Int. J. Heat Mass Transfer. Vol. 7, pp. 827-852. Pergamon Press 1964. Printed in Great Britain

HEAT TRANSFER, A REVIEW OF CURRENT LITERATURE

E. R. G. ECKERT, E. M. SPARROW, W. E. IBELE and R. J. GOLDSTEIN
Department of Mechanical Engineering, Heat Transfer Laboratory,
University of Minnesota, Minneapolis 14, Minnesota

(*Received* 9 *March* 1964)

INTRODUCTION

THIS review covers research in the field of heat transfer, the results of which have been published during 1963. The number of papers in this field is, as in previous years, 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.

An International Symposium on Humidity and Moisture, held in Washington, D.C. from 20 to 23 May, was sponsored by the American Society of Heating Refrigerating and Air-conditioning Engineers, the American Meteorological Society, the Instrument Society of America, the National Bureau of Standards, and the U.S. Weather Bureau. A considerable part of the 226 papers presented at that meeting dealt with transfer problems. The four invited papers were also devoted to the same processes. The Proceedings will be published in book form. The Sixteenth Heat Transfer and Fluid Mechanics Institute took place at the California Institute of Technology from 12 to 14 June; eighteen papers appeared on the program, a major part of them dealing with convective and radiative heat transfer. The Proceedings are available from the Stanford University Press. The Sixth National Heat Transfer Conference was held at Boston, Massachusetts on 11–14 August. It was dedicated to Dean L. M. K. Boelter who is retiring from his position at the University of California. Eighty-six papers on all phases of heat transfer were presented. They are or will be published in the *Journal of Heat Transfer* or in journals of the American Institute of Chemical Engineers. The program of the conference included two invited lectures and a well-attended forum for brief presentations and discussions of current investigations. Several books dealing with heat transfer have appeared on the market. They are listed at the end of this paper together with books in related fields.

The literature on channel flow indicates special interest in non-circular shapes and in non-elementary boundary conditions. The utility of the Spalding function for the calculation of heat transfer in turbulent boundary layers with arbitrary free stream velocity and wall temperature conditions has been emphasized. The extremely high velocities encountered in space technology have instigated studies of energy transfer between ionized gases and solid walls. The results of such analyses were found to depend critically on the transport properties, which are not well known at this time. Boundary layer and external flow experiments have been concerned mainly with specific aerodynamic configurations as proposed for air- and spacecraft. They are mentioned in this review in the section on applications. Radiation from the boundary layer contributes strongly to the energy transfer to spacecraft re-entering at very high velocities. This motivated a number of studies of radiative energy exchange between non-isothermal gases (usually gray) and solid walls. Radiative heat transfer between solid surfaces in complex geometric arrangements also found attention.

Continued interest exists in the instability of fluid layers with a negative density gradient in the direction of a body force (fluids heated from below). The question of whether contact resistance influences heat transfer between a flowing liquid metal and a solid wall is still being discussed and investigated. Transient methods for the measurement of thermal conductivity of liquids and gases are increasingly utilized. Discussions on MHD generators are beginning to appear in the literature devoted to heat-transfer applications.

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 with rotating surfaces, G
Combined heat and mass transfer, H
Change of phase, J
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Liquid metals, L
Low-density heat transfer, M
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CONDUCTION

A concern with various aspects of transient heat conduction dominates the activity in this area.

For one-dimensional, transient temperature distributions in slabs, one surface of which is suddenly exposed to a temperature different from that held constant at the other, Harmathy and Blanchard [15A] present Gurney–Lurie type plots. Two conducting bars (with identical, uniform, constant, physical properties), initially at different temperatures, are placed in contact and the resulting transient temperature distributions determined [1A]. Brunschwig [3A], considers the time dependent perturbation in uniform panel surface temperature, appearing at a rivet site, due to aerodynamic heating. For the transpiration cooled, porous wall, suddenly exposed to a constant heat flux on surface where coolant exits, parametric curves are presented [21A], for predicting the transient temperature response.

Cylindrical systems are considered by Phythian [24A], where pure radial heat flow occurs due to arbitrary, time-dependent, heat flux at the outer surface (inner surface adiabatic) and Olmstead *et al.* [23A], who determine the radial temperature distribution in a thin-walled circular cylinder rotating uniformly about its geometrical axis following sudden exposure to a time dependent source of radiation. Heyda [17A] considers a related problem for the orbiting sphere subject to alternate heating and cooling.

Two-dimensional, transient heat conduction is considered when the thermal conductivity is directionally dependent and such a thermally orthotropic plate is subject to varying heating rates [11A]. The results apply to materials used as heat shields and are tested by measurements made on a pyrolytic graphite plate. Tamurov [32A] treats the two-layer plane plate, whose surfaces contact a medium of linear, exponential, and periodic temperature variations, solving for the temperature field in the solid.

Systems involving phase changes or moving boundaries are considered in [31A] where the linear flow of heat in a continuously growing rod is treated; [14A] where Hamill and Bankoff give maximum and minimum bounds to the freezing-melting rates imposed by time dependent heat flux boundary conditions, and [4A], which examines temperature distributions and film coefficients at the interface of liquid and solid phase as a cold slab travels through a liquid metal bath causing solidification.

Pratt and Ball [26A] examine theoretically the temperature variation of air inside an enclosure where heat is generated at a uniform rate following a step change in outside temperature, considering influence of ventilation, internal heat storage, and thermal properties of enclosure walls.

A solution of transient temperature fields by electric analogy requiring minimal equipment is presented by Svoboda and Tůma [30A]. Analogue computer solutions for solving transient heat conduction problems are reviewed and compared in [10A].

Steady-state conduction studies determine the temperature distribution and heat loss to a cooling medium for a semi-infinite insulating strip placed between two isothermal heat sources [34A], the ratio of radial to total heat flow in a circular rod [33A], and the temperature distribution in a rectangular section, consisting of a finite number of isotropic materials, with prescribed temperature distribution on boundaries [35A].

For composite layers, Reid and Thomas [28A] describe the short machine program for quickly obtaining temperatures in a two-layer slab, and Vodicka [36A] the three-dimensional temperature distribution in a composite solid of n infinite slabs in perfect thermal contact at interfaces, subject to a prescribed two-dimensional temperature distribution at outer surfaces. For rapidly determining the two-dimensional temperature distribution and heat transfer through edge sections having convective boundary conditions, Johnson and Sunderland [18A] use electrically conducting paper to simulate the body. To facilitate either analogue or numerical solutions, a temperature function is presented [6A] for dealing with variable thermal properties.

Contrary to an earlier finding, Powell *et al.* [25A] find no dependence of heat transfer on direction of flow at interface of dissimilar metals in contact. Fenech and Rohsenow [9A] attack the problem of predicting contact resistance for any combination of metals, surface states, and fluids in the interfacial voids at the temperature and pressure considered. Experimental study on iron–aluminium system shows good agreement. Rapier *et al.* [27A], consider the same problem by a less complicated theory and realize general agreement with experimental results obtained on the uranium dioxide–stainless steel system.

Fin contour for radiation cooling at minimum weight and arbitrary finite tip thickness is considered by Grodzovsky [13A]. For annular fins with smooth radial variations of thickness and film coefficient, Bert [2A] gives the non-symmetric temperature distributions. The similarity between a thin-walled combustion chamber and the fuelrod-moderator component of nuclear reactors is noted by Gorski [12A] in determining the temperature distribution for a thin-walled circular duct with air flow over and through it and heat addition over the aft inside half.

Turning the mathematical aspects, Cannon [5A] solves for the unique temperature distribution prescribed by specifying the total energy content of a portion of the system and its boundary conditions. The variational principle is applied to a variety of one-dimensional problems by Lardner [19A], and to the coupled process of thermoelasticity and heat conduction in three-dimensions by Herrmann [16A]. Dicker and Friedman [7] consider transient temperature behavior in elliptical cylinders and cylindrical shells. Numerical methods deal with estimating the optimum convergence rate of the finite difference solution of Laplace's equation [29A] evaluating truncation errors inherent in the spatial difference formulation of heat flow [22A], a comparison of explicit and implicit methods of solving transient heat conduction [20A], and the successive application of integral transforms to the transient problem with heat sources [8A].

CHANNEL FLOW

Heat transfer in non-elementary internal flow configurations has been explored in several experiments. The effect of swirl on turbulent heat transfer to liquids was correlated [7B] in terms of a buoyancy force per unit volume. A significant increase in heat transfer and a corresponding increase in pressure drop resulted when the longitudinal turbulent flow in an annular gap was periodically interrupted by annular fins [5B]. The tests included hydrogen, helium, and water as working fluids. Similar results are reported for the turbulent flow of water in a circular tube having internal annular fins [27B]. Experiments with air flowing in an annulus reveal the existence of a maximum in local heat-transfer coefficient just downstream of an annular orifice [38B].

When a circular tube is wound in the form of a coil, the heat-transfer coefficient is higher than for a straight tube. The quantitative effect of the coiling has been determined for both laminar and turbulent flow [28B]. Very high heat-tıansfer coefficients are shown to exist in the vicinity of the point of impingement of an air jet which impinges normally on the inside of a circular tube [22B]. Turbulent heat-transfer results for air in rectangular ducts with aspect ratios 1:2 to 1:10 were correlated with the circular-tube equation [37B].

Specific measurement techniques have been devised to facilitate investigation of non-elementary flow configurations. One method utilizes the luminescence of impregnated chromotographic papers which are used in constructing a flow model of the duct [3B]. A new heat meter called an alphacalorimeter is described and applied in the study of the effect of upstream hydrodynamic conditions on turbulent heat transfer in a rectangular duct [14B]. A technique is proposed by which local wall shear and heat flux in a noncircular duct can be computed from measurements of the velocity and temperature profiles and the axial pressure gradient [2B].

It has been demonstrated that the general problem of heat transfer in a concentric annulus can be built up by the superposition of one or more fundamental cases [26B, 19B]. The solutions for all of the fundamental cases have been derived for laminar, hydrodynamically developed flow [18B]. The turbulent-flow situation presents greater difficulties, and thus far, solutions are available only for one of the fundamental cases [15B]. These have been checked experimentally for air. In an independent analysis, a method is presented for computing heat-transfer coefficients for either laminar or turbulent flow in an annulus with equal or unequal heat fluxes at the bounding walls [6B]. For the case of the eccentric annulus with slug flow, the circumferentially averaged Nusselt number is found to be lower than that for the concentric annulus [31B]; the boundary conditions of the analysis assumed no heat flow at the outer surface, and a longitudinally uniform heat flux and circumferentially uniform temperature at the inner surface.

The circumferential variation of the wall temperature corresponding to a circumferentially varying wall heat flux has been analytically predicted for turbulent flow in a circular tube [24B, 25B]. Results are also available for the alternate situation in which the wall temperature is prescribed [33B]. Within the simplifying assumptions of the analyses, it is found that the circumferentially averaged Nusselt number is identical to that for the case of circumferentially uniform thermal conditions. Two analyses relate to turbulent heat transfer in a parallel-plate channel. One of these presents fully developed Nusselt numbers for the symmetrically heated case for a wide range of Reynolds and Prandtl numbers [32B]. The other is concerned with the thermal entrance region and with unequal heating conditions at the bounding walls [11B]. In a fundamental experimental study, turbulent temperature fluctuations were measured for airflow in a circular tube [35B]. The maximum root-mean-square fluctuation was found to be about 10 per cent of the wall-to-bulk temperature difference.

Analytical papers have dealt with a variety of topics in laminar duct flow. The entrance-region and fully developed solutions are derived for the parallel-plate channel with arbitrary longitudinal variations of the wall heat flux or wall temperature, and of the internal heat generation in the fluid [34B]. The analytical results are confirmed by experiments in which the internal heat generation was created by the ohmic heating of an electrolyte. The catalogue of fully developed thermal conditions has been expanded by the discovery that a wall heat flux which varies longitudinally as e^{ax} (a = constant, x = longitudinal co-ordinate) yields a longitudinally uniform heat-transfer coefficient [10B]. This finding applies to turbulent as well as to laminar flows. The conditions have been derived under which solutions can be obtained for steady, fully developed laminar flow in a tube or channel under conditions of viscous dissipation and an arbitrary temperature-dependent viscosity [13B]. It is shown that if viscous dissipation is accounted for in laminar tube flow, then compression work ought also to be included [20B]. A simple relation is presented which gives the effect of longitudinal conduction on the fully developed Nusselt number for the parallel-plate channel. The correction due to this effect depends only on the Peclet number [9B].

The thermal response of a parallel-plate channel to time-dependent wall heat generation has been determined for the condition of a steady, slugflow velocity profile [29B]. A companion paper considers the effects of a time-dependent velocity but neglects the heat capacity of the walls [30B]. For magnetohydrodynamic flow in a parallel-plate channel, the relative magnitudes of the viscous dissipation, ohmic heating, and wall heat flux are reconsidered when proper accounting is made of the wall electrical conductance [40B]. An inviscid flow assumption was employed to facilitate the analyses of heat transfer for a radial outflow between two parallel discs [36B]; the predictions of the analysis were in satisfactory agreement with experiments carried out using water as working fluid. Two papers deal with heat transfer to non-Newtonian flows in a parallel-plate channel. The first relates to the fully developed condition, and specifically, to the effect of the non-Newtonian characteristics on the viscous dissipation and the corresponding temperature distribution [12B]. The second is concerned with the simultaneous development of the velocity and temperature distribution in the entrance region [39B].

Experimental investigations have also been carried out under laminar-flow conditions. For air flowing in a circular tube with large temperature differences between the tube wall and the fluid bulk, it was found that the data were in close agreement with the predictions of constant-property analyses provided the properties were evaluated at the local mixed-mean temperature [16B]. In an investigation using mineral oil as working fluid, the effect of heating was to flatten the velocity profiles and to introduce asymmetries; the tube was horizontal [8B]. Measured tube-wall temperatures corresponding to prescribed longitudinal heat flux variations were in close agreement with the predictions of laminar theory [1B]; water was the working fluid.

Several analytical investigations have been concerned with the transfer of heat and mass in a tube. Three of these relate to turbulent flow [17B, 4B, 21B], with the latter two also taking account of simultaneous chemical reactions. Another analysis studies the transient dispersal of soluble matter in laminar pipe flow [23B].

BOUNDARY-LAYER FLOW

Boundary-layer theory and solutions

A thoroughgoing and incisive survey is presented of the present state of knowledge relating to the transfer of heat across incompressible turbulent boundary layers [21C, 22C]. This serves as a prelude to the description of the so-called Spalding function, the use of which facilitates turbulent heat-transfer calculations. Spalding functions have been computed and are tabulated for a wide range of Prandtl numbers both for the prescribed wall-temperature boundary condition [13C] and the prescribed heat-flux boundary condition [43C]. Analysis shows that the skin friction and heat transfer for turbulent flow longitudinal to a circular cylinder are greater than the corresponding quantities for the flat plate [45C].

Exact solutions of the laminar boundary-layer energy equation can be derived for the limits of Prandtl number (Pr) approaching zero and infinity. The relationship of these limiting Nusselt numbers to those for fluids of finite Prandtl number is discussed [1C]. A correction to the limiting Nusselt number for $Pr \rightarrow 0$ is derived [30C] in the form of a series in terms of $Pr^{\frac{1}{2}}$. Solutions for large (but finite) Schmidt numbers are obtained by using an approximate representation for the velocity distribution as it appears in the energy equation; the analysis includes a finite mass-transfer velocity at the wall [14C]. It is well known that by employing the von Mises transformation, the momentum and energy equations can be recast into forms which appear similar to the diffusion equation. The conditions for the existence of similarity solutions in von Mises co-ordinates have been derived [2C].

For the laminar boundary layer in which the free-stream velocity and the wall temperature vary in powers of the streamwise co-ordinate, it is found that the temperature solution for $Pr = 1$ is proportional to the second derivative of the dimensionless stream function f [10C]. The Kármán–Pohlhausen method is used to solve for the temperature distribution which corresponds to a step change in wall heat-flux applied at a distance x_0 downstream from the hydrodynamic leading edge of a flat plate [15C]. The foregoing results are generalized to apply to arbitrary thermal boundary conditions along the plate surface [16C].

Various approximate methods for solving the boundary-layer equations are proposed. One approach replaces the partial derivatives in the streamwise direction with finite differences, but retains the partial derivatives in the transverse direction [44C]. A second method patches together a series solution which applies near the wall and a solution of a linearized von Mises equation which applies in the outer part of the boundary layer [26C]. Still another approach employs Rayleigh-type (impulse) solutions which are generalized by the introduction of free constants; the latter are determined by satisfying the boundary-layer differential equation at selected locations [37C]. The three-dimensional boundary layer which develops along a cone with surface heat transfer has been solved for by an integral method [49C].

The transient heat-transfer response of a flat plate subjected to a step change in surface temperature at time = 0 is analysed in terms of short-time and long-time solutions [35c]. Various computational expressions are examined which relate the instantaneous to the quasi-steady heat transfer for the condition of time-dependent surface temperature; these are synthesized to provide a more complete relationship [24c]. The effect of longitudinal conduction in the fluid is accounted for in a study of the steady heat transfer from a narrow isothermal strip imbedded in an insulated surface and exchanging heat with a stream having a different temperature [27c].

A wall jet is a flow configuration wherein the jet is bounded on one side by a wall oriented parallel to the jet axis. Fluid flow and heat transfer solutions are derived for the case where the wall is permeable and mass may be injected or removed. The distribution of the surface mass transfer is chosen to permit similarity solutions [11c]. For the impermeable wall, consideration has been given to a step change in surface temperature at some location along the wall. An integral momentum and energy analysis provides correlating parameters for experimental data obtained with air as working fluid [29c].

Dissociation and chemical reactions

A considerable number of analytical investigations was concerned with the effect of dissociation, ionization, and chemical reactions in boundary layers on heat transfer to surfaces with varying catalycity. Some experiments considering the same effects have also been performed. Dissociating iodine vapor in a compressible laminar boundary layer was investigated analytically and experimentally [12c]. The Lewis number varied between 0·5 and 1·8, the Prandtl number between 0·6 and 1. The reference enthalpy method was found to give values for heat- and mass-transfer coefficients which agreed with the exact analysis and with experiments within +14 to −7 per cent. A simple expression was derived [36c] which relates heat transfer in laminar flow over cones with free stream density, velocity, and cone angle. It was compared with experiments for altitudes up to 250 kft and velocities between 7 and 25 kft/s. Frozen condition could be maintained in a hydrogen stream with 0 to 75 per cent atomic hydrogen at a pressure of 0·1 to 1 mm Hg and at a temperature near ambient [8c, 9c]. Small cylinders were exposed to this flow and Knudsen numbers from 0·08 to 4·2, Reynolds numbers from 0·004 to 0·2 could be obtained at a Mach number 0·1. A recombination coefficient of 0·06 was measured on a stainless steel surface and it was found that this coefficient changes radically when substances are adsorbed at the surface.

Several analyses dealt with non-equilibrium conditions in the gas as well as on the surface. A calculation [18c]. using a simplified expression for the homogeneous reaction rate results in gooda greement with a previous analysis by Fay and Riddell Gas phase recombination can often be replaced by an equivalent surface reaction for a stagnation-point boundary layer [6c]. Arbitrary distribution of catalycity over the surface, together with frozen gas reactions, has been studied for plate, wedge, and cone flow assuming a first order recombination rate on the surface. Local similarity is obtained when the recombination rate varies as a power of the distance from the leading edge [19c]. The concept of local similarity was used to extend the analysis to other surface distributions. An approximate closed form solution is found to agree well with the previous analysis. The chemically frozen boundary layer with surface reactions is studied behind a strong moving shock to obtain information which is useful for the evaluation of tests in shock tubes [5c]. The flow of dissociated oxygen in a laminar boundary layer on a flat plate with finite recombination rates has been studied and it has been found that the concept of similarity gives results in reasonable agreement with a finite difference solution of the partial differential equations describing this process [3c]. Heat transfer from a 2-atomic gas to a flat plate with zero and infinite catalycity has been analysed for the condition that dissociation is produced within the boundary layer by viscous heating. A Lewis and Prandtl number equal 1, and a constant specific heat have been postulated. Atomic concentration profiles and heat transfer are calculated [34c].

The effects of ionization on stagnation heat transfer in air and nitrogen have been analysed

[32c] and it was found that differences in heat-transfer coefficients reported by Scala on the one side and other investigators on the other side are due to the assumed transport properties. The present theory gives Nusselt numbers which somewhat decrease with increasing upstream velocity in the range from 10 to 50 kft/s. Figure 1 taken from [32c] illustrates this. Experiments in an arc-driven shock tube at 24 to 30 kft/s [31c], using carbon dioxide, result in heat-transfer rates at the stagnation point which agree with analytical results by Hoshizaki and with the lower values in Fig. 1.

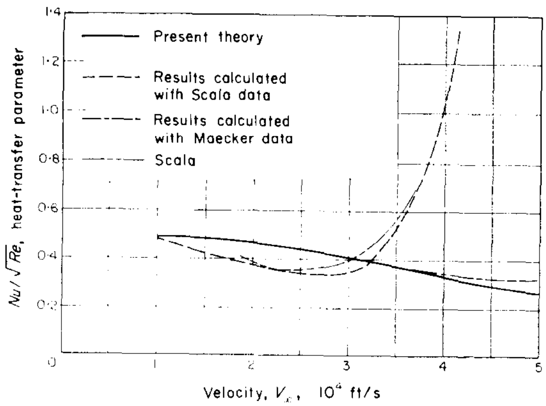

FIG. 1. Laminar stagnation-point heat transfer for ionized nitrogen; comparison of computations with different transport properties [32c].

The investigations discussed up to now considered surfaces without mass transfer to the boundary layers. An analysis [48c] studies the effect of surface combustion at a flat plate on the distribution of the total energy within the boundary layer. Dorodnitsyn's transformation is utilized and Prandtl numbers varying from 0·25 to 4, Schmidt numbers varying from 0·25 to 2, and Mach numbers between 2 and 5, have been considered. An equation has been derived [47c] which describes mass transfer in a turbulent boundary layer with homogeneous chemical reactions. The turbulent diffusivity is assumed to vary proportional to the third power of the wall distance near the surface and first order chemical reactions are postulated.

The influence of gas rarefaction on heat transfer to a hemisphere-cylinder was measured [17c] in a Mach number range from 2 to 6 and a Reynolds number from 38 to 1730. The pressure distribution was found to agree with Newtonian theory. The rarefaction effect on the temperature recovery factor was small and stagnation point heat-transfer data agreed within 10 per cent with boundary-layer theory. Regularly distributed buckles of various depth in the skin of a flat plate were found to increase the Stanton number and the heat flux density up to 150 per cent [40c]. The boundary layer in these experiments was turbulent and the Mach number had a value 3.

Effect of magnetic and electric fields

An analysis was concerned with the flow of an ionized gas in a laminar boundary layer over a flat plate under the following conditions [14c]. A constant magnetic field normal to the plate surface, a small magnetic Reynolds number, and zero electric conductivity outside the boundary layer have been postulated, and Kármán's integrated boundary-layer equations were utilized. The adiabatic wall temperature was found to be unchanged by the presence of the field, the viscous drag to decrease, and the total drag to increase with the magnetic field. An exact analysis for the flow of a viscous, incompressible electrically conducting fluid over a flat plate with a transverse magnetic field [46c] assumed the following conditions: Asymptotic suction is applied at the porous plate, the stream velocity oscillates, the magnetic Reynolds number is equal to the flow Reynolds number, the Alfven velocity is smaller than the suction velocity. Heat transfer and adiabatic wall temperature have been found to increase with increasing frequency of the fluctuation. Natural convection flow and heat transfer were analysed for two geometries [41c, 42c]: 1. Boundary layer flow on a vertical plate. Similarity and Pohlhausen-type solutions were found to depend on a Hartman and Grashof number. 2. Flow in a rectangular box with the two larger vertical walls at different temperatures and a magnetic field normal to these walls. The boundary-layer regime and the conduction regime were treated for this geometry.

The radial distribution of particle density was determined from measured H β-line intensities [23c] for an electric arc burning between two carbon electrodes in an argon–hydrogen mixture. It was found that the radial distribution of the electric conductivity could be presented by the equation

$$\delta = \exp\left[-\left(\frac{r}{r_{0\cdot5}}\right)\ln 2\right]$$

in which $r_{0\cdot5}$ indicates the radial distance from the arc axis at which the conductivity has dropped to half its maximum value [25C]. Formulas for the radial distribution of electric current and of temperature have been derived from this equation. The Elenbass–Heller equation was used to calculate the radial temperature distribution, and the electric characteristics of a nitrogen arc burning at 1 atm pressure [38C]. Maecker's values for the thermal and electric conductivity were used and the results were compared with experimental results by Maecker. The effect of an axial magnetic field was also studied [28C]. The generation of direct and alternating current in a magnetohydrodynamic device has been discussed in [7C]. It is concluded that alternating current generation will encounter difficulties with gas temperatures below 3000°K.

The influence of a direct or alternating strong electric field on heat transfer from an insulating liquid (transformer oil) to heated wires has been studied experimentally [4C]. It was found that heat transfer can decrease or increase depending on specific conditions. A non-homogeneous electric field increases laminar heat transfer in free convection of a paraelectric gas to a sphere up to 20 per cent [33C]. An analysis of turbulent flow of an electrically conducting liquid in tubes of rectangular cross section under the influence of an electric field resulted in expressions for the friction coefficient and in a stability criterion [36C]. The results were compared with experiments.

FLOW WITH SEPARATED REGIONS

Single bodies

The following relation is offered as describing heat transfer between a cylinder and an air flow normal to its axis and being valid up to the point where the boundary layer becomes turbulent

$$Nu = C_1\, Re^{1/2} + C_2\, Re^{3/4}$$

The constant C_1 has the value 0·37 to 0·55 depending on the free stream turbulence, the constant C_2 varies between 0·057 and 0·084. C_1 is also found to vary with the power 0·4 and C_2 with the power 0·33 of the Prandtl number [16D]. A similar relation

$$Nu = 0{\cdot}32\, Re^{1/2} + 0{\cdot}043\, Re^{3/4}$$

is proposed for heat transfer between an air stream and a sphere. It is also pointed out [17D] that the frequently used measurements by Hilpert are somewhat low compared with more recent measurements. A mathematical model for the analysis of separated flows in an incompressible liquid is proposed [7D]. The influence of sound on heat transfer was studied experimentally for the following condition [4D]: A cylinder with $\frac{3}{4}$ in diameter is exposed to an air stream normal to its axis and to standing sound waves with 1100 and 1500 c/s moving normal to the air flow and to the cylinder axis. Heat transfer was found to increase up to 25 per cent at Reynolds numbers of 1000 and 10 000, being only slightly influenced at other Reynolds numbers.

Packed and fluidized beds

The thermal conductivity of a bed of spherical particles with 29 to 470 μ diameter was measured at pressures from 10^{-2} to 760 mm Hg and compared with a theory based on contact resistance [10D]. The effect of thermal conductivity was also measured in a bed of alundum particles of approximately the same size and for a somewhat larger pressure range than in the previous paper [8D]. Rarefaction effects were clearly evident. The coefficients of heat transfer from beds of basalt, silica gel, and activated carbon particles to a flowing gas were measured [19D]. The transient temperature field in a porous wall with a coolant flow through it was analysed for the condition that a constant heat flux is suddenly imposed on the coolant exit surface [12D]. Heat and mass transfer between a bed of burning coke particles and gas flow through it was measured [2D]. The following relations [11D] represent the results of mass- and heat-transfer measurements for air flowing through a bed of spheres saturated with water within ±30 per cent

$$j_d = \frac{1.127}{Re^{0.41} - 1.52}$$

$$j_h = \frac{1.192}{Re^{0.41} - 1.52}$$

The Reynolds number is defined as

$$Re = \frac{D_p G}{\mu (1 - \epsilon)}$$

(D_p particle diameter, G mass velocity, μ viscosity, ϵ void fraction). Experiments showed that a frequently used theory by Anzelius for heat transfer in packed beds is not applicable to fibrous matrices [13D]. Flow non-uniformities are postulated as cause and a new theory is proposed on this basis [14D]. An analysis treats heat and mass transfer for gas flow through a packed bed of heat-producing spherical particles where cooling is applied to the walls of the bed [15D]. Prandtl's mixing length concept is utilized and the results are compared with experiments. Experimental results on heat transfer in a packed bed are reported for a wide temperature range [21D].

A new theory is proposed to describe heat transfer between the solid particles and a gas in a fluidized bed based on the assumption that irregularities in the flow pattern appear in a statistical distribution [22D, 23D]. Comments to this theory are offered [18D]. Heat and mass transfer in fixed and fluidized beds have been studied by the evaporation of water from porous particles [1D]. Heat- and mass-transfer coefficients are found to be independent of the gas velocity over a range of 1 to 4 times the minimum fluidizing velocity and to increase proportional to the power 0·7 in the fixed bed. Ergun's correlation for the friction factor of a packed bed was verified. Experimental results on the effect of screening on heat transfer in a fluidized bed have been reported [6D].

A number of papers studied heat transfer between a gas and fine particles carried along or between a stream carrying solid particles and confining walls. The interest in this theory is due to a new trend to process matter as fine particles. The first-mentioned effect has been measured in a cyclone [24D] and investigated analytically [20D]. Measurements on heat transfer between gas streams carrying fine particles and confining walls of a tube [3D, 5D, 9D] all indicate that heat transfer can be increased up to a factor of 3 and that this increase is the larger the smaller the particles. The measurements were done with particles of size 30 to 600 μ and at the Reynolds numbers between 15 000 and 27 000.

TRANSFER MECHANISMS

The Tollmien–Schlichting stability analysis has been extended to include temperature fluctuations and the thermal boundary condition for a compressible boundary layer [13E]. It results in two loops of complete stability and in this way tends to substantiate the transition reversal which has been observed experimentally in a number of investigations (see previous reviews). The stability of a two-dimensional laminar wake behind a flat plate and a cylinder was studied in a water tank by visualization with condensed milk [14E]. The stability curves were determined; the critical Reynolds number below which all waves damped was found to be one for the cylinder. A stability analysis was made for horizontal stratified flow with velocity and density gradients in the vertical direction [10E]. A method allows the prediction of the onset of turbulence in pseudo-elastic fluids with yield stresses [8E].

Two new correlation equations describing the velocity and eddy viscosity for turbulent flow near a pipe wall offer a continuous transition from the wall to the tube axis [15E, 17E]. Measurements of the turbulent fluctuations close to a pipe wall, as obtained from mass-transfer rates to small electrodes flush with the pipe wall, indicate that the root-mean-square fluctuation of the velocity gradient at the wall is at least 0·11 of the average velocity gradient [12E]. Hot wire measurements in a triangular duct, on the other hand, demonstrated that the flow is completely laminar in the regions of the duct corners even though it is turbulent in the core of the fluid [6E]. A harmonic form of Prandtl mixing length is obtained from a consideration of the eddy structure in a tube flow and gives results which agree well with Nikuradse's measurements [9E]. The constants in a semi-empirical equation by Pai describing the turbulent velocity profile have been determined [3E] and it was found that the actual velocities deviate from this equation at $y^+ = 75$ for Reynolds numbers larger than 100 000. Turbulent velocity profiles for the flow of non-Newtonian fluids with a shear proportional to a power n of the velocity gradient through pipes were found to be of essentially the same form as for Newtonian fluids when normalized with respect to the mean velocity or compared on the basis of the velocity defect parameter (centerline velocity minus local velocity divided by shear velocity) [2E].

Rates of energy transfer in isotropic turbulence and of the viscous dissipation of the spectrum were measured at three stations behind a square mesh screen [16E]. Similarity relations were found to hold. Two-point correlations were obtained from Navier–Stokes and energy equations for a field with uniform velocity and temperature gradients [7E]. The ratio of turbulent diffusivities for momentum and heat were shown to approach the value one for large velocity gradients regardless of the Prandtl number. Correlation functions were also studied for incompressible isotropic homogeneous turbulence in a magnetohydrodynamic fluid [1E]. Diffusion in turbulent shear flow is analysed [4E] based on a Lagrangian similarity hypothesis as suggested by Batchelor.

It has been shown that heat transfer may depend on viscosity and heat conductivity for flow across rough surfaces even when skin friction is not effected by viscosity [11E]. An historic review of the development of Clusius' apparatus based on thermal diffusion has been published [5E].

NATURAL CONVECTION

Analytical and experimental investigations covering a broad range of problems in natural convection have been reported. The boundary-layer analysis for the isothermal vertical plate has been generalized to include a body force which varies linearly with distance from the leading edge [22F], such a variation being intended to approximate a centrifugal-force field. Another generalization involves small horizontal variations in the plate surface temperature and small horizontal cross flows [43F]. Approximate laminar boundary-layer solutions for natural convection on an isothermal vertical plate and for combined forced and natural convection on plates with uniform heat flux or uniform surface temperatures are derived by applying a method devised by Meksyn for forced-convection flows [3F]. The agreement with existing exact solutions is satisfactory except at low Prandtl numbers. The width of the plume which rises above a line source of heat (e.g. heated horizontal wire) grows as the 0·4 power of the distance above the source [9F]; the characteristics of such plumes have been computed from the boundary-layer equations in the Prandtl number range 0·01 to 10. Buoyant elements of a considerably larger scale occur in the atmosphere. A study of the motion of such elements in turbulent surroundings takes account of the growth due to entrainment and of a loss of buoyant fluid to the environment [40F]. A formal solution, but without heat-transfer results, is derived for the buoyant flow of a viscoelastic fluid adjacent to a doubly infinite, isothermal vertical plate with uniform suction [18F]. The laminar natural-convection flow in a long vertical isothermal tube, induced by internal heat generation and modified by frictional heating, has also been solved for [26F].

Several papers have appeared relating to unsteady natural-convection processes. The time-variation of the spatial-average temperature of vertical elements with finite heat capacity has been computed for the cases of a step change in energy input and a linearly varying energy input [10F, 11F]. From experience gained from these studies, it is suggested that it may be unrealistic to ignore the heat capacity of the element in formulating transient problems in natural convection [12F]. The foregoing analytical predictions have been verified by experiments utilizing thin vertical metal foils suspended in air and subjected to a step input in power [13F]; good agreement is also found with water data. Temperature–time curves for step heat inputs to thin, electrically heated wires immersed in several liquids show an oscillatory behavior before approaching steady state [2F]. The response of the natural-convection, vertical-plate boundary layer to small amplitude periodic oscillations in surface temperature is analysed by seeking high- and low-frequency solutions of the linearized perturbation equations [24F, 25F]. These same authors derive the conditions for the existence of similarity solutions for the doubly infinite vertical plate with time-dependent suction and surface temperature [27F]. A "generalized Duhamel theorem" is devised to facilitate the solution of the problem of combined forced and free convection in a vertical circular tube under conditions of time-dependent pressure gradient, internal heat generation, and wall temperature [36F].

A variety of interesting experiments involving natural convection have been reported. The blowing of pre-heated or pre-cooled helium out of a porous horizontal cylinder into an air environment gave rise to the result that the surface temperature exceeded the environment temperature when the heat flux was zero [37F]. This finding was explained in terms of the diffusion-thermo effect which exists in binary flows. The use of an interferometer facilitated the study of free convection from a vertical plate to carbon dioxide near its critical point [34F]. From the data, thermal conductivities of the fluid were inferred which depended on the heat flux rate. Experimental results for free convection in water near its critical point were in good agreement with vertical-plate, boundary-layer solutions that had been carried out with variable fluid properties [8F]. The free-convection heat transfer from rectangular fin arrays to air was measured at various orientations in the gravity field [35F]. Detailed measurements of the velocity and temperature fields adjacent to a heated plane surface are reported for a range of inclination angles of the plate with respect to the vertical [38F] and at a slight inclination to the horizontal [39F]. The velocities were measured with a quartz filament.

An electrochemical method is described and is applied to obtain local mass-transfer coefficients for spheres and horizontal cylinders [32F]. The results for the latter are in close accord with heat-transfer correlations in the laminar range. The rate of evaporation of water, methanol, and benzene from a stationary porous sphere was measured in an electrically heated chamber [29F]. The data were correlated with a Reynolds number constructed with the mass-transfer velocity at the surface.

An analytical formulation was developed for natural circulation flow in a vertical multiple-channel system with different heat inputs to each channel [5F]. The analysis indicated certain metastable flow regimes which were confirmed by experiment. The assumption of large Peclet and Rayleigh numbers permitted the neglect of diffusion and thereby facilitated the analysis of steady vertical convection in a saturated porous medium [42F]. Equations and charts have been made available for convenient computation of the heat and moisture transfer by natural convection through openings in vertical and horizontal partitions [4F]. Formulas are proposed for heat transfer between a spherical surface and a gas under conditions of combined forced and natural convection [20F].

There has been a continuing lively interest in problems of convective instability. In such problems, a quiescent state becomes unstable due to negative density gradients in the direction of the body force. A method is devised for computing upper bounds on the critical Rayleigh numbers for completely confined fluids [28F]. Experimentally determined Rayleigh numbers are in close agreement with the theory. The stability problem for the plane, horizontal fluid layer has been generalized to include the effects of thermal radiation and a magnetic field (electrically-conducting fluid) [23F], the effects of thermal radiation and rotation [19F], and the presence of two components in the fluid [14F]. The effect of retaining non-linear terms in the perturbation equations has been explored with special reference to the corrections to linear theory [1F] and to turbulence [15F]. The linearized conservation equations appropriate to the problem of convection in lunar and planetary interiors are formulated and compared with those for convective instability [21F]. Certain purely mathematical aspects of the convective instability problem have been discussed [41F].

Schlieren photographs of the development of convective instability in a horizontal water layer reveal the existence of four distinct flow regimes [16F]. An empirical equation has been devised for predicting the heat transfer across a fluid contained between two horizontal surfaces under conditions wherein the Rayleigh number exceeds the critical value [33F]. Additional data for the foregoing physical situation are reported for water, glycerine, and several non-Newtonian liquids as working fluids [30F].

If water flowing in a vertical tube is heated or cooled, natural-convection effects can cause a transition to an unsteady flow. The effect of this unsteadiness on the Nusselt number has been measured both for upflow and for downflow [31F]. The influence of a sound field created by a siren increased the natural-convection heat transfer from a vertical plate by as much as three times [17F].

Analytical [6F] and experimental [7F] studies have demonstrated that a transverse magnetic field will decrease the free-convection heat transfer to an electrically conducting fluid between vertical parallel plates. A similar conclusion applies for the isothermal vertical plate [6F].

CONVECTION FROM ROTATING SURFACES

Heat-transfer characteristics for two rotating configurations have been inferred from mass-transfer experiments utilizing naphthalene coatings. One of these studies relates to a pair of parallel discs, one of which was rotated while the second was held stationary [3G]. Provision was made for introducing air through a hole at the center of the stationary disc, thereby creating a source-type flow. The second investigation was concerned with cones having vertex angles ranging from 60° to 180° (disc) [5G]. An independent heat-transfer experiment on a 60° rotating cone was undertaken in support of an analytical investigation of combined forced and free convection [2G]. Similarity solutions of the latter problem are possible only when the surface temperature varies linearly with distance from the cone vertex.

Heat-transfer data for a heated horizontal cylinder rotating in water were correlated by the relation: $Nu = 0{\cdot}133\ Re^{2/3}\ Pr^{1/3}$ [1G]. The Reynolds number in all tests exceeded 1000 and there was no evidence of free convection effects. Mercury, air, water, and oil were the working fluids used in a comprehensive investigation of flow and heat transfer about a rotating sphere [4G]. The results for $Pr \geqslant 0{\cdot}7$ could be correlated together, but the mercury data did not fit the correlation.

COMBINED HEAT AND MASS TRANSFER

Measurements of the heat transfer in the stagnation region of a transpiration cooled cylinder show good agreement with theory [5H]. Both the primary and secondary fluids in the experiment were air. Theoretical calculations of the heat transfer and friction in two dimensional stagnation flow of air with helium injection have been presented [2H].

A theoretical study has been pursued of the effects of the injection of various gases into the laminar boundary layer of a supersonic stream of air in a tube [3H]. Assuming the properties of the mixture to follow the Gibbs–Dalton rule, good agreement is found with earlier experimental studies of air and argon injection, but only fair agreement with experiments on helium injection. Reference states for using constant property solutions in predicting heat transfer in high speed flow with mass addition have been calculated for certain laminar flows [7H]. Alternative approaches for turbulent flows are also available [6H]. The definition of effectiveness in supersonic transpiration cooling has been re-examined [8H]. Some similarity solutions for transpiration cooling of a wall in a hypersonic flow have been presented [16H]. An integral method [1H] permits calculations of the heat transfer in a laminar boundary layer with blowing and also in the wall region downstream of the mass addition. The use of the concept of effectiveness is found to correlate transpiration cooling data quite well [17H]. Additional heat-transfer measurements with both blowing and suction have been reported [11H].

Measurements of the heat transfer and friction factor with an air flow along a porous wall, with and without a pressure gradient, show the effect of injecting various gases [13H]. The relative effects on both friction factor and heat transfer appear to decrease with increasing molecular weight of the injected gas.

An attempt to transpiration cool rocket nozzles with liquid metals has been described [12H]. Injection of a gas through a porous wall over which a liquid is flowing increases the heat transfer unless enough gas is injected to give a continuous film over the surface [4H]. If the latter condition exists, the heat transfer will be relatively low.

The methods of predicting heat transfer with mass addition of either a gas through a porous wall, vapor from a free liquid surface, or vapor from a liquid in a capillary material (porous wall) have been reviewed [10H]. The analysis of the heat transfer with liquid addition through a porous wall must include the effects within the wall. This type of mass addition is found to increase the heat transfer [9H].

Several other studies have been reported on combined heat and mass transfer. The effect of film cooling with multiple slots has been calculated using a previously obtained correlation for a single slot [14H]. Measurements on CO_2 cylinders show the effect of sublimation on stagnation-point heat transfer [15H].

CHANGE OF PHASE

Research in this area centers upon the boiling mechanism, bubble dynamics, and factors influencing the critical boiling heat flux.

Westwater [41J] reviews boiling heat transfer, emphasizing the direction of research in nucleate boiling. For a smooth, vertical, silver surface, Reeber [29J] studies the heat transfer to boiling helium, attributing the hysteretic nature of the results to the dependence of the nucleation mechanism on the thermal history of the specimen. Addition of small amounts of a volatile component increased the heat transfer in pool boiling experiments using pure organic liquids beyond that predicted by correlations [15J]. A series of experimental studies examine the influence of various factors upon nucleate boiling heat transfer: using distilled water, Marcus and Dropkin [22J] vary the angular position of the heated surface; Githinji and Sabersky [7J] test upward, downward, and vertical facing of heated surface; Graham and Hendricks [8J] the effect of multi-*g* accelerations; Norman and Spiegler [27J] the influence of particle radiation on bubble nucleation. Sims *et al.* [34J] discuss the experimental results of a system used to simulate nucleate pool boiling by bubbling gas through porous or drilled surfaces, the former comparing favorably with the theory of Kutateladze.

Moissis and Berenson [25J] consider the hydrodynamic transitions that occur in nucleate boiling, developing an analysis to predict them. Zuber [42J], considering experimental evidence of nucleate boiling, identifies two regions, one consisting of isolated bubbles, the other of bubble interference. Vapor removal pattern, flow pattern, and mechanism of heat transfer in the two regions are discussed and analyzed. Lienhard [20J] modifies Tien's model for nucleate boiling heat transfer in the light of recent experimental data. To obtain a better correlation with available data, Hara [11J] considers the fluid motion induced in the thermal boundary layer during the process of bubble generation, separation, and departure. Chang [3J] explains the limit on nucleate boiling heat transfer to be associated with maximum rate of bubble generation from a unit area of heating surface.

The cessation of film boiling of organic liquids on a submerged heating surface is investigated by Morozov [26J]. Photographic studies of the boiling heat-transfer mechanism are given by Isshiki and Tamaki [16J]; Kirby and Westwater [19J] who use a transparent hot plate photographed from below, and Semeria [31J] who studies the characteristics of vapor bubbles formed from a heated plate in water at high pressure. Some specific boiling situations include the study of Papell [28J] on subcooled boiling heat transfer under forced convection in a heated tube; a study of the effect of oil on the heat transfer from a horizontal tube to boiling refrigerant F-12 oil mixture [9J]; and an analysis by Meyer and Rose [23J] using a momentum integral model to study parallel channel boiling flow oscillations.

Film boiling studies range over predictions of surface temperatures at onset of stable film boiling by Spiegler *et al.* [36J], laminar, two-phase boundary layers in natural convection film boiling [5J], and the growth of a vapor film at a rapidly heated plane surface [10J].

Gambill [6J] presents a very useful survey of boiling burnout (critical heat flux regime) citing 1400 sources of experimental data, discusses the variables, and recommends correlations and predictions. Factors considered which influence the critical heat flux are acceleration [17J] and surface tension difference, when binary organic mixtures are boiled [13J]. Linehard and Schrock [21J] consider the influence of pressure, geometry, and equation of state on peak and minimum boiling heat flux, developing predictions which compare favorably with experimental results. Using a channel with varying wall thickness, Styrikovich *et al.* [37J] determine that burnout on thinner sections occurs with higher heat flux than that obtained from studies with uniform heat flux over tube. Rybin [30J] treats critical thermal loads during the boiling of a saturated liquid in tube flow. The specific problem of critical heat-flux in steam generating tubes is considered by Smolin *et al.* [35J], and Shitsman [32J] who, on the basis of experimental data, establishes a single-valued relationship between the critical heat flux and the length of the channel involved with steam generation. A new concept for predicting burnout conditions for forced convection in fuel elements of boiling water nuclear reactors is presented by Becker [2J]. For channels of various cross sections and orientation, von Glahn [40J] gives an empirical correlation of critical boiling heat flux. Topper [39J] reports a diffusion theory analysis of boiling burnout in fog flow having the same trend as earlier experiments.

Theoretical and experimental results for dropwise condensation are given by Kast [18J] for organic compounds on metal (steel, copper, chromium) surfaces. Missen and co-workers [38J, 24J] study the condensation of binary vapors of miscible liquids, determining the heat-transfer coefficients for systems undergoiing filmwise and non-filmwise (streaked) condensation. Chung [4J] analyses the problem of unsteady laminar film condensation on a vertical plate as might be caused by time dependent variation of wall temperature. For the condensing of vapors from non-condensing gases in laminar flow through vertical, cylindrical tubes, Baasel and Smith [1J] compare their solution to Graetz problem in heat transfer.

To predict condensation of metal vapors in flow through nozzles, Hill *et al.* [12J] review and apply condensation theory. Hrycak [14J] proposes an approximate solution to the problem of freezing an isotropic, semi-infinite slab, with Newton cooling at the surface, demonstrating its practicality by comparison with exact solution. Simpkins [33J] describes a series of experiments carried out in a high enthalpy argon stream using subliming materials; the teflon models ablating to stable shapes independently of the initial nose profile.

RADIATION

Considerable energy has been expended in the prediction of the ideal radiation characteristics of solid surfaces with various shaped cavities or protuberances. Interest has been aroused in determining the directional characteristics as well as the more conventional hemispherical, or overall, radiation behavior. The surfaces have generally been considered to be gray and to act as either perfectly diffuse or perfectly specular to incoming radiation. A groove with perfectly reflecting sidewalls and a black bottom surface has been found to have strong directional characteristics [19K]. The radiation behavior of specular asymmetric grooves [14K], diffuse conical cavities [27K], various diffuse cavities [32K], and specular V-shaped cavities [12K] has been examined. A rectangular groove is found to absorb more diffuse incoming radiation if the material is specular while for an incoming parallel bundle of radiation the relative absorption between the specular and diffuse surface depends on the angle of inclination of the rays [28K]. An experimental determination of the radiation from V-shaped grooves gives good agreement with calculations [21K].

Calculations for radiant heat transfer between surfaces are simplified by the use of contour integrals to determine angle factors [25K]. Calculations have been performed for the radiant interchange angle factors between circular cylinders and rectangular plane surfaces [36K], between parallel cylindrical tubes [26K] and for fin tubes [11K]. Equivalent angle factors for heat-transfer calculations involving people have also been obtained [7K]. The mutual irradiation between trapezoidal fins has been calculated [15K]. Longitudinal heat conduction is found to have a negligible effect on the performance of plate-type radiating fins [29K]. A study of the heat-transfer characteristics of several fin-tube radiator configurations indicates that the heat loss for the various configurations is of a similar magnitude for equal fin weight [30K]. An analysis [13K] evaluates the radiant interchange between two parallel specular metal plates; the emissivities

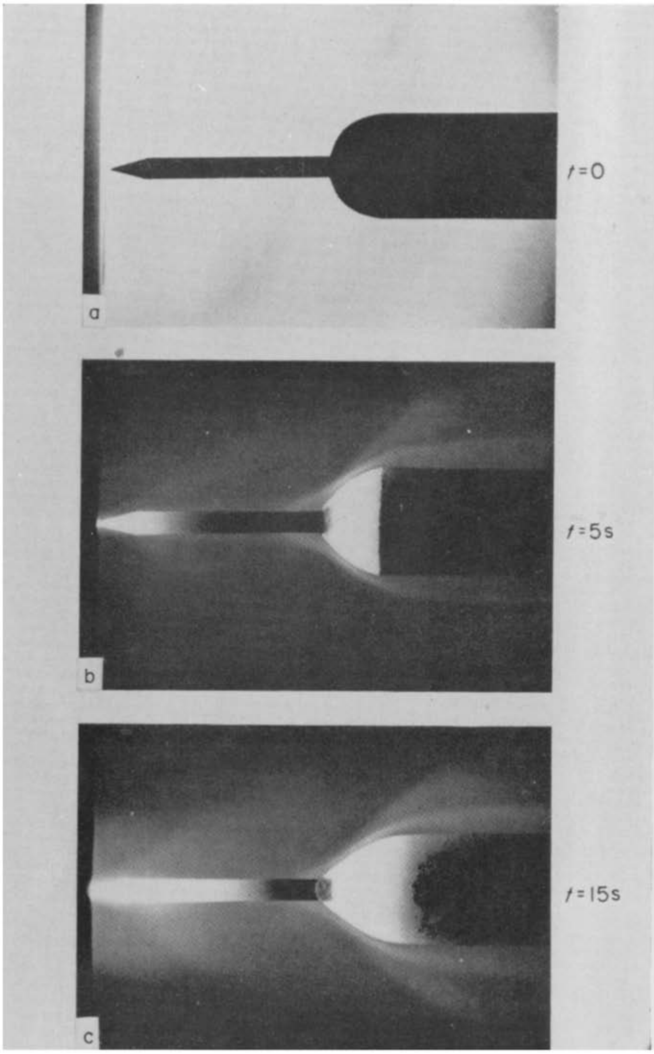

FIG. 2. The effect of a spike on the ablating profile of a telfon body [33J].

having been calculated from electromagnetic theory.

Absorption effects on the attenuation of radiation through packed beds are found [6K] to be small compared to the effect of back scattering. Other studies predict the temperature distribution in a rotating solid cylinder exposed to solar radiation [18K], and the radiant heating of a semi-transparent solid [5K].

An analysis [20K] indicates that the transmission of radiation down a circular tube is higher for a specular surface than for a diffuse one. The effect of radiation on the forced convection temperature distribution in a tube with a sinusoidal variation in axial wall heat flux has been determined [24K].

Interest in the effect of thermal radiation absorption and emission in a flowing gas, usually considered to be gray, is evident in a study on heat transfer from combustion gases [2K] and a general review of radiation effects in gas dynamics [37K]. Radiant heat transfer to a gas flowing between parallel plates [8K] and in circular tubes [9K] is found to go through a maximum as the gas opacity is increased. Another study on radiation in a gas flowing between parallel plates has been reported [33K]. The combined interaction of convection, conduction, and radiation in the laminar flow of an absorbing gas in a duct has been examined [34K].

The validity of using several limiting cases as approximations in radiant heat transfer to a flowing, absorbing gas has been examined [10K]. The radiation through a gas between two perpendicular rectangles has been calculated [35K]. Calculations of heat transfer through an absorbing gas has been performed utilizing a tensor representation [1K].

Optical properties of powders whose particles are large compared with the wavelength of radiation are calculated [17K]. The relationship of the emittance of a partially transmitting coating to other properties has been calculated [23K]. Spectral measurements in the infrared of the absorptance of magnesium fluoride, zinc sulphide, and other optical materials [31K] as well as the reflection and transmittance of materials used in standard infrared systems have been reported [16K]. Spectral measurements, in the visible region, of the reflectance and transmittance of thin metallic films have been described [22K]. Recent measurements [4K] show that the reflectivity of aluminum is higher when evaporated on a surface in an ultra high vacuum than under normal vacuum. Determinations have also been made of the total emittance of uranium surfaces under various conditions [3K].

LIQUID METALS

The possible existence of a thermal contact resistance at the interface between a liquid metal flow and a tube wall was investigated by comparing Nusselt numbers based on fluid temperature-profile measurements with those based on wall and bulk temperatures. For liquid sodium flowing in tubes fabricated from various materials, no evidence of a contact resistance was found [6L]. However, for a liquid metal with a Prandtl number of 0·02 (presumably mercury), the disparity between the aforementioned Nusselt numbers was interpreted as an indication of a thermal contact resistance [7L]. In a pool-boiling experiment in liquid sodium, heat fluxes up to 800 000 Btu/h-ft^2 were achieved at the surface of a horizontal rod [5L].

Semi-empirical equations for predicting Nusselt numbers for liquid metal flows frequently include the average effective value of the ratio of the eddy diffusivities for heat and momentum. An analytical procedure for evaluating this ratio is presented and application is made to various flow configurations [2L]. Fully developed Nusselt numbers predicted by a Lyon-type analysis for turbulent flow of a liquid metal in a concentric annulus are found to be in satisfactory agreement with available experimental information [3L]. The inviscid-flow assumption is used to facilitate the analysis of laminar heat transfer between a liquid metal and an elliptic cylinder [1L].

The design of a high-speed turbopump for liquid-metal service is described along with the results of tests with NaK at temperatures up to 1300°F [4L].

LOW-DENSITY HEAT TRANSFER

Attention is directed toward discrete aspects of low density by Lozgachev [5M] who considers the distribution of molecular flow on a surface during vacuum evaporation; by Stickney [14M] who measures momentum transfer between molecules of six gases and four metallic surfaces in free molecular flow using a molecular beam, and Smol'ski and Novikov [9M] who study the effect of vacuum on free and forced convection heat and mass transfer from a napthalene specimen. Logan [4M], finds that the propagation of thermal disturbances in rarefied gas flows occurs by simple waves having speeds either less than or approximately twice that of ordinary sound. Using a transformation of the temperature in thermal, boundary-layer, slip flow, Reddy [8M] solves the energy equation. For the same flow conditions Taylor [15M] treats heat transfer from single spheres at low Reynolds numbers.

Aspects of stagnation point heat transfer at high speed and low density are covered by Cheng and Chang [1M] who demonstrate the adequacy of a linear viscosity law in describing high and low Reynolds number regimes of boundary-layer flow; by Chow [2M] who introduces a shock-boundary-layer matching scheme to study a blunt-nose geometry, and Potter and Miller [6M] who measure total heating rates on this same geometry at a Knudsen number equivalent to an altitude of 315 000 ft based on nose radius.

Using the similarities between thermal radiation and mass-convective energy transport, Sparrow *et al.* consider mass and energy transfers in circular tubes [10M, 13M], tapered tubes [11M], and a parallel-plate channel [12M].

Haviland and Lavin [3M] apply Monte Carlo method based on probability theory to solve the Boltzmann equation for heat transfer between two parallel walls. Probstein [7M] gives a good review of the general features of rarefied gas flow with particular reference to high-speed, high-altitude flight consideration.

MEASUREMENT TECHNIQUES

A Schlieren system has been used for flow visualization studies in a water tunnel [6N]. Calculation of refraction effects in optical studies of thermal boundary layers enables one to obtain accurate knowledge of the temperature distribution [20N]. A system to rapidly read interferograms has been described [16N]. Local flow visualization is enhanced by the design of a two-piece tuft [30N] and a strong narrow light beam shining through a suspension of aluminum particles [8N]. Visualization techniques for use in hypersonic flow [15N] and the use of resonance scattering in a free molecule flow of sodium [39N] have been tested.

Measurements of void fraction are generally required for two-phase flow studies. A resistance probe has been described for local measurements in a mercury–nitrogen flow [26N], while in another study [1N] the void fraction is determined indirectly from wall shear stress measurements. A manometer has been constructed [2N] for measuring small pressure differences at a high pressure level.

A systematic method for the calibration of thermocouples has been described [4N]. More complete tables for the output of several standard thermocouple materials are included. The effect of conduction down a thermocouple well is discussed in [5N] and measurement of the time response of thermometers is described in [25N]. It is possible to obtain accurate values of surface temperature by reducing the heat flow from the surface to a measuring thermocouple [34N]. Thin film thermocouples [24N] and resistance thermometers [38N] have been described. These are generally used in the measurement of rapidly changing surface temperature. Infrared techniques are used to measure the temperature variation across very small surfaces [28N]. A probe is described [17N] which uses a transient technique to measure gas temperatures up to very high values [$\sim 7800^\circ$R]. A heat-transfer gage may be calibrated by "quenching" in a liquid [32N]. A heat flux probe intended for use at the stagnation point of a hemispherically shaped body has been tested [19N].

Interest in thermal conductivity measurements, as indicated by the number of contributions, is very strong. Particular emphasis appears to be placed on the conductivity of solids. In one system heat flows from a condensing vapor through the sample of unknown conductivity and then to a boiling liquid [29N]. Since the boiling points and latent heats of vaporization are known, measurement of the amount of condensate is all that is required to get the conductivity. Another system makes use of a thermal comparator to study powders [11N]. The conductivity of anisotropic porous materials are measured using an electric current flowing through the material as a heat source [36N]. Another system utilizes the Peltier effect as a heat source in the determination of a solids thermal conductivity [23N]. An analysis of guarded hot plate devices for measuring the conductivity of insulating materials shows that the errors may be reduced by matching the insulation to the sample being studied [14N]. The thermal conductivity of an electrical conductor may be obtained at high temperatures in an apparatus in which an electric current passes through a small sample held between two large masses of the same material [13N].

Transient methods are being used to measure the thermal diffusivity and thermal conductivity of solids. In one system a constant heat flux is applied to a plane surface and the transient temperature variation inside the material is measured [31N]. Another system uses a periodic heat input and measures the phase difference and damping of the temperature wave within the body [21N]. Finite difference methods have been utilized to obtain the thermal diffusivity in transient experiments [3N]. Transient techniques are particularly useful at high temperatures. Reviews [12N, 9N] of some of these methods compare apparatus using different boundary conditions on the surface temperature. Electron bombardment is used as the method of heat input in one transient system [10N].

Transient methods also offer promise in the accurate determination of the thermal conductivity of fluids. One such system [7N] contains a small wire immersed in a liquid. A step function in electric power input is applied and the temperature distribution near the wire is measured by interferometric means.

Radiation measurements are aided by using a quartz–iodine lamp as a working standard for spectral irradiance from 0·25 to 2·6 μ [33N]. Sulfur is found to be an excellent standard for diffuse reflectance in the infrared regime [22N]. Asymmetries in an integrating sphere cause the measured reflectivities to appear to be functions of the sample orientation [27N]. Extraneous radiation may lead to serious errors in using infrared spectrophotometers [35N]. The emissivity of a porous material has been measured while blowing a gas through it [37N]. A portable integrating sphere for reflectance measurements has been described [18N].

HEAT-TRANSFER APPLICATIONS

Heat exchangers

A recent review outlines the available methods for calculating the performance of segmentally baffled shell and tube heat exchangers [6P]. The overall performance has been calculated for a multipass heat exchanger where the overall coefficient of heat transfer is a linear function of temperature [13P]. Calculations for a counter current heat exchanger with internal heat generation in one stream predict a maximum temperature inside the system which may be much greater than the entering or leaving temperatures [7P]. A method has been demonstrated for determining the optimum tube sheet geometry in a shell and tube heat exchanger [5P]. An experimental study has been performed on the heat transfer and friction factor for liquid metal flow through tightly packed cylindrical heating rods [14P]. The effect of re-radiation from walls to furnace tubes has been examined [2P]. An experimental study verifies the use of a single differential equation for predicting the dynamic response of a double pipe heat exchanger [11P]. Simplified models permit the calculation of the transient temperature response of large reservoirs such as whole buildings [10P]. A study describes the application of fin tubes in comfort heating systems [9P].

Heat transfer in a container where a mixer agitates a fluid appears to be greater than previously believed [12P]. An experimental study permits a correlation for the heat transfer in a scraped surface heat exchanger which would primarily be used with viscous fluids [1P].

Heat exchangers for the utilization of solar energy continue to draw interest. Calculations have been performed on simple models of heat exchangers for use in a solar concentrator [3P]. Other reports on systems for use in solar concentrators examine the maximum possible heat recovery [8P] and the temperature distribution in such a system [4P].

Aircraft and space vehicles

Heat transfer to various bodies with shapes important for space and re-entry vehicles were measured and compared with analyses [5Q, 9Q, 14Q, 15Q]. The overall heat transfer to blunt, conical bodies having cavities to promote separation was found to be higher than for the same shape without separated regions because heat transfer is always high in the re-attachment zones of the flow [1Q]. The ablation process was studied on salt models in a water stream [17Q] or in arc-heated gas streams [16Q], and using different plastic and composite charring materials [2Q, 6Q, 13Q]. The thermal radiation of the ablation products injected into a hypersonic shock layer was measured on projectiles shot past photo-electric devices [3Q] and was found to depend strongly on the ablating material. Heat transfer to the walls of nozzles with non-ablating or ablating materials in chemical and nuclear rockets was investigated [4Q, 10Q, 12Q, 19Q]. In general, it is found that Bartz' equation

$$\frac{St\ Pr^{0.6}}{(D/L)^{0.1}} = 0.026\ Re^{-0.2}$$

represents the results quite satisfactorily and that heat transfer increases by solid particle impact [4Q].

Two papers calculate the temperature distribution in a spinning spherical space vehicle with thin shell exposed to solar heating [7Q, 11Q] and establish how the temperature fluctuations decrease with increased rotational speed. Coatings for solar absorbers are available with an absorptivity of 0·9 for solar radiation and of 0·2 to 0·3 for infrared radiation [18Q]. Contact resistance between beryllium oxide washers and metallic heat sink material in a transistor for space environment has been measured [8Q].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Experimental measurements are reported for high temperature and high pressure conditions and for the critical state. Analytical investigations continue the search for appropriate molecular models, better mixture property rules, and useful generalizations of the data at hand.

Thermodynamic properties

Specific heats are measured [13R] for niobium, molybdenum, tantalum, and tungsten [1200°–2400°K] by determining the amplitude of temperature oscillations in a thin, a.c. heated filament. Michels *et al.* [16R], report thermodynamic properties for hydrogen and deuterium in the range 150°–175°C and at pressures to 2500 atm. For organic coolants used in nuclear reactors, Bessouatt *et al.* [2R], report vapor pressure measurements up to 20 atm and 500°C.

Smith [30R] views real gases as being a mixture of stable species and transient collision complexes, obtaining a new form of the partition function, including continuum and bound states. Helium behavior attracts the attention of Predvoditelev [25R] who considers central forces varying as inverse powers of separation, leading to a highly accurate (max. dev. 0·04 per cent) fit of p–v–t data, and Mohling [20R], who obtains quantum corrections to the second virial coefficient at high temperatures based on a square-well, repulsive core model. Plasma thermodynamic properties are tabulated for argon to 35 000°K [7R], air and nitrogen to 15 000°K [12R], and hydrogen, argon, and air Mollier diagrams presented for plasmas of these substances [3R]. Martin [14R] treats the problem of carbon dioxide properties near the critical state using state and low-pressure heat-capacity equations. Empirically fitting only argon p–v–t data, Costolnick and Thodos [6R] propose a reduced equation of state, but without reference to the extensive literature on corresponding states. Fishtine [8R] reviews available methods for calculating latent heats of vaporization to within 5 per cent using a variety of initial information. Empirical ideal gas heat capacity equations for common products of hydrocarbon combustion are presented in reference [22R].

Transport properties

Using radioactive tracers, classical, gaseous, self-diffusion measurements in a temperature gradient for carbon dioxide and krypton are reported by Wendt *et al.* [36R], over range 230°–470°K; ternary mixture thermal diffusion measurements involving two isotopes and one non-isotropic component are given between 400° and 500°K by van der Valk and DeVries [35R].

Recent measurements [24R] of the thermal conductivity of rhenium (80°–500°K) are much lower than earlier published data. Continuing with the line source method of thermal conductivity measurements, Westenberg and deHaas [37R] report data for oxygen and oxygen–water mixtures from 300° to 1100°K. The hot wire apparatus is used to obtain measurements on nitrogen–oxygen gases, and gas mixtures from 30° to 200°C, [23R], and dimethylhydrazine (unsymmetrical) from 5° to 35°C [1R]. In a series of papers, Michels *et al.* report on the apparatus [19R] used to measure the thermal conductivity of carbon dioxide in the critical region, the measurements [17R], and the verification of the absence of convection [18R].

Refined viscosity determinations for superheated steam up to 275°C are estimated to be accurate to 0·48 per cent [11R]. The rotating cylinder viscosimeter is used to measure high pressure (5000 psia) viscosities for ammonia [5R] in the interval 40–400°F. Flow through a capillary is used to obtain nitrogen data up to 127 atm at 200°K [9R]. Thornton and Baker [33R] report viscosities and thermal conductivities for binary mixtures (Ar–Ne, Ar–He, Ne–He) at atmospheric pressure and 18°C, slightly different from previously published data.

Relaxation effects on transport properties are considered for a rough sphere gas by Monchick [21R], and for non-polar polyatomic gases by Brokaw and O'Neal [4R]. Saxena *et al.* propose a semi-empirical formula for calculating the viscosity of binary and multicomponent gas mixtures to within experimental uncertainties [26R], consider the relation between viscosity and translational thermal conductivity of gas mixtures [27R], and evaluate the second approximation term in the Chapman–Enskog treatment of gas binary viscosity to be approximately one per cent of the total viscosity [28R]. Difference between calculated and measured thermal diffusion data for krypton and xenon is attributed to the design of the experimental apparatus [29R]. Van der Valk [34R] derives a simple expression for the thermal diffusion factor for two components in a ternary mixture equivalent to the first Chapman–Cowling approximation.

Corresponding state considerations yield correlations for viscosity and thermal conductivity of water [32R], thermal conductivity of monatomic gases from −183° to 1100°C [31R], and viscosity of dissociated and undissociated gases up to 10 000°K [15R]. Harry [10R] describes Fortran language subroutine for calculating approximate thermodynamic and transport properties for molecular hydrogen from melting to dissociation up to 340 atm.

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