J].

Single bubble characteristics underpin much of the modeling and understanding of ebullient heat transfer. The growth and collapse of a vapor bubble in a small tube and in the space between two superheated or subcooled parallel plates are reported in [38J,36J], respectively. The interfacial characteristics of an isothermal bubble constrained in a quartz cuvette are the subject of [27J]. A perforated plate is used to study the effect of gravitational acceleration on vapor bubble kinematics in the pool boiling of liquid nitrogen [30J], while a finite-difference simulation is used to predict the behavior of a vapor bubble growing and departing from a horizontal surface [35J] and a theoretical, as well as experimental, study addresses the shape of a long isolated bubble in horizontal flow in [31J]. Oscillations in bubble volume and shape were examined in [28J] – focusing on the interplay between radial and shape oscillations for an initially deformed bubble, in [29J] – dealing with the response of a gas bubble to cyclic, impulsive changes in ambient pressure, and in [25J] – exploring the coupling between bubble dynamics and an imposed acoustic field. The literature also includes discussion of bubble characteristics in high-pressure bubble columns and three-phase fluidisation systems [23J] and the dynamics of bubble–particle interactions in water and a glycerin solution [26J].

13.3. Pool boiling

Fundamental studies of pool boiling behavior continued to attract the attention of the heat transfer community, leading to publication of a refined experimental determination of the constants in the Rohsenow correlation for water and other liquids [69J], a detailed mapping of the convective and nucleate boiling zones on small horizontal heater in saturated pool boiling in [71J], an evaluation of the boundary condition impact on boiling from a tube [47J], the inclusion of thermocapillary-driven flow in the predictive model for macrolayer transport at high-heat fluxes [66J], the clarification of the mechanism responsible for bubble waiting time in steady nucleate pool boiling [55J], and new theoretical methods for predicting nucleate pool boiling in binary mixtures [48J,42J].

Many of the pool boiling heat transfer studies in the 1999 literature deal with extension of the ebullient transport knowledge base to unconventional fluids, environments, and geometries. The pool boiling of liquid mixtures is the subject of [49J] presenting results for the pool boiling of ethanol–water mixtures, [56J] exploring dilute solutions of ethylene glycol and water, [58J] aqueous solutions of limited solubility, [39J] water/2-propanol mixtures in which Marangoni effects are strong, and [44J] describing the behavior of aqueous solutions with considerable solute deposition.

Boiling in the presence of magnetic fields is the focus of [54J], which examines the characteristics of water-based and ionic magnetic fluids, and [65J], which reports on the various boiling regions in a cryostable magnet. [74J] summarizes the results of an extensive microgravity Spacelab study of boiling from miniature heaters immersed in R11. The effect of heater orientation on the stability of boiling from a flat plate was examined in [61J], while [41J] reports on the pool boiling of water over vertical steps. Boiling from a miniature thermal ink-jet heater in water and during immersion frying are reported in [40J] and [53J], respectively.

In boiling heat transfer, the critical heat flux (CHF), or "boiling crisis", represents the heat flux value at which vapor blankets the heater surface and the heat transfer coefficient deteriorates. The 1999 literature includes several distinct studies on the influence of adjacent surfaces and/or boiling surfaces on CHF from flat plates. [50J] reports on critical heat flux in miniature heat sinks with microcapillary grooves, while [68J,46J,63J] all describe aspects of pool boiling CHF in an annular channel. The effects of reduced gravity on CHF are explored in [73J] and the effects of small departures from the vertical orientation are modeled in [51J]. A detailed parametric study of the transition to film boiling [43J] and of the heat exchange processes in film boiling [64J] was also reported.

Despite the relatively high heat transfer coefficients associated with boiling heat transfer, considerable effort is devoted to the identification, development, and implementation of pool boiling enhnacement techniques. In [70J] attention is focused on elimination of the FC-72 superheat excursion using spherical point contacts on a horizontal surface; in [59J] on the use of numerous microreentrant cavities to enhance pool boiling from a chip immersed in FC-72; in [52J] on the thermal characteristics of microroughened, ribbed tubes, and in [72J] on R-123 boiing from microchannel enhanced tubes.

Pool boiling from fins has received renewed interest, including [62J] – providing a theoretical and experimental exploration of boiling on a conical spine of variable cross-section, [60J] – theoretically investigating boiling on a straight fin with variable thermal conductivity, and [67J] – presenting experimental results for boiling from finned surfaces confined in a narrow channel. The pool boiling enhancement of R123 by the addition of *n*-hexane was described in [57J] and by the addition of surfactants/polymer additives to water in [76J]. The influence of electric fields on nucleate pool boiling was examined in [45J,77J] and on film boiling in [75J].

13.4. Flow boiling

The broad range of interactions between a pumped flow of liquid and vapor bubbles generated and released on a heated surface provides a large number of flow boiling heat transfer mechanisms and a diverse flow boiling literature. Many of the studies contained in the 1999 literature deal with geometric effects on flow boiling, including surface roughness and microgeometry in [107J], a round converging tube in [103J], plate heat exchangers with corrugated sine-shaped chevrons in [106J], microchannel heat exchangers in [95J], internally enhanced tubes in [78J,79J]; and an in-line array of simulated microelectronic chips in [84J], and very narrow channels in a quasi-annular flow condenser–evaporator in [83J]. Extensive data for refrigerant–oil mixtures flowing in low-fin and micro-fin tubes are correlated in [104J]. The flow boiling characteristics of unconventional liquids, such as *n*-pentane flowing over a horizontal tube bundle [97J], ammonia flowing in a smooth horizontal tube [108J], and water/ammonia and ammonia/lithium nitrate mixtures flowing inside vertical smooth tubes [96J], also received attention. Flow boiling modeling studies completed during this period can be found in [102J] – dealing with the influence of sliding vapor bubble on flow boiling heat transfer, [86J] – including the contribution of conjugate heat transfer to flashing within a ruptured pipe, and in [81J] – describing a two-dimensional model for a kettle reboiler.

The archival literature of 1999 provides evidence of further progress in the understanding and enhancement of the flow boiling "crisis", including both critical heat flux and dryout. The development of a new mechanistic approach to subcooled flow boiing CHF is presented in [82J], while the parametric sensitivity of the "boiling crisis" in positive-quality, low-pressure flow was the subject of [90J] and CHF during countercurrent flow in transient boiling systems of [91J]. Recently obtained data for CHF limits in water-cooled systems were compared to available correlations in [87J] and in [92J] attention is focused on the relationship between the hydrodynamic and thermal phenomena of dryout in horizontal and inclined tubes. Several publications, including [80J,100J,101J] examine various aspects of CHF in tubes subjected to one-sided heating, as might occur in a fusion reactor. Ultra-high CHF, under high velocity, subcooled water flows were investigated in [87J,88J,93J]. In [89J] the EHD-enhancement of CHF on a low-fin tube was found to increase dramatically in a liquid with a short electrical charge relaxation time, and in [98J,99J] experimental results and a theoretical model are presented for predicting the influence of centripetal forces on CHF from the concave surface of a curved tube.

Post-CHF, film boiling occurring on high-temperature melt jets was the subject of [85J,94J] and in [105J] an inverse conduction procedure was used to estimate transient heat fluxes during flow film boiling.

13.5. Two-phase thermohydraulics

The design of flow boiling systems must include attention to the thermohydraulic aspects of two-phase flow. Several fundamental studies of these phenomena appeared in the 1999 literature, including [116J] – presenting a moving-boundary model for stability analysis of boiling channels, [119J] – reporting extensive local measurements of two-phase parameters for bubbly flow, [131J] – exploring the pressure effect on the slug to churn flow transition in vertical, upwards flow, and [111J] –

providing measured values of turbulence intensity in annular gas/liquid flows.

The thermohydraulic phenomena that occur in horizontal tubes were examined in [110J] – focusing on the transition from dispersed to elongated bubble flow, [117J] – presenting an exact analytical solution for the interface shape in stratified flow, [113J,114J] – exploring the characteristics of horizontal two-phase helium flows, [132J] – describing the relationship between Froude number and slugging frequency, and [124J] detailing the flow regimes encountered in vertical, upward cross-flow in horizontal tube bundles. Prediction of various hydraulic parameters in boiling, two-phase flows can be found in [115J,130J], while [120J] discusses methods for estimating heat transfer relationships in non-boiling gas–liquid flow. Two-phase flow in microchannels also attracted attention, as described in [126J,127J] – dealing with flow patterns, pressured drop and void fraction in gas–liquid flow thru microchannels, [109J] – exploring the impact of desorption of non-condensables gas on the hydrodynamics of long microchannels, and [133J,134J] – reporting experimental results on narrow, vertical, rectangular channels. A transient, one-dimensional model for gravity-induced capillary flow in a square groove is discussed in [125J].

The 1999 literature provides the results of studies of the phenomena arising in the design and optimisation of two-phase heat exchange equipment. Thus, [128J] describes the effect of pipe inclination on flow distribution in parallel pipes, [129J] proposes an analytical model for two-phase instabilities in parallel channels, [122J] offers a simple three-field model to predict annular-dispersed flow in a converging nozzle, [118J] provides pressure drop data for axially grooved refrigerant tubes, [121J] describes thermohydraulic performance of a safety relief valve, and [123J] displays high-speed photographs of the phase distribution and bubble velocity in a bubbly slit flow.

In a novel application of two-phase theory [112J] presents a study of bubbly two-phase flow around a ship's surface.

14. Change of phase – condensation

Papers on condensation during 1999 are separated into those which dealt with surface geometry effects; those on the effects of global geometry, thermal boundary conditions and external influences; papers presenting techniques for modeling and analysis; papers on unsteady effects and papers dealing with mixtures. A discussion of the better-understood aspects of condensation heat transfer was presented in a review paper [1JJ].

14.1. Surface geometry and material effects

Papers on the peculiarity of the surface to condensation included one on predicting condensation in bulks of foodstuffs, like potatoes [7JJ], one on sublimation and condensation of snowpacks [2JJ], another on alkali vapor condensation on ash [6JJ], one on moisture condensation on rock in the underground storage of nuclear waste [5JJ] and a paper on condensation on thermoplastic gutta-percha using a vertical condensation technique at a root canal wall [4JJ]. Finally, results of an analysis of instability of films and of droplet formation on hydrophilic surfaces were presented [3JJ].

14.2. Global geometry, thermal boundary condition and external influence effects

Papers which describe the effects of global geometry include one on condensate drainage from a horizontal, integral-fin tube [30JJ] one on a partially wet radial fin assembly [24JJ] and another on downward-flowing refrigerant in a staggered bundle of horizontal low-finned tubes [15JJ]. The effects of fin height with steam condensation on a horizontal integral-fin tube were experimentally assessed [11JJ] and a numerical study of a finned tube assembly for dehumidification was presented [25JJ]. Condensation heat transfer coefficients on enhanced tubes with alternative refrigerants were measured [18JJ] and steam condensation [32JJ] and R-134 condensation [36JJ] on a plate heat exchanger were experimentally evaluated. Finally in this sub-category, the application of room radiators for dehumidification was evaluated [13JJ].

In somewhat simpler geometries, laminar film condensation on a finite-size horizontal plate [20JJ] and on a single horizontal cylinder [8JJ] was computed. Condensation of R-410A in a rectangular channel was experimentally evaluated [12JJ] as was condensation of R134 in a small pipe [35JJ]. Modeling of complete condensation of a two-phase flow in a miniature tube [9JJ] and condensation of alternative refrigerants in a micro-fin tube [19JJ] were presented. Flow characteristics in an annular flow were discussed [17JJ] and Nusselt numbers for flow through an inclined circular tube were presented [21JJ].

One particular geometry in which a considerable amount of condensation heat transfer attention had been paid is that of containment systems of nuclear power plants. One paper looked at natural convection and condensation in the condensers of the ESBWR reactor [22JJ], another focused on non-condensables in the containment [23JJ] and two others specifically addressed the SWR1000 reactor [26JJ,27JJ]. Finally for this sub-category, one paper addressed the plant behavior after a loss-of-residual-heat-removal event [28JJ].

A single paper discussed thermal boundary condition effects. Specifically, it dealt with variable wall temperature effects [16JJ].

The final sub-category is on external effects. Two papers discussed the effect of buoyancy, one on a vertical conduction wall [29JJ] and another on an isothermal wall [33JJ], while another studied the effect of a centrifugal force field on condensation where the force was parallel to the condenser surface [34JJ]. The effects of using a mechanical wall cleaning device to remove the film periodically were evaluated [31JJ] and the optimum period of washing was assessed. Finally, the effects of turbulence on condensation on a horizontal tube [14JJ] and the effects of EHD on smooth, horizontal and vertical tubes were evaluated [10JJ].

14.3. Modeling and analysis techniques

A critical review of prediction models for correlating condensation heat transfer coefficients was presented [43JJ] as was a general model for heat transfer during reflux condensation inside a vertical tube [39JJ]. Models for condensation heat transfer predictions on low-finned tubes were evaluated [37JJ] and a computational procedure for condensation inside enhanced tubes was proposed [38JJ]. A theoretical model for finding an optimum active double effect distillation system was proposed [41JJ]. A model for analyzing steam injector performance was suggested which was able to display the condensation shock [40JJ]. Finally, a lattice Boltzmann scheme was used to describe the heat and water vapor transport driven by natural convection in a potato container [42JJ].

14.4. Unsteady effects in condensation

Papers which focus on unsteady condensation include one which generally treats condensation behavior under transient conditions [50JJ]. Another presents measurements of heat transfer coefficients for direct-contact condensation during bubble growth in liquids [53JJ] and two deal with droplet growth; one discusses the Gibbs–Thomson effect [49JJ] and another is a digital simulation of condensation from the equilibrium droplet size [45JJ]. One study presents an investigation of the instability of a condensate film and capillary blocking in small-diameter-thermosyphon condensers [52JJ]. A model was presented for computing the moisture and thermal transient behavior of multilayer, non-cavity walls [44JJ]. With it, moisture transport and material moisture content within the wall system can be evaluated. Several papers were on materials processing. In one, solar processing to make composites by vapor-condensation was discussed [47JJ]. In another, growing films by sputter deposition were addressed [46JJ] and in a third, a plasma sampling mass spectrometry technique was discussed [48JJ]. In this technique, supercooled noble gas clusters act as nucleation sites for condensation. Finally, alternative methods for curing of flip-chip-on-board underfill were discussed [51JJ].

14.5. Binary mixtures

Fewer papers than last year dealt with mixtures. In a first category, mixtures of vapors and gases were considered. The first is on the prevention of fog in condensation of a vapor in the presence of an inert gas [57JJ]. A second is on condensation of a supersaturated steam–air mixture on a flat plate [56JJ]. A third is the analysis of laminar mixed-convection condensation on isothermal plates with a mixture of a vapor and a lighter gas [59JJ]. Finally, solar thermal dissociation of zinc oxide was suggested using condensation and crystallisation of zinc in the presence of oxygen [60JJ]. Several papers were with liquid mixtures. In one, condensation of a R12/R134a mixture on a horizontal tube with a capillary structure was investigated experimentally [58JJ]. Also, experiments were with the pure fluids separately. Experiments were carried out also with downward-flowing zeotropic mixtures of HCFC-123/HCFC-134a on a staggered bundle of low-finned tubes [55JJ], and condensation heat transfer coefficients for mixtures of R-32 and R-125 were measured [54JJ].

15. Change of phase – freezing and melting

15.1. Melting and freezing of sphere, cylinders and slabs

Planar studies included a one-dimensional solidification problem with free convection in an infinite plate geometry [5JM] as well as a semi-implicit FEM analysis of natural convection in freezing water [2JM]. In radial geometries melting of slush ice in a cylindrical enclosure was studied [3JM] as well as local ice formation in pipes in the presence of natural conection [4JM]. Another study presented finite element simulations of freezing and thawing using symbolic computing in Maple [1JM].

15.2. Stefan problems

Studies involving Stefan problems included: determination of unknown thermal coefficients for Storm's type materials [6JM]; linearized solution of quasi-steady Stefan problem in vertical gradient freeze configuration [7JM]; multi-dimensional Stefan problems emerging from three-dimensional phase boundary reconstruction under low Peclet number conditions [8JM]; analysis of the Stefan problem associated with ice and water film growth from supercooled droplets [10JM]; fast and accurate numerical schemes for solution of Stefan problems [9JM]; and Stefan problem(s) resulting from a mixed elliptic problem with flux and boundary conditions [11JM].

15.3. Ice formation in porous materials

Work in the area of food freezing included: development of predictive equations for thermophysical properties and enthalpy during cooling and freezing of food materials [12JM]; mathematical modeling for semi-batch operation of tray tunnels for food deep chilling [13JM]; mass transfer during immersion chilling and freezing of apples [14JM]; a numerical study of heat and fluid flow in food freezing [16JM]; modeling of food freezing with non-constant properties [19JM]; and the effect of heat transfer direction on numerical prediction of beef freezing processes [21JM].

Other studies in soil, rock and snow included: modeling of moisture transfer in freezing soil [15JM,20JM, 23JM]; radiative freeze occurrence in leafless forests [18JM]; coupled thermo-hydro-mechanical problem of freezing and thawing in rock [17JM]; and an urban snow deposit melt model [22JM].

15.4. Contact melting

Close contact melting of a spherical capsule was investigated numerically and analytically [24JM].

15.5. Melting and melt flows

15.5.1. EM processing

This section presents investigations dealing with electromagnetic processing of melt and melt flows. Studies included: a combined thermal and optical analysis of laser back-scribing for amorphous-silicon photovoltaic cells [25JM]; assessment of mechanism of melt ejection and striation formation in continuous wave laser cutting of mild steel [26JM]; high-energy electron beam irradiation for surface alloyed materials fabrication [29JM]; nitride formation in laser surface melting [31JM]; laser processing to melt and fuse vitreous material [33JM]; heat transfer during electron beam melting and refining [34JM]; melting and vaporisation in laser drilling [35JM]; magnetic field effects on floating zones during silicon processing [28JM]; excitation of thermoelectric instability in a liquid ionic melt [32JM]; bouyant melt flows in magnetic fields [30JM]; and fluid flow and heat transfer in molten metal stirred by a circular inductor [27JM].

15.5.2. Convection

In this section a simulation of coupled natural convection and melting from an isothermal vertical wall was studied [36JM]. In addition, estimation of melting rates in the two-phase plume region of a gas stirred bath [37JM] and simulation of convection and macrosegregation in a large steel ingot were presented [38JM].

15.5.3. Geological

Melt studies in geological systems included investigations of: natural convection mixing and stratification in basaltic and magma applications [39JM]; a two-stage thermal evolution model of magmas in continental crust [40JM]; evolution of zoned magma chamber in the central Andean upper crust [41JM]; melting within the lower earth's crust [42JM]; fluid content of slab melts at high pressures in earth crust [43JM]; transformation of rocks during frictional melting [44JM]; Hawaiian volcanic melt plume studied by three-dimensional convection model [45JM]; criteria for the recognition of partial melting of rocks [46JM]; use of superheated water to melt and mobilize sulfur in mining [47JM]; eruption heat transfer from hot magma during basaltic fissure eruption [48JM].

15.5.4. Sea ice and snowmelt

Ice–ocean interactions at the base of an ice shelf were thermodynamically modeled [49JM]. Additional studies focused on: sea ice melt layer stability [50JM]; the impact of melting sea ice on water properties [51JM]; ocean heat flux from the Weddel Sea with ice during winter [56JM]; and meltwater production in Antarctic blue-ice areas [54JM,55JM]. The impact of snowmelt models on climate simulations was studied [52JM]. Additional studies focused on: the melting of frozen sediment on the Beaufort sea coast [53JM]; and an energy balance and runoff analysis from a glacier [57JM].

15.5.5. Polymers

Interfacial heat transfer during melt blending of polymers was studied [59JM]. Additional work yielded: temperature gradients in molten polymers during cooling [60JM]; numerical prediction of non-isothermal flow of nylon-6 melt past a cylinder between plates [61JM]; and pressure and temperature effects in slit rheometry of polymer melts [58JM].

15.5.6. General

General melt and melt flow studies included: the effects of modulation on heat flow and phase shift during phase change measurements with modulated differential scanning calorimetry (TMDSC) [62JM]; axial conduction in laminar falling films and its effect on ice crystal growth [63JM]; effects of melt cleanliness and inclusions in Al–Si alloys [64JM]; heat transfer and fluid flow in the melt section of a single screw extruder [65JM]; coating of high melting point materials [66JM]; analysis of the effectiveness of counter current scrap pre-heating during smelter melting [67JM]; and mixing and bubble formation in slag re-circulation and heat transfer [68JM].

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

Studies in this section included: a quasi-stationary numerical model of atomized metal droplets [69JM]; mathematical modeling of the heat transfer between a coating and a metal substrate during HVOF spraying [70JM]; laser-induced diffusion in Ge/Sb evaporated onto Si [71JM]; metal melt gas-atomisation and spray formation measured with phase-Doppler anemometer [72JM]; cold extrusion and in situ formation of self-blends of UHMWPE [73JM]; melting of a subcooled powder bed with constant heat flux [74JM].

15.7. Glass melting and formation

These studies focused on: treatment of radiative transfer in glass [75JM]; measurement and prediction of glass surface temperatures in an industrial glass furnace [76JM]; approximate analytical solution for heat transfer in glass melting furnaces [77JM]; numerical analysis of instabilities in the glass melt surface [78JM]; and modeling of glass melting furnace design with regard to No_x formation [79JM].

15.8. Welding

Mass momentum and energy transport in a molten pool when welding dissimilar metals is discussed [80JM]. Other work was presented on: keyhole formation and collapse in plasma arc welding [81JM]; and thermal analysis of spot welding electrodes [83JM]. In addition, contact welding of host rocks during basaltic intrusion into pyroclastic deposits in Grants Ridge New Mexico was presented [82JM];

15.9. Enclosures

Studies included: melting of unfixed solids in square cavities [84JM]; enhanced heat transfer in free convection-dominated melting in a rectangular cavity with an isothermal vertical wall [85JM]; two-dimensional solidification in a corner [86JM]; freezing of water in a differentially heated cubic cavity [87JM]; flow instabilities in melting from the side of a cavity [88JM]; interfacial breakdown of a two-layer salt stratified system in different enclosures [90JM]; enhancement of melting of PCM in cylindrical annulus [89JM]; melting about a heated cylinder in an ice-filled enclosure with isothermal free surfaces [91JM]; contact melting under vibration within rectangular enclosures [92JM]; velocity distribution of double- diffusive convection of a binary mixture in a rectangular enclosure during solidification [93JM]; vortex flow of low concentration $NH_4Cl–H_2O$ solution during solidification in a rectangular cavity [94JM]; and analysis of the melting process in a rectangular enclosure [95JM].

15.10. Nuclear reactors

An overview of core melt stabilisation scenarios was presented [96JM].

15.11. Energy storage

An enthalpy method was presented to solve transport processes associated with the effect of density change on melting of unfixed rectangular PCMs under low-gravity environments [97JM]. Other studies in this section focused on: heat transfer in vertically aligned phase change energy storage systems [98JM]; a molten salt system with a ground base-integrated solar receiver storage tank [99JM]; cold cylinder PCM solidification [100JM]; thermal performance of a PCM storage unit [101JM]; thermal performance of a latent heat energy storage unit with ventilated panel heating [102JM]; accelerated thermal cycle test of latent heat storage materials [103JM]; and heat transfer during solidification of PCM inside an internally finned tube [104JM].

15.12. Solidification during casting

Work in this area focused on: an average heat capacity method for the analysis of conjugate heat transfer during the two-phase solidification process in continuous castings [105JM]; a control volume capacitance method for solidification modeling [106JM]; mathematical modeling of copper and brass upcasting [107JM]; an FEM method for casting simulations [108JM]; an analysis of flux flow and the formation of oscillation marks in the continuous caster [109JM]; minimisation of casting slag/probe contact resistance [110JM]; numerical analysis and optimal design of composite thermoforming processes [111JM]; indirect squeeze casting die geometry in Al alloy [112JM]; numerical modeling of the blow modeling process [113JM]; a numerical study of the casting process in a rectangular mold [114JM]; coupled fluid, heat and stress modeling in continuous round billet casting [115JM]; analysis of a water cooling system in cyclic mould casting process [116JM]; the extent of the equiaxed zone in continuously cast steel products [117JM]; modeling of microstructural development in hypoeutectic cast iron [118JM]; simulation of heat transfer between particles and matrix during solidification of a metal cast composite [119JM]; a boundary element model of coupled heat and mass transfer in solidifying castings [120JM]; and numerical study of macrosegregation during solidification of cast binary alloy [121JM].

15.13. Mushy zone – dendritic growth

Mushy later formation during droplet-based processing was analyzed numerically [122JM].

15.14. Metal solidification

An integrated modeling approach to solder joint formation of electronic components on circuit boards was presented [123JM]. Further work included: a numerical study of sedimentation by dripping instabilities in viscous fluids [124JM]; simulation of solidification of hypereutectic spheroidal graphite irons [125JM]; evaluation of solidification of a binary alloy in a cylindrical metal mould by the method of computational experiment [126JM]; an analytical approach to the conduction-dominated solidification of binary mixtures [127JM]; an experimental study to investigate the effects of grain transport on the columnar to equiaxed transition in dendritic alloy solidification [128JM]; thermal modeling and Fourier thermal analysis (FTA) study of near-eutectic aluminum silicon cast alloy to obtain solidification kinetics [129JM]; measurement of the heat transfer coefficient during unidirectional solidification of Al–Si alloy [130JM]; assessing the effect of the presence and packing geometry of reinforcing fibers in a solidifying aluminum [131JM]; analysis of residual stress in spray formed steel tools by FEM [132JM]; numerical study of thermocapillary effects in metal droplets with internal solidification [133JM]; numerical and experimental study of solidification in metal matrix composite casting [134JM]; numerical study of growing billet shape from the spray forming manufacturing process [135JM]; a new non-linear algorithm for the solution of phase change problems [136JM]; a method of least squares adjustment of thermal data and mathematical output to assure optimal convergence of theory and experiment [137JM]; numerical study of cooling behavior during solidification of squeeze cast Al alloy [138JM]; a method to obtain the contact resistance between a metal casting and mold [139JM,140JM]; heat transfer correlations between a vertical surface and gas-agitated melt [141JM]; experimental study of solidification behavior of different grades of steel [142JM]; thermal modeling of continuous MMC wire production [143JM]; and casting/chill interfacial heat transfer during solidification of Al/Si alloy studied by inverse modeling and experimentation [144JM].

15.15. Crystal growth from melt

Dynamics of lateral grain growth during the laser interference crystallisation of SI thin films was studied [145JM]. Additional work focused on: an analysis of solidification rates of binary mixture melts flowing as a thin film on a cold surface [146JM]; experimental measurements of pure succinonitrile dendrites grown in both microgravity and terrestrial gravity conditions for 0.1–1 K supercooling [150JM]; finite element modeling of 3D fluid dynamics in crystal growth systems [151JM]; Maragoni convective effect during crystal growth in space [152JM]; an analytical calculation on the behavior of point-defects in growing silicon crystals [153JM]; thermal stress simulation and interface destabilisation in indium phosphide grown by the LEC process [154JM]; kinetics of crystal growth in melt crystallisation with direct contact cooling [155JM]; flow induced crystallisation of semi-crystalline polymers with different chain conformations [156JM]; rime ice accretion and heating on electric charge transfer during ice crystal graupel collisions [159JM]; measurement of thermal pulsation effects on hydrothermal crystal growth [161JM]; transient modeling of sublimation growth of silicon carbide [149JM]; numerical simulation of heat transfer in reactors for bulk SiC growth [160JM]; simulation of heat transfer and fluid flow in a gas phase crystal growth furnace [158JM]; review of models for SiC sublimation growth [157JM]; simulation of sapphire crystal growth with FEM software [147JM]; and modeling of evolution of crystals during vacuum deposition [148JM].

15.15.1. Directional solidification

Facetting during directional crystal growth of oxides from a melt was studied [164JM]. Additional work included studies on: periodic solutions of the Sivashinsky and Riley–Davis equations for directional solidification [167JM]; mathematical models for use in prediction of industrial crystal growth processes [165JM]; the use of rotating magnetic fields to control single crystal growth processes [163JM]; modeling of heat transfer in the melt during crystal growth [162JM]; low indium incorporation during InGaN growth [169JM]; simplified model of dendritic growth in presence of natural convection [168JM]; and bulk growth of GaAs by both CZ and Bridgman techniques [166JM]. Further studies on crystal growth by Bridgman and CZ techniques, respectively, are given below.

15.15.2. Bridgman growth

Electromagnetic FEM modeling methods were used to analyze sensor ability to measure l/s interface location and curvature during vertical Bridgman growth of semiconductors [171JM]. Additional studies included: asymptotic analysis of a three-dimensional Bridgman furnace at high Rayleigh number [172JM]; the effects of convection and crystallisation in a liquid cooled from above [173JM]; influence of latent heat and natural convection on melt-crystal interface in vertical Bridgman–Stockbarger crystal growth [175JM]; the effect of heat and mass transfer in melts on inhomogeneity formation during Ge crystal Bridgman growth [176JM]; heat transfer during vertical Bridgman CdTe growth [174JM]; crucible rotation effects on segregation in high pressure Bridgman growth of cadmium zinc telluride [177JM]; and wall electrical conductivity and magnetic field orientation effects on Bridgman crystal growth [170JM].

15.15.3. Czochralski growth

Global temperature field simulation of the vapor pressure-controlled CZ growth of gallium arsenide crystals was presented [178JM]. Additional studies included: global heat transfer analysis in CZ silicon furnace with radiation on curved specular surfaces [179JM]; comparison of turbulence models for simulation of melt convection in CZ crystal growth of Silicon [180JM]; three-dimensional numerical characteristics of Si melt in a CZ configuration [181JM]; mechanisms of dopant transport and segregation in high pressure liquid encapsulated CZ grown crystals [183JM]; and numerical modeling of turbulent convection in CZ silicon melt [182JM].

15.16. Casting

A parametric study of cooling rate and casting speed in horizontal strip casting was presented [185JM]. Additional studies included: investigation of gate solidification time in ceramic injection molding [184JM]; development of a metal mould heat transfer correlation [186JM]; a thermal model of pressure die casting with injection [187JM]; boundary element modeling of the temperature field in a cast aluminum alloy billet [188JM]; investigation of casting-chill interface heat transfer during solidification of an aluminum alloy [189JM]; and the impact of species equation source terms in binary mixture solidification models on macrosegregation in semicontinuous direct chill casting systems [190JM].

15.17. Splat cooling

Parameters controlling solidification of molten wax droplets falling on a solid surface were studied [191JM]. An additional theoretical analysis of spreading and solidification of molten droplets during thermal spray deposition was also presented [192JM].

16. Radiative heat transfer

The papers below are divided into sub-categories, which 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 sub-category radiation.

16.1. Influence of the geometry

The most striking observation in this section is the decrease of papers dealing with the determination of view factors. Hong and Welty [6K] use a Monte Carlo simulation for the three-dimensional heat transfer in an enclosure containing a cylinder. For the case of an optically thin medium they calculate view factors.

The discrete ordinate method (DOM) is again popular for radiation studies. Fiterman et al. [2K] discuss the advantages of a pseudo-time stepping approach for three-dimensional systems. DOM and finite element methods for three-dimensional enclosures are assessed in [8K]. DOM and the diffusion approximation for the heat transfer in glass are compared in [10K]. Liu and Chen [13K] use both conventional DOM as well as even-parity formulations in irregular geometries. Parallel DOM formulations are discussed in [16K]. Versteeg et al. [21K,22K] discuss approximation errors for the heat flux integral in the discrete transfer method for transparent as well as participating media.

Finite element and finite volume methods are also popular for radiation heat transfer modeling. A time-dependent three-dimensional approach is used for the modeling of heating of steels in reheating furnaces [12K]. Minkwycz and Haji- Sheikh [15K] discuss the transition from the Sparrow–Galerkin solution to the finite element method. Raithby considers the finite volume method using three-dimensional unstructured meshes [17K], and discusses the discretisation errors [18K]. Liu et al. [14K] present a parallel implementation of an unstructured finite volume approach.

An inverse analysis of radiation problems is used in [7K,23K]. Fort et al. [3K] present an extended statistical thermo-dynamical theory for radiative heat transfer.

Unal et al. [20K] model radiative transfer for ladder-like structures in rectangular enclosures. Three-dimensional radiative transfer in glass cooling is considered in [11K], and in crystal growth in [9K]. Radiation in chemical vapor deposition reactors is studied in [1K], and in [4K] for vacuum deposition reactors. Hanzelka [5K] considers heat transfer between and to current leads in cryogenic systems. The two-dimensional problem of thermal radiation from cylindrical isothermal cavities with a longitudinal pyrometric slit is solved in [19K].

16.2. Participating media

Papers in this category can roughly be subdivided into papers dealing with the emission and absorption properties of the medium and those including scattering.

Between those papers focusing on the molecular emission and absorption properties of gases is the study of carbon-dioxide layers by Hutchison and Richards [38K], the studies of CO_2 and H_2O by Tang and Brewster [53K] and Kolenko et al. [40K], and of H_2O/N_2, and CO_2 /H_2O/N_2 mixtures by Liu [43K]. A non-gray, one-dimensional radiation problem is considered in [54K]. Fujita and Arakawa analyze a low power hydrogen arcjet [33K].

In addition, absorption and emission of gases also play important roles in radiative transfer during combustion. Radiation in furnaces is considered in [56K,47K]. Lean methane–air mixtures are studied in [29K]. Radiation in fluidized bed combustors is analyzed in [36K,41K]. The flame formation in oxygen/carbon-monoxide mixtures containing slag foam is studied by Zhang and Oeters [57K]. Makhviladze et al. [46K] investigate the emission of radiation from a fireball due to combustion of hydrocarbon fuel. The optical properties of soot are usually also important when radiative transfer in fires [27K,35K] is considered. Desjardin and Frankel [28K] investigate soot formation in premixed acetylene–air jet flames. The influence of soot on the radiative transfer in gas/soot mixtures is also studied by Bressloff [24K]. The presence of soot particles in the combustion gases is also of major influence on the radiative transfer in the combustion chamber of diesel engines [34K].

Scattering of radiation plays an important role in the presence of small particles, such as in polydispersion/gas mixtures [25K,26K]. Dombrovskii analyzes the radiation emitted by small semi-transparent particles [31K], and by particles immersed in liquids, which are surrounded by a vapor shell [30K]. Park et al. [48K] consider the thermophoretic transport and deposition of particles in a flow tube with variable wall temperature and thermal radiation.

The radiative properties of solid surfaces can significantly be altered by translucent coatings. Siegel studies this effect in several publications [49K–52K]. Using the Green's function method he compares the effects of several opaque and translucent coatings. Yao and Chung [55K] study the behavior of semi-transparent layers including emission, absorption and scattering. Heated disperse layers are considered in [39K]. Liu et al. [45K] use an inverse radiation analysis to study temperature profiles and wall emissivities in one-dimensional semitransparent media.

Liu et al. [44K] report results of a three-dimensional narrowband model for absorbing–emitting–scattering media. The radiative transfer in an anisotropically scattering media is discussed in [42K,32K,37K].

16.3. Combined heat transfer

Papers in this sub-category consider the combined effect of radiation with conduction and/or convection. Combined radiation and conduction play an important role for insulating materials [88K,65K,61K] as well as for greenhouse cladding materials [94K]. Abulwafa [58K,59K] considers conduction and radiation in inhomogeneous slabs with reflecting boundaries. Li [78K] solves the inverse conduction/radiation problem to estimate thermal properties. Transient radiation and conduction is studied in [91K]. Park et al. [86K] present a dynamic simulation of radiative/conductive transfer in three-dimensional enclosures with participating media. Vargas and Vilhena [92K] give a closed form solution for a one-dimensional problem, using the decomposition and LTSN method. The design and construction of an electromagnetic actuator for high-temperature environments is described in [89K].

A considerable number of papers discuss radiation combined with convection. Problems studied include the heat transfer in three-dimensional rectangular channels [62K], transparent gases flowing in tubes [67K], and loop heat pipes [75K]. The frequency response of temperature sensors is influenced by convective and radiative transfer [69K]. The stagnation point heat transfer for Pioneer–Venus probes is studied in [85K], the radiative flow field behind a reflected shock in air by Sakai [87K]. Natural convection–radiation problems are studied for different geometries: for differentially heated square cavities [81K], confocal elliptical cylinders [63K,64K], concentric and eccentric cylinder annuli [70K,77K], partitioned cavities [84K], and for isothermal horizontal plates [72K]. Jones [74K] discusses radiation and convection in cabin fires. Large-scale vertical parallel surfaces with fire-induced flow are studied by Wang et al. [93K]. The influence of radiation on flames is studied in [79K,83K]. Mastorakos et al. [82K] present results of CFD predictions of cement kilns including flame modeling, heat transfer and clinker chemistry. The electro-thermomechanical interactions of an oxygen sensor during warm-up are modeled in [73K].

Radiation, convection and conduction is modeled in [66K] for systems with moving boundaries. Other studies include those of side-vented enclosures [96K], finned tube banks [90K], horizontal circular cylinders [71K], horizontal narrow-aspect enclosures [60K], and heated blocks in vertical differentially heated enclosures [80K]. Kim et al. present an analysis of two-phase radiation in thermally developing Poiseuille flow [76K]. The cooling of a char bed after an emergency shut-down procedure also involves all three modes of heat transfer [68K]. The combination of all heat transfer mechanisms is also important for the design of RF power couplers to superconducting systems [95K].

16.4. Experimental methods

Several studies focus mainly on experimental aspects of radiation studies. Critoph et al. [97K] use liquid crystal thermography with radiant heating to measure the local heat transfer in a plate fin-tube heat exchanger. Inagaki and Okamoto [99K] use infra-red thermography to determine turbulent heat transfer coefficients. The far-infrared transmittance and reflectance of YBCO thin films is measured by Kumar et al. [100K]. Spectroscopic measurements of shock-layer flows in an arcjet facility are reported in [102K]. Makino et al. [101K] measure the directional reflectivity of rough metal surfaces. Heat transfer through layers of casting flux are studied with a thermal flux probe [98K].

16.5. Intensely irradiated materials

Only very few papers deal with intensely radiated materials. Longtin et al. [104K] measure the surface-tension driven flows in liquids exposed to high-intensity, short-pulse laser radiation. Measurements of transient glass surface deformations during laser light heating are reported in [105K]. Habuka et al. [103K] present a three-dimensional ray tracing model to evaluate the thermal condition of silicon substrates in rapid thermal processing systems.

17. Numerical methods

Considerable amount of research continues in the area of numerical methods for heat conduction, convection and diffusion, and fluid flow. New methods have also been developed for grid generation, solution of simultaneous equations, and parallel computing. The papers that primarily *use* numerical methods for solving a physical problem are referenced in the appropriate application category in this review. The papers that focus on the description of a numerical method are reviewed in this section.

17.1. Heat conduction

A precise algorithm in the time domain is presented for unsteady heat transfer [12N]. A formal basis is provided for the development of time-discretized operators [11N]. Enhanced computational efficiency is obtained by the use of multi-spatial- temporal grids [9N]. A new hybrid finite-element thermostructural model is developed and applied to the combustion chamber walls of a diesel engine [7N]. A semianalytical numerical scheme is used for one-dimensional phase change with periodic boundary conditions [8N]. Boundary element methods are used for steady-state problems in anisotropic media [1N] and for unsteady non-linear problems [3N].

Inverse problems in heat conduction is the subject of many publications. Fourier analysis of conjugate gradient method is applied to inverse heat conduction [6N]. Multi-dimensional inverse heat conduction problems are solved by using control volume methods [10N]. A variant of the Galerkin procedure is used for the solution of inverse problems [5N]. Various conjugate gradient methods are compared for solving inverse heat conduction problems [4N]. Reference [2N] deals with a two-dimensional inverse geometry problem.

17.2. Convection and diffusion

Stability of several common iterative schemes is studied for the discretized convection–diffusion equation [16N]. A locally exact finite-difference scheme is presented for convection–diffusion problems [14N]. Lagrangian interpolation is used in developing a convection–diffusion scheme [17N]. Two schemes based on a four-point interpolation are presented for the discretisation of the convection–diffusion problem [18N]. Numerical experiments are performed for selecting a suitable convection–diffusion scheme for the flow of hot air [13N]. A higher-order method with essentially non-oscillatory behavior is proposed and evaluated [15N].

17.3. Radiation

A procedure for computing radiative heat transfer in periodic geometries is described in the context of a finite-volume scheme [23N]. The coupling between the energy equation and the equations for radiation intensities is handled by simultaneous solution of the equations at a computational cell in a multi-grid scheme [22N]. An adaptive-mesh algorithm is developed for the discrete ordinates method for radiative heat transfer [21N]. The finite-volume method for radiation is parallelized using the decomposition of angular and spatial domains [20N]. A fast multi-level algorithm is proposed for the conductive–radiative heat transfer problem [19N].

17.4. Fluid flow

A finite element algorithm is proposed for steady flow using triangular meshes [30N]. The use of momentum interpolation method is discussed for unsteady flows [26N]. The SOLA-VOF method is used for the treatment of free surfaces in the mold-filling process [27N]. A velocity–vorticity formulation is developed in conjunction with a vortex particle-in-cell method [29N]. Adaptive finite element techniques are reviewed for solving complex flows [32N]. A technique is proposed for accelerating the convergence of segregated algorithms for the momentum and continuity equations [35N]. A comparative study is presented for conservative and non-conservative schemes for laminar flow in the context of domain decomposition [24N]. The treatment of the inlet boundary condition for open-ended channels is discussed for natural convection flows [31N]. A diagonal Cartesian method is developed for flow and heat transfer in complex geometries [28N,25N]. A boundary-domain integral method is presented for the solution of the Navier–Stokes equations [34N]. An adaptive finite-volume method is developed for annular liquid jets [33N].

17.5. Particle trajectories

A calculation procedure is described for the determination of particle trajectories in curvilinear meshes [38N]. A theoretical investigation is presented for the behavior of droplets in axial acoustic fields [39N]. Viscous incompressible flow with suspended solid particles is analyzed using a Lagrange multiplier fictitious domain method [36N]. The moving front in the resin transfer molding process is computed by a new implicit technique [37N].

17.6. Grid generation

A least-square technique is used for orthogonal grid generation with floating boundary points [40N]. The Delaunay triangulation method is used for automatic generation of unstructured grids [42N]. A novel approach to grid generation is evaluated by examining grid quality [41N].

17.7. Other studies

A Fourier–Chebyshev collocation method is parallelized for three-dimensional flow [43N]. Different preconditioning methods are analyzed for discrete approximations of the Laplace operator [44N]. A comparative study is presented for the Lanczos solver (with no preconditioning) and the CGS solver (with preconditioning) [48N]. Highly scalable implementations of the resin transfer molding process are developed [45N–47N].

18. Properties

Interest is greatest in the property thermal conductivity for special systems e.g., thin films and for unusual situations e.g., critical or supercritical states.

18.1. Diffusion

The poor solubility of benzene in water is studied by considering the transport of species between phases from a molecular viewpoint. By a combination of equations the diffusion equation for solute atoms under a temperature gradient is derived for carbon [2P,3P]. Experiments involve a number of systems. The diffusion and partial pressure of oxygen in the furnace are found important to the production quality of Ag-clad superconducting tapes. A narrow gap Couette device is used to study viscous resuspension in a bidensity suspension of uniform size spherical particles, and a differential scanning calorimeter to study polymerisation kinetics of thermoset resins (bone cement) with a kinetic model which accounts for diffusion. Vapor production through cavitation creates a temperature difference between liquid and vapor, particularly significant in cryogenic liquids. Tests were conducted using an R-114 loop. Data from a global spectral model yield values for the biharmonic horizontal diffusion coefficient and impulsive stimulated thermal scattering data lead to thermal diffusion constant evaluation [1P,4P–8P].

18.2. Thermal conductivity

A variety of experimental techniques are applied to study a range of systems. A thermoelectric module is found to be simple and effective for studying fluid thermal conductivity under critical and supercritical conditions (CO_2 specifically). A phase-sensitive scheme determines two independent properties (thermal conductivity and specific heat) for thin dielectric films. Also examined is the influence of an orthodeuterium impurity on the measured conductivity of solid parahydrogen. For conductors with discontinuities of unknown location, piecewise homogeneous conductivity has been identified using additional boundary and/or interior temperature measurements, during heat flow. Effective thermal conductivity of mixtures of fluids and nanometer-size particles is measured by the steady-state parallel-plate method [11P,17P,19P,20P,34P]. Other works measure polyurethane foam conductivity, 1,1-difluoroethane (HFC-152a), building material diffusivity and effusivity, and account for laser heating penetration in flash thermal diffusivity experiments. Food science experiments study the convective heat transfer during frying, including potato slices, [13P,15P,22P,27P, 28P,35P].

Analytical works consider a number of situations: a gas enclosed between two parallel, infinite plates held at different temperatures in the presence of a constant gravity field normal to the plates, using kinetic theory; thermal diffusivity in falling films; effective Lewis number where temperature and mass fraction gradients are very large (super-critical conditions); droplet vaporisation at critical conditions; long-time convective–diffusive profiles along the critical isobar; thermal mechanism of suppression of anomalies for non-linear characteristics of inhomogeneous media [10P,12P, 16P,29P,33P]. Other papers treat: the use of physical similarity to obtain general thermal conductivity for taiga soil; a thermo-mechanical model which predicts the change of thermal asperities as a function of increased area density; classifying heat conduction equations with a non-linear source by group; and the use of microporosity in highly efficient thermal insulating materials [24P,30P,32P,36P]. For specific systems investigators report on: a model for designing furnace conditions for crystal growth of lead bromide; predicting thermal conductivity and Prandtl number of liquids; conductivity of polyethylene forms; thermal transport and fire retardant for cellular aluminum alloys; heat transfer in disordered solid methane;

effective conductivities for unbonded and bonded silica sands; measurements and modeling of zeolites conductivity [9P,14P,18P,21P,23P,25P,26P,31P].

18.3. Heat capacity

Temperature-modulated differential scanning calorimetry measurements are reported in terms of complex or reversing heat capacity and in traditional thermal properties for a cup cake. An adiabatic calorimeter measures heat capacity for isopropylammonium trichlorocuprate (II). Other experimental efforts consider the influence of magnetic field and external pressure on magnetic ordering and transition temperatures in a superconducting system [37P,42P–44P,46P]. Modeling and analytical efforts include: heat capacity change when proteins are denatured; quantum cluster equilibrium theory for liquids (ethanol); a molecular model for hydrophobic solvation; superconducting properties of quasi-two-dimensional organic metals, a mathematical study of heat capacity results from modulated differential scanning calorimetry; and correlated one-dimensional electron systems [38P–41P,45P,47P].

18.4. Composite materials

Modeling is the focus here as investigators consider: the lamination process for thermoplastic composite laminates; determining short glass-fiber volume fractions in compression molded thermoset composites; thermal equilibrium for a one-dimensional superconductor, composite wire. Transient experiments are used to estimate effective thermal properties of composites. Also investigated was the temperature dependence of thermal conductivity of plasma-spray-deposited monolithic coatings and curing cycle effects on composite parts [48P–53P].

18.5. Thin films/coatings

The thermal conductivity of dielectric films becomes important in microelectronics because heat transfer from such devices is critical. A scanning thermal microscope images thermal properties of silicon dioxide films applied to silicon by plasma-enhanced chemical vapor deposition and measures the thermal conductivity. Also studied are: the influence of viscosity on linear stability of an annular liquid sheet; flux-flow instability in superconducting films; the role of supercritical carbon dioxide in the transfer of volative organic compounds in thermoplastic polymers and polymer blends [54P–57P].

18.6. Transport properties

Transport coefficients and equation of state are determined for supercritical ethylene by equilibrium molecular dynamic simulations. For two-phase flow the local volumetric interfacial area is linked to a transport equation and to a transport velocity valid for any two-phase flow regime. Transport and electrical properties are investigated for polycrystalline Li_2SO_4 and Ag_2SO_4. Transport and thermodynamic property influence on the performance of miniaturized absorption refrigerators is assessed [58P–62P].

18.7. Viscosity

The concept of a bulk viscosity is reviewed and a summary of existing experimental data presented. Specific works examine: the influence of viscosity variation on stationary instability for a bounding wall of finite conductivity; viscosities and densities of triethylene glycol monomethyl ether plus water solutions (25–80°C); and the measurement of the thermal and tribological effects of cutting fluid [63P–66P].

18.8. Miscellaneous

Aspects of calorimetry are discussed for the soluble chamber and modulated differential scanning types; density measurements reported for the ternary system water–decyltrimethyl ammonium bromide–pentanol and the parallel change of water structure and protein behavior with temperature. The concluding works describe a new method for deriving ocean surface specific humidity and air temperature; the measure of refractive index of PF-5060; and an exploration of the implications of dimensionless entropy [67P–73P].

19. Heat transfer applications – heat exchangers and heat pipes

The extent and variety of efforts to enhance heat transfer answer Prof. Bergles' question, "Endless Frontier, or Mature and Routine?"

19.1. Compact and microheat exchangers

A new, compact, gas-to-gas heat exchanger achieves increased heat transfer area by secondary surfaces, plate fin, strip fin, and louvered fin among other configurations. For louvered fin-and-tube design, data for 49 exchangers provide general heat transfer and friction correlations for various fin geometry. For microscale exchangers conduction effects are modeled numerically, plastic materials examined for possible use in the desalination industry and experimental results reported on the single-phase flow of R-124 in a parallel heat exchanger [1Q–5Q].

19.2. Design

General design approaches consider optimal design from the standpoint of (1) minimum heat transfer area required for a given duty and (2) full pressure drop utilisation in designing compact plate-fin exchangers and exergy and life cycle analyses. Other works treat the influence of mixed convection and U-bends on the design of double-pipe exchangers, the use of weighted heat transfer coefficients for optimum design of a multiple-effect evaporator, and the effects of design and operating factors on frost growth and performance of a flat plate fin-tube exchanger. Also examined are: a generalized quasi-steady-state solar collector model, a skin-cooling system for aircraft electronic packages and the simulation and design of plate-frame units to recover organic compounds [6Q–14Q].

19.3. Direct contact heat exchangers

Using the finite volume method (FVM), fluid flow and temperature distribution around and in a dry-cooling tower under cross-wind conditions are simulated numerically, Heat, mass and momentum transfers in the rain zone of three counterflow cooling geometries are analyzed by numerical integration [15Q,16Q].

19.4. Enhancement

A number of techniques developed to enhance convective heat transfer are considered and the many contributions of Prof. Ralph Webb recognized. A host of experimental works investigate a striking variety of enhancement schemes: turbulent flow and pressure drop data for chevron plate exchangers, fin heat transfer in the cyclone separator of a circulating fluidized bed, the role of circulating solid particles in maintaining clean heat transfer surfaces; heat transfer and flow characteristics of louvered fin surfaces and plate fin-and-tube exchangers; wavy fin-and-tube exchangers including the effects of waffle height on air-side performance; slit finand-tube exchangers and air-side performance; the effect of strip-fin location on pressure drop and heat transfer in a fin-and-tube exchanger; characteristics for fin and tube exchangers with interrupted surface; effect of perpendicular flow entry on convective heat and mass transfer from pin-fin arrays; and vertical fins and their influence on local heat transfer in a horizontal fluid layer [17Q,18Q,20Q–23Q,27Q–33Q,35Q–37Q]. Analytical papers include: air-side heat transfer and friction correlations for plain fin-and-tube exchangers with staggered tube configurations (based on 47 sets of exchanger data) applicable to exchangers with small tube diameters; correlations (heat transfer and friction) for wavy fin-and-tube exchangers; fin efficiency of annular fins made of two materials; performance of eccentric annular fins with variable base temperature; predicting thermal behavior of uniform circumferential fins; heat transfer for pressurized bath of He II and a saturated tube-type exchanger [19Q,24Q–26Q,34Q].

19.5. Fouling – surface effects

Efforts to understand and mitigate fouling of heat transfer surfaces occur by experimental and analytical investigations. Electronic anti-fouling (EAF) technology was found to reduce fouling ($CaCO_3$) in a once-through flow, single tube exchanger, control fouling in a spirally-ribbed water chiller, and, when combined with brush punching, remove scale in a water-cooled plain tube. Ultrasound prevents scale formation in sugar factory evaporators. Two strategies, the first based on modifying the energy and geometry characteristics of the heat transfer surface, the second on adjustments of hydrodynamic flow conditions by a pulsation technique, mitigate exchanger surface fouling. Other works study the role of plate corrugation patterns on rate of fouling in flat plate exchangers, the efficacy of scale control additives in multistage flash (MSF) desalination plants, and the influence of particulates on $CaCO_3$ scale formation [39Q–45Q,48Q]. Analytical papers examine: fouling in shell-and-tube exchangers where the formation of irregular fouling deposits with variable thermal conductivity is accounted for; improved analysis for interpreting fouling in shell-and-tube exchanger; and the sequence of scale forming reaction steps in distillers [38Q,46Q,47Q].

19.6. Mathematical modeling, optimisation

General approaches to convective heat transfer occur through the extension of constructal theory, which optimizes the access of a current that flows between one point and a finite-size volume, and the proposal of a closed-form model for the second-law-based thermoeconomic optimisation of constant cross-sectional area fins. Specific systems are addressed by: a three-dimensional study of heat transfer characteristics of extended fins in a two-row, finned heat exchanger; local flow and heat transfer in a two-row, offset, strip fin-tube design; a reexamination of the significance of two-dimensional heat transfer effects in fin assemblies; the analysis of a fin-tube evaporator in a vapor compression plant operating with R-22; numerical simulation of flow and heat transfer in the convective section of a utility boiler [49Q–56Q].

19.7. Performance – factors affecting

Investigations of broadest scope are represented by the application of the artificial neural network to heat transfer in systems of increasing complexity and the analytic comparison of constant area, adiabatic tip, standard fins, and heat-pipe fins. For counterflow heat exchangers in which both fluids encounter external heating, a mathematical model is developed to study performance. A number of efforts focus on certain factors affecting performance: wet conditions (airside) of herringbone fin-and-tube exchangers; coupled heat and mass transfer mechanisms in the absorbent of a waste heat absorption cooling unit; long-range intermolecular force influence in change-of-phase exchangers; longitudinal convective fins with symmetrical and asymmetrical profiles; the use of twisted tape and turbulence promoter in double exchangers. A novel approach improves the performance of the conventional concentric tube exchanger by inserting porous substrates at both sides of the inner tube wall. Other works treat oscillatory flow and heat transfer in a thermoacoustic stack, heat loss through the cold end wall of a cryogenic, counterflow exchanger, and the influence of fouling on diesel engine radiator performance [57Q–68Q].

19.8. Reactors

Heat transfer in gas–solid suspensions is used to assess the characteristics of different distributor designs in a gas–solid co-current downflow fluidized bed. For an oscillatory flow, electrochemical reactor the mass transfer and residence times are determined. Mathematical models are developed to study the dynamics of a parallel-plate electrochemical fluorination reactor and to evaluate the Nusselt and Sherwood numbers under reaction conditions in a single channel of a monolith reactor. [69Q–72Q].

19.9. Power and reversed cycles

A universal, irreversible, combined refrigeration model investigates optimal performance of an *n*-stage combined system as affected by irreversible heat transfer due to finite temperature difference, heat leak loss between external heat reservoirs and internal fluid dissipation. Using performance data for actual vapor-compression refrigeration systems a finite-time thermodynamic model is developed to study the performance of a variable-speed refrigeration system and predict an optimum distribution of heat-exchanger areas. Another analytical work considers optimum performance for a four-temperature-level irreversible absorption refrigerator at maximum cooling load. Absorption heat pump systems are studied to determine COP sensitivity to falling film tube lengths, the influence of adsorber exchanger design on performance and general characteristics of an irreversible absorption heat pump operating between four temperature levels [73Q–76Q,79Q,80Q]. The Brayton engine is studied using: finite time thermodynamics to determine the maximum ecological function as an irreversible power device, and analysis to establish the performce of an actual heat pump plant. Solar desalination with a humidification–dehumidification process is found an efficient use of solar energy to produce fresh water [77Q,78Q,81Q,82Q].

19.10. Shell and tube/plate

A mass transfer measuring technique is employed to determine shell-side local heat transfer coefficient for an exchanger fitted with disc-and-doughnut baffles. Large scale recirculation, due to unwanted free convection, severely reduces heat transfer performance to 40% below design expectations. Other works find the second law of thermodynamics applied to counter-flow, parallel-flow and cross-flow exchangers; exchanger response to step changes of flow rates studied; heat exchangers and coils modeled using catalog data for estimating parameters; dehumidifying exchanger, with and without wetting coating, performance assessed, and an enhancement device applied in an NH_3 flooded evaporator [83Q,85Q,89Q,94Q,98Q,100Q,101Q]. Thermal desalination and plate heat exchangers, spiral plate heat exchangers in adsorption refrigerators and experience with the operation of plate exchangers in certain applications are reported [84Q,90Q–93Q,96Q,102Q,103Q]. Regenerators, single blow and fixed bed, are modeled and analyzed; a finite element code developed for turbulent flow in tube bundles; and a design recommended for headers supplying small multiple pipes with a single phase fluid. Final papers treat scraped surface heat exchangers employed in the food industry and ground heat exchangers [86Q–88Q,95Q,97Q,99Q,104Q].

19.11. Thermosyphons (heat pipes)

Thirty years of heat-pipe technology have led investigators to consider issues of service life as well as performance. The corrosion mechanisms of alkali metals at elevated temperatures, responses of a compact two-phase thermosyphon to evaporator confinement and transient loads, use of heat-pipe thermal intercepts in a high temperature, superconducting test facility and the theoretical prediction that magnetic working fluid in a heat-pipe could possibly enhance and control heat transfer reflect the range of investigations. A contrasting work considers the capillary pumped loop technique for cooling spacecraft and telecommunications equipment as having some advantages and a major disadvantage, when compared with most heat-pipes [105Q,109Q,110Q,112Q,113Q]. Analytical and modeling efforts consider: the operation envelope for a closed two-phase thermosyphons; the supercritical startup behavior for cryogenic heat-pipes; application of heat-pipe cooling to advance the performance and life of tribological systems; and the modeling of the conventional cylindrical heat-pipe based on the second law of thermodynamics [106Q–108Q,111Q,114Q].

19.12. Miscellaneous

For rotary heat and mass exchangers, the influence of frost formation is examined by testing and analysis. For air-to-air energy wheels transferring both sensible heat and water vapor, fundamental dimensionless groups are found to characterize the transfer processes. Thermally stratified hot water storage for solar water heaters is characterized from a second law standpoint. Recent developments in multi-effect distillation (MED), the oldest process in desalination, are held to bring that venerable practice abreast of the multi-flash design, dominant since 1960 [115Q–118Q].

20. Heat transfer applications – general

Papers in some applications in this section are so numerous that only selections could be included. This applies to meteorology, manufacturing, chemical processing and reactors. Papers were selected which discussed the heat transfer process specifically.

20.1. Aerospace

Most of the papers deal with the reentry problems. The influence of solid particles injected into a shock layer of a heat shield is analyzed [7S]. Numerical simulation is presented [6S] for the thermoelastic response of a metallic protection panel of the X-33 test vehicle. Non-equilibrium dissociation heating affects shock–viscous interaction of catalytic surfaces [4S]. New rate constants for vibrational–translational vibrations of a pure diatomic gas are validated [2S]. The two-temperature model for the intermediate hypersonic flow regime is examined [1S]. Radiative equilibrium surface temperatures and other thermal parameters are predicted [5S] for reentry peaking rates of control-surfaces of the X-34 demonstrator, the base heating of the X-33 vehicle induced by an aerospike plume is analyzed [8S]. The paper [3S] describes the steady and transient response of an aircraft cab cooled by heat rejection through the skin.

20.2. Nuclear reactors

Heat transfer in high power bundles was enhanced in reflood tests at the Japan Atomic Energy Research Institute [12S]. This is important for increasing the safety margin in PWR-LOCA. A model of circonium oxidation allows for rearrangement of crystal phases during diffusion of oxygen [9S]. In a severe accident of light water reactors the cooling system piping may be subjected to thermal loads by the decay of deposited fission products [10S]. An advanced real-time simulator for pressurized water reactors [11S] should be helpful for the development of monitoring and controlling systems. A means has been devised [14S] to use heat removal by the coolant from fuel sub-assemblies following a reactor trip to estimate fuel temperatures and heat transfer coefficients. Experiments [13S] studied the behavior of a UF6 container during a fire.

20.3. Gas turbines

A new program [20S] to calculate gas turbine performance is based on a heat transfer correlation which presents non-dimensional heat flow in engine components as function of Biot and Fourier numbers without describing local phenomena in detail. Heat Transfer for a transonic turbine stage is calculated [19S] using a Navier–Stokes solver and a two-equation turbulence model. Unsteady state under variable operating conditions is considered. The inverse design problem of estimating optimal shape of coolant passages in turbine blades is developed. Adapted to a large number of unknown parameters, and to fast convergence [18S]. The effect of tip leakage is calculated [15S] for the GE-E-3 first stage. The aerodynamic effect of trailing edge ejection downstream of turbine blades was measured [21S] and compared with existing theory. External heat transfer coefficients are calculated using Navier–Stokes equations and various turbulence relations for two-dimensional blade cascades [16S]. Comparison with measured results shows good agreement in some cases but reveal problems with transition prediction and turbulence modeling. Calculation of heat transfer on the end walls of a modern first stage stator are presented [17S]. Surface heat transfer rates are compared with measured results on a vane model at correct Reynolds, Mach numbers and geometry. Navier–Stokes equations are used [22S] to simulate heat transfer in turbine cascades. A weighing factor term is introduced to account for free-steam turbulence and intermittent flows. Measurements are used to validate the calculations.

20.4. Automotive engines

Heat Transfer in the exhaust piping has recently found attention. Experiments [25S] determined steady and transient heat transfer. The governing equations, boundary conditions, and numerical solution techniques of this engagement process in a wet clutch consider viscous heat dissipation and heat transfer [24S]. A recent paper models the gas temperatures in the exhaust piping and the catalyst spacially and temporally [23S]. Study of the cold start can reduce hydrocarbon emission significantly [27S]. An optimal control framework is developed for endoreversible engines considering heat and mass transfer processes [26S].

20.5. Buildings

A two-dimensional turbulence model is able to predict air velocity, temperature, and turbulent kinetic energy in an air-conditioned room with ceiling air supply [37S]. A quasi-steady heat balance model predicts heat transfer across the walls of a residential building as function of time hourly, daily, and monthly. Results were compared with experimental results [33S]. A comprehensive in situ experiment determines the monthly thermal state of the ground floor of a modern commercial building [36S]. A phase change drywall system for a low-energy building is evaluated and indicates that higher thermal efficiency can be obtained by this construction [30S]. An inverse method to estimate building and ventilating parameters for non-intrusive monitoring of heating and cooling energy of large commercial buildings [35S]. A simplified numerical model is able to simulate thermal and hygrometrical transients in buildings. Results were validated in a test room [34S]. A numerical program simulated measured transient temperatures in the walls, floor, and surrounding soil of a buried structure [28S]. A numerical model calculates the steady-state performance of a direct-expansion air cooling coil. Results are compared with experiments using 134a as refrigerant [32S].

Theoretical predictions and measurements show how much illuminance can be increased in high-altitude greenhouses by use of double glazing panels to deflect low elevation sunlight onto crops [31S]. The forced convection adsorption cycle in a packed bed can be improved by preheating the refrigeration gas outside the bed [29S]. Heat transfer to the solvent is in this way increased.

20.6. Meteorology

Land surface schemes used for weather forecasting are developed for the Canadian Land Surface Scheme [42S]. Improved parameterisation for turbulent surface fluxes over inhomogeneous terrain provide mesoscale models for evaluating of local wind speed, air temperature and humidity estimates [38S]. Two-layer parameterisation of remaining land surface is recommended [39S]. A numerical model of the k–ϵ type was developed for computation of wind, air temperature, and humidity in the urban canopy layer [41S]. The energy balance above coniferous forests is influenced by differences in turbulent fluxes between snow-covered or snow-free areas [46S]. Diurnal variation of ground heat flux is determined in a novel method by measurement of surface soil temperature [52S]. The thermal roughness height associated with the surface radiation temperature varies diurnally over grassland [49S]. A simple snow–atmosphere–soil transfer model is useful for climate studies [50S]. The relation between soil moisture and leaf transfer coefficient for water vapor is examined [43S]. The currents and mixing in an ice-covered Russian lake were studied [44S]. The upper part of geological sections consists of loose sediments and heat transfer occurs by conduction and convection [47S]. The effect of surface warming on the groundwater flux is estimated using the temperature depth profile in the soil of the Tokyo metropolitan area [51S]. The vertical structure of a low level thermally forced wind on an equatorial beta plane is explored [53S]. Green's eddy diffusivity function is used to parameterize the eddy heat flux [55S]. The onset of thermal convection in an infinite Prandtl number compressible earth's mantle is determined by a critical Raleigh number and by an experimental approach [48S]. The instantaneous radiative impact of cirrus clouds in a static atmosphere is studied with three radiative transfer models [45S]. Thermoelastic stresses at the Earth's surface are investigated using a three-dimensional model for energy transfer by heat conduction and radiation [54S]. A review discusses thermal modeling of geothermal reservoirs for long time heat extraction [40S].

20.7. Electrics, electronics

The characteristics of heat transfer from a crystal laser slab to the coolant in high power DPSS laser operations were simulated [67S] to obtain optimum heat transfer coefficient and coolant flow rates. A paper [63S] responds to the challenge on how to remove increasingly large amounts of heat from supercomputers at the high end of the product spectrum and from the low end for portable computers. Integration of high-power electronic devices into existing aircraft while minimizing the impact of the additional heat load on the environmental control system requires innovative approaches [61S]. The lumped parameter network technique [57S] plays an important role for the solution of heat flow problems for complete systems as for electrical machines. Heat sink designers face a number of conflicting parameters when minimizing heat sink mass at prescribed temperature, fan power, and heat sources [59S]. A model is presented which describes transient thermal behavior of an insulated electric wire producing pulsating signals [56S]. A mathematical model [65S] describes the extrusion die flow of reactive electronic packaging material. Thermal hydraulic modeling of cable-in-conduit conductors is studied [68S] followed by a similar study [69S] for a (MOSFET) transistor.

Numerical finite element analysis is applied to the constant temperature distribution between surfaces in a sliding contact [64S] to metal forming problems

[60S], and to the computation of the stress field and temperature in the tube-sheet of heat transfer equipment [62S]. The residual stress in a steel cylinder with non-linear surface heat transfer coefficient with phase transformation during quenching is calculated [58S] as well as the thermoelastic response of ceramic–metal cylinders [66S] using an axisymmetric heat transfer equation.

20.8. Manufacturing

Computer modeling is extensively used for a variety of manufacturing processes. An isothermal journal bearing employing heat-pipe cooling was designed, constructed and tested [73S]. Energy recovery offers environmental benefits [78S]. The thermal behavior of mechanical seals is predicted computationally [81S]. Thermal modeling [84S] studies the effect of debris particles on sliding/rolling contacts. The temperature field in electric joule heating is numerically simulated [86S]. A water model simulates flow and heat transfer in continuous casting [88S]. The thermal field in electromechanical converters is studied [90S] analytically. Finite element studies [91S] simulate heat transfer to a ferrofluid in the presence of a magnetic field. Heat fluxes close to the edge of a solid plate arranged parallel to a standing source wave are measured [92S]. A "heat switch" is based on liquid crystals responding to applied voltage [72S]. Rayleigh–Benard convection in a magnetic fluid is investigated experimentally and theoretically [89S]. Heat transfer in ultrahigh vacuum scanning thermal microscopy increases significantly at smaller tip-sample distance [83S]. Testing methods for helmets as protection for workers are developed [80S]. Microsystems with integrated temperature sensors were designed and fabricated [79S]. Heaters for simulation of high-thermal loads (20–40 MW/m^2) were developed [70S]. A finite element analysis can predict heat transfer in machining of isotropic material [87S]. A paper highlights heat transfer on coated optical fibers [74S]. Numerical modeling is used for hot rolling work rolls [77S] and for orthogonal cutting [85S]. The effect of lubricants on heat transfer between workpiece and die [75S] and for turbulent flow in casting processes [76S] was analyzed. Roll surface temperature in hot rolling of an aluminum sheet was directly measured [93S] and was modeled for a rotating impulse drying press roll [71S]. The coating of aluminum sheets with a falling water film causing convection, nucleation and film boiling was modeled [82S].

20.9. Chemical processing

Gas/solid sorption chilling machines are difficult to control [95S]. This paper focuses on neutral networks for their control. Mass, momentum, and energy conservation serve for the dynamic modeling of the process in a blast furnace [96S]. Microporous hydrophobic membrane is used [94S] for vacuum membrane distillation. A simple criterion establishes the influence of transport resistances on separation efficiency.

20.10. Chemical reactors

The phenomena occurring in fixed bed reactors are described [98S] spanning the range from small-scale single pellets to the macroscale of a whole apparatus. A mathematical model describes [111S] the key design variables of a novel Internal Circulating Fluidized Bed Combustor. Temperature profiles are measured [106S] with and without reaction. Experimental results are presented and discussed for a fixed-bed chemical reactor [105S]. A dynamic heat transfer model and one based on a modified Damkohler number are compared for scale-up of solid-state fermentation processes [110S]. Systems of combined reaction and separation processes are of increasing interest. A systematic approach for their synthesis is presented [104S]. Heat transfer was studied computationally and experimentally [101S] in an innovative geothermal desalination plant. A simplified model of the warm-up of monolithic reactors is analyzed [107S]. Data from the present work and in the literature were used [97S] to produce a new correlation for the shear rates in an aerated loop of airlift reactors. A simple model describes a bio mass reactor for particle devolatilisation [102S].

A model describes gas absorption with irreversible chemical reaction in gas–liquid bubble media [103S]. The bubble rise velocity and bubble size decrease, but the bubble formation frequency increases as the pressure increases in high-pressure bubble columns [109S]. Transition from bubbling to jetting could be studied. Significant improvement was obtained in absorption columns. A new type of packing is investigated experimentally and theoretically [108S]. Enlargement of the pulsing flow regime is achieved by periodic operation of a trickle bed reactor [99S]. Heat transfer in a geothermal plant is analyzed [100S].

20.11. Food engineering

The quality of safe food is optimized by computational modeling of a continuous sterilization process [116S]. Surface heat flux and heat transfer were determined with a *k*-monitor [113S] for a tunnel-type industrial oven during baking of two cakes. A disinfestation system based on hydrodynamic heat transfer is judged for the uniformity and heating rates of a hot water drench [114S]. A fuzzy control system was developed for continuous peanut roasting [115S] and led to a kinetic model. An experimental study is the basis for characterizing the heat transfer of spherical objects stacked in bins and cooled by convection [112S].

21. Solar energy

Papers are broadly divided into solar radiation, low-temperature solar applications, high-temperature solar applications, and energy use in buildings. Papers on solar energy or energy conservation that do not focus on heat transfer, for example, papers on photovoltaics, wind energy, architectual aspects of building design, and control of space heating or cooling systems are not included.

21.1. Radiation

Using 20 years of hourly weather data, a modified Festa–Ratto method was used to establish a typical meteorological year for Athens [1T]. A model of luminance, correlated color temperature, and spectral distribution of skylight was compared with experimental data from Lyon, France [2T]. Improvements in handling cloud cover in the Heliostat method provided 5% improvements in the predicted value of global radiation [3T]. A numerical model of the effect of altitude on solar UV compared favorably to data obtained in the Chilean Andes [4T]. The use of a variability parameter to account for temporal variations improves radiation models based on clean air index and solar altitude [5T]. Methods to account for the Forbes effect on turbidity of air are evaluated by [6T]. Satyamurty [7T] developed correlations to predict ambient temperatures in the absence of data. Daily ambient temperatures are predicted for 269 locations. Data of infrared radiation in the water vapor rotational band are presented from an interferometer deployed at the SHEBA ice station 300 miles north of the Alaskan coast. Air-broadened water vapor continuum absorption coefficients are determined and compared to widely used models [8T]. One-minute probability distribution functions of solar direct and diffuse iradiance are modeled using data from Spain. The model presents a dependence on optical air mass [9T]. Time-space distributions of monthly latent heating from microwave satellite measurements over ocean regions are investigated for 1992 [10T].

21.2. Low-temperature applications

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

21.2.1. Flat-plate and low-concentrating collectors

Most papers address design of flat-plate collectors. [21T,28T] analyze the use of a double flow channel along the top and bottom of the absorber. Several papers consider enhancement of convective heat transfer with offset rectangular plate fins [18T–20T]. [14T] analyzes radiation heat transfer in transparent insulation made of honeycomb or glass capillaries. Collector efficiency was improved with the use of porous substrates in the collector tubes [13T]. A simplified approach to estimate glazing temperature and top heat loss coefficient is proposed by [11T,12T]. [16T] describes a computerized microscope to evaluate the reduction in optical efficiency caused by dust particles.

Numerical solution of the heat and mass transfer in a water film falling over the absorber shows the effects of film Reynolds number and ambient conditions on the interfacial heat and mass transfer. The effect of operating and design parameters on the transient behavior of heat pipes is the subject of [23T]. [15T] constructed a boiling collector from a commercially available evacuated flat-plate collector. The prototype collector uses a selective absorber, low pressure krypton in the casing and a reflective aluminum behind the absorber. Tests indicate efficiency exceeds 60% at 100 Celsius. [17T] simulates a hybrid photovoltaic/thermal collector.

Two studies address modeling and testing of collectors. [26T] proposes a statistical evaluation of the suitability of the collector models used in the ISO 9806-1 test. [22T] develops a method to calculate the short-term dynamic behavior of solar collectors with variable flow rates. The method is demonstrated for an unglazed and flat-plate collector.

Mid-temperature collection is considered for evacuated tube collectors and collectors with reflectors. [25T] discusses the use of shape memory alloys for higher temperature operation of evacuated heat pipe collectors. The design of a convex non-imaging Fresnel lens is described by [24T]. [27T] predicts that the use of V-corrugated as opposed to flat reflectors can increase annual collector output by 3%.

21.2.2. Water heating

Papers on solar water heating consider several relatively new concepts. [32T] develops a model of heat transfer in a lightweight inflatable hemisphere intended for heating small volumes of water. Results indicate that efficiency is on the order of 0.5. [34T] suggests use of an inner sleeve to reduce nighttime heat loss from ICS systems. Measured data in several tube-in-shell heat thermosphyon heat exchangers show that previously developed uniform heat, mixed convection heat transfer correlations are applicable to heat exchangers with forced flow in the tubes [29T]. Papers that model or evaluate conventional technology include tests of a solar-assisted heat pump water heater [30T] and evaluation of a large (2560 m^2) solar water heater for an egg powder plant [33T]. [31T] used artificial neural networks and limited operating data to predict performance of domestic water heating systems.

21.2.3. Space heating and cooling

Papers on heat pump and refrigeration systems are summarized. Direct expansion solar-assisted heat pumps are evaluated by [35T] and [42T]. [35T] presents sizing criteria for binary refrigerant mixtures. [42T] presents experimental data for a flat-plate evaporator and 350 W compressor. A mathematical model of a solar-assisted heat pump with latent heat storage is presented in [43T] and used to simulated performance of residential use in Turkey. [37T] models a two-pipe geothermal heat pump. Solar cooling is considered by [38T–40T,44T–46T]. [38T] models an absorption refrigeration cycle driven by both solar energy and electricity. Thermal performance of the co-driven system compares favorably to the traditional absorption cycle. [39T] gives an overview of carbon–ammonia refrigerators driven by condensation of steam in a heat pipe. He discusses monolithic carbon-adsorbent aluminum composites. [40T] presents a parametric analysis of a proposed combined Rankine and absorption refrigeration cycle that uses an ammonia–water mixture and a low cost concentrating collector. [44T] presents a numerical model of a prototype compound parabolic concentrating (CPC) collector for refrigeration. [45T] models performance of a solar adsorption heat pump that uses zeolite-coated wire gauze to increase heat transfer in the solar collector. [46T] presents an analytical expression for the COP and cooling capacity of solar absorption cooling systems.

Papers that address heating or cooling applications in buildings include a case study of a solar air ventilation system in Bangkok [41T], and a review of modern buildings that use hypocaust construction common to ancient Rome [36T].

21.2.4. Storage

Mixing and thermal stratification of sensible heat storage tanks are investigated by [47T] and [51T]. [47T] considered the effects of injection of cold water into a horizontal cylindrical storage tank. [51T] developed an approximate analytical solution for temperature distribution during charging. Latent heat storage was the subject of three papers. [48T] modeled cyclic operation of space solar heat receivers that use solid–liquid phase change storage. Cyclic efficiencies compare favorably with steady-state efficiencies. Methods to enhance conduction heat transfer in latent heat storage were studied by [50T]. [49T] developed a general model that considers the effect of geometric parameters on performance.

21.2.5. Desalination

The majority of the papers on solar desalination present models and optimisation of specific solar still designs [52T,54T,55T,57T–59T]. [56T] presents a software program for design of thermal desalination processes. In a brief communication, [53T] presents new selective water sorbents developed at the Boreskov Institute of Catalysis in Russia. Water production from the atmosphere is discussed. A demonstration of the technology produced 3–5 t of water per 10 t of dry sorbent per day.

21.2.6. Solar ponds

[61T] describes the operation of a 6000 m^2 solar pond in a milk processing plant in India. Intermittent operation from 1991 to 1996 is discussed. The major challenge was failure of the lining. [60T] investigates the generation of convective layers on the sidewalls of a solar pond that uses fertilizer salts. The addition of surface roughness reduced the growth of convective layers as much as 56%.

21.2.7. Buildings

This section includes papers on characterisation of energy consumption, and heat transfer in walls, and glazings. The use of a Fourier series approach to model hourly energy use in buildings is the subject of two papers by [64T,65T]. The first paper describes the model which relies solely on outdoor temperature to characterize weather variables. The second paper validates the approach using annual data for twenty-two commercial buildings.

Other modeling efforts address heat transfer in walls and daylighting. Modeling of walls include a transient analysis of the ability of an opaque wall to store solar radiation and heat the enclosed space [62T], a quasi-steady-state heat balance of residential walls [71T], and a two-port model of conduction in the building envelope [70T].

Reported works on daylighting address alternative methods of providing diffuse illumination. [63T] discusses diffuse ceiling illumination achieved with an optical wave-guide sandwiched between two glass sheets. Transmittance and reflectance of a lamellae system embedded in a plastic matrix sandwiched between glass sheets are measured and compared to predicted values [66T]. Illuminance measurements of scale models of three light guiding systems show that best approach is a light well with a reflecting wall [67T]. The reduction in electricity use achieved with daylighting of a commercial building in Hong Kong was modeled with DOE-2.1E. Results are presented in charts that are intended to be generally applicable for other building designs [68T]. Thermal performance of a low-emissive triple-gazing window is measured and compared to numerical analysis of convection and conduction heat transfer [69T]. An average month ratio of illuminance with an obstruction and without the obstruction is proposed to investigate the potential of facades to reflect daylight [72T].

21.3. 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.

Studies of concentrators include testing of a cone concentrator at the solar furnace in Cologne [78T], a model of secondary concentrators for central solar receivers [92T], and presentation of two new concentrator concepts [75T]. The efficiency and concentration of a purely imaging two-stage solar concentrator are compared to more typically used concentrating systems in [75T]. In [76T] the use of low attenuation optical fibers combined with small parabolic dishes is proposed. Experimental results for a heliostat control strategy aimed at optimizing the temperature distribution within the volumetric receiver of a power tower in Spain is presented in [77T]. A 0.5 MWt internal film receiver was tested at the same site [82T]. Test results from a study of the adaptation of volumetric receivers for small parabolic troughs are promising and development continues [81T]. [73T] and [87T,88T] model heat transfer in solar/stirling engines. Use of solar energy for propulsion in spacecraft is addressed in [93T] and [95T]. Papers that address measurement techniques in concentrating systems are a discussion of measurement of the reflectivity and absorptivity of opaque and diffuse materials using an optical fiber reflectometer and solar concentrator [80T], and development of a new optical measurement of the flux distribution [89T]. The influence of sunshape on the DLR furnace in Germany is described in [90T].

Solar thermochemical processes continue to gain attention. A new high-flux solar furnace, for study of thermochemical processing of solar fuels at the PSI in Switzerland, is capable of delivering 40 kW at peak concentration ratios exceeding 5000 [79T]. The thermodynamics and chemical kinetics of the decomposition of iron oxide are discussed in terms of the design of a solar reactor for producing hydrogen from water [94T]. Three papers [84T–86T] discuss the energy of the dissociation of ammonia for energy storage and present data from the first demonstration plant. [91T] analyzes the interface between a solar concentrator and a rotary kiln. The conversion of aluminum to aluminum nitride was achieved in a vibrating fluidized bed reactor in the solar furnace at NREL [83T]. Surface hardening of steel was investigated in a small solar furnace in France [74T].

22. Plasma heat transfer and magnetohydrodynamics

22.1. Plasma characterisation through modeling and diagnostics

Several papers deal with the description of turbulence effects, radiation transport and non-equilibrium effects in plasmas. Ye et al. [15U] investigate a radio frequency induction plasma using a k–ϵ model and find distinct regions of laminar flow and of turbulent flow. Modeling results of the effects of an evaporating copper anode on the radiation losses from an arc are presented by Menart and Lin [9U], and a cooling of the anode region through additional radiation losses has been found. The characteristics of a non-equilibrium high-pressure helium discharge have been calculated by Peres et al. [10U] based on a two-term solution of the Boltzmann equation, and resulting electron temperatures and electric fields have been compared to measured values. Ul'yanov [14U] presents a model for the various energy transfer mechanisms in a high-current vacuum arc, and his results can explain the regions of the operating parameter space where an arc can be operated. A low pressure microwave plasma consisting of pure argon has been investigated by Kelkar et al. [6U] based on a pseudo-one-dimensional solution of the Boltzmann equation and a collisional-radiative model, and comparison with experiments yield the thermal efficiency of the discharge. Another model of a low-temperature plasma [7U] concentrated on determining the molecular absorption cross-sections in a carbon–nitrogen–oxygen system for radiation transport calculations. A model for calculating thermodynamic and transport property data in LTE is proposed by Bottin et al. [3U].

Several papers deal with diagnostic characterisation of reacting non-equilibrium plasmas, and the information obtained usually is enhanced by the combination with a chemical kinetics model. A new microwave diagnostic for characterizing glow discharge plasmas is presented by Gundermann and Winkler [4U]. Spectral absorption measurements have been performed on a microwave plasma containing H_2–Ar–O_2 and methane, and a chemical kinetics model has been used to generalize the results [11U]. Hadrich et al. [5U] present the results of CARS measurements on hydrocarbon microwave plasmas, and the results agree with those obtained from a physical-chemical kinetics model. CARS diagnostics has also been used on a dielectric barrier discharge in N_2–O_2–NO mixtures and has yielded information on the important reactions, and a chemical kinetics model verified the effect of the presence of oxygen on reducing the destruction of NO [2U]. The spatially varying kinetics of electrons and excited atoms in a He–Xe glow discharge have been investigated by Lange et al. [8U] using a Langmuir probe technique in combination with spectral absorption measurements, and the change from non-local to local behavior of the electron kinetics with increasing He pressure has been demonstrated. An asymmetric thermal plasma jet has been characterized by evaluating calorimetric probe data using computer tomography [12U]. Laser scattering has been used to determine electron densities in a 150 A arc [13U], and the results have shown that non-equilibrium conditions exist in the arc column, and effects on the anode heat transfer are the consequence. Comparison of the results of a single temperature model of a hydrogen arcjet with diagnostic results has shown that some plasma characteristics can be predicted, but that non-equilibrium exists at the nozzle exit plane [1U].

22.2. Plasma–wall and plasma–particle interaction

The heat transfer to a steel surface during exposure of an ion beam has been investigated through a model by Lepone et al. [20U], and it has been found that the experimentally observed effects can be explained by the formation of a plasma bubble at the surface. Magunov [22U] describes experimental observations of the enhancement of the heat transfer through chemical reactions on a surface exposed to a non-equilibrium RF plasma.

Four papers present models treating different aspects of plasma–particle heat transfer. Chen has continued his particle heat transfer models by describing the effect of different Knudsen numbers [19U] and the effect of reflected atoms on the thermophoretic force acting on the particle [18U]. Another plasma–particle interaction model describes the effect of particle size and particle number density on the total energy transfer from the plasma to the particles in an arrangement similar to one encountered in plasma spraying [16U]. The effect of evaporation of the particle material on the heat transfer from the plasma has been calculated by Ramasamy and Selvarajan [23U] for different plasmas and different particle materials. A model of the evaporation of zirconia particles in a thermal RF plasma is presented by Buchner et al. [17U], and the modeling results are compared with those from emission spectroscopic investigations. An experimental study describes the purification effects in metallurgical grade silicon particles upon exposure to a thermal RF plasma [21U].

22.3. Plasma characterisation in specific applications

The trend of applying advanced plasma models and diagnostic techniques to specific environments and conditions associated with a particular application is continuing, although several of the studies have quite general validity. In particular, three-dimensional and multi-phase models are now quite commonly used for characterizing specific processes. A three-dimensional model of an actual steel nitriding reactor using a microwave generated Ar–N_2–H_2 plasma has been used to determine the effects of the loss of atomic nitrogen at the surfaces, and it has been found that the effect is confined to a mass transfer boundary layer [28U]. Swihart and Girshick [42U] present an analysis of the boundary layer in front of a substrate in a plasma CVD reactor, and the distortion of the chemical species distribution experienced when the substrate has an orifice for gas sampling purposes is described. Heat and mass transfer profiles in a 3-phase ac plasma reactor to be used for hydrocarbon cracking is modeled by combining a commercial fluid dynamics code with a description of the electromagnetics added, and the results are compared to high-speed images and to temperature measurements [39U]. Another three-dimensional model including electromagnetic effects on the fluid dynamics addresses the conditions and geometry of circuit breaker arcs, although the initial results are presented for steady-state conditions [40U]. A similar configuration has been modeled by Rachard et al. [37U], using a two-dimensional dynamic model to describe the arc movement from its ignition until it reaches the wall. Ramasamy and Selvarajan [38U] present a model of a plasma spray torch yielding the dependency of the thermal efficiency on the design and operating parameters. A comprehensive model of particle heating, melting, evaporation and resolidification during plasma spraying is presented by Wan et al. [44U] for zirconia and nickel particles, and effects on mass transfer on the convective heat transfer are included. Another paper related to thermal spraying describes the heat transfer processes during the formation of a ceramic splat on a substrate during coating formation [26U]. The effects of spray operating parameters on the residual stresses in a sprayed zirconia coating have been investigated using finite element models together with X-ray analysis of coatings, and the effects of the temperature history of the substrate and coating have been found to be important [43U]. A model of the plasma cutting process for multi-layered manufacturing uses a linearized formulation based on Green's function [32U]. Haidar [33U] describes a further development of his dynamic model for the gas metal arc welding process, including the evaporation of metal and the formation of fumes.

Addona and Munz describe a transferred arc process for decomposition of silica, in particular the decomposition rate as a function of operating parameters [25U]. A similar reactor has been investigated by Abdenouri et al. for reclamation of gold from iron sulfide, and this fuming process has achieved an extraction efficiency of 90% [24U]. Three papers describe developments of plasma processes using RF induction plasmas: an ozone generation process based on oxygen quenching of the plasma at atmospheric pressure [41U], an ammonia decomposition process at reduced pressure [30U], and treatment of liquid toxic wastes injected in liquid form into the reactor [46U]. Oxidation of liquid olefins in an oxygen glow discharge reactor is described by Patino et al. [36U]. Pulsed atmospheric pressure discharge reactors have been used to reform CO_2 and natural gas to CO and hydrogen [35U], and for sterilisation and deodorisation of dielectric surfaces such as glass or plastic bottles [34U]. The surface oxidation of brass foils using a low pressure oxygen plasma generated by an RF induction discharge has been investigated by Draou et al. [31U], including the kinetics of the oxide film formation. The effects of power delivery in multiple high-power pulses in an electromagnetic launcher are discussed by Budin et al. [29U], and several advantages are found compared to normal operation including increased thermal efficiencies and reduced electrode erosion. Pulsed operation of an arcjet thruster for space propulsion applications is described by Willmes and Burton [45U], and a time-dependent quasi-one-dimensional model is used to interpret the results. A new way to simulate re-entry conditions consisting of a solar furnace providing the heat combined with a microwave plasma providing the dissociated species is described by Balat et al. [27U], and this arrangement has been used to study the catalyticity of ceramic protective tiles.

22.4. Magnetohydrodynamics

This area continues to provide topics for the development of advanced models. A method for transforming the non-dimensional equations for unsteady magnetohydrodynamic boundary layer flow is presented by Ezzat et al. [52U] and solutions are obtained for an electrically conducting micropolar fluid flowing past a vertical plane in the presence of a transverse magnetic field. A method based on the use of Green's function has been used to provide analytical solutions for the case of fully developed natural convection in vertical concentric annuli [47U], and a similar approach has been used for obtaining analytical solutions for the flow in vertical porous channels [48U]. Exact solutions have been obtained for an oscillatory flow of an elastoviscous conducting fluid over a porous plate with variable suction for a variety of fluid parameters [53U]. Mixed convection from a rotating cone imbedded in a porous medium with heat generation has been described by using a similarity transformation to convert the partial differential equations to ordinary ones [50U]. Another model describes the propagation of non-linear waves on a viscous film flowing over an inclined plane while being under the influence of electric and magnetic fields [55U]. A model for a fusion reactor blanket considers either fully developed flow or non-uniform unsteady flow and provides solutions to the three-dimensional Navier–Stokes and Maxwell equations [57U].

An experimental study of MHD flow in a rectangular duct has been conducted by Xu et al. [58U], and the obtained velocity profiles have been compared to theoretical predictions. In another experimental study, temperature and potential profiles are obtained for a mercury filled cell with the liquid experiencing buoyancy forces under the influence of magnetic fields [51U]. The effect of a magnetic field on the convective heat transfer in molten gallium flow is presented by Juel et al. [54U] in a study combining experiments and numerical simulation. Potential probes and flow visualisation have been applied to the characterisation of two-dimensional turbulent flow of mercury in the presence of a steady magnetic field, and the effect of the turbulence on heat transfer has been determined [49U]. A novel scheme to enhance heat transfer is presented by Mochizuki et al. [56U]. This method consists of releasing drops of a conducting liquid into the flow of another inmiscible liquid between two electrodes.

22.5. Highlights

While there are no specific papers which should be singled out as highlights, the amount of realism brought to modeling of practical applications deserves to be mentioned. It is apparent that models are more and more used for supplying the process details in regions which are not accessible to diagnostics. The other notable feature is that there appears to be in some applications an increase in functionality of a device when it is operated with modulated (i.e., pulsed) power.

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