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HEAT TRANSFER—A REVIEW OF 1974 LITERATURE

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INTRODUCTION

THIS review surveys results that have been published in various fields of heat transfer during 1974. As in the past, the number of papers published during that period was such that only a selection can be included in the Review. A more complete list is contained in the heat-transfer bibliographies published periodically in this journal.

The most significant of the various conferences dealing with heat transfer was the Fifth International Heat Transfer Conference held in Tokyo from 3 to 7 September, 1974. The eight invited lectures dealt respectively with turbulence in heat and mass transfer, growth and decay of ice, holography, numerical methods in convective heat transfer, energy transfer in planetary atmospheres, biological thermo-regulatory systems, complex geometry channels, and radiative transfer at super high temperatures. Thirty-nine sessions were concerned with forced and natural convection, rheological systems, boiling, condensation, combined heat and mass transfer, and heat exchangers. Seven round table meetings, open forums, film sessions, and an equipment show rounded out the program of the Conference which was attended by 537 participants (210 of which were from abroad) and was well organized by the Japanese Organizing Committee. The proceedings, including discussions, are now available in book form.

The 1974 International Seminar of the International Centre for Heat and Mass Transfer was held from 26 to 30 August, 1974 in Trogir, Yugoslavia and was devoted to heat and mass transfer in the environment of vegetation. Invited lectures and short communications covered heat and mass transfer in the soil, in plants, and in the lower atmosphere and treated bioengineering of plant growth and pollution of soil, water, and vegetation.*

The 95th Winter Annual Meeting of the American Society of Mechanical Engineers had in its program 11 sessions dealing with thermal energy storage, solar energy applications, heat transfer in equipment, in gas cooled reactors, and in nuclear reactor safety, in addition to fundamental heat-transfer studies. In addition, a panel meeting considered heat exchanger standards.†

*A collection of papers of the conference is available in book form from the Scripta Book Company.

†Reprints of the papers are available through the Society and many of them will also be published in the Journal of Heat Transfer.

The AIChE Symposium Series, Volume 70, No. 138, 1974 "Heat Transfer in Research and Design," contains papers presented at the 14th National Heat Transfer Conference in Atlanta, as well as papers presented at various meetings of the American Institute of Chemical Engineers.

The 1974 International Gas Turbine Conference at Zurich was organized by the ASME and the Swiss Society of Engineers and Architects. Two of its 35 sessions were devoted to heat transfer, and papers in other sessions touched on this subject.

The 1974 Heat Transfer and Fluid Mechanics Institute was held at Oregon State University from June 12 through June 14, 1974. Thirteen of its 22 papers considered heat-transfer problems and two invited lectures discussed transport phenomena in heat pipes and research needs in process heat-transfer design. The proceedings of the conference are available through Stanford University Press.

Developments in heat-transfer research during 1974 can be characterized by the following highlights: The largest number of papers were devoted to conduction, natural convection, phase change, and properties. Conduction was studied under conditions of phase change by means of numerical methods, and for irregular, composite, and anisotropic bodies. The laminar entrance region, variable properties, and turbulence models were considered in channel flows, with analytical papers far outnumbering experimental ones. Combined natural and forced flow, unsteady conditions, wakes, and jets were investigated in the area of boundary layers. Transfer mechanisms were studied through hot wire measurements, through analytical or statistical theories, and through improvements in phenomenological models. Natural convection papers dealt primarily with enclosures, non-Newtonian fluids, and variable properties. Combined heat- and mass-transfer studies were considered with interaction of heated jets with surroundings, film cooling, and to a lesser degree, transpiration cooling. The larger number of applied papers on phase change originated primarily in the Soviet Union and in Japan.

Radiation was investigated in non-gray media, either by itself or combined with conduction and convection. Several papers also considered radiative exchange in cavities, in fins, and at very low cryogenic temperatures. Non-intrusive (optical) measurement techniques were described. A large number of papers was devoted to fluidized beds. Plasma heat-transfer studies included arc flow interactions, radiation effects, and heating of particulate matter. Correlations and skeleton tables were reported for thermodynamic equilibrium and transport properties, and contributions on water properties were numerous. Papers on heat-transfer applications considered augmentation of heat transfer in heat exchangers, heat pipes, and the space shuttle.

To facilitate the use of this review, a listing of the subject headings is made below in the order in which they appear in the text. The letter which appears adjacent to each subject heading is also attached to the references that are cited in the category.

Conduction, A
Channel flow, B
Boundary layer and external flows, C
Flow with separated regions, D
Transfer mechanisms, E
Natural convection, F
Convection from rotating surfaces, G
Combined heat and mass transfer, H
Change of phase, J
Radiation
  Radiation in participating media, K
  Surface radiation, L
Liquid metals, M
Measurement techniques, P
Heat-transfer applications
  Heat exchangers and heat pipes, Q
  Aircraft and space vehicles, R
  General, S
  Solar energy, T
Plasma heat transfer, U
Thermodynamic and transport properties, V

CONDUCTION

Major areas of heat-conduction activity included phase change; numerical methods; irregular, composite, or anisotropic bodies; and fins.

The phase change papers dealt with a variety of topics. Inward solidification of a cylindrical liquid medium subjected to surface convection or uniform cooling was studied in the context of heat storage and extraction for a solar energy system. Of particular concern in this application is the temperature drop across the solidified layer; the larger the temperature drop, the lower is the effective temperature level of the storage heat source [67A]. The presence of natural convection in the liquid pool was included in the conduction phase change analysis of a continuous casting process. The main effect of the convection was to enhance the formation of a nearly isothermal region at the bottom of the pool [35A]. In phase change problems with a linear variation of thermal conductivity with temperature, the conditions are identified where the use of the mean conductivity is sufficient [9A]. It was demonstrated that uncertainties in the thermophysical properties do not lead to large errors in the solutions of phase change problems, provided that specified conditions are fulfilled [6A]. Techniques used in the application of the finite element method to transient heat-conduction problems with variable properties can also be employed to take account of phase change when a suitable heat capacity–temperature relation is used [12A]. Inward solidification due to combined convection and radiation at the surface is markedly affected by the presence of radiation for $Bi < 1$ [20A]. For the range of parameters encountered in the melting and solidification of semi-transparent crystalline materials, radiation can cause the temperature profile within the liquid phase to take on a shape which leads to unstable interface growth [1A].

An approximate solution of a generalized Neumann phase change problem in which the surface temperature varies slowly with time was obtained by assuming a linear temperature profile in the solid phase and an error function profile in the liquid phase [60A]. Experimental data for the solidification of paraffin was employed to define the range of validity of an approximate solution of Stefan's problem for a sphere [33A]. Two approximate techniques were suggested for obtaining closed-form solutions for multidimensional phase change resulting from surface heating with instantaneous removal of melt [26A].

The problem of a moving vaporization front in a porous medium was formulated by writing conservation equations in the two regions partitioned by the front and then matching the solutions by employing continuity conditions at the front [21A]. The use of Green's functions enables diffusion problems with moving boundaries to be expressed in terms of an integral equation in which the concentration (or temperature) at any point in a spherical domain is expressed in terms of the concentration and its gradient at the boundaries [10A]. The equilibrium size and shape of a frozen region that forms around a point heat sink situated in a low Reynolds number flow has been found by the method of matched asymptotic expansions [80A]. The effect of chemical reactivity (i.e. dissociation and recombination) on heat conduction was analyzed for near-equilibrium conditions [19A].

Innovations and extensions related to numerical methods of solution have been described. A finite element formulation, in which the discretized equations are derived by the Galerkin method, was employed to solve for steady and transient conduction in the presence of an exponential temperature-dependent heat source [3A]. In connection with a finite element solution for the transient heat-conduction equation, it was found that a recurrence relation derived from the Galerkin method gives better short-time accuracy than the usual Crank–Nicholson formula [16A]. A finite element weighted-residual process in conjunction with rectangular prisms in a space–time domain was used to solve transient linear and nonlinear two-dimensional heat-conduction problems [8A]. The advantages and disadvantages of using a finite element representation of the time variable were discussed [32A]. Comparisons showed that the least squares time-stepping algorithm offers advantages compared with the Crank–Nicholson scheme and a finite element scheme [36A].

An examination of the stability aspects of the transient finite difference solution for a slab with surface radiation and convection yielded a bound on the time step [45A]. To somewhat relax the stability criterion of the conventional explicit finite difference formulation, a modified approach was employed in evaluating the time derivative in the unsteady heat conduction equation [66A]. A numerical method of solving steady heat-conduction problems, termed the singular integral method, envisions heat sources deployed along the boundary, the strength of the sources being determined to satisfy the boundary conditions [58A]. A proposed method for finding a numerical approximation for a boundary condition given at infinity in a diffusion problem is very similar to that which is employed in the solution of fluid flow and thermal boundary layers [65A].

Methods have been devised for deaing with bodies having non-elementary shapes. The method of matched inner and outer expansions was employed to solve steady conduction problems in irregular geometries; the solution method retains the two-dimensional nature of the problem in the boundary-layer region [28A]. For bodies whose boundaries depart slightly from standard shapes, a perturbation was found to be effective [62A]. A perturbation method was also employed to solve the transient conduction problem in a large plane region whose inner boundary is non-circular [27A]. From the shape factor of a single sphere in an infinitely extended medium, shape factors can be derived for the hemisphere in a semi-infinite medium, for two-sphere arrangements, and for buried spheres [22A]. The thermal resistance of a buried cylinder with a constant heat flux boundary condition is greater than that for the constant wall temperature boundary condition, but the difference becomes negligible when the depth of burial is three or more pipe radii [73A]. The critical radius concept for the maximum heat flow through cylindrical and spherical surfaces has been generalized to accommodate arbitrarily curved surfaces [40A]. Steady-state temperature field solutions for a rod are obtained which include the effects of various types of thermal connections at the ends of the rod [29A].

Solution methods and solutions for composite materials were described. To deal with transient heat conduction in a multi-layered composite material, the theory of the Sturm–Liouville equation with discontinuous coefficients was formulated and applied [57A]. Based on asymptotic expansions of the microstructure equations for transient heat conduction in laminated composites, a continuum model was developed in which microstructure effects appear as a consequence of the fact that the current state in a laminated medium is history dependent [5A]. The application of a finite element method facilitated the solution of the transient temperature field in a composite slab, with account being taken of variable properties and of radiation and convection on the surfaces [71A]. The influence of the presence of structural and supporting members within a plane layer of insulation was determined by obtaining solutions of Laplace's equation in contiguous rectangular regions and then matching the solutions [34A].

An interesting variety of approaches was employed in connection with anisotropic media. A similarity transformation enabled the solution for the two-dimensional, steady temperature distribution in a wedge with anisotropic thermal conductivity [11A]. To facilitate the use of finite differences for solving transient conduction in anisotropic solids, a transformation was employed which leads to an energy equation for an isotropic solid, but the boundary shape is altered by the transformation [30A]. By a constrained variational procedure, a finite element approximation was developed which can treat steady heat conduction in anisotropic media whose properties may be both spatially and temperature dependent [52A]. Through the use of series representations and the properties of adjoint differential operators, a semi-analytical finite element procedure was devised for solving steady and transient temperature fields in axisymmetric anisotropic bodies [53A]. Anisotropy imposes directional preferentiality on a random walking particle in a Monte Carlo formulation [54A].

Fins (i.e. extended surfaces) continue to be an interesting applications area. It has been demonstrated that the overall heat-transfer rate can be increased by inclining fins which lose heat by natural convection [55A]. The neglect of the slope of the fin surface, standard in studies of optimum fin shapes, has been lifted. The length of the newly determined optimum shape is shorter than that of the classical parabolic shape [39A]. Fin shapes which correspond to minimum mass have been determined for the case of combined convection and radiation [79A]. If the base temperature of a fin situated in a liquid environment is high enough, the fin may experience a range of boiling regimes along its length. The analysis of such a fin was performed using heat-transfer coefficients which vary according to a power of the temperature difference [72A]. To obtain maximum heat transfer from a horizontal finned tube, it is recommended that the fins have an efficiency in the range from 0·7 to 0·75 [37A]. A cylindrical tee plug presented an interesting challenge in the matching of the separate heat-conduction solutions for the cylindrical base and the stem [31A].

Papers have been motivated by other applications. The temperature distribution in a gun barrel was found by solving the two-dimensional transient heat-conduction problem for a hollow cylinder subjected to a pulsating time- and spatially-dependent boundary condition at its bore [14A]. An exact solution for the transient thermal response of toroidal coils with internal heat generation has application to the design of solenoids, transformers, and other current carrying apparatus [13A]. The craters obtained in electro-discharge machining were analyzed using a model in which a finite or semi-infinite body is subjected to a given heat flux within a circular disk situated on its surface [77A]. A highly time-dependent surface heat-transfer coefficient representative of quenching operations can be accommodated in analyzing the temperature–time history of a solid sphere; the solution method involves a nonlinear integral equation [15A]. Isotherms surrounding a moving cylindrical heat source tend to bunch together in front of the source and spread apart in the rear [75A]. The thermal resistance of a plate with spatially intermittent heating on one of its faces was determined both for uniform heat flux and convective boundary conditions [49A]. The periodic steady solution for the temperature distribution in an annular cylinder with timewise periodic internal heating and convective cooling on its surface was motivated by nuclear reactor applications [23A].

The neglect of heat conduction in the substrate to which a thin film gage is applied can lead to significant errors in the determination of heat-transfer coefficients [50A]. A solution for an embedded sphere with a time-dependent heat source is of use in the thermistor probe technique for determining thermal conductivity and diffusivity [4A].

Various aspects of thermal contact have been examined. Explicit expressions for thermal contact conductance were derived for (a) pure plastic deformation, (b) pure elastic deformation, (c) plastic deformation of the asperities and elastic deformation of the substrate [44A]. The transient processes that occur immediately after the contact of two solids having different temperatures was studied, and the conventional linear models were found to be inadequate [7A]. Heat transfer between two bars whose surfaces periodically make and break contact was analyzed via a system of two matrix equations [43A]. The overall resistance to heat transfer across a joint formed by solid or hollow metallic ○-rings in contact with smooth, flat ends of cylinders was measured for nine different ○-rings and correlated by dimensionless parameters [64A].

Additional solutions for transient problems were reported. The nature of the temperature response of one-dimensional solids to random initial conditions is different for bounded and unbounded domains [2A]. Transfer functions describing the thermal transient behavior of a pipe wall were derived via Laplace transform techniques [63A]. The heat balance integral was applied to solve a group of one-dimensional transient heat conduction problems for the plane wall, the cylinder, and the sphere. The boundary conditions included a step change in surface temperature, convection, and radiation [74A]. The accuracy of truncated forms of the transient solutions for simple geometries has been examined [56A].

Approximate solution methods have been proposed. The method of the local potential, which is a tool for obtaining approximate solutions for diffusion problems, is based on a variational principle [38A]. The implementation of the shrinking boundary method, an innovation to the Monte Carlo procedure for solving heat-conduction equations, was described and its advantages set forth [81A]. A method for obtaining upper and lower bounds for the steady heat transfer from a body with convective boundary conditions employs assumed isotherms and adiabatics within the body [17A]. For certain explicitly exhibited upper and lower bounds for the transient heat-conduction equation with a non-linear source term, the average of the bounds can serve as a good approximation to the solution [59A].

Some papers have dealt with more theoretical problems. Solutions for transient conduction problems with time- and space-dependent boundary conditions can be formulated employing a finite integral transform, which leads to a set of simultaneous ordinary differential equations [51A]. By use of Green's functions, the general transient heat-conduction problem can be expressed in terms of an integral equation involving surface values of temperature and/or heat flux [68A]. The uniqueness of solutions of nonlinear transient heat-conduction problems was investigated by formal mathematical arguments [24A]. A uniqueness theorem for transient heat-conduction solutions with finite wave speed has been established without the restriction that the heat flux and energy rate be independent of the current value of the temperature [25A]. A survey paper dealing with the nonlinear transient heat-conduction equation discusses existence and uniqueness of solutions as well as solution methods [82A].

English-language translations of Russian papers dealing with the following heat-conduction topics have appeared in *Heat Transfer, Soviet Research*: (a) steady conduction in an annulus with circumferentially variable heat-transfer coefficient and fluid temperature at the inner surface [69A]; (b) mean temperature of a tube wall with circumferentially varying heat flux on the outside surface and internal forced convection cooling [76A]; (c) effect of non-ideal contact on the transient heat flow between two adjacent plates [18A]; (d) temperature dependence of thermal contact resistance [42A]; (e) transient heat conduction in a plane wall in the presence of a temperature-dependent heat-transfer coefficient on one surface [41A]; (*f*) thin-walled structural components with temperature-dependent specific heat subjected to timewise varying heating rates [70E]; (g) simplified techniques for finding the transient temperature distribution in a multi-layered solid [78A]; (h) quasi-steady approximation for solving conduction phase change problems [61A]; (i) refinement of the approximating polynomial in the Heat Balance Integral and its application to the determination of thermal stresses [46A–48A].

CHANNEL FLOW

Laminar entrance region problems continue to motivate numerous research publications. Turbulent flow analyses were performed using a variety of transport models. Although some experimental work was reported, analytical studies appear to predominate in this year's channel flow literature.

Various facets of the laminar entrance region were dealt with. Mass-transfer measurements via the naphthalene sublimation technique yielded local laminar transfer coefficients in a parallel plate channel which agreed well with analytical predictions [24B]. The accounting of axial and radial wall conduction in the laminar Graetz problem leads to lower Nusselt numbers compared with the classical uniform heat flux case and to higher Nusselt numbers compared with the classical uniform wall temperature case [29B]. The matching of upstream and downstream solutions for laminar channel flow subjected to an abrupt change in wall temperature at $x = 0$ is accomplished by constructing an eigenvalue problem whose eigenfunctions are orthogonal [7B, 8B]. A general method which combines orthogonal collocation and matrix diagonalization was employed to solve the Graetz problem with axial heat conduction [27B]. A method, based on the exploitation of certain properties of the Laplace transform of the temperature, is developed for determining the large-x behavior of the Nusselt number for problems of the Graetz type [14B].

The accounting of the transverse velocity component in the laminar entrance region of a tube leads to a lower Nusselt number than that obtained when the transverse velocity is neglected [15B]. It is found that the effect of viscous dissipation on thermal entrance region heat-transfer characteristics is completely different for heating and cooling at the wall [35B]. A sudden change in the temperature at the entrance of a pipe activates two fronts that propagate down the pipe [5B].

An analysis of the Graetz problem for laminar flow in a curved pipe showed that the heat-transfer coefficient at first decreases with distance from the inlet, attains a minimum, and then increases toward its fully developed value. The minimum and subsequent increase are due to the effect of secondary flow [1B]. Numerical solutions for laminar flow in a helically coiled tube indicate that the secondary flow which is caused by the centrifugal forces brings about an increase in the Nusselt number [36B].

A summary of fully developed Nusselt numbers for a variety of duct cross sections was presented along with a discussion of the role of various thermal boundary conditions [44B]. The use of a triangular finite-difference mesh facilitated numerical solutions of the fully developed flow and heat transfer in polygonal ducts [34B]. Closed-form solutions for fully developed laminar heat transfer in an elliptical annulus with a variety of thermal boundary conditions were facilitated by the use of elliptical coordinates [53B]. Temperature and velocity solutions for laminar flow between a stationary and a cyclically moving wall were applied to the varying thickness film between a round shaft with axial reciprocating motion and its housing [37B].

A number of papers contained results for duct flows with fluid injection at the wall, mass transfer, and chemical reactions. Experiments showed that uniform injection of air through a porous tube wall into a turbulent airflow caused reductions in the local Nusselt number [25B]. For laminar flow between porous parallel plates, the Nusselt number is significantly reduced by the injection of a foreign component of high thermal capacity [58B]. In a porous walled tubular reactor, the injection of inerts flattens the temperature profile, but decreases the net conversion [3B]. A mass-transfer problem for laminar flow in a parallel-plate channel having wall mass diffusion proportional to a Sherwood number is analogous to a heat-transfer problem where the wall heat flux is proportional to a Nusselt number which characterizes the wall and external conductances [57B]. Local laminar Nusselt numbers for simultaneous heat and mass transfer in an externally heated parallel-plate channel are virtually identical to those for pure heat transfer provided that a suitable definition is employed [19B]. In a chemical reactor in which a highly exothermic reaction is taking place, the rate of conversion may be either high or low for a given set of input conditions. This is another example of the phenomenon of multiple steady states which occurs in flows with temperature-dependent heat sources [56B]. Coupled heat transfer and chemically reactive mass transfer in a tubular reactor were analyzed for the extremes of small and large mixing [40B].

Non-Newtonian effects have been investigated. For a power law fluid with temperature-dependent rheological properties, solutions for the entrance region indicated an important influence of viscous dissipation [12B]. Thermal entrance region solutions for an Ellis-model non-Newtonian fluid flowing in a circular tube exhibited very long entrance lengths [48B]. Experiments on turbulent flow and heat transfer in smooth and rough tubes with dilute polymer solutions revealed substantial reductions in both the friction and heat-transfer coefficients relative to those of ordinary fluids [9B]. Industrially observed instabilities of polymer melt flows prompted the analysis of the stability of the flow of temperature-dependent power-law fluids. The analysis was performed both for flows without [45B] and with [46B] internal heat generation.

Several papers dealt with variable fluid properties. A comparison of laminar heat-transfer results for liquid flow in an annulus showed that, in the presence of strong property variations, there was a substantial deviation between a numerical solution and an extended Leveque solution [50B]. The effect of temperature-dependent viscosity on laminar tube flow was analyzed by expanding the velocity in a power series in which the expansion parameter is the exponent of the viscosity–temperature relation [33B]. For lubrication applications, an equation was developed which generalizes the one-dimensional Reynolds equation to account for viscosity variations across the lubricant film thickness [59B]. A variational method for the determination of linear stability of non-isothermal laminar duct flows was applied to plane Couette flow with temperature-dependent viscosity and to isothermal Poiseuille flow [22B]. The surface renewal model for turbulent energy exchange, when employed for turbulent heat transfer in variable viscosity liquids of moderate Prandtl number, gave results in good agreement with pipe flow experiments [52B]. On the basis of experiments performed at various levels of heat flux, it was concluded that the effect of variable viscosity on the friction factor for turbulent flow of water in a tube is not adequately described by a simple power law, as is conventional [20B]. Experiments involving turbulent flow of supercritical carbon dioxide in a tube with axially varying heat flux yielded Nusselt number results that fall within the range of available predictions [38B].

Analyses of turbulent flows employed several different models for the turbulent transport. The Cebeci model for turbulent exchange, when applied to pipe flows, yielded good agreement with experimental heat transfer results [31B, 32B]. For the surface renewal model of turbulent transfer, relationships were developed for the velocity and temperature profiles in terms of the parameters of the model. With estimates of these parameters, application was made to high Prandtl number turbulent flow in a tube [41B]. Another surface renewal analysis of high Prandtl number turbulent tube flow subdivided the Prandtl number range into three sub-ranges and employed somewhat different models for each [39B]. Turbulent pipe flow with internal heat sources has also been analyzed by the surface renewal model [4B]. Anisotropy in the eddy diffusivity for heat was taken into account in analyzing fully developed turbulent heat transfer in a tube with circumferentially varying thermal boundary conditions [13B]. The transport mechanisms governing unsteady turbulent heat transfer for air flow in a tube were analyzed and a correlation of available data carried out [10B]. An analysis of the effect of flow pulsations on turbulent heat transfer indicated that the time-averaged results were not affected by the pulsations, within the range considered [51B]. The thermal transient in a turbulent flow caused by a step increase in the heat generated within the inner bounding wall of an annulus can be treated as quasi-steady if the wall heat capacity is sufficiently large [17B].

Experiments on direct contact heat and mass transfer between water and air in a large aspect ratio rectangular duct explored the effects of relative flow rates, water inlet temperature, and inlet air humidity [49B]. Whereas there is a general trend for the local turbulent heat-transfer coefficient to decrease downstream of the beginning of a divergence of the walls of an annular duct, a local maximum was also observed [16B]. A Nusselt number correlation for the entrance region boundary layer in a circular tube involves the degree of turbulence of the entering flow [47B].

Augmentation and roughness have been investigated. Mesh and brush inserts, used as augmentation devices in turbulent water flow, showed favorable performance based on equal pumping power [26B]. Nusselt number data are reported for turbulent flow in an internally finned tube, but no performance comparisons were made with unfinned tubes [11B]. Predictions of the friction factor and heat-transfer coefficient for both laminar and turbulent flows in a tube containing a twisted tape were made on the basis of finite-difference solutions of the conservation equations. The eddy viscosity needed for the solutions was obtained by solving differential equations for the kinetic energy of turbulence and for the energy dissipation rate [6B]. A critical review has been published of the methods used to evaluate the thermohydraulic performance of rough surfaces. In particular, the Hall transformation, which is employed to relate results for an annulus with roughened inner surface to those for a roughened tube, is re-examined [23B]. For turbulent flow and heat-transfer calculations in an annulus with a roughened core, eddy viscosity distributions were used that are invariant with respect to surface roughness [21B].

The rod bundle flow configuration is of interest with respect to reactor applications. Measurements of the structure of turbulent flow in a rod bundle revealed the presence of secondary flow and pulsations adjacent to the rod gap [42B]. An analytical method which can treat the longitudinal laminar flow in an entire array of rods enabled a full examination of design parameters [30B].

English-language translations of Russian papers dealing with the following channel flow heat-transfer topics have appeared in *Heat Transfer, Soviet Research*: (a) augmentation of heat transfer in pipe flows by the use of three-dimensional roughness [28B]; (b) effect of swirl on turbulent heat transfer in the entrance region of a pipe [18B]; (c) laminar flow of a radiatively non-participating gas in a tube where there is radiative interchange between the walls [43B]; (d) high temperature gas flows (2500–4000°K) in highly cooled tubes [55B]; (e) turbulent flow of supercritical nitrogen in a circular tube [2B]; and (f) the conditions at which fluctuations are observed for supercritical flow of water in a heated tube [54B].

BOUNDARY LAYER AND EXTERNAL FLOWS

Papers in this field are more or less equally divided between analytical and experimental investigations. They will be discussed in the following sequence: laminar boundary layers, turbulent boundary layers, supersonic and hypersonic boundary layers, liquid films, jets, unsteady boundary layers, and wakes.

An analysis [26C] of convective heat transfer in a laminar boundary layer along a flat plate includes the effect of heat conduction in the plate. Solutions are presented [16C] for laminar heat and mass transfer in wedge flow with suction and blowing for large Prandtl and Schmidt numbers and also for flow along a plane wall [17C] with suction through a series of slots. Errors in the influence function used for Merk's method of calculating boundary layer heat transfer are corrected [7C] and the functions have been tabulated. A series and a numerical solution include the effect of buoyancy forces within a uniform upwardly directed flow over a vertical flat plate with uniform surface heat flux [39C]. The series solution was found satisfactory for Prandtl numbers of order one. Analysis and experiments were compared [25C] for an ionized stagnation point air boundary layer with helium, argon, or hydrogen injection. The effects of wall catalyticy were found significant. The momentum integral method of Klineberg was simplified [15C] and extended to arbitrarily wall cooling. Results are compared with experiments for a flat plate and for compression and expansion corners. Forced convection from a cylinder in crossflow at moderate Reynolds numbers was found [24C] to deviate from boundary-layer analysis because of curvature effects. The following equation describes the Nusselt number for the front layer region:

$$Nu_D = 0{\cdot}3737 + 0{\cdot}37 Re^{\frac{1}{2}}.$$

Effects of curvature, displacement, free stream turbulence, and gradients in the total temperature are included in an analysis [1C] of effects of dissipation on heat transfer. Measurements of the laminar temperature boundary layer [3C] on a plate consider the influence of stream turbulence. The Nusselt number in a laminar boundary layer on a cylinder or sphere increase up to a factor 1·8 when the turbulence intensity in the outer flow reaches 26 per cent [12C]. The results of local heat-transfer measurements on plates in the transitional flow regime for fluids with Pr between 0·7 and 262 were reported [21C].

The effect of the turbulent Prandtl number on heat transfer in turbulent boundary layers of fluids with viscous Prandtl numbers between 1 and 100 was studied [33C] by numerical calculations. The Prandtl number increases with a change of the turbulent Prandtl number from 1 to 0·5 up to 40 per cent. The assumption that Reynolds stress and turbulent heat exchange are frozen along stream lines leads to good agreements between analysis and experiment for short turbulent boundary layers in severe pressure gradients [10C]. A mixing length made dependent on Richardson's number causes the prediction of momentum, heat, and mass transfer in swirling turbulent boundary layers on spinning cones, disks, and cylinders to agree well with experiments [22C]. Local turbulent Prandtl numbers throughout a turbulent boundary layer on a flat plate with a step increase in wall temperature were found to vary from 0·5 near the wall to one near the free stream in [32C] and between 0·7 near the wall and one near the free stream in [35C]. Heat and mass transfer between a rough wall and a turbulent fluid at high Reynolds and Peclet numbers were analyzed [40C] based on similarity arguments and compared with experimental data. Measurements of mass transfer on a wavy surface [38C] result in a relation which expresses a mass-transfer parameter as a power function of a Reynolds number formed with the friction velocity and the roughness parameter. Turbulent fluxes of momentum, heat, and vapor transfer were measured at the surface of the sea [11C, 28C].

A combined pressure and temperature probe for measurement in a turbulent supersonic flow was developed [27C] and compared with a Danberg probe. Van Driest's method predicts hypersonic turbulent skin friction and heat transfer within 10 per cent for a sharp cone at Reynolds numbers above 10^7, temperature ratios between 0·25 and 0·41, at a Mach number 7·9 [8C]. An analysis [31C] of heat transfer in hypersonic turbulent boundary layers indicates that turbulent density fluctuations have to be included in the governing equations.

The results of a theory [6C] of forced convective heat and mass transfer from a falling film to a laminar boundary layer of an upward flowing gas agrees well with the results of experiments. Values of the turbulent Prandtl number for liquids with viscous Prandtl numbers between 300 and 5000 were derived [20C] from experiments with vertical falling films. Heat transfer in turbulent falling films can be doubled by horizontal ridges of proper dimensions [9C]. An additive (Seperan) to make the liquid non-Newtonian decreases the heat-transfer coefficient. Heat transfer from a very hot vertical surface to a liquid film occurs in a dry region, a wet front region, a sputtering region, and a continuous film. Theory and experiments are presented [36C] for these regions.

Momentum, mass, and heat transfer in turbulent gas jets of strongly varying density at large Reynolds and small Mach numbers were studied [13C] using gases with strongly different mole masses. Heat transfer by direct contact between liquid jets and air in cross flow was found to be much less than for the situation in which the jet is enclosed in a tube of equal diameter [18C]. Experimental results are reported [29C] for a heated two-dimensional free jet discharging normally into a moving free stream. A generalized correlation of mass transfer was reported [23C] for a reattached jet at the stagnation point on a plate.

Unsteady heat transfer from a circular cylinder in a low Reynolds number flow is reported [19C] for a sudden increase in wall temperature. The temperature field and local heat transfer were calculated for a boundary layer in the vicinity of a discontinuous change in wall temperature [30C] including upstream thermal conduction. The surface renewal model was used to calculate unsteady heat transfer for turbulent boundary-layer flow with time dependent wall temperature [37C] and for mass transfer into stratified fluid layers [5C]. In the last mentioned paper, experiments are also reported in which SO_2 is absorbed in water layers. Mass transfer during laminar flow along a flat plate was analyzed [34C] for a nonlinearly viscous fluid.

The dynamics of heat transfer in the wake region of a cylinder in cross flow responded differently to the turbulence in the mean stream for two regions [4C]. One region extends from 85 to 140 deg. measured from the front stagnation point and the other region covers the remainder of the cylinder surface exposed to the wake. Experiments at Reynolds numbers between 3000 and 9000 established this behavior. The Nusselt number of a heated circular cylinder with integral heat conducting downstream splitter plate exposed to cross flow increases [14C] with proper selection of the plate length between one-third and two-thirds, whereas the drag is reduced. Mass transport around two spheres in line in flow direction was calculated [2C] for low Reynolds numbers (Stokes flow).

FLOW WITH SEPARATED REGIONS

Single bodies

Wang [42D] analyzes the boundary-layer structure over a non-spherical, non-conical blunt body at high incidence where the secondary separation on the lee side is closed. Flow reattachment occurs at about four plate thicknesses downstream of a blunt flat plate leading edge [25D] and the heat-transfer coefficient becomes a maximum at that point. Suslov [37D] develops an integral equality for the rate of fluid injection necessary to produce boundary-layer separation over a streamlined surface. The marker and cell method is used [6D] to study laminar mixing of two viscous fluids initially stratified within a rectangular cavity, the upper surface of which is suddenly set in uniform motion. The extent of separation and velocity distribution downstream of a confined two-dimensional corner was found to be relatively independent of the inlet profile selected [28D]. Inger [13D] extends supersonic, laminar, base pressure, heat transfer, and upstream influences to include small rearward-facing step heights relative to the incoming boundary-layer thickness. For hypersonic flow, the turbulent base heat-transfer distribution is not strongly influenced by forebody configuration but is sensitive to base geometry [7D].

In [32D] the separate branches of effort stemming from the Chapman–Korst component analysis and the Crocco–Lees critical point method are merged. The angles of spread of turbulent jets and wakes can be estimated as being those of the laminar flows at their critical Reynolds number [19D]. In [18D] the form of the temperature turbulence structure in a slightly-heated plane wake is investigated together with intermittency and interface structure. A Laser–Doppler velocimeter is used [2D] to measure two components of velocity in the vortex wake behind lifting hydrofoils.

Packed and fluidized beds

An investigation [29D] of mass transfer in a dispersed air/water flow through tube bundles shows the existence of an approximate analogy between heat and mass transfer processes. In contrast, Close and Bank [8D] observed coupled heat and mass transfer in a packed bed with the Lewis relation not satisfied. Reference [20D] provides much needed simultaneous measurements of porosity, velocity, and temperature profiles in cylindrical packed beds. Reference [14D] examines how a discontinuity in the temperature distribution of a coolant gas containing inert particles is attenuated. Koh and Colony [16D] analyze cooling effectiveness in a duct filled with porous material. Keshock [15D] presents measurements of porous materials, including an elastomeric heat shield, conducted in several gaseous environments including a simulated Martian atmosphere. Several papers describe thermal conductivities of porous solids [12D, 30D, 41D]. A series [33D–36D] of computational studies of forced convection in slow flow through ducts and packed beds deals extensively with cubic arrays of spheres.

Microwave heating was used to achieve a uniform solid temperature with a fluidized or fixed bed [3D, 5D] under unsteady conditions—eliminating particle-to-particle heat transfer. Reference [11D] consolidates the information available on heat transfer in packed and fluidized beds. The heat transfer is shown to depend not only on the particle Reynolds number but also on the void fraction of the bed. In [17D] a discussion is given on the fluid mechanics and structure of a fluidized bed in the vicinity of a plate submerged in it. Convective instabilities may develop in fluidized beds which can be suppressed by increasing the pressure drop across the bed support or by reducing the width of the bed [22D]. Only meager data exist in the literature for heat transfer in fluidized beds with coarse particles (larger than 2 mm) [21D]. Neale and Nader [24D] predict transport processes within porous media for creeping flow relative to a fixed swarm of spherical particles. Berg and Baskahov [4D] investigate local heat transfer between a fixed horizontal cylinder and a fluidized bed. Reference [38D] gives a rearrangement and critical analysis of the main equations of the "packet theory" in fluidized beds and rejects simplified models as unfruitful. An extensive investigation involving a non-isothermal jet flowing into a fluidized bed is given in [31D]. Wilde [45D] describes a minimum cos-design of a multimodel fluidized reactor–heater system.

An analysis of bubbles in gas fluidized beds [43D, 44D] is based on a model which represents the local bubble array by an array of geometrically similar ellipsoids of revolution. Grace and Clift study coalescence of bubble pairs in a three-dimensional fluidized bed [10D] while Mori [23D] examines heat transfer during bubble formation in gaseous fluidized beds. Finally, [1D] studies heat transfer in multistage, inclined fluidized beds.

A boiling liquid fluidized bed is recommended [39D] for processes requiring a high rate of heat transfer, together with reliability. The behavior of a boiling bed is described when a spray plume of atomized air is injected [9D]. Reference [27D] gives a mathematical description of the frequency spectrum of transport processes in nonhomogeneous boiling beds. Two other papers describe boiling bed thermal conductivities [26D] and heat-transfer coefficients [40D].

TRANSFER MECHANISMS

Detailed observations and measurement of turbulent flow continues to be of interest. A general criterion has been developed to decide experimentally when a fluid motion can be considered to be turbulent [5E], and measurements of intermittency in the outer region of a boundary layer have been made [6E]. Temperature signals from a slightly heated flow have been used to detect the interface between turbulent and nonturbulent regions [9E]. Positive spikes are found to exist in hot-wire measurements of isotropic turbulence [1E]. The turbulent boundary layer on a wall has further been investigated. Hot-film anemometer measurements of the fluctuating velocities in the viscous sublayer have been reported [4E], and visual observations of turbulent bursts have been made by the use of dye injectors and hydrogen-bubble wire in a turbulent boundary layer [12E]. An electrochemical technique has been used to measure the fluctuations of the velocity gradient near a pipe wall; the results can be used to identify regular eddies in the near-wall region [10E]. Some turbulence quantities in round jets have been measured by hot-wire anemometry [11E].

Measurements of temperature fluctuations in turbulent flow have also been reported. A resistance thermometer probe has been used to measure the temperature fluctuations in the wake of a circular cylinder [14E]. The fluctuations are also measured in the viscous sublayer on a wall by the use of micro-thermocouples [15E].

Various mathematical theories have been developed for the description of turbulence. The region near the wall in a turbulent channel flow has been subjected to asymptotic analysis by means of limit process expansion techniques [3E]. Statistical models have been proposed for the description of isotropic turbulence and the results have been compared with measurements in a strongly turbulent air flow [2E]. The transition to turbulent flow in pipes and channels has been linked to the thermodynamic instability based on Meissner's entropy principle [7E].

There have been some contributions to the phenomenological theories for the transfer of momentum and heat in a turbulent flow. A mixing length distribution for the near-wall region of a turbulent boundary layer on a porous wall has been proposed and tested for blowing and suction [17E]. The dissipation of turbulent kinetic energy at low Reynolds numbers has been examined and a formula has been devised which agrees well with experimental data [16E]. The turbulent Prandtl number calculated from measured velocity and temperature profiles in pipe flow has been shown to be approximately equal to one [8E]. An experimental investigation has been reported for the velocity and concentration fields in a rod bundle; the turbulent diffusivity was found to be close to that associated with the central region of a tube flow [13E].

NATURAL CONVECTION

Interest in natural convection continues unabated. Further experimental and analytical refinements have been made on a number of near-classical problems including external boundary layer flows and combined natural and forced convection. Significant efforts were directed towards understanding thermal convection within enclosures.

Natural convection heat transfer along vertical semi-infinite plates still draws considerable attention. Higher order effects where the boundary layer assumptions may not be valid have been considered near the leading edge of a plate [26F]. An experimental study [22F] of the transition from laminar steady motion to unsteady motion of such a natural convection flow finds the transition is not a function of Grashof or Rayleigh numbers alone but of the heat input to the boundary layer. A related study [35F] finds transitions in the velocity field before transitions are observed in the temperature field. Measurements are reported [56F] of the velocity and temperature fluctuations in a turbulent natural convection flow of mercury. A mixing length hypothesis has been used to predict the heat transfer and turbulent flow on a vertical surface [45F].

Several studies look at time dependent laminar flows on a vertical surface. An analysis of such flows produced by an oscillatory surface temperature yields results covering a wide range of frequency and amplitude of the oscillations [78F]. An analysis of the speed of the propagation of disturbances in a natural convection boundary layer have been reported [1F]. Another study [16F] analyzes the linearized buoyant motion on a suddenly heated plate. Parameter differentiation has been used [50F] to obtain results on the flow of natural convection fields.

An analysis of the natural convection heat transfer from a vertical surface to a non-Newtonian Sutterby fluid agrees with experimental measurements [18F]. Natural convection leading to a frost build-up has been studied on a flat plate [51F] and on a vertical cylinder [38F].

Combined forced and natural convection of external flows has been examined in several studies. Interferometric measurements [59F] of aiding flow on a vertical surface agree with predictions. For opposing flows, a numerical solution indicates the heat transfer on a vertical plate [76F].

The effect of curvature on the heat transfer from a vertical cylinder has been considered for fluids of different Prandtl number [17F]. Natural convection on a vertical cylinder has been studied [48F] using local non-similar solutions. Still another study on vertical cylinders considers large boundary layers on small diameter cylinders [41F]. An experimental investigation using finite length vertical cylinders indicates larger heat-transfer coefficients than on a flat plate [75F].

Three studies considered the natural convection adjacent to a vertical porous plate. The effects of transpiration as determined experimentally agree with numerical predictions for a uniform blowing rate or suction [57F]. Other analyses [68F, 69F] indicate the unsteady natural convection flow with time dependent suction.

The instability of natural convection flow on inclined plates has been studied analytically [34F, 36F]. Shadowgraph photos indicated cellular convection induced in a salinity gradient along a heated inclined wall [5F].

Laminar natural convection over bodies of different shapes have also been studied. A universal function was calculated to determine the convection over two dimensional and axi-symmetric bodies of arbitrary contour [43F]. The effects of enclosures on the heat transfer from cylinders and spheres have been examined to determine the upper and lower bounds on the applicability of the correlating equations [61F]. Measurements report on the low Rayleigh number convection from horizontal wires [25F]. Measurements on convection from wires [63F] show the effect of the presence of phase interfaces (solid–fluid and gas–liquid) on heat transfer. The local heat transfer from a horizontal cylinder to a non-Newtonian power fluid has been reported [19F].

An analysis [66F] gives the natural convection heat transfer from a vertical cone to a high Prandtl number fluid. Different second-order effects have been considered in natural convection external flows [73F]. Vibration of a horizontal cylinder yields increases of up to 200 per cent in the average Nusselt number [3F]. Earlier measurements on the effects of vibration on heat transfer have been compared to an analysis [65F].

An electrochemical technique is used [44F] to study natural convection adjacent to horizontal surfaces of different planforms. The effect of edge conditions on heat transfer from a horizontal plate facing downward has been measured [64F]. A theoretical model describes the entrainment of air by a rising thermal [67F]. A laminar plume in a thermally stratified environment has been examined experimentally and analytically [77F].

Thermal convection within a horizontal fluid layer heated from below continues to draw the interest of many researchers. The initial instability, the low Rayleigh number laminar-periodic flow, the transition to time dependent flow, and the turbulent flow in such systems all elicit wide theoretical and experimental interest.

An experimental study [42F] indicates the stability in a horizontal layer of water near the maximum density point (4°C). An experimental study at low Rayleigh number yields no higher order transitions in the heat flux curve [40F]. An analysis [13F] predicts the effects of variable coefficient of expansion on thermal convection flows. Damping of the convective currents in a horizontal layer is observed when the layer is divided by a permeable wall [46F]. The onset of convection for time dependent temperature profiles with a linear increase in heating from below [14F] and cooling from above a gas liquid interface [15F] has been observed.

A model of a conducting sheet separating two horizontal layers has been used to study convection through a two-fluid layer [24F]. Parameters determining the onset of natural convection in a stratified gas-liquid flow heated from below have been determined [30F].

The transition from a steady flow to time dependent convection in a horizontal fluid layer has been analyzed [7F]. A study of oscillatory motion in high Prandtl number fluids indicates that the Rayleigh number for the onset of the oscillations has a strong dependence on a Prandtl number [2F]. Calculations have been described which yield transitions in the heat flux curve with changes in the turbulent structure for heating from below [12F]. The influence of property variations on turbulent transitions has been measured experimentally [60F]. Oscillations observed in a wedge shaped layer of liquid heated from below are explained as due to instability of roll-cell convection [31F].

Calculations [72F] indicate little change in the Nusselt number due to visco-elastic effects in non-Newtonian fluids heated from below. A numerical simulation has been initiated [47F] to predict thermal convection in the Earth's mantle.

A two-dimensional convection analysis [58F] of heat transfer in a fluid layer with internal energy sources compares reasonably with earlier experimental results. The stability of such a layer with internal sources has also been analyzed to obtain critical Rayleigh numbers [20F].

Heat transfer during the solidification and melting of metals has been correlated well using predictions for thermal convection in horizontal layers [6F]. Convective oscillations have been observed in molten gallium in the presence of a transverse magnetic field [32F]. Convection in a shallow layer with differentially heated side walls has been studied analytically [10F], numerically [11F], and experimentally [33F].

Interest in heat transfer in inclined layers of fluid may be somewhat motivated by application to flat plate solar collectors. The maximum heat transfer across an inclined square channel occurs when the angle of inclination is about 50° [55F]. The Prandtl number effect on the initiation of convective flow in an inclined slot has been studied [39F]. The Galerkin method has been used to calculate natural convection flow in an inclined rectangular slot [4F]. Different flow regimes were predicted and observed for convection in an inclined channel [54F].

Thermal convection in porous media has been examined in a number of works. Experiments in a Hele–Shaw cell have been used [29F] as an analogue to study oscillatory convection in a porous medium. The Galerkin technique was used to study convection in a porous medium at Rayleigh numbers to ten times the critical value [70F]. Convective heat transfer in a porous layer heated from below was studied in a temperature range in which the fluid has a maximum density point [79F]. In one study, the critical Rayleigh number for convection in a porous medium was found to be larger than in the Benard problem [74F]. Another study finds the onset of flow in a porous media occurs at a Rayleigh number less than that predicted by linear theory [37F]. The characteristics of the solid phase have been included in modeling the convection in a porous layer [9F].

In a vertical channel with uniform wall heat flux, experiments show that decreasing the channel width increases the heat-transfer coefficient to a low Prandtl number fluid [8F]. Linear stability theory has been applied to natural convection flow of visco-elastic fluids in a vertical slot [23F]. A numerical analysis is used to obtain the convective flow between two vertical parallel plates at unequal temperatures [49F]. In a vertical layer of fluid, the stability of the flow induced by internal energy sources has been calculated [21F].

An analysis [28F] indicates the Rayleigh number regimes when convection can be neglected in calculating the heat transfer between concentric horizontal circular cylinders. A generalized treatment yields correlations for the heat transfer by laminar and turbulent natural convection in simple geometries [62F].

Combined natural and forced convection have been considered in several duct flows. The effect of natural convection in the entrance region of a horizontal rectangular channel has been analyzed for a large Prandtl number fluid [53F]. Mixed convection with a high Prandtl number fluid has also been analyzed for flow in a horizontal pipe [27F]. The type of instability in a thermally-stratified plane Poisseuille flow depends on the relative values of the Reynolds number and Rayleigh number [71F]. In low Reynolds number flow in a vertical annulus, the dependence of heat transfer on Reynolds number and Rayleigh number has been obtained [52F].

CONVECTION FROM ROTATING SURFACES

An analysis [3G] treats heat transfer on a rotating disk. The elasticity of a viscoelastic fluid enhances mass transport from a rotating disk to a laminar boundary layer as established by measurements [4G]. Laminar and turbulent regimes in the flow between closely spaced co-rotating disks were established by pressure distribution measurement and flow visualization [5G]. Natural laminar convection within a closed rotating cylinder with locally varying wall temperature were calculated [6G] from the full Navier–Stokes equations. Laminar heat transfer in the entrance region of a concentric annulus with rotating inner wall was studied [2G] in extension to a previous paper. A simple computation method for laminar forced convection over rotationally symmetric rotating bodies [1G] includes non-uniform surface conditions.

COMBINED HEAT AND MASS TRANSFER

Studies in combined heat and mass transfer continue with emphasis on techniques designed to protect surfaces exposed to high temperature gas streams. Interest in film cooling, particularly three dimensional, is maintained while activities related to transpiration cooling appear to be somewhat reduced.

Three-dimensional film cooling studies in subsonic flows consider the effect on downstream heat transfer of injection through a single hole or a number of holes. The heat transfer near a round hole through which air is being injected perpendicular to the free stream increases considerably with large scale blowing but this effect falls off downstream [4H]. With injection through a row of inclined circular tubes, low blowing rates have little effect on the heat transfer coefficient while at high blowing rates the jet-free stream interaction yields high turbulence and significant increases in the heat-transfer coefficient [5H]. Changing the injection hole geometry for three-dimensional film cooling from a straight circular cylinder by increasing the area near the jet exit significantly improves film cooling performance [6H]. A favorable pressure gradient appears to improve film cooling performance from a two-dimensional array of injection holes [11H]. Predictions of three-dimensional film cooling [16H] are in reasonable agreement with reported data.

An approximate analysis [8H] of two-dimensional film cooling shows the influence of variable thermal properties on film cooling effectiveness. Film cooling from an evaporating liquid, as would occur in a combustion chamber, has been examined [15H].

Several studies have dealt with film cooling of a surface exposed to a high speed gas stream. In one [9H], a Mach 6 flow with injection parallel to the exposed surface, but at two different angles to the main flow, has been studied. At approximately the same free stream Mach number, measurements indicate that the film cooling improves with adverse pressure gradient [17H]. Calculations of laminar film cooling show the effect of varying the injection angle of the entering secondary flow [13H]. Numerical studies have been reported on turbulent flows with slot injection [12H].

Measurements of the concentration of a gas transpiring through a porous wall into a turbulent boundary layer with zero pressure gradient [1H], and with severe streamwise pressure gradient [2H], compare favorably with a prediction utilizing a mixing length hypothesis. Another study uses a mixing length model with a modified van Driest damping function [14H]. Transient transpiration cooling has been studied [3H] following a step change of the surface heat-transfer rate.

An approximate treatment of viscous effects that would occur in planetary entry shows that the resulting pressure changes could significantly influence the aerodynamic properties of the entry vehicle [10H]. Ablation of carbon spheres in a flow of argon at temperatures to 3500K show that an increase in pressure often sharply reduces ablation [7H].

CHANGE OF PHASE

Boiling

Derjaguin [10J] develops a homógeneous nucleation theory by bypassing the conventional microscopic approach of Volmer and adopting a statistical one. Bubble growth on a non-wetted surface is quite different from that on a normal surface—the bubble is shaped like a bell [57J]. Reference [49J] also investigates heat transfer under conditions of strong boiling retardation where nucleation sites are not available. This condition is produced by good wetting of the heating wall, surface finish, and degassing of the system. A scanning electron microscope was used [36J] to examine pool boiling nucleating sites on 304 stainless steel in contact with distilled, degassed water. Under appropriate conditions, measurable delays in boiling initiation can be encountered which may be due to the time required to fill surface cavities [63J].

Persson [39J] obtains a simple criterion showing when the effect of radial convection on bubbles growth governed by mass transfer has to be taken into account. A second resonance is found for oscillating bubbles in superheated liquids [61J]. The increase in viscosity at higher concentrations in dilute polymer solutions, coupled to the lower strain rates may account for the retardation in growth rates of individual gas bubbles [55J]. The authors of [37J] were successful in applying a laser beam technique to the generation of a single bubble within an infinite body of liquid. Another series of bubble nucleation studies was made using fission fragments and fast neutrons [3J]. Reference [40J] suggests the coexistence, under non-isothermal conditions, of several boiling modes—resulting in mutual interference between them and in "smoothing" of the boiling curves. In dealing with the effects of heat transfer on collapsing bubbles, the value selected for the evaporation coefficient has a strong inference on collapse pressure and velocities [32J]. There is a marked similarity between water and sodium in subcooled boiling behavior [14J].

Pool boiling critical heat fluxes in slowly variable transient states can exceed steady state values by up to 25 per cent [16J]. The use of Reynolds analogy and measured pressure drop data provides a simple correlation of critical heat flux with velocities in excess of 10 ft/s and subcoolings greater than 25°C [54J]. Dhir and Lienhard [11J] include the influence of viscosity on peak pool boiling heat flux hydrodynamic processes. In film boiling under conditions of forced flow there exists three possible regimes; the core rod regime, the plug regime, and the dispersed regime. The plug regime, which is least understood, is examined in [28J]. The flow of a liquid film around a stable, dry patch on a wetted, inclined wall is examined [64J]. In this connection, [30J] studies the motion of the triple phase front to determine if a dry patch can be re-wetted, enlarged, or become stable. Two-phase, highly dispersed (post burnout) flows are characterized by a uniform (statistically) spatial distribution of droplets. "Big" and "small" droplets are spaced in a duct independently of the local vapor velocity, and there is no separation independent of vapor velocity gradient [8J]. The effect of a heat flux spike on the downstream dryout behavior is examined [22J]. The contact of two liquids, one at a temperature significantly above the boiling point of the other, may lead to explosive vapor formation and cause mechanical damage [4J]. Studies of the Leidenfrost phenomenon for mixtures [65J] show that the Leidenfrost point for a binary mixture is intermediate between the values for the pure components. A continuing problem is the validity of applying boiling data obtained with short test sections to real designs which are usually longer [60J]. Difficulties associated with starting up of boilers after short service interruptions are attributable to the unfavorable effects due to stepwise changes in inlet enthalpy [2J]. Reference [1J] studied the effects of thermophysical properties, k, c_p, ρ of the heating surface on heat transfer with boiling nitrogen from atmospheric to critical pressures. Reference [21J] correlates experimental data on pool boiling with several cryogenic liquids—agreement is not found for hydrogen and helium. A survey is available [59J] of experimental and theoretical work on boiling of cryogenic liquids in tubes, channels, and large volumes. The heat transfer to Freon-12 in a tubular heat exchanger is increased by insertion of twisted tapes up to a factor of two at the dryout point [9J]. Reference [15J] examines evaporation boiling on thin water films flowing over the outside of horizontal tubes.

Condensation

The process of condensation is not well understood in detail and the study of the mechanisms of condensation remains an underdeveloped area. In [45J] the authors are concerned with condensation of sodium chloride on clean surfaces and the effects of surface contaminants. The use of polytetrafluorethylene has widened considerably. Increased condensation heat transfer occurs when eutectic mixtures flow in coated copper tubes [42J]. Predictions using several turbulence closure models are compared [27J] with experiments of condensation from a turbulent stream onto a vertical surface. An exact solution exists [41J] for condensation on the bottom of a container where there is no motion of the liquid phase.

The macroscopic temperature and pressure jumps that occur at a condensate surface during a non-equilibrium phase change are calculated [7J] using a variational principle on the linearized Boltzmann equation. The effects of viscous dissipation on condensation heat transfer with noncondensables is to decrease the thickness of the thermal layer set up on the vapor side above the condensate [44J]. Reference [6J] gives a bibliography on film condensation with noncondensables which is of interest to designers of condensation heat exchanger equipment. Though the presence of noncondensables decreases heat transfer, an electric field may be used as a means of overcoming the poisoning effects of noncondensables [46J]. Boiling heat transfer of liquid N_2O_4 in the presence of recombining components NO and O_2 results in deterioration of heat transfer although their effect is weaker than for inert gas impurities [5J]. There have been very few investigations of direct contact heat exchange of a single vapor on a coolant in which the condensed vapor is immiscible. In a pair of papers [52J, 53J], the relative magnitude of the surface resistance, $1/h_i$, is found to be of the order of 50 per cent of the total resistance. Improved correlation [19J] of film condensation Nu based on a rigorous application of Reynolds, Prandtl and Weber number similarity, reduces the "random error" of data by 90 per cent or more. Reference [29J] attempts to analyze condensation of pure vapor in a vertical tube with constant wall temperature taking into account the effect of wave formation on the thermal resistance of the film. Nagendra [35J] studies inclination of laminar film condensates. Estimates [12J] of laminar film condensation on complicated shapes of submerged isothermal bodies can be made within a few percent of the exact value without going through tedious numerical calculations. It is commonly assumed that when condensation occurs, the heat- and mass-transfer coefficients remain constant as condensation proceeds. For dropwise condensation in cylindrical food cans, both coefficients were found to depend on the amount of condensation and the prevailing humidity [47J, 48J].

Scaling laws are derived [26J] which define the source parameters (T, p, size) of all those nozzle flows that show the same condensation effects for a given gas or mixture. Reference [67J] describes how variations in nozzle geometry affect the zone in which steam condenses in nozzles. Zener and Lavi [66J] examine a number of condensing drainage surfaces used in solar sea power plants utilizing the ocean temperature differences.

Two-phase flow

Reference [51J] dried porous solid spheres containing liquids in a fluidized bed and observed that the inner temperature dropped during drying. The inward freezing of a sphere or circular cylinder is studied [43J] that is initially molten and at the fusion temperature, when the outside surface is suddenly cooled. SINOD [31J] is a nonlinear, lumped-parameter model for steady state, transient, and stability analysis of two-phase flow in natural circulation boiling water loops. Gregory *et al.* [20J] and Soinowo and Charles [50J] comment on the prediction of liquid holdup and pressure drop for gas–liquid flow in inclined pipes. Tremblay and Andrews [58J] search for the best analytical model for two-phase (water–steam) pressure drop across a valve. For turbulent flow, a homogeneous model is superior. Modifications of free energy, entropy, internal energy, and enthalpy are deduced for droplets and vapor bubbles of uniform and non-uniform temperatures and size distributions [38J]. An energy method is used to determine linear and global stability limits for thermally-stratified, two-phase, plane flow [23J–25J]. Reference [62J] represents a first step toward the formulation of some of the fundamental mechanisms associated with two-phase evaporating flow instabilities on a statistical basis. The performance of a vapor bubble pump is investigated [34J] when a liquid coolant is injected into water at high temperature. In mist cooling [56J], drops are sprayed by any method, collide with a heated surface above the boiling point, and cool it by evaporation. Flash evaporation was found to undergo two exponential decaying processes [33J]. The effect of noncondensables on the performance of an evaporative thermosyphon is investigated [17J]. Reference [13J] gives power-law solutions for evaporation from a finned surface. Cyclic pressure freeze drying has been found [18J] to give faster drying than constant pressure processes.

RADIATION

Radiation in participating media

Several papers consider radiation transport in non-gray media; in particular in gases, particle suspensions, and flames, in liquids and in thin films. In addition, problems associated with simultaneous conduction and/or convection with radiation are of interest.

A formulation of the geometric band absorptance of a non-gray gas with arbitrary configuration is proposed. This formulation should provide the guidance needed for a systematic analysis of multi-dimensional problems of radiative transfer [6K]. The radiative heat flux in a molecular gas within a cylinder may be expressed in terms of an axial band absorptance. A closed form is obtained for the axial band absorptance for the exponential-winged band model [36K]. A perturbation technique for treating the problem of radiative transfer in homogeneous non-gray gases with nonisotropic particle scattering allows the use of non-gray narrow-band or wide-band models as well as Mie and Rayleigh scattering coefficients and asymmetry factors [7K]. Investigation of the total band absorptance of CO_2 and water vapor including the effects of overlapping shows that the absorption of triatomic molecules and their mixtures may be determined directly from the basic spectroscopic variables [21K]. A generalized method is proposed for calculating the equivalent heat-transfer coefficient for a radiating gas containing CO_2 and H_2O vapor [25K]. Total emissivities of CO_2–H_2O and CO_2–H_2O–soot mixtures arising in oil and gas combustion flames have been computed from the statistical band model and experimental spectral data for the gases and from the optical constants of soot using the Mie Theory [35K]. The distributions of temperature and species as well as the spectral intensities of infrared radiation have been studied using a premixed hydrogen flame. The predicted intensities of the $2{\cdot}7\,\mu m$ band agree well with those measured [33K].

Radiative heat transfer in solid suspension flows (laminar and turbulent) has been studied for circular tubes at constant wall temperature. The results confirm that solid suspension media exhibit superior heat-transfer characteristics at high temperature [9K]. A technique has been developed for calculating emission spectra from a stream of cooling particles which is of interest for determining radiant heating of regions adjacent to the exhaust of a rocket nozzle [31K]. Nitric oxide emissions from combustion products may be reduced by radiative flame cooling. Small amounts of soot greatly aid the radiative cooling of combustion gases which undergo microrecirculation by turbulent mixing [2K].

A numerical solution is given for the non-steady heating and vaporization of a spherical particle under the action of mono-chromatic radiation [30K]. Radiative heat transfer exerts a substantial effect on the steady evaporation of droplets of heavy liquids (fuels) at temperatures above 1000°C (34K). Strong monochromatic radiation in the optical range impinging on a solid body causes evaporation and heating of the generated vapor layer. Considering the effect of re-emission of the vapor layer, self-similar solutions of the governing equations are derived [4K]. Studies of the radiation characteristics of solid fuels (coal) indicate that for particle sizes in the range from 5 to $200\,\mu m$ which are typical for furnace heat exchange conditions, the anthracite particles and the largest brown coal particles have the smallest absorption power [5K]. Absorption coefficients have been measured for several samples of dry atmospheric dust collected in the desert of southern New Mexico. Results are found to be in good agreement with results of other investigators using different methods [22K].

Two two-parameter models, similar to the Elsasser and the statistical narrow band models used in gas radiation, are developed for predicting the total band absorption in regions of the liquid CCl_4 spectrum [27K]. The real and imaginary parts of the complex index of refraction of water at 27°C in the near i.r. have been determined from measurements of spectral reflectance at near-normal incidence and from measurements of the transmittance in absorption cells [28K]. Light scattering studies from aggregated silver and gold films in the visible and near infrared show maxima of scattered radiation in the spectral region studied, except for silver backscattering [1K]. Data of thermal radiant power reflected from a series of carefully prepared, roughened brass surfaces may be fitted to a four parameter empirical equation for a wide range of laboratory variables [23K]. An analysis of the interaction of radiation and convection for a plate in parallel flow reveals that the validity of the radiation layer model developed by Cess is restricted to weak radiation effects. For strong radiation the process of radiation heat transfer is quite different [16K]. Results of radiation-convection interaction studies for a laterally bounded flow past a hot plate are compared with several approximate solutions. The one-dimensional "radiation-layer" model is limited to weak radiation whereas for intermediate and strong radiation a distinct precursor is observed [17K]. An analysis of radiative–convective heat transfer with solid particles suspended in the gas flow shows the need for a simultaneous analysis of both radiative and convective contributions [12K].

The effect of radiation on hydromagnetic free and forced convection is studied in a vertical channel. Radiation tends to increase the rate of heat transfer to the fluid thereby reducing the effect of natural convection [14K]. Coupled radiative–conductive heat transfer has been studied in a plane layer of an absorbing and scattering medium taking selective optical properties into account as well as volumetric heat sources and a varying degree of transparency of the bounding surfaces. [3K].

The thermal remote sensing method for recovering temperature distributions in glass has been verified experimentally. The results show that the recovered and interferometrically measured temperature profiles agree within 2 per cent [13K]. Shape factors for remote gas volumes of various geometries are calculated which may be used in a simplified equation for calculating radiative energy transfer [10K].

In connection with radiative heat transfer during re-entry, minimum radiative transfer geometries are of interest. An analysis shows that an overall minimum radiative transfer geometry requires a cusped nose [11K]. A simple procedure for evaluating pressure-induced radiative transfer in hydrogen yields good agreement with more detailed calculations applied to planetary and satellite hydrogen atmospheres [15K].

The effect of thermal radiation on temperature distribution in the thermal laminar sublayer and in the turbulent core is studied experimentally. Results show considerable decrease of the temperature gradient at the wall in CO_2 in agreement with theoretical predictions [20K]. Studies of thermal radiation in laminar boundary layers on continuous moving surfaces show that the normal velocity induced in the free stream by the wall motion significantly affects the radiation heat transfer [29K]. A linear stability analysis is applied to a stably stratified, thermally radiating and absorbing shear layer [8K].

Particular solutions to the radiative transport equation are presented for an absorbing, emitting, and isotropic scattering medium with an arbitrary temperature profile [32K]. Steady, one-dimensional radiative heat transfer is analyzed considering an absorbing–emitting medium which occupies a semi-infinite space bounded by a plane wall [19K]. Radiative equilibrium temperature and surface heat flux distributions are calculated for an absorbing–emitting gray medium in an infinite plane layer bounded by gray diffuse walls with arbitrary temperature distributions [26K].

Steady radiative heat transfer is analyzed from a point heat source in a uniform flow of an optically thick, gray gas [18K]. When solving radiative heat-transfer problems involving integral equations, care must be exercised when numerical quadrature techniques are used concerning the applicability and usefulness of this technique [24K].

Surface radiation

Apparent emittance values have been calculated for various surfaces. Local and integrated values are reported [1L] for diffuse cavities in the shape of isothermal and non-isothermal cones and cylinders and the apparent hemispherical emittances [8L] for cylindrical cavities with an opening area restricted by a ring shaped disk. A paper [9L] considers a cylindrical cavity in a thick plate with a heat flux normal to the plate surface and at large distances from the cavity and answers the question how much the temperature field is changed by the radiation from the cavity. It is found that the effect of radiation is confined to a region with a depth equal two times the depth of the cavity and with a radius equal four times the cavity radius.

A numerical method [7L] considers radiation from an array of gray cylindrical fins with trapezoidal profile on a cylindrical rod and uses it to optimize the arrangement for minimum weight. Configuration factors for radiant heat exchange in cavities bounded by parallel disks and having conical center bodies were calculated [6L] to provide tools for the analysis of radiative exchange in gas turbines. It was shown [5L] that three widely used algebraic methods for the calculation of radiative exchange in an enclosure are equivalent. A method based on a new model calculates radiative heat transfer in a packed bed of microspheres [3L] in good agreement with experimental data. The dependence of the absorptance of metallic mirrors was found [4L] to have a strong effect on the mirror temperature in high power laser cavities. Very unusual results have been obtained [2L] for the heat flux by thermal radiation between closely spaced metal surfaces at cryogenic temperatures when the product of the distance l and the temperature T is less than 1 cmK. When $lT < 10^{-2}$, then the heat flux becomes inversely proportional to the fourth power of the product lT.

LIQUID METALS

An analysis [9M] studies how gas bubbles effect liquid metal heat transfer and explains previous experimental results not understood before. The distortion of the turbulent velocity and temperature profile in heated mercury flowing through a vertical pipe at *Re* from 20000 to 60000 was measured [4M]. Eddy diffusivities were found to depend strongly on the heat input. Flow and heat transfer in liquid sodium in a thermosiphon were studied [5M] in gravitational and alternating inertial force fields. Equations have been reported [3M] which describe boiling heat transfer in liquid metals for the following regions: liquid superheat, high heat transfer, boiling crisis, and transition. Inert gases play a very important role in determining the superheat in incipient boiling of alkali liquid metals [2M]. Boiling heat transfer of pure mercury is much higher on carbon steel surfaces than on 304 stainless steel [8M].

A few papers consider specifically the conditions in nuclear power stations. Calculation formulas are presented [1M] which describe heat transfer to liquid metals under such conditions. Experiments to determine sodium superheat [6M, 7M] employ LMFBR simulation parameters in a setup in which sodium flows vertically upward through an annulus with the inside wall heated.

MEASUREMENT TECHNIQUES

Developments in instrumentation continue with renewed interest in non-intrusive techniques. This usually implies optical systems in which the temperature distribution, heat transfer, or velocity distribution are determined from variations in the index refraction of a medium or a change in the wave length of scattered illumination as it passes through a test region.

Shearing interferometers permit quantitative measurements of density gradients in a flow field. From these, the temperature gradient may often be inferred. The analysis of such systems and methods for evaluating the resulting interferograms has been described [27P, 29P].

In holographic interferometry, a three-dimensional density field can be interpreted by considering different views through the test region [19P]. Under certain conditions, the three-dimensional field can be interpreted with a limited viewing angle [34P].

Temperature and concentration measurements in a flow field can be determined by Raman scattering. This highly sophisticated technique offers the promise of obtaining important remote measurements [25P]. Scattering of a laser beam by electrons has been applied to electron temperature measurements in plasma diagnostics [9P].

Spectral analysis of the radiation from a semi-transparent solid has been used to determine the temperature distribution at different depths within the solid [7P]. Remote measurements of atmospheric temperature have been made with a two-frequency radiometer at heights to 3 km [31P]. A description of random errors [18P] and systems for improving the accuracy [26P] in optical pyrometry have been presented.

A heat pipe was used to eliminate the stem correction for a partially immersed mercury-in-glass thermometer [28P]. The output of a thermocouple in magnetic fields to 100 kG has been reported from 4·2 to 100 K [6P]. The influence of one thermocouple on the output of a neighboring thermocouple is described [22P].

A small heat flux sensor used in thermal convection studies has been described [20P]. Analyses have been made of heat-transfer measurement from the transient temperature change of the skin of a model [24P] and of the sensitivity of transducers to measure heat flux from the temperature gradient in a material [8P]. Heat fluxes to 170000 kW/m^2 were measured with a calorimetric system [39P]. The transient temperature change of a sample has also been used to determine the thermal properties of a material [3P]. A self-balancing bridge to measure heat flow from a wire was used to determine the thermal properties of the material in which the wire is embedded [30P].

Mass-transfer techniques which can be applied to heat-transfer studies are also of interest. A simple system for coating spheres with benzoic acid has been described [12P]. Measurements of mass transfer by holographic interferometry have been described [16P].

Considerable interest continues in laser–Doppler anemometers (LDA) for application to a wide variety of problems with major efforts in developing further understanding of the technique. A general review paper concerning such systems has appeared [14P]. Estimates of the error in optical measurements due to spatial variation of velocity have been made [21P]. A review describes techniques for determining the sign of the velocity measured with an optical system [10P]. The relative merits of different optical geometries for velocity measurement have been studied experimentally [38P]. A method has been described that might increase the applicability of optical techniques to turbulence measurements by extrapolating out the effects of Doppler ambiguity [13P]. The light distribution at crossed coherent beams is studied for application to a LDA [5P]. Calculations indicate that atmosphere turbulence may not impose serious limitations on remote measurements using a LDA [36P]. Optical velocity measurements have been recently made in a furnace [1P]. Experiments on the applicability of a laser interferometer to measurement of particle size also reports on the importance of such size in LDA measurements [11P]. An analysis of the scattering in a LDA with a laminar flow shows the influence of particles of different sizes [15P].

A signal from crossed laser beams was used to study atmospheric turbulence [37P]. The phase fluctuations in a laser beam propagated through a turbulent atmosphere were measured in different areas over a path length of 3·5 km [4P]. A modified laser-schlieren system can measure the velocity of a shock wave [2P].

A conical hot film anemometer was calibrated for use in a recirculating water flow [33P]. A three sensor probe can measure simultaneously two velocity components and the mass fraction of helium in a helium–air flow [32P]. An analogue circuit can be used to detect the turbulent-nonturbulent interface in a shear flow [17P].

A thin sheet of light has been used to measure the distribution of drop sizes from a liquid jet [23P]. In another system for determining liquid drop size, the cooling of a thermocouple junction on which a droplet evaporates is measured [35P].

HEAT-TRANSFER APPLICATIONS

Heat exchangers and heat pipes

The discussion in this section is organized in the following sequence: recuperative heat exchangers, regenerative heat exchangers, heat pipes, cooling towers, and mixing vessels.

The performance of plate fin and herringbone heat exchangers per unit weight can be improved by perforations [13Q], whereas the ratio of heat transfer to pressure drop is not influenced. Necking of the tubes at the ends or dimples along the surface make heat exchangers more compact [17Q]. Inclining the vertical tubes of a heat exchanger was found [24Q] to increase heat transfer by 20–25 per cent. Heat transfer and pressure drop increase also by adding graphite particles of 5 μ size to the longitudinal flow around a tube bundle [29Q]. The mass-transfer analogy using naphthalene sublimation has been found useful in obtaining local heat-transfer coefficients for fin and tube heat exchangers [21Q, 22Q]. Experimental data describe heat transfer and pressure drop in transverse flow across bundles of finned tubes [27Q] at Reynolds numbers up to 10^6. Calculation methods include variable heat-transfer coefficients [18Q] and accelerate the design of condensors [19Q]. A new effectiveness parameter [2Q] for heat exchanger performance has certain advantages, and a new way to present turbulent heat-transfer data [10Q] allows rapid assessment of various heat transfer geometries. The dynamics of heat exchangers are discussed in two papers [3Q and 5Q]. Electroanalog models simplify calculations [23Q] for parallel and counter flow heat exchangers.

Analyses are presented for regenerators [6Q], for fixed bed regenerators with parallel and counter flow [4Q], and for rotary heat exchangers [8Q] with a granulate in an inclined rotating drum as well as for cross cooled dehumidifiers [20Q]. The periodic method [26Q] of testing heat exchanger surfaces is especially useful for matrix material.

A new book publication on heat pipes [31Q] is available. Papers deal with controlled heat pipes [30Q], with heat and mass transfer in wicks [1Q, 9Q], with an analysis of evaporator and condensor length [32Q], and with the use of heat pipes for cryogenic thermal control [15Q].

Analyses determine heat and mass transfer [16Q, 28Q] in cooling towers and account for the fact that droplets of various sizes have different temperatures in any horizontal cross section [7Q]. They also deal with the reduction of overall size and heat-transfer area for dry cooling towers [14Q]. Experimental data are available for the plume rise from large dry cooling towers into a stably stratified atmosphere [30Q]. A heat-transfer analysis determines heat-transfer coefficients for mixing vessels [12Q] and the effect of turbines and baffles agitating the liquid in tanks [11Q].

Aircraft and space vehicles

Papers in this section refer primarily to re-entry and rocket heat transfer, especially in connection with space shuttle.

Results of weight minimization studies of thermal protection systems for space shuttle indicate that variable angle of attack entries require less thermal protection system weight than entries at a constant angle of attack (35°) [5R]. Evaluation of aerodynamic heating uncertainties for space shuttle based on ground tests shows that the largest contribution to the uncertainty in thermal protection system weight for the orbiter occurred on lower surface areas as a result of heating and boundary-layer transition uncertainties [8R]. Space shuttle requires Reusable Surface Insulation (RSI) tiles. Studies of the aerodynamic heat transfer to RSI tile surfaces and gap intersections show that the heating to such surfaces is significantly increased in some areas as for example on tiles which protrude above the others [3R]. As a result of extensive experimental studies, a technique has been developed for predicting shock shapes, pressures, and turbulent heat-transfer rates on the leading edge of a fin, swept wing, antenna, or similar highly swept protuberance near its intersection with a high-velocity vehicle [2R]. Experimental studies of vortex-induced heating to a cone-cylinder body at Mach 6 indicate that the most severe lee-surface heating need not occur as a result of the interaction of the primary vortices with the lee surface [6R]. Vortex-induced heating studies to cone flaps also at $M = 6$ indicate that locally high heating can occur on leeside flaps at angle of attack. This heating is generally less than the maximum heating on the flap at zero angle of attack (for the same flap deflection) but can be greater than the vortex-induced heating on the configuration forebody at the same angle of attack [7R].

An extension of the boundary-layer heating relationships provides a good correlation for transpiration nosetip coolant flow requirements. For reducing coolant wastage, the correlation must account for mass transfer and angle-of-attack effects [9R]. Studies associated with advanced re-entry vehicles, both ballistic and manoeuvering, show that active transpiration cooling can provide shape stability for vehicle nosetips [13R]. High temperature properties and failure criteria for five different rocket nozzle materials have been obtained for temperatures up to 4000°F [11R]. A thermal analysis of the antenna window in AGM nosetips demonstrates that fused silica, a non-charring nosetip heat shield material, will perform adequately [10R]. A method is given for calculating the aerodynamic heating and shear stresses at the wall for tangent ogive noses that are slender enough to maintain an attached nose shock through that portion of flight during which heat transfer from the boundary layer to the wall is significant [14R].

A study of the entry and impact behavior of an isotope heat source for space nuclear power which disassembles into a number of modules entering the earth's atmosphere separating if a flight aborted, reveals thermal and structural survival under all possible re-entry conditions for speeds up to earth escape speed [12R]. Particulate i.r. radiation in aluminized solid-fuel rocket plumes plays an important role for vehicle detection. A basis for the analysis of this type of radiation is delineated [15R].

Thermoelectric devices (TED) may be applied for a direct thermal control of spacecrafts. Light-weight, thin-film TED's are currently in the research phase of development [1R]. A correlation has been developed for calculating radiative heating for Venus entry [4R].

General

Papers in this section are discussed in the following sequence: bearings, grinding processes, bio-engineering, gas turbines, selected subjects.

Thermal effects were found [4S] less pronounced in turbulent than in laminar films of thrust bearings. Temperature measurements using infrared radiation [18S] recorded values up to 360C at points of minimum film thickness in sliding point contacts. A three-dimensional analysis of squeeze films [12S] has been reported. The evolution of surface pressure and temperature measurements by transducers to study lubrication in metal rolling is described [5S].

Almost all of the energy going into chip formation, plowing, and sliding was found as heat in the workpiece [7S]. The surface temperatures of the workpiece were calculated to be around 2000°F at the cutting edge [8S]. A thermal analysis of the abrasive grains concludes [14S] that the wear is caused by thermally activated mechanisms.

The temperature field produced by a cryosurgical cannula in a gel was measured [2S] as well as heat transfer from models simulating annular appendages [19S]. Design relations for heat transfer in radiation–convection cooling of meat are reported [3S].

The effectiveness of spray cooling for gas turbines was investigated [16S]. Graphs of parameters describe the additional energy losses due to periodic fluctuations of the flow in the moving blades of gas turbines as a function of Strouhal number [20S]. Energy recovery systems from exhaust air are discussed [1S].

An electric model of thermal conditions in evaporation plants [10S] used resistors and amplifiers. Experiments studied augmentation of heat transfer in desalination facilities using boiling sea water [17S]. Transfer of heat from water surfaces to the atmosphere was calculated [11S]. The conditions in combustion chambers were modeled analytically to predict pollutant concentrations [6S]. They describe the recirculation flow pattern. Influence parameters describing turbulent dispersion of pollutants in the atmosphere were calculated [13S] based on statistic and thermodynamic considerations. The use of electromagnetic pyrometers for monitoring equipment temperatures in casting shops is discussed [15S]. A study of batch drying [9S] is based on two models.

Solar energy

The use of solar energy as an alternate energy source is attracting increasing interest reflected by an increasing number of heat-transfer studies in the solar energy field.

An ideal solar collector consisting of a trough-like reflecting wall of a specific shape concentrates radiant energy by the maximum amount allowed by phase space conservation [10T]. A simple, economical solar collector utilizing a selectively cooled tubular absorber (radiation trap) produces a thermal efficiency of approximately 90 and 73 per cent conversion efficiency for an earth based unit with moderately concentrated (~ tenfold) sunlight incident [8T]. There is a significant effect of dirt on transparent covers in flat-plate solar energy collectors. The dirt correction factor is 0·92 for a glass plate inclined by 45° [2T]. Analytical results show that there are advantages in using coated (anti-reflection) glass as solar collector covers. Such coatings increase the collected energy at normal incidence and reduce energy loss by reflection at large incidence angles [4T]. Different thermal capacitance models have been introduced for describing the transient behavior of a flat-plate solar collector. The results show that, when hourly meterological data are used, a zero-capacitance model is adequate [5T]. An application of solar energy for cooling and heating of large institutional buildings is described for the Rocky Mountain States region of the U.S. [1T].

The feasibility of large-scale orbital solar/thermal power generation is evaluated using a Brayton cycle heat engine. Economic feasibility depends on system technical performance, transportation cost, and cost of alternative power sources [7T]. A solar energy storage system utilizing salt-hydrates and their eutectics, including their containerization, have been explored. The system is presently tested in "Solar One" at the University of Delaware [9T]. By simulating forced circulation of solar-heated water using a hybrid computer the best methods can be determined for adding auxiliary energy to maximize solar energy gain [3T].

Utilizing the ocean thermal difference a preliminary design of a closed Rankine cycle power plant is proposed [6T].

PLASMA HEAT TRANSFER

Heat-transfer studies in ionized gases reported during the past year refer to fundamental investigations, as well as to applications.

A detailed comparison between theory and experiment of a steady, high-current arc in supersonic nozzle flow allows a complete quantitative assessment of all effects influencing the arc and the flow. Compared with the situation in the high-pressure section near the stagnation point [10U], the influence of radiative heat transfer decreases farther downstream and turbulence becomes the dominating heat exchange mechanism

[11U]. The conservation equations for axisymmetric arcs in axial flow are derived in integral form [4U] and the resulting relations are applied to arcs in uniform and in nozzle flow [5U]. Experiments have shown that the free recovery of an arc in a uniform flow field is influenced by both the axial convection of the thermal region and the simultaneous radial redistribution of energy within the thermal region and the arc core [14U]. Studies of local thermal equilibrium (LTE) in transient argon arcs at pressure levels between 510 and 1120 torr indicate that excitation equilibrium exists at least down to the $3P_6$ level if there is a relatively long rise time of the applied voltage pulse [2U]. A survey on induction arcs demonstrates that there is a fair agreement between experimental and theoretical data for a wide variety of induction arcs, indicating that heat balance and skin effect are the two basic processes governing the behavior of the plasma [7U].

Electrical conductivities as a function of temperature and pressure are derived from measurements of current, field strength, and radial temperature distribution in wall-stabilized arcs in argon at pressures from 1–200 atm. The results are in reasonable agreement with theory [1U]. The fraction of radiative to total heat transfer in a typical constricted laminar arc reaches values of more than 60 per cent for Kr and 75 per cent for Xe at atmospheric pressure [8U]. Thermocouple measurements of the gas temperature in the constricted positive column of a neon glow discharge reveal a systematic error which is mainly due to thermal radiation of the thermocouple [15U].

Radiative heat-transfer measurements from a plasma in tube flow show that the total radiation incident on the walls of the tube is much higher than analytically predicted. Non-equilibrium radiation effects are suspected to be the cause for this finding [13U]. The evaporation process of a superrefractory, spherical particle immersed in a thermal plasma is studied theoretically using variable plasma properties [3U]. A centrifugal plasma furnace is described rotating about a vertical axis in a power range from 30–60 kW. The furnace is being developed for fusion of refractories and glasses, and for studies of metallurgical extraction processes [12U].

In connection with MHD power generation relatively high electron densities may be produced in a relatively cool gas by means of gas-particle suspensions used as the conducting medium [9U]. An analysis of the entrance problem of convective MHD channel flow between two parallel plates subjected simultaneously to an axial temperature gradient and a pressure gradient shows that, for large Hartmann numbers, the velocity entrance length is inversely proportional to M^2. Free convection may prolong the developing process considerably [20U]. A substantial decrease in heat-transfer rates to the walls of a combustion-driven supersonic MHD power generator was observed which seems to be due to chemical non-equilibrium in the developing wall boundary layer [6U].

Studies of the radiation cooling effects on the interaction of a shock-heated plasma flow with a transverse magnetic field show that radiation cooling effects tend to reduce the strength of the interaction [16U]. It is shown that the electron temperature and other plasma parameters of shock-heated plasmas cannot be determined by means of a microwave system operating at a frequency well below the plasma frequency, because the plasma boundary layer exerts a prominent effect on the microwave measurements [18U]. The role of plasma boundary conditions on measured electron temperatures is further investigated considering microwave horns and waveguide probes as diagnostic tools [17U].

Estimates of the wall heating of metallic discharge vessels during the precollapse phase of documented linear, theta, and torodial pinch discharge indicate values of $\Delta T < 100°C$ [19U].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Thermodynamic data

Of particular interest to workers in the area of thermodynamic properties is the appearance of "thermodynamics—Data and Correlations", one of the Symposium Series of the AIChE edited by Zudkevitch and Zarember [62V] which includes fourteen contributions dealing with equilibrium thermodynamic properties. There appears to have been a substantial effort to organize existing thermodynamic and transport property data on water by Soviet workers, the results of which are useful to designers and investigators. Thus, Vasserman and Kreizerova [58V] develop an equation of state of the virial form in density utilizing some 3000 data points, accurate to 0·015 per cent over the temperature range 0 to 400C and from 0 to 10000 bar pressure. In a theoretical study, Zubarev and Krupina [61V] use the Keesom potential joined to a Lennard–Jones representation of the symmetrical part of the potential to obtain an equation of state for steam up to 2500C and 1500 bar.

The late M. P. Vukalovich and co-workers [59V] report experimental data on air and derived properties in the range 20–700 bar and temperature range 20–600C with errors in the volume less than 0·2 per cent. Altunin *et al.* [2V] study the thermodynamic properties of commercial grade gaseous carbon dioxide and determine the influence of a small amount (up to 2·0 per cent) of impurities in the gas, e.g. the heat capacity in the vicinity of the critical state is affected by as much as 65 per cent. Altunin and Spiridonov [3V] organize a system of empirical equations for calculating the thermodynamics properties of some technically important gases in the range between normal boiling temperatures and 1300K and pressures up to 100 bar.

Experimental techniques other than p-v-t measurements have been employed to obtain thermodynamic data. Kovelev and co-workers [31V] use an optical method (interferometer) to investigate the visual coefficients of carbon dioxide; Dawe and Snowden [12V] measure methane vapor behavior using the Joule–Thomson effect to obtain enthalpy-pressure characteristics in the range 224–366K and 1–100 bar with a reported accuracy of $\pm 5\,J\,mol^{-1}$.

Analytical studies include the work by MacRury and Steele [35V] who calculate second virial coefficients for water and ammonia; Edwards and Thodos [13V] correlate the saturated vapor densities for twenty-five non-polar substances using reduced variables—density, temperature, pressure, and the compressibility at the critical state with an average deriviation of 1·9 per cent. Fokin [14V] reviews the procedure for determining equation of state parameters from phase equilibrium data, treating the critical properties as parameters to be fitted rather than rigorously determined quantities. Lagutkin and Kuropatkin [34V] consider the thermal equations for the phase change liquid–vapor using the virial form of the equation of state for both phases and obtaining virial coefficients in terms of saturated liquid and vapor volumes which compare with reported values in the literature.

Corresponding states concepts are applied by Streett and Stavely [55V] to examine the conformance of the equations of state of liquid argon, krypton, and xenon to a single reduced equation of state. Velocity of sound measurements in liquid argon are reported by Streett and Costantino [54V] from 90 to 100K and pressure to 3400 atm to 0·2 per cent accuracy using an acoustic interferometer. Additional experimental investigations include the work of Popov [42V] who considers a variety of double-calorimeter methods in the comparative study of the specific heats of solids, liquids, and compressed gases; Bloembergen and Miedema [6V], who study the specific heat of some layered copper compounds; Krasnobokiy *et al.* [32V], who study experimentally the effects of mineral fillers on the thermophysical properties of epoxy resin; and Chekhovsky [10V], who determines the entropy specific heat and isobaric isothermal potential of silicon carbide from test data departing less than one per cent from average curve.

Mixture behavior attracts the interest of a number of investigators. Hellemans *et al.* [24V] examine the possible extension of the corresponding states principle proposed by Kestin and co-workers to calculate low density properties (binary collision range) of monatomic gases and their multicomponent mixtures. The extension is tested using recorded measurements of isotopic thermal diffusion factors and ternary monatomic gas mixtures. Nagata and Ohta [39V] compute vapor–liquid equilibrium data from binary and ternary vapor pressure and boiling point measurements by determining the excess Gibbs free energy.

A number of studies are concerned with the properties of mixture systems. Thus, Snyder *et al.* [52V] report four liquid phase isotherms measured for two binary and one ternary mixture comprising four straight-chain hydrocarbons, $\pm 0{\cdot}06$ per cent accurate in volume. The velocity of sound in binary mixtures of benzene, hexane, and methanol is measured over the temperature range 0–75C and a minima found by Snyder and Snyder [53V]. Griffiths [20V] uses a phenomenological model of the Landau type to describe the relationship between tricritical points in ternary and quaternary fluid mixtures. In the area of practical interest, Brodowicz and co-workers [7V] describe the prodedure used to construct an enthalpy–temperature graph for multicomponent systems exemplified by ammonia–ammonia synthesis gas–hydrogen–nitrogen–methane–argon. The matter of hydrogen solubility in water, seawater, and NcCl solutions is measured by Crozier and Yamamoto [11V] with an accuracy of 0·5 per cent.

Theoretical studies report aspects of imperfect gas behavior. Fujita [15V, 16V] used exact closed evolution equations for one-body and many-body distribution functions describing an imperfect gas. Isihara [26V, 27V] first considers the existence of the thermodynamics limit and the Van der Waal's equation of state in a direct way for a system with a hand-sphere potential and a long range attractive potential. Beegle *et al.* [5V] consider a thermodynamic stability criterion for pure substances and mixtures; Henin [25V] treats entropy, dynamics and molecular chaos using McKean's model.

Transport properties

Work in this area is noteworthy for the rather special effort which has gone into correlating and interpreting existing data on water and in extending our knowledge of water properties by measurement.

For gases, Gotoh *et al.* [18V, 19V] in a two-part study use a modified Loschmidt cell to measure the binary diffusion of twenty-four equimolar gas mixtures at one atm. pressure and from 300 to 44K with an accuracy of 1 per cent. Lennard–Jones and Stockmeyer potential parameters determined from these measurements are found to be superior to those determined from viscosity measurements. Ita and Sonntag [28V] use a two-bulb apparatus to study thermal diffusion in binary and ternary mixtures of helium, nitrogen, and neon over a temperature range 120–270K, and pressure range 3–40 atm. Three binary hydrocarbon liquid systems, *n*-octane, *n*-decane, and 17-dodecane each with carbon tetrachloride are studied for their diffusion coefficients and densities at 25°C and over a full range of composition with an average error of 0·3 per cent [60V]. Hanson [21V] uses a shock-tube to study dissociation kinetics of carbon monoxide in the temperature range 5600–12 000K, finding results to be independent of the proportions of the collision partners $M = CO$, C, and O.

Thermal conductivity articles range over a wide variety of materials, conditions, and purposes. Altunin and Sakhabetdinov [4V] analyze 1800 data points for carbon dioxide thermal conductivity obtained by 18 investigators using a variety of experimental methods. The region covered extends from 195–1373K and 1–1200 bar pressure and differences are seldom in excess of 2–5 per cent except in the zone around the critical point where the error is an order higher. Tarzimanov and Zainullin [56V] report results on the thermal conductivity of steam in the range: 425–500°C, 100–1000 bar, with error less than 3 per cent and generally in agreement with 1964 International Skeleton Table. Sirota and co-workers [51V] use a specially designed hot plate to measure thermal conductivity values for water in the critical region (200–300 bar, 350–400°C) and determine well defined maximum for the property. In a two-part study, Heemskerk *et al.* [22V, 23V] measure the thermal conductivity of gases in a magnetic field. The results show the temperature dependence of the magnetic field effect on the thermal conductivity for the gases N_2, CO, CH_4 and CO_4 between 85–300K and for HD between 40–300K; the concentration dependence effects is measured for the systems HD-noble gas and N_2-noble gas.

For liquids, the thermal conductivity for distilled water in the range: 0–300°C, 1 atm–1400 bars is measured to ± 1 per cent accuracy by Castelli and Stanley [9V] using a concentric cylinder apparatus. Theoretical studies for binary liquid mixtures use a quasi-lattice model the results of which are tested by predicting thermal conductivities for five binary mixtures and comparing with measured values [47V]. The thermal and electrical conductivity of two-phase systems are calculated using the theory of elastic moduli of composite materials and compare favorably with measurements [41V].

Thermal conductivity determinations for special systems are reported for four high temperature organic coolants of the diphenyl methane series as obtained by experiment [57V]; for epoxy-resin powder composite materials [17V]; for two-phase amorphous polymers [8V] for rocks utilizing monotonic heating of a thin-layered plate [37V] and for highly-filled rubber [48V]. Saegusa *et al.* [46V] compute thermal conductivity values for solid media with a distribution of spherical voids. Rassokhin [43V] consider the influence of iron oxide deposits on heat-transfer surfaces and the desirability of using an effective thermal conductivity to account for the processes occurring in the layer of oxide deposit. Adams [1V] usefully examines the influence of the presence of moisture on the thermal conductivity of a number of building materials (synthetic foams, concrete, wood) and proposes equations to account for the effect.

The viscosity of water was the focus of interest on the part of a number of investigators: thus, Rivkin and co-workers [45V] determine an equation for the coefficient of viscosity in the range: 0°C critical pressure 1000–1200 bar, and compare results with the First-1964 Skeleton Tables. This effort is followed by a second [44V] which reports the results of experiments (maximum random error 0·2 per cent) of water viscosity in the supercritical region: 375–500°C, 225–500 bar. Using a platinum capillary, Mamedov *et al.* [36V] examine the representation of viscosity data for liquid water by an equation analogous to the equation of state for liquid and obtains agreement within 0·2 per cent of first representation in the range 0–350C, 1–1000 bar. Partially overlapping this study is one by Kessel'man and Kamenetskii [29V] who examine available experimental data using a correlation equation whose maximum departure reaches 3 per cent but is usually with 1·5 per cent. Additional measurements of the viscosity for water substance are contributed by Kingham *et al.* [30V] who determine this property for water in the region of its maximum density (0–10°C) with a precision of $\pm 0{\cdot}014$ per cent, and Nagashima *et al.* [38V] who measure the pressure effect on steam viscosity using a capillary viscometer in the range: 250–600°C and pressure to 200 bar.

Two papers deal with rather special systems. Kuliev *et al.* [33V] study the viscosity anomalies of oils and composites of group hydrocarbons; Shpil'rain *et al.* [50V] consider binary systems of alkali metals of characteristic composition (eutectic, azeotropic) with the goal of improving the information on the properties of these substances as coolants.

Schrodt and Davis [49V] use a model developed by the latter to predict transport properties for liquid argon and obtain good agreement with measured values. Nagle [40V] obtains a series expansion for the dielectric constant for ice, relaxed to allow for faults, and discusses the need for more refined ice models.

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