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HEAT TRANSFER: A REVIEW OF CURRENT LITERATURE

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INTRODUCTION

THIS review is concerned with research in the field of heat transfer, the results of which have been published during 1962. The number of papers in this field is, as in previous years, so large that only a selection can be included here. A more complete listing is contained in the "Heat Transfer Bibliographies" published periodically in this Journal.

The fifth of the yearly "National Heat Transfer Conferences" sponsored jointly by the American Institute of Chemical Engineers and the American Society of Mechanical Engineers was held at Houston, Texas, during August of 1962. Seventy-seven papers were presented, and approximately half of them are collected in No. 41, Vol. 59 of the Chemical Engineering Progress Symposium Series. Most of the others are published in the *Journal of Heat Transfer*. An "International Symposium on Rarefied Gas Dynamics" held at Paris during June of 1962 included papers on heat transfer. The "Second Symposium on Thermophysical Properties" took place at Princeton in January, 1962. The proceedings of this meeting have also been published. A "Symposium on Measurement of Thermal Radiation Properties of Solids" was organized at Dayton, Ohio, in response to needs for such data in space engineering. Only preprints are available to date. A number of books dealing with heat transfer and related fields has appeared on the market. They are listed at the end of this paper.

The large temperature differences existing in various advanced engineering devices have caused research in recent years to be directed towards the study of the influence of property variations on heat exchange. This trend has continued in 1962 with papers dealing with channel flow as well as with boundary-layer situations. The higher velocities with which aircraft and space vehicles move through the atmosphere cause higher and higher temperatures in the boundary layers surrounding such objects. Accordingly, special attention has recently been directed toward a clarification of the influence of ionization of the air atoms on heat transfer. Also, transpiration cooling as an effective means to protect the surfaces of spacecraft has found continuing attention. On the other hand, liquid metals as coolants appear to have lost some interest, at least as far as can be concluded from the number of papers on that subject.

Combined free and forced convection, and its influence on heat transfer for various geometries, is a process which depends on a large number of parameters and consequently requires extended effort for its clarification. This is reflected in the number of papers on that subject. Heat transfer in boiling and in two-phase flow is another physical process which, because of its complexity, is understood and can be predicted only in certain aspects. Its investigation has found considerable interest in the period covered in this survey.

CONDUCTION

Research continues apace upon the various aspects of transient heat conduction.

For one-dimensional, unsteady heat conduction Wing [53A] presents several analytical methods which yield time–temperature curves for thin walls exposed to aerodynamic heating, Wells *et al.* [49A] consider the problem of planetary atmosphere entry, Reid [39A] the composite thin shell, and Manos and Taylor

[25A] the interpretation of data from thin-skinned models. Mathematical considerations show the utility of a finite transform in attacking this class of problems [44A] and solutions which can be expanded in series form [50A]. Unterberg [46A] determines analytic solutions for the temperature of thin bodies with heat generation when cooled by convection and/or radiation. Jeglic [18A] reports an analytic determination of temperature oscillations in an electrically (alternating current) heated wall. Averaging temperature over a finite time interval allows a single, numerical approximation of the convective boundary condition [2A].

Conduction with time dependent sources and boundary conditions is treated by a separation of variable technique [30A]. Composite geometries with heat generation and time-dependent surroundings are considered [40A] while the temperature–time behavior of a super-critical mass of a self-heating chemical is simulated on a digital computer [32A]. A moving heat source along the boundary of a semi-infinite solid is considered [28A] as well as the closely related problem of temperature distribution resulting from sliding, frictional contact [48A, 1A].

Systems undergoing phase changes are considered from the aspects of fusion times [3A], transient melting and vaporizing ablation [9A], and a reduction of the freezing phenomena to simple form [37A].

Conditions for solution of unsteady, two-dimensional, constant property conduction are set forth by Kim [19A]; a series form solution for the three-dimensional problem with convection appears in [5A]. Finite difference methods for solving the transient case are examined for stability [15A] and applied to estimate the surface temperature of a slab with radiation at one boundary [12A].

Consideration is also given to unsteady heat transfer in the region exterior to a rectangle [8A], transient temperature distribution in an orthotropic sphere [47A], and in porous bodies undergoing convective heat transfer [29A].

Paul [33A] gives a generalization of the Schmidt plot for transient heat conduction.

For steady-state conditions, temperature distributions are found for long cylindrical shells subject to non-uniform circumferential heat input [13A] and heat flow with variable thermal conductivity determined in one [20A] and two dimensions [26A]. Heat source effects are considered for a homogeneous, constant property, semi-infinite solid [21A], a cooled reactor core [10A], and a body convectively cooled [34A]. Phase change considerations include the determination of location and time history of the one-dimensional solid–liquid interface [36A], the heat conduction occurring for a moving, two-dimensional, solidification front [35A], the problem of a half-space subjected to a constant rate of heat input at the melting surface [6A], and the analytical solutions of heat and mass transfer equations for a semi-infinite medium [45A].

Thermal contact resistance receives consideration [14A] and the related question of the relationships between this property and the direction of heat flow [27A, 38A]. Special systems or situations include the determination of the temperature distribution in a hollow cylindrical cup with a stem [23A], in a medium of rectangular cross section having a constant strength lone heat source perpendicular to it [17A], the calculation of heat transfer across small gas-filled gaps [22A], and the two-dimensional conduction in a tubular thrust chamber [43A].

Boswirth [7A] reduces heat flow through a wall with convective heat transfer on each side to an equivalent conduction problem, and Schenck [42A] uses a "fictive" isothermal surface to obtain orthogonal mapping solutions for a convective cooled, non-isothermal surface.

Cooling fins are considered first without heat generation for general conditions suitable for treatment by variational methods [24A], and then with heat generation for optimal [51A] and practical [52A] configurations.

Mathematical aspects and aids include the use of Duhamel's equation [41A], an alternate solution technique avoiding integral transforms [31A], implicit numerical methods for the heat conduction equation [16A], and numerical values of some integrals occurring for conduction in regions of cylindrical symmetry [4A].

Dillon [11A] observes from experiments a coupling between the temperature field and components of strain in torsional oscillations.

CHANNEL FLOW

Several aspects of turbulent heat transfer in tubes have been explored experimentally. Variable property effects have been studied for gases and liquids with large wall-to-bulk temperature differences, for fluids near the critical state, and for dissociating gases. Results for heating of air, helium, and carbon dioxide flowing in circular tubes could be correlated [1B] by the McAdams' equation, $Nu = 0{\cdot}023\, Re^{0{\cdot}8}\, Pr^{0{\cdot}4}$, provided that bulk properties are used and a correction factor $(T_w/T_b)^m$ is included as a multiplier of the right-hand side. The exponent m depends on the gas. New data for water in the Reynolds number range 40000–280000 were obtained [33B] in an apparatus consisting of an isothermal tube heated by dropwise condensation. A new correlation equation is proposed which represents the data better than either Dittus–Boelter or Sieder–Tate. Another experiment on heating of water with large wall-to-bulk temperature differences leads to the conclusion [3B] that among the correlations of Colburn, Sieder–Tate, and McAdams, the latter is conservative as well as the easiest to apply. Heat transfer measurements for five polyphenyl and two aliphatic liquids in electrically-heated circular tubes were well represented [42B] by the relation, $Nu = 0{\cdot}0175\, Re^{0{\cdot}84}\, Pr^{0{\cdot}4}$, with properties evaluated at the bulk temperature. Again, Sieder–Tate and Colburn type equations were not found to be suitable. A qualitative discussion of the variable property problem for turbulent heat transfer suggests [38B] the correlation, $St_b = f(Re_b, Pr_b, T_w/T_b)$, but a quantitative relation is not given. Experimentally-determined Nusselt numbers for air and water flowing in electrically-heated tubes at moderate temperature differences showed [11B] some deviations from McAdams' equation, the air data ($Pr = 0{\cdot}7$) falling low and the water data ($Pr = 4$–12) falling high.

High heat-flux experiments were carried out [44B] in an electrically-heated tube for hydrogen near the critical state. Accompanying analytical predictions based both on the Deissler turbulence model and the Hsu modification were only partially satisfactory, with the former being somewhat closer to the data. Heat transfer experiments are described [20B] for RP-1 and diethylcyclohexane flowing turbulently in electrically-heated, thin-walled tubes at supercritical pressure and supercritical wall temperature. At these conditions, an audible vibration emanated from the test section. Experimental data for dissociating N_2O_4 in an electrically-heated tube agreed [12B] reasonably well with an analysis based on Deissler's model when effective thermal conductivities and specific heats (including reaction and diffusion) were used. The heat transfer from acoustically resonating gas flames to the cooled wall of a cylindrical combustion chamber increased linearly [51B] with the sound pressure level.

An extensive experimental study of the thermal entrance region for air flowing turbulently in a uniformly heated tube included [28B] the effects of rounded and sharp inlets, trip wires, elbows and turnings, and unheated starting lengths. For the rounded inlet, a transition from laminar to turbulent flow in the entrance region was clearly evident. A similar experiment [8B] carried out with an unheated starting length gave Nusselt number results which were in good agreement with the analysis of Sparrow, Hallman, and Siegel both in the entrance and fully-developed regions. Total conductivities, including both molecular and eddy contributions, have been evaluated [49B] from measured temperature profiles in a parallel-plate channel and corrected for the effects of viscous dissipation.

The results of experiments for turbulent air flow in a parallel-plate channel suggest [2B] that the Nusselt number may be lower when there are different heat transfer rates at the two surfaces than when the heating is symmetric. Nusselt numbers for the heating of air in turbulent tube flow have been shown experimentally [26B] to be independent of whether the boundary-condition is uniform wall temperature or uniform wall heat flux. The detailed effects of longitudinal pressure gradient on turbulent air flow and heat transfer have been measured [32B] in diverging and converging water-cooled tubes.

A procedure is proposed [17B] for interpreting turbulent heat transfer and friction data in channels whose bounding walls are partly smooth and partly roughened, e.g. an annulus with roughened inner tube. Experimental data for such an annulus have been measured [5B] for water flow in the Reynolds number range

200–100 000. An extension of the Colburn analogy has been proposed [24B] for predicting heat-transfer j factors for the inner and outer surfaces of concentric annuli.

There have also been a few papers reporting purely analytical studies of turbulent heat transfer. Two of these [41B, 10B] are concerned with the asymptotic expressions for eigenvalues and eigenfunctions which arise in a Graetz-type solution of the thermal entrance region. Another paper [13B] demonstrates that solutions for the transient heat transfer corresponding to tube flow with a steady inlet temperature and time-dependent wall temperature can be carried over to the case of time-dependent inlet temperature and steady wall temperature. The transformation applies to both laminar and turbulent conditions. An analysis for the entrance and fully-developed heat transfer in the range of transition Reynolds numbers utilizes [14B] a modified eddy diffusivity and velocity profile as input to a Graetz-type formulation. It is interesting to observe that a Graetz-type analysis for either turbulent or laminar flow can also be carried out for the mass transfer problem [47B] in which there is a homogeneous chemical reaction between a dilute species in the flow and a dilute species diffusing away from the tube wall.

In contrast to the case of turbulent flow, most of the research on laminar flow has been analytical. Papers continue to appear on various modifications of the Graetz problem which relate to the thermal entrance region of ducts. Among the particular cases considered are the concentric annulus [18B, 40B] with various thermal boundary conditions at the inner and outer surfaces, the parallel-plate channel [19B] with different temperatures at the two walls, the isothermal elliptical duct [9B], and the isothermal conical duct [7B] of small taper angle in which there is an inviscid flow. Another problem of the Graetz-type is the separation by thermal diffusion of an initially uniform solution into its components during flow through a parallel-plate channel with walls at different temperatures [48B].

There has been a special interest in non-Newtonian fluids with power-law velocity profiles. Graetz-type solutions including viscous dissipation have beeen carried out for the parallel-plate channel [46B] with walls at the same uniform temperature, and for the circular tube with either uniform wall temperature or uniform wall heat flux [15B]. A fully-developed solution of the latter problem has been independently derived [27B]. Leveque's method for the thermal entrance region problem for a tube with uniform wall temperature has been extended [16B] to include a power-law flow. Finite-difference solutions for non-Newtonian flow and heat transfer in an isothermal tube including a temperature-dependent viscosity were carried out and compared with experiment [6B]. In the range where natural convection was unimportant, the mean deviation between theory and experiment was ± 7 per cent.

An elegant mathematical analysis using the methods of complex variables has been applied [45B] to a fully-developed heat-generating laminar flow in a duct of arbitrary cross section. Experiments carried out [22B] with an electrolyte (NaCl) flowing in an insulated circular tube have verified the Sparrow–Siegel analysis for a laminar, heat-generating fluid.

The thermal response of a parallel-plate channel to either prescribed time-variations of pumping pressure and/or prescribed time-variations in the thermal boundary conditions is the subject of a pair of papers [37B, 29B]. A related problem for the annulus [43B] includes suction and injection at the surfaces, but is restricted to fully-developed conditions and to sinusoidal pressure pulsations.

Analytical solutions [50B, 25B] have highlighted the effects of variable fluid properties on laminar heat transfer along the entire tube length. The first of these [50B] is restricted to liquids, and only the viscosity variation is included. The second [25B] considers the variation of all the fluid properties, and gives specific treatment to CO_2 near the critical state.

When the pressure of a flowing gas is reduced, the gas begins to slip over the wall and a temperature jump may also occur. The net effect of these is to decrease the fully-developed Nusselt number for laminar tube flow [39B]. The temperature profile corresponding to viscous dissipation in a parallel-plate channel is also flattened [23B].

Finite-difference solutions have given some insight into the development of the velocity and temperature profiles in a parallel-plate channel [35B] and an annular channel [34B] subjected to a transverse magnetic field. In an experimental study, the presence of an axial magnetic field with strength up to 20000 G has led to a reduction in the heat transfer to a circular tube not exceeding 20 per cent [30B]. The experiments were carried out with partially-ionized air. Explicit solutions are given [4B] for a one-dimensional, compressible, electrically-conducting, constant-temperature channel flow which is not restricted to uniform electric field or to constant cross-sectional area.

Interest in the vortex tube continues. A new explanation of the Ranque–Hilsch tube is presented [36B] based on an analytical model which derives the flow and temperature development from that of a corresponding unsteady flow. On the basis of new data, a subsequent paper [31B] suggests that caution be adopted in appraising the foregoing theory. A discussion of measurement technique [21B, 31B] indicates that the vortex flow is significantly disturbed by the insertion of probes on the order of $\frac{1}{16}$ in diameter. Also, reference [21B] presents velocity and temperature data along with a simple theory to explain their radial variations.

BOUNDARY-LAYER FLOW

Boundary-layer theory and solutions

A fundamental investigation of the solutions for viscous flow at large Reynolds number revealed [62C] that Prandtl's boundary-layer theory is the first level in a sequence of successive approximations. The energy equation has been carefully rederived and then specialized [15C] to forms appropriate to a perfect gas, to a liquid, to a fluid at constant pressure, and to a fluid at constant volume. The boundary-layer form of the energy equation has been recast [67C] in tensor form in terms of generalized co-ordinates.

The limitations of the well-known analogy between heat and mass transfer were brought sharply into quantitative focus [1C, 47C]. The difference between the two processes arises because a velocity normal to the surface is present in mass transfer but not in heat transfer. The concept of the heat transfer coefficient is revealed to have definite limitations as illustrated [5C] by an analysis of boundary layer heat transfer along a surface whose temperature varies sinusoidally with position. Because of a phase lag, the heat flow and the wall temperature may be of opposite sign, thus leading to a negative heat transfer coefficient.

Similarity solutions for the complete Navier–Stokes and energy equations have been constructed [46C] using similarity variables involving powers of the streamwise co-ordinates. The relation of these solutions to forced and natural-convection boundary-layer solutions and to channel-flow solutions is carefully explored. A series expansion method, the first level of which is the boundary-layer solution, is used [27C] in an attempt to solve the full Navier–Stokes and energy equations for flow over an isothermal two-dimensional wedge. The second approximation solution was not numerically evaluated.

The Stewartson–Illingworth transformation correlates compressible and incompressible two-dimensional boundary layers. The transformation has been extended to three-dimensional boundary layers with small cross flow [10C] and to two-dimensional boundary layers on non-isothermal surfaces [37C]. The energy equation for a compressible laminar boundary layer with pressure gradient could be solved approximately [11C] after representing the velocity profile by a three-term polynomial and assuming $\mu \sim T$ (μ = viscosity, T = absolute temperature). For stagnation point flow, this restriction on the viscosity was replaced [3C, 42C] by the more flexible representation $\mu \sim T^{\omega}$. The heat transfer results of the foregoing analyses were in satisfactory agreement with experiment [3C, 42C]. An analytical method has been developed [19C] for determining the effect of shock curvature and entropy gradient on heat transfer in the nose region of blunt bodies at hypersonic speeds. Experiments at a Mach number of 8 support the theory. A simplified prediction method has been evolved [65C] for calculating the ratio of local to stagnation-line heat transfer on a yawed, infinite circular cylinder in laminar compressible flow.

The longitudinal flow over axisymmetric bodies differs from plane boundary-layer flow when the thickness of the boundary layer is no longer small compared with the body radius.

This is called the transverse curvature effect and usually precludes similarity solutions. The heat transfer solution for an isothermal cylinder was constructed [6c] by finding series solutions which apply at small and large downstream distances and then bridging the gap by an integral solution. An alternate approach [56c] in a study including mass transfer and pressure gradient as well as heat transfer was to use an integral method over the entire length.

The effects of longitudinal conduction in a low Prandtl number boundary layer were explored for both large [45c] and small Peclet numbers [45c, 9c]. The error in the surface heat transfer associated with the neglect of longitudinal conduction decreases with increasing Peclet number, but also depends on the distance from the leading edge. Solutions for the constant-property, boundary-layer energy equation have been carried out [38c] for the uniform heat flux boundary condition over a range of Prandtl numbers.

The important characteristics of fifteen methods for predicting the heat transfer coefficient for laminar constant-property boundary layers on isothermal surfaces are summarized [54c]. These are then applied to the problem of cross flow over a cylinder, but the absence of fully-reliable data prevents final conclusions to be drawn about the relative merits of the methods. One of the prediction methods included in the aforementioned survey is extended [51c] to cover the Prandtl number range 0·5–20 000.

Two papers deal with heat transfer from a doubly-infinite plate. One [53c] treats an isothermal plate moved impulsively from rest in a fluid whose freestream temperature fluctuates sinusoidally with time. The other [41c] relates to a stationary isothermal plate through which there is uniform suction and above which there is a fluid with a transverse temperature gradient and uniform longitudinal velocity.

The boundary-layer heat-transfer response to a change in surface temperature is calculated by an integral method [25c]. It is shown that the response of a high Prandtl number boundary layer is slower than that of a low Prandtl number boundary layer. A detailed study [8c] of the transient for a low Prandtl number flat-plate boundary layer suggests that the heat-transfer response to a step-change in wall temperature can be well approximated by a curve consisting of the pure conduction solution and the steady-state solution.

Relatively few papers have appeared on the subject of turbulent boundary layers. Spalding has recast the turbulent boundary-layer energy equation in a form similar to that for transient heat conduction with a time-dependent thermal diffusivity. This is solved [32c] for a Prandtl number of unity by applying Schmidt's finite-difference scheme. For very high Prandtl numbers, the thermal boundary layer is much thinner than the velocity layer. As a consequence, the energy-transfer process is confined to the laminar sublayer, and this fact is used [33c] as a basis for solving for the turbulent heat transfer for a high Prandtl number fluid. The Howarth transformation, which is used in relating compressible and incompressible laminar boundary layers, is proposed [52c] for a similar role in turbulent compressible flow.

Dissociation and chemical reactions

The continuously increasing re-entry velocities which are considered for space vehicles instigated analyses on heat transfer in laminar air boundary layers under conditions in which an appreciable portion of the atoms is ionized. Two calculations [44c, 30c] agree well among themselves, and with proper adjustment also with the well-known relation by Fay and Riddell. A third analysis [49c], considering a four-component mixture of N_2, N, N^+, e^-, resulted in heat fluxes which are up to twice as large as those of the previous calculation for flight velocities above 30 000 ft/s. The differences between various experimental results is such that they do not indicate which values agree better with reality. The reference enthalpy method was found to predict the laminar boundary layer skin friction on a flat plate under equilibrium conditions to 25 000 ft/s within 5 per cent [66c]. Recombination of oxygen and nitrogen in different parts of the boundary layer may change the heat flux into the surface by up to 35 per cent [18c]. New classes of similar solutions and a scheme for an approximate solution by Kochin and Loitsyansky are discussed [22c].

Heat transfer in a laminar boundary layer with ablation of a vapor, the molecular weight of which is $\frac{1}{4}$ to 4 times that of air in the mainstream, has been calculated [16c]. It was found that the assumption of a Prandtl and Schmidt number equal to unity leads to a good approximation as long as the proper variation of the product density times velocity is introduced. The effect of deceleration forces on molten layers created by ablation is investigated and the significant dynamic parameters are determined in [43c].

Heat transfer with homogeneous and heterogenous reactions is studied for shear flow [7c, 70c] and for a laminar boundary layer [57c] with consideration of chemical non-equilibrium. Experiments in a low density, partially dissociated nitrogen stream at Mach number 6 demonstrated a heat transfer to the model which was twice as large for a polished copper surface than on a silicon monoxide coated surface [68c]. Experiments also demonstrated that the transport processes in a combustible turbulent boundary layer could be well predicted by constant property relations using a reference temperature for the properties and with a proper blowing correction [36c]. Heat and mass transfer at the stagnation point of blunt bodies in a gas flow and with heterogenous chemical reactions of finite rate were studied with special attention to the ignition and extinction process [39c]. Heat shielding of a porous plate by ejection of a liquid with consideration of chemical reactions was analysed [63c]. The Schwab–Zeldovich technique for reacting flow systems was applied to turbulent reacting jets and boundary layers [35c]. The enthalpy reference method was checked [28c], and extended using a momentum-thickness Reynolds number [59c] and by introduction of a reference concentration [34c]. The heat flux potential which can linearize the heat conduction equation was used for the calculation of convective heat transfer in chemically reacting gases and its accuracy was evaluated [48c].

Magnetofluid-dynamics

The existence of similar solutions to the energy equation of a moving fluid has been studied for magnetic fields normal or parallel to the surface [26c]. The solutions include stagnation point and stagnation line flow. Another analysis [2c] for axisymmetric stagnation point flow with the magnetic lines parallel or normal to the flow studied especially the situation at small and large diffusion numbers (ratio of magnetic viscosity to magnetic diffusivity). A uniform magnetic field in stream direction causes the boundary layer on the magnetized plate to separate when the strength of the field exceeds a critical value [24c]. Heat transfer in stagnation flow is reduced much more by a magnetic field with fluid ejection from the plate than without it [55c]. The analysis considered Prandtl numbers between 0·01 and 1. A transverse magnetic field in flow over an infinite wall with uniform suction increases skin friction and heat transfer [58c]. All values are also increased when the velocity fluctuates in magnitude.

The heat flux to the anode of an arc, free burning in argon, is reduced from 80 to 20 per cent when a transpiration-cooled carbon anode is used instead of a water-cooled copper anode [13c]. Heat transfer to cold electrodes in the form of thin tungsten wires exposed to the flow of a gas, slighted ionized by seeding with potassium, was investigated in a shock tube [17c]. The heat flux increased essentially proportional to the electrode current.

Experimental investigations

Heat transfer from air, water, and transformer oil flowing over a flat plate with Reynolds numbers between 2×10^4 and 3×10^7 was measured [71c]. Prandtl numbers varied between 0·701 and 380. A turbulent boundary layer existed for Reynolds numbers larger than 5×10^5. For this condition the Nusselt number could be expressed by

$$Nu_{fo} = 0{\cdot}037\, Re_{fo}^{0\cdot 8}\, Pr_f^{0\cdot 43}\, (Pr_f/Pr_w)^{0\cdot 25}$$

in which f indicates conditions outside the boundary layer; w, at the wall surface; and o, a parameter based on heated length. The effect of angle of attack on local heat transfer was determined for a cylindrical object with a hemispherical nose in a supersonic wind tunnel [60c] and for slender cones in a hypersonic shock tunnel at Mach numbers 11 to 13 [69c]. In general, good agreement with analytical results was obtained. Measured heat transfer coefficients for flow over a lenticular aerodynamic body (saucer) at a Mach number 3·97 and with a turbulent boundary layer agreed with a stripwise analysis [12C]. The composition of dissociated air in equilibrium at the stagnation point of a blunt body during re-entry along various trajectories was calculated and used to determine the design requirements for an arc-heated hypersonic wind tunnel [29C]. Photographs of the boundary-layer structure, with high-intensity illumination, lasting a few nanoseconds have been obtained [21C]. Measured stagnation point heat transfer parameters exhibited a smooth transition from molecular flow to continuum boundary layer flow conditions [20C]. Heat transfer to a flat plate measured in a shock tunnel at Mach numbers from 8 to 25, at stagnation temperatures from 2500 to 6500°R, and at Knudson numbers from 0·38 to 85·5 demonstrated that slip reduces heat transfer drastically [40C]. The boundary layer equations for flow of a non-Newtonian fluid over a cylinder were solved using the equation $\tau = k(du/dy)^n$ to describe the shear [50C]. Experiments with carboxymethylcellulose solutions gave results in good agreement with this analysis. Nusselt numbers were determined from measurements on a platinum wire with 0·001 in diameter located in the boundary layer of a 1 in diameter cylinder in cross flow [64C].

An important parameter for the prediction of heat transfer is the Reynolds number at which the boundary layer flow becomes turbulent. Measurements on a flat plate indicated that this transition Reynolds number doubled when the Mach number increased from 2 to 4 [31C]. Sweep and leading edge bluntness decreased the transition Reynolds number. The effect of a 3-dimensional roughness (spheres) on boundary layer transition at a Mach number 2·71 was investigated [61C]. Boundary layer transition on a $\frac{1}{10}$-power nose shape in free flight at Mach numbers to 6·7 and free stream Reynolds numbers to 16×10^6 occurred at a Reynolds number based on momentum thickness with a value between 350 and 1600 [23C]. Aerodynamic heating rates agreed poorly with theory on the forward portion but well further downstream.

Ablation tests on models manufactured from teflon and lucite in a wind tunnel at Mach number 4·4, at 2000°R, and 600 psia, stagnation temperature and pressure, respectively, agreed well with theory [14C]. Ablation in a turbulent boundary layer was studied by a technique in which the heat of combustion is used to cause ablation rather than high stream enthalpy. Graphite models were exposed to the flow of an oxygen–nitrogen mixture with high oxygen concentration. In this way re-entry ablation conditions could be simulated [4C]. Calculations based on incompressible friction factors gave results up to 30 per cent too high.

FLOW WITH SEPARATED REGIONS

The results of experiments on forced convection heat transfer from a heated cylinder to water and ethylene glycol covered the range of Reynolds numbers between 40 and 100000 and of Prandtl numbers between 1 and 300 [17D]. The results could be represented by the equation

$$Nu\,(\mu_w/\mu)^{0\cdot 25}\,Pr^{-0\cdot 4} = 0\cdot 30\,\sqrt{(Re)} + 0\cdot 10\,Re^{0\cdot 67}.$$

Experiments [6D] on forced convection heat transfer from a heated sphere to water in the range of Reynolds numbers between 5000 and 480000 and for Prandtl numbers between 2·2 and 6·8 resulted in the relation

$$Nu\,Pr^{-0\cdot 50}\,(\mu_w/\mu)^{0\cdot 25} = 0\cdot 14\,Re^{0\cdot 66}$$

and corresponding mass transfer experiments [2D] at Reynolds numbers smaller than 100 gave Sherwood numbers in good agreement with an equation by Ranz and Marshall

$$Sh = 2 + 0\cdot 6\,Re^{1/2}\,Sc^{1/3}$$

for Schmidt number near 1 and with a very similar relation by Griffith for a Schmidt near 1000. In all of the above relations, the properties have to be introduced at bulk values except for the viscosity μ_w. The effect of freestream turbulence on combined heat and mass transfer on a 1 in sphere in forced convection was measured at Reynolds numbers between 1800 and 7500 and for a stream turbulence from 0·013 to 0·15 [22D]. The Reynolds numbers increased up to 30 per cent with turbulence level. The influence was especially strong in the separated region. An approximate method requiring two quadratures was developed to calculate the effect of heat transfer on laminar boundary layer separation [7D].

Heat transfer and pressure distribution on bodies with conical flares resulted in upstream flow separation at Mach number 6·8 [3D] and 5 [20D, 9D]. The length of separation decreases with surface cooling and increased Reynolds number, heat transfer is lower than in attached flow in the region of laminar separation and higher in transitional and turbulent separation with a peak at the re-attachment point. An analysis [14D] finds that heat and mass addition in separated flow increases the base pressure of a blunt object. A chart based on the preceding analysis has been published [8D]. Strong velocity fluctuations of order of the approach velocity have been measured in the wake immediately behind a plate placed normal to the flow [1D]. No similarity of the temperature and concentration fields of admixtures exists. The coefficient $\rho\, c_p\, \overline{T'v'}$ for turbulent heat transfer was found to be somewhat greater than the corresponding coefficient $\rho\, \overline{u'v'}$ for momentum transport in the turbulent wake behind rotationally symmetric bodies [18D]. An analysis was presented to calculate turbulent diffusion in the wake of a blunt-nosed body at hypersonic velocities [15D]. It was applied to calculate the radar trail of electrons for a body travelling at Mach number 22 and 100 000 ft altitude.

Heat transfer from air to spheres in a packed bed was measured by two methods [10D]; a regenerative method and by heating a single sphere electrically. The results were represented by the equation $Nu = 1{\cdot}25^{0{\cdot}58}$ for Reynolds numbers between 300 and 4000. Whether the bed was packed regularly or irregularly had no influence on heat transfer. The effective conductivity for packed beds of glass beads with 29 to 940 μ diameter in CO_2, N_2, He, and an organic liquid showed no effect of flow for Reynolds numbers from 0 to 6·6 [23D]. A method [4D] was developed to calculate axial conductivities in a packed bed from known radial values. Heat and mass transfer for flow of air through a packed bed composed of particles with various geometries could be represented by a relation between Nusselt and Peclet number when an appropriate length parameter was used [13D]. The general equations describing unsteady heat transfer for a fluid flowing through a semi-infinite homogeneous porous medium were solved numerically and compared with experimental data from literature [11D]. This analysis can be applied to thermal methods of oil recovery from underground reservoirs. Heat transfer to particles in liquid fluidized systems was measured and the results were represented by a relation with ± 20 per cent [19D]. Heat transfer from a tube in a fluidized bed itself was obtained as time average and instantaneous values [16D]. Rapid fluctuations of this value were observed. Available data were surveyed and correlated as relation between a j factor and a modified Reynolds number [12D, 5D]. The transfer of heat to solid particles in a stirred bed was calculated on the assumption that the effective thermal conductivity in the part through which the impeller blades pass is infinite [21D]. Experiments agreed with the analytical results.

TRANSFER MECHANISMS

The derivation of the conservation equations describing heat and mass transfer from the principles of irreversible thermodynamics is discussed in [3E]. From experiments with a boundary layer into which liquid evaporates from the surface, it is concluded that submicroscopic particles of liquid move into the boundary layer [9E]. Irreversible thermodynamics is applied to this process. The errors have been analysed which arise in the customary equations for the mean velocity and temperature field in turbulent flow when large temperature differences and, accordingly, large variations of properties occur [16E]. Temperature fluctuations have a strong influence on the stability of a compressible boundary layer above a Mach number 2 [8E].

Goertler's analogy between the stability theories for flow along a concave and a heated wall has been extended to arbitrary Prandtl numbers [7E]. Couette flow, channel flow, and boundary-layer flow are included. The measurement of transition in shock tube boundary layers by a thin film gauge is discussed [10E]. Transition to turbulence in the hypersonic wake of blunt bodies occurs at a Reynolds number around 7×10^4 [5E]. The transition from originally turbulent to laminar flow in a pipe has been studied experimentally [13E]. The rate of transition was found to be more rapid at lower Reynolds numbers. Free stream turbulence has no effect on heat transfer in a laminar boundary layer along a flat plate as long as the pressure is constant in flow direction [6E]. Heat transfer increases with stream turbulence when a negative pressure gradient is imposed.

The energy transfer in isotropic turbulence is analysed using various models [14E, 11E]. Energy spectra are calculated for the viscous sublayer of a turbulent flow [15E], for a contaminant undergoing a first-order reaction in a turbulent fluid [1E], and for weak turbulent shear flow [4E]. Some remarks to this are contained in [12E]. An excellent survey of our present knowledge of turbulent flow has been presented [2E].

NATURAL CONVECTION

Various aspects of combined natural and forced-convection flows have been studied both experimentally and analytically. Electrically-heated vertical tubes were employed in experiments with water [19F, 22F, 33F] and with oil [22F] flowing either upward [19F, 22F, 33F] or downward [19F, 33F]. Measured Nusselt numbers agreed satisfactorily with theory when the flow was steady. The breakdown of the laminar regime into a fluctuating regime occurred by a different mechanism and at different values of the parameters depending upon whether the flow was upward or downward. An extension of Lighthill's analysis for natural convection in a closed vertical tube to the case of a linearly decreasing temperature with height was compared with experiments employing glycerine, water, and mixtures of the two [11F]. Agreement was very good in certain ranges of Rayleigh number and rather poor in other ranges, suggesting the existence of various flow regimes.

A finite-difference solution [2F] of the conservation equations, including buoyancy effects, yielded information on the entrance region of a vertical, parallel-plate channel with isothermal walls. The computed entrance lengths were remarkably long; for instance, for a temperature difference of 1 degC between the walls and the entering air and a half-spacing of 0·1 ft, a channel height of 10^3 ft would be needed for flow development. The transient response of a fully-developed combined natural and forced convection flow in a vertical parallel-plate channel was analysed [46F] for prescribed variations of wall temperature, of forced-convection pressure gradient, and internal heat generation. In an illustrative case in which the forced convection was suddenly removed, the Nusselt number dipped below its terminal value during the transient period. The analysis of fully-developed combined forced and natural convection in vertical rectangular channels can be substantially simplified with little loss in accuracy by application of a variational method [1F]. Ostrach's analysis for the vertical parallel-plate channel with viscous dissipation has been extended [32F] to include suction and injection at the walls.

There have been several studies relating to combined natural and forced convection in horizontal flows. Boundary layer solutions [16F, 41F] for flow along a horizontal flat plate show that low Prandtl number fluids are more sensitive to buoyancy effects than are high Prandtl number fluids. The injection of mass into a horizontal boundary-layer flow also accentuates the effect of buoyancy [17F]. From an analysis [6F] including three-dimensional effects, the influence of natural convection on fully-developed horizontal tube flow is shown to depend on the Grashof and Reynolds number in a very complex manner. The dependence is simpler for flow in a horizontal parallel-plate channel when only two-dimensional effects are included [16F]. A new laminar heat transfer correlation for natural convection effects for flow in a horizontal tube was based on new data for water, ethyl alcohol, and glycerol–water mixtures plus prior data in the literature [30F]. The new data included both heating and cooling runs.

The necessary and sufficient conditions have been derived [29F] for the existence of similarity solutions of the boundary-layer equations which describe three-dimensional natural convection flow in rectangular co-ordinates. It was demonstrated by analysis [15F] that the effects of viscous dissipation in the natural convection boundary

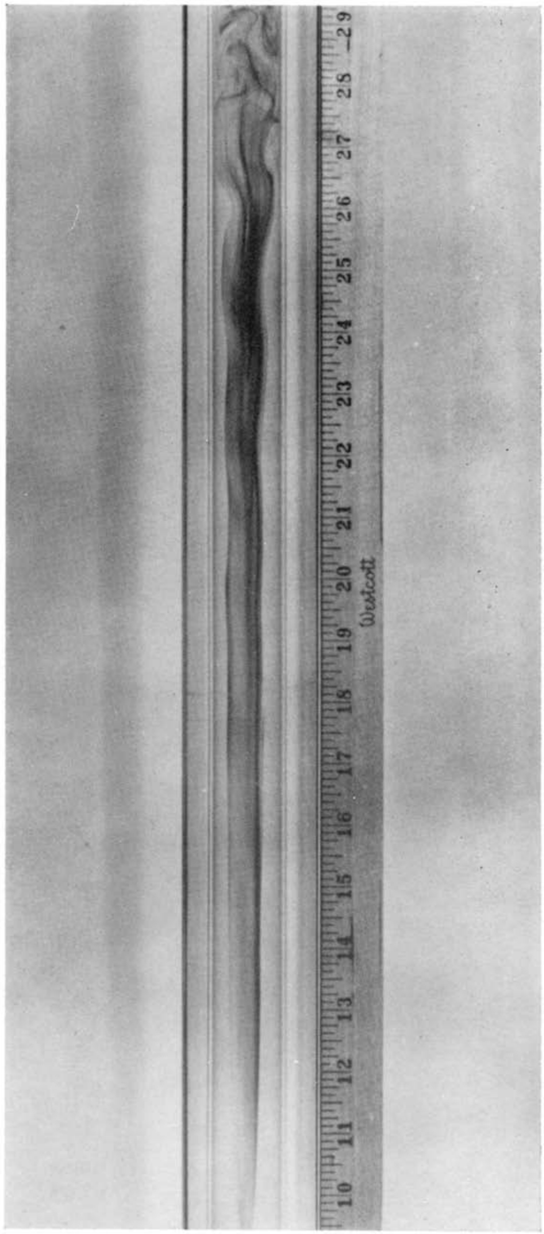

FIG. 1. Dye flow pattern obtained testing water in upflow at $R = 125$ [33F].

layer adjacent to an isothermal vertical plate are small for all Prandtl numbers when the body force is normal gravity. Another analysis shows [34F] that the detailed configuration of the leading edge of a vertical plate does not affect the velocity and temperature profiles at sufficient upstream distances other than to set the effective starting location of the boundary-layer development. Solutions for the vertical-plate boundary layer with surface mass transfer were applied [28F] to evaporation or condensation of moisture at a vertical wall. Results for $Pr = 0{\cdot}7$ for the vertical cone with uniform or linearly-varying surface temperature have been added to the store of similar boundary-layer solutions [21F]. Finite-difference solutions of the complete conservation equations for natural convection in a horizontal concentric annulus reveal twin kidney-shaped circulation patterns [9F].

Transient heat transfer from a doubly-infinite vertical plate can be found by applying solutions for transient heat conduction [27F, 35F]. The pure-conduction temperature distribution serves to establish the buoyancy force in the momentum equation. A direct finite-difference solution of the unsteady boundary layer equations for natural convection on a vertical plate ($Pr = 0{\cdot}733$) reveals that after a step change in surface temperature, the heat transfer follows that for pure conduction quite closely, but later dips below the steady state value [20F]. Part 2 of this paper [20F] treats the transient and steady natural convection in a horizontal cylinder, the two vertical halves of which are at different temperatures.

A new method [12F] for measurement of small flow velocities uses photographic techniques to measure the trajectories of small dust particles carried with the flow. Application of the method to the natural-convection velocity profile in air adjacent to a heated vertical plate gives data in satisfactory agreement with theory. Experiments have delineated the effects of frost accumulation on the natural-convection heat transfer at a highly-cooled plate exposed to humid air [45F]. Overall heat transfer data for natural convection from an electrically-heated aluminum sphere could be correlated [3F] by the relation, $Nu = 0{\cdot}513\,(Gr\,Pr)^{1/4}$. Experiments on heat transfer from a $\frac{3}{4}$ in horizontal cylinder to air at pressures ranging from one atmosphere to 0·04 psi did not correlate with the usual Nusselt–Grashof curve, even though slip effects should have been absent under the conditions of the tests [42F].

The heat transfer between two communicating cavities containing air at different temperatures has been measured for both situations in which the cavities are side by side and one above the other [5F, 4F]. The data are correlated using dimensionless parameters suggested by analysis. The turbulent natural convection above a line fire has been studied both analytically and experimentally [25F]. A problem related to this is the motion near the advancing front of a vertical plume which is being established in a uniform atmosphere by emission of a buoyant fluid from a point source [44F].

Experiment shows that local natural-convection heat transfer coefficients for a heated horizontal cylinder are substantially increased by the superposition of an intense sound field [14F]. The extent of the increase is different on the upper and lower portions, and the physical mechanisms governing the phenomenon are correspondingly different. Additional experiment leads to the conclusion [13F] that the interaction between natural convection on a horizontal cylinder and horizontal transverse vibrations is essentially the same regardless of whether the vibrations are acoustically or mechanically introduced. Heat transfer data for a heated horizontal wire immersed in a water bath and oscillating in a vertical plane could be classified [10F] according to natural convection, forced convection, or mixed convection. A transverse vibration of a heated vertical plate sets up a buoyancy force in addition to the usual. A perturbation solution of the boundary-layer equations was made to determine the effect of the vibration [36F].

Several papers have appeared dealing with magnetohydrodynamic effects. Three of these [18F, 26F, 40F] are concerned with a horizontal magnetic field imposed on a vertical plate having a variety of thermal boundary conditions. The presence of the magnetic field reduces the heat transfer. Results for the isothermal plate suggest that the local heat transfer reduction may not be too sensitive to the details of the vertical variation of the imposed magnetic field [40F]. For combined forced and natural convection in a vertical channel with two walls at different temperatures and a horizontal magnetic field, the combined effect of joule heating and viscous dissipation is reduced with increasing field strength [31F]. This is because the reduction in viscous dissipation exceeds the increase in joule heating. Joule heating alone was considered in reference [8F]. A low-strength horizontal magnetic field was found capable [7F] of reducing the heat transfer in a vertically-oriented toroidal tube subject to a higher temperature below.

The stability of a natural-convection flow on a vertical plate was analysed by perturbation theory, and the corresponding transition problem was studied experimentally on an electrically-heated brass plate in water [43F] using dye as a tracer. Both studies indicated that the breakdown of laminar flow began at positions beyond the location of the peak in the velocity profile. From data in the literature, it was concluded [23F] that the transition values of the Grashof–Prandtl product are not the same for vertical plates and for spheres. Further analytical contributions [38F, 37F] have been made to the problem of determining the motion which follows the breakdown of the quiescent state in a horizontal layer heated from below. The stability of revolving fluids is analysed for the cases of an annulus having walls at different temperatures with a circular magnetic field [24F] and of a finite cylinder heated from below [39F].

CONVECTION WITH ROTATING SURFACES

Heat transfer measurements were made with and without axial through-flow of air in an annular system consisting of a heated, rotating inner cylinder and a cooled, stationary outer tube [1G]. The data could be classified according to whether the flow was laminar, laminar with Taylor vortices, and turbulent. A stability analysis of the aforementioned system without throughflow suggests that heating at the inner surface delays the onset of Taylor vortices [2G]. A mixing length concept, modified to include tangential motions, is employed [3G] in an analysis of turbulent heat transfer between a rotating inner cylinder and a stationary outer tube for turbulent flow without Taylor vortices.

Finite-difference solutions for unsteady heat transfer from a rotating disk to an adjacent rotating or stationary flow reveal a rather short transient period [4G]. For instance, for a disk rotating in still air at 100 rad/s, only 5 ms are required to reach steady state after a step change in disk surface temperature. Analytically-determined mass transfer rates from a rotating disk immersed in a stationary fluid are reported for Schmidt numbers covering the range from 0·1 to 10^4 [5G]. Series expansion methods have been employed in the analysis of heat transfer in a system consisting of a rotating disk and a parallel stationary disk with mass injection or removal at the hub [10G]. The application of an axial magnetic field to an isothermal rotating disk decreases the heat transfer rate [11G], with the greatest reductions for low-Prandtl-number fluids (liquid metals).

A theoretical study is made of the energy distribution during the transient decay of a motion which begins with an inner core of stationary fluid and an outer ring of fluid rotating with uniform tangential velocity [9G]. Another theoretical paper seeks to predict the fluid motion in an annulus of finite height which is rotated about its axis and is subjected to a radial temperature gradient [7G].

It has been demonstrated that the rotation of a sphere about an axis at right angles to the free-stream velocity can significantly reduce the surface temperatures which result from aerodynamic heating [6G, 8G].

COMBINED HEAT AND MASS TRANSFER

Interest continues in methods for protection of a solid surface from a high temperature mainstream flow by interposing a secondary fluid between the surface and the hot gas. When the secondary fluid is injected over a large area of the surface, such as through a porous wall, the method is called transpiration cooling. When the secondary fluid is injected through slots at discrete locations, one has film cooling.

Further measurements have been made of the velocity and temperature profiles downstream of a single slot in subsonic film cooling [16H]. As in previous investigations, it was found that the velocity boundary layer is rather complex while the temperature profiles displayed a high degree of similarity as one proceeds downstream from the slot. The film cooling effectiveness with variable freestream velocity has been found to be little different from that for uniform free-stream velocity [17H]. Experiments [3H] with a hemisphere in a main-stream at Mach 10 and 8700°R stagnation temperature showed that the heat transfer over the entire surface could be decreased by up to 60 per cent using injection slots near the stagnation point.

The flow and heat transfer from a tangential wall slot is equivalent to film cooling in the absence of a main-stream flow. Measurements [18H] of the velocity and temperature profiles along an adiabatic flat plate show agreement with earlier analytical studies. Predictions of the heat transfer based on these results are presented.

The importance of thermal diffusion effects in transpiration cooling has been discussed [26H]. A new definition of the cooling effectiveness is required when these effects are significant [25H].

Transpiration cooling measurements have been performed with air injection on conical surfaces at Mach numbers of 2 and 4 [31H]; with helium, nitrogen, and air injection through a cylinder wall to an internal mainflow parallel to the axis [7H]; and with both helium and air injection on a hemisphere [6H]. In these last two series of experiments, irregularities in the results were found for helium injection. This may be due to thermal diffusion effects.

A solution has been found [27H] for transpiration cooling in hypersonic flow using the integrated boundary layer equation and a first-order approximation for the inviscid region behind the shock. An analysis for helium injection taking into account the laminar sub-layer compares favorably with experimental results [11H]. The effect of hydrogen injection (with no chemical reaction) on a flat plate has been calculated [4H] over a wide range of parameters. A one-dimensional transient analysis of the temperature response of a transpiration-cooled porous wall has been presented [15H]. Calculations indicate [9H] that the introduction of a radiation-absorbing gas by transpiration could considerably reduce heat transfer at a stagnation point.

When the wall downstream from a transpiration-cooled section is impermeable, one encounters a situation somewhat intermediate between film cooling and transpiration cooling. Here, the velocity and thermal boundary layers at the start of the impermeable region are determined by the previous transpiration-cooled section, but there is no velocity normal to the wall at the plate surface. The solution to the laminar boundary layer equations was obtained for this condition when both the injected fluid and the mainstream are air [12H]. For large rates of injection, the boundary layer is characterized by an inner isothermal shear-flow and an external, relatively thin region where the flow velocity and temperature change to their free-stream value. The integrated boundary layer equations are developed for the downstream region. A similar treatment [5H] has been made for helium injection. The integral analysis has been extended [1H] to the case of hypersonic flow conditions with large rates of mass addition. Decreasing the coolant temperature and increasing the injection are found to decrease the heat transfer to the body. Experiments [2H] with nitrogen and helium injected on a blunt-nosed 30° (half angle) cone showed good agreement with the above analyses. By a judicious choice of temperature and velocity profiles, a different integral solution was found to give good agreement with air injection in subsonic flows [28H].

Liquid injection in a laminar boundary layer along a flat plate also shows the possibility of greatly reducing heat transfer [29H, 20H]. Approximate calculations were used to determine the cooling effects and the expected fluid consumption. Measurements of the heat transfer from a liquid to a turbulent gas boundary layer indicated that evaporation may cause the Nusselt number to be larger than under similar circumstances when there is no mass transfer [22H]. Photographs of the liquid–gas interface when the secondary fluid is a liquid have been obtained [19H].

Several specific problems concerning combined heat and mass transfer have been approached theoretically. Equations for the sublimation of a solid near the stagnation region in plane and axisymmetric flows of an incompressible gas have been derived and solved [23H]. Heat and mass transfer problems have been examined for drying on the inside surface of circular cylinders

[14H], and also under conditions of highly intensive heat transfer [21H]. A combined experimental and theoretical study of the drying of paper on cylinders showed considerable heat transfer by vaporization–condensation cycles [13H]. An analysis of the interaction of heat and mass transfer from a sphere at low Reynolds number was made possible by linearizing the flow equations [10H].

Measurements [30H] in a turbulent airstream show that the heat transfer from a sphere at moderate Reynolds numbers is increased when there is evaporation taking place at the surface; the effect being relatively less important as the turbulence level increases. The mass and heat transfer in a fluidized bed of drying silica gel were studied with varying parameters to get empirical relations [8H]. A rigorous theoretical treatment of the heat and mass transfer at a gas–liquid interface in a binary mixture [24H] shows that the approximate methods usually used for this problem are not always valid.

CHANGE OF PHASE

Research in this area continues actively, particularly in the experimental study of specific systems.

Boiling

Kutateladze [27J] formulates, for nucleate boiling, a system of differential equations and a rational criteria for its characterization. Other investigations are concerned with: transient pool boiling of water on a vertical surface with a step heat input [33J], a hydrodynamic model [53J] and a statistical analysis of nucleate-pool-boiling data [21J], and measured pressure drop and vapor volume for sub-cooled nucleate boiling [23J]. Schafer *et al.* [47J] consider the practical problem of using forced-convection, nucleate boiling of water for nozzle cooling at high heat fluxes. A useful survey of conditions affecting the convection and nucleate boiling regions for heat transfer to binary mixtures is given in [58J] while [52J] reports measurements of forced convection (vertically upward) boiling of water in stainless steel tubes where the various boiling regimes were present simultaneously in various parts of the tube.

For laminar film boiling Koh [26J] analyses the two-phase flow problem of boiling on a vertical flat plate; effect of liquid sub-cooling is examined in [50J]. Cess [10J] gives a simple approximate analysis for the flat plate with non-isothermal surface applicable to film boiling. Measurements on specific systems include: film boiling on a horizontal plate for water and Freon-11 [18J], forced convection between a free liquid sheet and air in crossflow [59J], heat transfer coefficients for the external condensation of two refrigerants on horizontal tubes [28J], and evaporation heat transfer in a vertical tube by natural circulation [30J]. Correlation of boiling hydrogen data appears in [17J], a useful survey of binary boiling mixtures at onset of film boiling [57J], and an empirical expression correlating film boiling data for horizontal tubes of various diameters [9J].

Experiments considering surface effects involve hydrodynamic drag [8J], evaporation of drops from "teflon" [34J] and in a moving gas stream [4J], evaporation coefficients for glycerine [16J], and a coating for promotion of boiling [13J]. Paul [42J] has collected the scattered data on evaporation coefficients from eight-six references.

Single component phase change is considered from the view of transient temperature distributions [25J] and the specific heat during the transition [1J].

Bubble characteristics and dynamics receive consideration from a number of aspects: growth rate [5J], heat transport [6J, 7J], dynamics of noncondensible bubbles in water [24J], relation between frequency and diameter [35J], size range of active nucleation cavities on a heating surface [22J]. The related problem of vapor void behavior during heating is treated analytically [19J] and by empirical correlations [20J, 55J, 56J].

Experimental work on the problem of critical heat loads includes the effect of non-uniform heat flux [51J], data for three fluids (ethanol, water, and carbon tetrachloride) [38J], flow maldistribution in reactor fuel assemblies [32J], effect of tube length [36J], a two-part study of boiling burnout [46J, 45J], and a photographic study of acceleration effects [12J]. For better correlation of burnout data, Levendahl [31J] proposes a new parameter.

Two-phase flow phenomena embrace an

analyses of entrance effects in slug flow [37J], slug dynamics in vertical tubes [39J], evaporation experiments in vertical tubes [3J], calculated heat transfer in long vertical tubes [2J], and a brief note on the proper form for the energy equation [54J].

Phase change studies for specific systems and/or fluids include condensing mercury [14J], laminar condensation in horizontal and inclined tubes [11J], high area ratio nozzles [40J], promoters for dropwise condensation [41J] and cryogenic liquids [60J]. Romie [44J] calculates density changes in boiling coolants. Those aspects of phase change pertinent to reactor technology are reported in [15J].

The corresponding states principle is applied to predict vapor–liquid equilibria [29J].

Other two-phase studies consider liquid–solid suspensions in vertical transport [43J] and vapor–solid transitions [49J, 48J].

RADIATION

Thermal radiation continues to arouse wide interest, particularly in relation to space problems. Heat exchangers in which the energy is removed by radiation drew a considerable amount of attention both direct and indirect. In most studies, the surfaces were assumed to be gray and to reflect and emit radiation diffusely.

Annular fins were found to give a significant increase in energy radiated even with mutual irradiation between the elements [41K]. Predictions have been presented for the effectiveness of a vee-type fin array with parallel radiation striking the fins [13K]. The radiant interchange between a fin and its base was found to be a significant fraction of the total heat transferred [38K]. If fins are coated to increase their emittance, the low thermal conductivity of the coating may have a deleterious effect on the overall heat transfer [29K].

The radiation characteristics of enclosures of various shapes have been studied. Spherical cavities [40K], cylindrical holes [33K], and concave circular cylinder sections [14K] (including specular reflection [35K]) have been considered with or without incident radiant energy. As the cavity gets deeper, or the emittance increases, one approaches the limit of a black surface with an area equivalent to the projected area. Thus, a cylindrical hole four diameters deep with an emittance of 0·5 would be equivalent to an apparent surface emissivity of 0·99 [36K]. Similar calculations [39K] for rectangular grooves also include the local radiative heat transfer from different parts of the cavity.

Calculations [2K] of shape factors between surfaces made of good conductors show a significant difference from those normally found assuming diffuse surfaces. Other studies [34K, 3K] indicate that only small errors arise by assuming uniform temperature or heat flux when using angle factors for simple surfaces. A large change in the spectral emissivity of a surface has been shown to permit large variations in the equilibrium temperature of the surface [15K]. A semi-empirical relationship was found [5K] for the radiant energy transfer between two parallel tungsten plates including the non-graynesss of the surface and the variation of emittance with temperature. Reversing the usual problem, a method and apparatus have been described [22K] for determining the size and shape of a radiating source from measurements of the radiation field.

Further studies have been made on the radiative exchange inside enclosures. A method of images was used to show the effect of a specular surface [37K]. Opaque and non-opaque surfaces have been considered in determining the temperature distribution from an assigned radiation flux [10K].

Many measurements have been taken to determine the radiation properties of solid surfaces, particularly at high temperatures. A compilation of some previous determinations has been presented [31K]. Newer measurements include the total normal emittance of several refractory oxides, cermets, and ceramics from 600°F to 2000°F (including tests that showed the validity of assuming diffuse emission) [46K]; total normal emittance of boron nitride from 1200°F to 1900°F (with some determinations of the normal spectral emittance) [47K]; and total hemispherical emittance of Platinum—10 per cent Rhodium wires from 600°C to 1450°C [4K] and of various niobium surfaces from 500 to 1100°C [18K]. Measurements of the total hemispherical emittance of ceramic-coated and uncoated inconel and types 321 and 430 stainless steel (up to 1000°C) showed that surface finish was more important than composition in determining the values of emittance [29K]. For the uncoated samples the emittance increased with temperature, while for the coated ones it decreased. A study [1K] of the total and spectral (at 0·65 μ) emittance of tungsten-bearing alloys and porous tungsten from 1600°K to 3200°K found that the emittance of the refractory-bearing alloys tended to reflect the emissivities of their constituents.

The transmittance and reflectance, from 15 to 118 μ, of aluminum oxide films of various thickness has been measured [11K]. Calculations [8K] for solar collectors have been made of the spectral and directional radiation characteristics of selective surfaces.

Clouds of small particles (particularly carbon) in gases have been found to obey Beers' law for transmission with a constant absorption coefficient in the spectral range studied (0·2 to 1·0 μ) [24K]. An analysis of the radiant heat transfer to clouds of droplets and particles has been performed in a manner analagous to a calculation for a radiation absorbing gas of non-uniform temperature [16K].

Some calculations have been made for radiation exchange in a non-gray enclosure containing an absorbing medium. These were performed using the Oppenheim network method and assuming absorption in specific wavelength bands for isothermal water vapor and carbon dioxide [9K], and carbon dioxide–nitrogen mixtures [7K].

The problem of combined conduction and radiation in an absorbing medium appears to be gaining in interest. In one paper [45K], the temperature distribution between two black parallel plates is calculated for various relative magnitudes of the effective absorption thickness of the medium (assumed gray). A continuation of this work for gray diffuse surfaces [44K] shows that absorption and emission in the medium can increase the heat transfer considerably even if there is very strong absorption. An approximate solution to this problem has been presented [25K] for a relatively (optically) thin layer of gas. Discussions on a similar problem have continued [17K, 23K].

Calculations [43K] of the temperature profile in a radiation-absorbing and emitting fluid boundary layer for wedge flows show that the wall temperature gradient may be increased or decreased when the wall is cooled while it always decreased for a heated wall. In all cases the total heat transfer increased. Radiation from a gas to a heat exchanger wall has also been studied [12K].

In the case of convective heat transfer from a non-isothermal surface, radiation from the solid surface may play a large role in determining the wall temperature distribution and thus the heat transfer coefficient. On a flat plate, this effect was found to be large with a laminar boundary layer, but negligible with a turbulent one [6K]. Tube flow calculations for a black surface [27K] indicate that the effect of wall radiation is greatest in relatively short tubes, and that, for long tubes a smaller emittance (with a gray diffuse tube wall) does not give results greatly differing from that of a black surface in the central region of the tube [30K].

Calculation of the heat transfer from a radiating shock layer to the stagnation region of a blunt body has drawn considerable interest; in particular the validity of some of the assumptions often used. A correction of the frequent approximation considering a plane radiating shock and surface in place of the spherical nose cone has been calculated [48K]. Another calculation [26K] gives the effect of radius at the stagnation point on radiation heat transfer. Both of these calculations essentially assumed the shock layer to be black. This approximation has been examined for the shock standing of an ellipsoidal nose cap assuming the air to be gray [42K]. The gray body assumption was found [32K] to be a reasonable one for temperatures greater than 12000°K but its validity disappears at lower temperatures. The effect of a temperature variation in the air was found [20K] to require only a small correction to the usual isothermal results.

The effect of radiation on the convection near the stagnation point has been studied [19K] by examining the energy radiated by the gas along the streamlines in this region. Calculations [21K] indicate that radiation exchange between the surface and the surrounding gases has little effect on the convective heat transfer in flow, up to a Mach number of 40, along a flat plate in the atmosphere.

LIQUID METALS

Experiments for liquid mercury flowing in a water-cooled tube gave average Nusselt numbers which fell about 20 per cent below Lyon's equation. Values of ϵ_h/ϵ_m (ϵ_h = eddy diffusivity for heat, ϵ_m = eddy diffusivity for momentum) deduced from temperature profile measurements were very similar to those found from auxiliary experiments for heat transfer to water in turbulent tube flow [3L]. An experimental heat transfer study employing both alkali metals and heavy metals suggests that there is little effect of interfacial contact resistance for the former but considerable effect for the latter [4L]. A NaK–NaK heat exchanger consisting of an inner tube and a concentric annulus provided average heat transfer data for the tube for the Peclet number range 200–2500 and for the annulus for the range 100–1500 [1L]. The tube Nusselt numbers generally fell lower than Lyon's equation, while those for the annulus fell higher than Lyon's equation.

An axial magnetic field imposed on mercury flowing in glass and in aluminum tubes was shown experimentally to increase the transition Reynolds number and also to decrease the friction factor for turbulent flow [2L].

LOW-DENSITY HEAT TRANSFER

Effort here centers upon specific heat transfer problems and the characterization of gas-surface interactions.

For slip flow, laminar heat transfer in ducts is considered without [11M] and with [5M] internal heat generation. Low density stagnation point measurements indicate that vorticity and viscous effects increased heat transfer significantly above boundary-layer predictions [13M]. Solomon [10M] analyses first-order slip effects on the laminar boundary layer over a slender body of revolution with zero pressure gradient. In [6M], the full-range moment method of Lees is applied to heat transfer across a large temperature difference.

Heat loss from wires in rarefied gases is considered by Baldwin [1M] and described by kinetic theory in [7M].

Earlier theories of accommodation coefficients are critically reviewed by Gilbey [3M], and Goodman [4M], using classical dynamics of simple cubic lattices, predicts accommodation coefficients in good agreement with earlier experiments. Thermal accommodation effects on free molecule aerodynamics coefficients are considered by Sentmann [9M].

Gas-surface interactions are treated by Thomas [12M], rare gas–platinum systems receiving study in [2M]. Pashchenko [8M] raises aerothermodynamic questions about the free-molecule flow model.

MEASUREMENT TECHNIQUES

Much work has been expended in studies of temperature determination. General papers include a rather complete bibliography on recent works concerned with temperature measurement [17N], a review of physical properties of many different thermocouple materials for use at high temperature [8N]: a discussion on platinum resistance thermometry [2N], and a detailed review of theory and methods of optical pyrometry [22N].

Emphasis is still strong on thermocouple techniques. A study [38N] of noble metal thermocouples at temperatures between 1000° and 1700°C found the principal source of instability, in the calibration, to be due to contamination by impurities from ceramic protection tubes. A method for increasing thermocouple response rate by putting in a phase advance in the self-balancing system has been tried [33N]. Methods for constructing small-diameter (0·005 in) thermocouples [12N] and for sealing thermocouples passing through fused silica [30N] have been described.

Errors in thermocouple measurement and means for correcting them have come under further scrutiny. The errors in transient surface temperature determination due to conduction have been studied [7N]. This effect in low conductivity walls may be very large [3N]. A calibration to determine the temperature generated e.m.f. when a thermocouple is directly welded to a d.c. heated test section has been successfully demonstrated [11N]. Often errors may arise in temperature measurement due to the large size of a thermocouple junction in a non-isothermal field. The reverse of this has been used in designing a long junction to locate a temperature discontinuity along its length [21N].

A water-cooled probe which is capable of being used at very high temperatures has been constructed [5N]. In operation and use it is very similar to a constant temperature hot-wire anemometer. A calorimetric probe for local determination of high temperature gas enthalpy has been described [15N].

The possible errors in the measurement of surface heat fluxes due to uncertainties in thermocouple location [9N] (in a transient method of heat flux determination) and surface temperature mismatch [40N] (for plug-type calorimeters) were studied. A method for determining the angular distribution of heat transfer on the outside of a cylinder which has a liquid heat sink (or source) flowing within it has been demonstrated [35N]. A solution of the conduction equation in an annulus shows that only the outside surface temperature distribution is required for determining the local heat flux if there is a known heat-transfer coefficient on the inner surface.

Thin film gauges for shock tube measurements have been reviewed [37N]. Recent measurements [18N] show that temperature variation in the properties of the backing materials commonly used in these gauges may be large enough to give significant errors.

Other fairly novel measuring devices have been suggested for specific systems. These include an acoustic method where the speed of sound in a gas is measured to determine the temperature [1N]; an infra-red emission and absorption technique for temperature measurements in plasma jets [34N]; temperature determination in flowing N_2 using an electron gun to cause excitation and subsequent measurement of rotational and vibrational band intensities [27N]; a beta ray densitometer for shock tube density measurements [25N]; and determination of boundary layer thickness from the point of peak intensity in a Schlieren photograph [16N].

Measurements of the thermal diffusivity of solids have been performed using a transient energy input to a sample's surface. One system [28N, 32N] uses an impulse-type input by thermal radiation and another [10N] a sinusoidal input from an electron gun. In both systems the time variation of the temperature of the back surface of the sample must be measured. A steady-state system for determining high temperature thermal conductivities using a radiant energy input has also been described [14N].

An apparatus for measuring the thermal conductivity of solids at temperatures down to 1·7°K has been constructed [19N]. For liquids, a system using a transient heat input to an immersed wire has been used to obtain thermal conductivities of several refrigerants [41N].

A system has been demonstrated for measuring the thermal conductivity of gases [39N]. It makes use of the relationship between the thermal conductivity and the width of the thermal wake downstream from a line source of heat in a uniform velocity gas stream.

Thermal radiation measuring instruments have elicited considerable interest. A generalized theory of metal film bolometers [36N] and the design of a wedge-immersed bolometer [13N] for use in spectrometers have been presented. A continual-flow radiation calorimeter for calibrating radiometers in the range from 0·1 to 1·5 cal/cm^2 s has been constructed [26N]. The use of an integrating sphere in conjunction with a photomultiplier has been shown to give a relatively uniform reading with varying input angle [31N].

Calorimetric methods for determining emittances of metal surfaces have been described [20N, 6N]. A quite different system [24N] may be used to measure angle factors or emittances of systems (whichever of the two is unknown). Apparatus for determining the spectral emissivity (from 1 to 13 μ) of metals by using a black body for comparison has been constructed [23N].

Radiant energy sources for simulating solar radiation are of interest for reflectance measurements applicable to objects in space. One study [29N] found that a quartz mercury lamp gave relatively greater energy in the far infra-red than a globar source. Another [4N] concluded that two different sources, xenon arc and tungsten lamp, both with filters, are necessary to approximate the solar spectrum.

HEAT TRANSFER APPLICATIONS

Heat exchangers

The transient behavior of heat exchangers is a problem still undergoing much study. Transfer functions for predicting the time response of certain simple models of heat exchangers have been presented [4P]. The models included fluids thoroughly mixed, temperature of both streams varying (as in double-pipe heat exchangers), multipass exchangers, and one-stream isothermal and the other changing continuously. The transient problem in a heat generating cylinder with the heat removed by fluid flowing outside it has been presented [5P]. The lumped parameter model was found to adequately represent most heat exchanger transients while the distributed parameter method is required for an inlet temperature transient [2P].

Considerable effort has been expended in trying to predict the performance of rotating regenerative heat exchangers. A solution to the temperature distribution after quasi-steady state is reached has been presented [9P]. Calculations for rotary-kiln type exchangers have been extended [6P]. Complete mixing (essentially homogenization) and no mixing were considered as the two limiting cases. Solutions to the differential equations for the single screen element in a rotary matrix wire exchanger have been examined [7P].

Measurements made on spiral-plate heat exchangers [13P] indicate that correlations obtained for heat transfer from coils may be used to predict performance. Other studies have been performed on plate-fin heat exchangers [15P]. Theoretical solutions have been obtained for the temperature distribution and heat transfer in twice-through crossflow heat exchangers [10P] and heat exchangers where one fluid is transferring heat to two other fluids [8P]. Measurements were made on heat transfer and pressure drop with transverse flow across finned tube bundles [1P].

A scraped surface heat exchanger, where a rotating member with fins disrupts the boundary layer to enhance the heat transfer, has been experimentally examined [11P, 12P]. It was found that the work input to the rotating system may be a considerable fraction of the total heat transferred.

Other studies have been made on the economics of using promoters to improve heat exchanger performance [3P] and on the methods of determining heat transfer in vessel jackets [14P].

Aircraft and space vehicles

The increasing entry velocities through the atmosphere make the radiative heat input comparable to the convective heat transfer [16Q]. The optimum body radius minimizing the total heat input to the stagnation point for radiative and convective heating has been calculated [6Q]. The performance of subliming and charring ablators was tested in a subsonic arc jet with addition of a graphite radiator [8Q]. The efficiency of transparent ablators was strongly reduced in the presence of radiative heat input. 26 000 ft/s re-entry velocity can be handled with thin beryllia or thoria-tipped graphite leading edges for hyper-velocity wings [7Q]. Tests of teflon and polyethelyne models in an arc-heated nitrogen stream gave performances which agreed with the analysis for catalytic surfaces [13Q]. Evaporation of vapor and transpiration cooling by ejection of the vapor through the porous skin is an effective means for thermal protection of hypersonic glide vehicles [1Q]. Diatomaceous earth and quartz felt are the best water absorbent materials [3Q]. Composite thermal protection systems were found superior to simple systems [12Q]. Hypersonic heat transfer was measured on umbrella-type models in a shock tube [4Q]. Foils and heat shields appear to give the most effective thermal protection for space vehicle cryogenic-propellant tanks [11Q]. Man can handle 20 Btu/ft^2 min for 15 min with proper clothing [14Q]. Measured local heat fluxes in liquid propellant rocket nozzles agreed with calculations using Bartz' method in the expansion region and gave values 80 per cent above to 45 per cent below the calculated ones at the throat [15Q]. Film cooling of rocket motors with RP-1 propellant was investigated [10Q] and radiation cooling of a nuclear rocket nozzle with hydrogen propellant was analysed [9Q]. The temperature can be maintained in an explorer satellite within the desired range by proper coating of the surface [5Q]. The solar radiation pressure is found to have an important effect on the motion of the Echo I satellite [2Q].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Experimentally, interest continues to focus on extreme conditions of high or low temperature, pressure effects, and critical state behavior. Theoretical considerations embrace molecular models, mixture property rules, and generalization of available data through propositions based on the corresponding states principle.

Thermodynamic properties

Measured *p-v-t* data are reported for propane [19R], propyne [19R, 86R], hydrogen chloride [80R], and mercury vapor [78R]. Second virial coefficient determination is considered generally [69R] and specifically for steam by Keyes [44R]. For mixtures, critical properties are determined for the methane-ethane-*n*-butane system [29R, 15R]. Fomichev *et al.* [28R] discuss calorimetric means of determining enthalpy and heat capacity and in [4R] argon constant volume heat capacities around the critical point are reported. Schamp and co-workers [68R] measured nitrous oxide (N_2O) compressibilities, calculated second virial coefficients, and deduced inter-molecular forces. Enthalpy data are reported for seven polar compounds [24R], and heat capacities for water–hydrogen peroxide mixtures [31R] and molybdenum [45R].

Theoretical studies of thermodynamic data at high temperatures (above 1000°R) include correlation formulae for air [85R], argon plasma properties [58R], carbon dioxide properties to 24000°K [60R], and hydrogen plasma properties [63R, 72R, 53R]. The latter reference [53R] also treats helium and lithium plasmas. The equation of state for an ionized gas is discussed in [20R].

New equations of state for steam and low temperature helium are considered in [5R, 52R] respectively.

Poland *et al.* [59R] report ideal-gas thermodynamic functions for some selected, heavier elements, while for polar gas, [25R] gives dilute phase thermodynamic properties and [65R] second virial coefficient data. Gray [34R] considers saturated, dissociating vapor heat capacity and vapor pressure curves.

Machine computation of thermodynamic properties for dichlorotetrafluoroethane are presented by [84R].

Aspects of determining gas mixture thermodynamic properties are discussed in [7R], specific thermodynamic and electrical properties of the H-C-N-O-K system reported by Moffatt [55R].

Generalizations based on corresponding states principles include a form of the principle for argon and xenon [17R], a vapor pressure equation [61R], velocity of sound [71R], an equation of state [23R], relation of molecular properties to the accentric factor [18R], and prediction of intermolecular force constants from critical properties [76R].

Transport properties (experimental)

(a) *Thermal conductivity.* Guildner describes the coaxial cylinder cell for gas thermal conductivity measurements [36R]. Other devices concentrate on low temperature [40R], liquids [30R], and use of a line source technique for N_2, CO_2, and N_2–CO_2 mixtures [89R]. Other studies consider compressed helium at high temperatures [42R], carbon dioxide near the critical point [37R, 70R], singly and doubly dissociating nitrogen peroxide [6R], and the binary and ternary mixtures of ten gases [14R]. The shock tube is employed to measure high temperature nitrogen conductivity [1R]. O'Neal and Brokaw report Prandtl numbers based on recovery factor measurements [56R].

(b) *Diffusion.* Measurements reported are: self-diffusion results for CO_2 at high temperature (1180–1680°K) [22R], binary diffusion for the H_2–Ar system [90R], and Kr–He system [74R], and mutual diffusion of polar-nonpolar gas mixtures [73R].

Thermal diffusion results are reported [66R, 82R] and the pressure influence on this effect in [47R].

(c) *Viscosity.* Viscosity measurements were performed on N_2 [91R], water [91R, 51R], ethane [21R], and in the critical region for ethane, propane, and *n*-butane [75R]. High temperature viscosities for NO–N_2O mixtures are given in [39R], magnetic field influence on transport properties for diatomic molecules being studied by Beenakker *et al.* [8R].

Transport properties (theoretical)

General aspects of the problem are considered in [3R] while high temperature behavior is emphasized in the following calculations of transport properties for hydrogen [62R], both dissociating [35R, 83R] and atomic [16R], and for dissociating nitrogen and oxygen [92R]. Collision integrals for air transport properties may be found in [93R]. An approximate theory for thermal conductivity and viscosity in dense polyatomic fluids is given in [64R] and Amdur [2R] discusses limitations on current calculating methods in the light of experimental data. Further studies concern transport properties for gases obeying the Morse potential [48R], for polar gas mixtures [50R], graphical correlations for SO_2 [54R], and the Lewis number [26R, 10R].

Specific thermal conductivity research centers on argon plasma [9R], polyatomic and polar gases [49R] relaxation rate effects [11R], gaseous mixtures of ammonia [33R], mixtures of nitrogen and hydrogen [32R], two-phase materials [87R], and heterogeneous two-component systems [38R].

Diffusion coefficient estimates from experimental viscosity measurements are found for hydrogen atoms and molecules [88R] and generalized treatment by an equation [13R] and a nomogram [57R]. Kotousov [46R] relates the thermal diffusion coefficient to the thermodynamic properties of binary mixtures.

Viscosity investigations treat atomic hydrogen [12R], polar gases [79R, 77R], dense gases and liquids [41R], plasmas in magnetic fields [43R], and the relation of Lennard–Jones viscosity based force constants to critical properties [27R]. Thornton [81R] considers viscosities of binary mixtures of rare gases, multi-component gaseous mixtures at high temperature being the subject of study in [67R].

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