Int. J. Heat Mass Transfer. Vol. 11, pp. 1421-1460. Pergamon Press 1968. Printed in Great Britain

HEAT TRANSFER—A REVIEW OF CURRENT LITERATURE

E. R. G. ECKERT, E. M. SPARROW, W. E. IBELE, R. J. GOLDSTEIN and C. J. SCOTT
Heat Transfer Laboratory, Department of Mechanical Engineering, University of Minnesota, Minneapolis, Minnesota, U.S.A.

INTRODUCTION

THIS review is concerned with research in the field of heat transfer, the results of which have been published during 1967 or late in 1966. The total number of papers in this field continues to be so large that only a selection can be included. 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 1967 Heat Transfer and Fluid Mechanics Institute was held in June 1967 at the University of California, La Jolla, California. The majority of the papers presented were concerned with heat transfer. Proceedings are available at Stanford University Press. The Ninth National Heat Transfer Conference in Seattle, Washington, on 6–9 August 1967, offered an invited lecture by Eli Reshotko on "Flow and thermal stability analysis" and by J. G. Knudsen on "Industry's need for research in process heat transfer" and papers in the fields of boiling, internal flows, radiation, bubble dynamics, boundary layers, conduction and heat exchangers. The papers are, or will be, published in the Journal of Heat Transfer or in the Journals of the American Institute of Chemical Engineers. A semi-international symposium was organized by the Japan Society of Mechanical Engineers at Tokyo during September 1967. Thirty-three papers in the field of heat transfer were presented, in the majority by nationals from countries other than Japan. They are collected in the Proceedings of this meeting. The first Brazilian symposium on heat transfer and fluid mechanics, held in December 1966, gave researchers and educators from South America for the first time an opportunity to discuss heat-transfer problems.

Among the several books dealing with fields related to heat transfer, three texts dealt with energy transfer by thermal radiation.

Developments in research on heat-transfer problems during 1967 can be highlighted by the following remarks: The number of papers indicates that special attention was directed toward the analysis of the radiative energy exchange between gases and surrounding surfaces, with an effort to get away from the gray gas simplification. Mean emission and absorption coefficients were properly defined and determined and radiative exchange was calculated for a variety of geometries and boundary conditions. The number of papers in the field of boiling was also especially large. Attention was directed toward the detailed processes occurring on a single bubble and to conditions near the critical point. In condensation, the effects of surface coating were studied. Exact solutions and approximate procedures for the analysis of heat transfer in boundary-layer flow have been presented including unsteady conditions and the effects of chemical kinetics when chemical reactions had to be accounted for. Experiments considered the effect of stream turbulence, of slip, of catalytic walls, and of separation at low and large Reynolds numbers. Semi-analytical methods were used to describe film cooling processes. Entrance regions, non-circular cross-sections, and turbulent transport phenomena were investigated in channel flow. The analytically predicted Nusselt number 4·36 was finally verified experimentally for laminar tube flow of a liquid metal. A large number of experimental investigations concerning turbulent heat transfer in separated regions is found in the literature. In natural convection, attention has been given to the horizontal fluid layer heated from below covering the onset of instability to the development of turbulent condition. The methods of irreversible thermodynamics are increasingly used to obtain information on transport properties. The combined effect of gas radiation and convection on heat transfer to ablating surfaces is still finding considerable attention.

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.
Thermodynamic and transport properties, S.

CONDUCTION

Temperature discontinuities at the corners of solids, frequently introduced for analytical convenience, may lead to infinite heat-transfer rates on the adjacent boundaries [20A]. Various models for achieving a continuous temperature variation in the corner region are examined. The unsteady heat-conduction equation, as normally written, permits infinite propagation speed of heat waves. When a term $\tau(\partial^2 T/\partial t^2)$ is introduced (τ = relaxation time), infinite propagation speeds are precluded [3A].

Monte Carlo methods are capable of providing solutions for steady and transient heat conduction in arbitrarily shaped solids with arbitrary boundary and initial conditions [12A]. A variant of the Green's function technique is devised for solving unsteady one-dimensional heat flow problems [24A]. The actual boundary condition is represented in terms of a source distribution on the boundary, the source strength varying to accommodate the given boundary condition. The number of unknowns which must be handled simultaneously in an implicit (transient) finite-difference scheme may be reduced by subdividing the solid into sub-volumes, thereby confining the computations to the high-speed memory of a computer [31A].

Several papers dealing with unsteady-state heat-conduction problems have been published. In one, the timewise variation of the temperature of a fluid environment that raises an adjacent solid to a given temperature in a minimum time is determined [11A]. In another, solutions are obtained for the transient response of slabs and cylinders subjected to timewise variations of the fluid environment temperature and of the heat-transfer coefficient [26A]. The transient temperature field in a sphere is analyzed for the case of spatially varying, but timewise steady, surface heat flux [19A]. The thermal surface impedence, defined as the ratio of the temperature difference to the surface heat flux for sinusoidal heat waves, is evaluated for a layered wall [9A]. The solution for the transient heat transfer for a periodically heated and cooled wall facilitates the evaluation of a lumped heat-transfer coefficient which includes both the thermal resistances of the wall and the fluid [23A].

A variety of problems involving internal heat generation has been solved. These include the case of a discrete, moving heat source [4A], dissipation of mechanical energy due to forced oscillations in a viscoelastic solid [15A], sudden discharge of electric current from part of a superconducting wire [8A], and thermal detonation in a spherical region [10A]. Applications to current-carrying solenoids and coils have motivated analysis of an orthotropic solid (different thermal conductivities in the principal directions) with linearly temperature-dependent internal heat generation [5A]. A procedure has been devised for determining upper and lower bounds for the steady temperature distribution in a fin with temperature-dependent properties, internal heat generation, and surface convection and radiation [14A]. Steady-state temperature solutions are presented for internally heated composite solids consisting of rods or annuli with radial ribs [27A].

Moving boundary problems are related to phase changes or chemical reactions. An analysis of diffusion-controlled oxidation of an ablative char layer accounts for reaction of carbon in both the char and the pyrolysis gases [30A]. Solutions for various phase change problems are examined by starting from the assumption that the location of the moving boundary is given by $\alpha(1 + \beta t)^{\frac{1}{2}}$ where α and β are constants [18A]. Finite differences are employed to solve for surface recession due to sublimation [7A]. In a highly mathematical treatment, uniqueness and existence of solutions for moving boundary problems are investigated [28A].

The interaction of conduction with radiation heat transfer continues to be of interest. The heat balance integral has been generalized to accommodate unsteady conduction with time-dependent radiation boundary conditions [1A]. Solutions are obtained for the temperature field in a solid rotating cylinder exposed to solar radiation [22A]. The uniqueness and existence of solutions for Laplace's equation with radiative boundary conditions has been demonstrated [21A]. The thermal trap is a selectively radiatively transparent slab of low thermal conductivity that is used to produce high temperatures. The characteristics of the thermal trap have been examined by solving a transient heat-conduction problem with a distributed (radiative) heat source [6A].

The degree of temperature uniformity of a convectively cooled surface of a slab is evaluated for the condition that the back side of the slab is heated by periodically spaced heating elements [29A]. Predictions have been made of the streamwise temperature variation of a thin heating strip embedded in an insulated wall and exposed to a boundary-layer flow [25A]. In general, when an internally heat-generating vertical wall loses heat by free convection, the surface temperature is not known in advance. The solution of the problem requires simultaneous analysis of the conduction problem for the wall and the free convection problem for the fluid, with matching at the surface [17A].

The thermal contact resistance of two materials in a vacuum environment is mainly a result of a constriction. A semi-empirical formula is proposed for predicting the constriction resistance for two right-circular cylinders of similar or dissimilar materials [16A]. A method is devised for determining the thermal contact conductance as a function of time for transient situations [2A].

In an intrinsic thermocouple, each wire is independently attached to the surface whose temperature is to be measured. The response characteristics of such a thermocouple have been determined by solving the coupled transient heat-conduction equations for the solid and the thermocouple wires [13A].

CHANNEL FLOW

Experiments dealing with a wide variety of topics in turbulent tube and duct flow have been performed. Among the fundamental investigations, a flash photolysis method was employed to study the viscous sublayer in a square duct with ethanol as the working fluid [25B]. Adjacent to the duct wall, a layer of thickness $y^+ = 1{\cdot}6 \pm 0{\cdot}4$ was found to have a linear velocity profile at all times, but the slope of the profile varied with time. Experiments

[35B] at high values of Schmidt number show that near the wall, the ϵ/ν ratio varies as $(y^+)^4$. Temperature profiles at all positions around the wall of a square duct were representable by the conventional inner-law parameters, provided that the local wall shear and heat-transfer rates were used in the defining equations [4B]. For turbulent airflow in a circular tube, the circumferential variation of the heat-transfer coefficient is found to be substantially smaller than the imposed circumferential variation of the wall heat flux [2B]. Flow and heat-transfer measurements on viscoelastic fluids in an electrically heated tube suggest that, relative to Newtonian fluids, there is a major decrease in the eddy transport coefficients near the wall [8B]. By evaluating the viscosity at the tube inlet temperature, it was found that the critical Reynolds numbers for laminar–turbulent transition in heated and cooled water and oil flows were essentially identical to that for isothermal flow [29B].

Entrance region heat-transfer measurements are reported for turbulent airflow in a circular tube [9B] and in a concentric annulus [26B], respectively for conditions of uniform wall temperature and uniform heating at the inner bounding wall. Mass-transfer experiments for various liquids covered a range of Schmidt numbers up to 30000 [15B]; the resulting data showed that $Nu \sim Sc^{0 \cdot 5}$. The effects of separation were strongly manifested in heat-transfer studies in a subsonic diffuser [36B]. For unequal heating at the walls of a parallel-plate channel, it was shown analytically that the heat-transfer coefficient at either wall can be deduced from a knowledge of the heat-transfer coefficients for single wall heating and for symmetric heating [1B].

Cylinders, installed in a rectangular channel, served as turbulence promoters and gave rise to significant increases in mass-transfer coefficient in the Reynolds number range from 1000 to 3500 [37B]. The effect of internal interrupted fins on friction and heat transfer for argon flow was also investigated [24B]. Another technique of increasing the heat-transfer coefficient was to wind a wire in helical fashion along the heating surface [30B].

Experimental and analytical studies indicate that the curvature of the axis of a pipe increases both the friction factor and the heat-transfer coefficient [21B]. In first approximation, for curved pipes, the Nusselt numbers for uniform wall temperature and uniform wall heat flux are the same, both for laminar and turbulent flow [22B]. Overall measurements indicate that the heat-transfer coefficient for a coiled tube increases linearly with the ratio of the tube diameter to the coil diameter [14B].

For a straight pipe rotating about an axis parallel to that of the pipe, the Nusselt number for laminar flow depends on the group $(RaRe)^{\frac{1}{2}}$, where Ra is the rotational Rayleigh number and Re is the conventional Reynolds number [23B]. Experiments on such a rotating system show that the Nusselt number increases with rotation, but that the effect weakens as the Reynolds number increases [13B].

Several solutions for thermally developed laminar duct flows have been published. For flow in a hexagonal duct with internal heat generation and different wall heat fluxes on different pairs of sides, the lowest values of the local heat-transfer coefficient were found to occur in the corners [12B]. Finite-difference calculations yielded fully developed Nusselt numbers for triangular and rectangular ducts for various thermal boundary conditions [28B]. The thermal boundary conditions on the walls of polygonal ducts were satisfied approximately by a point-matching method, thereby facilitating solutions for the case of longitudinally uniform heat transfer, circumferentially uniform wall temperature, internal heat generation, and viscous dissipation [7B]. A variational method was employed to solve for the coupled fully developed velocity and temperature fields in Poiseuille and Couette flows with temperature-dependent viscosity and viscous dissipation [5B]. Coupled velocity and temperature fields were also treated for the case of fully developed radial outflow in a plane-walled diverging channel [38B].

The thermal entrance region continues to be a subject of research interest. The Graetz method (series solution) has been employed by many investigators. Solutions for the elliptic duct with prescribed uniform environment temperature and external resistance show that the flatter the duct, the higher the fully developed Nusselt number [27B]. The effect of a non-uniform inlet temperature on downstream thermal development in a tube has been investigated [10B]. Mass injection into a slug flow with linearly varying wall temperature tends to decrease the Nusselt number [40B]. The effect of longitudinal conduction in a tube flow with uniform wall heating is investigated, but conduction upstream of the duct inlet is suppressed (i.e. the temperature is uniform at the inlet). The calculations show that the Nusselt number increases with decreasing Péclet number [11B]. A conformal mapping technique, used in conjunction with the method of weighted residuals, has been devised to facilitate solutions for non-circular ducts [6B].

Series methods have also been utilized in a number of problems involving diffusion of mass, the solutions of which may also be applied to heat-transfer problems. These include a binary mixture with non-uniform inlet concentrations [10B], first-order homogeneous chemical reaction in the fluid and first-order heterogeneous chemical reaction at the wall [34B], and first-order chemical reaction at one wall of a rectangular duct [31B]. A generalization of the latter analysis to accommodate a reaction rate of arbitrary order required the use of finite-differences [32B].

Whereas Graetz-type series solutions represent, in effect, a working back from the fully developed region toward the duct inlet, an alternative approach is to start at the inlet and proceed downstream toward the fully developed region. A generalized Lévêque method is devised for determining heat-transfer results near the inlet of tubes and annuli [39B]. For the time-dependent Lévêque problem in which the wall temperature is step-changed at $t = 0$, the heat-transfer process is governed by one-dimensional diffusion [33B]. Boundary-layer models for the entrance region have been used in conjunction with a series form of solution [3B] or with an improved Kármán–Pohlhausen solution method [17B].

Finite difference solutions also proceed from the inlet cross section toward the fully developed region. This solution method was employed for the simultaneously developing velocity and temperature fields for low Prandtl number fluids flowing in a uniformly heated tube [19B] and for gas flows with temperature-dependent physical properties [16B].

The entrance region temperature field in a parallel-plate channel was measured interferometrically and was found to be in satisfactory agreement with corresponding predictions of laminar theory [20B]. A simple correlation equation is presented for the local Nusselt number for airflow in a uniformly heated tube under conditions of high heating rates and variable properties [18B].

BOUNDARY-LAYER FLOW

Boundary-layer theory and solutions

The question whether self-similar, laminar boundary-layer solutions describe physical reality is answered by an analysis which assumes an arbitrary velocity profile at some initial position and investigates the profile changes in downstream direction when the free stream velocity varies proportional to a power (larger or equal to zero) of the distance $x + d$ measured along the surface [36C]. It is found that the velocity profile changes uniquely and asymptotically to a wedge-type profile and the rate of convergence is estimated. An integral technique to solve laminar compressible boundary-layer equations with arbitrary pressure gradient uses the concept of local similarity [28C]. A numerical solution of the variable property laminar boundary-layer equation for flow of water over a flat plate and over an infinite rotating isothermal disc can be well approximated by the following equations

$$Nu/Re^{\frac{1}{2}} = 0{\cdot}3334\, Pr^{0{\cdot}3394}$$

$$Nu/Re^{\frac{1}{2}} = 0{\cdot}4127\, Pr^{0{\cdot}4404}$$

for the flat plate and the rotating disc, respectively, when the properties are introduced at a reference temperature

$$T_r = T_w + \gamma(T_m - T_w)$$

with T_m indicating the fluid temperature outside the boundary layer and T_w the wall surface temperature. The factor γ has the values 0·60 for the heated and 0·69 for the cooled flat plate; the values 0·41 for the heated and 0·44 for the cooled rotating disc [32C]. The integration of coupled non-linear boundary-layer equations near the stagnation point in three-dimensional flow is discussed in [12C]. The reference temperature or enthalpy proposed by Eckert is found to describe the recovery factor and the Stanton number–friction factor ratio for high speed, laminar boundary layers of nitrogen and carbon dioxide with an accuracy which is even better than the one established for air [37C]. Flow and heat transfer on a flat plate which enters and moves through a stagnant fluid has been investigated analytically and experimentally for laminar and turbulent boundary layers [42C]. The same physical process has been analyzed with the difference that a cylinder of radius a is cooled when moving through the fluid. The results for very large Prandtl numbers are described by the equation

$$Nu = 0{\cdot}56\left(RePr\frac{x}{2a}\right)^{\frac{1}{3}}$$

where x indicates the distance from the entrance plane and the dimensionless parameters are based on the velocity and radius of the cylinder [20C]. An integral analysis of the compressible laminar boundary layer with suction and pressure gradient demonstrates that it should always be possible to prevent separation for finite pressure gradients [26C]. An iterative method for the integration of the laminar boundary-layer equations including diffusion can be applied for situations where no similarity exists [21C]. A set of similar solutions of the laminar compressible boundary-layer equations for flow over a flat plate is obtained for the condition that the wall temperature varies like $(x + \alpha t)/L$ with t indicating the time and L a reference length. This timewise variation can have significant effects on wall shear and heat transfer [11C]. An analysis of heat transfer across a laminar boundary layer for the condition that small time-wise fluctuations are superimposed on a steady main flow demonstrates that the effect of oscillations on heat transfer is very small [18C]. Larger increases in heat transfer, which have been measured in the presence of sound, are postulated to be due to some gross effects like the generation of flow instabilities. Illingsworth's analysis of heat transfer from a sphere at small Reynolds numbers with velocities which fluctuate around a mean value has been extended to higher Péclet numbers [6C].

The time-averaged turbulent boundary-layer equations are derived before the constitutive equations are introduced and it is hoped that in this way a decision can be made how well the conventional boundary-layer equations describe the physical reality [30C].

A numerical finite difference procedure for solving the two-dimensional boundary-layer equations uses the stream function as independent variable and a grid which adjusts itself automatically to the boundary-layer thickness [29C]. The method is applied to high Mach number flow over a flat plate, to the axisymmetric turbulent jet, and the radial turbulent wall jet. Charts for the Spalding and Chi method cover the range of Mach numbers from 0 to 20, Reynolds numbers from 10^5 to 10^9 and ratios of wall to total free stream temperature from 0·01 to adiabatic condition in air flow [27C]. In accelerated flows through nozzles, measured heat-transfer coefficients were found to be lower than calculated ones. Stanton numbers estimated from Deissler's analysis of locally homogeneous turbulence result in values which show good agreement with the experimental values [10C]. Similar solutions to turbulent boundary-layer heat- and mass-transfer problems are obtained for the condition that the thermal and diffusion layers are confined within the constant shear layer which is the case at high Prandtl and Schmidt numbers [5C]. It is claimed that triple correlations like $(\rho v)'u'^2/2$ and $(\rho v)'\, C_i h_i'$ (C and h, respectively, denote the concentration and enthalpy of component (i) must be maintained in the compressible turbulent boundary-layer equations [34C]. An iterative method for the investigation of three-dimensional turbulent boundary layers with heat transfer at the wall uses a third degree polynomial for the temperature polar [7C]. Calculated heat transfer to turbine blades which accounts for the presence of secondary flow is compared with experimental results. It is found that the analysis is in good agreement with the experiments for laminar boundary layers and overestimates the heat transfer in turbulent boundary layers [44C].

Dissociation, ionization, and chemical reactions

A numerical solution of similar non-equilibrium boundary-layer equations by a finite difference method with forward integration becomes increasingly difficult as the parameter K describing the ratio of flow time to reaction time increases. A new method circumvents this difficulty [8C]. Its application to stagnation point flow of dissociated nitrogen demonstrates that the flow is nearly frozen at $K = 10^{-4}$ and is near equilibrium at $K = 10^4$. An integral method studies the interaction of surface chemistry and mass transfer in non-similar boundary-layer flows, assuming an arbitrary surface interaction for each component. A numerical solution for combustion of a graphite cone demonstrates a surface reaction limited condition near the peak and a diffusion limited condition further downstream [23C]. An asymptotic solution of frozen dissociated laminar boundary-layer flow over a flat plate with arbitrarily distributed catalycity is presented [22C]. The uncertainty of transport properties causes an uncertainty in the stagnation point heat transfer up to 20 per cent at an enthalpy difference of 20000 Btu/lb [14C]. Heat-transfer and binary diffusion in a variable property, laminar boundary layer on a flat plate includes the thermal diffusion and diffusion thermo effect and presents an error estimate on the use of $T_w - T_{aw}$ as driving force for the heat flux [45C].

Experimental studies

Experiments in a wind tunnel at turbulence intensities between 0·1 and 6 per cent gave the result that heat transfer increased up to 30 per cent in the laminar boundary-layer region of a flat plate and up to 70 per cent on a cylinder [38C]. A theory is offered which agrees with the experimental results. In similar studies on a flat plate boundary layer with pressure gradient, in which the turbulence intensity was varied between 0·4 and 8·3 per cent and the local Reynolds number between 4×10^4 and 4×10^5, it was found that no effect of turbulence level existed in a laminar boundary layer at constant pressure, that with a pressure gradient the heat transfer increases with turbulence level, and that no increase occurred in a turbulent boundary layer at a favorable pressure gradient [16C]. Heat transfer from circular cylinders at low Reynolds numbers was studied analytically [17C] and experimentally [1C]. The experiments were done on wires in nitrogen, helium and nitrogen–helium mixtures. The helium data exhibited large thermal slip effects. Comparison with theory was used to establish a mixture rule for the thermal accommodation coefficient of the nitrogen–helium mixtures. The impingement of a shock wave on a cylinder at a Mach number of 14 and Reynolds number of 8000 resulted in heat fluxes at the stagnation line up to 2600 W/cm^2, that is, ten times the values without a shock [13C]. Laminar heat-transfer measurements on a catalytic flat plate in dissociated oxygen were carried out in a shock tube [43C].

The results could be correlated by the following equation

$$St = \frac{c_f}{2\,Pr^{\frac{2}{3}}}\left\{1 + \frac{u_e^2/2}{H_e - h_w}(Pr^{\frac{1}{3}} - 1) - \frac{\alpha_e h_D}{H_e - h_w}\left(\frac{\alpha_w}{\alpha_e}\right)\right\}$$

where the Stanton number is defined as

$$St = \frac{9}{\rho_e u_e (H_e - \alpha_e h_D - h_w)}$$

α denotes the species mass concentration, H the total enthalpy, and h the static enthalpy. The index e refers to conditions at the outer edge of the boundary layer, and w to conditions at the wall surface. The Prandtl number at the wall surface was 0·67 and the Lewis number 1·28. Experiments at a Mach number of 13·8 and Reynolds numbers between 1000 and 10000 on ablating cylinder-flare models and blunt-faced base models demonstrates that the thick laminar boundary layers could experience large-turning angles without separation [19C]. Convective heating was measured on blunt-faced models in regions of large favorable pressure gradient at Mach number 10 [25C]. Analysis based on local similarity gave good agreement with experimental results. An experimental study of stagnation point heat transfer in arc heated nitrogen at an enthalpy level resulting in 40 per cent ionization obtained heat-transfer coefficients in general agreement with previously published information [24C]. A review of previous studies on the effect of turbulence found that the influence on Nusselt number was largest at $Re = 40000$ and small above 200000 [9C]. Experiments on heat transfer across turbulent boundary layers on a flat plate partly heated with a constant heat flux agree with a proposed analytical method which utilizes Spalding's function [15C]. This was also true for an investigation of the turbulent boundary layer at a Mach number of 6 and Reynolds numbers between $2{\cdot}4 \times 10^6$ and $28{\cdot}7 \times 10^6$ [35C]. A critical review of experimental heat-transfer coefficients and temperature distributions in turbulent boundary layers at supersonic and hypersonic flow is presented in [33C]. A study of turbulent boundary-layer flow over a flat plate containing a time-dependent heat source established regions for which the heat transfer in the boundary layer could not be considered as quasi-steady [39C]. Heat transfer to a wavy wall in hypersonic flow with laminar, transitional, and turbulent boundary layers of air and helium at Mach numbers between 2 and 16 was strongly affected by separation occurring on the waves. Local peak heat-transfer values were up to thirty times larger than corresponding values on a flat plate. The average heat transfer was not affected to any extent [2C]. The length of an uncooled inlet section on nozzles with 30 and 60° convergence angles had little effect on heat transfer. The peak heat transfer at the throat was by 40 per cent larger for the nozzle with 60° angle and was over-predicted by various analytical methods [3C, 4C].

New results on momentum and heat transfer in axially symmetric turbulent jets in a quiescent air have been reported [41C]. Turbulence promoters in the form of an array of parallel rods normal to the air flow resulted in a maximum heat transfer improvement for $[e(\tau_0/\rho)^{\frac{1}{2}}/\nu] \geqslant 40$ with e denoting the promoter height [40C]. The diffusion from a ground level line source into a boundary layer disturbed by a fence downstream from the source has been studied in a wind tunnel [31C].

FLOW WITH SEPARATED REGIONS

Single bodies

Predicting boundary-layer separation on entry vehicles continues to be a problem because theoretical methods are inadequate and appropriate experimental data limited. One important variable, not yet thoroughly investigated, is the influence on separation of mass added to the boundary layer by ablating sur-

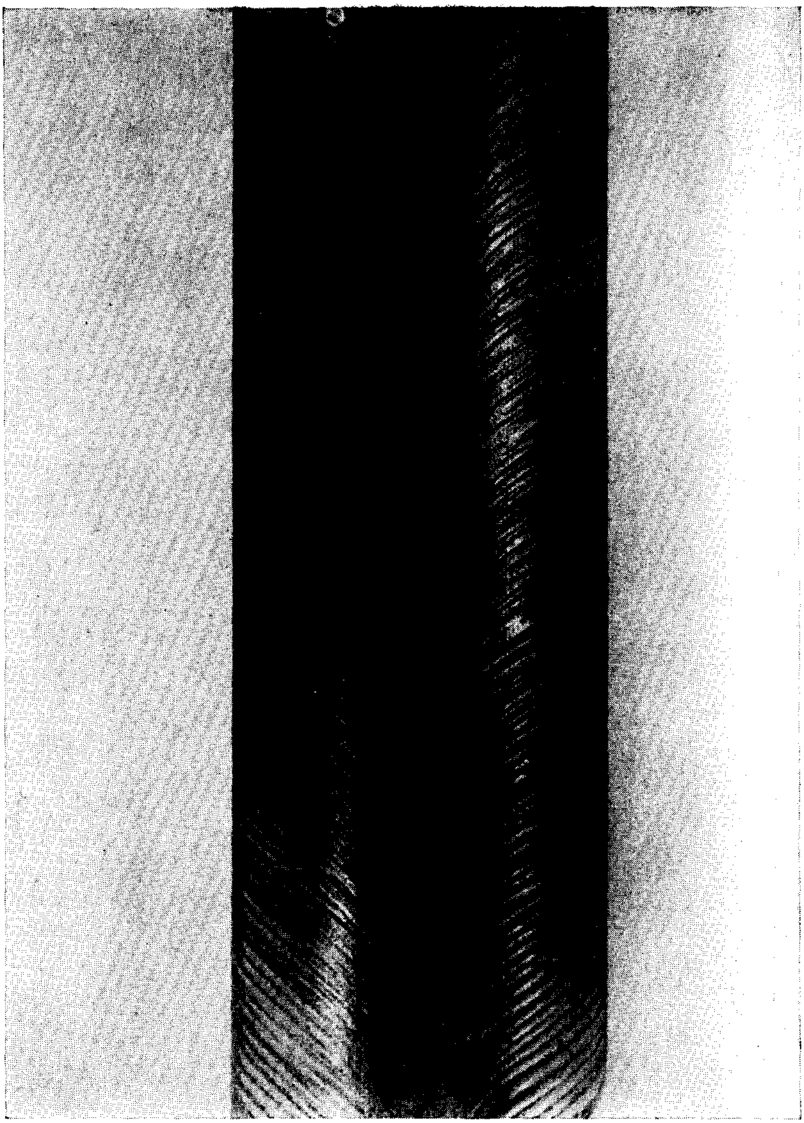

FIG. 1. Appearance of yawed cylinder after 1h at $Re = 93\,000$ ($D = 6$ cm; $U_\infty = 24$ m/s) and $Tu = 0{\cdot}3$ percent. Angle of yaw $\Lambda = 36°$ with respect to normal to free stream (This photograph originally appeared in the following reference: E. A. BRUN, G. A. DIEP and J. KESTIN, *C.R. Hebd. Séanc. Acad. Sci.*, Paris, **263**, 742–745 (1966). See also discussion by Kestin to paper [16C].)

faces. Laminar separated and attached flows were studied [18D] on ablating and on non-ablating models at $M = 13{\cdot}8$. Ablation influenced surface pressures, boundary-layer transition, but generally had very little influence on the extent of laminar separation.

An AGARD specialists' meeting on separated flows [24D], excluding the topic "Wakes", lists seven papers on laminar two-dimensional flows, twelve papers on turbulent two-dimensional flows, four papers on three-dimensional flows, and seven papers on applied problems. The theoretical and experimental aspects of separated and reattaching flows are surveyed [5D] with special reference to the heat-transfer characteristics. Three-dimensional effects contribute to unsteadiness in both laminar and turbulent reattachment. There is a need to examine the conditions for pulsation in subsonic and supersonic cavity flows and to determine the influence of cellular vortex stability on turbulent subsonic cavity flow.

Experiments with uniform temperature and uniform heat flux on a cavity wall reveal no substantial difference while the correlation of average Stanton number points to only a small effect of the relative size of the oncoming boundary layer, a pronounced effect of the cavity depth–length ratio, and a variation with $Re^{-0{\cdot}25}$ where Re = Reynolds number based on cavity length [11D].

Hot wire measurements [12D] are presented for Reynolds stresses in a cavity. Experimental data are compared with plane free jet eddy diffusivities. Agreement was obtained with empirical constant adjusted by 33 per cent while other "constants" vary by 20 per cent across the width of the slot. Cavity floor heat-transfer coefficients are very insensitive to the shape of the recompression step, in contrast to the recovery factor which was noticeably affected [7D]. The three-dimensional behavior of a cavity has been reported [14D] which substantially defines the mass-transfer variations on the four walls and floor of a rectangular cavity. Experimental and calculated results [9D] for the base pressure on a cylinder end, on the end bases of a plane channel, and in a nozzle are in fair agreement.

The Chapman–Korst flow model is extended to include modified recompression processes [22D]. Allowance is made for upstream boundary layers with the limitation that its thickness must be less than one step height at low Mach numbers, dropping to about one-third of a step height at $M = 3{\cdot}0$.

Measurements of heat transfer are reported in the entry region of a supersonic parallel diffuser with a sudden enlargement where the generating nozzle joins the diffuser [2D]. Very high heat transfer is observed with transitional separation. After re-attachment following laminar separation, the heat transfer is less with supersonic flow than with subsonic flow resulting from a normal shock at reattachment. The flow near the entrance to a flat duct in which there is an abrupt symmetrical enlargement in flow cross-section is characterized by a long stall on one side and a short stall on the other [8D]. Maximum heat transfer in both cases occurs at the point of reattachment, followed by a decay toward the values for fully developed duct flow. Heat-transfer measurements are discussed on a flat plate and a 17° ramp (with and without longitudinal stringers) and attached protuberances [6D]. High heating rates are obtained in a large area upstream of bluff protuberances while for streamline configurations the heating rates were much lower.

Ray [23D] presents a mathematical model for the pressure rise coefficient for shock-induced separation of laminar and turbulent boundary layers. He relates the pressure rise coefficient to the skin friction coefficient, laminar sublayer thickness, region of interaction of the shock and boundary layer, and a mixing parameter. Results are presented in terms of a critical pressure rise coefficient.

Reference [9D] summarizes theoretical and experimental study of submerged non-isothermal turbulent jets in a temperature range from 50°K to 20×10^3°K. The expansion angles of a jet, as well as the profile configuration, mainly depend on the initial density ratio.

Packed and fluidized beds

Heat transfer and drag experiments on spheres indicate that the product of the Reynolds number and turbulence intensity is an important parameter and that the scale of turbulence is of minor significance [20D]. Heat-transfer data for beds of spheres oriented in cubic lattices indicate that the generalized *j*-factor correlations can be extended to Reynolds numbers as high as 100000 [3D]. Mass- and heat-transfer *j*-factors obtained by the vaporization of water from porous spheres were increased by up to 20 per cent with the elimination of entrance and exit effects [21D]. Evaporation data for simultaneous heat and mass transfer from a wetted tile were obtained. Reynolds analogy did not apply—possibly due to particle-dependent transfer mechanism [17D]. The apparent anomaly of experimental observations on heat or mass transfer in packed beds at low Péclet numbers ($Pe < 10$) is attributed to channelling or local uneven contacting of fluids with solids [19D]. In packed beds the existence of channelling results in a different mechanism of axial mixing from the ordinary diffusion model.

A derivation is given for the temperature distribution for fixed-bed reactors, taking into account the effects of heat of reaction and the volume change due to the reaction [15D]. The response of a packed bed to a sine wave of temperature in a stream of fluid through it is analyzed [26D]. Experiments on tube bundles show unexpected behavior at Reynolds numbers above 2×10^5 where a sudden rise in the slope of the Nusselt–Reynolds numbers curve leads to an exponent of nearly unity [10D]. The pressure-drop coefficient shows a minimum in the same Reynolds number range rising again to remain constant for $Re > 10^6$. In a fluidized bed, the particle itself not only acts as a heat carrier but also penetrates into the boundary layer and breaks up the layer [16D].

Fluid-to-particle systems were studied in a constant-area, vertical pipe with aluminum granules of 0·027-in dia., flowing with gravity while heated air was forced concurrently [25D]. The resulting small pressure drop and large surface area-to-volume ratio (2980) permits very compact heat exchange—with possible application to turbine-powered vehicles. The electrical conductance of a fluidized bed consisting of cryptol and activated coal grains is studied—resulting in an equation for the time required for periodical heating of the fluidized phase, the maximum temperature of the fluidized phase, and the critical velocity of fluidization [4D]. Hoogendoorn [13D] studied liquid-phase axial mixing of gas–liquid flow through a packed column. Results for bubble flow indicate that one obtains about one ideal-mixing-stage per foot.

TRANSFER MECHANISMS

The variational method has been applied with good success to cases for which exact solutions are available and has been extended to more complex problems [1E]. The transient linear equations describing heat and mass transfer have been put into the form of integral equations which were solved by successive approximation [14E]. The dimensionless parameters describing heat- and mass-transfer phenomena were deduced assuming that the properties follow the law of corresponding states [2E]. Coupled diffusion of moisture and heat in hygroscopic materials was studied by a finite difference solution of the coupled, non-linear differential equation [11E]. The temperature–vorticity analogy was investigated for turbulent boundary-layer flow over a flat plate with a heat source at the leading edge [8E]. It is concluded that this analogy does not hold, probably because of the three-dimensional nature of turbulence. Heating was also found to delay transition. Boundary-layer transition on blunt bodies with local three-dimensional roughness elements in the form of small spheres was measured at a Mach number 2·01 [15E]. Insight into the transition from laminar to turbulent flow in a two-dimensional channel was gained by a measurement of the growth of turbulent spots to intermittent plugs in the inlet region [10E].

A statistical analysis of locally homogeneous turbulence sufficiently weak that triple correlations could be neglected indicates that the vorticity aligns itself longitudinally in accelerating flow and in a transverse direction in decelerating flow [4E]. The analysis was also extended to include the combined effects of buoyancy and shear [5E]. Isotropic turbulence becomes quickly unisotropic in this situation. The ratio of turbulent diffusivities for heat and momentum assumes values between 0·5 and 3, depending on the magnitude of a buoyancy and shear parameter. Turbulence measurements in a boundary layer with mass addition and combustion indicate that the turbulence intensity near the wall is approximately doubled by the combustion process [16E]. Turbulent mixing of hydrogen into an air stream flowing through a cylindrical duct at Mach numbers between 2 and 3 was investigated experimentally [9E]. The hydrogen was injected from wall slots either normal to the main flow or in downstream direction and the turbulent diffusivity for the mass transport was determined. Turbulent heat transfer in visco-elastic fluid (water with a drag-reducing agent manufactured by Dow Chemical Company) results in a ratio of the Colborn factor to the friction factor which is smaller than in water [7E]. Both factors were also found to be reduced individually. The limiting relation $\epsilon/\nu = 0.00032 y^{+4}$ close to the wall was obtained from experiments for the eddy diffusivity ϵ in pipe flow and annular flow [13E]. Experiments indicate that in the equation

$$u^+ = \frac{1}{K}\left[\log\frac{u^* y}{\nu} + A\right]$$

the constant A only is changed by transpiration [3E]. The expression $A = 2 + 550\ (v_w/u^*)$ is proposed as describing this constant for $0 < v_w/u^* < -0.08$ with v_w indicating the transpiration velocity and u^* the shear stress velocity.

The analysis of a two-fluid model of helium II predicts the existence of heat exchange torques on a non-uniformly heated body of such a magnitude that they should be readily observable [12E]. An analysis studies diffusion caused by gravitational acceleration in a mixture of a heavy and a light gas [6E].

NATURAL CONVECTION

Many papers have appeared, as usual, concerned with the heat transfer and flow induced by buoyancy forces. There is still considerable interest in various aspects of the problem of natural convection on a vertical plate. Such variations as non-constant properties, non-Newtonian fluids, and transients have been considered for this basic type of flow. In addition, interest continues to mount in the heat transfer and fluid mechanics in the Bénard problem, where a horizontal fluid layer is heated from below. The stability, nonlinear effects and turbulent flows in horizontal layers of fluid are continually being examined. Other studies during the past year have considered combined free and forced convection in boundary layers and duct flows.

The laminar natural convection heat transfer from an isothermal vertical plate has been calculated for a power law fluid in which the stress is proportional to the velocity gradient raised to some power [32F]. Another study for this geometry examines the effects of variable properties. With steam as the fluid adjacent to the wall, the coefficient of expansion should be evaluated at the free-stream temperature and the other properties at a reference temperature approximately the mean of the free-stream and wall temperatures [2F]. A numerical solution of the natural convection on a vertical plate with a step change in wall temperature (at some distance above the leading edge) has been completed [12F]. The effect of slip on the laminar free convection for a vertical plate has been calculated for systems in which the mean free path is of the same order of size as the boundary layer [25F]. The local free convection heat transfer from a vertical plate is found to increase significantly in the presence of a large electric field [23F].

Diffusion-thermo effects are included in an analysis of natural convection with combined heat and mass transfer [38F]. Simultaneous heat and mass transfer in laminar natural convection has been studied when there is a moving interface present [3F]. Studies of the transient natural convection from a vertical sheet following a step input (with time) of heat have included the effects of heat capacity of the sheet [10F] and the rate of propagation of leading edge effects up the sheet [9F].

There has been considerable study of the stability for the Bénard problem. The validity of the quasi-static assumption when there is a time dependent heating on the bottom of a horizontal fluid layer has been examined [26F]. The lower bound for the critical Rayleigh number in a completely confined horizontal fluid layer is calculated [31F]. Finite difference calculations of stability in a rectangular region of fluid heated from below do not agree well with earlier linearized theory at low Prandtl number (less than one) while at high Prandtl number there is good agreement with linear theory [28F]. A study of the stability of a fluid within a porous medium indicates that the thermal diffusivity term in the critical Rayleigh number should be calculated using the thermal conductivity of the solid and fluid mixture but the density and specific heat of the pure fluid [17F]. The critical Rayleigh number for the onset of flow in a spherical region of fluid has been studied [30F, 35F]. Linear stability analysis has also been used to determine the onset of convection produced by combined temperature and concentration gradients in a horizontal fluid layer [22F]. Gravitational effects on thermal stability have been studied [18F]. The effect of sidewalls on the onset flow in a horizontal fluid layer has been studied experimentally. When the ratio of width-to-length of the layer is greater than five there is relatively little effect of the sidewalls on the critical Rayleigh number [4F].

The possibility of secondary flows with the onset of convection in horizontal fluid layer has been analyzed [14F]. A simplified cellular flow is postulated to predict the laminar heat transfer in a horizontal layer of high Prandtl number fluid heated from below [33F]. Numerical analysis of Bénard convection for a Rayleigh number between 2000 and 20000 is in relatively good agreement with experiments only at large values of the Prandtl number [29F].

The Rayleigh number at which short term fluctuations in the temperature first appear within a horizontal fluid layer heated from below is found to increase rapidly with Prandtl number [36F]. Probe measurements of the temperature and velocity distributions in such a layer give credence to a thermal structure dominated by plumes throughout the region between the plates [6F]. Oscillatory flow is found for free convection heat transfer from a single horizontal plate [21F].

A correlation for free convection in a fluid layer above a melting solid has been obtained [37F]. A study [2F] of the effect of buoyancy on melting and freezing for an ice water system has been described in which ice is either above or below the liquid. An analysis based on present-day knowledge of heat transfer in horizontal fluid layers has been applied to the Earth's mantle to evaluate continental drift. Free surface boundary conditions are used and it is interesting to note that a Prandtl number of approximately 10^{22} and a Rayleigh number of approximately 10^7 are postulated [34F].

Measurements of the buoyant plume above a heated horizontal wire give good agreement with laminar theory although the plume tends to sway back and forth with time [8F]. The natural convection heat transfer from a horizontal wire can be almost doubled by sound waves propagated perpendicular to the wire. At a very high sound pressure (greater than 8 lb/in^2) the flow becomes turbulent [19F]. Measurements of the natural convection from a horizontal array of fins indicates that the shorter length fins produce considerably higher heat-transfer coefficients [11F].

Possible perturbations in the natural convection flow in a vertical layer of fluid have been examined [27F]. Experiments have been performed in an enclosed rectangular cavity in which the two vertical walls are maintained at different (uniform) temperatures [5F]. A numerical solution of the flow with natural convection in a vertical layer has been presented [7F] for certain boundary conditions. The nonexistence of certain fully developed profiles in vertical channels for frictionally heated flow has been demonstrated [16F].

The relative importance of free convection in the case of combined free and forced convection is determined by the ratio of Grashof number to the product of Reynolds number squared times Prandtl number to the one-half power at high Prandtl number and Grashof number divided by Reynolds number squared at low Prandtl number [1F]. Finite difference calculations of combined forced and free convection turbulent flow in a vertical tube indicate that volume heat sources have little effect on the velocity profile, but significantly change the temperature profile [24F]. The heat transfer is found to be less dependent on detailed analysis of combined free and forced convection in horizontal tubes than is the pressure drop or friction factor [13F]. Non-linear stability theory has been applied to various problems of free and forced convection including Couette flow in a horizontal layer heated from below [15F].

CONVECTION FROM ROTATING SURFACES

An exact solution for the heat transfer in laminar flow of a constant property fluid over a rotating disc including the effect of heat dissipation could be obtained when the disc temperature was prescribed as a quadratic function of the radius or when the disc was adiabatic [3G]. A short note discusses rotation induced, free convection heat transfer in a zero gravity field resulting in a laminar boundary layer of a constant property fluid on a rotating disc [1G]. Non-similar laminar boundary layer heat transfer on a rotating cone was calculated for a cone half-angle of 53·5°, and for Prandtl numbers between 0·2 and 10 [2G].

COMBINED HEAT AND MASS TRANSFER

An integral analysis has been used to correlate experimental results for the film cooling effectiveness downstream of a two-dimensional tangential slot [9H]. Increasing the boundary-layer thickness by a factor of four decreases the film cooling effectiveness only by 5 per cent [4H]. A heat balance analysis has been extended [12H] to predict film cooling effectiveness with foreign gas injection. The results of previous film cooling studies have been applied to predict the cooling in gas turbine systems [13H].

An integral method is developed and extended to problems of combined heat and mass transfer in a porous body [5H]. When a periodic boundary condition is applied to one surface of a porous slab in which there is coupled heat and mass transfer, different phase lags are found for the mass flow and heat transfer [3H].

The effect of diffusion thermo with transpiration cooling to a turbulent boundary layer has been calculated [10H]. Compressibility effects are included in the above study. Solutions for a general three-dimensional stagnation point flow (including two-dimensional and axisymmetric flows as special cases) for heat transfer with and without transpiration have been obtained [6H]. Concentration profiles have been measured downstream of foreign gas injection into the stagnation region [16H]. Calculations for heat transfer near the stagnation point with fluid injection indicates higher heating rates when the dissociation effects in the boundary layer are included [15H]. The results of a study of the transpiration cooling of a surface exposed to a 6200°R freestream indicate that a temperature difference rather than an enthalpy potential is more convenient in predicting the heat flux [7H].

The effect of surface injection on heat transfer to a blunt body in hypersonic flow has been evaluated [1H]. In another study, the effects of transverse curvature and binary diffusion are considered in the transpiration cooling of a surface exposed to hypersonic flow [2H].

The evaporation of molten spheres of naphthalene has been studied when the surrounding air temperature is somewhat above the melting point of naphthalene [17H]. Combined free and forced convection from an evaporating water sphere [8H] gives higher heat transfer with opposing flow rather then aiding flow due to mass transfer at the surface. This could be compared to the case of pure heat transfer where the reverse is true.

The heat transfer to a surface through which an absorbing–emitting gas transpires has been studied with a mainstream Couette flow [14H]. Although the radiation heat transfer to the surface will decrease with transpiration, the increase in convective heat transfer when the solid surface absorptance is low may cause a net increase in total heat transfer. Mass transfer cooling with a liquid will not, for certain values of surface tension, be adversley affected by spattering of the fluid [11H].

CHANGE OF PHASE

The greater part of the work in this area is concentrated in the area of boiling, its various modes, bubble behavior, and correlations. The overwhelming part of the work continues to be experimental. Condensation studies number one-half those in boiling and treat modes of condensation, the influence of various effects, and appropriate models to explain the process. A few, selected papers in two-phase flow complete the section.

Boiling

For nucleate boiling, a series of papers treat aspects of the phenomena: assessment of convection, conduction, and evaporation [31J], temperature difference and its role [1J], the influence of low liquid levels [59J], and a two-part study [91J, 92J] which considers the mechanism in pure liquids and binary mixtures and surface boiling. The increased attention to the details of the boiling process is shown by the studies on bubble, formation, growth, detaching and motion. Heled and Orell [37J] consider the characteristics of active nucleation sites in pool boiling, van Wijngaarden [93J] the growth of small cavitation bubbles by convective diffusion, Howell and Siegel [39J] the activation, growth, and detachment of boiling bubbles in water from artificial nucleation sites of known geometry and size. Shekriladze [80J] also treats the mechanism of steam bubble formation, Cole and Shulman [16J, 17J] bubble frequencies and departure volumes at subatmospheric pressures and growth rates at high Jakob numbers, and Ivey [42J] the relationships between bubble frequency, departure diameter and rise velocity. Rehm and Chiang [71J] examine bubble growth parameters for both saturated and subcooled conditions. In a somewhat similar study, Tolubinsky and Ostrovsky [89J] consider the mechanism of boiling heat transfer including bubble growth rate in boiling liquids, solutions, and binary mixtures. Special considerations include the collapse of vapor bubble with translatory motion by Wittke and Chao [97J], effect of surface orientation on delay time of bubbles from artificial sites by Williams and Mesler [96J], and bubble growth and heat-transfer mechanism in the forced convection boiling of water containing a surface active agent by Frost and Kippenhan [24J]. Torikai [90J] examines heat transfer in a contact area of a boiling bubble on a heating surface. Frost and Dzakowic [23J] give a graphical estimation of nucleate boiling heat transfer. Lai [48J] considers temperature distribution in a fin partially cooled by nucleate boiling. Other studies dealing with special influences are Schmidt *et al.* [79J], effects of an ultrasonic field in a nucleate boiling system, and Nangia and Chon [58J], who observe the effect of interfacial vibration on saturated boiling heat transfer. In pool boiling, minimum heat fluxes are investigated by Kovalev [47J], and the effect of subcooling on wall superheat by Bradfield [10J]. Subcooled boiling generates a self-excited standing wave according to Hayama [35J]. Elrod *et al.* [22J] give boiling heat-transfer data at low heat flux.

For film boiling, Nukiyama [62J] gives the extreme values for heat transmitted from metal to boiling water under atmospheric pressure. Baumeister and Hamill [3J] do a laminar flow analysis for a horizontal wire, and two experimental studies [43J, 75J] use a horizontal plate and both pure liquids and mixtures. Levy [50J] considers the important problem of predicting the vapor volume fraction during forced convection subcooled boiling. In a series of papers, Zuber and Staub [100J] investigate analytically the transient response of the volumetric concentration in boiling forced-flow, and then study the system experimentally [83J]. In two parts, Prakash and Pinder [69J, 70J] consider direct contact heat transfer between two immiscible liquids during vaporization. Kesselring *et al.* [45J] study transition and film boiling from horizontal strips, and Hamill and Baumeister [33J] the effect of subcooling and radiation on film-boiling heat transfer from a flat plate. Manson [52J] also treats a periodic non-uniform heat-transfer mechanism in film boiling.

The evaporative process is considered for the transient case through a finite region by the generalized Galerkin–Kantorovich method [7J] for the interface in a porous medium and an external gas stream [57J], and the transient temperature distribution in a system during sublimation dehydration [21J]. Maa [51J] gives evaporation coefficients for various liquids, and Furter and Cook [25J] review the literature of the salt effect in distillation. Boiling in tube flow is studied in a variety of ways: Tarasova *et al.* [87J] consider local fluid friction in the surface boiling of water in tubes, Styushin and Varshnei [86J] study heat-transfer rate of a subcooled boiling liquid, Sala and Tozzi [77J] burnout, giving a new correlation for round ducts and uniform heating with comparisons with world data. Hayama [36J] treats the problem of hydrodynamic instability in boiling channels, and Owhadi and Bell [65J] forced convection boiling inside helically-coiled tubes. Laverty and Rohsenow [49J] consider the specific system of saturated nitrogen flowing in a vertical tube undergoing film boiling. Critical heat flux and flow pattern observations for low pressure water flowing in tubes is reported by Bergles and co-workers [5J]. Critical heat flux with organic coolants is given by Cumo and Palmieri [19J] and local heat transfer and pressure drop for refrigerants evaporating in horizontal tubes by Chawla [11J].

A series of interesting studies treat rather special aspects of the film boiling process. Nishikawa *et al.* [60J] investigate surface film boiling under free convection, Gottfried *et al.* [30J] the Leidenfrost phenomenon: film boiling of liquid droplets on a flat plate. A three-part study by Ponter *et al.* measure film contact angles under equilibrium and mass-transfer conditions [6, 7], under conditions of heat transfer when a liquid film breaks on a vertical surface [67J], and evaluate the influence of mass transfer on liquid film breakdown [68J]. At the critical point, Sabersky and Hauptmann [76J] examine the forced convection heat transfer for carbon-dioxide. For a gas liquid-droplet suspension flowing laminarly over a circular cylinder, Goldstein, Yang and Clark [27J] examine momentum and heat transfer. Konsetov [46J] considers heat transfer during bubbling of gas through a liquid, and Chochran *et al.* [15J] study experimentally boiling in normal and zero gravity.

Orell [64J] comments on S-shaped boiling curves, Bewilogua *et al.* [8J] considers heat transfer in liquids with low boiling points, and Nitsche [61J] reports the results of a study of the diffusion of gases in a liquid-soaked porous space.

Condensation

A number of papers employ models and analysis to detail the process under a variety of situations. Thus, Rosner [74J] considers the enhancement of diffusion-limited vaporization rates by condensation within the thermal boundary layer. In a comprehensive study, Minkowycz and Sparrow [55J] analyze condensation heat transfer in the presence of non-condensibles, interfacial resistance, superheating, variable properties, and diffusion. Zinsmeister's [99J] approach is to work through Frenkel's theory of condensation. Measurements of the influence of gas in a condensing vapor–gas mixture are reported by Marschall [53J].

For dropwise condensation, Gose *et al.* [29J] propose a model for the process occuring on randomly distributed sites, while Rose [73J] considers the mechanism of the phenomenon. Other studies consider the influence of a variety of factors upon the process: Griffith and Lee [32J], the effect of surface thermal properties and finish; Medwell and Nicol [54J], the effect of surface roughness on condensing vapors at high and low Prandtl numbers; Mizushina *et al.* [56J], the effect of tetrafluorethylene coatings on condenser tubes. Certain specific substances, systems, or configurations receive attention in the following: dropwise condensation of steam at atmospheric and above atmospheric pressure [63J], drop size, behavior, and mass exchange in pulsed, packed extraction columns [95J], mercury droplet size and distribution in glass condenser tube in normal and zero-gravity environments [85J], thermal instabilities and the formation at low-mass condensations [2J], and the effect of molecular–kinetic resistance upon heat transfer with condensation [6J]. Heat exchanger considerations are reflected in the studies by Chisholm and Leishmann [14J], who study the process in surface heat exchangers; Boyko and Kruzhilin [9J], heat transfer and hydraulic resistance during condensation of steam in a horizontal tube and in a bundle of tubes; Goodykoontz and Brown [28J], local heat transfer and pressure distributions for Freon-113 condensing in downward flow in a vertical tube. In a more basic vein, Gerstmann and Griffith [26J] consider laminar film condensation on the underside of horizontal and inclined surfaces.

A group of papers evoke interest because of the range of problems treated involving liquid–solid phase change. Yang [98J] considers ice formation in plane stagnation flow, Beaubouef and Chapman [4J] the freezing of fluids in forced flow, Savino and Siegel [78J] the experimental and analytical study of transient solidification of a warm liquid flowing over a chilled flat plate, C-Y. Cheng and S-W. Cheng [12J] the freezing process based on the inversion of melting points due to applied pressure, Dschu [20J], ice formation from flowing brines on cooled surfaces, and Harriott [34J] the growth of ice crystals in a stirred tank. For a stratified medium, Hrycak [40J] examines heat conduction with solidification present, and Tien and Geiger [88J] consider the related problem of heat transfer during solidification in a binary eutectic system. The London–Seban equation is corrected for the case of molten metal solidification [72J]. For the freezing problem with the fixed surface radiating into a medium of arbitrary varying temperature, Westphal [94J] determines a series solution. The solid–vapor transition is represented by the paper of Collins *et al.* [18J] who study microsphere ablation in a free-flight range.

A few papers from the voluminous literature on two-phase flow are cited because of their direct concern or relation to heat-transfer problems in such systems. Spinks [82J] considers the conservation laws for two-phase flow with a change of phase. As a next step, St. Pierre and Bankoff [84J] detail vapor volume profiles in developing two-phase flow, and Hewitt and Leslie [38J] take up two-phase flow and heat transfer. Stability is a question which arises in this context and is considered by Shotkin [81J]. The paper by Huey [41J], though dealing with adiabatic homogeneous bubbly flow, is nevertheless useful in this condition for understanding two-phase heat transfer in horizontal pipes. Kennedy's paper [44J], which considers plug flow through pipes, is similarly useful as is the photographic study of the interfacial disturbances of liquid films in falling film flow, and in vertical, downward, annular two-phase flow by Chien and Ibele [13J].

RADIATION

Participating media

Planck's mean absorption coefficients are presented in diagrams for CO, CO_2 and H_2O at temperatures between 1000 and 5000°R [1K]. It is also pointed out that Planck's coefficients are actually mean emission coefficients and the evaluation of Planck's mean absorption coefficients is discussed [7K]. Formulas and tables describe average absorptance of regular bands [47K]. A simple method for calculating the frequency integrated radiation due to weak, closely spaced lines in a uniform gas has been developed [21K]. Spectral absorption coefficients have been compiled for neutral and singly ionized C, N and O atoms [45K]. Total absorption coefficients of air heated by strong shock waves to 13000–65000°K at 0·1–0·5 mm Hg have been determined [30K]. A calculation of radiative transfer in nitrogen with uniform properties and at local thermodynamic equilibrium for temperatures between 5000 and 35000°K, between 10^{-5} and 10^{-1} atm, and 0·2–35 cm gave the result that atomic and ionic lines are generally dominant and that Doppler broadening is significant except at the highest densities and the lowest temperatures [22K].

Radiative transfer through a spherical shell of an absorbing–emitting gray medium enclosed by opaque, diffuse, gray walls has been analyzed and the results are presented in a number of figures [43K]. A similar analysis considered unsteady energy transfer in a stagnant layer of gray gas heated by a diffuse or directional radiant flux [42K]. Convection and radiation as well as scattering has been excluded. Radiation slip between absorbing–emitting regions with heat sources is discussed in [19K]. Measurements of absorption and emission by non-isothermal CO_2 and H_2O are compared with various analyses [12K]. The gray gas analysis gives results in complete disagreement; the band model analysis agrees within approximately 20 per cent. Radiant energy transfer through non-gray gas layers with a spectrally and temperature-dependent absorption coefficient has been analyzed [39K]. An approximate analysis for a non-gray, non-scattering gas uses new mean absorption coefficients which agree better with physical reality than Planck's mean absorption coefficient [29K]. The method should be useful for plasmas in local thermodynamic equilibrium. Source functions for the analysis of radiative transport in a gray gas are available in tabulated form [16K].

A semi-isotropic model for radiation heat transfer is aimed at a better description of the temperature discontinuity at the wall [24K]. An approximate analysis for radiant heat transfer from gray isothermal dispersions absorbing, emitting, and scattering isotropically is compared with available exact solutions and is found satisfactory for design computations [11K]. A closed form solution is obtained for a gray isothermal dispersion of an emitting, absorbing, and scattering medium in a finite slab [4K]. Radiative heat transfer between parallel plates separated by a non-isothermal medium with unisotropic scattering and a prescribed linear or parabolic temperature field (generated by heat sources) is investigated [20K].

In using Rosseland's approximation, $q = (16\sigma T^3/3k_r)\, dT/dy$ to describe the heat flux q in the flow past a flat plate, it is found that the result is sensitive to the choice of the absorption coefficient k_r [35K]. An expression $k_r = aT^n$, with n varying between 0 and 6, was used in the calculation. A study of thermal radiation effects in laminar boundary-layer flow included viscous dissipation [38K]. The effect could be characterized by the Eckert number. An approximate solution of the differential equations describing steady heat transfer from the heated walls of a tube to an air–solid particle stream studied the combined effect of radiation and convection

[25K]. An analysis of the transparent limit for heat-transfer problems by radiation and conduction led to non-linear differential equations when radiation was predominant and to non-linear integral equations when conduction was predominant [44K]. The interaction of thermal radiation with free convection was studied for a laminar boundary layer [6K].

Blunt models gun-launched into an air stream with a relative velocity of 11·3 km/s were used to measure the spectral emission from a shock layer [8K]. The results compared well with an analysis which included continuum, atomic line, and molecular band radiation. Measured radiative energy losses of an argon plasma at 10000 to 20000°K agreed well with Emmons' results [14K]. Chemi-luminescent radiation from the far wake of hypersonic spheres accelerated by a light-gas gun to 14000 or 22000 ft/s was found to come essentially from the recombination reaction $NO + O \rightarrow NO_2 + h\nu$ [33K]. Precursor i.r. radiation was observed up to thirty body diameters ahead of an ablating body [26K]. It is probably caused by resonance absorption of photons created in the shock wave. H_2O radiation was found to be a most important contributor.

The off-specular peak phenomenon, whereby the intensity of reflected radiation from a roughened surface achieves a maximum at angles beyond the specular angle, has been explored analytically [41K, 28K]. Both analyses postulate local specular reflection from surface elements, plus internal scattering beneath the surface. The roughened surface is assumed to consist of small, randomly dispersed facets [41K] or undulations having the form of a sine-wave [28K]. Hemispherical-angular reflectance data for a variety of roughened surfaces were correlated as a function of the ratio of surface roughness to wavelength [3K].

The Fresnel equations for specular reflection have been evaluated for a large range of the complex index of refraction and of incidence angle [17K]. Radiation tunneling and wave interference are shown to be responsible for a variation of net radiant exchange with separation distance between two plane dielectrics [9K]. The effect is significant only when the separation distance is of the order of the wavelength of the radiation.

Experimental values of the directional reflectance of well-defined particulate layers are presented and compared with the predictions of various theoretical models [18K]. The spectral reflectance of compacted powder mixtures is calculable from the reflectances of the components [34K]. An analytical model, in the form of parallel plates or an array of opaque cubes, is proposed for the computation of the transient temperatures in a particulate medium wherein the transient response is radiation controlled [46K].

Band emissivities of carbon dioxide and water vapor are deduced from spectroscopic considerations in conjunction with the total emittance data of Hottel [10K]. The statistical band model is applied to compute the spectral emittance of the 4·3 μ band of carbon dioxide as a function of pressure, temperature and optical path [2K]. The experimental techniques employed in an extensive investigation of i.r. absorption and emission of carbon dioxide and water vapor are described [5K].

The computation of radiant interchange continues to be of interest. The characteristics of radiators are dealt with in two papers. In one of these, the results of a two-dimensional finite-difference solution for the central fin and tube radiator are used to evaluate the utility of various one-dimensional calculation methods [36K]. In the second, the performance characteristics of several fin-tube radiators and a reflector-tube radiator are compared [23K]; however, the radiant interaction between the radiator elements may have been incorrectly accounted. Further information has been published on the emission characteristics of cavities, among which are cavities with partially obstructed openings and grooved walls [32K]. The transmission of radiation through rectangular passages is shown to be significantly affected by the details of the reflection process, specifically, polarization and angular variation of the reflectance [13K].

Angle factors for diffuse interchange between a variety of plane surface elements are tabulated [15K]. The method of images, originally developed for interchange among plane specularly reflecting surfaces, is generalized to include specular reflection in non-planar surfaces [31K]. Voltage-dependent resistances are employed in developing an electric analogy to radiant interchange, with application being made to plane heat shields exchanging heat by both radiation and convection [37K]. An approximate technique, similar to the Kármán–Pohlhausen method of fluid mechanics, has been devised for solving the integro-differential equations that arise in connection with radiant interchange between thin heat-conducting plates (e.g. fins) [40K].

An analysis of the circular foil radiometer provides the sensitivity and response characteristics of this instrument [27K].

LIQUID METALS

The value $Nu = 4{\cdot}36$, resulting from analysis of fully developed heat transfer in flow through a tube, was also obtained experimentally in a liquid metal [1L]. Pressure drop and heat transfer in laminar and turbulent flow of pure mercury through a tube indicated absence of an interfacial resistance [7L]. An analysis has been presented for slug flow with uniformly distributed heat sources through rectangular channels with side ratios 1 to ∞ [4L]. The results can be applied approximately to turbulent liquid metal flow as soon as turbulent transport of heat is negligible. Slug flow of a liquid metal through a parallel plate channel with intermittently hot and cold walls of prescribed temperatures lead to negative Nusselt numbers at certain locations [3L]. Measured heat transfer of NaK flow through unbaffled rod bundles could be represented by the equation

$$Nu = \left(\frac{\Phi}{D}\right)^{\frac{1}{2}} \left(\frac{P - D}{P}\right)^{\frac{1}{2}} \left(\frac{\sin\beta + \sin^2\beta}{1 + \sin\beta}\right)^{\frac{1}{2}} [5{\cdot}44 + 0{\cdot}288\, Pe^{0{\cdot}614}]$$

where Nu represents the average Nusselt number, Φ a hydrodynamic potential function, D the rod diameter, P the distance of rods, and β the angle between the flow direction and the rod axis. The Péclet number, Pe, is based on the maximum velocity between the rods [5L]. The above equation holds for constant wall temperature. For uniform heat flux, the term in square brackets is to be replaced by $[4{\cdot}60 + 0{\cdot}193\, Pe^{0{\cdot}614}]$. The local distribution of the heat-transfer coefficients around the periphery of a rod can be described by a cosine function. Heat-transfer coefficients between 1650 and 3420 Btu/h ft^{2}F were measured for non-wetting condensing mercury flow through a horizontal tube cooled externally by NaK. The outside Nusselt numbers scattered around the value 5·8 at Péclet numbers between 65 and 127 [6L]. Steady-state performance of a seven-tube NaK cooled potassium condenser in countercurrent was also studied [2L].

LOW-DENSITY HEAT TRANSFER

An increasing number of classical fluid mechanical situations are being considered with low density fluids. A compilation of the mathematical relations required to obtain solutions to the problem of free molecule flow through converging or diverging slots and tubes are given [9M] along with numerical results such as the distributions of wall entrance flux, exit plane flux, flux distributions downstream of the exit, and several transmission factors. For example, a divergent slot yields a more collimated beam than a convergent slot of the same length to inlet width ratio and the same wall half-angle.

Linearized heat transfer between parallel plates is solved by the Bhatnagar, Gross and Krook (BGK) model [1M]. The heat flux resulting from numerical and variational methods agreed to within 0·5 per cent for inverse Knudsen numbers ranging from 0 to 10. The energy transfer in an absorbing, emitting and conducting medium with a low density between parallel plates involves strong coupling between radiation and conduction [3M]. In a continuum, the coupling may be neglected and the two "separate" heat fluxes added. Quarmby [8M] presents a solution for the flow of a viscous, incompressible, low pressure fluid in the entrance region of an annulus with wall slip for radius ratios of 1–10 and Knudsen numbers from 0 to 0·1. The probability of the passage of gas molecules through the cells of a grid is analyzed assuming the grid dimensions are less than the mean free path of gas molecules and the grid material is ideally heat conducting [2M]. Transient heat transfer through a monatomic collisionless ideal gas enclosed between parallel walls with wall accommodation coefficients of unity is analyzed [6M] for the case of a step change in one wall temperature. The steady-state heat-transfer condition is approached in an oscillatory manner requiring 20–30 crossings of the atoms across the channel.

Accommodation coefficient data are summarized for helium, argon, hydrogen and nitrogen with metallic surfaces of aluminum, silver, gold and platinum in the energy range between 500 and 12000 eV [4M]. Measurements of the heat-transfer coefficient from a sphere to rarified gas mixtures were made over a range of Knudsen number, Kn, of 0·008–0·4 by utilizing a thermistor [5M]. The experimental results were in agreement with the analytical equation obtained for a pure Maxwellian gas:

$$Nu = \frac{2}{1 + \frac{15}{2}\frac{Kn}{\alpha_{mix}}}$$

where α_{mix} is the multi-component gas accommodation coefficient.

Heat transfer from an electrically heated tungsten filament is investigated at pressures ranging from 4×10^{-3} to 770 torr in order to distinguish between the convective, conductive and radiative components [7M]. For the horizontal filament surrounded by an open-ended, coaxial cylinder, $Nu = 2{\cdot}35\ (Ra)^{0{\cdot}12}$ in the range $10^{-4} < Ra < 1$ (Ra = Rayleigh number $= GrPr$). An experimental investigation [10M] on a thin, sharp-leading-edge, flat plate in a low density supersonic wind tunnel with incident flow conditions $5{\cdot}7 \leqslant M \leqslant 14$; $30 \leqslant Re_{\infty}/mm \leqslant 600$ is given. Freestream rarefaction leads to a reduction in the strong interaction induced pressure field at $Kn_{\infty} > 10^{-3}$ such that the induced pressure depends not only on the hypersonic interaction parameters but also on the density of the undisturbed flow.

MEASUREMENT TECHNIQUES

An analytical and experimental study indicates the rapid response of an intrinsic thermocouple, where two wires are welded directly to the specimen surface [18P]. With such a system, the heat capacity of the junction does not enter into the time constant. Analysis of the response of temperature measuring devices to a periodically varying fluid temperature is extended to include the effect of conduction along the sensor [8P]. The time response of thermocouples is measured [33P] using an optical system to get the true temperature variation of the surroundings. A sensitive calorimeter using a quartz-crystal oscillator for temperature measurement has a temperature stability of approximately 10^{-5} °C at 25°C [16P].

Relatively simple equipment for the calibration of thermocouples at the zinc, antimony, silver and gold points is described [36P]. Tungsten–rhenium thermocouples are found usable, when properly sheathed, to temperatures as high as 2850°C [1P]. A thermocouple in the form of a venturi tube with a junction at the throat is used to measure the temperature of a high temperature gas stream. The high heat transfer at the throat tends to give relatively accurate results [11P]. A probe is described [14P] for the measurement of the local total enthalpy in arc jets. In measuring the internal temperature in a charring ablator relatively small error is introduced if thermocouple wires are placed perpendicular to the direction of heat flow [4P].

A review of methods for the temperature measurement of solid surfaces has appeared [34P, 35P]. The effect of radiation coming from beneath the surface can seriously affect pyrometric measurements of surface temperature [25P]. An instrument has been developed to determine surface temperature from measurements of the polarization of reflected and emitted radiation [24P].

A single thermocouple inserted at a fixed distance from a wall is used to obtain the heat flux in a flowing fluid in a matter analogous to the use of a Preston tube for shear measurement [5P]. Heat transfer across a solid–fluid boundary is determined from the strain birefrigence in a photoelastic solid. The resulting pattern is used to determine temperature gradient in the solid and the heat flux [21P]. An electrode which measures local gas concentration permits measurement of mass-transfer coefficients during transients [15P].

An extended analysis compares the tilt introduced in two different laterally shearing interferometers [23P]. A review of laser interferometers of different designs has been presented. Interferometers considered are those which might specifically be used in fluid mechanics or heat-transfer studies [32P].

When using a capacitance method for void fraction measurement, it is necessary to do a direct calibration of the system when the void fraction is greater than 40 per cent. At lower values of void fraction, the theoretical prediction gives a satisfactory prediction of instrument performance [9P]. Local measurements of humidity have been made using a small thermocouple junction cooled to the dew point by the passage of an electric current [12P]. A hot-wire cell for measuring the thermal conductivity of gases has been described [31P]. A transient system, with a spherical shell geometry, for determining the thermal conductivity of insulating materials, has been tested [19P]. Using a periodic radiant energy input, the absorptance and emittance of a sample are obtained from the amplitude and phase lag of the sample temperature [20P].

Measurements of the mean velocity and the root mean square of the velocity fluctuation have been obtained for turbulent flow in a circular tube from the Doppler shift of scattered laser radiation [17P]. Flash photolysis, in which a tracer line is produced by a high intensity light beam, permits velocity measurements in the laminar sublayer of a turbulent boundary layer [28P]. Velocity measurements in the developing region of a tube have been obtained from the periodic flashing of a light source and resulting time exposures of particle positions [2P]. Spatial and time filtering permit measurement of local velocities from the radiant energy passing through an optically thin flow [3P]. The effect of the velocity component tangential to the wire must be included when measuring velocity with a hot-wire anemometer, if the wire is not normal to the velocity. A simple cosine relation cannot be used in this situation [6P, 7P]. By the use of two probes of different size, a thermo-anemometer can be compensated to determine velocity in a non-isothermal boundary layer [22P]. A thermistor anemometer which is operated neither at constant temperature nor constant current but rather as one arm of an unbalanced Wheatstone bridge is found to have a relatively linear output as a function of velocity [27P].

A critical review of methods for flow visualization in water has been presented [10P]. An oil smoke generator for flow visualization in gases at pressures up to 4·5 atmospheres has been described [29P].

Previous predictions of the error introduced from finite size holes used to measure static pressure have been confirmed [30P]. Analysis of a Preston tube for determining wall shear stress with a power-law velocity profile is presented [26P]. Two static pressure holes of different size are used in combination to determine the local wall shear stress [13P].

HEAT-TRANSFER APPLICATIONS

Heat exchangers

Seymour [35Q] presents an experimental study of flow properties and flow patterns resulting from insertion of spirally-twisted tape into tubes. The performance of twisted steel strips as turbulence promoters is due to the forced multiple vortex motions [44Q]. An analysis of the flow based on a boundary-layer model did not shed much light on the details of flow. The heat transfer in a scraped-surface heat exchanger is described [43Q] by a relation derived on the basis of penetration theory in combination with an empirical correction. Experimental data [20Q] confirm most of the previous paper.

"State-of-the-art" formulas for the average Nusselt number are given for laminar and turbulent flow [3Q]. Correlations are presented for Nusselt numbers for equipment-like tanks with high-speed agitators and with large paddles. A criterion is given [17Q] for the incipience of nucleates boiling on a straight fin. Single-tube heat transfer and mechanical strain gauge test data are presented for bi-metal extruded and interference fit fin tubes [37Q]. Applications of geometric programming to chemical process equipment was demonstrated by finding the optimal design of a horizontal tube condenser [5Q].

Experimental data is given on convectively-cooled, shell-and-tube condensers using water as the working fluid [7Q]. The predicted values of the overall heat-transfer coefficient and condensing lengths agreed within ± 20 per cent with measured values. Condensing coefficients, Carpenter and Colburn film coefficients, Dittus–Boelter correlation condensing lengths, and predicted pressure drops were within $+50$ and -20 per cent of measurements.

Heat exchange between three fluids is required in such applications as air separation systems and ammonia gas systems [4Q]. NTU-effectiveness relations are given for the general three-fluid heat exchanger in which all three streams are in thermal communication. Agreement with experiments is good. Digital computer programs coded in FORTRAN IV are summarized for the design of the coolant passage dimensions of a convectively-cooled nozzle for a specified gas-side wall temperature distribution using a range of heat-transfer correlations, different surface roughness conditions, and a tube splice [31Q]. Design charts are presented for compact-fin heat exchangers taking into account (1) heat conductance of the fin in the direction of the flow, (2) the warming of the fluid along the fin, and (3) temperature changes of the fin base in the flow direction [41Q]. To determine the operating temperature of fuel elements in a nuclear reactor one must know thermal conductivity of material. The thermal conductivity behavior of a cermet (ceramic fuel particles embedded in a matrix of metallic materials—such as tungsten–uranium dioxide) is predicted under a variety of conditions [23Q]. Auxiliary (bleed-gas) cooling will be necessary for nuclear rocket components because of gamma heating [32Q]. When exposed to the $9{\cdot}5 \times 10^4$ Btu/h ft^2 of radiation expected near unshielded high-power nuclear rocket reactors, steel in thickness $\geqslant 0{\cdot}25$ in would remain intact but aluminum would melt in a few hours.

There are five kinds of transients for the flow characteristics in a single heated tube of circular cross section [19Q]. These transients, which are approximately independent of past initial conditions, can be simply described by a family of curves in a phase-plane plot. In a steady laminar flow with heat addition in constant area passages [30Q], and a fluid whose viscosity increases with temperature, there are two mass flow rates possible for a given pressure drop and heat input ratio. Such passages are unstable when rate of change of pressure drop with weight flow at constant heat input is negative. The instability is associated with the matching of the heat-transfer characteristics of the flow passage and of the reactor core. Characteristic times are in seconds or minutes. No oscillation occurs—rather a steady drift away from unstable equilibrium points.

Integral methods have been used to study crossflow heat exchanger transients with one fluid mixed [25Q]. The response to a step change in the inlet temperature of a mixed fluid is evaluated and results are summarized by a design chart for calculating the time required to obtain 90 per cent response. Experimental frequency response techniques were used to measure the inlet dynamic impedence of a forced-flow single tube boiler over a range from 0·04 to 4·0 c/s [16Q]. Using superposition of known solutions [18Q], it is possible by means of hand calculations to determine fluid and solid temperatures at any time and location in a regenerative heat exchanger in cases where the initial temperature varies arbitrarily with longitudinal position in the matrix and the entering fluid temperature varies arbitrarily with time.

Experimental, transient forced-flow heat exchanger data are compared with analytically-derived, exact and linearized temperature responses [39Q]. The available literature on heat transfer, pressure drop and thermophysical properties associated with the flow of dilute gas–solid suspension is reviewed [29Q]. Acetylene, propane, and stabilized methylacetylene propadiene are compared with respect to rates at which their flames transmit energy as a function of flame cross section [10Q].

Simple formulae and charts are presented [11Q] to calculate the performance of cooling towers if the relation expressing equilibrium between the phases is exponential and the transfer coefficient is given. Research is summarized on a water boiler heat sink module [12Q] including testing of wick heat transfer, wick performance and wicking height. A breakthrough analysis was performed on a water sublimator heat sink module, and capillary tubes were tested to verify analytical predictions. Using wool as an example of a hygroscopic material, it is shown that transfer of moisture from air to wool and from wool to air are not symmetrical processes when allowance is made for the rate of sorption (change of phase of water vapor) [28Q].

The transmission of some of the materials suitable for transparent covers of solar stills is nearly constant for angles of incidence less than some critical value and then decreases for larger incident angles [22Q]. Tent-shaped covers maximize the area on the cover where the angle of incidence of radiation is less than the critical angle. Evaporation in the deep-basin solar still continues during an entire 24-h period while the tilted-tray ceases to produce a short time after sunset [42Q]. Dropwise condensation is promoted with tetrafluoroethylene coatings with an increase in overall heat-transfer coefficient from 16 to 30 per cent over film condensation values [24Q]. These results were found for steam but not for organic vapors. An experimental study of tubes in strip solar collector plates [6Q] revealed that 100 Btu h/ft^2 °F could be justified for the film heat-transfer coefficient in the calculation of fin efficiency factors for solar collectors whereas it has been the practice in recent publications to use values of 40–60. A design equation has been developed and tested [13Q] for the prediction of batch heat-transfer coefficients for pseudo-plastic fluids in agitated vessels.

Heat-transfer data have been obtained for the flow of heat through a helical coil in a baffled agitated vessel, using flat head turbine agitators [27Q]. A simplified model of the heat-transfer phenomena occurring in a rotary kiln has been developed and tested [34Q]. Holt [14Q] presents an exhaustive survey of equipment and techniques for heating or cooling of pellets, flakes, powders, or molten solids. Hruby [15Q] develops a technique for the prediction of heat transfer in agitated vessels taking into account the heat of reaction, heat introduced by the power driving the agitator, and the viscosity-temperature relation. Local heat-transfer coefficients are given for the inside wall of an agitated vessel [1Q]. Local nonuniformity in temperature, concentration, or current can significantly reduce fuel cell performance [9Q].

Sarkies [33Q] presents a review of heat recovery equipment giving a description of boilers used with gas turbines. Car body aerodynamics play an important role in heater air flow [36Q]. Favorable pressure conditions become critical as the car body is made leakproof to dust, air and water. A general equation giving the cooling rate of a brake drum as a function of speed is applicable to the design of the area of a brake [26Q].

Dissociation rate and temperature have been determined as a function of the heating condition for an arbitrary reaction regime in the case of heat protective machinery materials with high working gas temperatures [8Q]. Heat input to welds is a controlling factor in the penetration, base metal dilution and ultimate metallurgical structure of welds [38Q]. Analysis predicts heat input before the arc is initiated to within 4·7 per cent error. Notch geometry and variation of material chemistry have little effect on cooling rates of Charpy impact specimens [2Q].

A method is given to calculate combined radiative and convective heat losses from a solidifying melt [21Q]. For typical steel-making conditions, the combined loss is 20–30 per cent of that lost to the ladle walls. The heat-transfer coefficients for several methods of cooling pistons in internal combustion engines are evaluted experimentally [40Q].

Aircraft and space vehicles

There is an increase of up to 25 per cent in heat transfer in the atmospheric mixtures containing large amounts of argon for the velocity range where ionization becomes significant [16R]. In the Martian entry range below 25000 ft/s, ionization is not significant and heat-transfer rates are similar to those of nonargon atmospheres. For a nonuniform atmosphere, the lag between the temperatures of a falling drop and the atmosphere has a significant effect on the evaporation rate [5R]. Error is largest at high relative humidity.

The evaporation of spherical droplets in free molecule flow were investigated [15R] to examine the feasibility of water injection as a means of alleviating communication blackout in the re-entry induced plasma sheath. In this case the mean free path may be large compared to the drop diameter and the usual continuum approach inapplicable. For a flow Mach number of four and a density ratio of $\rho/\rho_0 = 10^{-2}$, a 10 μ water droplet in a 5000°K stream would evaporate 80 per cent of its initial mass in less than 1 cm.

Guy [12R] gives an analytical study of the effect of test chamber pressure level on the accuracy of deep space heat-transfer simulation —using as parameters the test vehicle emittance and surface temperature. A test chamber pressure of 10^{-5} mm Hg provides the best thermal simulation. Static tests in a high enthalpy plasma jet reveal that artificial meteors of gabbro or basalt ablate and radiate similarly to samples cut from natural stone meteorites [31R].

The effects of ablation on re-entry body dynamics is a problem that has advanced from one of general interest to one of general concern. Analysis shows that ablation will have opposite effects on static and dynamic stability [9R]. During the portion of re-entry where boundary-layer transition moves from the base forward to the oscillation center, the undamped effect of ablation is greatly aggravated.

Tantalum melted and was swept away by a high velocity gas stream at a temperature of 1800°C, which is much lower than the melting temperature of tantalum (2980°F) [24R]. The phenomenon was attributed to reaction of tantalum with oxygen in the gas. Heat protection requirements for refurbishable systems having various materials and backface temperatures were established [4R] for the M2-F2 vehicles during ascent, abort, and re-entry including effects of ablation, reradiation, and ablation over reradiation.

Flow field, pressure, and heat-transfer distributions were studied at $M = 8$ for several bell-shaped configurations called tension shells —a shape which provides possible minimum weight entry vehicle structure [20R]. Jorgenson

[21R] extends earlier work to "not so slender" cones where for moderate mass loss rates (up to about 4 per cent of freestream mass flux) no appreciable effects of ablation on forces and moments were found, in contrast to earlier results on slender cones.

Twenty-two ablative materials were evaluated as nozzle sections [28R]. The mechanisms by which ablative materials provide thermal protection include heat rejection through reradiation, transpiration of gases formed by degradation of the materials, insulation, heat absorption due to the heat capacity of the materials, and the latent heat of thermal degradation [25R].

There are significant increases in heat-transfer rate over large regions of the Apollo command module due to the presence of protuberances and cavities (re-entry configuration) at $M = 10$ and $1{\cdot}4 \times 10^6 < Re < 2{\cdot}6 \times 10^6$ [2R]. Fourteen ablation materials were tested on twenty-seven models at conditions simulating the leading edge of the X-15 at $M = 8$ and altitude of 32 km [7R]. Material irregularities produced rapid and irregular loss of material and formation of deep cracks and fissures. A precast elastomer ablated uniformly and did not blister or crack. A facility consisting of a rotating multiple shock tube device which delivers 8 lb/s of uncontaminated test gas with reservoir conditions up to enthalpies of 2200 Btu/lb, pressures at 110 atm, and running times of 15 s is being used to study shock and viscous losses and combustion kinetics, for full-scale SCRAMJET engines at velocities up to 24000 ft [6R].

Comparison is made between the theory of Kutateladze and Leont'ev and experimental data from cooling devices representative of current European production practice. The study reveals that the effects of practical slot geometries are unaccounted for [32R]. Experimental study demonstrates the effectiveness of reducing the required coolant quantity for film cooling by means of dual slot injection as an attractive method of protecting the internal surfaces of rocket motors [35R]. The use of complex cooling systems [10R] for space conditions is sensible only when they are driven by a highly efficient energy unit.

Cooling system of conical nozzle with hydrogen fuel ducted in a jacket along the nozzle is studied [8R]. Local combustion gas-to-wall and wall to gas heat-transfer rates and coefficients as well as coolant pressure loss characteristics were determined. An experimental investigation of gaseous-film cooling of the nozzle of a small JP-4 gaseous oxygen rocket motor was conducted using tangentially injected nitrogen as the coolant [23R]. The wall temperature data were correlated for a hundred slot heights downstream by a modified Hatch–Papell equation. For low coolant flow rates wall temperatures were lower than expected which indicates that a coolant flow optimization might be possible in a design application. In the analysis of cooled gas turbine cycles, the quantity of heat removed by the coolant is termed as "cooling loss". A new ratio—cooling loss number—is found to be more practical when using a digital computer for cycle calculations [26R].

The three principal phases of operation of a nuclear rocket propulsion system are (1) system chilldown associated with reactor startup transient, (2) steady-state design power operation, and (3) systems shutdown and decay heat removal [33R]. Therefore, the transient pressure drop-heat-transfer characteristics of two-phase flow are of increasing importance.

Rapid estimates of turbulent flat plate heating equation based on Eckert's reference enthalpy and Hansen's air properties yield correlation expressions for heat transfer in terms of pressure, velocity, distance from leading edge, and enthalpy which agree to within 8 per cent with previous results [1R]. Selected incompressible flat-plate turbulent heating expressions used in an appropriate manner produce good correlation with flight test data over large ranges of Mach number, Reynolds number, wall temperature ratio for bodies with various cone half-angles and bluntness ratios [39R]. For Reynolds numbers 10^7, claculated heating rates based on Blasius or Schultz–Grunow friction factors were within +22 and −10 per cent of measurements. For $10^7 < Re < 8 \times 10^7$ the Schultz–Grunow C_f gave a better correlation. The formal solution of the temperature field in a satellite assumed to be a spherical shell of finite thickness rotating about an axis perpendicular to the solar radiation is given in [29R].

The combined effects of radiation cooling and self-absorption can reduce the radiative flux to the surface by an order of magnitude but has little effect on the convective heating [17R]. As re-entry speeds increase, the radiative component of heating begins to dominate convection and optimum shapes to minimize the heat input become conical [30R]. A radiant heat-transfer computer program has been developed [18R] to calculate radiation from inhomogeneous gases prevalent in rocket exhaust plumes from clustered engines, using radiation of water vapor, carbon dioxide, carbon monoxide, and carbon particles.

The radiative properties of the boundary layer and near-wake of ablative bodies flying in ballistic ranges and the observed absolute amount of radiation varied greatly for various materials [27R]. The chemical species responsible for the radiation in the spectral range from 0·2 to 1·1 μ were CN, C_2, NH, H, and solid carbon microparticles (soot). Results indicate a strong correlation between the radiation species present and the carbon–oxygen ratio of the ablating material.

H_2O and CO_2 radiation from the exhaust plume is a major contributor to the heating in the base region of multi-engine vehicles. Spectral emissivities ε_λ (4·40 μ, 1660°K) at Mach 4 were found to be about 80 per cent for normal propellant–oxidizer combinations [22R]. An explicit closed-form solution is given for radiative heat transfer to a body in flight in the Earth's atmosphere at speeds such that radiation is the dominant mode of heat transfer [38R]. The solution was obtained by assuming a grey-gas radiator and then linearizing the radiative transfer equation. The solution includes the effect of self-absorption in a strong shock layer, the interaction of thermal radiation with the shock layer, the preheating zone, and the ablated vapor layer.

Charts are presented which relate equilibrium shock-layer temperatures and densities of vehicles entering proposed Martian and Venusian atmospheres to flight velocity and ambient density [37R]. These data are used to estimate stagnation-point radiative heat transfer for entry trajectories. The overall scatter in correlated experimental observations limits the accuracy of predicting equilibrium radiance from shock layers to within a factor of 2 to 4. for entry into the atmospheres of Venus or Mars [36R]. Approximately 10^{-5} particles/cm^2/s of mass $> 10^{-14}$ g may be encountered by the thermal control coating on space vehicles although over a period of one year only approximately 0·01 per cent of the surface would be affected [3R]. Black coatings, prepared by a variety of processes for possible use as stable highly absorbing surfaces for spacecraft or as flat absorbers for use in ground test space-simulation facilities are studied in the wavelength range from 0·25 μm to 25·0 μm [34R]. Nearly all black coatings experienced only negligible change in emittance due to exposure to a simulated space environment of high energy electron radiation up to 10^{15} electrons/cm^2 for five months' exposure.

Based on the work of Biot, simple equations are given for temperature distributions due to kinetic heating in various structural configurations [19R]. Temperature rise and thermal heat transfer coefficients at various interfaces in thin metal-dielectric sandwich type of structure were measured at liquid helium temperatures using glass, niobium and aluminum substrates [11R]. Thermal conductivities of substrates had considerable effect on temperature rise. Hassan investigates the problem of simultaneously simulating radiant exchange between spacecraft and space [13R]. The problems involve simulating space with "warm-walled" chambers, important from the viewpoint of reducing initial and operation costs.

Average heat-transfer rates more than ten times the value with no shock wave impingement were measured in small localized regions on the stagnation line of a cylindrical leading edge. The results suggest this extreme interaction-induced effect on heat transfer [14R] is associated with the impingement of a vortex sheet or slip line (generated at the intersection of the bow shock and the impinging shock wave) onto the leading edge.

THERMODYNAMIC AND TRANSPORT PROPERTIES

Thermodynamic properties

A number of papers treat various computer schemes for determining equilibrium composition and thermodynamic properties. Thus Raju and Krishnaswami [85S] describe a free energy minimization method for calculating a chemical system equilibrium composition. Bailey [5S] gives a number of programs for computing equilibrium thermodynamic properties of gases. The concern with specific systems, sometimes under special conditions, is evidenced by the following: *air*, properties at high temperature [6S]; *argon*, composition and thermodynamic properties, 2400K to 35000K [43S]; *hydrogen*, computer programs for thermodynamic and transport properties [36S]; *hydrogen-peroxide*, thermodynamic properties (including dissociation effects) from 273 to 2000K and pressures 0–500 bar [109S]; *nitrogen*, thermodynamic properties up to 1300K and 1000 bar [113S]. For the group of freon refrigerants, Misra [71S] gives a theoretical evaluation of thermodynamic properties. For mixtures, Erickson *et al.* [27S], employ a method for computing the chemical-equilibrium compositions of reacting-gas mixtures which reduce to a single iteration equation. Shih *et al.* [97S] present high temperature enthalpy-composition charts for heterogeneous carbon–nitrogen mixtures. Also at high temperature, Karp *et al.* [50S] give machine calculations of the equilibrium thermodynamic properties of products resulting from combustion of methane–oxygen mixtures. For system analysis, Hust and Stewart [46S] present thermodynamic property computations.

In the area of molecular models and the calculations of properties based on such representations, Klein [54S] presents a most useful paper which describes the determination of intermolecular potential functions from macroscopic measurements. Boyd *et al.* [12S] present exchange and direct second virial coefficients for the hard sphere model. Henderson and Oden [41S] use the 6:12 potential and determine the virial expansion for the radial distribution function of a fluid. The nonadditivity of intermolecular forces and influence on the third virial coefficient is treated by Sherwood *et al.* [96S]. Third virial coefficients of nonpolar gases and their mixtures is considered by Chueh and Prausnitz [19S]. The intermolecular potentials of Krypton and Xenon based on the core model is described by Roy and Deb [90S]. A selection of some empirical and semi-empirical interatomic and intermolecular potentials is surveyed by Axilrod [3S].

From the viewpoint of irreversible thermodynamics, Hill [42S] examines the statistical thermodynamics of a simple steady-state membrane model, and Kluitenberg [55S] treats the thermal energy dissipation due to mechanical phenomena in continuous media.

Equation of state papers range from treatments of specific substance to special classes of substances. Thus, the equation of state of argon at high temperature is discussed by Frisch *et al.* [30S]. In the cryogenic region Lippold [62S] gives isothermal compressibilities and densities up to pressures of 1000 atm. Particular interest is exhibited in water, steam, and water–steam mixtures. Gibson and Bruges [33S] consider equations for saturated liquid and vapor phases; Juza [49S] the state equation for water and steam and tables in the critical region and the range 1000–100000 bar; and Hecht [40S] the determination of pressure and density from the liquid–vapor curve by means of reduced state equations. Kaye [51S] presents an equation of state for non-Newtonian fluids.

Specific *p-v-t* measurements are reported by Bottomley and Spurling [11S] on the temperature variation of second virial coefficient of benzene, and Tsiklis and Poliakov [108S], who measure the compressibility of nitrogen at 10000 atm and 400C by the displacement method. Hamrin and Thodos [38S] use ethane *p-v-t* data to obtain coefficients of thermal expansion.

Heat capacity investigations are concerned with *nitrogen* near the critical point [117S], *argon* in the two-dimensional critical region [7S], and methanol–water solutions using a calorimeter and an adiabatic shell [48S]. Nowak and Groeneveld [77S] consider the influence of small volume changes on measurements of the heat capacity at constant volume. Thermal behavior of fluids at the critical point receives Straub's attention. Additional critical state studies are concerned with mixtures: interaction model for critical pressures of multi-component methane-free aliphatic hydrocarbon mixture [26S]; graphical determination of the critical temperature for binary systems [31S]; critical temperatures and pressures of the ethane-*n*-pentane system [25S]. Lehigh and McKetta [60S] give vapor–liquid equilibrium in ethane-*n*-nitrogen systems.

Yesavage *et al.* [124S] describe the determination of fluid enthalpies at elevated pressures and low temperatures; Kipnis [53S] proposes a scheme for extrapolating experimental thermal data to high pressures. For non-equilibrium systems, Tip *et al.* [106S] derive rotational relaxation numbers from thermal transpiration measurements.

Quickened interest in surface tension is suggested by the studies of Sprow and Prausnitz [100S] for simple liquid mixtures, of Fuks and Bellemans [32S] for krypton, methane and their mixtures, of Watkinson and Lielmezs [118S] who apply the corresponding states principle to surface torsion, and to White [120S] who evaluates the effect of surface tension in relating the flow rate and mean thickness in liquid flow down plates.

Relation of liquid thermodynamic properties to the structure of fluid phases is reported by Melrose [70S]. Estimating liquid heat capacities is the subject of Bondi's [9S] inquiry; Hayward [39S] compares the compressibility equations for liquids; and Narismhan [76S] considers the temperature dependence of liquid heat capacities. Water thermodynamic properties in the region of maximum density are reported [125S] and supposed anomalies in the thermal properties of water and aqueous solutions [37S]. Van Dael *et al.* [111S] record sound velocity measurement in liquid argon, oxygen and nitrogen.

For liquid metals, thermodynamic properties and ordering in NaK alloys is reported [15S], the equation of state and electrical resistivity of liquid mercury at elevated temperatures and pressures [83S], and sound propagation [99S]. Lehmann and Ruschitzky [61S] consider the solubility of solids and liquids in compressed gases.

Miscellaneous works consider the dynamics of real air from subcritical temperatures to 1500K [79S] and a report of the All-Union Conference on the thermal properties of materials at high temperatures [8S].

Transport properties

The major effort in this area is focused on thermal conductivity, it's measurement and prediction for pure substances and mixtures under extremes of pressure and temperature.

General studies include an estimate of the triple collision contributions to the transport coefficients of a rigid sphere gas by Sengers [94S], the development of simplified expressions for the transport properties of ionized monatomic gases by Devoto [24S], the free-flight theory of gas mixtures by Monchick and Mason [72S], and the study of transport coefficients for binary gas mixtures by Gupta [35S]. Other investigations deal with the influence of molecular rotation on the viscosity of liquids [23S], and the effect of viscosity and thermal conductivity on the propagation of sound pulses [91S].

Diffusion

Mathur and Saxena [68S] describe a new method for the calculation of diffusion coefficients of multicomponent gas mixtures. Two separate studies [20S, 115S] take up the problem of the dependence of the diffusion coefficient on composition. Ivakin *et al.* [47S] present the time function for the diffusion coefficient of binary gas mixtures. In a two part study, Lund and Berman [63S, 64S] study the flow and self-diffusion of gases in capillaries. In another two-part study, Kotousov [56S, 57S] considers in detail the thermal diffusion effect. The He–CO_2 mixture at moderate pressures is used by Velds *et al.* [114S] to investigate thermal diffusion. This same phenomena in isotopic gas mixtures is used by Saxena and Mathur [93S] to investigate intermolecular forces. Van Dael *et al.* [110S] report measurements of the thermal diffusion factor in the pressure range 1–400 torr.

Thermal conductivity

Brain [13S] reports new measurements for *argon*, *nitrogen* and *steam*. *Argon* plasma is investigated experimentally by Asinovskii and Kirillin [2S] to determine thermal conductivities. The same gas is used in a shock tube study of thermal conductivity by Bunting and Devoto [14S]. At moderately high temperatures, Choy and Raw [18S] report conductivity values for some polyatomic gases. Das Gupta and Barua [22S] consider the representation of the density dependence of the thermal conductivity of superheated steam. The dense gas and liquid region thermal conductivity is calculated for normal hydrogen [123S] and reported for argon [89S]. Mukhopadhyay *et al.* investigate a number of gas mixtures: hydrogen–helium [73S], nitrogen–argon, oxygen–argon [74S], and hydrogen–nitrogen and hydrogen–carbon-dioxide [75S]. Other binary mixture studies include ammonia and various inert gases [101S], hydrogen–helium, deuterium–helium [107S], sulphur dioxide and various inert gases [21S]. Saxena *et al.* consider the methods of calculating thermal conductivity of binary mixtures involving polyatomic gases [66S], the Wassiljewa form for polyatomic gas mixtures [92S], and the conductivity of binary, ternary, and quaternary mixtures of rare gases [69S]. From the heat transfer occurring in reacting gases, Wise *et al.* [121S] determine both thermal conductivity and accommodation affects. Resvyanniko investigates experimentally the thermal conductivity of the system [86S]

$$2NOBr \rightleftarrows 2NO + Br_2.$$

In the liquid domain, Poltz and Jugel [82S] describe the temperature dependence of thermal conductivity. Measurements on specific substances are reported by Carmichael and Sage [16S] on *n*-Decane, by Tauscher [105S], on liquid refrigerants using an unsteady hot wire method, and by Vanderkool *et al.* [112S] for several glycols and their aqueous solutions, and five high molecular weight hydrocarbons. Viswanath [116S] gives general consideration to the thermal conductivities of liquids. Two special studies are concerned with conductivities in the cryogenic region below 1°K [95S] and the experimental investigation of the thermal conductivity of liquid cesium [98S].

In the solid region, Powell and Tye [84S] report new measurements for reference materials. For tantalum and niobium, the study by Akhmetzyanov *et al.* [1S] focuses on the temperature dependence of the temperature coefficient of the thermal conductivity. The work by Steere [102S] considers the thermal diffusivity of low-conductivity materials and that by Pitman and Zuckerman [80S] the effective thermal conductivity of snow at −88, −27 and −5°C. Special systems conclude the work on this particular transport property. Swift [104S] examines the thermal conductivity of spherical metal powders including the effect of an oxide coating. Granular materials are analyzed by Kropiczka [58S]. Platonov and Shramko [81S] consider the theoretical bases of measuring the thermal diffusivity of heat resistant materials in the case of free cooling of square rods. Finally, Fouché and Cordier [29S] consider the contact thermal resistance of parallel layers and Ziman [126S] discusses in a general and readable fashion the thermal properties of materials.

Viscosity

Childs and Hanley [17S] report both viscosity and thermal conductivity values for dilute nitrogen and oxygen. For the dense gas region, predictions are given for helium, neon, and nitrogen by Reynes and Thodos [87S]. The influence of pressure on the viscosity of water is the subject of two studies [122S, 44S]. In the cryogenic region of 0·36–2·6K, viscosity coefficients are given for liquid helium-3 [119S]. The corresponding states principle is applied to determine the viscosity of simple liquids [10S], to develop generalized charts for viscosity estimation [4S], and to compare saturated liquid viscosities of low molecular weight substances [88S].

A high pressure, capillary-tube viscometer is described and results from its use reported for methane, propane, and their gaseous and liquid mixtures [34S]. The viscosity of four binary gaseous mixtures at 20 and 30°C measured by the oscillating disc viscometer by Kestin *et al.* [52S]. Lee and Eakin [59S] report results for methane-*n*-decane mixtures. Somewhat more general studies consider the viscosities of binary liquid mixtures [28S], the Sutherland–Wassiljewa coefficients for binary rare gas mixtures [45S], and the viscosity of polar gas mixtures [67S]. Martens [65S] evaluates the accuracy of formulas for predicting values of viscosity and Parnpuu [78S] considers the theory of a two atomic gas coefficient accommodation.

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