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HEAT TRANSFER, A REVIEW OF CURRENT LITERATURE

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INTRODUCTION

HEAT transfer problems are encountered and have to be solved in almost every engineering activity. They become crucial for various modern developments like high-speed aeronautics and space flight. This is obviously the reason for the fact that research activity in heat transfer is very strong as evidenced by the growing number of publications in this area. Space limitations have prevented us, therefore, from including all references in this literature survey. Many engineering conferences devoted considerable time to a discussion of heat transfer processes. The National Heat Transfer Conference, organized as an annual event by the American Society of Mechanical Engineers and the American Institute of Chemical Engineers, was held in August, 1960, at Buffalo, with an attendance of almost 1000 persons in twelve crowded sessions. A forum for discussion of heat transfer problems on an international basis will be provided by the International Heat Transfer Conference which will be held in September, 1961, at Buffalo. The preceding international conference, held at London in 1951, brought together scientists and engineers from all nations engaged in heat transfer research. The present magazine, the *International Journal of Heat and Mass Transfer*, started publication in 1960. A number of new books present either an introduction to or a cross-section through the present state of the field of heat transfer or related areas (Table 1 in Reference Section).

We have introduced in this review a new section discussing thermodynamic and transport properties because such properties are more and more intimately connected with heat transfer considerations. The available space permitted only the coverage of fluid properties on the basis of a small number of selected papers. They contain correlations and analytical predictions for a range from 3° to 15 000°K; whereas experimental determinations were mainly restricted to temperatures below 1300°K.

A significant increase in the number of papers dealing with radiation becomes immediately apparent by a comparison with last year's review.§ It obviously is caused by the fact that space applications have generally to rely on radiation for energy transport. Surface-to-surface heat transfer is analyzed for a number of geometries, including various types of heat exchangers, and calculation methods for radiative transfer in gas-filled enclosures have been developed.

Papers on heat conduction are almost exclusively of an analytical nature dealing with composite layers, transient condition, and variable properties.

In the field of channel flow, the Graetz problem with its variants is discussed in 15 papers. Experiments cover special fluids like CO_2, hydrogen, and N_2O_4, as well as swirling flow. Boundary-layer analysis was mainly restricted to the development of approximate solutions. Chemical reactions with finite reaction rates (mainly restricted to a Lewis number

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equal 1) and the influence of magnetic fields were included. Several reports describing experiments on various models in supersonic or hypersonic flow have found their way into the open literature. Detailed observations and measurements have made it possible to develop analytical models for the description of flow and heat transfer in separated regions. This development has been favored by the fact that engineering interest now includes low Reynolds number flow which is more amenable to an analytic approach. A fairly well developed model describing qualitatively the transition process from laminar to turbulent flow has evolved from flow observations and hot wire measurements.

A significant engineering advance in the effort to obtain high heat transfer coefficients for evaporation and condensation processes has been possible by selection of proper geometries (Fig. 2). A considerable number of papers, mainly experimental, covers the area of heat transfer with change of phase, obviously due to the complexity of this process which prevents analytical predictions in most cases.

CONDUCTION

The problem presented by conduction, steady and unsteady, through a composite wall received increased attention. Extending the generalization of classical problems in heat conduction to include the composite layer case [34A], Vodicka also considers the steady temperature distribution in the specific geometries of an infinite plate [35A] and hollow, infinite, circular and elliptical n-layered cylinders [36A]. A semi-infinite, 2-layer body of uniform temperature suddenly encounters a fluid of different temperature [26A] where the heat transfer between fluid and surface is described by a constant film coefficient. Out of a concern for designing a thermal barrier, [31A] uses separation of variables and matrix methods to solve the case of a 2-layer slab, one face of which is adiabatic, the other subjected to sinusoidal temperature variation. It is noted, [5A], that the problem is solvable for a triangular heat impulse through analogy with an appropriate electrical circuit. Steady-state temperature distribution and calculated heat transfer through honeycomb-type sandwich panels for simultaneous radiation and conduction agree to within 15 per cent of experimental values [32A].

Concern with solutions for unsteady state heat conduction problems continues. Thus, for a semi-infinite medium, [6A, 4A] impose boundary conditions involving temperature in a non-linear manner which, in some cases, lead to an integral equation for the surface temperature; [25A] imposes various heat inputs over the surface; and [15A] presents a scheme for computing thick wall temperatures for arbitrary variations of adiabatic wall temperature and heat transfer coefficient. The heating of a plane wall behind a constant velocity plane shock moving parallel to it into a stagnant gas is accurately represented by integral equations solved by successive approximations [33A]. Several approximate solutions for the melting of a semi-infinite slab are noted and compared to exact solution by [8A]. Cooling of solid particles in a fluid by suitable assumptions reduces to system of linear, simultaneous equations with constant coefficients, solvable as eigenvalue problem [24A]. For transient heat conduction in hollow cylinders and slabs, [14A] presents dimensionless temperature for range of heat input for isotropic, constant properties, adiabatic boundary conditions. Disregarding evaporation, [18A] investigates the unsteady temperature and humidity fields in the vicinity of an infinite plate. For variable properties, [13A] considers conduction through a semi-infinite gas medium having a uniform initial and constant boundary temperature, determining integrated air thermal conductivities for oxygen dissociating temperatures.

Additional transient studies, involving melting or freezing, arise from diverse sources. Thus, after onset of melting, [7A] describes simple successive approximation solution of ordinary, non-linear, differential equations which permits the heat input to be arbitrarily varied to a semi-adiabatic slab. The melting rate of a finite slab (initial temperature uniform and below melting point, one face adiabatic or constant temperature) for constant heat input is solved approximately by the heat balance integral [11A]; Ref. [20A] extends previous work to include melting effect; and [19A] removes the prior condition that a molten region exist. Heat flow into an infinite, homogeneous medium from a moving heat source, represented by a finite cylinder with time dependent radius, is determined [1A] with specific application to secondary oil recovery by underground combustion. A related cooling problem [16A] concerns the steady addition of metal at uniform temperature to an isothermal liquid metal column of different temperature, the bottom temperature of which is constant. Treating conductivity as arbitrarily temperature dependent, [10A] considers transient conduction in a cylinder with one moving boundary using infinite differences and applies results to re-entry problem.

Transient conduction, with heat source, is examined for the case of a cylindrical, isothermal source in a semi-infinite body of constant boundary temperature using integral equation method to yield temperature field and heat flux [17A]. The transient temperature distribution in a uranium rod depends on heat source and removal rates according to [21A]. In the same vein, [28A] examines the two-dimensional heat conduction problem for a uniform volume heat source, cooled by fully developed flow of coolant in circular passages arranged in triangular or square array. The generalization of heating and cooling rates, when the temperature rate of change describes all points in the system and is not influenced by the original temperature distribution, has application to temperature measurements and thermal behavior of complex systems [9A].

Steady state heat conduction in a circular cone with initial, non-uniform, surface temperatures is solved rigorously by [23A]. Ref. [29A] solves numerically the steady, linear, conduction equation when heat generation and conductivity are arbitrary functions of temperature. Using a heat balance error to correct the choice of gradient at the surface, [27A] gives steady-state results for a bar losing heat by radiation. An implicit numerical method for solving the two-dimensional conduction equation includes exact solution in linear case and uses iterative scheme to extend method to non-linear cases [2A].

Variations and extensions of the fin problem occur in [22A] which considers thin, rectangular, triangular, and optimum fins with internal heat generation and in [12A] which discusses the relation between heat transfer and thermal stress in fins. In this connection, [37A] notes the effect of unsteady thermal stress fields upon the formulation of the conduction equation.

Reference [30A] considers the inverse problem of heat conduction: to determine the surface heat flux knowing an internal temperature variation with time. The numerical methods are developed for spheres but apply to other simple geometries.

Finally, [3A] treats the problem of predicting, and correcting for, temperature disturbance caused by thermocouples placed beneath a surface of a heat sink (or calorimeter) exposed to heat flux during re-entry.

CHANNEL FLOW

Laminar heat transfer in the thermal entrance region of ducts continues to be of analytical interest. The classical Graetz problem, in which a hydrodynamically-developed isothermal flow enters a heated section of duct, has been analyzed by new calculation methods and for a broader class of boundary conditions. The eigenvalue problem associated with the solution of the energy equation for the parallel-plate channel or circular tube with uniform wall temperature has been solved to ten figure accuracy [6B]. This same method of analysis is applied to prescribed symmetrical or unsymmetrical heat transfer at the walls of a parallel-plate channel [7B, 8B, 9B]. The effect of heat conduction from the heated fluid into the unheated starting length is examined for a parallel-plate channel and found to be important only at low Peclet numbers [2B]. More accurate solutions of the energy equation very near the entrance section of tubes and channels were obtained by abandoning the eigenvalue approach in favor of a boundary-layer formulation [26B, 25B].

Problems of the Graetz-type have been considered for laminar flow in non-circular ducts. In one case, the eigenvalue problem for a square duct was attacked by a variational method [36B]. In another, the eigenfunctions for a rectangular duct were expanded in terms of slug-flow eigenvalues [14B]. An attempt has been made to bring together laminar heat transfer results for various non-circular ducts, but notational difficulties make the final correlations difficult to interpret [39B].

As a variant of the Graetz problem, the simultaneous development of velocity and temperature distributions in the entrance region of tubes and ducts has been analyzed [35B, 29B, 38B]. The first two of these are highly theoretical and are not easily applied. However, [38B] presents Nusselt number results in a relatively simple form and these show favorable comparison with air data [4B].

Fully-developed laminar heat transfer is analyzed in annuli with blowing and suction for the condition of constant longitudinal mass flow [20B]. A circumferentially variable heat flux may lead to large circumferential variations in wall temperature [30B].

Two interesting problems in laminar heat transfer in tubes relate to the effects of non-isothermal chemical reactions [10B] and to non-Newtonian viscosities [28B]. In the latter case, correlations are given with an accuracy of $\pm$10–15 per cent for flow in tubes having uniform wall temperature.

In contrast to the purely analytical studies for laminar flow, the turbulent case has been treated both analytically and experimentally. For flow in tubes, analytically-derived Nusselt numbers for both the entrance and fully-developed regions are only slightly different for the boundary conditions of uniform wall temperature and uniform wall heat flux when the Prandtl number $\geqslant 0{\cdot}7$ [34B]. An analysis gives heat transfer results when there is an internal heat generation in the flowing fluid [33B]. A critical review of the analogies between heat, momentum, and mass transfer resulted in a correlation for turbulent heat transfer in smooth tubes covering Prandtl (or Schmidt) numbers between 0·46 and 3000 [27B]. Experiments were made on the turbulent flow of gaseous hydrogen in circular tubes at high pressures and high heat fluxes [17B, 24B]. The results could be correlated by Dittus–Boelter type formulas, provided that the fluid properties were properly evaluated. An extensive experimental program covering the Reynolds number range 20 000 to 250 000 produced data for heating and cooling of air and carbon dioxide with large gas-to-wall temperature differences [41B]. It was found possible to correlate data for the low-temperature dissociating system $N_2O_4 \rightleftarrows 2NO_2$ by using suitably-averaged equilibrium properties and a mean kinematic viscosity in the Reynolds number [5B]. Thermal entrance region effects were clearly delineated in an experiment with air in the transition and low turbulent regimes [16B]. In a fundamental experimental study, temperature and velocity profiles were measured in the thermal entrance region of a circular tube (hydrodynamically-developed velocity) [1B]. Eddy diffusivities for momentum ϵ_m and for heat ϵ_h were computed from the data, and the ratio ϵ_h/ϵ_m was found to be almost constant across the section, but rose to high values ($\sim$3 or 4) near the wall. A complementary analysis of the distribution of the radial heat flux [11B] was found useful in analyzing the data.

Turbulent heat transfer in non-circular ducts has been studied. Calculation of heat transfer at one wall of a parallel plate channel (other side insulated) by using the *heated* periphery in the evaluation of the hydraulic diameter was analytically explored and found to apply only for Prandtl number = 2 [19B]. A critical survey of heat transfer data for the annulus led to the conclusion that heat transfer at the outer pipe surface is calculable using the hydraulic diameter with *wetted* perimeter, but that there is no simple rule for the inner pipe [40B]. Analytical heat transfer predictions for turbulent flow in equilateral triangular and square cross-sections were calculated by applying generalized velocity and temperature profiles from circular tubes [13B]. Experiments for air flowing in an electrically-heated duct of isosceles triangular cross-section (11·46° apex angle) reveal thermal entrance lengths in excess of 100 diameters, in contrast to 10–20 diameters for the circular tube [15B].

Unsteady laminar and turbulent heat transfer results corresponding to prescribed time-variations of tube wall temperature were derived by solving the time-dependent energy equation for the fluid [32B, 37B]. Another approach assumes that the turbulent heat transfer coefficient is unchanging with time and position and computes the temperature response of the fluid and tube wall to changes in internal heat generation in the wall [3B]. An experiment ($Re < 2200$)

demonstrates that large increases in heat transfer can be attained by vibrating a duct wall normal to the direction of the main flow [31B].

Several interesting studies relating to swirling and vortex flows were carried out. Experiments with water and air flowing through pipes with several types of inserts and swirl promotors show both large increases in heat transfer and reductions in the pumping power per unit heat transfer [21B]. Additional experimental results on this same problem are also reported in [18B]. Electrically-heated rotating tubes and annuli with throughflow, some running full and others partially filled, provided heat transfer data for water characterized by three distinct flow regimes depending on rotational speed [22B]. The throughflow Reynolds number was under 1000. Two analytical treatments of the vortex tube have appeared, neither fully predictive. In one, an inviscid flow model is assumed which combines a vortex, a sink, and a uniform axial flow [23B]. In the second, a turbulent compressible vortex is postulated in which $\rho\epsilon$ (ρ = density, ϵ = eddy viscosity) is assumed constant, with ϵ undetermined [12B]. It is concluded that energy separation is primarily caused by the turbulent shear work.

BOUNDARY-LAYER FLOW

Boundary-layer solutions

The main emphasis in recent boundary layer heat transfer analysis has been on approximate solutions and calculation methods. However, some work relating to exact solutions and classical-type problems continues. Among these, the requirements for similar solutions of the energy equation were examined for laminar flow [58C]. If the wall temperature is uniform or varies according to a power law, the similarity requirements are identical to those for the velocity problem. Adiabatic wall temperatures for laminar flow of high Prandtl number fluids over a flat plate have been re-examined [37C] and more accurate results calculated. An analysis has provided the heat transfer response of a cylinder or sphere immersed in a fluctuating laminar flow with small mean velocity [27C]. There has been further study of the wall jet (a free jet bounded on one side by a wall) relating to compressibility and heat transfer characteristics [5C]. A study of Reynolds analogy for the laminar flat-plate boundary layer with blowing reveals that the ratio of Stanton number to friction factor increases with the blowing velocity [20C]. Mangler's transformation, which reduces axial-symmetric boundary-layer problems to plane problems, has been successfully applied in the analysis of the high-speed, compressible boundary layer on a cone and results were obtained utilizing prior flat plate solutions [23C]. The unsteady flow and heat transfer on a flat plate moving with time-dependent velocity into a compressible fluid has been attacked using a series-expansion method [19C].

The calculation of heat transfer from non-isothermal surfaces continues to be of interest. A set of variable wall temperature solutions for laminar and turbulent flow over a flat plate is tabulated [4C]. Application is made to laminar flow over a plate whose surface has two separated isothermal zones and is otherwise insulated; mass transfer experiments with naphtalene agree well with the theory [53C]. Lighthill's superposition integral for computing laminar heat transfer with variable wall temperature and variable free-stream velocity has been generalized to include the effects of aerodynamic heating [34C].

The compressible laminar boundary layer with variable free-stream velocity and isothermal wall has been analyzed to various degrees of approximation. In one case, Stewartson's transformation is used to reduce the compressible conservation laws to those for an incompressible fluid and a series solution obtained [42C]. In a second study, the energy equation is eliminated by writing the temperature as a quadratic function of the velocity, which is in turn approximated by a quintic polynomial in the normal coordinate [16C]. Practical calculation procedures for determining the laminar heat transfer on blunt hypersonic vehicles are presented in [41C] and [65C].

An initial study of laminar non-Newtonian boundary-layer flow and heat transfer is based on the assumption that the shear stress is proportional to a power of the velocity gradient [1C]. For the flat plate, it was found that although the velocity solutions obeyed similarity, the temperature did not. Also of particular interest are the finite-difference solutions for axially-symmetric blunt bodies which were carried out without similarity assumptions [33C]. Laminar flow and heat transfer on a flat plate with wedge-shaped grooves in the flow direction was analyzed by the Kármán–Pohlhausen method [28C]. Relative to laminar flow over a plane plate, the grooves lead to an increased heat transfer.

Turbulent boundary layers continue to resist exact solution, but there is considerable activity in finding approximate results. Deissler's eddy diffusivity expressions form the basis of an analysis of high-speed flat-plate flow and heat transfer under conditions of variable fluid properties and frictional heating [17C]. Results are given for Mach numbers up to 20. Another approach to this same problem starts by analyzing velocity data and obtains the variation of the shear across the boundary layer [54C]. This information is then utilized to integrate the energy equation for the flat plate [54C, 55C]. This same paper [55C] evolves a relationship between compressible and incompressible turbulent boundary layers with pressure gradient and Prandtl number not equal to unity. The turbulent compressible boundary layer over a slightly yawed cone is made tracable by assuming 1/7-power laws for the velocity distribution and a modified Blasius shear law [7C]. For a highly-cooled, blunt-nose body under hypersonic conditions at an angle of attack, it is demonstrated that the cross-flow velocity is negligible and that heat transfer is calculable by two-dimensional methods [62C]. A relatively simple relation for calculating turbulent heat transfer on a blunt body has been derived by postulating a simple, but unsupported, relation between enthalpy thickness and momentum thickness [64C].

Three interesting Russian papers relating to approximate heat transfer calculations have recently appeared in the literature. For the laminar boundary layer with arbitrary free-stream velocity, a method is proposed in which successive moments of the energy equation are taken [51C]. Various form factors (i.e. thickness parameters) are needed and these are obtained from flat plate and wedge-flow solutions. A second study treats the same problem, but extends consideration to laminar, transition, and turbulent flows [68C]. An integral analysis is utilized, and this is implemented by a semi-empirical law for the convective thickness. The final results require a knowledge of the locations at which transition begins and ends. A third paper considers the heretofore-neglected effects of density fluctuations on compressible turbulent flow and heat transfer about a flat plate [32C].

Dissociation and chemical reactions

Fourier's equation, describing heat conduction in a medium with variable heat conductivity, can be made linear by introduction of a heat flux potential defined as the integral of heat conductivity over temperature. This equation is used to study analytically unsteady heat transfer in a stationary gas with chemical reactions [26C]. A considerable number of papers are concerned with the prediction of laminar heat transfer to high-speed objects, like missiles or satellites, moving or re-entering through the atmosphere. The air surrounding the object is then heated to such a degree that dissociation of the molecules may occur. The problem to determine whether chemical equilibrium or frozen condition with regard to dissociation of oxygen exists is investigated by a comparison of a characteristic residence time of the atoms within the boundary layer to a characteristic chemical reaction time [2C]. The simultaneous effect of a finite recombination rate of oxygen atoms and of fluid injection has been calculated for Couette flow and for a flat plate of infinite extent suddenly set in motion (Rayleigh's problem) [9C]. A similar calculation using an integral method and the assumption that Prandtl and Lewis numbers are equal to one and that the dissociation is a second order reaction gave the result that for Mach numbers between 10 and 20 and a flight altitude of between 50 000 and 200 000 ft, equilibrium is never approximated within the boundary layer on an adiabatic flat plate [11C]. A similar calculation for flow over blunt bodies is reported in two papers [61C, 12C]. Re-combination may also occur on a catalytic surface even when the dissociation is frozen within the boundary layer itself. A calculation of such a situation assumes a first order surface re-combination, a constant Schmidt number, constant wall temperature and a gas for which the product of density times viscosity is constant [10C]. The results are well approximated by a simple empirical equation. The postulate of local similarity and use of constant property relations, into which the properties are introduced at a reference enthalpy, leads to heat transfer information which is in good agreement with the results of more involved boundary-layer solutions [18C]. Tables have been prepared from which laminar skin friction and heat transfer parameters can be read for flow of air with equilibrium dissociation over flat plates at angles of attack from 0 to 50°, for wall temperatures from 1000° to 3000°R and free stream velocities of 10 000 to 28 000 ft/s [48C]. Simple relations for the properties of a dissociated gas with frozen chemical composition are reported [22C].

The chemical reaction of a gas released from a surface with a gas flowing in a laminar boundary layer over the surface occurs in a narrow reaction zone, provided the reaction rate is very rapid. The location of this zone is calculated, assuming a gas with Prandtl and Schmidt numbers equal to one and with a constant product of density and viscosity [21C]. A corresponding experimental study has been reported [36C]. The derivation from basic principles of the energy equation of a chemically reacting gas flowing at a low density over a surface indicates that energy transport caused by shear work at the surface has to be considered when slip occurs at the surface [47C].

Magnetohydrodynamics

An excellent introduction into magnetogasdynamics and its possible aeronautical applications discusses the use of magnetic fields to modify the forces and heat transfer on objects exposed to the flow of a conducting fluid [50C]. Air is becoming electrically conducting by ionization at sufficiently high temperatures. The electric conductivity can also be increased by seeding with caesium or potassium. The influence of a magnetic field on heat transfer has been calculated for a number of various geometries and laminar flow situations: flow between two infinite parallel plates with the plate temperature varying stepwise in flow direction and with a magnetic field normal to the plates [39C]; hypersonic flow in the region of a 3-dimensional stagnation point [30C]; wedge-type flow resulting in similar solutions for proper boundary conditions [31C]; flow past an infinite porous flat plate in the presence of a transverse magnetic field and with fluid ejection [25C]; steady and transient free convection on a vertical plate with a transverse magnetic field [24C]; convective motion of a conducting fluid between parallel vertical plates [44C]; free convection in the layer between a lower heated and an upper cooled surface [38C]; free convection of mercury in a closed circular tube with a transverse magnetic field [52C]. The calculations re-confirm the fact that heat transfer can be decreased by the proper application of a magnetic field. However, very large fields are required to get a reasonable reduction. The analogy between the magnetic vector potential and the temperature field, which exists when the electric field in the flow is zero or negligible, has been utilized to obtain information on the magnetic field for various geometries [35C]. The stability of laminar flow in a boundary layer or channel and the influence of a magnetic field has been analyzed by an extension of Tolmien's method [46C]. In general, a magnetic field stabilizes the flow except for conditions where it creates velocity profiles with inflection points. One of the rare experimental studies in magnetofluidmechanics is reported [6C]. A hemispherical model of an eutectic alloy of bismuth with 117°F melting temperature was exposed to a stream of hot water and the melting process was filmed. A coil around the model support and a 6 V battery generated a magnetic field of 5000 G in the water. The velocity in the molten layer decreased and the thickness increased when a magnetic field was applied. A preliminary report [56C] describes experiments on heat transfer to a water-cooled copper tube exposed to a carbon arc discharge with 7000°K temperature or a water plasma jet with 14 000°K. Heat flux densities of 10^6 W/m^2 and 10^8 W/m^2, respectively, have been measured.

Experimental investigations

A considerable number of papers reported on experimental investigations measuring heat transfer in supersonic flow to objects with various geometries. Use of a shroud with proper design, surrounding the model, gives the possibility to investigate large models in wind tunnels with restricted cross section [15C]. Laminar heat transfer on a cylinder normal to rarefied flow was found to be in good agreement with predictions by Lees' method [60C]. Use of the reference enthalpy method and flat plate relations based on local conditions described satisfactorily turbulent heat transfer on blunt objects [15C]. Simple approximate expressions were developed describing the maximum turbulent boundary layer heating rates on a hemispherical nose [3C]. Experiments on heat transfer in Laval nozzles with flow of superheated steam gave good agreement with a turbulent boundary-layer method by Bartz but showed considerable deviations from tube flow relations [43C]. Measurements on heat transfer to cones arranged in supersonic flow with Mach numbers between 2 and 5 and with various angles of attack [8C, 29C, 59C] indicate that heat transfer at the stagnation line increased up to four-fold with increasing angle of attack. The heat transfer in the separated region was sometimes found to be as large as the heat transfer at the stagnation line. Skin friction in a compressible turbulent boundary layer on a cone is reduced by the injection of air, or Freon-12 and especially of helium [40C]. The reduction was found to decrease with increasing Mach number. The effect of surface cooling on boundary-layer transition was studied on a 15° cone at a Mach number 4 [66C]. Heat transfer to the leading edge of a wing exposed to a high Mach number flow can be considerably reduced if the leading edge is arranged oblique to the flight direction [14C]. Experiments on turbulent heat transfer from a non-isothermal flat plate established the following relations

$$St_T = 0{\cdot}0296\, Re_x^{-0{\cdot}2}\, Pr^{-0{\cdot}4}\, \frac{T_\infty^{0{\cdot}4}}{T_w}$$

(St_T = Stanton number, Re_x = Reynolds number, Pr = Prandtl number, $T\infty$ = upstream fluid temperature, T_w = plate surface temperature) for a constant wall temperature and

$$St/St_T = [1 - (\xi/x)^{9/10}]^{-1/9}$$

describing the Stanton number at location x for a wall temperature which changes at location ξ from T_∞ to T_w [45C, 13C]. Experiments on heat transfer near a convex corner normal to the flow direction [67C] and near a concave corner parallel to the flow direction [57C] were reported. In the latter situation, laminar heat transfer was found to be up to 50 per cent higher near the corner due to shock boundary-layer interaction. Turbulent heat transfer was not influenced by the vicinity of the corner. Free stream turbulence produced by a screen had the following effect on local heat transfer to a cylinder normal to the flow direction: laminar heat transfer increased, transition Reynolds number was reduced, transition in the separated boundary layer occurred earlier, and the low temperature recovery factor at the rear of the cylinder disappeared [49C]. Local heat transfer coefficients on a surface, on which an air jet impinges normally, have been measured [63C]. Some peculiarities of the results are probably caused by the specific test configuration.

FLOW WITH SEPARATED REGIONS

Analytical and experimental studies in the recent past have considerably increased our understanding of the heat transfer process in a separated region. The separated boundary layer behind a step in the surface contour can either be laminar or turbulent. Heat transfer measurements [9D] in the region of a separated flow with laminar boundary layer agreed well with an analysis by Chapman. In flow with a turbulent separated boundary layer, experimental heat transfer coefficients were considerably lower than calculated [9D, 11D]. A maximum heat transfer occurs at the point where the flow re-attaches to the surface. The average heat transfer coefficients are, however, considerably lower for separated flow than for attached boundary layers. This suggests the possibility to utilize separated flow at locations where one wants to have a small heat transfer, for instance, on high velocity aircraft or satellites. The shroud technique described in the boundary-layer section has been successfully applied to study heat transfer on the downstream part of blunt objects [2D]. Accommodation coefficients and Nusselt numbers have been determined for hypersonic gas flow normal to a cylinder from the free molecule to the continuum regime [13D] and also for a fluid with small Prandtl number [1D].

Pebble bed heaters are widely used to generate a high temperature gas stream, for instance, for supersonic wind tunnels. Experiments on such a heater [8D] established the following relation for the heat transfer to the packed alumina spheres in the heater

$$St\,Pr^{2/3} = 0{\cdot}400\,Re^{-0{\cdot}437}$$

(St = Stanton number, Pr = Prandtl number, Re = Reynolds number). This relation is surprisingly close to the one for a single sphere. Experiments were also concerned with heat transfer to the wall surface in a packed bed [14D] as well as in the bed itself [4D]. An analysis on laminar flow through a pebble bed heater with internal heat generation (nuclear reactors) established the tendency to develop hot spots [5D]. A similar analysis allows calculation of the unsteady temperature distribution in a packed bed for any initial temperature distribution and temperature variation of the entering gas [7D]. Heat transfer coefficients from a moving bed of quartz sand to the walls of a circular tube have been established [6D]. Measurements on heat transfer to the particles in a fluidized bed [10D, 3D] established heat transfer relations and a survey of previous experiments on heat transfer between a fluidized bed and a vertical tube resulted in two correlations, one for fine particles with predominantly viscous flow and another one for coarse particles with predominantly inertial forces [12D]. Considerable deviations between the results of the various experiments demonstrate the relatively poor knowledge of this flow and heat transfer process.

TRANSFER MECHANISM

Knowledge of the laminar or turbulent state of the flow and of the transition location is one of the most important prerequisites to a prediction of heat transfer. Visual observation and hot wire measurements contributed strongly to our understanding of the transition process [6E, 3E, 5E, 8E, 13E, 9E]. The following model of the transition process has evolved from these studies: Transition is usually initiated by instability waves which amplify in downstream direction and roll up into vortices. Such vortices with straight axes in shear flow are unstable and deform in the way that the axis builds loops. At the loops, the fluctuations are especially intense and cause the vortex to break down rapidly into finer and finer vortices (turbulent spots). This transition process occurs also in a separated laminar boundary layer [10E]. The reverse transition from a turbulent into a laminar boundary layer can occur under specific situations [14E]. The effect of an isolated [1E] or distributed [17E] roughness on transition in a supersonic flow can well be characterized by a roughness Reynolds number based on roughness height and velocity at roughness height for subsonic flow or sound velocity corresponding to the state at roughness height for supersonic flow. A shock tube is an excellent tool to study heat transfer and boundary-layer transition at high Mach numbers and temperatures [7E]. The turbulence intensity at the center of a flame holder plane was found to decrease when the ratio of mean free path length to Kolmgoroff scale exceeded a value 0·01 [11E]. Analytical work on the transition process has proceeded [4E] and it is claimed that it now predicts the end of transition as well as its initiation [15E]. The theory of decaying homogeneous turbulence was improved by inclusion of quadruple correlations [2E]. The ratio of eddy diffusivities for momentum and heat is predicted as one by an analytical study [16E]. Van Driest's relation for the friction factor for turbulent flow near a wall is extended to flow at high Mach numbers and large temperature differences [12E].

NATURAL CONVECTION

Analytical and experimental activities covering a broad range of problems in natural convection and combined natural and forced convection have been reported. Among the analytical studies, boundary-layer problems continue to be of interest. The wall temperature variations which permit steady and unsteady similarity-type boundary layers were examined [42F] in a formal manner, but without numerical solutions. Two improvements in the integral method of solution (i.e. Kármán–Pohlhausen) are proposed. In one, velocity and temperature profiles are used which contain both exponentials and powers of the distance from the wall [9F]; while in the second, the boundary layer is subdivided into two zones depending on the relative importance of various transport mechanisms [4F]. Generalization of a previous integral solution is made to provide the wall temperature corresponding to an arbitrary variation of wall heat flux [1F]. The natural convection in a heated plume (jet) which rises above a horizontal wire has been analyzed by similarity solutions [5F, 34F]. Blowing or suction through a vertical isothermal plate ($v_w \sim x^{-1/4}$, x vertical) is found to significantly alter the heat transfer [6F]. An integral method is utilized to study the effects of a horizontal magnetic field (B = magnetic intensity $\sim x^{-1/4}$) for the case of an isothermal vertical plate [15F]. Conditions have been derived under which unsteady natural convection in gases can be treated as quasi-steady [37F].

Several papers relating to the analysis of combined natural and forced convection have appeared in the literature. The flow and heat transfer in a vertical tube with a linear temperature gradient in the vertical direction has been solved (once again) by direct mathematical methods [26F]. A new approach appropriate to this thermal boundary condition uses complex variable theory and is illustrated for circular [38F] and rectangular [39F] cross sections. Another method for this type of problem is based on successive use of finite Fourier and Hankel transforms [23F] and solutions are given for the circular sector. Analytical studies have been performed to determine the interaction of a transverse (i.e. horizontal) magnetic field on the flow in a vertical tube [35F] or parallel plate channel [33F]. A correction formula for small buoyancy effects in fully-developed laminar flow and heat transfer in a *horizontal* tube has been found to involve the product of the Reynolds and Rayleigh numbers [27F]. Buoyancy effects have also been studied for low Reynolds number flow about a sphere for both aiding and opposing conditions [21F].

Further analyses have covered a variety of subjects. The thermosyphon, which is a heated tube closed at the bottom and open at the top to a cooled reservoir, has been studied for the condition of a small angle of tilt relative to the vertical [22F]. A small increase in heat transfer is predicted. Closed-loop natural convection inside a horizontal cylinder whose temperature varies sinusoidally over the surface is analyzed by an integral method assuming a boundary layer near the wall and a rotating core [10F]. A mathematical study has been made of the uniqueness of solutions for weak (low Grashof number) convection [8F]. The hot gases produced by a fire experience an upward buoyant force. The characteristics of the ensuing turbulent natural-convection flow are predicted for a fire of arbitrary size in an atmosphere of arbitrary lapse rate [28F]. An order of magnitude estimate leads to the conclusion that natural convection caused by centrifugal forces (e.g. internal cooling of turbine blades) can be important even if the forced-convection mainflow is turbulent [43F]. A new correlation formula

$$Nu = 0{\cdot}11\,(Gr\,Pr)^{1/3} + (Gr\,Pr)^{0{\cdot}1}$$

is proposed [16F] for predicting overall heat transfer from vertical plates and horizontal cylinders over the Grashof–Prandtl range from 10^{-7} to 10^{12}.

Considerable interest, both analytical and experimental, continues in the Benard problem, wherein a thin horizontal layer of fluid is heated from below. For sufficiently large temperature differences, the quiescent state becomes unstable and fluid motion in various cellular patterns sets in. A non-linear theory is advanced to explain the preference for hexagonal cells [31F]. For such a cell pattern, the streamline pattern at the point of instability has been derived [32F]. The heat transfer through such a flow has been determined [29F] and the effects of a superposed magnetic field studied [29F]. When the heated layer is subjected to a time-dependent body force, the Rayleigh number at which instability sets in is found to be much higher than in the steady case [11F]. Another interesting variant of the Benard problem is the superposition of a rotation about the vertical axis of the heated fluid layer. If a metallic liquid such as mercury is thus heated and rotated, the flow pattern at the onset of instability is characterized as overstable oscillations. The characteristics of this flow pattern are explored experimentally [30F] and the heat transfer determined [13F].

A very large increase in free convection heat transfer near the critical point has been reported in past investigations. Additional experiments to explore this phenomenon have recently been undertaken. In one test, an electrically heated horizontal wire was immersed in Freon-114A [14F]. Visual observations at pressures beyond the critical revealed bubble-like aggregates (Fig. 1), but there was no large heat transfer increase as in nucleate boiling. A second experiment carried out with Freon-12 in a natural-circulation loop also failed to find dramatic increases in heat transfer [17F].

Several experiments on unsteady free convection are reported. A vertical plate immersed in water was subjected to a step-function change in wall heat flux [12F]. Interferometric studies of the temperature field revealed that during the transient, the boundary layer overshot its steady state thickness; but, there was no marked overshoot of the wall temperature. The question of whether the transient surface temperature can overshoot the steady state value was further explored with the aid of an electric circuit analogue [2F]. This apparatus was used to analyze overshoot data from an electrically heated wire immersed in a sucrose solution [3F]. Disturbances have been set up in a free convection boundary layer by periodic pulsing with a fine heated wire, and the resulting boundary layer oscillations observed with an interferometer [18F, 19F]. Photographic techniques have also been used to observe the effect of a sound field on free convection about a horizontal cylinder [7F]. Above a certain critical sound pressure level, a flow pattern characterized by the presence of two vortices above the cylinder is formed.

Steady-state natural convection experiments have been carried out for a variety of configurations. The utility of the interferometer as a research tool is discussed and illustrated by photographs of the temperature field about various plates and cylinders [36F]. The measured effect [24F] of tilting a liquid-filled thermosyphon is to decrease heat transfer for small tilt angles (in contradiction to Ref. 22F) and to increase heat transfer at larger angles of tilt. Steady-state heat losses from an inclined tube, heated at the base and filled with air, are reported as a function of inclination angle, tube diameter, and wall conductivity [20F]. No consistent trend with angle is apparent. Temperature distributions and heat transfer have been determined for natural convection within a horizontal cylinder, the two vertical halves of which are maintained at different temperatures [25F]. A detailed investigation of the mean and fluctuating temperatures above a horizontal heated flat plate was performed to gain insight into the structure of the turbulent convection [40F]. The heat transfer characteristics of spheres, both for purely natural convection [41F, 44F] and for combined natural and forced convection [44F], have been furnished by experiment.

CONVECTION FROM ROTATING SURFACES

By extending a previous analysis for a rotating disc, an approximate evaluation of the effect of curvature on the laminar heat transfer from a rotating spherical cap has been investigated [1G]. The theory which is valid for large Prandtl numbers allows an arbitrary meridional distribution of surface temperature. Another study [4G] relates to the heat transfer by laminar flow from a rotating sphere and thus also examines the curvature effect.

A rotating disc with mass injection or suction at the disc surface has been investigated [5G]. Laminar results are given for the velocity, temperature and mass-fraction distributions as well as for the heat transfer, mass transfer, and torque requirements. Asymptotic solutions are given for large suction velocities and it is shown that fluid injection sharply decreases the heat transfer at the disc surface.

An infinitely long rotating circular pipe has been investigated under the conditions of constant rotational speed and a constant axial temperature gradient [2G]. The effects of compressiblity are examined by considering the fluid to be a perfect gas. Another internal flow situation, the motion of a fluid inside a rotating annulus of square cross section, has been studied [3G]. The inside annulus dimensions are taken to be small compared to the distance from the axis of rotation, and the side walls are held at different constant temperatures. Particular attention is paid to the cell-like flow which develops at low thermal Rossby numbers.

The final paper in this series [6G] presents an

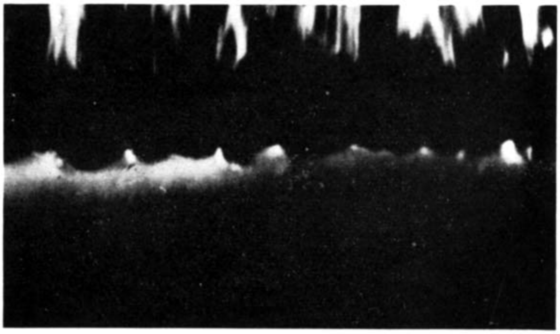

FIG. 1. Bubble-like aggregates in free convection at supercritical pressures (Ref. 14F).

FIG. 2. Mixed dropwise and film condensation on a smooth chrome-plated surface (Ref. 21J).

analysis of the cellular motions within a horizontal rotating fluid layer which is heated from below. The distortion of the cell boundaries due to rotation are described.

COMBINED HEAT AND MASS TRANSFER

Under the influence of the re-entry problem, a number of papers have been published recently which report mass transfer experiments and design criteria for surfaces under the influence of large heat fluxes. The ablation characteristics of a number of plastics reinforced with inorganic fibers are reported in [20H]. The information which was obtained in a rocket exhaust is reported as "effective heats of ablation" for the various materials. This figure of merit represents the heat absorbed per unit mass of ablated material. A discussion [16H] is given of the agreement between experiment and various analyses when Teflon is exposed to the stagnation enthalpy and pressure levels encountered in hypersonic flight. The study concludes that caution must be exercised in the prediction of mass transfer rates of chemically reacting species.

A simplified analysis is presented of hypersonic ablation in [14H] where it is concluded that the radiation heat flux is negligible compared to the heat absorbed by ablation. A calculation also illustrates the change in shape of a hemispherical nose cone during re-entry. In [10H], the results of ablation tests in a plasma discharge on copper, aluminum, stainless steel, molybdenum, zircon, mullite, alumina, linen bakelite, nylon, and graphite are reported. Heat balances and "effective heats of ablation" are included.

Ablation characteristics of clear and opaque quartz were determined experimentally in an air arc wind tunnel [2H]. Comparison of the data with the analysis of Bethe and Adams showed agreement within 8 per cent. Another analysis of stagnation point melting-ablation [1H] indicated that for glassy materials the thermal diffusivity is an important parameter when designing for minimum weight. In a paper considering sublimation in a hypersonic environment [15H], the pertinent equations are derived for the simultaneous processes of diffusion, convection, and thermal exchange and applied to the vaporization of a refractory material.

A series of studies has been reported which deal with mass injection into turbulent boundary layers. New experimental results [4H] with refined radiation-conduction corrections over previously published results indicate that the Rubesin analysis tends to overestimate the reduction in Stanton number from blowing. Another experimental study [18H] reports on sublimation mass transfer from an adiabatic sharp-edged flat plate under free stream Mach numbers of 0·43, 2·0 and 3·5. An analysis of friction and heat transfer in turbulent compressible flow extended to these low mass transfer rates shows good agreement with the experimental data.

A study of available experimental data has been carried out to evaluate various turbulent theories [8H]. Particular attention was given to the influence of the molecular weight of the injected gas on the reduction in Stanton number. An analysis [21H] is presented for injection into an incompressible turbulent boundary layer under the hypothesis that the effect of injection is restricted to the sub-layer region. Experimental measurements tend to substantiate this hypothesis and the solution for this model is particularly simple for small values of injection and contains no arbitrary parameters. A two-dimensional Laval nozzle with nitrogen injection into a nitrogen free stream has been studied [7H]. Experimental heat transfer measurements are compared to Rubesin's turbulent theory. A series of measurements has also been made [13H] of the skin friction in a compressible turbulent boundary layer on a cone. Injected gases into an air free-stream consisted of helium, air and Freon-12.

An experimental study is reported [12H] of the effect of slot injection angle in film cooling effectiveness. Data were obtained from normal hole configurations and angled slots. The effect of shock generated vorticity on mass transfer effectiveness has been investigated [9H]. It is shown that reduction in heat transfer rates due to mass injection is substantially less than boundary-layer predictions for spheres and cylinders due to this vorticity.

A laminar analysis of helium injection into air has been carried out considering the effect of a free stream pressure gradient [3H]. The influence of the pressure gradient on both the skin friction and heat transfer was investigated. Another laminar analysis [6H] considers the case where there is constant injected mass flux at the plate surface. This condition is compared to the previous cases investigated of either a blowing velocity distribution that yields a constant surface temperature or one of uniform blowing velocity. Solutions have also been presented [5H] for the compressible laminar boundary layer on yawed cylinders with transpiration cooling. The results indicate that at large Mach numbers and yaw angles an incompressible analysis underestimates the amount of coolant required.

An unusual mass transfer condition has been investigated [17H] where the injected velocity was as large as 19 times the free stream velocity. This was done by examining an evaporating liquid into a low-speed inert gas at pressures near the vapor pressure of the liquid. Another study [11H] has examined the effect of a deceleration force on a melting boundary layer which opposes the downstream flow of the liquid.

The reader's attention is called to a summary article by Professor D. B. Spalding entitled "Heat and Mass Transfer in Aeronautical Engineering" [19H]. Utilizing the mass transfer literature, Professor Spalding develops design procedures for a number of specific technical problems. Typical of the problems considered are the calculation of the rate of burning of a graphite heat shield and the rate of enlargement of the throat area of a solid-propellant rocket motor having a graphite nozzle.

CHANGE OF PHASE

The extensive experimental and analytical work in this area reflects both the broad scope and complexity of the problems.

To gain understanding of the boiling mechanism, experimental studies have examined bubble mechanics. Photographic evidence of nucleate boiling in a rectangular cross section flow channel yields expressions for bubble growth, collapse, and distribution of maximum bubble diameters which are related to bubble energy transport [33J]. Examining the problem of bubble formation in superheated liquids and drops, [22J] reports data and correlations useful in predicting conditions required for homogeneous nucleation, while [4J] gives measured bubble growth in various superheated liquids. Using aqueous solutions of surface-active agents, bubble formation was observed and the increased boiling coefficient attributed either to a decrease in dynamic surface tension or an increase in active nuclei in solution [14J]. High speed photographs show generation and growth of bubbles from a single orifice source in a liquid N_2–O_2 mixture [6J].

A step toward the economic recovery of fresh water appears in the use of thin, evaporating and condensing films (Fig. 2) to yield overall heat transfer coefficients as high as 8000 Btu/h ft^2 °F [21J]. Heat transfer coefficients for film boiling of Helium I from a single wire agree with those for other liquefied gases [7J]. The forced vaporization of water, carbon tetrachloride, benzene, methanol, and *n*-butyl alcohol in a tapered tube permits the influence of evaporation area to be evaluated [5J] and natural convection boiling results for liquid Freon-12 in a single tube appear in [20J]. Using hydrodynamical model, [36J] examines transition of water from bubble to film boiling for various values of pressure, water velocity, and subcooling. Liquid superheating shows influence on boiling coefficients [34J, 16J] depending on presence or absence of bubbles which originate from active sites determined by surface roughness [16J].

Analytical efforts consider the hydrodynamic boundary condition (i.e. temperature jump and pressure deviation from equilibrium) for evaporation and condensation [15J] and vaporization processes in the hypersonic, laminar boundary layer for a vehicle of arbitrary material [25J]. The correlation of existing data yields generalizations of heat transfer for nucleate boiling [23J, 18J].

Evaporating liquids into low-speed, inert, gas streams at pressures nearly that of the liquid vapor pressure shows the influence of high concentration gradients and evaporative velocities on mass transfer rates for the Graetz number range 0·1 to 1800 [26J]. Observation of rates of evaporation of drops containing dissolved solids in a hot air stream affords a basis for predicting spray-dryer performance [3J]. Evaporation rates predicted for small drops (diameter of order of mean-free-path of steam molecules) compare favorably with experimental data and suggests valid use for larger drops [8J]. Further drying implications are inherent in the examination of convective heat exchange between a current of hot air and a flat, wet surface [13J]. Ref. [30J] attributes the diminution of humidity of porous materials in the presence of water saturated atmospheres to capillary effects. The application of energy and mass transfer equations permits an accurate estimate of the reduction of evaporation from a water surface caused by the application of a mono-molecular film [11J].

Continuing earlier work in condensation, [19J] compares theoretical equations with experimental data for laminar and turbulent film condensation and introduces correction factors (accounting for effects of liquid inertia, convective transport, wave motion and variable properties) which give good agreement. Also part of a continuing study is the determination of the influence of vapor drag on heat transfer during condensation for Prandtl numbers 10 and 0·008 [28J]. Considering the inertia forces and energy convection terms neglected by Nusselt, [29J] performs a boundary-layer analysis of laminar film condensation on a horizontal cylinder and reports heat transfer results for the Prandtl number range 0·003 to 100. Factors examined for the influence they exert on condensation are (a) crossflow in the case of steam and steam–gas mixtures condensing on a vertical tube [9J], (b) geometry in the case of Freon-22 condensing on the outer surface of single, horizontal, smooth and ribbed tubes [27J], and (c) viscosity of condensate (water and glycerine) [37J]. Ref. [10J] presents experimentally verified equations for calculating water vapor transfer through composite walls.

Interest in burnout heat flux continues with the reporting of the influence exerted by non-uniform, peripheral heating of steam–water mixtures in vertical tubes [31J]. Further data [1J] for water in a vertical tube (8·2 mm i.d.) at varying pressures (20 to 300 atm), subcooling (0 to 140°C), and tube length (35 to 135 mm) disagree on several counts with previously published data. For the vertical upflow of water in uniformly heated rectangular, burnout heat-flux data at 2000 p.s.i.a. shows correlation with fluid mass velocity and burnout enthalpy [2J]. Further comparisons of tube burnout data for boiling water are made in [32J]. Experiments showing the hydrodynamic instability of a two phase layer are related to burnout heat flux and afford a predictive criterion [17J].

Ablation of solids (naphthalene and camphor spheres) receives photographic study in [35J, 38J], leading to the determination of local ablation rates for Reynolds number range 120 to 16 500. Analytically, [24J] examines the unsteady mass loss and energy accumulation caused by aerodynamic heating of blunt bodies.

Reference [12J] reports measured heat and mass transfer rates for the interesting case where a weak NH_3 in water solution flows down the outside of a water cooled, $\frac{1}{2}$ in o.d. tube while absorbing anhydrous NH_3 at 1 atm.

RADIATION

A unique feature of the past years' radiation literature has been the large number of papers concerned with radiation heat exchangers and the equilibrium temperature of objects in space. Some of the studies deal with a single fin exchanging radiation with specified black environment, and one paper presents an exact formulation of the multi-fin radiation problem which leads to a number of mathematical complexities.

The radiation fin efficiency for a single circular fin has been studied [9K] under the conditions of no incident radiation. Companion papers [23K, 2K] investigate a radiating rectangular thin fin which is irradiated by a uniform source. Optimum fin geometries for minimum weight are investigated. Another paper [36K] reports on the same problem with the inclusion of a discussion of meteorite puncture probabilities. Two papers [38K, 25K] discuss the important problem, as far as space applications are concerned, of the best shaped radiation fin of minimum mass. In the first paper [38K], it is shown that the best shaped fin has 61·2 per cent of the mass of a rectangular fin with the same performance. It should be pointed out, however, that these optimum shapes are always convex and no account has been taken of radiation exchange between different parts of the fin. An exact formulation of the problem of radiating fins with mutual irradiation as well as radiant interchange with nearby surfaces and the environment is presented in [14K]. The formulation leads to an integro-differential equation.

A unique type of heat exchanger for space applications is described in [37K]. A rotating circular belt picks up waste heat on one point on its circumference and radiates this heat to a sink in its travel around the periphery. The analysis of the temperature distribution in a rotating cylindrical shell which is heated on one side by the sun in space is given in [11K]. The shell is considered to have a finite thermal conductivity. A transient analysis of a similar geometry in space but without rotation and having a specified infinite thermal conductivity is reported in [28K].

Selective non-gray coatings which have a different absorbtivity for solar radiation from their emissivity value have been studied. The use of such coatings for the temperature control of satellites is discussed in [16K]. Another paper [21K] describes the preparation and high temperature stability of selective coatings that will withstand surface temperatures up to 1000°C.

The general problem of radiant interchange within an enclosure continues to receive consideration. A series of three papers [5K] presents an analysis of this situation using the radiation network method. Gas conduction is neglected. The radiation characteristics of long cylindrical cavities have been determined by numerical solutions of the governing integral equation [31K]. Thermal radiation between infinite parallel plates separated by an absorbing and emitting gas is described in [35K]. This analysis also neglects the effects of conduction in the gas. Equations of radiative transfer in gases are formulated for the one dimensional case to include radiation exchange with solid boundaries [15K]. An example of the solution of these equations is given for an infinite flat layer of gas bounded by parallel plane surfaces. In this analysis, the effects of gas conduction are considered.

The four dimensional heat flux integral for diffuse radiation between two surfaces separated by an absorbing gas is considered in [26K]. The complex integral is transformed into a sum of one dimensional integrals for the case of opposite-parallel and adjoining-perpendicular rectangles. The results are suitable for numerical integration techniques. Analytical relations have been obtained [20K] which suggest an experimental procedure for the determination of radiation geometric factors as well as the radiation properties of the surfaces involved.

A new approach to the formulation of the radiation transport equation is described in [12K]. The method involves replacing the standard spectral absorption coefficient with an error function absorption coefficient. The advantages gained are that the error function coefficient is well behaved and has been measured for a number of gases. The paper describes how to rewrite the radiation transport equations in terms of the new coefficients.

A "three measurement" method of measuring the spectral emmisivity and temperature of solid surfaces has been described [33K]. Involved in the procedure is a simultaneous determination of the brightness and color temperatures at three wavelengths. Another interesting experimental paper [32K] describes a high-speed bolometer for measuring large incident radiation fields such as those coming from nuclear fireballs. The response time of this instrument is of the order of 50 micro-seconds.

The normal spectral emissivities of ceramic-coated and uncoated specimens of inconel and stainless steel have been reported [27K]. The measurements were made at temperatures of 900, 1200, 1500 and 1800°F over a wavelength range of from 1·5 to 15 μ. Spectral radiation properties have also been reported [13K] for a number of fabric materials from 1·0 to 23 μ. Materials examined included cotton, linen, silk, orlon and nylon.

A transient technique for measuring the total hemispherical emissivity of highly polished metals has been reported [8K]. The apparatus, which can be operated from 100 to 900°C has an accuracy of 8 per cent. It can also determine the specific heat of the material to within ± 2 per cent. The analytical solution of a constant area fin radiating into a low-temperature environment has been utilized to design an experimental apparatus to measure the total hemispherical emissivity of polished iron in the temperature range from 300 to 500°R [7K]. The method has the advantage, important in low-temperature work, that no calorimetric measurements are required.

Two papers have appeared which deal with unsteady heat conduction in a solid with a radiation or non-linear boundary condition. The transient temperature field in an infinite slab with radiation cooling at the surfaces is solved by an integral approach in [29K]. Another study [10K] considers a semi-infinite solid with a non-linear transfer process at the surface. As an example, the temperature distribution in the solid is determined under the conditions of Stefan–Boltzmann radiation at the surface.

Radiation in diathermanous materials such as glass is discussed in [24K]. Analysis and experiment are coupled to investigate the temperature distribution in the glass. Another paper dealing with the same subject [4K] presents a calculation of the spectral radiation emitted normally from the surface of a thin sheet of glass. The results of the calculation are used to design a pyrometer to measure glass temperatures.

The influence of internal radiation exchange in the reduction of temperature differences in solid structures has been examined. A transient analysis [3K] investigates the structural temperature distribution under the conditions of external convective heating. Simple models such as parallel plates are used in [1K] to evaluate the same effect. The use of insulation in the areas of greatest aerodynamic heating is discussed as a method of reducing structural temperature differences.

The subject of radiative transfer through particulate media continues to be of interest. Radiant transfer through fibrous and foamed insulating materials was investigated theoretically and experimentally in [22K]. The optimum diameters of fibers and pores were determined for minimum radiative transfer over the temperature range from 200 to 800°F. A related study [17K] reports on radiative transfer between discrete solid particles in a bed. A theory is presented which accounts for different particle geometries, and experiments are reported which show satisfactory agreement with the analysis.

The analysis of laminar compressible flow in the stagnation region has been modified to examine the effects of foreign gas injection from the surface [18K]. It is found that the overall heat transfer to the surface may be reduced by as much as two-thirds by the injection of a gas having an absorption coefficients several orders of magnitude higher than water vapor. Another analysis [6K] deals with the effect of thermal radiation on the inviscid flow over a blunt body. It is deduced that for practical hypersonic flows, the velocity distribution outside of the boundary layer will not be significantly affected.

An experimental investigation was reported [19K] on the effect of injection of carbon black on the radiation properties of flames. It was found that such injection produced a significant increase in flame emissivity.

The use of the calculus of variations as a tool in radiation analysis has been described [30K]. An example is given of the application of this method to the case of two finite non-black parallel plates and a comparison is made with the exact solution. Among other solution techniques, the variational method described above is utilized to examine the thermal radiation from a finite cylindrical enclosure with a specified wall flux [34K]. The inside temperature distribution is also determined for both gray-diffuse and black surfaces.

LIQUID METALS

A survey covering the current state of knowledge in liquid metal heat transfer has been published [3L]. The large spread among data for tube and duct flows which was highlighted in the 1955 Lubarsky–Kaufman survey remains. Information on free convection, boiling and condensation is given, but in the latter two areas, the data is particularly sparce.

The lack of agreement between theory and experiment is sometimes ascribed to the existence of a surface contact resistance. A static experiment using mercury and chrome-plated copper finds a resistance too small to explain the discrepancy [6L]. In response to reactor applications, information on the maximum temperature in a tube or annulus having a longitudinally-varying sinusoidal wall heat flux has been obtained by correlating mercury data [7L]. Nucleate boiling of mercury (with wetting additives) in a natural convection loop achieved heat fluxes of 600 000 Btu/h ft^2 without yet reaching the critical value [9L]. Another boiling study is reported [4L], but a translation could not be found.

Tests and operating experience on heat exchangers utilizing NaK with air or a molten salt are described [5L], and design precepts based on this knowledge set forth [2L]. A feasibility study relating to boiling mercury under zero-gravity was carried out in an airplane flying a zero-gravity arc [8L]. The tests were generally positive, but the effects of non-condensable gases were demonstrated to be particularly important.

An analytical study led to the conclusion that the effects of variable fluid properties on liquid metal heat transfer in tubes is moderate and is not the cause of discrepancies among data [10L]. A modification of Prandtl's mixing length theory is applied to the analysis of turbulent tube flow [1L]. The final equation for the Nusselt number contains a separate dependence on the Prandtl and the Peclet numbers which is neither supported nor refuted by currently available data.

LOW DENSITY HEAT TRANSFER

Experimental and theoretical efforts focused on heat transfer between simple geometries (cylinders and spheres) and high-speed, rarefied gas streams. This concern arises from technological needs of missile, satellite and space vehicle design and because of the interest in the physical processes at work in this region.

Experiments with chromel–alumel wires in crossflow at about Mach 6 covered a Knudsen number range of 0·001 to 15 and yielded Nusselt numbers 0·01 to 10 and accommodation coefficients of 1·0, 0·9 and 0·4 for argon, nitrogen, and helium respectively [9M]. Another study, [8M], gave similar results for a 0·5 in cylinder in continuum and slip flow regimes for the Mach range 1·3 to 5·7. Measuring the heat loss from thin wires ($L/D \gg 1000$) in the transition regime showed the effect of wire diameter [2M]. Collecting new and existing data, [1M] reports a general Nusselt number correlation for transverse and yawed cylinders in continuum, slip, and free molecule air flow at subsonic and supersonic conditions. Excluding dissociation effects, the results cover a Knudsen number range 4×10^{-6} to 37 and a Mach range 0·001 to 6·0.

Application of the complete Navier–Stokes equations to the viscous layer—thin shock and the merged layer—thick shock portions of the transition regime gave heat transfer rates in the stagnation region of adiabatic and highly cooled spheres and cylinders in hypersonic flows [6M]. Considering a hot wire in forced convection with a low Mach number stream, [5M] obtained Nusselt numbers reasonably accurate throughout the transition regime. Introducing slip and temperature jump into an incompressible shock layer analysis, stagnation point heat transfer for blunt bodies in hypersonic streams approaches boundary-layer predictions [4M]. Solutions of the Boltzman equation for parallel plate heat transfer throughout the transition regime are compared with other predictions [3M] and a useful review [7M] cites investigations, kinetic theory developments, and salient features of the free and nearly-free molecule flow regime.

MEASUREMENT TECHNIQUES

Several new techniques for temperature measurement have recently been proposed. An absolute noise thermometer has been developed [7N] in which use is made of the relation between temperature and thermal noise, measured electrically, in a resistor. The method has particular utility at temperatures lower than 140°K.

The accurate measurement of surface temperatures of solids at temperatures in excess of 1500°K has long been a difficult experimental problem. It has been proposed [14N] that measuring the velocity distribution of a beam of atoms which has been reflected from the surface offers a promising method. It appears that the reflected beam is in temperature equilibrium with the surface over a wide range of surface types, smoothnesses, and temperatures. Thus the effect of departure from black body conditions which must be accounted for in pyrometric measurements is absent.

Another paper [12N] discusses the relative merits of thin film probes versus hot wires. The film probe has the advantages of ruggedness and low sensitivity to contamination products in the gas stream. Its chief disadvantage is in its considerably greater size.

A number of studies have appeared concerning the measurement of thermal properties. An apparatus has been developed [17N] for the determination of thermal expansion coefficient, specific heat and thermal conductivity of refactories to temperatures up to 3650°C. Another device [9N] measures the thermal conductivity of insulating materials from liquid nitrogen temperature to room temperature. A special feature of the equipment is the short time necessary to reach thermal equilibrium. A measurement can be made at different temperature levels every 15 min.

Ångstrom was the first to show that by subjecting one face of a material to a time dependent and cyclic temperature pulse its thermal conductivity could be determined if the amplitude and phase of the pulse were measured at two interior points. This method has been adapted to measure the thermal conductivity of semiconductors [8N]. Thermal measurements of diathermanous materials in which more than one mode of heat transfer prevails are particularly difficult. A study is reported [2N] dealing with the determination of thermal conductivities of transparent substances.

The last paper in this series [6N] deals with the development of a probe for measuring the thermal conductivity of building materials. The probe is only 0·11 inch in diameter and may be used to determine the thermal conductivity at various locations in the cross sections of structures up to about 1·2 in below the surface.

Another group of papers is concerned with errors which exist in temperature measurements. The study of errors involved in measuring boundary-layer temperatures because of conduction down the leads is reported in [18N]. A similar study [5N] discusses the effect of lead conduction errors when making ground temperature measurements in geological researches. The greatly neglected technique of substituting manganin for copper in a copper–constantan thermocouple is shown to substantially reduce the lead conduction error. A third paper [1N] presents an analysis of the errors when a thermocouple is placed beneath the surface to measure surface temperatures. Two problems considered are the disturbance in the temperature field caused by the presence of the thermocouple and the effect of having the thermocouple removed a certain distance from the surface.

A method of measuring temperatures downstream from a shock wave is discussed in [13N]. The technique is based on the use of the emitting and absorbing characteristics of sodium D lines. Temperatures from 4000 to 5000°K were measured under laboratory conditions with an error of from 100 to 200°K. A probe for the measurement of gas temperatures is described in [23N]. Probe errors of radiation, base conduction and thermocouple wire conduction are minimized by electrically heating the probe base and shield.

Transient temperature measurements are discussed in [16N] and [3N]. In the first paper, a thermocouple installation is described to measure the temperature change on the cylinder wall surface of an internal combustion engine. The temperature measurement is made over an area only 0·25 mm in diameter and the junction is located only 25 μ below the surface. The second paper [3N] discusses a special thermocouple plug developed to measure transient temperatures at relatively large distances from the surface within rocket nozzle walls.

Two thermocouples suitable for the measurement of temperatures up to 2800°C are described in [4N]. They are made from tungsten/26% rhenium–tungsten and tantalum/26% rhenium–tungsten respectively. Important features are the suitability for operation at higher temperatures than is possible for existing thermocouples and their high sensitivity of 15 μV/°C. In connection with thermocouple installations, a quick connector for multipoint thermocouple assemblies is described [11N] which is easily constructed and which affords protection against factors which affect thermocouple calibration.

An improved method for measuring turbulence in wakes [10N] uses a condenser-type microphone and a hot wire annemometer. Results of measurements made with this instrument indicate the contribution of pressure fluctuations to the turbulence characteristics. Another experimental investigation [21N] relates to the effect of relaxation times on impact-probe measurements. The proper probe size for such measurements under a variety of conditions was determined.

Two new techniques for making flow measurements have been described. The use of nuclear resonance detection in tracers is discussed in [19N]. This technique offers promise in measuring flow rates in blood vessels where conventional methods are difficult to apply. By X-raying with a narrow beam [15N] it is possible to measure both the average vapor content in a channel cross section in two phase flow and the local vapor concentration in a small portion of a boiling-layer.

A pair of general papers complete this section. The first [20N] is a convenient listing of papers in the literature which describe pitot and static probes, their origin, principles, evaluation, performance, modern modifications and applications. The last paper [22N] gives a complete description of a temperature standards laboratory in a research laboratory. A complete list of all the instrumentation is included as well as the accuracies obtainable in the different kinds of calibrations.

HEAT TRANSFER APPLICATIONS

Heat exchangers

Interest remains high on the transient response of heat exchangers. The last paper of a three part series [1P] presents a general solution for the transient temperature distribution resulting from an arbitrary time rate of change of heat generation starting from an arbitrary initial condition. The reader's attention is also directed to the discussion at the end of this paper. The relative merits of "exact" and numerical solutions are presented ably and cogently by adherents of both viewpoints.

Another paper [9P] investigates the transient response and the steady state behavior of a solar heat exchanger wherein the energy transfer processes are by radiation. Other papers related to radiation heat exchangers are discussed in the section on Radiation in the present review.

Experimental data on the effect of flow pulsations on the efficiency of shell and tube heat exchangers are presented in [2P]. Pulsation frequencies of 40, 80, and 160 cycles/min are applied over a tube Reynolds number range from 4000 to 50 000. It is found that the increase in heat transfer caused by the pulsations decreases as the Reynolds number increases.

Two types of special purpose heat exchangers have been investigated [3P, 10P]. The former are nuclear reactor heat exchangers which operate with power densities up to 10 MW/ft^3. Under these severe conditions, critical problems are thermal stresses and methods of metal fastening. The latter paper presents heat transfer and pressure drop data on heat exchangers involving liquid metals and molten salts on the two sides. The two types of flow investigated were through round tubes and flow outside an array of round tubes and parallel to the tubes' axes.

Another pair of papers deals with artificial methods of increasing heat transfer. The study of mechanical wiping on surfaces of evaporation has received attention in [7P]. Analysis which is substantiated by experiment shows large increases in heat transfer over conventional surfaces. The second paper [8P] reports an investigation of the effect of turbulence promoters in three typical heat exchanger designs. Suitable correlations allow the prediction of heat transfer coefficients for these designs under a variety of operating conditions.

Tube sheets of U-tube and bayonet-tube exchangers have been investigated for the strengthening effect of tube-bending reaction [4P]. This effect is evaluated and presented in the form of simple design factors. A regenerative pebble-bed heat exchanger has been constructed to produce large quantities of high temperature air [6P]. Data have been obtained on both the air and bed temperature distributions and compared with predicted values.

Another study has reported the heat transfer and friction characteristics of compact heat exchangers [5P]. The exchangers which were examined have the largest surface to volume ratio of any investigated thus far in the program at Stanford University.

Aircraft, missiles, and satellites

Interest in aeronautics has now mainly shifted to an analysis of the re-entry conditions through the atmosphere of manned and unmanned satellites. It is concluded [4Q] that either a blunt, dense vehicle with an ablation cooling system, or a radiation cooled vehicle with drag break or lifting surface is best suited for this purpose. Similar conclusions are reached and simple procedures for a surface temperature prediction have been developed [5Q, 8Q, 2Q, 3Q, 1Q]. These studies consider entry into the atmospheres of other planets as well. The possibility of simulating atmospheric re-entry conditions in experiments with small scale models has been investigated, with the conclusion that such a simulation is possible as far as the thermal stresses and the skin temperatures are concerned [10Q]. The chemical decomposition process on an ablating Teflon wall is investigated [9Q]. Film cooling with water is proposed for the re-entry of satellite vehicles and experimental results for this method are reported [7Q]. The temperature conditions in orbiting satellites are essentially determined by the radiation to and from the surface and by internal conduction and radiation processes. The thermal control of the Explorer satellites is described and analyzed [6Q].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Experimental and theoretical efforts extend from cryogenic to plasma temperatures for a variety of fluids.

Thermodynamic properties

Investigation of the *p-V-T* behavior of water and steam [13R] obtained data in the pressure range 700 to 900 kg/cm^2 and temperature range 650 to 700°C accurate to 0·06 per cent. Compiled and correlated data for helium resulted in *T-s* and *h-s* charts for the temperature range 3·0 to 20°K and pressure range 0·5 to 100 atm [14R]. Use of statistical mechanics [20R, 6R] predicts equilibrium air properties for temperatures 500 to 15 000°K and pressures from 0·0001 to 1000 atm. Ref. [7R] reports similar data for nonionized N_2–O_2 mixtures to 10 000°K. Hydrogen data from 600 to 5000°K and 0·01 to 100 atm are compiled for calculating rocket performance [12R].

Transport properties

Employing hot wire techniques, [22R] reports thermal conductivities for the nonatomic gases [He, A, Kr, Xe, Hg (vapor)] from 0 to 500°C at 1 atm pressure with a maximum error of 1·8 per cent while [4R, 3R] finds that the $N_2O_4 = 2\ NO_2$ system has conductivities 9 times that computed for equivalent non-reacting systems in the region 20 to 215°C and 0·02 to 1 atm pressure. Coaxial, cylindrical cells yield thermal conductivities of air, A, N_2, CO_2, and steam to 900°C at 1 atm pressure [21R], liquid and gaseous N_2 and A in the region 85 to 200°K and 1 to 135 atm [3R], and D_2O in the region 75 to 260°C and 24 to 294 atm [24R]. Ref. [5R] reports direct Prandtl number measurements for He–air mixtures at 270°K.

Absolute viscosities for air, A, CO_2, D_2O, He, H_2, Kr, Ne, N_2, O_2, and H_2O (vapor) at 20°C by the oscillating-disc method are reported accurate to 0·05 per cent [10R] and the soundness of the method further verified [11R].

Statistical mechanics methods applied to air [6R, 2R] supply estimates of transport properties, from 500 to 15 000°K and from 0·0001 to 100 atm, useful in hypersonic laminar boundary-layer applications [19R]. Based on the Lennard–Jones potential, transport properties from 200 to 1500°K are estimated for He–air mixtures at low pressures [5R] and for the atmospheres of Venus, Mars, and Jupiter [8R]. Ref. [12R] reports equilibrium, hydrogen transport property predictions for the temperature range 600 to 5000°K and warm plasma (an equilibrium mixture of plus ions, neutral particles, and mobile electrons) conductivity is predicted in [17R].

For point source diffusion, [18R] reports the effect of concentration-dependent coefficients on the concentration distribution in one, two, and three dimensions, while [1R] notes that diffusion coefficients may be calculated from the change of asymmetric concentration profiles over known distances.

Addressing the problem of microscopic behavior at elevated temperatures, [16R] reports collision integrals for the exponential repulsive potential and [15R] the effect on these of excitation and charge exchange in mixtures, both important in predicting the transport properties of gases at high temperatures. A useful review of molecular transport properties of fluids is given by [9R].

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