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HEAT TRANSFER—A REVIEW OF 1969 LITERATURE

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INTRODUCTION

THIS review surveys research in the field of heat transfer, the results of which have been published during 1969 or late in 1968. The number of papers in this field is such that a selection only can be included in this review. A more detailed listing is contained in the Heat Transfer Bibliographies published periodically in this journal.

As in previous years, a number of conferences were devoted to heat transfer. The 1969 Heat Transfer and Fluid Mechanics Institute was held in June at the California Institute of Technology, Pasadena, California. A large part of the papers presented were concerned with heat transfer. Proceedings are available from the Stanford University Press. The Eleventh Annual Heat Transfer Conference, held on 3–6 August 1969 at Minneapolis, Minnesota, offered two invited lectures. Dr. B. Gebhart reported on "Natural Convection Flow, Instability and Transition," and Dr. L. E. Scriven on "Flow and Transfer at Fluid Interfaces." Fifteen sessions dealt with research in the fields of two-phase flow, convection, laminarization, transient heat transfer, heat pipes, change of phase, process heat transfer and reactor applications. The papers are or will be published in the *Journal of Heat Transfer* or in the journals of the American Institute of Chemical Engineers.

The Second International Seminar on Heat and Mass Transfer in Flows with Separated Regions and Measurement Techniques was organized by the International Centre for Heat and Mass Transfer at Herceg Novi, Yugoslavia from 1 through 13 September, 1969. The program included six invited lectures, fifteen lectures and a number of short presentations. The proceedings will be published by the International Centre for Heat and Mass Transfer. The Third National Congress of Chemical Engineering, Chemical Equipment, Construction and Automation (CHISA) included sessions on fundamental heat and mass transfer, on non-Newtonian flow and heat transfer, and on engineering heat- and mass-transfer problems. The Congress was held on 15–20 September 1969 at Mariánské Lázně, Czechoslovakia. The Ninetieth Winter Annual Meeting of the American Society of Mechanical Engineers, held at Los Angeles, California on 16–20 November 1969 contained in its program twelve sessions on various phases of heat transfer. In addition, panel discussions dealt with tubular heat exchangers, cryogenics in medicine and surgery, and with undergraduate experimentation and laboratory instruction. An open forum provided the possibility for short presentations of new findings in heat transfer research. Two invited lectures by F. Kreith and D. R. Willis dealt with the thermal design of high altitude balloons and instrument packages and with a new interpolation scheme for predicting heat transfer in rarefied gases. A considerable number of short summer courses has also been presented at various universities in the United States.

Several books have been published on various subjects in the field of heat transfer or related to heat transfer. They are listed at the end of this review. A new journal, *Heat Transfer, Soviet Research*, published bi-monthly by the American Society of Mechanical Engineers republishes in translation significant papers from the Soviet Union.

Developments in research on heat transfer problems during 1969 can be highlighted by the following remarks: Thermal radiation in participating media is still finding special attention. Otherwise, conduction, convection and radiation have been studied to about the same degree. In conduction the influence of contact resistance, moving boundaries caused by phase change, and numerical techniques have found special attention. Results of measurements on the turbulent Prandtl number in channel flow do not agree well among themselves nor with previously published data. Non-Newtonian flows and subliming, freezing, or melting at the channel walls have been studied and various means for augmentation or reduction of heat transfer have been investigated.

Exact and approximate solutions to laminar and turbulent boundary layer heat transfer include unsteady state, injection or suction, centrifugal forces, and non-equilibrium effects in ionized gases formed in electric arc discharges. Experimental studies on boundary layers were carried out in the Mach number range from 5 to 10. Shedding frequencies and turbulent transport properties found special attention in free shear layers and separated flows.

The stability and transition to turbulence were investigated analytically and experimentally for natural convection in horizontal fluid layers and in boundary layers on a vertical surface. Research in boiling concentrated on bubble dynamics and on the effect of a micro layer between the bubble and the heating surface. A number of papers treated boiling in liquid metals. Condensation coefficients in water and mercury were found to be close to unity. Stability regimes of slip flow and the transition and free molecular regimes for Couette flow have been studied.

An increasing level of sophistication characterizes the models used to describe heat transfer by radiation in participating media. Spectrally resolved radiation properties replace gray gas approximations, and various geometries and boundary conditions are included. The radiative energy transfer in the stagnation region and radiating shock layers have found special attention.

Interaction of various modes of heat transfer found attention for combined conduction and radiation, for combined free and forced convection, and for combined heat and mass transfer. A considerable number of applications was covered including the ablating heat shield, transpiration, film and radiative cooling, and heat exchangers for non-Newtonian fluids.

To facilitate the use of this review, a listing of the subject heading 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 that category.

Conduction, A
Channel flow, B
Boundary-layer flow, 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, K
Liquid metals, L
Low-density heat transfer, M
Measurement techniques, P
Heat exchangers, Q
Aircraft and space vehicles, R
General applications, S
Thermodynamic and transport properties, T

CONDUCTION

The thermal contact resistance at the interface of contiguous solids is a matter of considerable practical importance. A reconsideration of the interaction between randomly rough surfaces shows that the contact resistance in vacuum depends more critically on the distribution of the few peaks of the surfaces than had been previously realized [9A]. The contact resistance between two aluminum surfaces was increased by factors of 2–1000 by use of various low-conductance interstitial materials [11A]. The constriction alleviation factor, which accounts for interference between the temperature fields associated with discrete points of contact, has been accurately evaluated [18A]. Electrolyte analogue experiments verified a general expression for the overall constriction resistance between contacting rough wavy surfaces [46A]. Low-density effects were accounted for in evaluating the gas layer contribution to the contact resistance at a microgap [34A]. Transient temperature measurements within a thermally thick or thin body may be employed in determining the contact resistance as a function of time [3A].

Several papers were concerned with heat conduction problems involving thermal radiation. Series solutions, appropriate to the limits of weak conduction and strong conduction, were utilized in solving for the temperature distribution in a radiating spherical shell subject to incident solar radiation [40A]. Among several approximate methods employed in treating two-dimensional steady conduction with radiation boundary conditions, a least-squares technique was found to be the best [38A]. A numerical iterative procedure proved to be effective for the steady-state solution of conduction in a rod having temperature dependent thermal conductivity and radiant heat exchange at its surface [8A]. Biot's variational method was applied to one-dimensional transient conduction problems with radiation boundary conditions [47A]. Conditions for the existence of periodic solutions for the semi-infinite slab with non-linear boundary conditions have been examined [23A].

Conduction problems involving phase change are made complicated because of the motion of the phase boundaries. The treatment of problems involving phase changes which occur over a range of temperatures require simultaneous consideration of solid, two-phase and liquid regions [5A]. Axial conduction effects may occur in radially propagating phase changes in the annular space between two concentric cylinders, but such effects may be accounted by synthesizing results from solutions in which axial temperature variations are absent [41A]. Analysis and experiments on ice formation in the presence of a sinusoidal surface temperature indicated that the steady periodic regime is rapidly achieved [27A]. The solidification of a liquid flowing in a duct was modeled as a one-dimensional process in which there is a known convective heat flux from the liquid to the growing layer of solid and a heat loss from the outside of the duct wall to the environment [43A]. An analytical iteration scheme was outlined for solving the frozen layer formation on a cooled wall when the adjacent liquid is in convective motion [37A]. The heat balance integral was employed to predict the thickness–time relation for the fluidized bed coating process, wherein a hot object is immersed in a fluidized bed containing the coating material in powdered form [14A].

In practice, heat conduction problems are frequently solved by finite-difference and other numerical procedures. An explicit technique, suitable for transient problems and stable for all time increments, is claimed to be faster and more accurate than the Crank–Nicolson method [26A]. Computational experiments were reported to illustrate the relative accuracies of the Crank–Nicolson and implicit methods [45A]. Representations of the boundary conditions in transient problems were examined in [6A] and [22A]. Analogue computer circuits appropriate to a variety of boundary conditions were described and accuracy estimates of analogue computer solutions made [21A]. Statistical estimation and correction techniques were applied to improve the accuracy of digital thermal network models [4A].

Fins (extended surfaces) are found in a variety of heat exchange equipment. Measurements of the local heat transfer coefficient for a longitudinal fin revealed a minimum at the root and a non-monotonic increase along the height

[42A]. The conventional fictitious extension of an adiabatic-tipped fin to take account of actual tip heat losses was placed on a more rational and exact basis [28A]. An exact solution for the efficiency of a circular fin of triangular profile was derived and the results compared with approximate information in the literature [39A]. The temperature response of thin fins subjected to stochastic root temperature variations was treated according to the theory of random processes [17A]. A rigorous mathematical examination of the optimum shape of a cooling fin attached to a convex cylinder showed that the temperature gradient should be a constant [10A].

A number of papers dealing with heat sources have appeared. Two of these are motivated by nuclear reactor applications. In [16A], a solution for the temperature field in the heat generating fuel and in the clad was achieved by satisfying continuity of temperature and heat flux at the interface, while [1A] was concerned with a cylindrical fuel rod having a temperature-dependent thermal conductivity. The heat generated by the cutting process in which a tool removes material from a work piece in a lathe was modeled as a circumferential ring source of heat [44A]. The transient temperature field associated with a point heat source on the periphery of a disk was solved and then used as input to determine the associated thermal stresses [19A]. In the presence of a distributed heat source which depends non-linearly on temperature, there may be either no solutions, one solution, or multiple solutions for the steady one-dimensional temperature distribution [33A].

There has been speculation as to whether the thermal conductivity may depend on the temperature gradient, but experiments performed to examine this question were not definitive [12A]. The incorporation of a timewise second derivative into the transient heat conduction equation gives rise to a finite velocity of propagation of the wave that follows a step change in surface temperature [2A]. The initial stage of a transient heat conduction problem is sometimes treated, in first approximation, as one dimensional in a thin layer adjacent to the surface. This approach has been generalized by a method which accounts for possible curvature of the surface [25A]. An analysis of the influence of container heat capacitance on thermal transients in slabs, cylinders, and spheres indicates that the container can be neglected if its capacitance is less than 10 per cent of that of the enclosed contents [32A].

The variables affecting the dynamic response of a thermocouple attached to a thin-skinned model have been identified by means of a transient conduction solution for the skin and the thermocouple wire [24A]. A technique for measuring the response time of a thermocouple employs infra-red radiation as a heat source [30A]. A new method for simultaneous measurement of thermal conductivity, diffusivity, and specific heat is based on the one-dimensional transient solution for a plane heat source situated in an infinite solid [20A]. The transient solution of a two-layered system was motivated by measurements of the thermal diffusivity of insulating materials, in which it is necessary to account for the heat capacity of the heater [15A]. An electric conductive-sheet analogue was developed and applied to the determination of heat losses and temperature distributions for pipes embedded in a layer of insulating material in the ground [13A]. A study of the steady-state temperature fields in a quarter-infinite region and in a semi-infinite solid bounded internally by a circular cylinder was motivated by the design of an underground storage reservoir [29A].

In some papers, mathematical solutions were worked out, but without numerical results. These include: The sphere, for which the surface heat flux and internal heat generation are arbitrary functions of time and space and the initial temperature is arbitrarily distributed [35A]; the rectangular parallelepiped under the influence of an arbitrary volume heat source, an arbitrary initial temperature distribution and convective boundary conditions [36A]; the thin plate, losing heat by convection on all its faces, with an arbitrary time and space dependent volume heat source [7A]; the time-dependent temperature and humidity distributions in a one-dimensional body subjected to general boundary conditions [31A].

CHANNEL FLOW

A number of investigations of turbulent duct flow has been concerned with basic features of the transport process. Measurements performed for air flowing in an electrically heated tube indicated that the turbulent Prandtl number is less than unity [27B]. In contrast, mass transfer experiments using a point source technique gave values for the turbulent Schmidt number which fell either above or below unity depending upon whether the molecular Schmidt number was below or above unity [25B]. Concentration field measurements of nitrous oxide gas injected into air flowing in a tube were in good agreement with predictions based on Jenkins' model for the ratio of the eddy diffusivities for mass and momentum [50B]. Experimental results for non-axisymmetric turbulent mass transfer in a tube suggest equality of the radial and circumferential eddy diffusivities [51B]. On the basis of an examination of pipe flow heat transfer data and analytical predictions in the low Reynolds number turbulent regime, it was concluded that the turbulent Prandtl number is dependent on Reynolds number [32B]. Low frequency fluctuations associated with eddy motion near the pipe wall were accounted in a model which predicts the Sherwood (or Nusselt) number up to a Schmidt (or Prandtl) number of 10^5 [26B]. A boundary layer growth-breakdown model has been applied to predict turbulent heat transfer in the fully developed and entrance regions of ducts [46B].

A new turbulent heat transfer correlation, intended to supplant the standard Dittus–Boelter relation, uses an exponent of 0·795 for the Reynolds number and an exponent for the Prandtl number which depends on the magnitude of the Prandtl number [18B]. Variable viscosity effects in turbulent liquid pipe flow were accounted by multiplying the constant property correlation by a factor $(\nu_b/\nu_w)^{0\cdot18}$, where ν_b and ν_w are, respectively, the bulk and wall values of the kinematic viscosity [60B]. Predictions for low Reynolds number turbulent heat transfer, based on Reynolds number dependent velocity and eddy diffusivity distributions, were confirmed by experiments involving helium and air [53B]. The dependence of the velocity profile on the Reynolds number was accounted in computations of turbulent heat transfer in concentric annuli [52B].

As a result of the curving of the streamlines in a contraction section downstream of a tube, an adverse pressure gradient was found to exist, such that the heat transfer distribution on the curved wall section resembled that for a separated flow regime [4B]. Measurements are reported for turbulent mass transfer from the inner bounding wall of an annular duct for a Schmidt number of 0·76 and for the range of radius ratios from 0·16 to 0·74 [11B]. High heat transfer coefficients, both for turbulent and laminar flow, were measured when an isolated heated element was situated near the beginning of the hydrodynamic development region of an annular duct [14B]. The use of superposition integrals for extending solutions for uniform wall temperature and for uniform wall heat flux to more general thermal boundary conditions is respectively examined in [43B] and [3B], with the findings being applicable both to turbulent and to laminar flow.

Studies of laminar heat transfer are usually analytical in nature. Results for thermally developed conditions have been derived for a variety of duct shapes, among which are regular polygons [13B, 28B], cross sections bounded by inscribable non-circular curves [49B], large aspect ratio cross sections [38B], and longitudinal flow in a rod bundle [58B].

A number of contributions has also been made to the literature on the laminar thermal entrance region. A finite-difference solution confirmed that transverse convection plays an important role in the early stages of thermal development when the temperature and velocity fields develop simultaneously [39B]. The Leveque solution, which is appropriate to the immediate neighborhood of the tube inlet, has been extended to greater downstream distances by means of a series expansion [45B]. Strengths and limitations are delineated for solutions for laminar velocity and temperature development which are based on simplified forms of the inertia and convection terms [73B]. Information on the thermal entrance region for ducts of various cross sections has been brought together and presented in terms of new nondimensional groups [2B]. As an alternative to a previously used generalized Graetz formulation, an integral method was employed to treat laminar counterflow heat transfer between adjacent parallel-plate channels [69B]. An analysis of the thermal development in a heat generating fluid in a parallel-plate channel took account of axial conduction, but omitted consideration of the attendant non-uniformity of the temperature profile at the start of heating [44B]. Four different boundary conditions involving prescribed temperature and zero heat transfer are treated in a study of the thermal development of a Couette flow [56B]. An available analytical solution for the Nusselt number corresponding to inviscid flow in a cone was generalized to accommodate arbitrary vertex angles [37B].

For a power-law non-Newtonian flow with temperature-dependent thermophysical properties, a finite-difference solution showed that under some conditions, the temperature profile may have a local maximum at a cross sectional location off the centerline [23B]. A finite-difference approach was also employed to find the wall shear in a non-Newtonian tube flow characterized by a temperature-dependent form of the Ostwald–deWaele power-law model [15B]. In the presence of viscous dissipation associated with a non-linear temperature dependence of the non-Newtonian viscosity, steady state solutions of the energy equation cannot be found for certain values of the governing parameters [71B]. This situation occurs because the viscous heating cannot be carried away rapidly enough. In experiments on laminar non-Newtonian flow in a flattened circular tube, the higher-than-expected Nusselt numbers were ascribed to a secondary flow resulting from the non-circular cross section [47B]. An effect of couple stresses on laminar flow in a parallel-plate channel is to introduce additional dissipation in the energy equation to augment the usual dissipation [66B].

Solutions involving mass transfer are generally relevant to corresponding heat transfer problems. The mass transfer analogy was employed to study the transverse heat transfer between channels in a longitudinal rod bundle, the results of the investigation suggesting the presence of a secondary flow [62B]. An analysis for the concentration field in an electrolytic flow reactor with a moving wall applies, with a change of notation, to the thermal entrance region of a channel having one wall at uniform temperature and the other wall at uniform heat flux [21B]. A detailed analysis for the laminar concentration field in a tube in the presence of a first-order chemical reaction (analogous to an internal heat source proportional to temperature) illuminates conditions for which the one-dimensional Taylor–Aris model is valid [74B]. Stable operating conditions encountered in a reacting CO, O_2 flow in an annulus were consistent with the stability diagram for the reaction [30B]. Companion studies of mass transfer in pulsating laminar flow in rigid [19B] and in distensible [20B] tubes showed that higher transfer rates occur in the latter. A finite-difference analysis revealed that when a light gas is injected into a heavier gas flowing in a tube, the concentration profile is considerably more uniform than when a heavy gas is injected into a light gas [35B]. An axial dispersion model, which employs cross-sectionally averaged velocities and concentrations, was formulated for the transfer of heat and mass between adjacent streams in a concentric tube system [24B].

Problems involving change of phase at the duct walls have been solved. An analysis involving simultaneous heat transfer and sublimation mass transfer at the wall of a parallel-plate channel showed that, in some cases, the local Nusselt number was lower than the corresponding fully developed value [65B]. When sublimation occurs at only one wall, the axial development of the temperature and mass fraction fields is slower than when both walls are participating [12B]. In a channel wherein there is liquid flow and a solidified layer on the walls, the thickness of the layer grows in the streamwise direction, causing a change in the flow cross section and giving rise to an acceleration [34B]. Integral transforms were employed to solve the coupled transient temperature fields in a laminar tube flow and in a freezing layer that builds up along the inner surface of the tube [48B].

Strong interest in techniques to augment heat transfer continues. On the basis of equal pumping power, swirl induced by twisted tapes in tubular test sections can result in increases in the heat transfer coefficient for water of approximately 20 per cent compared with that for straight flow [36B]. The heat transfer augmentations due to tape-induced swirl and surface roughness have been found to be approximately additive [5B]. Experiments involving airflow in annuli with roughened inner tubes revealed a maximum increase in Stanton number when the pitch of the roughness was 7–12 times the height [22B]. For a ribbed rectangular channel [8B] and an annular channel with surface roughness [9B], empirical correlations are presented from which heat transfer coefficients can be calculated using input information on pressure drop. The relative increase of the pressure drop exceeded the relative increase of the heat transfer coefficient in tests involving water flow in tubes with V-shaped rectangular grooves [54B] and nitrogen flow in tubes with twisted tape turbulence promoters [29B].

In studies of a circular tube rotating about its own axis, it was found that the rotation had no effect on the turbulent heat transfer and a modest effect on laminar heat transfer, but significantly delayed the transition from laminar to turbulent flow [10B]. Experiments for water flow in coiled tubes showed that the heat transfer coefficient and friction factor increase during heating and decrease during cooling when the tube-to-coil diameter ratio is increased [42B]. The reduction in drag which is associated with the presence of polymers in a turbulent liquid flow is accompanied by a reduction in heat transfer [64B, 72B]; on the other hand, for a laminar flow, the heat transfer is unaffected [64B]. In an analysis of turbulent heat transfer in a tube containing a flowing gas and a suspension of fine particles, a heat transfer coefficient was assigned to characterize the interphase heat transfer [6B]. The diffusion of decaying products from the disintegration of an inert gas in a laminar tube flow is governed by a differential equation and boundary conditions identical to those for the developing temperature field in an internally heat generating flow in an isothermal tube [67B].

High temperature duct flows are treated in a number of papers. Very large cross-sectional fluid property variations were obtained by passing arc-heated argon through a water cooled tube. Measured enthalpy and velocity profiles and longitudinal heat flux variations agreed satisfactorily with variable property laminar theory [40B]. A finite-difference method of solution was used to provide friction factors and Nusselt numbers for the flow of argon plasma through the heating region of a constricted arc plasma generator [7B]. Experiments on combustion-heated airflow in a short, highly cooled circular tube were performed under conditions of both natural and artificial boundary layer transition [1B]. Wall temperatures up to 2275°K were achieved in tests on hydrogen flowing through electrically heated passages. The results were successfully correlated by modified Dittus–Boelter equations [63B]. A ternary model for diffusion was employed in studies of a partially ionized diatomic gas in

Couette flow [41B]; the ionization causes an increase in the heat transfer rate.

The accounting of gas radiation in an optically thin gas flowing turbulently in a tube leads to a higher fully developed Nusselt number than when the gas is non-participating [31B]. Radiative exchange between wall elements of a circular tube in the presence of a non-participating laminar gas flow and uniform wall heat flux appears to preclude the establishment of a fully developed value for the Nusselt number [70b].

At slightly supercritical pressure and in the neighborhood of the pseudo-critical temperature, it is demonstrated that a marked deterioration of the heat transfer coefficient can occur [57B]. Analytical results for para-hydrogen in Couette flow near the critical point show that the effect of the fluid property variations is to decrease the heat transfer [61B]. In turbulent tube flow experiments with CO_2 in the vicinity of the critical point, forced convection was the dominant mechanism, but free convection effects were in evidence even for *Re* of the order 10^5 [55B]. Measurements of heat transfer to superfluid helium flowing in tubes of relatively larger diameter were consistent with earlier data from tubes of smaller diameter [16B].

The usually neglected Hall current was shown to have a significant effect on laminar magnetohydrodynamic (MHD) heat transfer in a parallel-plate channel [17B]. In a low Péclét number MHD channel flow, the developing temperature field is substantially affected by axial heat conduction [33B]. Suction decreases the Nusselt number for the uniform heat flux boundary condition in laminar MHD channel flow [59B]. Analysis has shown that the presence of a transverse magnetic field in MHD plane Couette flow cannot decrease the rate of heat transfer [68B].

BOUNDARY-LAYER FLOW

Boundary-layer theory and solutions

A rigorous mathematical proof [19C] was presented, showing that the velocity profiles for similar solutions of a compressible laminar boundary layer exhibit an overshoot over the free stream velocity for a favorable pressure gradient and a heated wall. This holds for suction, blowing, and slipping at the wall. A boundary layer analysis [11C] includes the effect of centrifugal forces for the case that the boundary layer thickness cannot be considered as small compared to the radius of curvature. Logarithmic coordinates simplify the laminar equations and facilitate obtaining similarity solutions. It is demonstrated that the influence of wall curvature is identical with the influence of suction or blowing. Wall shear and wall heat flux as influenced by mass transfer and by a transverse curvature are analyzed for laminar axisymmetric boundary layer flow [8C]. Lee's theory is used [29C] to investigate the effect of tip blunting on hypersonic laminar cone heat transfer. The Kármán–Pohlhausen method is used [24C] to calculate forced convection flow over a flat plate with a viscosity and conductivity varying like

$$\frac{\mu}{\mu_0} = \frac{1}{1 + \alpha\theta}, \qquad \frac{k}{k_0} = 1 + \beta\theta$$

(θ temperature excess over reference condition 0). The parameter, $Nu/Re^{\frac{1}{2}}$, is found to increase with β and α, if property values in the Nusselt and Reynolds numbers are based on stream values.

The following group of papers considers unsteady laminar boundary layers: A small time solution [31C] describes velocity and temperature profiles as well as wall shear and wall heat flux for an insulated and an isothermal compressible boundary layer on a flat plate. Solutions [25C] to the boundary layer equations for wedge flow and for a step jump in wall temperature or in wall flux consider fluids with vanishing Prandtl number. Liepmann's method is applied to two-dimensional stagnation point flow and a step function in wall temperature [13C]. Numerical calculations show that in experiments, usually quasi-steady state is established. The effect of external vorticity on stagnation point heat transfer has been attributed to a stretching of vortex filaments. An examination [26C] for a fluid with high Prandtl number concludes that the effect on heat transfer increases with increasing Prandtl number.

The mixing length concept is applied in the wall layer and the defect law in the outer layer to calculate the temperature field in a turbulent boundary layer with uniform injection and with heat transfer beginning at a downstream station [14C]. The Reynolds analogy factor is shown to depend on a pressure gradient parameter and a velocity profile parameter [28C]. An adverse pressure gradient causes the factor to increase and a favorable pressure gradient to decrease. The analysis [17C] of turbulent boundary layer flow between converging plates demonstrates that the thermal boundary layer penetrates beyond the velocity boundary layer causing the Stanton number to decrease and creating an effect similar to laminarization. Spalding's function and the law of superposition has been used [15C] to calculate turbulent heat transfer from a surface having stepwise discontinuities of the wall temperature. Experimental results verify the method.

Dissociation, ionization and chemical reactions

A computer analysis [30C] for the stagnation point boundary layer with suction and injection includes the Cohen–Reshotko and the Fay–Riddell solutions. It indicates that injection of equilibrium dissociating air increases the heat transfer rate. An analysis [10C] for boundary layers in dissociated chemically frozen air on flat plates and slender cones suggests possible serious errors in the conventional evaluation of catalytic gages. Calculations [16C] of hypersonic dissociated laminar boundary layers by means of integral equations result in good agreement with exact solutions for flat plate and stagnation flow. An investigation [23C] clarifies how non-equilibrium affects heat transfer in stagnation point flow of arc heated helium and argon. A calculation [3C] of the electron number density distribution in laminar air boundary layers on cones and wedges indicates that the peak number density increases by an order of magnitude when the wall changes from catalytic to non-catalytic condition. Direct and indirect measurements [C4] in a co-axial arc configuration at a pressure range from 1 to 40 mm mercury determine the anode fall of a high intensity argon arc to be approximately 1·55 V.

Experimental studies

Transition to turbulence on a slender cone for flow at 9·6 Mach number and 0·214 temperature ratio exhibits large circumferential variation of the heat flux density in the transition and turbulent boundary layer coupled with variations in time with a magnitude up to 100 per cent [21C]. Careful experiments [5C] for a turbulent air boundary layer approaching constant property conditions at $Re = 250000$ and $Pr = 7{\cdot}5$ result in a universal temperature profile of the form $\theta^+ = 4{\cdot}85 \log y^+ + 47$. Experiments [22C] on a cone-cylinder-flare model at Mach numbers between 5 and 7 indicate an increase of the separated region with Reynolds number in good agreement with an analysis by Childs. Velocity fluctuations with 0·1–200 Hz and 8–92 per cent amplitude generated by a shutter valve increase heat transfer in a turbulent boundary layer on a flat plate by 3–5 per cent [20C]. Sinusoidal vibrations of a sphere in a vertical direction have no effect on heat transfer for vibrational Reynolds numbers smaller than 200 and increase the heat transfer coefficient up to seven times for larger Reynolds numbers [2C]. The vibrations have no effect on forced convection for flow in horizontal direction as long as the vibrational velocity is less than 19·6 per cent of flow velocity. Local heat transfer from a cylindrical jet to a tube located at the axis is influenced by the transverse curvature effect [18C]. The measurements resulted in Stanton numbers up to 1·7 times the Stanton numbers for a plane wall jet. An array of two-dimensional jets ejecting a fluid in normal direction towards a flat plate results in heat transfer coefficients described by the following equation [12C].

$$Nu = 0{\cdot}139 \frac{(B/l)^{0{\cdot}36}}{(H/B)^{0{\cdot}16}} Re^{0{\cdot}755}$$

with B denoting the slot width, l the slot distance and H the distance between the slots and the heat-transfer surface. Nusselt and Reynolds numbers are based on the slot width and the Reynolds number on the jet exit velocity.

Magnetofluid dynamics

A solution of the velocity field for laminar flow through MHD channels including the Hall effect has been supplemented by a calculation of the fully developed temperature profile [9C]. The Nusselt number is presented as a function of the Hall parameter in the form of a diagram. Combined natural and forced convection in hydromagnetic flow through vertical channels, with a crossed magnetic field and internal heat sources, has been analyzed [6C]. Transient heat transfer in MHD plane Couette flow with a crossed magnetic field is not affected on one wall and is increased on the other wall by an increasing magnetic field [27C]. An analysis [1C] of compressible turbulent magnetohydrodynamic boundary layer flow closes the conservation equations by the introduction of "universal turbulence parameters". Measurements [7C] of the electron temperature and number density in a shock tunnel for air at 6850°K and 22 atm and for argon at 8000°K and 9 atm result in values significantly higher than calculated ones.

FLOW WITH SEPARATED REGIONS

Single bodies

Hamielec and Raal [17D] present numerical solutions of viscous flow around circular cylinders at Reynolds numbers of 1, 2, 4, 10, 15, 30, 50, 100 and 500. Sarpkaya [38D] proposes a simplified model for the creation and growth of vortices behind bluff bodies which includes the interaction between the vortex feeding zone and the near-wake. Low-speed, near-wakes cannot be represented by a time-independent mean flow with oscillations imposed upon it—in contrast with wakes at remote distances from a body [19D]. Recent investigations have been devoted to the effects of vibration on convective heat transfer, a process known as thermal acoustical streaming [11D]. Decreases in drag coefficient and increases in Nusselt number can be obtained when surface vortex generators are fitted to a cylinder in cross flow [25D].

Steps and cavities are often present on re-entry vehicle surfaces due to fabrication tolerances, sensor installations, and differential expansion or ablation rates between non-similar materials. A simple relation [33D] developed from $h \propto p^{0{\cdot}8}$ agrees well with experiment and should be adequate for engineering predictions. The thermal performance of a recompression step appears to be governed only by the shape of the step and the flow that is formed within one cavity depth from the step [10D]. Regarding wake recirculating flows generated by supersonic flows over rearward facing steps, the constant vorticity assumption is not suitable for the primary core flow [39D]—some curvature is necessary at the interface between the cores. For supersonic near-wake flows, centerline recovery of concentration, temperature, and velocity are proportional to $(X/D)^{-2}$ for turbulent flows and $(X/D)^{-1}$ for laminar flows [48D]. Richardson [37D] concludes that a major contribution to heat transfer in a region of separated flow behind a bluff body cannot be atrributed to the oscillations at the shedding frequency by themselves, or to the secondary streaming motion driven by them. Maximum centerline pressures in the far wake behind four wedge models at $M_\infty = 6$ were generally 10 per cent higher than the freestream pressure [1D]. Lamb and Bass summarize turbulent free shear layer data in which the spreading factor σ deviates by 15–50 per cent [27D].

Cook and Singer [8D] present data on free jets using helium, argon and methane discharging at low velocities into air. Analytical–experimental agreement was obtained by using the Ferri expression for turbulent viscosity and an entrainment coefficient twice the Prandtl value. Ghia *et al.* [14D] study confined laminar mixing of a slow-moving, heavy-gas, central jet and a co-flowing, fast-moving, light-gas, annular stream with a view of understanding a gas-core nuclear reactor where minimum mixing is desired. Heat transfer between a submerged jet of water and a flat surface held normal to the flow was studied for plate to nozzle diameter ratios of 8–58 [41D].

Packed and fluidized beds

Borges [2D] presents vortex shedding frequencies for the flow through two row banks of tubes. Displacement of a rod in an unbaffled rod bundle from its symmetrical position can result in large reductions in both its own average heat transfer coefficient and those toward which it is displaced [21D]. Staggered tube banks with small tubes are most advantageous [46D]. A method is described for fabricating a very compact (up to 300 m^2/m^3 transfer surface) counter-flow heat exchanger [45D]. Significant differences were found between isothermal and strongly nonisothermal velocity profiles and thermal conductivities in packed beds [40D]. Handley and Heggs [18D] examine transient heat transfer in packed beds when (1) intraparticle conduction dominates, and (2) axial conduction in the solid is important. In [7D] a general equation for predicting the thermal conductivity of packed and powder beds is developed in terms of the thermal conductivity of the particles and the gas in the pores, discontinuous phase volume ratio, contact resistance, size of particles, radiative transfer in the gaseous pores, pore size, and surface properties of the particle. Heggs [20D] and Jefferson [24D] discuss transient heat transfer in packed beds while [22D] deals with two-phase co-current downflow in packed beds.

In [35D] Petrovic and Thodos give extensive compilation of data for mass transfer of gases through packed beds in the low Reynolds number (1–300) region. In [36D] the same authors generalize the effectiveness factor ξ, the ratio of rate of heat transfer for a fluidized bed to that for a packed bed, to be $\xi = 1{\cdot}063\,\alpha^{-0{\cdot}314}$ where α is the ratio of fluidized void fraction to packed void fraction. In [29D] general two-phase theory is applied to the case of a liquid and a granular solid flowing together up a vertical tube. The question is whether the solids flow in a particulate fluidized state or as a packed bed. Following the results reported by Toor and Marchello for mass transfer, [47D] proposes a mechanism of heat transfer in a bubbling fluidized bed which includes steady conduction across the wall layer and intermittent renewal of bed elements. For freely bubbling fluidized beds the rise velocity of a swarm of bubbles is greater than that for a bubble in isolation [15D, 34D]. Bukareva *et al.* investigate a vibrofluidized bed [4D]. Stelczer [44D] deals with abrasion of bed load materials and presents verified relations for the reduction in diameter in terms of the original diameter, bed load transport rate, and times of movement and rest of the particles. Other summaries include heat transfer between a fluidized bed and staggered bundles of horizontal tubes [13D], various geometrical forms [12D], non-uniform cross-sectional bed area [31D], or internal fin baffles [5D]. References [6D, 9D, 16D, 30D, 43D] deal with thermal aspects of flow through porous media. Finally, references [3D, 26D, 28D, 32D, 42D] deal with mechanical mixing problems in agitated tanks and kettles, multistage mixer columns and various modes of agitation.

TRANSFER MECHANISMS

An analogy exists between the total enthalpy and the shear stress in laminar boundary layers with variable properties and heat dissipation for $Pr = 1$ and for certain classes of unsteady flows [12E]. The number and size of cells in a fluid layer heated from below depends at a particular Rayleigh number on the ratio of the horizontal extent of the layer to its height [8E]. Steady-state solutions are shown to be not unique.

A computer study [4E] of boundary layer transition, using an analytical model two-dimensional in the averaged velocities and three-dimensional in the velocity fluctuations, considers fairly large disturbances introduced into the critical layer of a boundary layer. Boundary layer transition on a cone with rough surface and cold wall at Mach numbers between 14 and 16 was found strongly affected by the Mach number and the unit Reynolds number [22E]. The roughness consisted of single, double and triple rows of spheres. The reduction of the critical Reynolds number by the roughness diminishes with increasing Mach number. A correlation between transition and unit Reynolds number was also observed in a hypersonic boundary layer [19E]. A turbulent flow leaving a solid wall tube and entering a porous tube with fluid injection experiences a reverse transition from turbulent to laminar state [6E]. Reverse transition has also been found in a highly accelerated boundary layer [13E].

A physical model of isotropic, homogeneous turbulence was created by superposition of vortex sheets [16E]. The calculated spectrum was found to be in close agreement with the measured one. A closed system of model equations describing non-homogeneous turbulence was solved for a class of rectilinear flows [10E]. Correlations for heat and momentum transfer in the viscous sub-layer at rough walls were developed, utilizing Spalding's function and a transformed logarithmic law, and applied to parallel plate flow, pipe flow and annular flow [20E]. The Kolmogorov–Prandtl turbulence energy hypothesis, together with the conservation equations, was formulated so that it is valid for the viscous sublayer and the turbulent region and used to calculate velocity and temperature distributions for Couette flow and duct flow [23E]. The results are presented in new dimensionless parameters. A rate equation for the effective diffusivity containing two empirical constants, together with the conservation equations, was solved for an incompressible boundary layer at constant pressure and for the turbulent–nonturbulent interface of a boundary layer [14E]. Prandtl's mixing length theory emerges as a limiting case for a nearly homogeneous domain. Calculated magnitudes of the three velocity fluctuations increase linearly with increasing wall distance in the viscous sublayer [11E]. An analysis [15E] suggests that the turbulent diffusivity increases with the third power of the wall distance close to a wall for high Prandtl or Schmidt numbers and constant wall temperature or heat flux. Hot-wire measurements [3E] indicate that the flow in an axisymmetric, turbulent incompressible wake is intermittent over all but a small range around the axis. A calculated variation of the turbulent diffusivity across a tube is used to obtain the equation $Nu = 5 + 0{\cdot}025\, Pe^{0{\cdot}8}$ describing turbulent heat transfer for a liquid metal flowing in a tube [1E].

An analysis [5E] of an isothermal free turbulent jet results in a turbulence intensity of 20 per cent at the axis, increasing to 80 per cent towards the rim. A critical review [7E] of analyses of turbulent mixing problems including combustion points out the difficulty to obtain experimentally well defined conditions for the mixing of two streams. Howard's upper bound for heat transport by turbulent convection is further investigated [2E]. Measurements [9E] of instantaneous heat flux rates at the end wall of a resonant tube with periodic shock-fronted pressure waves result in instantaneous heat fluxes which are very large compared to the average flux. The penetration of jets ejected into a turbulent stream from a number of cylindrical nozzles in a triangular array was investigated [21E] including the influence of the angle of ejection and the turbulence level in the main stream. A model is proposed [18E] and investigated which describes mass transfer induced by the Marangoni effect. The interfacial turbulence is represented by a roll-cell structure. A review [17E] discusses new research results in the field of flows with energy supply and considers applications to combustion chambers and to flowing gases receiving electromagnetic energy.

NATURAL CONVECTION

Judging by the number of papers recently published, interest in natural convection continues to be very strong. Much of the work concerns thermal convection in a horizontal layer heated from below. Studies on this problem can be divided into three more or less distinct areas. The first concerns the problem of stability or the onset of flow for different boundary conditions and initial conditions. The second is the pattern of flow and heat transfer at relatively low (but greater than critical) Rayleigh numbers where non-linear effects appear and the flow may be in a cellular or roll-like pattern. Still other studies deal with the heat transfer at high Rayleigh numbers when the motion is essentially turbulent.

The critical Rayleigh number for horizontal fluid layers heated from below with almost zero shear upper and lower boundaries has been measured experimentally [20F] and found to agree quite well with Rayleigh's prediction. The effect of lateral temperature gradients on instability in a horizontal fluid layer has been analyzed [59F]. The effect of variable wall temperatures [32F], permeable horizontal boundaries [49F], and some special boundary conditions [19F] have been analyzed to indicate their effect on the critical Rayleigh number. Modulation of the wall temperature can either advance or delay the onset of convection in a horizontal fluid layer [60F].

A stability analysis has been performed for a horizontal layer heated from below containing a non-Newtonian fluid [55F] and for a liquid with a maximum density within the layer [53F]. Experiments on the onset of convection in a water layer from melting ice indicate the critical Rayleigh number is a function of position of the density extremum within the layer [65F]. The stability of a fluid layer stratified by both temperature and salt content distributions has been analyzed using linear approximations [2F].

The effect of side walls on a horizontal fluid layer heated from below is to produce finite rolls whose axes are parallel to the shorter side of the rectangle [45F]. An extended solution of flow in thermal convection also predicts rolls [31F]. An analysis indicates that a continuum of finite bandwidths of convective modes is found above the critical Rayleigh number [33F]. The suppression of cellular convection by lateral walls has been shown [11F]. The failure of a boundary layer model to describe cellular convection has been demonstrated [40F]. Another study analyzes the formation processes of convective cells in thermal convection [37F].

A study of the nonlinear profile of solute concentration in a fluid layer heated from below has been measured experimentally [48F]. Separate flow layers were sometimes observed. Measurement of the temperature profile and temperature fluctuations in a high Prandtl number fluid at Rayleigh numbers up to about 3×10^8 have been measured [50F]. A comparison of different procedures for calculating thermal convection at moderate Rayleigh numbers in an infinite Prandtl number fluid is presented [24F]. Two-dimensional, finite amplitude calculations of thermal convection in a fluid with high Prandtl number indicate significant effects of lateral boundary conditions [15F].

A study of the natural convection above an unconfined horizontal surface indicates large scale instabilities above a critical Rayleigh number [41F]. The heat transfer by natural convection above a horizontal circular plate has been measured in the critical region of carbon dioxide where properties change rapidly with temperature [22F]. A numerical calculation and experiment [34F] on free convection through vertical layers indicates that the Rayleigh number correlates the Nusselt number at $Pr \geqslant 1$, but a separate Prandtl number dependence must be used at a lower value of Prandtl number. Under certain conditions, the effect of a barrier in a vertical fluid layer can have a negligible effect on the overall natural convection heat transfer [13F]. The stability of transient natural convection between two infinite vertical plates has been analyzed [21F].

Experiments [56F] and analysis [57F] agree on the natural convection flow in enclosures with local hot spots to simulate a fire in a chamber. Experiments have also been performed on turbulent convection from a local source in a confined region [3F].

Prediction of heat transfer by natural convection in closed cylinders heated from below [12F] is compared to previously reported data. Experiments in a tall, narrow cylinder of mercury indicate several modes of oscillatory motion above the critical Rayleigh number [61F]. Natural convection due to Joule heating within a fluid contained in a vertical circular cylinder can produce laminar cellular flow [10F]. Studies conducted on heat transfer in a horizontal cylindrical annulus in which an inner surface is heated indicate different flow regimes at different values of the parameters [38F] and also indicate possible oscillations in the flow [5F].

Asymptotic solutions have been presented [28F] of the nonlinear Boussinesq equations that might apply in a free convection boundary layer. A general series solution describes the laminar natural convection heat transfer from a vertical plate for a nonlinear wall temperature variation [29F]. Negligible spanwise velocities are observed from an isothermal plate with a non-horizontal leading edge [51F], indicating that such a geometry can still be handled as a quasi two-dimensional flow. A model for a non-Newtonian fluid has been used in a natural convection analysis for flow along a vertical isothermal plate [54F].

Turbulent natural convection on a vertical plate has been studied to Rayleigh numbers of 10^{13} [63F]. In a similar study, the Nusselt number is bound to be a function not only of the Prandtl and Rayleigh numbers but also of other parameters [8F].

An analysis of the natural convection heat transfer, including variable properties, has been performed for an isothermal vertical plate in a supercritical fluid [35F]. Heat transfer has been found to be considerably increased by vortices produced in air by a high voltage electric field near a vertical isothermal plate [16F]. An approximate analysis was performed on the transient free convection from a vertical plate [23F].

The stability of a laminar natural convection boundary layer on a vertical plate has also been studied. Low frequency disturbances which become unstable first are often found to be amplified more slowly than higher frequency disturbances [9F]. The effect of thermal capacity of the plate on stability of natural convection boundary layers is analyzed [27F]. A summary of recent work on stability and in transition of natural convection boundary layers has been presented [17F].

Similar solutions for natural convection boundary layers with dissipation have been found for a few restricted boundary conditions [18F]. Dissipation is found to be significant in some natural convection boundary layers of very high Prandtl number fluids [42F].

Secondary flow vortices are observed with natural convection on an inclined plate [52F]. The effect of inclination on the natural convection heat transfer from a flat plate has been correlated by a simple angular relationship [64F]. Measurements of the local natural convection heat transfer on inclined surfaces are correlated over a range of conditions [62F].

A series solution is presented [44F] for laminar natural convection about a horizontal circular cylinder in a fluid of low Prandtl number. An analysis has also been made on the temperature profiles at the bottom of a heated cylinder [36F]. An empirical relationship correlates the natural convection heat transfer from a horizontal cylinder to fluids over a range of Rayleigh numbers from 10^{-5} to 10^{10} [4F].

The equations for certain three dimensional natural convection flows are separable, in particular for flow about inclined cylinders [43F]. Similarity solutions have been described for convection from a vertical needle [6F]. The interaction between natural convection flows produced by individual surfaces has been studied optically [30F].

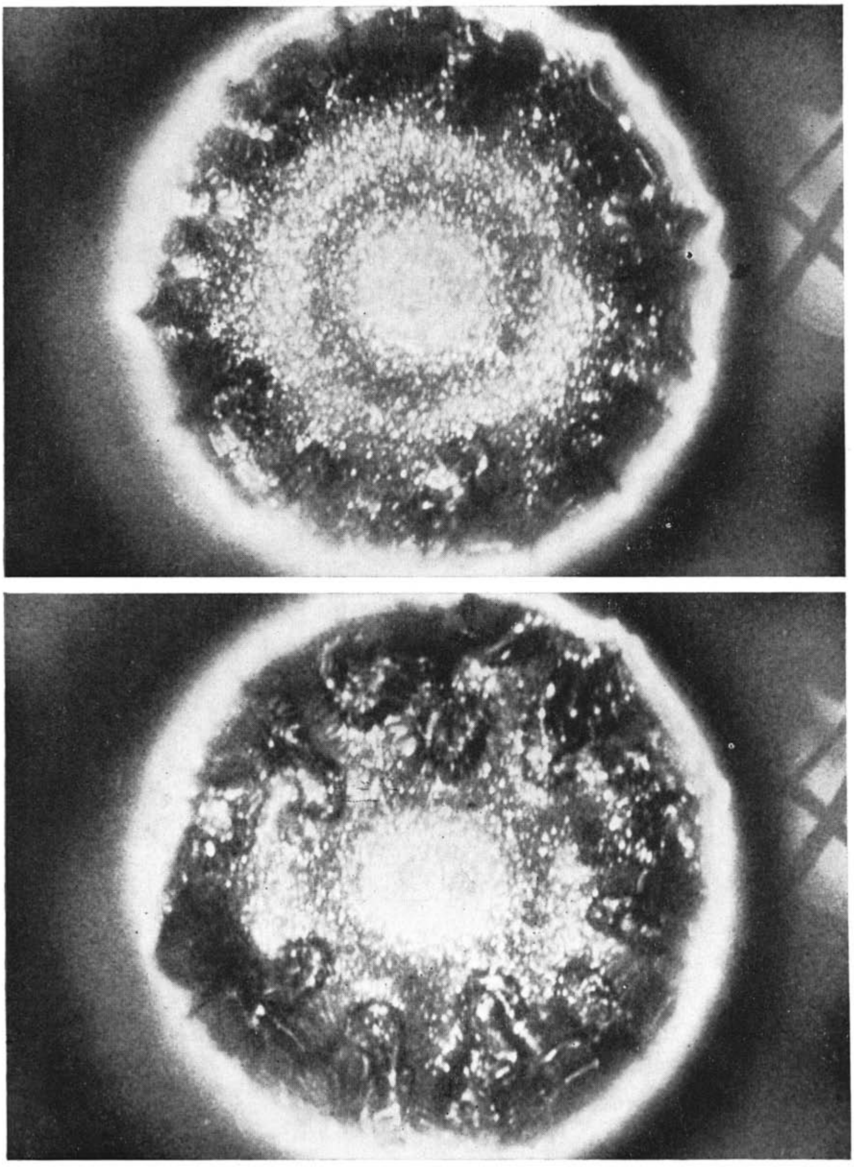

FIG. 1. Stages in the development of the flow field in a rotating cylinder following the onset of heating at the cylinder wall [3G]. Water is the working fluid.

Combined natural and forced convection phenomena have been examined for a number of problems including boundary layer flows and duct flows. One study concerns effects on a vertical flat plate [58F]. A study of combined natural and forced convection from a sphere leads to conjectures about pure natural convection [25F]. A correlation has been obtained for natural and forced convection from a heated horizontal tube in a cross flow [47F].

Combined natural and forced laminar convection in vertical non-circular ducts has been analyzed for a uniform heat flux boundary condition [26F]. Solutions for combined free and forced convection flow in vertical triangular ducts are presented [1F], including the effect of volume energy sources. Combined natural and forced convection in vertical semi-permeable ducts has been studied as it might be applied in a reverse osmosis installation [39F]. The effect of variable viscosity as well as natural convection have been found to seriously influence the laminar flow heat transfer in a heated horizontal tube [46F]. An analysis of combined convection in a horizontal tube with uniform heat flux has been performed over a range of Prandtl and Nusselt numbers [14F]. Combined natural and forced convection heat transfer has been calculated for flow in a horizontal rectangular channel at two Prandtl numbers using a numerical solution [7F].

CONVECTION FROM ROTATING SURFACES

Transient heat transfer on a rotating disc has been studied in several papers considering a step function change of the rotational speed [7G], a step change in disc surface temperature [1G], and a disc which is impulsively started from rest with the surface temperature changed at the same time [6G]. The time to approach steady state was calculated to be of the order of several seconds, decreasing with increasing Prandtl number. The integral boundary-layer equation for laminar heat transfer from a disc with a radially stepwise discontinuity in surface temperature, rotating in a uniform forced stream, was solved [9G], with the result that the transient Nusselt number is obtained by multiplication of the steady state Nusselt number with the step function factor

$$[1-(r_0/r)^3]^{-\frac{1}{3}}.$$

r denotes the radial distance on the disc and r_0 the location of the step in surface temperature. The effect of suction or injection on heat and mass transfer in a laminar boundary layer on a rotating disc was found [10G] in qualitative agreement with the effect of mass release from a flat plate into a laminar boundary layer. The temperature distribution generated by conduction in a thin rotating disc which is cooled over its frontal surface and heated over an angle 2δ of the periphery has been analyzed [5G] and the results have been presented in a number of figures. A solution was obtained [12G] describing the temperature rise due to viscous dissipation in a fluid between a rotating and a stationary disc. The study was motivated by viscometer applications.

A fluid, flowing inside a pipe rotating about its longitudinal axis, may revert to laminar flow as the rotation is increased [4G]. The onset of turbulence occurs as a burst. Heat transfer is somewhat changed by rotation in laminar flow, whereas no change was observed in turbulent flow. A photographic study [3G] of a fluid in a heated, rotating cylinder revealed a cell-like structure of rotating vortices during the development of the flow field (see Fig. 1). The flow was made visible by Alcoa aluminum powder. A paper [8G] analyzes laminar flow in a short cylindrical vortex chamber, assuming that the flow enters with a peripheral velocity component through the cylindrical wall of the chamber and leaves through a line sink at the axis. The spin down of a viscous fluid in a circular cylinder was calculated [13G] with the Boussinesq approximation, prescribing a step change in the rotational speed.

A calculation [2G] of heat transfer in a fluid flowing with a superimposed swirl and laminar boundary layers through a convergent–divergent channel demonstrates an increase in heat transfer with increasing swirl. Unsteady coupled diffusion of heat and vorticity in a gaseous vortex was studied [11G] for the condition that a rotating hot core is initially surrounded by a cold irrotational outer region as well as for the reversed temperature condition in the core and the outer region. A flow is generated in a rotating annulus with one side wall at a constant temperature and the other side wall with a temperature which fluctuates sinusoidally in time. The onset of motion in the form of waves and the wave forms were studied [14G], with the intention to model the atmospheric circulation.

COMBINED HEAT AND MASS TRANSFER

Studies continue on the effect of mass injection into a boundary layer to reduce the heat load on a wall exposed to a high temperature gas stream. An integral analysis of the heat transfer effects of arbitrarily distributed blowing into a laminar boundary layer on a hypersonic flow over a blunt body shows significant heat transfer reduction [6H]. Another integral approach is made to the hypersonic flow over a blunt body with mass injection [8H]. As the degree of rarefaction increases, a larger blowing rate is required to produce significant effects. An inviscid rotational flow model is used to study the massive blowing problem when the boundary layer can be blown off a surface [13H]. The relative advantages of transpiration cooling and different types of film cooling in protecting a surface exposed to a very high temperature gas stream have been presented [2H].

An integral method is used to calculate non-similar solutions for binary boundary layers [9H]. The method is designed to include effects of variable properties. Calculations of the temperature distribution in a high Prandtl number boundary layer with mass injection indicate that the thermal boundary layer can essentially be blown into the velocity boundary layer, resulting in a steep gradient of temperature away from the wall [12H]. The effects of suction and blowing on an incompressible laminar boundary layer have been analyzed [1H].

Several studies have been concerned with geometric effects on incompressible film cooling with a turbulent boundary layer. The effect of varying slot geometry on film cooling effectiveness has been measured [3H]. Another study [7H] indicates significant effects of the lip thickness, even far downstream from the injection slot. Surprisingly significant changes in film cooling have been observed [11H] with very slight changes in relative slot-lip thickness, apparently due to a change in the separated flow pattern over the lip.

In three-dimensional film cooling, geometrical effects can be very important. Film cooling downstream of a discrete hole in a surface has been measured. As the injection rate of the secondary fluid increases beyond a certain point, the entering jet no longer is turned down towards the surface but penetrates into the main flow producing much smaller film cooling effectiveness with increased blowing rate [4H].

Film cooling in compressible flows has been analyzed using a reference temperature to determine fluid properties. This enables subsonic film cooling correlations to be used at a free-stream Mach number of 3 for injection of air through a porous strip into an air mainstream at a Mach number of 3 [5H].

Film cooling by injection through a rearward-facing slot into a supersonic stream yields much better film cooling than the corresponding subsonic flow studies at low mass injection rate, while at higher mass injection rates this difference is reversed [10H].

CHANGE OF PHASE

Boiling

Gal-Or *et al.* [31J] present an extensive review of fundamental work on bubble and drop phenomena published since 1965. Cho and Seban [11J] predict steam bubble collapse when the motion of the vapor in the bubble is oscillatory. Pan and Acrivos [62J] describe the shape of a drop or bubble at low Reynolds and Weber numbers. Solutions are given [12J] to the dynamic equation for the oscillation of a noncondensable gas bubble in a nonvaporizing, infinite, incompressible liquid with the gas pressure specified in terms of a polytropic process $p_v R^{3n} = \text{const.}$ where $n = 1$ and $1 \cdot 3$. Experiments [52J] confirm the Malkus–Zuber relation for the "liquid fluctuating velocity"—a kinematic quantity characterizing the agitation induced in a liquid by an ordered flow of gas bubbles.

Under certain conditions, an isolated vapor bubble growing at a heated wall apparently has beneath it a thin liquid layer, the "microlayer," which affects bubble growth [78J]. Factors promoting microlayer formation are high wall and bulk temperatures and low system pressure [15J]. Olander and Watts [61J] and Cooper [16J] give analytical expressions for microlayer size and shape. In [41J] an optical technique is described which allows simultaneous determination of both microlayer geometry and macroscopic bubble dynamics. [84J] also presents experimental verification of the common physical background underlying the "relaxation microlayer" theory for the mechanism of nucleate boiling. Hospeti and Mesler [38J] studied vaporization at the base of bubbles of different shape. The growth rate, initial surface temperature, maximum surface temperature drop and bubble volume contribution due to microlayer vaporization at the bubble base all progressively increase for spherical, oblate, and hemispherical bubbles in the same order.

Reil and Hallett [65J] describe an apparatus for the production of uniform-sized water drops between 0·4 and 2·0 mm at desired time intervals. Growth rate of vapor bubbles under normal and zero-g conditions verify Scriven's theory particularly with regard to the added effect of mass transport [29J]. [69J] describes a similarity transformation used for solving the problem of mass transfer to a growing drop or bubble when the tangential velocity component is accounted for. Droplet vaporization at "high" pressures cannot be steady—the droplet vaporizes unsteadily from its injection condition until complete vaporization takes place [53J].

A new correlation assumes the main mechanism of nucleate boiling is transient heat conduction to, and subsequent replacement of, the superheat layer around the boiling sites [57J]. It is known that the presence of plating can either increase or decrease nucleate boiling heat transfer but in [5J] it is shown that the thermal properties of the plating material do not by themselves account for these effects. For boilers, the effects of surface treatment on boiling fade so rapidly there seems little point in abrasive cleaning of the tubes [9J]. Non-wetting is explained as the mechanism for enhanced heat transfer of Teflon-coated stainless steel specimens in pool boiling [87J].

Studies dealing with special influences include the effects of ultrasonic sound emission [63J]; the (negligible) influence of heated-surface vibration [2J]; the influence of oscillating the heating surface [66J]; and a composite study of the effects of electrostatic force, relative humidity, heating surface temperature, and size and shape on droplet evaporation rate [1J]. The quantity of heat transferred during the splattering or bouncing process (an extension of the classic Leidenfrost problem to finite impact velocities) exhibits a maximum at a saturation temperature excess of about 300°F for three substances [54J]. Hodgson [37J] summarizes hysteresis effects in surface boiling of water. Agreement between predicted and measured incipient-boiling wall superheats is obtained if the loss of inert gas from the cavity is considered [25J]. In [40J] experiments clarify the narrow-space, restricted-boiling effect and a new type of correlation equation for the coalesced bubble region given. Yeh and Yang [89J] and Lubin [50J] analyze film boiling with appreciable radiation.

Maximum heat flux on partly ill-wettable heating surfaces is studied when the formation of stable vapor film is not clear due to drastic hydrodynamic interactions [35J]. Van Stralen and Sluyter [85J] investigate effects of diameter and gravity orientation on critical heat flux. Staub [80J] extends critical heat flux modeling to Freon-22. Roemer [67J] studies the effect of power transients on peak heat flux. In [4J], an analysis is given which correctly predicts the trends of critical heat flux when discontinuities such as hot and cold patches are present. Judd [43J] analyses transient boiling of liquid metals whereas [34J] deals with potassium boiling in pipes. Heat-transfer coefficients for the boiling of a liquid in a thin film created by a spray nozzle are commensurable with those in pool boiling [44J].

In [39J] boiling on a fin is treated using heat transfer coefficients in various boiling regions approximated by various nth power functions of the superheat. Boiling in internally-finned circular tubes is examined in [71J] for a number of fin arrangements and vapor qualities. Except at high values of the Sterman parameter ($q_w/\rho_v U h_{fg}$) nozzle heat transfer is increased up to a tenfold enhancement by the presence of subliming particles [42J]. Turbulent forced convection is the dominant heat transfer mechanism in the immediate vicinity of the critical point for carbon dioxide in tubes [72J].

Davis and Cooper [20J] deal with thermal entrance effects in stratified gas–liquid flow. Drda and Weger present estimates of the lower limit of the height for incipience of boiling for laminar flow in small vertical tubes [24J]. Sources [26J] and [33J] give a broad collection of new data for steady forced vaporization of water and calculation of multistage evaporators. Finally, Shotkin [74J] lists a number of similarities between boiling and condensation.

Condensation

[17J] presents results of calculations of heat and mass transfer with evaporation or condensation on a surface that retains moisture, such as soil or plants. Kunz and Yerazunis [45J] present an analysis of film condensation, film evaporation, and single-phase heat transfer for liquid Prandtl numbers from 10^{-3} to 10^4. [22J] deals with nonsimilar solutions for laminar film condensation on a vertical surface and evaluates the validity of the extended Nusselt result in terms of the effects of (1) forced vapor flow, (2) variable wall temperatures, and (3) variable fluid properties. Nusselt's equation is modified in [81J] by empirical coefficients to include both saturated and superheated vapors. The necessity for including the effect of mass transfer on momentum transferred by interfacial shear during annular film condensation is demonstrated [48J]. Sparrow and Marschall [79J] discuss binary, gravity-flow film condensation. An explicit analytical solution is given in [21J] for laminar film condensation of a flowing vapor on a horizontal cylinder at normal gravity. Rose [68J] gives an approximate solution for condensation with natural convection along a vertical surface.

Minkowycz and Sparrow [58J] and Henderson and Marchello [36J] study the effects of superheating and the presence of noncondensable gases on condensation. [83J] deals with direct contact condensation in the presence of a noncondensable gas where the vapor is condensed directly on a stream of cold liquid. Slegers and Seban [77J] report that some of the apparently low condensation coefficients quoted in the literature are due to the presence of noncondensable gases. Condensation experiments using a jet tensimeter [51J] confirm the belief that the condensation or evaporation coefficients are unity, i.e. there is little or no resistance to molecules crossing the vapor–liquid interface in addition to that imposed by the gas laws. Condensation coefficients for water [86J] and liquid metal vapors [28J] are close to unity. Concerning mechanisms for dropwise condensation, Mikic [56J] found that for stainless steel as a condensing surface over 80 per cent of the total resistance is due to non-uniform heat flux over the surface whereas for copper this contribution is 20 per cent. There is only a slight increase in heat-transfer coefficient with surface inclination during dropwise condensation for angles less than 60° to the vertical [14J]. Experiments for steam condensing on a vertical, vibrating tube show the condensation heat transfer increased with vibration intensity up to 55 per cent above the vibration free value [23J].

Sherman and McBride [73J] give a simplified solution for the downstream effects of condensation in nozzles and for some of the newer propulsion schemes such as colloidal thrustors and EHD generators. The solution applies far downstream of the condensation zone where the amount of vapor left uncondensed is very small. Frass [30J] discusses phenomena occuring on the cooling surface when the temperature drops below the dew point of the flue gases. A method for generating quickly-convergent solutions by analytic iterations was applied for predicting the instantaneous thickness of a frozen layer that forms on a cold wall at constant temperature in a stream of liquid [70J]. In [82J] the solidification of fluids flowing along a plane wall is calculated with the assumption of a finite ambient heat transfer and an imposed heat flux to the solid–liquid interface. The analysis avoids the normal simplifying assumptions that the liquid near the liquid–solid interface is at rest and at the solidification temperature.

Two-phase flow

A few selected papers on two-phase flow are cited to provide a general survey of the typical areas of interest related to heat transfer. In [27J] the application of the gamma-absorption method to the measurement of vapor volumetric fraction is discussed. Davis [18J] describes interfacial shear measurements for two-phase gas–liquid flows by means of Preston tubes. An empirical equation for the ratio of interphase friction to wall friction shows useful agreement with various experiments for adiabatic flow of evaporating water up to 1000 psia [49J]. Chand [8J] gives a method for calculating pressure drops using the momentum balance principle. Recent experiments [76J] show that the Levy model for liquid film flow rates in annular flow with entrainment predicts low flow rates with deviations up to 64 per cent. Chawla [10J] presents a two-phase frictional pressure loss law and claims it to be more accurate than any known in the literature. Larsen and Tong [46J] use a bubble boundary layer model to predict void fractions in subcooled boiling at elevated pressures. In [3J] Bergles and Dormer give data for subcooled boiling pressure drop data at pressures below 100 psia in horizontal round tubes of diameter less than 0·2 in. Such low pressure systems exhibit a maximum in the pressure drop–flow rate curve which leads to flow instabilities. A void fraction model [7J] that assumes the radial distribution of liquid velocity and void fraction are parabolic has the advantage that it accounts for the effects of buoyancy and differentiates between upward and downward flows. Prins [64J] suggests that if a "vertical mass" of gas bubbles is included, the slip flow model fits experimental momentum flux data. [13J] claims to be the first to measure slip ratio by a direct determination of the linear velocity of the vapor phase. Yu and Sparrow [90J] describe experiments on two-component stratified flow of immiscible liquids of different density and viscosity in a horizontal duct. Davis and Cooper [19J] present heat transfer data in the thermal entrance region for horizontal concurrent air–water flows over a flat plate and compare these results with the theory for non-rippling films. A computer program has been written [88J] for the comprehensive analysis of core-pressure-vessel heat transfer during a loss-of-coolant accident. Local boiling, cavitation, and cavitation collapse have been observed in the heat induced counterflow of He II in a convergent–divergent nozzle [6J]. Pressure pulse transmission provides a physical formulation for critical flow and sonic velocity in both single and two-phase systems [59J]. Critical flow corresponds to a stationary pulse and sonic velocity corresponds to pulse transmission in a stationary fluid. Data on two-phase flow in horizontal pipes with twisted-tape turbulence promoters agree with a modified single phase analysis of Smithberg and Landis [60J].

There are three regions of flow on a shear stress vs. shear rate diagram for suspensions with high solids concentration [32J]. In [75J] a study of the heat transfer processes to a two-phase mixture of well-dispersed subliming particles and vapor flowing over a heated surface reveals that for large surface area per unit volume of the particle phase, the phase change dominates the heat exchange and hastens thermal boundary layer developments. Michael [55J] studies the motion of a sphere in a dusty gas and finds that a dust-free layer exists near the sphere when the product (Stokes number) (Reynolds number)$^{\frac{1}{2}}$ $\gg 1$. Lee and Zerkle [47J] give an analytical method for predicting the effects of solidification upon laminar flow heat transfer in tubes.

RADIATION

In order to make the complex problem of radiative heat transfer tractable, various simplifying models have been adopted Present trends in the literature indicate that the level of sophistication of such models is continuously increasing, resulting in better agreement between theoretical predictions and experimental findings.

The problem of transfer of radiation energy in a semi-infinite atmosphere, bounded by a totally absorbing wall and illuminated by a beam of radiation is solved, assuming isotropic scattering (Mie scattering) and absorption in the homogeneous medium, by expanding the kernel of the integral equation and the source function in Fourier cosine series [34K]. A normal-mode expansion technique is applied to solve the uncoupled radiative heat transfer problem for an absorbing, emitting, isotropically scattering, nonisothermal gray medium confined between specularly reflecting, gray, parallel boundaries held at uniform but different temperatures [57K]. For infrared radiation transport [27K], an exponential approximation in the radiative heat flux equation yields results which are in good agreement with exact solutions. Another investigation demonstrates that models for radiation heat transfer in participating media based on the assumption of anisotropic, isotropic, or no scattering at all are of limited value only [63K].

For the case of a Maxwellian gas of free electrons, it is shown that for low temperatures and photon energies ($\ll 0{\cdot}5$ MeV) the scattering of photons can be described by a relatively simple second-order differential operator [59K]. The author of [23K] shows that the semigray model can accurately predict radiative fields in gases whose spectra may be represented by several spectral steps. A substitute-kernel approximation for radiative transfer shows that results of existing gray-gas solutions for radiative transfer may be reinterpreted in terms of a nongray gas by applying an appropriate normalization [25K]. The Monte Carlo method is applied to calculate the emissive power, the temperature distribution of a radiant gray gas, and the heat absorption rate by the walls of a rectangular furnace as a function of the furnace dimensions, the emissivity of the gray, isothermal walls, and of the geometry of the flame, assuming radiation as the sole heat-transfer mechanism [69K]. Campbell [7K] shows that for the solution of nonlinear, frequency-dependent radiative transfer problems with one-dimensional symmetry, a finite difference method is superior to the Monte Carlo approach. The effects of sudden change of the wall temperature in a thermal radiating gas have been investigated [40K]. Approximate analytical solutions of the conservation equations are found to be valid in the four limiting cases of strong and weak radiation, and small and large times. For large time and weak radiation, the wave front precedes the pressure maximum and there is no significant separation of the wave from the heat transport. For small time, the formation of an acoustic wave is separated from diffusion of heat. For a weak radiation and small time, there is appreciable radiation slip.

The availability of spectrally resolved radiation properties of gases and vapors is a prerequisite for an exact solution of radiative problems in such media. Gray-gas approximations are of limited validity only. For the situation of a constant absorption coefficient and uniformly distributed heat sources, algebraic equations describing the temperature distribution in a radiating gray gas are in good agreement with exact solutions for the entire range of opacities [60K]. From the various correlations for total band absorptance of radiating gases, available in the literature, a simple expression is derived for an asymptotic value of a parameter which can be easily realized under normal thermodynamic conditions. The advantage of this simple expression for the calculation of the mean beam length is demonstrated [71K]. Strengths and half-widths of lines in the R-branch of the CO fundamental band are determined for temperatures as low as 113°K [32K]. For all temperatures the observed line strengths are in excellent agreement with calculated line strengths (Herman–Wallis) whereas half-widths differ considerably from theoretical predictions at the lowest temperatures.

The absorption spectrum of water vapor has been studied quantitatively with a resolution of approximately 0·12 cm^{-1} between 475–692 cm^{-1} [36K]. The intensities show deviations from those calculated for a rigid asymmetric rotor, which are attributed to effects of centrifugal stretching. Half-widths are shown of H_2O–H_2O, H_2O–N_2, H_2O–CO_2, H_2O–H_2 broadening at 80°C and H_2O–air at 24°C. Sample calculations which consider the introduction of hot CO_2 in water vapor at rest and of hot air introduced into CO_2 at rest [54K] reveal that the temperature distribution of a non-gray gas is higher than predicted for the gray gas, i.e. the gray-gas approximation overestimates the effect of radiation considerably in this flow problem.

A stabilized CO_2 laser in connection with a 1 km path absorption cell is used to measure the absorption of pure water vapor and water vapor–air mixtures in a laboratory experiment. The results compare favorably with outdoor transmission studies over a 1·95 km path [47K]. Another long-path study of infra-red absorption [44K] utilizes a steel cell containing two mirrors of 91·4 cm aperture placed 30·5 m apart. This cell is operated in a pressure range from 15 atm to 10^{-3} Torr. Samples of CO_2 absorption spectra of a 92 m path at 1 atm are shown.

The spectral properties of air heated by reflected shock waves are found to be in satisfactory agreement with theoretical predictions for a range of incident Mach numbers from 20 to 24 [37K]. For measurements of the total radiant intensity of air plasmas, Wood *et al.* [79K] apply a new type of heat transfer gauge using the reflected shock region of an arc-heated shock tube. A comparison with theoretical predictions shows that the experimental results agree at lower temperatures (10^4 °K), but fall below by a factor of 2 at higher temperatures (16000°K). A spectroscopic analysis of the radiation from a luminous flame of liquid and gaseous fuels in the wavelength range from 1·5 to 4·5 μ revealed band spectra of the gas and a continuous spectrum of the soot particles [62K].

Various geometries and boundary conditions have been studied to facilitate solutions of practical radiative transfer problems. Problems of radiative equilibrium and combined conduction–convection and radiation pertaining to the geometry and boundary conditions of the simple model suggested by Taitel [67K] lend themselves to approximate solutions, which is illustrated for the case of radiative equilibrium in the presence of a gray gas of constant properties. Radiative heat transfer between parallel plates and concentric cylinders is considered for the case of a gray gas in radiative and local thermodynamic equilibrium enclosed between diffusely reflecting surfaces assuming that both walls are black and one of them is at zero absolute temperature [45K]. It is shown that for such radiative heat-transfer problems variational methods yield very accurate results with little computational effort.

Solutions of radiative transfer between concentric spheres enclosing a gray gas using a differential approximation based on half-range moments are burdened with considerable errors, especially for the optically thin limit for walls of different temperature [17K]. Emanuel [21K] considers radiative heat transfer from a single sphere of radius a imbedded in a quiescent nonconducting gas with a constant volumetric absorption coefficient α for small values of the Bouguer number ($B_u = a\alpha$. The results show that the application of an asymptotic approach has the important advantage of mathematical simplicity and physical clarity. By introducing an improved closure condition [74K] which satisfies both the limiting conditions of isotropic and unidirectional radiation, the problem of radiative equilibrium of a gray gas between two concentric black spheres at different temperatures has been solved. Both radiative heat flux and temperature distribution from the present model compare favorably with known exact results. An approximate method for multidimensional problems is suggested [26K]. This technique, applied for the prediction of heat transfer between plane parallel plates and between concentric cylinders for a gray medium in radiation equilibrium, yields results which are in excellent agreement with previously published numerical solutions for all values of the optical thickness.

Heat transfer by simultaneous conduction and radiation has also been investigated. Exact solutions for the "radiation layer" over a flat plate delineate the conditions for which a two-layer model composed of an outer "radiation" region and an inner "conduction" region may be applied [68K]. The effects introduced by radiative heat transfer between two partially transparent media in intimate contact (for example, a crystal growing in its own melt) are derived from a simplified model assuming one-dimensional, steady-state, diffusion [70K]. The stability of solid–liquid interfaces depends on the heat transfer rate [55K]. The authors of [55K] conclude from their calculations that the temperature gradient at the interface is invariably steeper in combined radiative and conductive systems as compared to the pure conduction case, resulting in a stabilization of the interface during crystal growth. Effective slip coefficients for coupled conduction–radiation problems have been derived [33K]. The authors conclude that their results published in a previous NASA technical note, dealing with coupled radiation and conduction in systems with black boundaries, are applicable for any geometry and are better in accuracy than results available in the literature.

The application of Biot's principle is extended for a treatment of combined transient conduction–radiation problems. The simplicity of the results shows the advantage of the variational formulation [42K]. Another study [39K] is concerned with unsteady radiative heat transfer in a stationary plane layer of a nonconducting medium initially at a uniform temperature. This system is analogous to the conventional problem in heat conduction and, therefore, permits ready comparison with results for simultaneous conductive and radiative transfer.

In a number of papers, the interaction of radiation with a gray or non-gray boundary layer is considered. For a non-gray boundary layer [53K], the results for CO_2, CH_4 and H_2O in terms of the ratio of the total heat flux with radiation to that for pure convection demonstrate that the maximum effect of interaction of radiation occurs at a pressure of less than one atmosphere, with the results approaching pure convection as the pressure increases toward infinity or approaches zero. The effects of radiation cooling at a stagnation point [56K] can be adequately accounted for through the use of simple non-gray absorption coefficient models. It is shown that reasonable estimates of the stagnation-point radiation heating rates can be obtained by multiplying adiabatic heating rates with the cooling factors which are available in the literature.

In another radiation-coupled stagnation-region analysis [6K], use is made of consistent model absorption coefficients having one to nine spectral steps which include free–free, free–bound, bound–bound and molecular transitions. Results of this analysis indicate that the detailed absorption can be simply modeled to achieve results with good accuracy and the retention of all significant trends. The problem of fully radiation-coupled, inviscid stagnation flow [15K] is treated with a finite-difference formulation of radiation transport by using up to 21 spectral regions for air and ablation vapor continua and 75 discrete atomic lines. The results indicate that the ablation layer is very effective in reducing the wall heat flux and that self-absorption and energy-loss effects reduce the sensitivity of the wall radiative flux to environmental variables and to uncertainties in radiative properties.

Considering tube flow of heated hydrogen under a pressure of 100 atm, radiation is found to make a significant contribution to the wall heat flux up to 9000°K for a tube of 0·3 cm radius, and up to 6500°K for a tube of 3 cm radius [76K]. Numerical calculations show [1K] that the specific enthalpy of a jet consisting of a radiating gas decreases from its zero-radiation value at any point in the jet. Consequently, the density increases and the velocity decreases from its zero-radiation value except at the center of the jet. Computer predictions and laboratory experiments of the thermal behavior of space vehicle window systems under various transient thermal conditions imposed by convective and radiative heat transport at their boundaries are generally in good agreement [24K]. Experimental and analytical studies show that the effect of radiation on the laminar free convection boundary layer of absorbing gases is negligible [22K].

Anderson [2K] demonstrates in an engineering survey of radiating shock layers the significant improvements accomplished during the past three years in the status of shock-layer radiative heat transfer and stresses the need for additional work in this field. Analytical investigations in an argon-like gas [51K] reveal that just behind the shock wave, the electron gas is cold relative to the atom gas, whereas farther in the relaxation region the electron temperature approaches the gas temperature, establishing thermal equilibrium. The precursor ionization depends directly on the ratio of radiative to convective energy transfer; thus, decreasing the ambient pressure increases both the extent and magnitude of the precursor. Radiative cooling decreases the convective surface heat-transfer rate and reduces the overall shock structure and shock-layer thicknesses and augments the shock-slip effects [43K]. Radiative contributions become less important toward the free-molecular range. In connection with Martian entry studies [19K], radiation measurements have been performed in a shock tube and shock-shape measurements in a shock tunnel. Extrapolated results of the shock tube to radiation measurements obtained in the ballistic range and to the theory are in satisfactory agreement for the blunt cone and for Apollo shapes.

For the emittance of a homogeneous gas-particle cloud, an approximate method based on a one-dimensional beam approximation is suggested for connecting the simple Lorentz line model and the Elsasser band model with the thin cloud model and the emittance for arbitrary optical depth and smeared line. The results give at least the qualitatively correct behavior of the emittance as a function of the parameters of interest [4K].

The results of an experimental and analytical study of heat transfer in a gas–solid fluidized bed for purely radiative heat transfer are interpreted in terms of a model postulating transient radiative heat transfer from the source to the particles during their finite residence time at the wall [66K]. Predicted heat-transfer rates are in good agreement with measurements. Caren [9K] studied radiative transfer from a metal to a finely divided particulate medium. If $\bar{n}$ is the effective dielectric constant of a particulate medium (for example, Plexiglas or Tissuglas), then the emissivity of a metal radiating into this medium is $\bar{n}^3$ times the emissivity of the same metal radiating into vacuum. Measurements of the transmissivity of a carbon-particle-seeded nitrogen jet [41K], taken in a wavelength range between 0·3 and 3·5 μ using 0·009 μ nominal carbon particles as seed material at densities from 10^{-5} to 10^{-4} g/cm^3, show that the absorption cross section is almost independent of wavelength and decreases as the seed density increases which is attributed to particle agglomeration.

By using a highly convergent relaxation method, the temperature profile of a relatively unknown atmosphere can be unambiguously determined by measuring the outgoing radiation [11K]. The method is illustrated by considering the radiance in the Earth's atmosphere for the 4·3 μ CO_2 band. Using Monte Carlo techniques [58K], it is possible to calculate the complete radiation field in the atmosphere–ocean system. The radiance and flux are given for $\lambda = 0{\cdot}65$ μ and $\lambda = 0{\cdot}46$ μ, three solar angles, shallow and deep oceans, various albedos of ocean floor, various depths in the atmosphere and ocean, and with and without clouds in the atmosphere.

The results of a one-dimensional unsteady analysis for the growth of a vapor film on a suddenly heated plane surface [28K] show that thermal radiation increases the rate at which the vapor film grows and that the importance of radiation increases the rate at which the vapor film grows and that the importance of radiation increases with increasing wall temperature. An analysis of laminar film boiling [80K] indicates that the presence of surface radiation results in an increase in the heat transfer rate and a decrease in the skin friction.

Choking of a subsonic gas flow by thermal radiation is studied utilizing a simple model [49K] which predicts the radiation source temperature required to produce choking by absorption of this thermal radiation in a gray, ideal gas.

A survey article by D. K. Edwards on radiation properties has brought into focus the state of present knowledge as well as those areas where further research is needed [20K]. Laser beams were employed in measurements of reflected radiation from rough metallic surfaces at discrete wavelengths of 0·63, 3·39 and 10·6 μ [14K]. From a graphical presentation of normal spectral reflectances of ten pure metals and an alloy at low temperatures, it is seen that the reflectance generally drops off at short wavelengths [18K]. The emittance of corundum powders in the wavelength range from 7·5 to 25 μ was measured by means of infrared interferometry [3K]. The optical constants of soot in the range 0·4–10 μ differ significantly from those of other graphitic materials, the disparity being ascribed to a larger hydrogen-to-carbon ratio and a consequent decrease in the number of free electrons [16K]. Spectral emittance measurements show that ablating phenolic graphite radiates nearly as a gray body in the visible and in the wavelength range from 3 to 10·5 μ [13K].

The measured reflectivity of liquid mercury at 0 and 45 deg was found to be in excellent agreement with the predictions of the Drude theory [50K]. The indices of refraction of gases in the liquid and solid states were determined at the wavelength of the sodium D line [46K]. Scattering and absorption coefficients for various paints varied inversely with a power of the wavelength of the incident radiation in the range from 0·8 to 2 μ [38K]. Hemispherical-directional spectral reflectances of paints, metals, brick, slate, and tree bark were measured with an integrating sphere reflectometer [52K]. The normal and hemispherical emittances of an aluminum substrate coated with a film of SiO_2 increased markedly as the film thickness increased [31K].

The optical constants of a thin oxide layer can be deduced from measurements of the change in the state of polarization due to reflection [5K]. On the basis of a theory using geometrical optics, it has been shown that unpolarized incident radiation will become polarized after reflection from a roughened surface [73K]. Experiments have shown that polarization of the source of illumination plays an important role in determining the actual degree of diffuseness of various diffuse reflection standards [10K].

The Fresnel equations have been rephrased in a form in which the optical constants n and k are functions of measured reflectivities, thereby facilitating the experimental determination of these quantities [61K]. The formulas which relate the components of the complex index of refraction for a thin film to the measurable optical reflection and transmission coefficients have been put into a simpler and more usable form [72K]. Experimental verification has been provided for the Kramers–Kronig relation, which relates the real and imaginary parts of the complex index of refraction of a liquid [8K]. Several techniques for measuring emittance in the laboratory and in the field were examined and their merits described [48K].

Analysis has shown that the amount of radiation incident on a temperature sensor situated in a tube having nonisothermal walls increases as the emittance of the walls decreases [65K]. Calculations of thermal radiation from the lunar surface incident on a nearby flat plane gave results significantly different from those based on diffusely distributed leaving radiation [30K]. The integral equations for the radiosity, appropriate to interchange among gray diffuse surfaces, were recast into contour integral form. The explicit parts of these equations are purported to serve as approximate solutions or as starting functions for an iteration procedure [12K]. Comparisons have been made of the apparent emittances of several diffusely and specularly reflecting cavities [78K]. Radiation from a strongly heated V-groove cavity was measured and compared with that from a plane surface, but comparisons with theory were not made [35K].

Angle factors for a torous, determined by employing Eckert's optical technique [64K], were in good agreement with those calculated analytically [29K]. Information on angle factors for two spheres in contact was applied to radiant transfer in a packed bed [77K]. Angle factors relevant to the computation of radiation locally incident on tubes in a bundle are tabulated [75 K].

LIQUID METALS

Careful experiments [1L] demonstrated that pure degassed mercury in laminar or turbulent flow through a tube behaves like a normal liquid with respect to flow and temperature fields. An argon film on the wall had no effect on heat transfer. The maximum of the fluctuations in a turbulent temperature field for NaK flowing through a tube was found [2L] to occur at $y/r_0 = 0$ as compared to the maximum in the velocity fluctuations which occurred at approximately $y/r_0 = 0{\cdot}07$, with y indicating wall distance and r_0 tube radius ($Re = 26800$ and $Pe = 690$).

A number of regimes were established [8L] for heat transfer in boiling sodium under free convection conditions. More experiments are recommended to completely clarify this boiling process. A generalized relationship for the critical heat flow in boiling of alkali metals was derived [4L] from available experiments

$$q_{cr} = 0{\cdot}666 \times 10^6\, k^{0{\cdot}6}(p/p_c)^{0{\cdot}6}.$$

The critical heat flux q_{cr} is expressed in kcal/m^{2}h, the thermal conductivity in kcal/m h°C, p_c indicates the critical pressure. Experiments [6L] on sodium boiling on horizontal surfaces containing artificial cavities suggest that the time for bubble growth and departure is a small fraction of the total cycle time. This suggests an analysis based on transient conduction is appropriate. An analysis [7L] of the effect of an inert gas on incipient boiling of a liquid metal suggests that reports of past experiments do not contain sufficient information to describe the system. In pool boiling of mercury, increasing the concentration of dissolved sodium at first causes a decrease in heat transfer; for further increase in concentration beyond 0·232 wt. %, the heat transfer increases [5L]. The ratio of the number of molecules of mercury vapor condensing on a pure liquid mercury surface to the number impinging was measured [3L] as 0·8–1. Previous measurements resulted in lower values.

LOW-DENSITY HEAT TRANSFER

An analytical study of heat transfer at low densities applies an extension of the Grad 13-moment approximation [4M] which yields, in addition to the usual gas dynamic equations of continuity, momentum, translational energy, viscous stresses and translational heat flux, relations for the conservation of internal energy and for the internal heat flux. For an investigation of the transition and free molecular regime [3M], new boundary conditions are derived based on the Boltzmann equation which, however, match with the Navier–Stokes equations. This new approach is applied to plane Couette flow, plane and cylindrical Poisseuille flow, heat transfer between parallel plates and concentric cylinders. Results compare favorably with exact numerical solutions.

Temperature profiles in Couette flow derived from the BGK-model for the entire regime of Knudsen numbers [2M] are in fair agreement with those in the literature and the variation of heat fluxes with increasing Knudsen number is also in agreement with numerical results of other investigators. By adopting a rigid-sphere model for the molecules, assuming a wall accommodation coefficient of unity, and a target molecule velocity distribution consisting of the sum of two different half-Maxwellians, Perlmutter [5M] obtains all macroscopic quantities of interest in a Couette flow regime. For MHD Couette flow between conducting walls [7M] temperature jump boundary conditions have been introduced in order to find temperature distributions between and Nusselt numbers at the walls assuming that the gas is viscous but incompressible.

The results of an analytical and experimental study of the heat loss from cylinders (tungsten wires of $1{\cdot}27 \times 10^{-3}$ cm dia.) at low Reynolds numbers in binary mixtures of nitrogen–helium and nitrogen–neon at atmospheric pressure reveal that the heat loss in nitrogen–neon mixtures qualitatively involves the same slip effect as does helium [1M]. The stability regions of slip flow in heated passages are defined by the ratio of outlet to inlet temperature, Knudsen number at the inlet to the passage, and the product of Reynolds number at the inlet and the passage diameter-to-length ratio [6M].

MEASUREMENT TECHNIQUES

A general review of temperature measurement techniques for use at very high temperatures has appeared [5P]. Another review examines recent publications on temperature measurement [8P].

An oxide semi-conductor thermistor has been tested for measuring temperatures in the range from 1000 to 2500K [42P]. An acoustical thermometer can measure discrete temperatures in nitrogen from 300 to 700K [18P]. Evaporated silver–aluminum thermocouples [2P] and pyroelectric thermometers [29P] have been used for measuring very low temperatures.

An improved interpolation formula for carbon resistance thermometers has been demonstrated [23P]. Connecting a thermocouple and Wheatstone bridge in series with another thermocouple results in an approximately linear output with temperature [9P]. The dynamic response of thermocouples on thin models has been calculated [30P]. A folded electric resistance element can be used to measure surface heat flux [3P].

A laser interferometer has been designed to study mass transfer boundary layers [6P]. An interferometer can be used to measure binary diffusion coefficients [19P]. Modification of the optical system of a Mach–Zehnder interferometer simplifies the alignment procedures [20P]. The potential of holographic interferometry for wind tunnel studies has been demonstrated [7P]. An interferometer containing a coupled CO_2 laser has been used to measure the density of transient plasmas [22P].

Bidirectional reflectance can be measured photographically using a film-coated hemisphere

[41P]. An instrument to measure spectral reflectivity for normal incident radiation has been described [37P]. A calorimeter has been constructed to measure radiant heat exchange of small animals [4P].

A number of applications and advances of different techniques for flow measurement have been studied. Optical systems include laser-Doppler anemometers and light-scattering methods. Studies of hot wire anemometry include a number of important effects. Other velocity measuring techniques as well as flow visualization and shear stress measurement methods have been reported recently.

A Fabry-Perot interferometer has been used to determine the Doppler signal of scattered laser radiation in rocket exhaust velocity measurements [32P]. Doppler-shifted light from a schlieren system can be used to measure fluid velocity [36P]. A review of laser–Doppler techniques for velocity measurement has been presented [1P].

Analysis of the intensity of a schlieren signal permits measurement of turbulence parameters [38P]. Turbulence properties of gas flows have been studied by light scattering from a locally heated region [12P]. The fluctuation of scattered light from cold gas or plasma flows has been analyzed to determine turbulence parameters [11P].

A single probe permits measurement of temperature and pressure simultaneously in a compressible flow [31P]. A multi-hole probe measures the velocity vector in subsonic flow [10P]. A small combination probe for measuring temperature, pressure, and flow direction has been tested in both subsonic and supersonic flows [17P]. The effective position of a rectangular impact tube in a wall shear flow has been measured [34P]. Matched piezo-electric crystals can measure transient pressures in a rarefied shock tunnel [25P]. A constant-area passage meters flow with characteristics similar to a critical flow orifice [14P].

A new method of calculating the calibration curve for a constant-temperature hot-wire anemometer at high wire temperatures has been presented [21P]. Limitations of a constant-temperature hot-wire anemometer in measuring large velocity fluctuations at high frequency has been demonstrated [15P]. A temperature-compensated linearizer has been used with a hot wire anemometer [28P]. The effect of inclination to the flow on hot wire anemometer response has been studied to determine the errors introduced at low levels of turbulence [24P] and to determine parameters for such applications [16P].

Calibration of a hot wire anemometer for measuring low velocities in a liquid has been performed by moving a liquid container in which the anemometer is placed [13P]. Photoelectric recording of the deflection of a fiber anemometer can be used to measure small velocities in a liquid or gas stream [39P].

A yaw probe used as a Preston tube can measure both the magnitude and the direction of a wall shear stress [35P]. A thin coating of cholesteric liquid crystal mixtures can be used to measure shear stress since they respond to shear forces by changes in the wavelength at which maximum scattering occurs [26P]. The optimum viscosity for a liquid layer placed on a surface to measure the local shear stress has been calculated [40P].

Stream lines and schlieren photos have been observed simultaneously in a supersonic flow [33P]. Moulded dry ice models have been used to model ablation studies [27P].

HEAT-TRANSFER APPLICATIONS

Heat exchangers

A new finned tube configuration, with 26 fins per in. instead of the conventional 19 fins per in., resulted in a 25 per cent improvement in heat transfer rate for refrigerant condensing [9Q]. Stanton and friction numbers were found [6Q] to be smaller for heat exchangers with tubes interconnected by longitudinal fins than for tubes alone. The configuration does not appear attractive. Shell-side heat-transfer coefficients were measured [7Q] in helical coil heat exchangers with water flowing outside the tubes. An approximate solution [12Q] for laminar countercurrent heat exchangers utilized generalized Graetz solution for the heat transfer coefficients. Computer solutions with corresponding programs were published for surface condensers [4Q] considering local variations of the heat transfer coefficients and for plate heat exchangers [2Q].

Nusselt numbers were predicted [1Q] for a regenerator considering the heat transfer as a function of longitudinal location and time, and assuming plug flow. The Anzelius–Schumann curves were found to be a good approximation except close to the entrance. A paper [14Q] considers the effect of conduction in the matrix normal to the gas flow.

Analyses by Gardner and Kays–London were extended [3Q] to an assembly of heat exchangers of any types. Three hundred dollars in construction costs could be saved by tailoring the individual heaters of the regenerative feed water system in a power plant cycle to optimum condition [11Q].

The Graetz problem was solved [5Q] for the flow of molten polymers through a heat exchanger considering the density as function of pressure and temperature, and using the following expression for the shear

$$\tau = -Ae^{-k_1 T}\left|\frac{dv_z}{dr}\right|^{n-1}\left(\frac{dv_z}{dr}\right)$$

with T indicating the temperature, v_z the axial flow component, r the radial direction, and k_1 and n denoting constants. The results agreed within ± 6 per cent with experiments. Heat transfer relations for agitated turbulent non-Newtonian fluids were approximated by the corresponding relations for Newtonian fluids with apparent viscosity [10Q]. The addition of dilute quantities of polymers as drag reducing substances reduces heat transfer as well as drag [13Q] so that no beneficial effect is obtained. Alkali metal–ammonia solutions appear attractive [8Q] as heat transfer fluids to -185°C because of the low freezing temperature and the high conductivity, especially since technology has been developed to overcome decomposition and corrosion.

Aircraft and space vehicles

Ablation and heat shield performance are still of great interest in aerospace application. The thermal destruction of heat protecting materials (teflon) which may occur during the re-entry process is simulated with an arc gas heater by Luikov and co-workers [14R], producing a high temperature plasma jet with argon, nitrogen, air and oxygen as working fluids. The dimensionless entrainment velocity of teflon is shown to increase with oxygen concentration in the main stream, especially at lower temperature in agreement with theoretical predictions. Blowing of depolymerization products into the boundary layer reduces the heat fluxes up to 25 per cent. Model tests at hypersonic speeds using an oil-film technique showed that the boundary-layer-edge, Mach number, and the model wall temperature have a strong influence on the magnitude of surface upwash angles [15R]. Tests of ablating cones at transitional Reynolds numbers resulted in upwash groove patterns which are probably due to vortices intensifying local heating rates. Lee [13R] presents for the first time ground-test data which demonstrate that ablation reduces the Apollo afterbody heat transfer by as much as 40 per cent. Analytical heat-transfer rates of rocket exhaust impingement on flat plates and curved panels based on the Spalding and Chi turbulent skin-friction relation and experimental data are in agreement in the weak-shock region for cases of high chamber pressure and moderate altitudes [20R]. During AS-501 and AS-502 flight tests in connection with the Apollo moon landing program [18R], the Saturn V/S-IC stage base revealed maximum heating rates, mainly due to radiation, of 22 and 32 Btu/ft^2 s on the heat shield and the engines, respectively. Maximum base heat shield and engine gas temperature of 2100°R, and 2700°R, respectively, were experienced. Low-density charring ablators are best suited for thermal protection systems for a Mars-entry vehicle [12R]. Foamed silicone and epoxy silicone low-density elastomers are shown to have low thermal conductivities, high decomposition temperatures and excellent low-temperature properties. Teflon exposed to 6943 Å radiation bursts of a Q-switched ruby laser with a pulse duration of approximately $4{\cdot}5 \times 10^{-8}$ sec and an average flux of 3×10^8 W/cm^2 reveals a previously unobserved carbon char leading to an increase of the relative dielectric constant and of the loss tangent [4R]. The transient behavior of infiltrated composites during melt layer formation has been studied. A transient, one-dimensional heat-transfer analysis is applied to predict the temperature distributions and interface locations for Hg, Cu, Sn, Pb, Mg, Li and Zn infiltrants during the initial heating period before the melt layer begins to vaporize below the surface of the tungsten matrix. Inclusion of the melting process and of the temperature-dependent properties in the analysis is necessary to describe the early stages of the self-cooling process adequately [3R]. A heat shield material designed for high radiative heating rates [9R] consists of a low-density (<10 lb/ft^3) sandwich of quartz cloth and Fiberfrax filler (a fibrous high-purity alumina–silica), has low heat conductivities ranging from 0·38 at 400°F to 1·73 Btu/ft h°F at 1800°F and can withstand heating rates up to 50 Btu/ft^2 s (tested for 40 s) with no apparent degradation. Measurements of heat fluxes parallel and for combined parallel and normal heat fluxes of multilayer, aluminized-plastic-foil insulation systems show that calculations which do not consider radiation leakage between layers can lead to an underestimation of the heat transfer by a factor of more than 3 [1R].

Heat transfer rates in the Gemini and Apollo space suits have been measured [6R]. Heat-transfer data over a wide range of simulated environmental conditions are presented in terms of both surface total and regional heat flux distributions taking thermal emission and convective heat exchange into account.

In addition to ablation cooling, transpiration and film cooling has attracted widespread interest in aerospace applications. An analysis of heat transfer in an evaporative-transpiration-cooled system demonstrates that lithium as coolant performs superior, not only because of its high latent heat which allows to absorb a large amount of heat within the porous body, but also due to its low molecular weight which reduces the convective heat input to the boundary layer [24R]. The energy absorption of ammonia flowing through a heated porous nichrome plate was found to be mainly due (up to 65 per cent) to dissociation of ammonia [8R].

A Russian report [17R] describes experimental results for transpiration cooling of porous plates, impermeable plates with porous inserts, and porous cylinders in cross-flow, for laminar flow over these bodies including the transition regime to turbulent flow and for a turbulent boundary layer along a flat plate. Investigations conducted in the Langley Continuous Flow Hypersonic Tunnel which operates at a nominal freestream Mach number of 10 show that a simple lumped parameter formulated from approximate theoretical considerations provides a basis for the correlation of the cooling effectiveness [7R]. Among the various active cooling systems, the distributed film cooling and partial film cooling systems show special advantage and warrant further investigation [5R].

The importance of radiative heat transfer in space applications is stressed in the following papers. Measurements of the solar constant and the solar spectrum from a research aircraft flying at 11·58 km altitude (above absorbing constituents of the atmosphere) is reported [22R]. The new value of the solar constant is $S = 135{\cdot}1$ mW/cm^2. In addition, a revised spectral irradiance curve is shown. In another paper [10R] the influence of the moon's infrared non-diffuse radiation on temperature calculations is demonstrated. A quick method is described for obtaining temperature predictions during spacecraft manoeuvers [2R] based on the determination of projected areas by using the camera Lucida or camera Obscura, etc., to find the temperature response of spacecraft components in a nonstandard solar orientation. A plane, isolated surface which is fully illuminated by a collimated and uniform solar flux assumes temperatures which are 34 per cent lower to 18 per cent higher than those acquired by the rough surfaces considered in this paper if the surface roughness is completely neglected [11R]. An analysis of the thermal control system for orbital and interplanetary space exploration demonstrates that the required fin width and tube length of space radiators are very sensitive to the level of incident radiation [23R]. The implication of the bidirectional reflectance of spacecraft surfaces is considered in [19R]. Experimental and theoretical methods are described for determining luminous fluxes in a certain direction. Results show that reasonable agreement exists between the experimental–analytical approach and model simulation studies.

For an analysis of a belt-type heat transport device [16R], an equation is derived which describes for all belt speeds, taking the belt conductivity into account, the heat transfer capability of such a belt.

The effects of deposits on heat transfer to aviation kerosine has been studied [21R]. The thermal stability of a fuel, deduced from heat-transfer data of model tests, correlates with the breakpoint temperature measured with the ASTM-CRC fuel coker.

General

An increase of the turbine inlet temperature to 2500°F doubles the turbine engine power. Thermosyphon cooling of the blades using a closed water loop for each blade and fuel as heat sink, or transpiration cooling using air have been proposed and tested [4S]. The temperatures in an assembly of fuel rods with defects (for instance, by cracks) have been determined, using as analogy a network of electric resistors [10S]. Measurements [7S] of the critical heat flux in a 16 rod square array simulating a nuclear fuel assembly at 1000 psia established a considerable variation with geometry and with misalignment of some rods. The risk of local boiling and an unstable character of downward flow of the moderator in a pressure tube reactor was investigated [3S]. Average heat transfer coefficients for air flowing through three screens have been measured [12S] and represented by the equation $Nu/Re^{\frac{1}{2}} = 0{\cdot}5\, L/(L + D)$ for sonic velocities established at the minimum cross section of the screen and for Reynolds numbers above 400. L denotes the clearance between the wires, D the wire diameter, and the properties are introduced into the above relation at sonic condition.

The thermal conductivity of expanded plastics, measured [8S] as a function of internal air pressure and temperature, assumes values between 0·002 and 0·03 kcal/mh C. The effectiveness of new insulating materials (mineral wool, glass fiber, foam glass, silicate, styrene, urethane foams) was discussed [9S]. A table of water vapor transmission is included. A solution [5S] of the energy equation and the diffusion equation describing vapor diffusion through pipe insulations results in the temperature field, the vapor pressure field, and the amount of condensate. The axial and radial temperature fields were calculated [11S] for transformers with aluminum foil winding and air cooling. Equations derived by Luikov were used [1S] to calculate the temperature and moisture distributions during contact drying of a sheet of moist material. Temperature profiles above the liquid level of dewars have to be known for cryogenic applications and have been measured [2S]. Convective heat transfer in a gas fired combustor, resonating as a one-fourth wave length organ pipe with combustion driven oscillations of 100 Hz, increased by 100 per cent in agreement with a quasi-steady analysis [6S].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Thermodynamic properties

A modest increase in interest in the foundations and applications of thermodynamics is noted. G. Mohan [42T] examines the methodology of thermodynamics; B. Banks [3T] considers aspects of biology from the thermodynamic viewpoint, and carrying forward another aspect of the re-examination of fundamental concepts, Canagaratna [9T] gives a critique of the various definitions of the quantity, heat. R. Gaggioli [20T] continues with his generalizing of the definitions of the quantities, heat and entropy.

In the area of equations of state, MacDonald [38T] reviews, selectively, experimentally and analytically based equations. Tsonopoulos and Prausnitz [61T] also review equations of state but with the particular criterion of their applicability and utility in engineering applications. The virial equation of state is one which has an experimental and theoretical base and enjoys considerable use in engineering calculations. Kilpatrick and Ford [34T] consider the inversion and other manipulations of the virial equation of state; Hajjar *et al.* [27T] report second virial coefficients of eight compounds in the range 40–2000°C. Using a vapor-flow calorimeter fitted with an adjustable throttle, Francis and co-workers [17T] measure the isothermal Joule–Thomson coefficient of benzene and determine the temperature-dependence of the second virial coefficient for this substance. At high pressures (up to 10000 atm), Tsiklis and Polyakov [60T] measure the gas compressibility of nitrogen by the displacement method to temperatures of 400°C. For the same substance, Enkenhus and Culotta [15T] report formulas for the thermodynamic properties of the dense phase.

Other studies on specific substances are those of Barbe [4T] who gives the properties of air at high temperatures, the sixth part of a series including summary and conclusions; Tanishita *et al.* [58T] who determine a new equation of state for steam up to 800°C and 1000 bar; and Verkhivker and co-workers [63T] who report their results for the thermodynamic properties of uranium hexafluoride (UF_6).

Work in the area of phase equilibrium occurs through Goodwin [24T] who reports nonanalytic vapor pressure equations with data for nitrogen and oxygen. For water, Stimson [55T] measures precisely its vapor pressure in the temperature range from 25–100°C. In the solid phase, melting curves of graphite, tungsten and platinum up to 60 kbar are given by Vereshchagin and Fateeva [62T].

Critical phenomena are examined by Smith [51T] in the context of present interests and activities. Spear and co-workers [52T] treat the problem of critical states for mixtures and their equation of state. Workers in the area of liquid behavior and properties are referred to the review by Neece and Widom [43T]. Rajagopalan [46T] reports on molecular sound velocity and compressibility in liquids at constant densities. Heat capacity data are reported in two papers: Dass and Varshneya [12T] study the constant volume heat capacity of water and Gasparini and Moldover [22T] the specific heat of He^3–He^4 mixtures very near the λ line.

Kell [31T] contributes to the long running discussion on the freezing of hot and cold water. Concluding the works in the area of thermodynamics is a paper by Douglas [14T] discussing the conversion of existing calorimetrically determined thermodynamic properties to the basis of the International Practical Temperature Scale of 1968, and one by Pathak *et al.* [45T] describing a recording instrument for measurement of thermal expansion.

Transport properties

The greatest effort in this area continues to be directed toward the thermal conductivity determinations for various substances in various phases.

Diffusion. Annis and co-workers [2T] consider the problem of non-isothermal, nonstationary diffusion. Oost and deVries [44T] report on dimers and their thermal-diffusion factor at slightly elevated pressures. In a practical context, Meier [40T] considers the influence of concentration- and temperature-dependent diffusion coefficients on the drying of hygroscopic plastics.

Thermal conduction. In the gas phase, Saxena and Gandhi [48T] review the methods by which thermal conductivity has been measured. V. K. and S. C. Saxena [49T] combine to report the results obtained for helium using a hot-wire type of thermal diffusion column. For water, a number of studies are addressed to the thermal conductivity of this substance in various phases and states. Brain [8T] reports data for the vapor phase at atmospheric pressure; Behringer, Kollmar and Mentel [6T] give high temperature data in the range 2000–7000°K, Grigull, Mayinger and Bach [26T] treat, in addition to the thermal conductivity of the gas phase, also the viscosity and Prandtl number for the vapor and liquid phase. In the area of polyatomic gases, Sandler [47T] reports thermal conductivity behavior. The influence of a magnetic field on the thermal conductivity of gases is analyzed by Gorelik and Sinitsyn [25T]. Gambhir [21T] examines heat conduction through polyatomic gas mixtures and Tondon and Saxena [59T] calculate the thermal conductivity of polar–nonpolar gas mixtures. The conductivity for binary gas mixtures of nitric oxide, carbon monoxide, as well as values for the individual pure components, is given by Barua *et al.* [5T].

In the liquid phase, thermal conductivity data for sodium in the temperature range 35–98°C is reported by Fritsch and Lüscher [19T]. For the liquid hydrocarbon class of substances, Kanitkar and Thodos [30T] present a generalization of thermal conductivity data. Kellner [32T] gives the critical point exponent of the thermal conductivity of fluids, and French and Adams [18T] the heat transfer coefficients and thermal conductivity of cold liquids.

Thermal conductivity values for substances in the solid state are reported by Sugawara [56T, 57T] for pure fused quartz from 0 to 65°C. Zinov'ev and co-workers report thermal diffusivity and thermal conductivity for vanadium [65T] and palladium [64T] at high temperatures. Yet another study on palladium is performed by Jain *et al.* [28T] using the Jain–Krishnan method. Thermal conductivities for particular industrial material are reported by Küster [36T]—thermoplastic substance; McTaggart and Slack [39T]—an electrical varnish, and Merrill [41T]—an evacuated, idealized powder over a temperature range of 100–500°K. Mixtures involving the solid phase are considered by Cheng and Vachon [10T], who predict thermal conductivity of two- and three-phase solid heterogeneous mixtures, and Kerber and Siems [33T] who report data for two-phase (solid–liquid) systems.

Viscosity. For ordinary and heavy water, Agaev and Yusibova [1T] give viscosity values at high pressures in the 0–150°C temperature ranges. Chusov [11T] employs the law of corresponding states to investigate gas viscosity, and Srichand and Tirunarayanan [53T] correlate viscosities for mixtures of Freon-12 and Freon-22 vapors.

Theoretical work. Transport collision integrals for gases using the Lennard–Jones (6, n) potentials are reported by Lin and Hsu [37T]. For molecules with rotational degrees of freedom, Stevens [54T] calculates transport cross-sections.

For dense gases, Ernst *et al.* [16T] develop a theory of transport coefficients for "moderately dense gases". Devanthan and Bhatnagar [13T] consider transport properties in dense gases. External field dependence of transport properties concern Klein *et al.* [35T] who determine thermal conduction in a fluid of rough spheres.

The Chapman–Cowling higher order bracket integrals for the viscosity coefficients of multicomponent gas mixtures are presented by Joshi [29T]. Bernstein [7T] gives variational calculation of transport coefficients in a binary mixture. For estimating the thermophysical properties of liquids, Gold and Ogle [23T] present a useful treatment. Finally, Schlier's review of intermolecular forces [50T] reflects progress made in this important area over the last year.

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