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HEAT TRANSFER—A REVIEW OF 1968 LITERATURE

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INTRODUCTION

THIS review is concerned with research in the field of heat transfer, the results of which have been published during 1968 or late in 1967. The number of papers in this field published annually is now exceeding a figure of 2000. A selection only can, therefore, 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 1968 Heat Transfer and Fluid Mechanics Institute was held on 17 and 18 June at the University of Washington, Seattle, Washington. The majority of papers presented were concerned with heat transfer. Proceedings are available at Stanford University Press. The Tenth National Heat Transfer Conference held in Philadelphia, Pennsylvania, on 11 through 14 August 1968, offered special lectures by A. E. Dukler on "Transport in Presence of Interphase", and by D. B. Spalding on "Applications of Boundary Layer Theory", as well as an invited lecture by E. R. G. Eckert on "Plasma Heat Transfer". In addition, the topics of process heat transfer, analytical methods, heat transfer in fast reactors, boiling, radiation, loss of coolant, transpiration and film cooling were discussed. 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 Third All-Union Heat and Mass Transfer Conference of the USSR assembled a large number of scientists and engineers at Minsk during the days 14 through 18 May 1968, for the discussion of 434 papers in the fields of liquid and gas flows interacting with bodies, heat and mass transfer involving physical and chemical conversions, in rheological systems, in technological processes and chemical engineering apparatuses, in dispersed systems, in capillary porous bodies, and in drying as well as physical properties and mathematical methods. The papers have been published in Russian in a series of volumes and translation into the English language is in preparation. An international Summer School at Herceg-Novi, Yugoslavia, on 9 through 21 September 1968, was devoted to the subject of heat and mass transfer in turbulent boundary layers. The topic was discussed by researchers from England, France, Russia, the United States, and Yugoslavia. It is planned to have such symposia annually on specific topics, organized by an International Centre for Heat and Mass Transfer which was created for this purpose. 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. Springer publishers have started the publication of a new journal, *Wärme- und Stoffübertragung*, to provide a vehicle for the presentation of results of heat transfer research in Germany and adjoining countries.

Developments in research on heat transfer problems during 1968 can be highlighted by the following remarks: Heat transfer by thermal radiation has found special attention as indicated by the large number of papers. Non-gray gases, emitting, absorbing, and scattering media were considered in analyses of heat transfer caused solely by radiation or in combination with conduction and convection. Directional variation of surface properties was also included. In channel flow, papers dealt with augmentation or diminution of heat transfer by turbulence promoters, particles, polymers, and similar means. The effects of secondary flow caused by rotation, curvature, and heating from below found attention. A considerable number of boundary layer solutions were presented for various boundary conditions whereas the interest in the study of chemical effects appears to have declined. Detailed measurements indicate that none of the available models describes the turbulent mechanism adequately for all situations. A separate equation for the growth and decrease of turbulent energy was used in the study of turbulent heat transfer. Turbulent Prandtl numbers for liquid metals have been found from measurements to be quite different from values for normal fluids on the temperature field. The upstream effect of axial conduction in laminar channel flow of a liquid metal was studied analytically. Basic problems in the transition regime between slip flow and free molecule flow, for instance heat conduction between parallel plates or concentric cylinders, found attention. The effects of variable wall temperature and mass injection on heat transfer in separated regions was investigated and the influence of turbulence level on heat and mass transfer in packed beds has been studied. The classical problem of natural convection heat transfer on a vertical flat plate in laminar and turbulent flow found renewed interest as well as the problem of heat transfer in a horizontal layer heated from below in the laminar, unstable, and turbulent region. In boiling heat transfer, the effects of surface roughness and the development of methods to specify surface conditions as well as the effects of a low gravitational environment were investigated. Condensation under the presence of noncondensible gases was studied. Heat conduction was studied for the condition of a phase change at interphases, of contact resistance, and of special boundary conditions like those created by radiation. Optical techniques for the measurement of flow and heat transfer parameters were developed and applied.

Research in thermodynamic and transport properties continues to reach toward the extremes of very low and very high temperatures by analytical and experimental efforts. An increased interest in predictive schemes for determining transport properties of multicomponent mixtures (both liquids and gases) is noted as well as several efforts to collect, organize, and correlate information on the behavior of certain classes of solids.

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

Several papers dealing with heat conduction in the presence of a phase change were published throughout the year. The solidification of a binary eutectic system does not take place isothermally, so that a mathematical model of the solidification process involves consideration of a finite non-isothermal freezing zone separating the regions of pure liquid and pure solid [46A]. When a solid slab is immersed into its parent liquid (e.g. a slab of ice in water), a multi-boundary phase change problem ensues [4A]. Equations correlating the results of finite-difference solutions are given for evaluating the time required to fully freeze an initially saturated liquid in the form of a slab, a cylinder, or a sphere [45A]. The continuity conditions at a three-dimensional phase change interface are examined and rephrased [25A]. Series expansion methods have been employed in solving one-dimensional phase change problems with moving boundaries [10A, 23A]. In a mathematically oriented paper, existence, uniqueness, and stability for the Stefan problem (one-dimensional conduction with phase change) are investigated [3A].

Heat conduction in solids whose surfaces exchange heat by thermal radiation has been subjected to analysis. Biot's variational method is applied to transient conduction in a one-dimensional solid [31A]. When more classical methods are applied to such problems, one encounters an integral equation, solutions to which are obtained numerically [1A] and by a method involving the approximation of the kernel of the integral equation [6A]. Solutions for the steady-state heat loss from radiating-convecting fins are derived by applying a self-correcting linearization of the radiation term [43A] and in closed form in terms of integrals which must be evaluated numerically [41A]. For transient heat transfer in a radiating fin, the governing energy equation can be reduced to an ordinary differential equation by use of a similarity variable, but with limitations on the time dependence of the fin base temperature and on the initial temperature distribution [36A]. The temperature field within thick-walled and solid cylinders irradiated by a distant source (e.g. solar radiation) is solved by a variational method [13A] and in closed form subsequent to linearization [27A], respectively in the absence and in the presence of cylinder rotation. An analysis of the circumferential temperature distribution in a thin-walled rod illuminated by solar radiation was motivated by application to control rods for earth satellite stabilization [9A].

Certain mass diffusion problems are governed by equations identical to those of heat conduction, so that the solutions can be carried over and utilized directly. Among recently investigated transient diffusion problems, a variational formulation is devised for solving problems involving concentration-dependent diffusion coefficients [11A]; the transient response of a system consisting of two finite, contacting slabs having initially different concentrations of a diffusable material is analyzed [5A]; and the time-dependent distribution of charged particles in a plasma is solved for, taking account of diffusion and recombination [20A]. The steady-state mass transfer between a point source and a reactively participating plane surface is determined for a range of operating conditions characterized by the relative importance of diffusion and reaction [19A].

The thermal resistance at the interface of contacting solids is a matter of considerable practical importance. In a comprehensive analytical study involving metallic surfaces, consideration is given to: contact between the same metals when the thicknesses of the solids are large compared with the surface roughness [37A], different metals and small thicknesses [38A], oxidation of the contacting surfaces [39A], and waviness of the contacting surfaces [40A]. The magnitude of the interfacial resistance for certain dissimilar metals depends on the heat flow direction, the extent of the directionality being a function of the flatness and roughness of the interfacial surfaces [17A]. The region of contact between two media is envisioned to be a heterogeneous layer and the resulting perturbation of the temperature field studied by a rheoelectric analogue [24A].

Application-oriented solution methods described in the recent literature include a generalization of the Monte Carlo method such that large numbers of random walking particles are simultaneously released [7A], the use of orthonormal functions for solving steady and transient problems in arbitrarily shaped bodies with arbitrary boundary and initial conditions [42A], an analogy method involving a continuous resistive medium (a liquid) and discrete capacitances [32A].

Solutions to several specific steady-state heat transfer problems have been published. These include: the 30-deg right triangle [33A], a circular cylinder consisting of two axial sections of different thermal conductivities [15A], a plane slab having a disk-shaped region of prescribed non-uniform temperature on its mid-plane [26A], circular bars with various internal geometries [18A], and the two-dimensional pin fin [14A]. The latter investigation demonstrated that errors in the traditional one-dimensional fin model are strongly dependent on the Biot number.

Steady-state problems involving internal heat generation were also dealt with. Theorems are developed and applied which relate changes in the average temperature of a heat generating region with changes in the relevant physical parameters (e.g. source strength, thermal conductivity) [21A]. A nonlinear estimation technique is employed to treat nonlinear temperature dependent heat sources [44A], while a series solution is constructed to describe the three-dimensional temperature field in heat generating plates [22A]. A problem of multiple heat sources in a rectangular solid is solved in connection with ceramic or glass substrates for integrated and thin film circuits [12A].

A number of papers was devoted to various aspects of transient heat conduction. Temperature-dependent thermal properties in a semi-infinite solid are accommodated by a series solution in terms of the magnitude of the temperature step applied at time = 0 [2A]. A solution is given for a finite cylinder, initially at uniform temperature, subjected to a prescribed temperature on one of its end faces while all other surfaces are adiabatic [8A]. Classical methods, in contrast to integral transforms, are applied to solve unsteady problems wherein the boundary conditions are functions of time [34A]. The use of transcendental profile functions in the approximate solution of one-dimensional transients yields results of high accuracy [35A]. Solutions are given for one-dimensional problems in which the temperature and the heat flux are both prescribed at the same boundary [16A]. A series of mathematically oriented papers is concerned with general transient problems characterized by arbitrary initial temperature, arbitrary boundary conditions, and internal heat generation [28A, 29A, 30A].

CHANNEL FLOW

Several investigations reported during the year were concerned with techniques for either increasing or decreasing heat transfer coefficients for internal flows. Suspensions of glass beads or graphite particles in air augmented the heat transfer coefficients in the low Reynolds number turbulent range [43B], while a similar experiment performed with glass beads at $Re = 130000$ showed no augmentation [3B]. The effect of twisted strips [41B], spiral ribbing [36B], screening [12B], and screw threads [8B] on turbulent heat transfer and friction in tubes and annuli was investigated experimentally and, whenever possible, predictive correlations were devised. The addition of small amounts of certain polymers to turbulent liquid flows reduces the friction factor and the heat transfer coefficient [32B, 42B].

The multiplying factor $(Pr_b/Pr_w)^{0.11}$ (b = bulk, w = wall) extends constant property turbulent Nusselt numbers for liquids to variable property situations [18B]. A finite-difference analysis, supplemented by experiments, has led to an improved prediction method for variable property heat transfer in turbulent gas flows in the thermal entrance region of tubes [25B]. Temperature profile measurements covering the Prandtl number range from 0·026 to 14·3 are brought together and presented in semi-logarithmic form [13B]. Pai's turbulent velocity profile was employed as the basis of Nusselt number predictions covering the Prandtl number range from 0·01 to 10 [14B]. Results for turbulent tube flow with axially varying wall heat flux were derived by superposition of the uniform heat flux solution and verified experimentally [15B].

Independent analyses for annuli with heated inner tube and adiabatic outer tube provide turbulent Nusselt number results over a wide range of Prandtl number, both for the thermal entrance region [22B] and the thermally developed region [44B]. Experimental results for turbulent airflow in annuli with small cores and with a variety of heating conditions are correlated in terms of the j factor [6B]. Local heat transfer results for turbulent airflow in an electrically heated equilateral triangular duct were found to be about 10 per cent below the corresponding circular tube results [4B]. The effect of flow acceleration in a converging nozzle on the throat heat transfer was explored analytically and a criterion for re-transition of the turbulent boundary layer derived [39B]. Experiments on direct contact heat transfer between oil and water flowing in a pipe have been performed for high velocity, non-stratified conditions [45B].

Plasma jets of helium, argon, and nitrogen were employed in experimental investigations of entrance region heat transfer in a tube [20B]. A finite-difference analysis of the thermal entrance region for an argon plasma spanned the range of wall to bulk temperature ratios of 0·05–0·4 [19B]. An independent analysis provides results which can be used for estimation of the flow in arc-tunnel channels [26B].

Most studies involving laminar flow tend to be primarily analytical in nature. Graetz-type problems are shown to be amenable to solution by Monte Carlo methods [5B]. Fully developed Nusselt numbers for ducts of arbitrary cross sectional shape can be bracketed by upper and lower bounds [31B]. Solutions for the upstream portion of the thermal entrance region, originally derived for a single flowing stream, are generalized to apply to two co-current streams [11B].

Sublimation at the wall of a channel is analyzed under the condition that the heat of sublimation is supplied by the gas flowing through the channel [38B]. Uniform injection of mass at the wall of a circular tube decreases the Nusselt number, while mass extraction has an opposite effect [21B]. Experiments on water flow through a tube having a layer of ice at its inner surface show that the predictions of analysis can be rendered inaccurate by the influence of free convection [46B]. Mass transfer across the interface of a two-layered stratified flow in a horizontal parallel-plate channel is studied analytically [1B].

A combined analytical and experimental investigation of heat transfer to oil (SAE 60) in laminar tube flow yields Nusselt numbers that show only fair agreement between theory and experiment [40B]. The accounting of temperature-dependent liquid viscosity gives rise to a nonlinear internal heat generation in a Couette flow; studies involving a power-law non-Newtonian fluid confirm the Newtonian finding that there is a maximum shear that can be applied to the flow [10B]. The thermal response of a Couette flow to the initiation of viscous dissipation is slower when the heat capacity of the bounding wall is taken into account [33B]. The transient response of a laminar channel flow to a periodically varying inlet temperature is analyzed both as a solution of the energy equation and on the basis of the quasi-steady model, and the conditions are delineated under which the latter is applicable [37B].

Secondary flows, superposed on the main axial flow in a tube, are found to increase the heat-transfer coefficient. The quantitative effects of such secondary flows have been investigated for a uniformly heated horizontal tube [27B], a tube rotating about an axis perpendicular to the axis of the tube [28B], a tube rotating about an axis parallel to the axis of the tube [29B], and a curved tube [30B].

Low Peclet number laminar flows are known to be affected by axial conduction. On the basis of a finite-difference analysis, it is shown that axial conduction in the region upstream of the heated tube plays a decisive role, and that the assumption of a uniform fluid temperature profile at the beginning of the heated section is not realistic [16B].

Several papers have appeared dealing with various aspects of heat transfer to laminar magnetohydrodynamic flows in tubes [9B] and in parallel-plate channels [2B, 7B, 17B, 23B, 35B]. In some of the analyses, the effect of axial conduction was accounted for, but without consideration of the aforementioned nonuniformity of the temperature profile at the start of heating.

In a pair of applications-oriented papers, a model is proposed and applied for determining the hot channel factor for a rod-bundle nuclear reactor [24B], and design equations are developed for the prediction of heat transfer coefficients for the flow of refrigerants through evaporator tubes [34B].

BOUNDARY-LAYER FLOW

Boundary-layer theory and solutions

Solutions have been obtained for laminar wedge-type boundary layer flow with variable wall temperature and with transpiration including viscous dissipation [13C]. Results are presented in tables and graphs. The requirements for similarity solutions of the three-dimensional compressible laminar boundary layer are discussed and four such solutions are singled out because of their practical interest [29C]. How to use relations for self-similar solutions to the compressible boundary layer to obtain relations for non-similar flow over an air foil is discussed [20C]. Cole's transformation of the compressible laminar boundary layer equations to their low speed equivalent is extended to flow with heat and mass transfer and with pressure gradients [19C]. Laminar flow heat transfer from a flat plate is calculated by successive approximation when the thermal conductivity of the plate varies linearly with temperature [30C]. The variable property laminar boundary layers of water are investigated in the region of adverse pressure gradient [23C]. The position of separation is found to move upstream when the wall is heated and downstream when it is cooled. The velocity profiles within a stagnation point boundary layer with large wall to free-stream enthalpy ratio exhibit a strong overshoot [22C]. A calculation of high Prandtl number boundary layer flow with injection indicates that at certain blowing rates the thermal boundary layer is blown off the wall but remains embedded in the viscous boundary layer [16C]. Shear in the flow outside the laminar boundary layer can increase heat transfer significantly [9C]. A numerical solution of the flow and heat transfer in the axially symmetric boundary layer over a circular cylinder covers the whole range of boundary layer thickness to cylinder radius from zero to 50 [10C]. The shapes of the velocity and temperature profiles are presented in graphs. The effect of transverse curvature on skin friction and heat transfer in laminar flow of air past slender circular cylinders is investigated for a parameter $u_e r_0^2/r4\nu x$ varying from 0·01 to 1000 and for heating and cooling (u_e free stream velocity, r_0 cylinder radius, ν kinematic velocity x distance from the upstream end of the cylinder [5C]). Various methods to solve the laminar boundary layer equations for continuous flat surfaces moving into a fluid are compared for a wide range of the injection or suction parameter at the surface and for Prandtl or Schmidt numbers respectively of 1, 10 and 100 [12C]. The integral method compares well with numerical solutions.

The method by Kutateladze, Leontev and Druzhinin for turbulent boundary layer calculations has been extended to large Mach numbers [26C]. Spalding numbers for use with the energy equation of the homogeneous incompressible turbulent boundary layer have been calculated for constant laminar and turbulent Prandtl numbers, for uniform blowing or suction, for a step-wise wall distribution, and the results have been compared with experiments [35C]. The Spalding number for step-wise wall heat flux has been recalculated, some errors have been removed, and the results have been extended to a source heat flux [31C]. The rate with which the shear stress distribution in a turbulent boundary layer moves toward a self-similar situation was found to be proportional to the extent of the original departure [21C]. Approximate solutions for the compressible turbulent boundary layer in three-dimensional flow have been obtained using a coordinate system based on the trace of the inviscid stream lines [4C]. The cross flow within the boundary layer was assumed small. The results for a yawed infinite cylinder are compared with experimental information.

Oscillatory hypersonic boundary layer flow with ablation was investigated assuming small amplitudes, low frequencies, and laminar flow for two cases: the flat plate in a stream with sound waves and the oscillating plate in a continuous velocity stream [18C]. Heat transfer and shear in an unsteady boundary layer on a flat plate as it develops following the passage of a shock wave has been investigated and previously available solutions for a short time or a long time respectively after the shock are extended to the intermediate time interval [11C]. Results are checked with experimental information. The time required to achieve steady condition for laminar boundary layer heat transfer of fluids with Prandtl numbers between 0·01 and 100 is found to be inversely proportional to the free stream velocity and for $0.72 < Pr < 100$ to be proportional to the Prandtl number to the one-third power [6C]. The Howarth–Dorodnitzin transformation and the Crocco integral are used to relate the temperature field to a laminar constant property velocity field and to calculate the transient boundary layer development for impulsive start from rest with the momentum integral equation [27C]. A Prandtl number of one and a constant value of the product of density and viscosity are assumed. The development of an unsteady compressible boundary layer over a semi-infinite flat plate, whose temperature is varied with time, is investigated for constant acceleration starting from rest [28C]. The calculation by H. Mirels of the wall shear and heat transfer in laminar boundary layers behind an advancing shock has been extended to include the recovery factor [1C].

Dissociation, ionization and chemical reactions

A technique is discussed which leads to rapid convergence for a non-similar solution of the multicomponent laminar boundary layer by an integral-matrix method [17C]. Diffusion and thermo-diffusion are included. Laminar boundary layer flow of a dissociated gas past catalytic surfaces is investigated describing the gas in the boundary layer as a chemically-frozen mixture of atoms and molecules [14C]. Surface reaction rates and reaction orders are varied. Experiments on stagnation point convective heat transfer in frozen boundary layers on surfaces having widely different catalytic activity were found to be in good agreement with a theory by Goulard [24C]. Results are obtained experimentally of the convective stagnation heat transfer in air, CO_2–N_2, and CO_2–Ar_2 mixtures in a shock tube for enthalpy levels between (9·3 and 48) $\times 10^6$ J/kg, for stagnation pressures between 15 and 160 at. The results agree well with theory [2C].

Effects of magnetic and electric fields

The Kármán–Pohlhausen method was used to study MHD boundary layers for two cases: a semi-infinite plate with a magnetic field normal to the wall and to the flow direction moving along with the fluid, a two-dimensional channel with an applied field generated by a current-carrying conductor in the lower wall, and a semi-infinite plate with a magnetic field normal to the wall and to the flow direction but fixed in position with the plate [25C]. Mass transfer in an aligned-field, magnetohydrodynamic flow of a viscous electrically conducting constant property fluid past a porous plate with suction or blowing was analyzed [34C]. The critical Rayleigh number for the thermal instability of a fluid in a vertical rectangular channel with a horizontal magnetic field was found to depend on the Hartmann number and the aspect ratio [36C]. Temperatures in a plasma jet were measured by spectroscopy [8C]. The electric current was varied between 200 and 600 A and the mass flow between 10 and 130 g/min. The plasma produced in a shock tube was made to flow into an X-band rectangular wave guide [3C]. The temperature measured with this device was found to be between 4800 and 6000°K at Ma = 7–10, and a pressure of 4 mm Hg in argon.

Experimental studies

Transient heat transfer in forced convection flow over a flat plate of appreciable thermal capacity and containing an exponential time dependent heat source was studied experimentally and analytically for a fluid with a Prandtl number close to one [32C]. Depending on the parameter $L/u_e t_0$ (L plate length, u_e free stream velocity, t_0 time scale), the steady turbulent flow solution or Chambre's slug flow solution or an intermediate transient range describes the situation. The results of an experimental investigation of heat transfer from a highly cooled boundary layer to a hollow cylinder in axial flow obtained in dissociated air in a shock tube agree with the analysis using the method by Spalding and Chi [15C]. The Reynolds range investigated was between 10^5 and $1{\cdot}4 \times 10^6$, the stagnation enthalpy corresponded to a velocity of 8 km/s, and the ratio of cooled wall enthalpy to adiabatic wall enthalpy varied from 0·01 to 0·04. Heat transfer on blunt curved plates with concave and convex surfaces producing a positive or negative pressure gradient was investigated at Mach numbers from 6·8 to 9·6 and for Reynolds numbers between (0·05 to 3) $\times 10^6$ [7C]. A similarity analysis was found to agree well with the results of experiments and of a numerical machine solution. The velocity field in a turbulent cylindrical wall jet created around a cylindrical rod was studied experimentally and was found to be describable by the model of a turbulent boundary layer which merges into an outer free shear layer [33C]. Significant curvature effects were found in the boundary layer region.

FLOW WITH SEPARATED REGIONS

Single bodies

Flow processes in cavities received special emphasis. Bales [4D] studied heat transfer across nearly circular cavities including the effects of variable wall temperature and mass bleed. The effect of mass bleed on cavity heat transfer in supersonic flow is highly sensitive to injector location and bleed air temperature [11D]. For flow in rectangular cavities, a turbulent external boundary layer is unsteady when the cavity is less than 20 times the sublayer thickness [38D]. Pan [36D] deals with steady flow in a rectangular cavity where the motion is generated by the translation of the covering wall—experimentally by the rotation of a large wheel. For such finite cavities at large Re, the flow consists of a single inviscid core with viscous effects confined to thin shear layers near the boundaries.

The interaction between a viscous, dissipative layer near a body surface, or in its wake, and an isentropic flow is considered to be the main mechanism in determining the flow conditions in supersonic separated flows [44D]. The injection of helium into a ramp-induced separated zone on a flat plate at $M = 20$ decreased the heating rate by less than a factor of 2 while injection into a normal boundary layer produced a factor of 7 decrease [31D]. The effect of suction on wedge-induced laminar separation at $M = 12$ is to remove the low momentum fluid near the wall, enabling the remaining shear layer to negotiate a higher compression at reattachment [5D]. Ginoux [23D] gives an empirical correlation between reattachment pressures and heat transfer peak as a function of injection rate into a conical cavity at $M = 5{\cdot}4$. Bushnell [9D] presents correlations of peak heating at reattachment in the form $St \sim Re^{-n}$ where $n = \frac{1}{2}$ for laminar separation and $\frac{1}{5}$ for turbulent separation. Back [2D] presents experimental heat transfer results for shock-induced flow separation in supersonic nozzles. When separation due to a pseudo-shock system occurs just downstream of the throat, the local heat flux exceeds the throat values with laminar boundary layers in the throat.

The problem of flow separation over a rearward facing step is characterized by a large local expansion around the corner which dominates the downstream separation point. The base pressure influences the expansion process for a distance proportional to $(M_\delta \delta)$ upstream of the trailing edge [50D]. The reattachment point and peak pressure are insensitive to Mach number [45D]. An implicit finite difference method is used to study the interaction with sharp or rounded rearward facing steps [7D]. The parameter that correlates base pressure in accelerated supersonic free streams must include length scales deduced from the free stream pressure gradient and its derivatives [10D]. The pressure gradient and thickness of the mixing layer at reattachment are related [13D]. The specific impulse for base burning of hydrogen is about 10 000 s [15D]. The effect of base hydrogen combustion on the base properties is correlated in terms of the recirculation zone fuel concentration [18D]. A modification of recompression component of the conical flow pressure rise model plus accurate computer solutions of the axisymmetric mixing produces base pressure predictions in better agreement with experiment [34D].

Agreement is found [27D] for velocity profiles across hypersonic projectile turbulent wakes using a sequential spark technique or an array of electrostatic probes. The near-wake flow field behind a sharp cone is severely altered by an instrumentation boom [14D]. Aluminum ablation vapor excitation temperatures in the wake of a sphere were observed spectrometrically [32D]. Experiments [22D] in the wake of a sphere include the observation that no region of continuous turbulence exists (even on the wake axis) at that small scale velocity, and temperature fluctuations are nearly homogeneous at a wake cross section. Compressible far-wake temperature and velocity defects decay according to the inverse $\frac{2}{3}$ decay law characteristic of the incompressible axisymmetric wake [16D]. This region is preceded by a relaxation distance of at least 40 virtual diameters. Experimental results [39D] suggest that as a result of incorrect turbulent diffusivity models, current turbulent wake programs all predict a wake that cools too rapidly. Baker investigates the mixing of two parallel streams (velocity ratios 1–1 and 5–1) of dissimilar fluids (density ratios 1–1 and 7–1) using hot wires [3D].

Packed and fluidized beds

Clamen [12D] reviews a number of experimental studies concerned with the influence of turbulence on heat and mass transfer. Experimental results on a sphere [29D] indicate that the product of the Reynolds number and turbulence intensity is a significant parameter while the scale of turbulence is not. Total heat and mass transfer from a hailstone can be intensified (up to 100 per cent increase by the effect of roughness and turbulence intensity [1D]). The effect of transverse vibration upon the mass transfer from horizontal cylinders is increased by a factor of 30 for sublimation and a factor of 10 for gaseous systems [48D]. A method of "dry spraying" of napthalene was used to determine local Sherwood numbers on a sphere for $3200 < Re_d < 25\,000$ [30D]. The high intensity of turbulence in a 40 kW direct-current, nitrogen, plasma jet increased the heat transfer to a sphere [28D]. The local Nusselt number at the rear stagnation point of a sphere in Stokes flow is 1·192 [47D]. Studies of spheres and cylinders suspended freely in a shear flow as $Re \to 0$ indicates a difference in heat and mass transfer at high Pe between an approaching uniform and shear flows [19D]. Dennis [17D] has analyzed the steady laminar forced convection from a circular cylinder at low Reynolds numbers using the "correct" velocity distribution in the field according to the full Navier–Stokes equations in the range $0{\cdot}01 < Re < 40$.

Comparisons [49D] of h values for particles and for bodies immersed in a fluidized bed confirms the idea that low effective values of h of solid particles appear simultaneously with large true values because of gas channeling. Quantitative analyses of the effects of holdup, average residence time, surface active agents, viscosity, and average particle size on heat and mass transfer rates in dispersions are given for two major domains [21D]. Barnstone [6D] and Gal–Or [20D] discuss the frequency response of gas mixing in a fluidized bed reactor. Barnstone's generalized model accounts for the effects of channeling, transfer lag, mixing, and mass transfer that occur on each plate of a column in the process of separating a multicomponent mixture in unsteady operations. Beckman [8D] and Ryazantsev [41D] deal with fluidized beds in furnaces and porous materials.

No generalized correlation has been developed for heat transfer in fluidized beds as a result of experimental difficulties in evaluating the proper temperature difference, transfer area, and channeling effects [37D]. Myklestad [35D] analyzes the transient flow of heat and moisture during drying of granular beds. The theory, applicable for numerous products in the chemical and food industries, is developed for materials drying in 4 stages. Siegel [46D] presents correlations for nitrogen flow across banks of electrically heated meshes or tubes for the following variables: (1) porosities from 0·37 to 0·88; (2) wire or tube diameters from 0·0076 to 0·375 in; (3) surface temperatures to 5500°R; (4) outlet gas temperatures to 3160°R, and (5), Reynolds numbers from 3 to 30 000. Schmidt-Pathmann [43D] investigates the effective heat conductivity of wire gauge packings with fluid throughflow. Momentum and heat transfer mechanisms are studied in rectangular shaped packings [25D], elliptical tubes [42D], tubular coils [33D], concentric sphere heat exchangers [40D], oblique packed columns [26D], and general packed beds [24D].

TRANSFER MECHANISMS

The effect of streamwise vortices on laminar boundary layer flow and heat transfer was studied for flow over a flat plate by a perturbation solution for any value of the Prandtl number, assuming the transverse velocity fluctuations to be small [5E]. Such vortices have been observed in reattaching flows. A temperature dependent velocity has a stabilizing effect on laminar boundary layer flow of water and other liquids; whereas it acts slightly destabilizing in air provided the wall temperature is larger than the free stream temperature [6E]. The critical Reynolds number for boundary layer transition depends on the frequency spectrum of the free stream disturbances [11E]. The effect of acoustic noise fields was investigated particularly. The influence of cooling on the size of a single spherical element required to produce earliest transition on a 10 degree cone in supersonic flow was studied experimentally [13E]. Equations are presented describing the effect of the wall temperature, the Mach number, and the element size on the trip position.

A statistical analysis of weak, locally, homogeneous turbulence in a field with a uniform normal strain was made and the longitudinal transfer of heat was calculated for accelerated and decelerated rotationally symmetric flow [4E]. Heat transfer to a stagnation point is discussed and it is pointed out that the velocity fluctuations became larger as the stagnation point is approached. A similar analysis was made considering a combined two-dimensional shear and normal strain with initially isotropic turbulence [3E]. The turbulent Prandtl number was found to decrease at first and then to increase again, reaching a minimum of approximately 0·4. Correlation measurements in a two-dimensional turbulent boundary layer with zero pressure gradient gave results which are not consistent with any of the models of the large eddy structure [12E]. It is maintained that the model of a coherent eruption from the viscous sublayer is also unsatisfactory. The spectral power density, the amplitude density, and the intensity of heat transfer fluctuations in wall turbulence were measured in pipe flow of water using hot film sensors. The average frequency of the heat transfer fluctuations was found to be $18{\cdot}2 + 6{\cdot}5 \times 10^{-4}\ Re$ [1E]. The diffusion process in turbulent mixing between two coaxial supersonic streams was found to follow the relation $\rho D_t = kr_{\frac{1}{2}}\ (\rho u)_c$ {ρ density, D_t turbulent mass diffusion coefficient, $r_{\frac{1}{2}}$ radius at which concentration is one-half, $(\rho u)_c$ mass velocity on center line}[14E]. It is shown that momentum diffusion, enthalpy diffusion, and mass diffusion are of different form. The mixing length and the kinematic eddy viscosity were obtained from measured velocity profiles in a compressible boundary layer by integration of the boundary layer equations [7E]. The influence of Mach number between 0 and 5 on the mixing length was found to be quite small; the effect on the eddy viscosity to be larger. A method to calculate the boundary layer development using the turbulent energy equation has been described [2E].

The turbulent energy equation is converted into a differential equation for the turbulent shear stress and empirical functions are introduced for the generation, diffusion, and dissipation of turbulent energy. Expressions by Tien for the asymptotic forms of momentum and heat transport in the turbulent sublayer near a wall are extended to include the effect of transpiration [8E]. It is found that the turbulent diffusivity of heat increases proportional to the third power of the wall distance. The effect of upstream turbulence on the average heat transfer from spheres has been investigated experimentally in a Reynolds number range between $3{\cdot}6 \times 10^3$ and 5×2^2 [9E]. The Nusselt number was found to increase with turbulence intensity and with the ratio of diameter to scale of turbulence up to 5. A cross flow support increases heat transfer by approximately 10 per cent. The following equation describes the Nusselt number for turbulence free air (turbulent intensity smaller than 0·0015) $Nu = 2{\cdot}0 + 0{\cdot}210\ Re^{0{\cdot}606}$, with an average deviation of 0·8 per cent and a maximum deviation of 2 per cent. A spherical protuberance has a maximum effect on heat transfer in a turbulent boundary layer two diameters downstream of the sphere and the effect is limited to four diameters in width [10E]. This was established by experiments for a ratio of sphere diameter to boundary layer thickness between 2 and 0·7.

NATURAL CONVECTION

There continues to be great interest in natural convection phenomena as indicated by the large number of recent analytical and experimental studies. One area of emphasis is on natural convection from a vertical flat plate; a problem which many thought had been laid to rest years ago. However, a number of modifications to the well-known solutions have been presented recently and, in particular, there appears to be considerable interest in the heat transfer under turbulent flow conditions. The other major focal point in natural convection studies appears to be thermal convection in horizontal fluid layers. The studies in this area have been concerned with stability, laminar flow, and high Reynolds number turbulent flow. In addition, there have been studies of other natural convective phenomena including the effects of different geometries, variable properties, and combined free and forced convection.

At sufficient height above a heated region on a vertical flat plate, laminar free convection velocity and temperature distributions behave as though generated by a line source at the base of the plate [39F]. A companion analytical study has been performed for a partially heated plate [40F].

Measured velocity and temperature fields agree with an analysis of the free convection on a non-isothermal vertical surface [4F]. Calculations [19F] indicate the response of the laminar free convection boundary layer on a vertical plate to a wall temperature oscillation. A composite Grashof number is found to predict simultaneous heat and mass transfer in laminar free convection from a vertical plate [10F]. Heat transfer from a vertical plate in water near its maximum density point has been studied [44F]. An integral method is applied to study the laminar natural convection heat transfer from both an isothermal and a non-isothermal plate to a power-law fluid [42F].

Some limiting cases of combined free convection heat and mass transfer have been analyzed [26F]. At small Prandtl number, deviations from boundary layer theory due to neglect of the streamwise second derivative of temperature appear at relatively high Grashof number [38F]. A transcendental approximation to the velocity and temperature profiles has been used to obtain integral solutions of the natural convection boundary layer at small Prandtl number [8F]. An experiment [32F] shows a similarity solution with magnetic laminar convection with mercury on a vertical flat plate.

Calculations have been performed [20F] for the laminar free convection boundary layer on vertical cylinders and cones with radii of the order of the boundary layer thickness. A combined conduction and free convection analysis agrees well with the experiments on a downward projecting fin [28F].

Experiments on turbulent natural convection from a vertical plane surface are in general agreement with each other although there are differences in a number of the details. One study [5F] of the temperature and velocity profiles, as well as the heat transfer, shows agreement with the predictions of Eckert and Jackson, as does a somewhat earlier study [7F]. Another experimental study [47F] finds that the heat transfer is more closely given by the theoretical prediction of Bayley. The absence of a laminar sublayer has been noted in another study of the turbulent free convection boundary layer [27F] and an analysis predicts the turbulent velocity and temperature profiles using eddy diffusivities similar to those found in forced convection [17F].

An analysis [1F] predicts the interaction of combined heat and mass transfer at a subliming vertical surface. A numerical solution for combined free and forced convection to non-Newtonian fluids indicates the parameters that determine the relative importance of the free convection effects [23F].

An analysis of the free convection heat transfer from a sphere at small Grashof numbers utilizes an inner solution and a matched outer asymptotic expansion [12F]. Combined free and forced convection in the Stokes fluid region is studied using a single drop in a liquid–liquid system [33F]. Experiments on free convection mass transfer from electrodes in the form of a mesh have been reported [48F].

An experimental study [13F] of heat transfer by free convection from a horizontal wire to carbon dioxide in the critical region indicates that constant-property free-convection correlations can be used in this region with the proper choice of properties. Another study [18F] indicates similar results utilizing a different means to determine the reference state at which to evaluate the thermo-physical properties of the fluid in the critical region. Heat transfer to sulfur hexafluoride in the critical region has been studied in a natural circulation loop [41F].

A study comprising analysis [21F] and experiment [22F] indicates finite amplitude convection in a horizontal fluid layer with a changing mean temperature and a hexagonal flow pattern near the critical Rayleigh number. Another study shows the possibility of subcritical instability with heat sources present in a horizontal fluid layer [16F]. With a stabilizing gradient of solute, the onset of flow in a horizontal fluid layer may begin with oscillatory motion [45F]. An inhomogeneous fluid with a linearly increasing density in the upper direction can be stabilized by heating from above [2F]. Subcritical instabilities are found possible in a horizontal layer of water cooled from below with a lower surface at zero degrees Celsius. If the depth of the layer is large and the upper surface is well above 4°C, the upper region of the horizontal layer does not greatly influence the flow [31F]. Another study in a horizontal layer of water near the maximum density point compares measurements and predictions of stability [43F]. A lower bound for the critical Rayleigh number in the development of secondary fluid motion in channel flow has been calculated [37F].

A perturbation analysis has been carried out for conditions near the onset of instability in a horizontal fluid layer heated from below [15F]. Numerical calculation for two-dimensional steady laminar thermal convection has been completed at relatively low Rayleigh numbers over a range of Prandtl numbers [34F]. Two-dimensional rolls at Rayleigh numbers slightly above critical have been examined experimentally [6F]. A two-dimensional model [9F] has been used to simulate thermal convection in the Earth's mantle.

The flow pattern in a horizontal fluid layer heated from below has been studied up to Rayleigh numbers of about $1{\cdot}5 \times 10^6$. These measurements include cell size and some temperature distributions [24F]. Calculations for the second and third transitions predicted by Malkus for the thermal convection have been performed [35F]. A numerical study [46F] has been made of two-dimensional convection in a rotating fluid.

The free convective flow pattern above a horizontally heated surface has been examined experimentally [14F]. Series expansions of the temperature and stream function have been used to determine velocity and temperature profiles for natural convection between horizontal concentric cylinders [29F]. A calculation [30F] of the natural convective heat transfer between concentric spheres has been performed at low Rayleigh numbers. The heat transfer through a gas contained between two vertical cylinders has been studied with interest in application to thermal conductivity cells and accommodation coefficient measurements [25F]. A model has been suggested [11F] to correlate transient natural convection in a vertical cylinder.

An empirical correlation has been obtained for two-phase flow in a thermosiphon reboiler [3F]. With the addition of free convection, the laminar forced convection Nusselt number in a horizontal tube is affected significantly far downstream but relatively little in the thermal entry region [36F].

CONVECTION FROM ROTATING SURFACES

A numerical calculation produced velocity and temperature profiles for convection near an infinite cooled disc rotating with its environment [2G]. The effect of dissipation on laminar heat transfer from a disc rotating in a uniform forced stream normal to the disc is analyzed for a constant property fluid and for a disc either insulated or with a temperature varying proportional to the square of the radius [4G]. Laminar flow between a rotating disc and a parallel stationary wall, with and without radial inflow of water, was studied by the pulsed dye technique for rotational Reynolds numbers between $4{\cdot}45 \times 10^3$ and 10^4, for a ratio of distance of the discs to the disc radius from 0·0476 to 0·0952 and for the ratio of radius times angular velocity of the disc to the inflow velocity of the water between 1·7 and infinity [1G]. Convection in a silicone oil layer between a non-uniformly heated lower copper plate and an upper cooled glass lid, both rotating around a vertical axis, indicates that concentric rings develop in the fluid which change over to vortices with radial axes at larger angular speeds [3G]. Flow generated by free convection and rotation in an annulus rotating around a vertical axis was studied by dye injection [5G]. Heat was added at a constant rate from the inner cylinder into water filling the annulus. No motion occurred up to a critical angular velocity when the upper surface was free. When the upper surface was a solid plate rotating with the annulus, two circulations occurred: an upper one supporting the free convection and a lower one counteracting it.

COMBINED HEAT AND MASS TRANSFER

A number of studies, primarily experimental, have been performed on film cooling. In these, a secondary fluid is injected at one or more discrete locations on a wall to isolate the solid surface from a high temperature gas stream to which it is exposed. Most of the recent experiments have used gas as the injected or secondary fluid and a primary flow also of gas, usually air. The principal emphasis has been on two-dimensional film cooling in which the secondary fluid is introduced uniformly across the span of a wall.

A strong adverse pressure gradient, leading to separation, has little effect on film cooling with injection through a porous wall [5H]. With tangential injection, the film cooling is maximized when the mass velocity of the secondary fluid is approximately equal to the mass velocity of the free stream. For a given lip thickness, however, the maximum film cooling effectiveness decreases as the slot-height decreases, indicating that separation at the lip may have an adverse effect on film cooling [9H]. The two studies mentioned above are actually performed using a mass transfer analogy to measure the film cooling effectiveness. A very high free stream turbulence level decreases the film cooling effectiveness [2H]. Heat transfer with film cooling was studied for injection through non-tangential slots [13H]. An analytical study [8H] predicts the film cooling effectiveness for injection of a secondary gas at different angles to the main stream, including the effect of a coolant gas different from the main stream.

Film cooling with injection through discrete circular holes has also been reported [6H]. The film cooling effectiveness is then sharply reduced from that found with a continuous slot, apparently due to penetration of the secondary flow jet away from the wall.

For film cooling with injection through a porous strip across the span of a wall, the proper choice of a reference state permits the use of incompressible flow correlations to predict the film cooling effectiveness with a supersonic mainstream [7H]. Another study [18H] with an external supersonic flow indicates that the interaction of a gas jet with the main stream can be likened to the flow over a forward-facing step.

Interest continues in transpiration cooling in which a secondary fluid or coolant is introduced over a relatively large distributed area through a permeable—usually porous—surface. A numerical calculation [11H] indicates that an upstream impermeable wall significantly affects local skin friction with transpiration cooling. An approximate analysis of the non-similar boundary layer with mass transfer has been presented for high speed laminar flow [1H]. Numerical solutions for compressible similar laminar-flow boundary layers in a favorable pressure gradient with injection have been obtained [10H] including the determination of the heat transfer. Mach number effects on transpiration cooling have been analyzed [16H]. Dissociation reduces the heat transfer with transpiration cooling of carbon dioxide into a nitrogen mainstream [12H].

Linearization of the convective term permits the analysis of the forced and free convection boundary layers with mass addition [17H]. Experiments with uniform blowing or suction are well correlated by previously presented semi-empirical analyses [15H].

Combined heat and mass transfer with application to drying processes has been studied [14H]. The rate of moisture removal in freeze drying depends strongly on temperature level, but much less so on pressure level and very weakly on the humidity in the surrounding air [4H].

The effect of a localized energy pulse on the evolved material from a solid wall, including the jet of gas leaving the surface, has been studied analytically [3H].

CHANGE OF PHASE

Boiling

Throne [49J] gives a summary of boiling heat transfer. Nishikawa deals with nucleate boiling

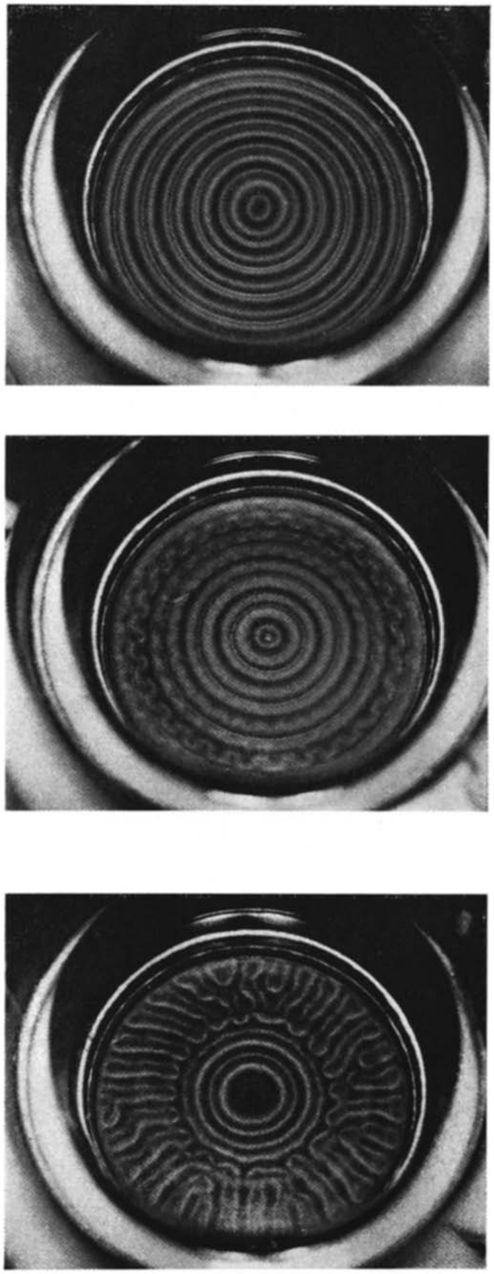

FIG. 1. Flow patterns resulting from convective motions in a non-uniformly heated, rotating fluid layer [3G].

at low liquid levels [35J] and also investigates the assumption of smooth liquid vapor interface [34J]. He finds that bubble formation is influenced by the size of the heating surface. Gregor'ev studies boiling of three component mixtures [15J]. Lippert and Dougall [30J] find similarity of time averaged temperature profiles within the sublayer during pool boiling. Past history of the test surface, including the time spent while boiling, can significantly alter the nucleate boiling curve of liquid nitrogen [31J]. A maximum in nucleate boiling heat transfer may be reached with a certain roughness for unidirectionally polished surfaces. Chemically etched surface data emphasize [56J] the inadequacy of using r.m.s. surface roughness without specifying surface preparation. Recent evidence supports the premise that the coefficient C_{sf} and the exponent r of the Rohsenow pool-boiling correlation vary with surface preparation technique as well as liquid–surface combination. Boiling was independent of gravity at high subcooling and transition from discrete bubble region occurs at a lower heat flux in zero gravity than normal gravity [10J]. In low g environments, phase separation requires effective pressure relief venting. Nucleate boiling then produces a general liquid level rise such that a bubble containing liquid could fill the entire fluid tank [1J]. Acceleration has little effect on the temperature difference in nucleate boiling while an increase in acceleration results in an increase in heat flux at the incipient boiling point [54J]. Large accelerations (200 g's) nearly eliminate disturbances at the liquid vapor interface, reduce the number and size of bubbles, and promote direct evaporation across the interface [13J]. Nicol [33J] studied boiling heat transfer from a horizontal copper cylinder rotating on its axis in water. Below 150 rev/min the effects of rotation are correlated using a Weber–Reynolds number term in Lienhard's boiling equation while above 150 rev/min the same basic equation was modified to include a Froude number. Wide discrepancies have been observed on the effects of ultrasonic vibration on burnout heat flux [64J]. The major effects of an electric field on boiling occur in the regions of peak heat flux, transition boiling, and minimum transition boiling. These boiling regions are known to be heavily influenced by hydrodynamic stability which is, in turn, influenced by the presence of an electric field [19J]. Torikai [53J] concludes that heat conduction through a thin layer between a bubble and a heating surface is a substantial contribution to vapor formation from areas other than those in contact with the thin liquid film. Experiments with air bubbles injected through a heated plate indicate that heat transfer is most intense during the time the bubble detaches from the surface [4J]. Tokuda *et al.* study the dynamics of moving gas bubbles in binary systems in injection cooling [50J]. A minimum growth rate of released vapor bubbles occurs [58J] at low concentration of the more volatile component (1–2 per cent) in quantitative agreement with the analysis of [57J]. Vapor bubble growth and collapse in liquid nitrogen exhibit behavior similar to vapor bubbles in non cryogens [16J]. A solution is presented [63J] for the potential flow pattern in a semi-infinite liquid surrounding a sphere that is growing while remaining tangent to a plane solid surface. Bubble growth measurements [21J] in the asymptotic phase agree with the theory of Plesset and Zwick while over the complete growth, an extended theory (which includes a pressure driven growth term) is in agreement with data. Cheh [6J] extends asymptotic bubble growth dynamics to include initially non-uniform concentration field. Mendelson proposes a new expression for the terminal velocity of rising bubbles [11J].

The phenomenon of pool boiling crisis is governed by the balance between the consumption of liquid film on the heated surface and the supplying of liquid through the intermittent removal of vapor masses [20J]. The dependence of the extreme heat flux on $g^{\frac{1}{4}}$ developed for the flat plate is inapplicable to other geometries [29J]. Tong [51J] studies the departure from nucleate boiling in bundles of reactor fuel rods.

Grigor'ev [14J] presents experiments on the critical heat flux with binary mixtures. Staub [47J] and Rouhani [41J] predict the inception of vapor generation in subcooled boiling. There is current interest in the possibility of metering and pumping small volume, periodic fluid flows by means of boiling heat transfer. Pitts *et al.* describe a pertinent experimental and analytical investigation of transient film boiling of water from a horizontal submerged platinum wire following a large step change in wire temperature [37J]. Forslund and Rohsenow [12J] present dispersed flow film boiling data for liquid N_2. They improve the analysis of Laverty to account for droplet breakup due to vapor acceleration, modified drag coefficients for accelerating droplets and a "Leidenfrost" heat transfer from the wall to droplets at lower qualities.

The long tube vertical falling film evaporator is one design for the multiple effect distillation process that holds promise for the economical conversion of sea water to fresh water [25J]. The interface boiling mechanism proposed by Dukler plays the major role in the heat transfer. Water droplets do exist temporarily within superheated steam atmospheres. It is necessary to know the lifetime of a drop if its continued existence presents a threat—as in rotating machinery. Lee and Ryley [26J] study evaporation of water droplets for diameters $230 \leqslant d \leqslant 1130\ \mu$ where the heat flux is determined from $\overline{Nu} = 2 + 0{\cdot}04\ Re^{0{\cdot}5}\ Pr^{0{\cdot}33}$. The mixture–vapor transition point in a horizontal tube evaporator is oscillatory and only the mean position is predicted [61J]. Chawla [5J] summarizes equations from the literature and presents working charts for average heat-transfer coefficients in a horizontal tube for the case of total evaporation.

In contrast to Kutateladze's model of flow boiling crisis which adds the boundary layer separation heat flux to the pool boiling critical heat flux computed from Helmholtz instability. Tong [52J] correlates critical heat flux data by using only the concept of boundary layer separation. Zuber and Staub [66J] analyze the transient response of the volumetric concentration in boiling forced flow by transforming the vapor continuity equation into a "void propagation" equation and applying Lighthill's concept of the kinematic wave. The resulting rate of propagation of voids is checked experimentally using the two-beam X-ray attenuation method [48J]. When boiling occurs in forced convection, bubbles depart with considerably smaller size than in pool boiling [22J]. The departure size decreases with increasing flow velocity.

Condensation

The condensation of potassium vapor in the presence of argon or helium non-condensable gases is governed by the ordinary molecular diffusion equations [24J]. The reductions in heat transfer due to noncondensables are accentuated at low operating pressure while condensation in a forced convection flow is much less sensitive than in a gravity flow [46J]. Shortcut design procedures are developed which eliminate trial-and-error calculations in laminar condensation [17J]. Poots and Miles [39J] analyze the effects of variable physical properties on laminar film condensation of saturated steam on a vertical flat plate. For condensation controlled by heat conduction, the change in temperature of the vapor is closer to isentropic expansion than to equilibrium expansion and causes overcooling and nucleation [40J]. Leppert and Nimmo [28J] discuss mechanisms for laminar film condensation on surfaces normal to the body or to inertial forces, whereas Leonard and Estrin [27J] designed a vertical-surface condensation apparatus to vary vapor velocity while holding condensing rates constant so that shear stress could be studied separately from gravity or condensate effects. A general heat transfer correlation for annular flow condensation is given which agrees with data over a wide range of vapor velocities and $1 < Pr < 10$ [45J]. Experiments [32J] show there is no measurable interfacial heat-transfer resistance during film condensation of steam at low pressures. The condensing heat transfer coefficient is increased by the application of electric fields which produce electrohydrodynamic waves at the liquid–vapor interface [8J].

In the field of dropwise condensation, precise and respectable measurements of the stream-to-surface temperature difference can only be obtained when special precautions are taken to obviate the effects of non-condensing gases [9J]. For high degrees of subcooling, there is some improvement in the heat transfer coefficient for teflon treated surfaces at low ΔT's and an opposite effect at high ΔT's [2J]. Schingnitz [42J] shows that surface fluctuations in free-falling drops may increase the mass transfer rates up to 33 per cent. Sagawa [42J] describes an experimental determination of transient condensing heat transfer with the heat absorption in circular cylinders. Williams *et al.* [62J] reviews methods of enhancing heat transfer in surface condensers. Yeh and Yang [65J] analyze two-phase (gas–droplet) stagnation flow in which the presence of non-condensing liquid drops increase heat transfer and wall friction.

Two-phase flow

Two-phase flows have been of continuing interest in such engineering situations as liquid fuel rocket systems and petroleum pipe lines. Cryogenic propellant storage tanks and lines undergo longitudinal vibrations which can give rise to two-phase flows [43J].

Measurements of momentum flux in a pipe with steam–water and air–water are used to evaluate two-phase flow models [3J]. The slip model yields low values while the homogeneous model correlates the data because of compensating errors. Equations are developed in terms of the Lockhart–Martinelli correlating groups for the friction pressure gradient of two-phase mixtures which allow for interfacial shear forces [7J]. The analysis of Zuber for void fraction in two-phase flows is extended [23J] to cover bubbly turbulent flow through rectangular ducts. Two-phase heat-transfer coefficients are greater than the computed coefficient for either phase flowing alone [38J].

The Reynolds flux concept described in a monograph by Spalding postulates transverse mixing velocities in order to account for transport phenomena in a one-dimensional flow model. The concept is extended to two-phase flows in [59J]. The resulting theory gives improved predictions of pressure gradient during film condensation and provides a criteria for two-phase "choking" [60J]. Huey and Bryan [18J] give a theory for isothermal two-phase (liquid–gas) flow in a horizontal pipe by introducing the concept of Mach number and considering the medium to be a pseudogas. The occurence of flow choking is confirmed. Ogasawara also gives a theoretical prediction of two-phase (wet steam) critical flow in a constant area duct [36J].

RADIATION

Spectral and integrated intensity of the CO fundamental band was calculated for temperatures between 300 and 1500°K [1K]. The results near room temperature compare well with experiments. Theoretical expressions for overlapped lines were used to calculate the emissivity of water vapor for the 2·7 and 6·3 μ regions [51K].

Radiative exchange in emitting and absorbing media bounded by solid walls of different shape were investigated in a number of papers: in a layer between two parallel walls [42K, 47K] and for a gray medium between two concentric spheres [10K]. The method of regional averaging was examined [26K] and form factors for parallelepipeds were obtained [12K].

The usefulness of approximate procedures was investigated. A series expansion of the emissive power was found to give accurate results over the whole range of optical thickness; whereas Rosseland's approximation has to be limited to the optically thick situation [45K].

In this case, it is acceptable provided a temperature jump is introduced at the walls [13K]. For a non-gray gas, the Rosseland limit was found not to apply [29K].

The effect of scattering was included in several analytical investigations. The equation of radiative transfer of isotropic point scatterers was derived statistically [6K]. A scattering medium between two parallel plates is treated in [37K] and [38K], with allowance for Fresnel reflection at the boundaries in [25K], and for a transient situation in [31K]. Radiative transfer in absorbing, emitting, and isotropically or unisotropically scattering media on opaque substrata was analyzed [28K]. The Monte Carlo method was applied to radiative heat transfer from a cylindrical cloud of particles [43K]. A study was made in view of situations occurring in rocket exhaust.

Combined radiative, conductive, and convective heat transfer is considered in the following papers: for a semi-infinite gray medium in [20K] and for a medium between two concentric spheres in [50K]. The following equation has been offered by R. Greif in the discussion to describe the radiative transfer in a gray medium between two concentric spheres with radii r_1 and r_2, with temperatures T_1 and T_2, and with emittances ε_1 and ε_2.

$$\frac{q_{rad_1}}{\sigma\,(T_1^4 - T_2^4)} = \frac{1}{\dfrac{1}{\varepsilon_1} + \left(\dfrac{r_1}{r_2}\right)^2 \left(\dfrac{1}{\varepsilon_2} - 1\right) + \dfrac{3}{4}\tau_1 \left(1 - \dfrac{r_1}{r_2}\right)}$$

with $\tau_1 = \int_0^{-r_1} \beta \, dr$, $\beta = \kappa + \pi$, π indicating the scattering coefficient, and κ the absorption coefficient. Radiation in a shock layer is considered in [3K, 8K], in a boundary layer on a flat plate in [16K, 46K], on a stagnation point in [4K], for a hypervelocity boundary layer in [40K, 41K], for an ablating boundary layer in [24K, 27K], in a non-similar boundary layer [39K], for laminar free convection on a heated vertical plate in [5K], and for laminar developed flow of a non-gray gas through a black wall tube in [11K].

Shielding of radiation between two surfaces can be obtained by arranging a number of screens in the form of black plates with holes. This arrangement acts similar to a gray gas generating a temperature jump near the bounding walls [44K]. New types of glass transmit only 50 per cent of solar radiation in a 6 mm thickness compared with 80 per cent for normal glass [32K]. Reflecting glass covered with a thin electrically conducting ceramic layer reflects up to 40 per cent of incident infrared radiation compared to 5 per cent on normal glass. An instability can be caused in a bounded plasma by lack of radiation equilibrium according to an analysis in [2K].

The computation of radiant interchange among surfaces is commonly performed under the assumption that both the emitted and reflected radiation are diffusely distributed. Computational studies taking account of other directional distributions have been carried out, from which it is found that the results may be critically affected by the model selected for describing directional characteristics [35K, 48K]. Experiments involving both rough and smooth surfaces in simply arranged configurations are in better agreement with the predictions of the diffuse model than with other computational models [36K]. The traditional radiosity method is generalized to accommodate two wavelength bands and to include specular and diffuse components of the reflected radiation [21K]. Several methods of solving the problem of radiant transport through a diffuse walled tube are compared [22K].

A V-groove cavity with a flat, black-surfaced bottom and specularly reflecting side walls possesses directional emission and absorption properties [7K]. The results of several alternative derivations of the apparent emittance of a diffuse spherical cavity are brought together and shown to be identical [14K, 30K]. Angle factors are given for interchange between a small flat plate and a sphere [19K], a pair of spheres, and a cone and a sphere [9K].

The effect of increasing the thickness of oxide layers on substrates of zinc and galvanized steel is found to decrease the spectral hemispherical reflectance [18K]. Measurements of the spectral directional emittance of aluminum oxide ceramic show a slow tendency toward the diffuse limit as the surface roughness increases [49K]. The relationship of the measured angular distribution of radiation scattered by a monolayer of spheres to the predictions of Mie scatter theory is examined [34K].

A theory is developed to explain the nature of polarized and depolarized scattering of electromagnetic waves from a slightly rough dielectric surface [15K]. Experiments are reported on the effect of microroughness on the emittance of metallic surfaces [33K]. The accuracy of approximate representations of the Fresnel equations is examined and the relationship between the hemispherical and normal emittances determined [23K]. Results are obtained for radiant heat transfer through fibrous insulation wherein the fiber diameters are large compared with the wavelength of the participating radiation [17K].

Radiative transfer at the surfaces of heat conducting solids has been treated in a number of papers published during the year. These papers are summarized in the conduction section of this review.

LIQUID METALS

Heat transfer in liquid metals is at low Peclet numbers influenced by axial conduction. This effect is analyzed for laminar Poiseuille flow in a tube, the heated section of which is either held at a constant temperature or supplied with a constant heat flux; whereas the entry and exit sections are either at the entry temperature of the fluid or adiabatic [5L]. Results are presented for Peclet numbers between 1 and 50. They demonstrate how the temperature field penetrates asymptotically in upstream direction into the entry section. The results can also be used for mass transfer situations when the Peclet number is replaced by the product of Reynolds and Schmidt number. The same problem was investigated for an annular duct with slug flow, arbitrary distribution of the heat flux along the heated section, and adiabatic inlet and outlet sections [3L]. The effect of axial diffusion becomes negligible for Peclet numbers larger than 35. Several papers study heat transfer in ducts neglecting axial conduction. The law of the wall is used to describe heat transfer in turbulent flow through a tube [11L]. The thermal entry length for turbulent flow in pipes with constant heat flux was analyzed with expressions for the turbulent Prandtl number developed by the author [1L]. The following equation approximates the results

$$\frac{L}{D} = \frac{0{\cdot}701\, Pe^{0{\cdot}827}}{7 + 0{\cdot}025\, Pr^{0{\cdot}15}\, Pe^{0{\cdot}83}}.$$

the thermal entry as well as the developed thermal region is considered for the turbulent flow of a liquid metal with internal heat sources [8L]. Measured temperature profiles in turbulent flow through a vertical tube with constant heat flux demonstrate the effect of superimposed free convection for Reynolds numbers up to 50 000 [2L]. Turbulent Prandtl numbers obtained from these measurements have values between $\frac{1}{3}$ and 5. Heat transfer from a sphere to liquid sodium in forced convection is described by the equation

$$Nu = 2 + 0{\cdot}386\,(Re\,Pr)^{0{\cdot}5}$$

obtained from measurements in the parameter range $35000 < Re < 153\,000$, $100 < Re^2/Gr < 1000$ [12L]. An analytical study of heat transfer to liquid metals flowing along a row of spheres resulted in the following equation

$$Nu = C\, Pe^{\frac{1}{2}}\, \phi^{\frac{1}{2}}$$

with $C = \sqrt{2/\pi}$ for uniform surface temperature and the values for ϕ changing from 2 for a single sphere to 1·5639 for touching spheres [7L]. A photographic study of mercury vapor condensing as it flows through a horizontal glass tube shows drops moving along the wall with one-third to full vapor velocity [9L]. Absence of gravity has little effect on the condensation process. Superheats from 17 to 117 degrees were measured in incipient boiling of potassium in forced flow [4L]. The amount of superheat was found strongly dependent on heat flux [6L]. Heat transfer from spheres with temperatures up to 3600°F to subcooled liquid sodium in forced convection is essentially determined by conduction in the liquid metal [13L]. The extremely thin vapor film offers negligible resistance. A recent analysis for double pipe heat exchangers which indicated that significant errors may result when traditional relations are used has now been verified by experiments [10L].

LOW-DENSITY HEAT TRANSFER

Linearized heat transfer between two parallel plates is considered for inverse Knudsen numbers ranging from 0 to 10 and arbitrary accommodation coefficients [3M]. Comparisons [2M] are made with these results and the non-linear analysis of Willis, the linearized 4-moment solution, and Takao's experimental data. Temperature and density profiles were determined experimentally for rarefied gases at rest between two unequally heated plates in the transition regime [14M]. Heat flux and profile agreement within 2–3 per cent were found with the 4-moment methods of Lees and Gross–Ziering and 10–20 per cent with the Gross–Ziering 8-moment method. A rarefied gas with hard sphere molecules enclosed between parallel walls is analyzed [10M] by a model sampling procedure in which the target molecular velocity distribution is taken to be the sum of two different half-Maxwellians. By scoring the properties of sample molecules, the macroscopic quantities are obtained.

Heat conduction through a rarefied gas contained between concentric cylinders is studied [12M]. Emphasis is placed on relations for experimental determination of thermal accommodation coefficients by the low pressure method. Lord [9M] gives an approximate solution for the transition regime heat transfer and shear stress between coaxial cylinders or concentric spheres which agrees with experimental data over a narrow range of radius ratio.

For heat conduction between concentric cylinders, the lowest order deviation of the heat flux from its free-molecular value is of order ln k_n/k_n [13M]. Agreement with experiments with argon and air over a wide range of Knudsen numbers is found [4M] between the results of a linearized BGK model of the Boltzmann equation applied to Couette flow of a rarefied gas between two concentric cylinders. Darrozes [6M] gives results for slip velocity in shear flow over plane surfaces using Krook's model. For a free, infinite, isothermal disk rotating in a rarefied gas, Barbee [1M] suggests that for pressures above 1400 μs the effect of slip is insignificant. The normal and shear forces are determined and the total drag predicted [11M] for low density flow over a flat plate with a normal protuberance emphasizing the effects of multiple surface collisions.

Epstein [7M] analyzes the effect of incomplete energy accommodation on free molecule recovery temperature. Wimberly [15M] gives a closed-form solution of the convective heat transfer to a yawed concave hemisphere with variable accommodation at the surface. Kogan's general expression for slender cone drag in hypersonic near-free-molecule flow is extended [8M] to arbitrary cone angle and general intermolecular collision laws. Experimental data [16M] at $M = 4$ on a sphere with $75 < Re < 230$ do not agree with the Mott–Smith model—the shock thickness, around 9 mean free paths, is higher than found elsewhere.

An experimental study of diffusion in porous solids was made [5M] with emphasis placed upon the change from Knudsen diffusion to transition diffusion.

MEASUREMENT TECHNIQUES

Recent instrumentation studies include continued development of special purpose thermocouples for use in different temperature ranges, advances in radiation techniques, and applications of laser techniques to local measurement of fluid velocity. Publications include an anotated review [3P] of articles and books on heat transfer measurements.

Tungsten-niobium and molybdenum–niobium thermocouples have been calibrated for up to 2000°C for use in a vacuum at 10^{-5} torr [27P]. The effect of extraneous circuits parallel to a thermocouple junction has been studied [45P]. Gold–iron thermocouples are found [31P] to be useful in measuring temperatures between 0·4 and 85°K. A very sensitive thermocouple can be produced by using a thermistor at the junction of a Pt–PtRh thermocouple [15P]. Thermocouples with response time as low as 50 μs have been studied [2P]. A review [19P] of thermocouple characteristics concentrates on their application to temperature control devices.

A recent paper [17P] reviews errors in radiation pyrometry. Temperature measurement of natural surfaces (as might be studied in meteorology) using infrared radiometers has been discussed [22P]. Pyroelectric detectors were developed [1P] for thermal imaging systems and applied to measurement of surface temperature distributions. Infrared techniques have been described which can be applied to measuring temperature in microcircuits [14P], and through a special microscope [47P]. Fiber optics have been used [5P] to measure surface temperature during welding. The effect of extraneous radiation on pyrometric measurements of surface temperature can be eliminated by using a variable wavelength narrow bandwidth pyrometer [32P].

Interpretation of band-reversal temperature measurements under nonequilibrium conditions has been developed to measure the average gas temperature in such systems as gas turbine exhaust ducts [30P]. Relativistic effects on temperature measurement using a moving thermometer have been analyzed and discussed [21P].

Pyroelectric heat-transfer sensors are found [38P] to have a very high sensitivity for heat flux measurement. An infrared camera has been used [43P] to measure heat transfer from a model in a hypersonic blowdown tunnel. The use of dynamic techniques in radiation measurements has been studied [24P]. The usefulness of thermopiles out to a wavelength of 330 μ has been demonstrated from a comparison with a Golay cell [39P]. Thin film heat-transfer gages can be used to measure rapidly changing radiation fluxes [46P]. Measurements of the diffusion of platinum into the pyrex substrate of a thin-film resistance thermometer indicate that it is necessary to empirically determine the thermal parameters of such a gage [23P].

The development of a quantitative three-color Schlieren system has been described [26P]. A numerical program has been developed to evaluate refraction errors in interferometric studies of heat transfer [33P]. The sharpness of fringes produced by laser interferometers has been examined [41P].

Thermal properties of a solid can be determined by irradiating it for a short time and measuring the surface temperature rise from the emitted radiation [34P]. A technique to determine thermal properties of solids from contact surface temperatures has been studied in detail [40P]. An apparatus for rapid determination of the conductivity of insulators has been developed [18P].

The design and operation of a degassing device that would be useful in producing gas-free liquids for boiling studies have been described [28P]. A small sensor for measuring relative humidity has been tested [20P].

A laser–Doppler system has been developed which is capable of measuring fluid velocity with an accuracy of better than 0·1 per cent [13P]. A Fabry–Perot scanning plate interferometer has been used to measure frequency shift in a laser–Doppler system [16P]. The feasibility of laser–Doppler technique measuring clear air turbulence is not great due to the small amount of light that is backscattered [6P]. The change in the speed of light passing through a flowing transparent medium has been used to measure gas velocity profiles [10P]. The time of passage of suspended particles between two laser beams can define fluid velocity [44P].

The errors encountered in quantitative application of the hydrogen bubble technique to velocity measurement have been examined [9P]. A recent paper reviews various thermal methods of flow measurement with the major emphasis on hot wire anemometry [7P]. Low velocities can be measured with a thermistor anemometer in a fluid with a non-uniform temperature [25P]. A comparison is presented [11P] of the noise produced by constant temperature and constant current hot-wire anemometers. A statistical analysis [35P] highlights the problems in measuring turbulence in flames.

The importance of the shock stand-off distance when measuring pitot pressure distributions in velocity gradients has been demonstrated [37P]. The measurement of stagnation-point heat transfer by using three different models permits the inference of the viscosity and other flow properties in a hypervelocity nozzle [29P].

The measurement of Reynolds stress by rotating a single hot-wire anemometer has been described [12P]. An empirical correlation has been applied to skin friction measurements in a transpired turbulent boundary layer [36P]. The value of thin-film sensors for measuring skin friction in pressure-gradient flows has been demonstrated [8P]. The effect of conduction through the base material has been found to significantly affect the performance of thin gage thermal flux meters in shear flows [42P].

HEAT TRANSFER APPLICATIONS

Heat exchangers

Numerical solutions are given [20Q] for steady state and transient behavior in counter-current heat exchangers with short contact time and compared with the classical solution using addition of resistances. The double Laplace transform method is an effective tool for the solution of the single-blow problem [10Q]. Perforations increase heat transfer performance of plate-fin surfaces without a large frictional power penalty [16Q]. Kohlmayr [9Q] studies the effects if errors due to a deviation of inlet fluid temperature change from a step change on the maximum slopes of the transient response curves. As a result, a method is described [8Q] which permits the reduction of transient matrix heat transfer test data in the range $0{\cdot}5 < Nu < 5{\cdot}0$ from single blow tests.

Willmott [24Q] discusses the simulation of a thermal regenerator under conditions of variable mass flow. Varshavskii [21Q] determines the maximum work in an isolated system with limited capacities of the source and sink. If a composite heat exchanger is treated as a counter-flow heat exchanger in series with a cross-flow heat exchanger, the result is very close to the exact solution over a wide range of operating conditions [7Q]. Willis [23Q] presents the first systematic analysis of three-fluid, cross-flow, heat exchangers. Heat transfer and pressure drop characteristics are presented for crossed tube heat exchangers [15Q], offset rectangular plate-fin surfaces [12Q], and in oblique flow-headers [13Q]. Sealing the gaps between baffles and tubes decreases the efficiency for $Re > 2 \times 10^4$ [4Q]. The resistance due to tube spacing in bundled tubes in a fluidized bed is not important since there is no detectable influence of clogging (bridge-forming) on heat transfer [3Q].

A radio tracer technique was utilized to measure axial dispersion in both phases in liquid–liquid spray towers operated near flooding [14Q]. Results [5Q] for a horizontal, isothermal circular cylinder exposed to a crossflow of a water-in-air spray indicate that two-component heat transfer coefficients may be 30 times those of single component (air) flow. Casing temperatures and well bore heat losses are critical variables in steam and hot water injection wells [22Q].

The process of axial cavity formation in UO_2 rods of nuclear fuel is investigated [6Q] by means of a nodal model incorporating a space dependent heat source and both temperature and irradiation dependent thermal conductivity. Heat flux relations are derived and verified in a square-array fuel bundle [11Q]. Heat transfer and flow rate data are presented [1Q] for a single tube thermosiphon reboiler under vacuum conditions where up to 90 per cent of the length is needed for liquid heating. There is a large density decrease from reactor inlet to exit such that the momentum pressure drop can be a significant quantity. Resulting deviations in flow rate or passage diameter can cause reactor walls to overheat [17Q]. Local heat transfer coefficients for hydrogen from 10 investigations using symmetrically heated tubes were used to determine a single correlating equation that includes surface to bulk temperatures of 23 which has the form [19Q]

$$Nu_b = 0{\cdot}023\, Re_b^{0{\cdot}8}\, Pr_b^{0{\cdot}4} \frac{T_w}{T_b} \exp - \left(0{\cdot}57 - 1{\cdot}59\frac{D}{x}\right).$$

The gas dynamic forces on a MPD arc are capable of generating unsteady arc operation [25Q]. When a MPD arc is operated at elevated pressure levels transition to turbulent flow severely increases anode heat flux [18Q]. A film-cooled anode of a plasma generator allowed a higher percentage of electrical energy to be transferred into thermal energy of the plasma than a conventional water-cooled anode [2Q].

Aircraft and space vehicles

A general thermochemical equilibrium program is used [51R] to compute isentropic functions of a 15-specie air model for free stream velocities from 10 000 to 50 000 ft/s and altitudes from 50000 to 300000 ft. Bartko [5R] estimates non-gray equilibrium temperature distribution above the clouds of Venus. Borchmann [10R] discusses thermal protection for re-usable booster stages. Improved heat protection of tail fin leading edges was sought [39R] following a sounding rocket flight failure. The thermal design performance test of the Anchored Interplanetary Monitoring Platform is reviewed [36R]. Retro-motor exhaust contamination of the spacecraft produced data which exceeded predictions. The temperature response of refractory coated blades of the Rotor Entry Vehicle are analyzed [32R]—the amplitude of the temperature oscillation is negligible for practical rotor angular velocities.

Aihara [1R] presents optimum body shapes for minimum total laminar convective heat transfer. The merging of the shock wave and the boundary layer at a distance of approximately 500 mean free path lengths from the leading edge results in major deviations from continuum theory [9R]. Strong effects of leading edge thickness are found down to a thickness of $\frac{1}{5}$ of a mean free path. Standard techniques for computing flow field and radiation and convective heat transfer are applied to the thermal protective system design for the Apollo Command Module for a variety of trajectories and [19R] presents experimental verification. An equivalent lumped resistance–capacitance transient analysis of the Apollo Service Module was performed [48R] using 260 nodes with 785 resistors. Correlation with experiment was within $\pm$ 20°F for 85 per cent of the nodes during steady state and $\pm$ 30°F during highly transient conditions. The effect of wall cooling on turbulent heat transfer has been a topic of dispute since X-15 flight data indicated that turbulent heat transfer coefficients are independent of wall-to-recovery temperature ratio. Recent results [13R] obtained in ground facilities substantiate the flight measurements. Turbulent peak heat transfer for either attached or separated flows on wedges or flaps is well predicted [30R] by using a Spalding-Chi calculation modified to include a virtual origin at the junction of the wedge or flap and appropriate inviscid pressures.

Free flight data on the flat upper surface of a sharp-edged delta wing reveal vortical separation at the leading edges with reattachment along the centerline [18R]. Additional flight data taken on a sharp cone at $M = 3{\cdot}8$ (21R) show heat flux to be uniform across the base—no evidence of high values at the stagnation point.

Fortran programs are available [17R] describing the performance of single phase cryogenic storage systems that account for fluid, vessel geometry, and both fluid withdrawal rate and input heat leak being arbitrary functions of time. Alumized mylar reflective layers for liquid hydrogen tankage failed to evacuate to low interlayer pressures due to outgassing [15R]. For typical large cryogenic propellant tanks, the Rayleigh number Ra is $\approx 10^{13} - 10^{18}$ during boost phase, and tank wall boundary layers are predominantly turbulent [26R]. Under reduced gravity conditions, Ra is decreased and the boundary layer may become laminar—particularly at the bottom of the tank.

Barber [4R] discusses the feasibility of spacecraft electric propulsion. Reverse transition from a turbulent boundary layer at the inlet to an essentially laminar boundary layer at the throat can occur in a Laval nozzle [3R]. Greater side force directional control can be achieved by expanding a secondary gas jet into the supersonic region of the main rocket nozzle than by expanding it into the atmosphere [37R]. The drying efficiency of nozzle fields is equal to that of a single nozzle for wide spacing, whereas for smaller spacing a simple geometric correction factor is given [31R].

Mechanical erosion may account for two-thirds of the total re-entry surface recession [43R]. Crosshatched ablation patterns have been repeatedly found on solid surfaces [12R]. Decisions on the relative reactivities of graphites or chars based on observations in undissociated air, or in the absence of accurate 0-atom simulation, can lead to systematic errors as large as 50 per cent in the total ablated mass [42R]. Kemp [29R] presents a simple derivation of the steady recession formula for an ablating polymer which includes the heat of decomposition. When surface recession is a result of diffusion-controlled surface combustion, the surface and char interface velocities and the mass degradation rates are functions of a single parameter, P_s/R_n = surface stagnation pressure/nose radius [34R]. Laboratory experiments conducted in an arcjet wind tunnel [46R] or a rocket nozzle [6R] provide macroscopic details of hypervelocity heat protection schemes. The effects of diffusive separation were measured in underexpanded jets for a binary mixture of nitrogen and helium using an electron beam [8R]. The greatest diffusive separation was found near the aft portions of the jet where the boundaries are converging.

The design, fabrication, and test of a transpiration cooled test panel module for re-entry vehicles are described [27R]. Zlotnick [50R] analyzes non-equilibrium sublimation. When a porous wall is subject to a radiant heat flux, the maximum temperature of the solid wall rises above the average temperature of the gas at the wall [2R]. The measurement of heat flux with porous wall cooling using the transient technique is described [44R] along with a critical examination of the simplifying assumptions made in the data reduction process.

The most severe mechanism of degradation of solar mirror reflective surfaces is blistering [20R]. In the absence of blistering, the optical degradation produced by either protons or ultraviolet radiation is not strongly temperature dependent. Rear-surface mirrors may be used on external surfaces of satellites to dissipate large amounts of power or to provide a low operating temperature with a passive cooling system [45R]. Surface roughening of rear surface mirrors can increase the effective solar absorptivity by a factor of 3.

The effects of vacuum, temperature, photon radiation and electromagnetic radiation on spacecraft thermal control materials is being studied [25R, 40R]. Black coating experiences negligible changes in thermal radiation characteristics due to exposure to simulated space—the greatest change in thermal emittance (12·9 per cent) was experienced by black nickel plate [47R]. Total radiation properties for four heat shield materials: teflon, refrasil, carbon phenolic, and pure epoxy resin, were similar even though their visible and ultraviolet emissions differed widely [38R]. Particle transport and behavior in simulated Martian storms are quite similar to those of Earth sand and dust storms [16R]. Short exposure to a simulated average Martian dust storm decreases the amount of coating and greatly increases its solar absorptance such that soft, resilient coatings resist the abrasive Martian environment better than hard paint coatings. Optical properties of white (low α/ε) thermal control and of penetrable surfaces in space will degrade more slowly in a micrometeoroid environment than will optical properties of structural materials [35R]. The spectral and temperature dependence of the absorption coefficient of small carbon particles produced by research rocket engines burning RP-I was determined [11R] between 1 and 4 μ between 1000 and 2600° K. That the combined uncertainty in temperature due to variances in solar absorptance and infrared emittance can be determined by the root-mean-square of the individual contributions is justified [14R] for most spacecraft applications. The emittance of ablation chars is studied [41R, 49R] and found to be a maximum in the visible—decreasing with wavelength in the near-infrared. A titanium alloy honeycomb has an apparent hemispherical emittance of the order of 0·1 with a cell diameter of 13 cm and a L/D of 6 [7R]. It is useful for absorbing solar energy to pass through the absorber surface while attenuating the re-radiation.

A solution to the space radiator problem [33R] (radiator rejects a given amount of heat under a given set of conditions) is accurate and economical with respect to computer time. A digital computer program has been developed to optimize mass and structure for a space flight power system [28R]. Grodzovskiy [22R] discusses spacecraft radiator systems including consideration of optimum heat dissipating elements with minimum mass, systems using flat-tubed radiator with fins, annular fins, and belt systems. The temperature excursions that exist for known isothermal flat plates exposed alternately to sun and shadow depend primarily on the ratio of plate time constant to period of rotation [24R]. Analytical comparisons [23R] of flat, direct condensing radiators constructed of three different fin-tube geometries are given for a 500-day mission of a 500 kW output high temperature Rankine space electric power generator using potassium as the working fluid.

General

Chui and Kline [4S] study bistable, steady, turbulent separation in a two-dimensional fully-stalled diffuser. Most important changes in the flow data occur within two inlet widths upstream or downstream of the throat. Patmore [13S] discusses a series of ejector systems that turn rocket exhaust gases through 90°. The maximum local heat rate was reduced 85 per cent when the ejector had a long radius compared to a short 90° turn and by 80 per cent permitting the gases to shock down to subsonic flow prior to entering the short radius bend. Pereverzev [14S] investigates stationary and non-stationary temperature fields in a cooled rotor of a steam turbine in view of designing turbogenerators using supercritical steam. Complex thermal scaling is discussed [6S] for the case where conduction, radiation, and storage terms appear simultaneously. The absence of a gravitational force [5S] did not affect the performance of a heat pipe [7S]. The ASHRAE presents new works on dehumidification in the field of preservation and drying [1S], indirect evaporative cooling [10S], and construction of a psychrometric table by use of a computer [8S].

The thickness dependence of the thermal e.m.f. of thin-film, copper–constantan thermocouples shows near bulklike behavior when the thickness of both elements is greater than 1200 Å [3S].

When dealing with heat transfer across bolted or clamped sheet metal surfaces, Veilleux [17S] concludes that finely machined surfaces with closely held flatness tolerances are not necessary when sheet metal joint surfaces are filled with a silicone grease. When determining a thermal resistance, an apparent filler material thickness of $0{\cdot}003 < t < 0{\cdot}005$ in. is satisfactory. The dependence of thermal conductivity of foamed plastics on volume fraction of cells is studied [11S] by the statistical cell model. The average forced convection heat transfer coefficient for single broad leaves can be calculated under windy conditions prevailing in nature to within $\pm$ 35 per cent by $\overline{Nu}_L = 0{\cdot}6\ Re_L^{\frac{1}{2}}$ while in a quiescent atmosphere the corresponding free convection result is $\overline{Nu}_L = 0{\cdot}37\ Gr_L^{\frac{1}{4}}$ [12S]. Siegel and Savino [16S] discuss transient solidification of a liquid flowing over a cold plate that considers heat capacities of frozen layer and plate. Pinto [15S] writes a survey of industrial temperature measurements and control while Fill [9S] analyzes an acoustic temperature switch and Bruce [2S] deals with transient temperature rise in semiconductors.

THERMODYNAMIC AND TRANSPORT PROPERTIES

Thermodynamic properties

Interest in the area of thermodynamic properties concentrates on regions of unusual behavior: high temperature, low temperature, high pressure, the critical region, mixtures, and the influence of fields.

Gurtin and Williams [37T] consider continuum thermodynamics from a foundation based on axioms. Viewing the principle of corresponding states, Anderson and Soga [8T] set forth a restriction to this law. Fixman [29T] studies the critical region and discusses the behavior at this state in terms of hidden variables.

In the area of theoretical determinations of properties, McDonald and Singer [56T] calculate the thermodynamic properties of liquid argon from Lennard-Jones parameters by a Monte Carlo method and Brooker and Green [16T] report an exact solution of Boltzmann's equation for a gas composed of rigid spheres. In this same area, Rice and Young [66T] give an equation of state for a monatomic fluid with a 6–12 potential. Through statistical mechanics, O'Connell and Prausnitz [58T] calculate equilibrium configurational properties of fluids and fluid mixtures.

Turning to actual materials, Thomas [76T] reports on the equations of state of real gases, and Vukalovich and co-workers [81T] give computer methods of formulating equations of state of substances from experimental thermodynamic data.

Along or near the phase boundaries, investigations focus on measuring specific heats at constant volume close to the liquid–vapor critical point [80T] and a freezing process based on the inversion of melting points due to applied pressure [20T]. Further heat capacity measurements on copper are made by Boerstoel *et al.* [13T], using a cryostat in the temperature range 1°–30°K. At high temperatures, Watts [84T] reports properties of liquid metals, and Affortit [4T] specific heat measurements on metals up to their melting point. Josephson derives an inequality for the specific heat [43T] and applies it to critical phenomena [44T].

In the area of alkali metals, Achener and Fisher report results of an evaluation program including the vapor pressure of lithium [1T] and the specific heat of liquid sodium and lithium [2T]. Golden and Tokar [34T] give thermophysical properties of sodium. Gurvich and co-workers [38T, 39T] report two volumes of a compilation of the thermodynamic properties of individual substances. To represent caloric variables in equation form, Rimpel and Meffert [67T] develop approximate polynomials.

For monatomic gases, activity ranges from a concern with determining thermodynamic functions of liquid argon from simple geometric theory by Allison and Collins [7T] to an evaluation of the normal thermodynamic boiling temperature of helium by Astrov *et al.* [10T] and a report of the molar volume, coefficient of thermal expansion, and related properties of liquid He^4 under pressure by Elwell and Meyer [26T].

For diatomic gases, McCarthy [55T] gives computer programs for saturated properties of hydrogen and Patch and McBride [61T] calculate partition functions and thermodynamic properties to high temperatures for H_3 and H_2 ions.

Several papers are concerned with aspects of water behavior. Szkatula and Fulinski [73T] consider the dynamical and thermodynamical structure of water as determined by the scattering of cold neutrons: Gibson and Bruges [31T] report an equation of state for compressed water from 1 to 1000 bar and from 0 to 150°C; Vukalovich and co-workers [82T] describe an equation of state for superheated steam, useful in steam turbine calculations, using a digital computer.

For several pure fluorocarbons, Crowder *et al.* [22T] give vapor pressure and triple point temperatures. High temperature air at equilibrium has its composition described by approximate closed form expressions developed by Kentzer and Evans [46T].

Under mixtures, Maslov *et al.* [53T] present a new method of deriving simple, internally consistent formulas for the temperature dependence of the thermodynamic properties of multiatomic gases. In the cryogenic area, Gladun [32T] measures the Joule–Thomson effect in neon–helium mixtures. Jacoby [40T] takes PVT measurements on petroleum reservoir fluids and demonstrates some of their uses.

For various non-linear materials, Schapery [68T] describes the application of a thermodynamic constitutive equation.

Transport properties

Diffusion. In argon gas, De Paz and co-workers [23T] report new self-diffusion measurements in argon gas, Tubbs [78T] describes a demonstration of the gaseous diffusion process, and van Heijinigen, Harpe and Beenakker [79T] determine the diffusion coefficients of binary mixtures of the noble gases as a function of temperature and concentration. From a study of diffusion and thermal diffusion in helium–krypton and hydrogen–krypton mixtures, Annis, Humphreys and Mason [9T] seek an understanding of intermolecular forces.

Thermal conductivity. Appreciable activity continues in this area for gaseous, liquid and solid phases, pure substances and mixtures.

For argon, Bailey and Kellner [11T] report data for liquid and gaseous states, Fay and Arnoldi [27T] concentrate on the temperature thermal conductivity of argon; Gambhir *et al.* [30T] report data for rare gases, deuterium and air; Jones [42T] calculates the same property for normal hydrogen in the dense gas and liquid states; and Carroll and co-workers [19T] do the same for air at moderate and high pressures. Using the established recovery factor method of determining Prandtl numbers, Desmond and Ibele [24T] report results for steam (including thermal conductivity) at one atmosphere. Matula [54T] gives high temperature information for rare gases and gas mixtures.

In the very high temperature region, Levinsky and Rand [50T] describe effects of electron interactions on the plasma conductivity, Ahtye [5T] calculates total conductivity for ionized gases and Korving *et al.* [48T] consider the influence of a magnetic field on the transport properties of polyatomic molecules.

For liquids, Gluck [33T] reports thermal conductivity of monatomic liquids; Carmichael *et al.* study propane [17T] and a mixture of methane and *n*-butane [18T]. In an interesting study, Meyer [57T] investigates the relationship between the sonic velocity and the thermal conductivity for liquid fluorine–chlorine derivation of methane and ethane. An unsteady state, hot wire method by Tauscher [74T] measures liquid refrigerant conductivities.

In the solid phase, the thermal diffusivities are reported by Shanks and coworkers [71T] for gold, and Kanamorie *et al.* [45T] for rockforming minerals from 300 to 1000°K. Further data on selected solids are provided by Powell, Ho and Liley [62T] and specifically on insulations for rocket tanks filled with liquid hydrogen [59T]. Nonconducting crystals are studied by Ranninger [64T] and polycrystalline graphite by Taylor [75T]. For high temperatures, Yupko and others [86T] give measurements of both thermal conductivity and electrical resistance for ZrC, HfC, NbC and TaC. Additional measurements of thermal conductivity are reported for sintered uranium dioxide [6T], uranium oxycarbides [12T] and magnesium stannide [52T]. The special case of heat conductivity in liquid semi-conductors is studied by Fedorov and Stillbans [28T].

Activity in the area of viscosity measurements and calculations for scientific as well as technological purposes is diverse. Shih and Ibele [72T] examine the representation of helium transport properties by the Lennard-Jones 6–9 potential; Pal and Barua [60T] determine the effect of cluster formation on the viscosity of dense gases; Maksimov and Mihailova [51T] treat transport phenomena in diatomic gases at low temperatures and in a magnetic field; and Walker [83T] considers transport phenomena of general non-equilibrium gas systems. For the case of non-Newtonian viscosity, Cramer and Marchello [21T] describe a data fitting technique. Brokaw presents two useful works on high temperature gas transport properties [14T] and the viscosity of gas mixtures [15T], Tondon and Saxena [77T] following with a proposed modification of the latter. Guruaja and co-workers [35T] also considers the dynamic viscosity of gas mixtures. For ternary gas mixtures, Gura Raja and Watarajan [36T] note the constancy of the dynamic viscosities, and Devoto [25T] gives the third approximation to the viscosity of multi-component mixtures.

For liquids, a great variety of interests is clear. Achener and Fisher [3T] report viscosity for liquid sodium and lithium under an alkali metals evaluation program. For lubricants, Rätzsch [65T] measures viscosity and compressibility at 500–200 kp/cm. Krishnan and Laddha [49T] attempt prediction of binary liquid mixture viscosity using composition and pure component data.

Cryogenic liquids and their mixtures are considered by Preston *et al.* [63T] for the purpurposes of transport property calculation. Jerome and others [41T] present viscosities of aqueous glycol solutions; Sears and Dawson [70T] consider the temperature dependence of conductances and viscosities for some moderately concentrated nonaqueous electrolytic solutions; and Yamada and Kawasaki [85T] investigate nonlinear effects in the shear viscosity of critical mixtures.

Two concluding papers concern relations between viscosity and specific situations. Thus, Kestin and Shah [47T] determine the effect of long range intermolecular forces on the drag of an oscillating disk and on the viscosity of gases, and Schonborn [69T] discusses the surface tension–viscosity relationship for liquids.

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