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# HEAT TRANSFER—A REVIEW OF 1972 LITERATURE

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## INTRODUCTION

THIS review surveys the field of heat transfer, the results of which have been published during 1972. The number of papers published during that period was still such that a selection only can be included in this review. A more complete listing is contained in the *Heat Transfer Bibliographies* published periodically in this journal.

Several conferences have provided valuable information on heat transfer processes. The 1972 Heat Transfer and Fluid Mechanics Institute, held 14–16 June at San Fernando Valley State College, California, presented twenty-five papers, most of which were in the field of heat transfer. Invited lectures were given by E. M. Sparrow on "Experimental Methods in Mass Transfer and Fluid Mechanics"; by D. K. Edwards on "Grey Versus Nongrey Radiative Transfer"; by S. Ostrach on "A Critical Evaluation of Research on the Dispersions of Waste Heat in Large Bodies of Water"; by A. Hertzberg on "Photon Generators and Photon Engines for Laser Beam Power Transmission"; and by B. Gebhart on "Instability and Transition to Turbulence in Buoyancy-Induced Flows." The Proceedings of this conference were published and are being distributed by Standford University Press.

The Fourth All-Union Heat and Mass Transfer Conference was held in Minsk, U.S.S.R. from 15 to 20 May, 1972. Eight hundred and eighty-two papers and communications were presented on heat transfer by convection, in rheological systems, in chemical engineering, in dispersed systems, and in drying processes.

The Thirteenth National Heat Transfer Conference held in Denver, Colorado from 6 to 9 August, 1972 was organized in fifteen sessions, a panel discussion on problems of cooperation in research between universities and industry, and an open forum. Invited lectures by J. W. Westwater on "Development of Extended Surfaces for Use in Boiling Liquids," and by J. W. Deardorff on "Computer Methods for Simulation of Multidimensional, Incompressible Flow," rounded out the program which also included an "overlap day" with the Cryogenic Engineering Conference. The presented papers are available in preprint form through the American Society of Mechanical Engineers or the American Institute of Chemical Engineers.

The 1972 International Seminar organized by the International Centre for Heat and Mass Transfer was held from 30 August to 6 September at Trogir, Yugoslavia and was devoted to recent developments in heat exchangers. Information on the publication of the papers can be obtained from the Secretary General of the Centre, Professor Z. Zaric, P.O. Box 522, 11001, Beograd, Yugoslavia.

The 93rd Winter Annual Meeting of the American Society of Mechanical Engineers was held 26–30 November, 1972 in New York City and contained in its program twelve sessions on various subjects in heat transfer, an open forum, and the invited heat transfer lecture by H. Emmons on "Heat Transfer in Fire." Two sessions on solar energy and a forum on "The Energy Crisis" drew an especially large audience. Preprints of the papers are available through the Society and many of them will also be published in the *Journal of Heat Transfer*.

The Annual Meeting of the American Institute of Chemical Engineers, held in New York City from 26 to 30 November, 1972, contained in its program a number of papers on various topics in heat transfer. These, as well as papers at other AIChE meetings, are published in special issues of the *Chemical Engineering Progress Series*; number 118 in volume 68 (1972) has the title: "Heat Transfer—Tulsa." Another publication by the same society, which is of interest to the heat transfer community, is: "CEP Technical Manual Cooling Towers"; it contains papers presented at a special symposium on cooling towers held in Houston, Texas in 1970.

An unusually large number of books relating to heat transfer were published in 1972, especially by McGraw-Hill. The books are listed at the end of this paper.

Developments in heat-transfer research during 1972 can be characterized by the following highlights: In the field of thermal conduction, special attention was directed towards processes with phase change, for instance, solidification of metals or drying processes, as well as to improved instrumentation. The effect of surface roughness on flow and heat transfer, of solid suspensions in the fluids, and of changes in cross-sectional areas were topics in channel flow. Computer calculations for laminar boundary layers and experiments on turbulent boundary layers considered a variety of boundary conditions and geometries and included the effect of chemical reactions, partially with finite rate chemistry. The large discrepancy in reported turbulent Prandtl and Schmidt numbers was pointed out and results of new analyses and measurements were published for liquid metals and oils. The effect of upstream turbulence on heat transfer in the laminar boundary layer on a sphere was found to be much smaller than on a cylinder in crossflow. Van Driest's damping factor was frequently used in analyses of turbulent boundary layers. The effect of relaminarization was studied. A large number of papers studying free convection came from the U.S.S.R. Applied mathematicians and physicists have made computer calculations on various natural convection situations. Film cooling and transpiration cooling applied to gas turbines and rockets were topics in the field of combined heat and mass transfer. Boiling on fins and in situations specific to various applications have been studied. The fluidized beds have obviously found many new uses. Solar energy found increased attention in papers devoted to applications of heat transfer.

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

Conduction, A
Channel flow, B
Boundary-layer and external flows, C
Flow with separated regions, D
Transfer mechanisms, E
Natural convection, F
Convection from rotating surfaces, G
Combined heat and mass transfer, H
Change of phase, J
Radiation
  Radiation in participating media, K
  Surface radiation, L
Liquid metals, M
Low-density heat transfer, N
Measurement techniques, P
Heat transfer applications
  Heat exchangers and heat pipes, Q
  Aircraft and space vehicles, R
  General, S
  Energy production, T
Plasma heat transfer, U

## CONDUCTION

The current literature on heat conduction deals both with applications and with basic problems. The process of ingot freezing of alloys can be qualitatively divided into two stages. The initial stage terminates when the liquidis front reaches the center of the ingot. An analysis of the subsequent stage was performed in which account is taken of the liquid flow caused by the density change that accompanies freezing [44A]. A finite element method was employed in a two-dimensional model of a solidifying ingot, but the density change was not considered [41A]. Solution of the coupled energy equations for fluid and wall yielded the temperature of a liquid metal flowing in the flat passages of sand molds [7A]. A quasi-steady analysis for freeze-drying spheres and cylinders of beef took account of the diffusional and bulk flow of a binary gas mixture inside the product [10A]. Experiments on the drying of an absorbent material (cotton) with the aid of microwave heating indicated that the mass concentration remained uniform throughout the process [27A]. Steady-state solutions of the heat conduction equation with internal heat generation were applied to predict the maximum lesion created by a cryoprobe used in cryo-surgery [9A]. A two-state system such as an electric discharge or a combustion process can be modeled by the transient heat equation with a nonlinear heat source term [18A].

Nonlinear estimation is a procedure which may be used to determine material properties from experimental data. The basic idea of the method is to minimize, in the least squares sense, the difference between the experimental and the analytical response of the system. The method was successfully employed to determine the properties of ablating teflon [8A]. The energy equation can be rephrased into a form in which it serves as a differential equation for the determination of the temperature dependence of the thermal conductivity [37A]. Solutions for the transient temperature field induced in a solid by an energy pulse on the surface (e.g. a laser pulse) can be employed in connection with the pulse technique of measuring thermal diffusivity [13A]. For a particulate composite, it has been found that there is a minimum ratio of system dimension to particle dimension below which the composite can no longer be considered macroscopically homogeneous and isotropic [15A].

The Gardon heat flux sensor is analyzed from the standpoint of transient thermal response and results are given which eliminate the requirement that the sensor be very thin [23A]. The transient response of heated wires has been examined from the standpoint of applications to hot wire anemometry [11A]. The inside wall temperature of a tube heated by a helical coil on its outside surface can be taken to be uniform if the axial spacing between the turns of the coil is smaller than the tube wall thickness [38A]. Photomicrographs of a metallic specimen which had been heated to high temperature revealed a grain structure pattern from which regions of sharp temperature gradients can be inferred [2A].

Dimensional analysis applied to thermal contact conductance between surfaces in vacuum took account of the rms roughness of the surfaces [43A]. The presence of waviness at an interface leads to an increase in the thermal contact resistance [39A].

The one-dimensional model for analyzing fin heat transfer is valid when the Biot number based on the smallest transverse dimension is much less than unity [26A]. There is a temperature depression at the base of a fin which results from the presence of the fin itself. The extent of the depression depends on the ratio of the thermal conductivities of the fin and the base [24A]. The time-averaged fin efficiency of a straight rectangular fin subjected to a periodic variation of the base temperature is reduced owing to the time varying temperature [49A]. A composite fin configuration, consisting of an axially conducting rod with attached radially conducting longitudinal fins, is analyzed by lumping the influence of the longitudinal fins into an effective heat transfer coefficient for the rod [4A]. The influence of fins embedded in a heat conducting solid can be characterized by shape factors [20A]. Finite difference solutions of the steady heat conduction equation were used to predict the heat transfer performance of ribbed surfaces such as are used in turbulence promoters in tube flows [1A].

The accuracies obtained from various finite-difference formulations for variable thermal conductivity were assessed by comparing numerical results with those of an exact solution [45A]. A finite element formulation for heat conduction problems is made in terms of the heat flow field instead of the temperature field [17A].

In the classical demonstration experiment for the regelation of ice, a weight-loaded wire is passed through a block of ice, but does not cut it apart because the plane of separation refreezes again. Recent experiments have revealed a strong influence of the thermal conductivity of the penetrating wire [19A]. A spherical shell of freezing material is subjected to large thermal stresses which may ultimately cause rupture. The temperature field needed as input to the stress problem was formulated as a spherical Stefan problem [21A]. The transient process of simultaneous condensing and freezing of a pure vapor on a cold plate can be solved exactly if the wall temperature is constant, but necessitates an approximate solution if the wall or coolant have finite thermal resistances [34A]. Application of Green's functions to moving boundary problems converts the non-linear governing differential equations into a single transcendental equation which can be solved numerically [5A].

The temperature and moisture distributions in capillary porous bodies are linear combinations of the solutions of boundary value problems of pure heat conduction, provided that the two distributions have the same type of boundary conditions [28A]. A transient diffusion analysis for mass transfer between a sphere and its finite-volume surroundings took account both of interfacial resistance (i.e. finite mass transfer coefficient) and of the time-variation of concentration in the surroundings [14A]. The heat balance integral, when applied to evaporation from the surface of a semi-infinite region with a non-volatile solute, gave good agreement with an exact solution at short times but significantly overestimated the surface concentration at long times [6A].

The hyperbolic heat equation may yield a transient temperature rise which exceeds the imposed boundary temperature as well as the initial temperature [42A]. The finite propagation speed of heat transfer can have significant effects in determining the temperature rise in crystals caused by exothermic reactions [3A]. The hyperbolic heat equation has been interpreted geometrically in terms of a mean curvature of a Riemannian space having a particular metric [25A]. The transient heat conduction problem with finite wave speed was solved by the use of the Laplace transform on time and the sine transform on space [32A].

A closed-form solution in terms of the gamma function has been obtained for the surface heat flux for a semi-infinite slab whose surface temperature is a non-integer power of time [22A]. A more convenient form was found for the transient temperature solution in an infinite medium due to a plane source of finite duration [30A]. The maximum temperature in an internally heat generating solid with uniform surface temperature depends on the spatial distribution of the heat sources. Estimates of this maximum temperature are given in terms of the maximum temperature for a solid with spatially uniform heat sources [48A]. Exact solutions are reported for the steady temperature distribution in internally heat generating slabs, cylinders, and spheres subjected to simultaneous surface convection and radiation [47A]. In the treatment of variable thermal conductivity by the Kirchhoff transformation, the non-linearity that results after the transformation of convective boundary conditions can be removed by using an effective fluid temperature [12A]. A method is described for linearizing the differential equation and the boundary conditions of heat conduction, the respective non-linearities resulting from temperature-dependent properties, radiative transfer, etc. [40A].

A variational principle for the transient heat conduction problem can serve as the basis of an integral-type solution method [46A]. Green's functions were employed to solve for the transient temperature field inside a region consisting of two coaxial finite circular cones [33A]. By the application of a finite integral transform, an analytical solution for a large class of conduction problems was found in terms of infinite series and contains quasi-steady and transient terms [29A]. In a highly mathematical treatment, Laplace transformation was used to obtain the transient temperature solution for a composite solid, one of whose faces is heated by radiation and cooled by convection [16A]. The Vodicka type of orthogonality condition was employed in solving for the transient heat flow in a composite material with internal heat generation [31A]. Analytical solutions involving complex mathematics have been obtained for the conjugate unsteady heat transfer problem consisting of boundary layer convection and conduction in the adjacent solid. Under certain circumstances, the boundary layer heat transfer can be treated as being quasi-steady [35A, 36A].

## CHANNEL FLOW

Papers on heat transfer in duct flows have dealt with both basic and applied problems.

Augmentation devices, roughness, and inlet configuration have been investigated. The use of slightly protruding orifices, periodically spaced along the bore of a tube, gives rise to significant heat transfer augmentation for transitional and turbulent flows [26B]. The validity of generalized heat transfer and friction correlations for repeated-rib roughness is substantiated by its success in correlating the data of several investigators [63B]. Different formulas had to be used for correlating smooth and rough tube turbulent heat transfer data in the case of high temperature air flowing in a cooled tube [24B]. By the introduction of a Stanton number based on the shear velocity, a correlation is proposed which is purported to apply for turbulent flow in both smooth-walled and rough-walled tubes [37B]. Similarities in the wall region analysis of turbulent heat and mass transfer in smooth and rough tubes have been pointed out [19B]. An electrochemical technique was used to advantage in studying the effect of V-shaped roughness grooves, situated normal to the flow direction, on the turbulent mass transfer in a square duct [12B]. Entrance region heat transfer coefficients in parallel plate channels having plate spacings between 0·1 and 0·5 mm were obtained by means of a transient measurement technique; both smooth wall and rough wall channels were investigated [29B]. Experiments demonstrated that the entrance region heat transfer coefficients for turbulent tube flow decrease as the radius of curvature at the tube inlet increases [2B].

Attempts to achieve a general correlation of the large body of existing data for particle-laden gas flows in tubes have met with only partial success [50B]. Additional experimental data have been reported on the effect of solid particles on heat transfer to turbulent gas flows in tubes; the particles were in the size range from 100 to 230 μ [51B]. From experiments in which $T_{wall}/T_{bulk}$ reached values as high as 2, it was found that the heat transfer coefficient for a particle-laden gas increases as $T_{wall}/T_{bulk}$ increases [59B]. In a tube flow, by introducing cold particles into a warmer air stream and measuring air temperatures at various points along the tube, heat transfer coefficients between the air and the particles were deduced [3B]. Particles injected normal to one of the bounding walls in a laminar Couette flow act to decrease the wall shear, but the heat transfer can be either increased or decreased [42B]. In a turbulent pipe flow, the effect of increasing the concentration of solid particles is initially to extend the thermal entrance region, but further increases in particle concentration do not alter the entrance length [52B]. Drag reducing additives were found to reduce mass transfer coefficients in turbulent pipe flow, whereas the laminar transfer coefficients were little affected [47B].

Motivated by applications to gas-cooled reactors, a combination analytical-experimental investigation was performed for forced convection heat transfer for longitudinal flow through a roughened rod bundle [62B]. For either longitudinal laminar flow or slug flow, the average

Nusselt numbers for the corner and edge rods in a hexagonal rod bundle array are lower than for a symmetrically positioned rod [20B]; furthermore, for a rod situated in the interior of the array, displacing the rod from its symmetrical position can cause considerable reduction in the average Nusselt number [21B, 22B]. Application of an improved point matching method for solving the heat transfer problem for longitudinal slug flow through a rod bundle indicates that the presence of a bounding wall only affects the Nusselt number of the rod adjacent to the wall [15B].

Heat transfer in ducts in which there are changes in the flow cross sectional area has been studied both analytically and experimentally. Analysis shows that the heat transfer coefficient for turbulent flow in a plane-walled diffuser is greater than that for a parallel plate channel [39B]. On the other hand, the results of experiments indicated that turbulent heat transfer rates for plane-walled, two-dimensional diffusers are greatest when the angle of divergence is zero degrees [48B]. Finite difference solutions for laminar flow in an isothermal-walled converging channel indicated that the Nusselt number increases as the angle of taper increases [66B]. For laminar flow in tapered passages, there is a family of thermal boundary conditions which yields thermally developed Nusselt numbers [61B]. Numerical solutions of the laminar flow equations and complementary experiments using high temperature argon gas showed that for a convergent-divergent nozzle, the wall heat flux increased along the convergent section, reached a peak value upstream of the throat, and then decreased through the rest of the throat section and in the divergent section [6B]. An experimental investigation of the effect of changing the wall-to-stagnation temperature ratio for flow through a converging-diverging nozzle revealed that the friction coefficient decreases as the ratio increases [5B]. An empirical improvement to Bartz's integral method yielded improved estimates for local and overall heat transfer in nozzles [8B]. A comprehensive experimental investigation yielded heat transfer results in converging-diverging conical nozzles having throat Reynolds numbers ranging from $6 \times 10^5$ to $5 \times 10^6$ [7B].

Forced convection heat transfer correlations, based on available experimental data, are formulated for laminar and turbulent pipe flows as well as for various external flows, packed beds, and tube bundles. The turbulent pipe flow correlation exhibits a 0·83-power dependence on the Reynolds number rather than the usual 0·8 power [64B]. For thermally developed turbulent flow in ducts at large Prandtl numbers, it is demonstrated that in the limit as $Pr$ approaches infinity, the results are independent of geometry and boundary conditions for cases including parallel plates, tubes, and annuli with either uniform wall heat flux or uniform wall temperature [17B]. Turbulent heat transfer results for the thermal entrance region of rectangular ducts were correlated by examining experimental data for ducts having aspect ratios ranging from 1:1 to 25:1 [33B].

Direct measurements of velocity–temperature fluctuation correlations in turbulent pipe flow of air gave turbulent Prandtl numbers which increased from the center towards the wall, but were always less than one [23B]. From detailed measurements of the flow and temperature fields in ethylene glycol flowing in a vertical tube at a Reynolds number of about 6000, it was concluded that the microscales of the temperature fluctuations are three or four times smaller than those of the velocity fluctuations [31B]. The eddy diffusivity for mass transfer in the central core of a turbulent pipe flow increases with injection and decreases with suction through the pipe walls [53B]. Heat and mass transfer experiments in a circular tube gave results for the radial and tangential eddy diffusivities. The ratio of the radial diffusivity for heat or mass to that for momentum displayed a maximum value of about two near the tube wall and decreased to one near the axis [44B]. Results of calculations for non-axisymmetric turbulent diffusion in a tube indicate that the higher the Schmidt number, the greater is the sensitivity of the results to the assumed model for the tangential eddy diffusivity [43B]. A simple model, consisting of a wall region where the molecular conductivity predominates and a turbulent core with a constant eddy conductivity, is employed to predict the circumferential distribution of the wall temperature corresponding to circumferentially non-uniform wall heat flux for turbulent flow in a circular tube [45B].

The use of argon gas at 3000°K enabled variable property heat transfer results to be obtained for turbulent flow in a cooled tube over the range $T_{bulk}/T_{wall}$ from 1·8 to 8·1 [35B]. Extensive experiments involving water flowing in tubes indicate that at lower heat fluxes, the heat transfer coefficient has a maximum at a bulk temperature slightly less than the pseudocritical temperature. The maximum becomes progressively less pronounced as the heat flux is increased [65B]. Temperature distributions in an airstream flowing in a square duct having different heating rates on the bounding walls were measured for Reynolds numbers of 10000, 50000 and 100000 [18B]. A Graetz-type problem for turbulent flow in a parallel-plate channel having one uniformly heated wall and one insulated wall is solved by finite differences, starting from the inlet cross section and marching downstream [32B].

Studies of laminar flows tend to be analytical in nature. The heat transfer results for thermally developed laminar flow in curved pipes are only slightly different for the two basic boundary conditions of uniform wall temperature and uniform heat flux [1B]. Finite difference solutions for thermally developed heat transfer for laminar flow in curved circular pipes gave results for Dean numbers covering the range from 1 to 1200 and for Prandtl numbers between 0·005 to 1600 [25B]. A study of the asymptotic behavior for $Pr \to \infty$ motivated the correlation of the Prandtl number effect for laminar forced convection in tubes and channels in the presence of a secondary flow [10B].

The effect of axial diffusion in the low Peclet number mass transfer problem for laminar flow in a circular tube was solved by matching series solutions for the upstream and downstream regions [56B]. Corrections of an earlier analysis of the axial conduction effect in laminar tube flow have taken account of conduction at the entrance cross section [40B]. The integral energy equation is applied to solve laminar flows with axial conduction, including pipe flows; however, conduction through the inlet cross section of the pipe is not taken into account [54B]. Finite difference solutions for a high-temperature laminar gas flow in a highly cooled tube indicate that, owing to the large energy loss caused by heat transfer to the wall, the gas decelerates along the tube [4B].

Local laminar Nusselt numbers in a parallel plate channel with injection or suction are found to be higher when the velocity and temperature fields develop simultaneously than when the velocity is fully developed [14B]. Solutions for convective heat transfer in a parallel plate channel with one porous wall were applied to a freeze drying problem; it was demonstrated that if a gap separates the heater and the product, radiation is the dominant mode of heat transfer to the product surface [36B]. A laminar-flow analytical model consisting of a parallel-plate channel with fluid injection through one of the walls was employed to examine a scheme for internal cooling of gas turbine blades [13B]. The steady-state diffusion of aerosols in a gaseous stream flowing in a duct is governed by a conservation equation similar to the energy equation with a heat source [55B]. A Graetz-type problem for superposed Poiseuille and Couette flows in a channel was solved with the aid of Laplace transformation and the solution expressed in terms of Airy functions [9B]. Complex variable theory is used to find closed-form solutions for fully developed laminar heat transfer for a class of non-circular ducts [60B]. The transient response of laminar heat or mass transfer in a tube to impulse or step changes was solved exactly by means of a series [58B]. The problem of heat transfer between two immiscible liquid layers can be analyzed by first obtaining Graetz-type solutions for each layer and then matching at the interface [38B]. The accounting of temperature-dependent viscosity for liquid flow in a parallel plate channel leads to a decrease in the critical Reynolds number at which small disturbances are amplified [41B].

Measured temperature distributions for laminar flow of water and a non-Newtonian fluid in a cooled tube agreed well with the predictions of constant property analysis except near the wall [28B]. Experimental heat transfer results for laminar flow of water and transformer oil in flat ducts were correlated by using the ratio $(Pr_b/Pr_w)^{0.25}$ to account for variable property effects [34B]. Heat transfer and flow visualization experiments were performed on the influence of an obstacle situated in a channel flow [27B].

Stanton numbers of viscoelastic fluids in turbulent pipe flow may be lower than for Newtonian fluids because of a thicker buffer layer [11B]. A new correlation for heat or mass transfer in fully developed turbulent pipe flow of power-law fluids at large Prandtl or Schmidt numbers is based on a continuous eddy diffusivity distribution from the wall to the center of the pipe [30B]. For tube flow of a power-law, non-Newtonian fluid with an exponential viscosity–temperature relation, the specification of the mean velocity gives a unique pressure drop and unique velocity and temperature profiles [49B].

An experimental investigation of the influence of a transverse magnetic field on heat transfer to mercury flowing in a pipe indicated that the presence of the magnetic field inhibits the mechanism of heat transfer by damping the turbulent velocity fluctuations [16B]. The effect of axial heat conduction was included in an analysis of fully developed heat transfer in a low Peclet number magnetohydrodynamic channel flow, but the effect was neglected in the analysis of the thermal entrance region [57B]. The fully developed temperature distribution for non-Newtonian MHD channel flows can be calculated from a knowledge of the cross sectional distribution of the shear stress [46B].

## BOUNDARY LAYER AND EXTERNAL FLOWS

Self-similar solutions of the laminar incompressible boundary layer equations with heat transfer include lengthwise and lateral curvature, external vorticity, and stagnation enthalpy gradients [1C]. The same effects were also analyzed using the method of matched asymmetric expansion [18C]. Significant improvements in the analysis of heat transfer in boundary layers could be obtained [8C] by incorporating the effect of streamwise pressure gradients. Forced convection heat transfer to fluids near the critical point were analyzed [14C] considering the Prandtl number to be a function of location. The non-steady three-dimensional thermal boundary layer with buoyancy effects was studied [4C]. Velocity fluctuations affected the temperature field by dissipation as demonstrated for an incompressible, constant property fluid in Couette flow [16C]. A positive pressure gradient decreases the enthalpy recovery factor for laminar boundary layer flow with mass transfer [43C]. Recovery factors between 0·6 and 1 were obtained at $Pr = 0{\cdot}7$. An integral Pohlhausen type method for laminar flat plate boundary layer flow of a binary mixture of atoms and molecules with non-equilibrium dissociation was presented [17C]. A similar analysis [3C] considered stagnation point heat transfer. The results of experiments studying convective heat transfer between dissociated combustion products and a cold surface in the stagnation region of a blunt body were compared with analytical results [10C]. Thermal recovery factors in rarefied supersonic flows of heliim–argon and hydrogen–nitrogen mixtures assume values as high as 1·6 at the stagnation point of a hemisphere [24C]. The energy increase in hypersonic steady laminar compressible boundary layers by combustion of hydrogen was analyzed [22C]. Minimum drag bodies with minimum heat flux in laminar and turbulent hypersonic flows were treated in [32C].

Two equations describing the turbulent kinetic energy and a turbulent length scale are added to the conservation equations [30C] to analyze turbulent boundary layers and are applied to flat plate boundary layers, developed pipe flow, channel flow, and plane wall jets. A numerical marching procedure for three-dimensional parabolic flows was used to study heat transfer for laminar flow through a square duct with one wall moving laterally [31C]. An explicit and non-iterative finite difference method [33C] for laminar and turbulent flow with heat transfer gives results which compare well with experiments. Matched asymptotic expansions are used [2C] to develop a theory of heat transfer in two-dimensional boundary layers of a gas with $Pr = 1$ and $Re \to \infty$. The Reynolds analogy factor and the recovery factor were calculated for the outer fully turbulent part of turbulent equilibrium boundary layers [38C]. Measured velocity profiles in a compressible turbulent boundary layer on a rough surface with pressure gradient can be correlated [9C] on a universal curve when using generalized velocities suggested by Van Driest. Measured heat and mass transfer coefficients in turbulent boundary layers on a flat plate with a step in wall temperature or wall concentration do not support the customary assumption that the turbulent Prandtl or Schmidt number is equal to 1 [40C]. Large discrepancies in measured turbulent Schmidt and Lewis numbers for boundary layer flow have been pointed out [37C]. The Van Driest damping factor has been expanded [7C] to account for the effect of mass transfer in incompressible turbulent boundary layers. The results of measurements on a 7·25° half angle porous cone at $Ma = 8$ with fluid injection into the turbulent boundary layer are compared with available correlations [25C]. A moderately strong acceleration on turbulent boundary layer heat transfer on a porous plate results in relaminarization [39C]. Temperature profiles and Stanton numbers were measured. Mass transfer relations were obtained [34C] for a flat plate in parallel channel flow at Schmidt numbers of 0·7, 2 and 2000 and Reynolds numbers between 3000 and 30 000. Drying rates of sponges can be increased by the presence of an electric field [35C].

The unsteady temperature field for flow of a sphere through a fluid of different temperature was analyzed [20C] for low Reynolds numbers. The effect of dissipation was also studied [36C] again at vanishing Reynolds number. Heat and mass transfer to a sphere at moderate Péclét number can be described [41C] by an equation of the form

$$Nu(Sc) = C_1 Pe^n + C_2.$$

The two constants are functions of Prandtl or Schmidt number and are tabulated in [41C]. Measurements of heat transfer to fine wires resulted in the equation

$$Nu(t_w/t_a)^{-0\cdot 17} = 0\cdot 24 + 0\cdot 56\, Re^{0\cdot 45}$$

for Reynolds numbers between 0·02 and 44 [6C]. A correlation equation is developed [11C] which describes the influence of property variation on forced convection heat transfer from cylinders and spheres in cross flow of liquids. Local and average Nusselt numbers are reported for flow of air, water, and oil over cylinders with circular and eliptic cross section at Reynolds numbers between $10^3$ and $2 \times 10^5$ [19C]. The flow and heat transfer was studied for two cylinders in cross flow where one cylinder is located downstream from the other for Reynolds numbers around $10^4$ [21C]. The electrochemical method was used to study the effect of freestream turbulence on local and mean mass transfer from a cylinder to a fluid with a Schmidt number of 1230 [28C]. The mass transfer increased from 10 to 100 per cent with an increase of the turbulence intensity up to 2·3 per cent. A miniature heat flux meter was used [29C] to measure the effect of free stream turbulence on local heat transfer from a sphere to air. No influence could be observed for turbulence intensities up to 9·4 per cent and an increase up to 15 per cent was measured when the turbulence levels increased to 15 per cent. The effect of turbulence intensities up to 25·6 per cent was also measured for a sphere [12C]. Local heat transfer coefficients resulting from measurements on a yawed blunt conical nosetip in air flow at $Ma = 5$ are reported [42C].

Heat and mass transfer on a flat plate normal to a two-dimensional laminar jet was calculated and compared with measurements [27C]. Experimental results for the same arrangement are also reported in [5C]. Heat transfer data from turbulent jets to adjacent surfaces arranged under various angles were obtained [23C] through the mass transfer analogy by sublimation of naphthalene. Heat transfer results are reported for a row of air jets impinging on a surface with superimposed crossflow [26C].

Experiments established the boundaries between steady, wavy, and turbulent flow of a liquid film falling along a vertical surface [13C, 15C] and established heat transfer correlations.

## FLOW WITH SEPARATED REGIONS

### *Single bodies*

Freestream turbulence intensities of 10 per cent result in increases of 100 per cent in the rear of cylinders in crossflow [26D]. Carpenter [5D] summarizes a numerical investigation into the effects of compressibility and total enthalpy difference on the development of a laminar free shear layer.

In [27D], an attempt to predict separation of a turbulent boundary layer over a cone-flare configuration with blowing is successful. Fully separated flows have been studied extensively but less attention has been paid to incipient separation. In [33D], the effect of wall cooling was to increase the incipient supersonic separation angle and reduce the separation distance. Additional experimental results [32D] show increasing plateau pressure and decreasing length of interaction region with decreasing Reynolds number and decreasing wall-to-recovery temperature near a supersonic forward-facing step.

Extensive data are summarized [22D] on flow patterns, characteristic dimensions of separation zones, and static pressure distributions needed for heat transfer calculations ahead of steps. Telionis [35D] suggests a simplified model for engineering estimates of the heat transfer in the neighborhood of reattachment for supersonic flow over a rearward-facing step with a large suction slot. In [20D], earlier analyses of Korst and Scott are compared with heat transfer data downstream of a backstep in supersonic turbulent flow. Experimental results are given [37D] for the residence time of foreign gases in the wake behind two slender bodies with either laminar or turbulent boundary layers. Average mass transfer coefficients were determined [28D] in a cavity using sublimation of naphthalene and paradichlorabenzene. Pressure correlation measurements and turbulence properties of the flow reveal that fluctuating wall pressures are driven by the shear layer above the recirculating flow [10D, 11D]. Similarly, convection, production, diffusion, and dissipation of temperature fluctuations were measured [9D] in a turbulent wake behind a circular cylinder 1140 diameters downstream of a cylinder at $Re = 960$.

In [18D] a new procedure is given for numerically integrating the boundary layer equations through a region of reverse flow which takes into account downstream influences. Normal pressure gradients are reported [30D] for the near-wake down to 30–40 body diameters which are strong enough to invalidate the boundary layer assumptions. The use of an intermittency factor in the wake-region, eddy viscosity did not improve the numerical predictive results [14D].

### *Packed and fluidized beds*

New heat transfer analyses [8D] in packed beds include radial temperature gradients. Studies of a porous plate heated by high frequency current and cooled by air, nitrogen, ethyl alcohol, and some oils is aimed at identifying the dependence of heat transfer on coolant physical properties [23D]. Conceptually simple models have been developed [3D, 29D] to evaluate 10 separate mechanisms controlling axial heat transfer in packed beds. The solution for sinusoidal gas input temperature to a fully described packed bed is obtained [16D] by finding the real root of a fourth-order algebraic equation. Asymptotic relations are used [15D] to predict the effects of Reynolds number, Grashof number, and Schmidt number on mass transfer rates in packed beds. A description [34D] of the flow field in a packed bed containing a spatially distributed flow resistance is used to predict channeling and by-pass phenomena. A packed bed, axial-thermal-conductivity, empirical relation [36D] includes effects of all significant heat transport mechanisms. The flow of a tracer gas in a fixed granular bed helps in hydrodynamic modeling [17D].

The Carman channel flow model for flow in packed beds correlates mass transfer in the laminar region and heat and mass transfer in the turbulent region [13D]. Two Russian papers deal with the determination of the convective component of the coefficient of heat transfer to a gas in a fluidized bed and with interfacial heat and mass transfer in fluidized systems [1D, 19D]. A simple model [7D] for fluidized bed heat transfer based on the surface renewal and penetration concept agree well with experiments. Gabor [12D] analyzes wall-to-bed heat transfer in fluidized beds. In [21D] the basic mechanism of surface-bed heat transfer in fluidized beds is recognized to be due to solids renewal at the surface. Higher heat transfer rates are attained at the bed wall than at the surface of immersed cylinders. In this connection, [6D] describes heat transfer from a vertical tube in a fluidized bed filled with a cylindrical helical packing. Similarly, Brea and Hamilton [4D] describe heat transfer in liquid fluidized beds with a concentric heater.

The temperature field on the surface of a sphere submerged in a fluidized bed is determined experimentally [2D] and this distribution is used for calculating local heat transfer coefficients.

Finally, a series of papers describe the behavior of bubbles in fluidized beds [24D, 25D] and the aerodynamics of jets discharged into fluidized beds [31D].

## TRANSFER MECHANISMS

The production of turbulence near a smooth wall in a turbulent boundary layer occurs exclusively during the intermittent bursts as was demonstrated [9E] by experiments with hydrogen bubbles, hot wires, and dye. An interpretation of measured variations of the eddy conductivity in a heated channel is presented [5E]. A laser anemometer has been used to measure the structure of turbulence in non-Newtonian pipe flows [3E] and to demonstrate the delay of transition by additives to water. A double Pitot tube has been developed which is able to measure the position of maximum velocity in turbulent shear flow within 0·03 mm [4E]. The effect of the difference in location of the maximum velocity and of zero shear in asymmetric turbulent velocity profiles on momentum, heat, and mass transfer is discussed [11E].

An analysis [6E] of existing data shows that the logarithmic velocity profile describes low Reynolds number flow, that viscous effects are present in the outer layer of a boundary layer, but not in duct flow. The derivation of the Prandtl–Nikuradze skin friction law was extended [8E] to heat and mass transfer and its use was shown to give results which agree with experimental information over a $Pr$ or $Sc$ range from $3 \times 10^{-3}$ to $10^6$. The transport equations are presented in transfer coordinates [13E], and the use of a model describing the wall region of turbulent flow by a succession of laminar boundary layers was extended [14E] to describe turbulent heat transfer in non-Newtonian fluids. The formulation of turbulent heat transfer by surface renewal through random eddy models is discussed [2E]. The prediction of laminarization with a new two-equation model of turbulence (for turbulent kinetic energy and for the energy dissipation rate) leads to results [7E] which agree well with measured values. The structure of initially fully developed low Reynolds number turbulent pipe flow and the change occurring when the flow enters a porous section with fluid injection was studied [12E] by a hot film anemometer. Measurements of the large scale eddy structure of a turbulent boundary layer during relaminarization through a favorable pressure gradient reveals [1E] that the absolute level of the fluctuating velocities and of the Reynolds stress stays constant along mean streamlines, but that the relative levels decrease. A statistical transfer theory in non-homogeneous turbulence is based on a finite number of one-point correlation equations [10E].

## NATURAL CONVECTION

The number of technical contributions concerned with natural convection remains large. Much of the interest is in refinements of old problems with effects of non-Newtonian fluids, transients, and vibrations considered. Natural convection is of considerable interest to people outside the normal engineering practitioners of heat transfer. Applied mathematicians and physicists in particular are making significant contributions to our knowledge of thermal convection in an enclosed fluid layer heated from below. In this problem there are interesting non-linear problems as well as important approaches to a fundamental understanding of turbulence. Some industrial activity also is apparent in the natural convection studies. Although quite limited, it includes work from such organizations as communications companies which rely on natural convective cooling for much of their remote equipment.

Heat transfer from a heated vertical flat plate remains of interest. The flow field has been studied for turbulent natural convection [36F]. The local heat transfer has been measured from a longitudinal vibrating vertical plate [34F]. An estimation of aerosol deposition in a natural convection boundary layer along a vertical isothermal surface has been made [23F]. Experiments with different non-Newtonian fluids [20F] agree with past theoretical predictions. An analysis of transient free convection in a Bingham plastic indicates a more pronounced minimum of the heat transfer coefficient with time than had been calculated for a Newtonian fluid [33F]. A study [4F] of the effect of thermal radiation on natural convection along a vertical plate considered both transparent and absorbing boundary layer fluids. Two independent studies correlate the heat transfer from an inclined plate using vertical plate predictions with the body force calculated from the component parallel to the plate surface. In one of these studies [22F], the heat transfer is measured directly, while the other [42F] uses a mass transfer analogy. These studies also showed transition to turbulence at a lower Rayleigh number as the plate is inclined from the vertical.

A solution for the fully developed laminar free convection between vertical plates heated asymmetrically has been obtained [5F] considering both constant temperature and constant heat flux boundary conditions. The entry flow in such a geometry has also been examined [6F]. A numerical study [32F] predicts the developing flow between two vertical plates heated suddenly.

Similarly solutions have been obtained [49F] for laminar natural convection from vertical thin needles. Measurements [52F] in natural convective heat transfer from vertical cones pointed downward agree approximately with a previous analysis. Asymptotic solutions for the flow distribution and heat transfer on a long vertical cylinder with suction have been calculated [10F]. A solution [48F] indicates the effect on natural convection with both blowing and suction at the surface. Viscous dissipation effects in unsteady natural convection along a porous plate with suction have been studied [66F]. The effect of a non-uniform body force field on convective heat transfer includes the flow on a flat plate rotating about an axis in the plane of the plate [40F]. An analysis combining conduction through a rotating plate and convective heat transfer to the surrounding fluid has been completed [43F].

A number of studies are concerned with natural convection heat transfer from horizontal circular cylinders. In one study [50F], the diameter of a wire was shown to be important in heat transfer to super-critical carbon dioxide. The transient heat transfer from a heated horizontal wire was determined [74F]. The addition of polymers which reduce drag in the flow of aqueous solutions also reduces the laminar heat transfer from a horizontal cylinder [44F]. The natural convection heat transfer from a horizontal wire is considerably increased when vibrating the container housing both wire and fluid [54F]. The effect of combined natural and forced convection from thin hot wires has been examined [78F]. The heat transfer from a cylinder placed in the wake of another cylinder can be increased or decreased depending on the spacing between the cylinders [47F]. The boundary layer equations have been transformed to simplify the solution for natural convection about cylindrical bodies with horizontal axes [76F]. Observations have been made of the wake formation over a cylindrical surface [57F].

The natural convection from a horizontal surface has been analyzed, including effects of buoyancy produced by concentration differences, as well as temperature differences [58F]. A non-similar boundary layer is found below a heated horizontal plate [2F]. The temperature and velocity fields in natural convection about an isothermal sphere in water have been measured over a large range of Rayleigh numbers [3F]. The velocity field around a horizontal torous has been measured by following the flight path of small particles in the surrounding air [1F].

Natural convection in the annulus between two coaxial cylinders has been studied including the effect of conduction on the temperature distribution in the central cylinder [62F]. A finite difference procedure has been used to calculate the temperature distribution and heat transfer for transient natural convection in a cylindrical container [75F]. Natural convection inside a horizontal cylinder with non-uniform surface temperature was measured [80F].

Performance in a closed thermosyphon is shown to be high when the interaction between the rising and falling flows is eliminated [37F]. Flow in a two-phase thermosyphon has been studied [38F]. Measurements have been made of the heat transfer in an open-ended cavity as a function of inclination [59F]. A numerical study [60F] shows the flow in a cavity with two side walls at different temperatures, and the top and bottom walls insulated. Natural convection cavity flows, including the effects of a moving wall, have been analyzed [69F].

As has been true for a number of years, the studies related to thermal convection in enclosed horizontal layers heated from below are quite numerous. Flow visualization demonstrates that in a rectangular cross section layer, rolls are obtained with the axes parallel to the short side [67F]. Another study describes the inception of convection in rolls [51F]. Increase in the size of two-dimensional rolls is observed as the Rayleigh number is increased [77F]. Two-dimensional rolls have been stabilized for study by inclining the horizontal layer [24F]. The instability of inclined fluid layers has been examined; in particular, the onset of rolls was studied [72F]. The flow induced in horizontal layers with transient thermal boundary layer conditions has been examined [11F]. A stability analysis shows the effects of periodically varying boundary conditions [45F].

The critical Rayleigh number of rectangular cavities has been calculated including effects of conductivity in the walls [14F]. A honeycomb to reduce the horizontal extent of the fluid layer can be used to retard the onset of flow [16F]. The effect of insulating vertical walls on determining the critical Rayleigh number at different aspect ratios has been examined [15F]. Experiments on heat transfer and thermal convection in small cells indicate that even with narrow width (compared to height), the Nusselt number–Rayleigh number relationship approaches that of a very wide horizontal layer as the Rayleigh number increases [31F].

The transition of convective rolls in horizontal fluid layers of a low Prandtl number fluid has been studied [12F]. A general minimum principle has been obtained for the post-critical Rayleigh number flow in a horizontal layer and related to earlier principles that maximize the heat transport [55F]. Experiments on the onset of low and post-critical heat transport in a horizontal fluid layer containing uniform energy sources find no sub-critical instability [35F]. Conversion of potential energy to kinetic energy in plumes and thermals has been discussed [71F]. Oscillatory instabilities are found in heating from below of certain non-Newtonian fluids [65F]. Another study also examines non-Newtonian fluids including the effects of transients near the critical Rayleigh number [53F].

A number of studies are concerned with thermal convection in porous media. One finds no sub-critical instability [7F]. Bounds for heat transport in convection of a porous layer have been obtained [13F]. The analysis of transient three-dimensional thermal convection has been posed [28F]. The heat transfer coefficient has been obtained in a horizontal porous layer [19F]. A strong dependence of heat transfer on angle of inclination has been found in thermal convection in confined porous material [27F]. Several forms of convective motion have been observed in inclined porous layers [9F]. The convection in a vertical porous wall significantly increases the overall heat transfer [8F].

The effects of thermal diffusion on the stability of two component layers of fluid heated from below has been analyzed [64F, 73F]. Instability can occur even when the density gradient is not adverse. Another study of stability of a two component layer emphasizes thermal diffusion [39F]. The importance of surface tension forces in two fluid layers has been shown [79F]. The effect of heats of solution on surface tension driven flows has been examined [25F].

The hydrodynamic stability of dilute surfactant solutions when heated from below was analyzed [56F]. Thermohaline instability and the resulting salt fingers in a porous medium with combined temperature and concentration differences have been studied [68F]. Stable and unstable situations have been described for thermohaline convection in which body forces result from both temperature and concentration differences [41F]. Convection problems occurring in water desalination were described [26F].

A number of studies were concerned with combined forced and natural convection heat transfer. In one, perturbation methods are applied to obtain the heat transfer along a vertical flat plate [70F]. The effects of secondary flow on heat transfer in a horizontal channel are correlated by the product of Reynolds, Prandtl, and Rayleigh numbers [18F]. Secondary flow and heat transfer in a horizontal parallel plate channel have been calculated [29F]. The classical Graetz problem has been treated including the effect of buoyancy on heat transfer in the entrance region of a horizontal rectangular channel [17F]. Experimental studies indicate the combined natural and forced laminar flow heat transfer in an asymmetrically heated channel [61F]. The effects of heat conduction in the duct walls on combined convection in a non-circular duct have been studied [30F]. Combined convection of a non-Newtonian fluid in a vertical tube has been analyzed [46F].

A review of present-day computer methods includes applications to the study of buoyancy effects in convective heat-transfer problems [21F]. Dissipation effects in natural convection have been examined [63F].

## CONVECTION FROM ROTATING SURFACES

The flow around a horizontal disk arranged within a cylindrical vessel was made visible by tracers [5G]. Mass transfer caused by the boundary layers on all disk surfaces was also measured. Sublimation of naphthalene from a rotating disk into air approaching normally to its surface was used [6G] to obtain local heat transfer coefficients. The experiments explain previously noted differences between analysis and experiment by the existence of a rim effect. The Navier–Stokes and energy equations were solved [1G] for a fluid between two disks

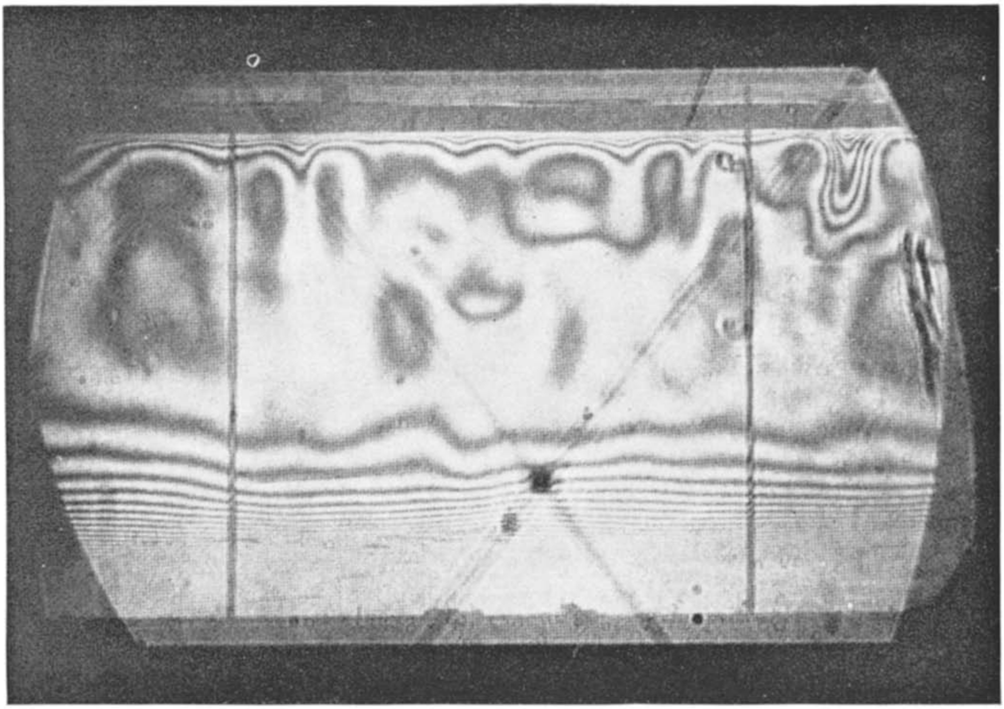

FIG. 1. Interferogram of natural convection in a horizontal fluid layer with volumetric energy sources. Note stagnant region below and unstable region above with plumes descending from the upper bounding surface [35F]

rotating with a speed ratio between $-1$ and $+1$ at Reynolds numbers from 0 .to 125, and for Prandtl numbers between 0·7 and 7·5. Vortices arise in a fluid rotating in solid body rotation between two horizontal disks when the lower disk is heated to a radically varying temperature. The solution to this problem was obtained [3G] for small Ekman numbers. The effect of rotation of water in a vertical annulus on Nusselt number was correlated [4G] through the Ekman layer thickness $\sqrt{(\nu/\Omega)}$ with $\Omega$ denoting the rate of rotation. Mass transfer in concentric rotating cylinders in the presence of Taylor vortices could be correlated [2G] by the equation $Sh/Sc^{\frac{1}{3}} = 9{\cdot}30\, Re_d$. The influence of chemical surface reactions was also studied.

## COMBINED HEAT AND MASS TRANSFER

Important applications for combined heat and mass transfer continue to be related to protection of surfaces exposed to high temperature gas streams, in particular, those encountered in rockets and gas turbine applications. Other work reviewed herein includes some questions related to heat transfer in drying.

Measurements were made of film cooling downstream of porous sections exposed to a high temperature gas flow. The secondary flow, although it significantly influences the adiabatic wall temperature, appears to have little effect on the heat-transfer coefficient [13H]. Measurements of the film cooling effectiveness in a Mach 6 airstream indicate that film cooling is much more effective downstream of injection than had been found in previous studies at lower Mach numbers [5H]. A model nuclear rocket chamber was film cooled to reduce the wall heat transfer [15H]. A finite difference method was used to predict the heat transfer and effectiveness downstream of injection through a tangential slot [1H].

Non-similar solutions for multicomponent boundary layer flow over ablating surfaces have been obtained [10H]. Film cooling measurements performed on a conical nozzle with non-adiabatic boundary conditions are reported in terms of a special film cooling effectiveness [4H]. A finite difference procedure is used to calculate the turbulent boundary layer along a surface on which coolant is added [11H].

A two-dimensional film cooling system with accelerated primary and secondary flows was used to simulate the conditions which might be encountered in gas turbines [19H]. Film cooling from the trailing edge of a turbine blade has been described including the effect on turbine performance [14H].

The effect of gas properties on heat transfer with mass addition along cones at various angles of attack was studied [17H]. Numerical solutions of the differential equations of flow show the influence of foreign gas injection on heat transfer in three-dimensional stagnation point flow [18H].

Empirical correlations of liquid film cooling are extended to include mass transfer data [7H]. Liquid film cooling has been applied to rocket chambers [2H] to reduce rocket wall temperature.

In using the mass transfer analogy, the effect of natural normal mass velocity at the surface is usually neglected. One study indicated that this assumption is valid in many applications [9H]. A key assumption in transpiration cooling is that the injected fluid accommodates completely to the temperature of the porous wall. If, however, the contact surface area within the wall is not large, there may be a difference in temperature between the wall and the exiting fluid, depending on the heat-transfer rate [12H]. A study of the heat transfer within a two-dimensional porous medium can also be applied to transpiration cooling [16H].

A variational analysis is used to study the mass-transfer rate from spherical particles; the effect of finite velocity normal to the surface is included [6H]. Combined heat and mass transfer to drying solids has been examined [3H]. The combined heat and mass transfer on a wetted-wall column has been measured [8H]; temperature and humidity profiles were also obtained.

## CHANGE OF PHASE

### *Boiling*

Experimental data in subcooled flow boiling are almost nonexistent. In [1J] high-speed photography was used to investigate the effect of fluid velocity on the growth and collapse of water vapor bubbles. Bode [7J] photographed growing steam bubbles near a flat horizontal wall in the presence of a mass transfer controlled electrolytic reaction. Sixty to seventy per cent of the heat necessary to produce a detaching vapor bubble is transmitted directly from the hot surface while the remaining 30–40 per cent is transmitted during the waiting time through the same area [21J]. Malenkov [55J] studied the dependence on breakaway frequency of bubble size. Unsteady motion of growing bubbles can be predicted using information on the steady-state motion of bubbles of constant size [69J]. Large Jakob number, nucleate boiling bubble growth rate, and experiment-analysis discrepancies [86J] were primarily due to neglect of liquid inertia. A technique for solving moving boundary problems by successive substitutions is applied to the bubble growth problem [46J]. Bubble growth and collapse in narrow tubes with nonuniform initial temperature profiles are studied in [22J]. Other related studies include the influence of pressure on heat transfer in bubble evaporation [91J], and the effects of liquid motion induced by phase change and thermocapillarity on the thermal equilibrium of a vapor bubble [27J]. The evaporating meniscus is one of the limiting parameters in heat pipes, grooved evaporators, fuel cells, suction nucleate boiling devices and sweat cooling devices [71J]. Marangoni effects play a dominant role in boiling from a downward-facing plate [40J]. In a droplet interchange model [62J], the intensity of droplet deposition and entrainment governs the axial velocity of each drop size and allows calculation of maximum stable drop diameters which agree with Wicks' data. Models based on mean drop size of a spray are not adequate in predicting the evaporation rate of polydisperse sprays [66J]. Data on droplet heat transfer during splattering is extended to smaller sizes using an electrostatic drop generator [37J]. A method of analyzing forced convection droplet evaporation with finite vaporization kinetics and liquid heat transfer has been developed [87J] for the computation of entire droplet vaporization rates from unknown stagnation point rates. Hupfauf [39J] describes temperature measurements on individual droplets in a cloud of drops. Three other related droplet papers deal with mechanism of vaporization, within a liquid, of immiscible moving droplets [76J], drag and stationary mass and heat transfer at bubbles and drops [8J], and evaporation in an air-droplet free turbulent jet [19J].

Hebert and Price [35J] studied droplet heat transfer for drops falling down a heated channel of small diameter. All appreciable heat transfer occurs in a short distance after the drop first contacts the channel. In experiments of droplet evaporation in stagnant environments, the effective mass difussion coefficients agree with analysis at 6·8 atm and was more than six times greater at 102 atm [59J].

Using thermodynamic similitude, a large volume of data are correlated [93J] for free convection boiling of Freons under conditions corresponding to the operation of refrigeration, heat pump, and thermal power devices. Pool film boiling experiments continue to receive attention [65J]. Additional experimental verification is given to the assumption that transient nucleate-boiling phenomena occurring in systems of sufficient thermal capacity can be assumed to be quasi-steady [67J]. With extremely small wires, hydrodynamic transitions in the boiling curve disappear. Nucleate boiling does not occur on such small wires [3J]. Reference [72J] discusses fully developed boiling with allowance for microgeometry of the surface. As yet, there is not complete theory of nucleation. Madejski's three-component effect model is improved in [54J]. Two stability papers describe the dependence of the stability criterior of nucleate boiling on the compressibility of the vapor [50J] and the thermal stability of surfaces heated by convection and cooled by boiling [34J]. The heat flux prediction of six different models proposed to explain nucleate boiling are unsuccessfully compared with measurements [44J] at varying levels of subcooling and acceleration. Vertical tube nucleate boiling of saturated helium I was carried out at boiling temperatures from 2·5 to 4·6° and noticeable hysteresis effects were found [36J].

In pool boiling, when the burnout heat flux is approached, a large number of dry areas are observed—some dry areas disappear while others grow and cause burnout. The differences are due to conduction along the heating surface [92J]. An analysis is given [48J] for the relation between critical heat flux and contact angle in pool boiling of flat heaters. Theoretical results agree with data for contact angles of 20–60°. Boiling heat transfer and crisis are correlated [81J] by $(T_w - T_s)/(T_{sup} - T_s)$ where $T_{sup}$ is the limiting superheat temperature where a very large number of fluctuating bubble nuclei appear. A hydrodynamic prediction for peak nucleate boiling heat flux on spheres employs no empirical constants and agrees with 27 experiments [15J]. An improved two-phase flow heat transfer has been discovered [12J] in coiled ducts (compared with straight) with higher burn-out heat fluxes. Reference [88J] describes the influences of coatings and deposits on heat transfer conditions downstream of burnout.

A new generalized correlation [11J] for stable natural convection film boiling heat transfer compares more favourably with the data than earlier expressions. A time-dependent heat transfer model [32J] of film boiling is adequate to describe natural convection of saturated and subcooled liquids. Transient film boiling data are reported [94J] for tetrachloride and Freon-113 on a submerged horizontal cylinder. Film boiling on vertical surfaces [89J] show that the laminar vapor film with a steady interface is confined to a short length and effects of interfacial oscillations and turbulence must be included even at short distances from the leading edge. High-speed photographs are used to explain oscillation effects on film boiling from a sphere [75J].

The idea of using a coating material of low thermal conductivity to improve fins in boiling liquids is attractive [79J]. The stable occurrence of all three regimes of boiling is possible on finned surfaces making it possible to obtain high heat fluxes without destroying the surface [68J]. Boiling of oil-contaminated Freons in bundles of finned tubes proceeds at lower rates than with pure refrigerants [13J]. Discrepancies in boiling heat transfer data in smooth and internally finned tubes using Freon refrigerants are a result of differences in experimental methods [38J]. Heat transfer in two-phase heat exchangers improves with increasing coil curvature according to Dean [9J, 31J]. A design correlation equation for subcooled boiling includes data from 10 sources, 6 heating surfaces, and widely different test section geometries [63J]. Empirical local heat transfer coefficients in falling-film evaporators are judged accurate enough for design [10J]. Upstream bubble injection increases heat transfer of water in a channel by 50 per cent due to induced secondary flows near the wall [47J]. Various investigators have studied the effects of additives in order to obtain increased heat-transfer rates. The enhancement of heat transfer in solutions of cleaning agents NaOH and $Na_2CO_3$ can be used to improve the performance of boiler systems [20J]. Heat transfer to water with "pseudoboiling" is studied [56J] for $P > P_{crit}$, $T_{liq} < T_{crit}$, $T \gtreqless T_{crit}$ coupled with high frequency pressure oscillations with frequencies from 2000 to 20 000 Hz. In [53J], the existence of thermoacoustic effects in liquids is formulated. Three-dimensional waves and roll waves increase heat transfer in stratified gas-liquid flow by more than 100 per cent [23J]. A dynamic analysis of the single phase region of a boiling channel is given in [95J] which accounts for wall heat capacity and the effects of pressure variations on the movements of the boiling boundary.

In comparing a theory [70J] for heat transfer in annular, two-phase, two-component flow with data, 85 per cent of the predictions were within $\pm 60$ per cent of recently measured values. In [6J] measurements of the structure of temperature fluctuations due to large gas bubbles in two-phase nonisothermal flow are characterized. Heat transfer from a hot water layer to a heavier Freon 113 layer was studied [80J] in a cell in which each layer could be independently stirred to yield parallel or counter-flow.

Rugin and Schweitzer [73J] analyze heat transfer in porous media with an evaporation front propagating into the medium. Unstable regions are examined. Possible flow regime limits for falling fluid flow, climbing flow, and circulation reversal are given for evaporator tubes and other evaporator equipment [90J]. References [14J] is typical of several papers dealing with heat transfer to air–solids suspensions in turbulent flow.

An extended Lockhart and Martinelli flow model [43J] can be used to predict pressure drop and void fraction for stratified and wavy flow where the L and M method is least exact. R. Martin [58J] describes void fraction measurements at high pressure in a heating channel. Commercial bubbly fluidized beds probably have radial variations in porosity up to 30 per cent [51J]. Hank's stability criterion has been extended [84J] to two-phase flows and the predicted transitions agree with experiment if the maximum velocity prior to transition appears in the less viscous phase. Calculations [61J] have shown that both the sound speed and the sound attenuation are strong functions of frequency in two-phase, single-component (liquid–vapor mixtures).

Six types of bubbling action in the dynamic regime are distinguished [60J] for inviscid flow into a deep pool from a single orifice. A new fragmentation mechanism is proposed [33J] based on the entrapment of quench liquid inside a molten globule caused by the collision of the globule with surrounding liquid. Falling-film solidification rates for water–ice inside a short vertical tube agree with London and Seban analyses [64J]. An analysis is made of the rates of drainage and evaporation of a liquid film on the horizontal surface that forms at either the interior or exterior surface of a tube [28J].

*Condensation*

Complex combinations of effects are now included in condensation problems. As an example, [18J] describes the effect of forced flow, noncondensables, and variable properties on film condensation of pure and binary vapors at the forward stagnation point of a horizontal cylinder. In another paper [83J] an interpolation formula is suggested to apply to all condenser geometries. A companion paper [41J] extends forced film condensation to include pressure gradients and small Prandtl number fluids. Reference [16J] deals with a related topic, effects of forced flow and variable properties on binary film condensation. Reference [74J] presents an integral solution for vapor and condensate flows on an arbitrary curved body in laminar flow at low Mach number. Reference [77J] contains an attempt to demonstrate that the role played by momentum transport of the condensing mass in the process of film condensation is significant. Reference [26J] analyzes the effect of vapor velocity on laminar condensation on a single horizontal cylinder. At high vapor velocities, up to 80 per cent of the total condensation takes place on the upper half of the cylinder. Guided by extensive numerical solutions, a semi-empirical method is developed [17J] for engineering calculations of laminar film condensation including noncondensable gas and forced flow.

Prior boundary layer solutions for condensation with suction can be replaced with a simpler (Nusselt–Rohsenow) calculation in almost all cases of practical importance [52J]. In reference [78J] an analysis of film condensation in a vertical cylinder with constant heat flux is favorably compared with experiment. Film condensation on downward-facing horizontal rippled surfaces are up to five times larger than the rates attainable on a flat horizontal surface of the same projected area [57J]. Laminar film condensation is examined on a vertical surface using the approximate integral method of Jacobs [24J].

Numerical simulation of dropwise condensation is receiving interest [29J] since the heat-transfer coefficient for dropwise condensation is an order of magnitude larger than for filmwise condensation. Local heat transfer during the condensation of water vapor in a vertical pipe reveals local maxima which are due to stripping of the condensate [42J]. An empirical interfacial-shear-stress correlation for high vapor velocity two-phase annular mist condensing flows is presented [5J]. Heat transfer from condensing mixtures of Freons 12 and 22 [49J] and 21 [30J] are tabulated. In [30J], condensation heat transfer for moving vapor is affected by the effect of suction from the boundary layer of the vapor on the coefficient of friction between it and the condensate surface. Heat transfer during condensation at vertical cylindrical surfaces is analyzed [85J] for the case where the effects due to curvature of the condensate film strongly influence heat transfer. Interfacial temperature drop is included on metal vapor condensing on a vertical surface [45J]. Condensation heat transfer from oil contaminated ammonia is higher than from pure ammonia [2J].

In keeping step with the ever-increasing size of steam turbine units, the design of condensers has been improved. The most efficient arrangement of tubes or tube banks is studied in [25J] for low pressure steam. Heat transfer data in a densely-packed, finned-tube bundle decrease sharply from the first to the fifth row and then remain constant for subsequent rows [82J]. Finally, a warning—examples of the danger of extrapolating condensation heat transfer effects by analogy with a single phase are given in [4J].

## RADIATION

### *Radiation in participating media*

Many papers consider radiation transport in nongray media; in particular in shock layers, particle clouds and aerosols, in liquids and in thin films. In addition, problems associated with simultaneous conduction and/or convection with radiation attracted great interest.

For closely spaced metal surfaces at low temperature, the heat transfer due to traveling waves greatly exceeds the results of classical theory which may be explained by the higher modal density resulting in a greater than classical energy density in the cavity and, therefore, in greater heat transfer. The results of the presented theory are consistent with experimental findings [5K]. Deviations of real cavities from an ideal black body are discussed and the effect which wall roughness may have on the spectral density of radiation within symmetric closed cavities in good conductors [18K]. The $S_n$ method, commonly used in neutron-transport theory, is successfully applied to radiative-transfer problems. Results for the simulation of re-entry problems show that the $S_n$ method is convergent and accurate [10K]. For the case of axisymmetric radiative transfer with isotropic scattering, a simple technique is described for finding solutions of the radiative transport equation in terms of eigenvalues and eigenvectors [37K]. A generalized integral equation for radiative heat exchange is derived which takes the selectivity of the radiation and the anisotropy of the bulk and surface scatter into account in systems of arbitrary configuration [1K]. Olfe's modified differential approximation is applied to the radiation-layer problem on a flat plate, and there is evidence that this approximation should yield not only qualitatively but also quantitatively quite accurate results for the two-dimensional radiation field of the hot-plate problem [27K]. Hottel's formula for the absorptivity of black radiation are validated for calculating the absorption of a nonisothermal medium from its weighted average temperature. The use of these formulas for calculating non-black incident fluxes is also demonstrated [12K]. The radiation characteristics of a scattering, absorbing dielectric layer are analyzed for the entire range of the optical constant $\beta$ by means of the two-flux model. For the limiting cases

($\beta = 0$ and $\beta = 1$), complete agreement with the correct solutions exists [8K].

A simplified expression for the rapid calculation of volume interchange factors describing radiative heat transfer is derived for non-homogeneous gases taking the non-gray spectral variations of the gas properties into account [16K]. An approximation to radiative transfer in a non-gray gas is proposed and its utility is demonstrated by considering one-dimensional finite and semi-infinite problems [19K]. A simple method for calculating non-gray radiation employs a step-wise gray approximation of the radiative absorption coefficient which reduces the numerical computer time. The utility of the method is demonstrated for the case of a hydrogen plasma, although the method may be used for plasmas made up of several species [33K]. For non-viscous, non-conducting flow of a radiating plasma over a flat boundary, the non-gray solutions differ significantly from the gray results and the differential approximation does not join the two limiting solutions in the non-gray case as it does in the gray case [36K]. Analytical expressions are derived for the absorption coefficient and the total band absorptance for a vibrational–rotational band and an application to CO reveals good agreement with experimental results [22K]. Broadening measurements of infrared absorption lines at reduced temperatures in $CO_2$ show that the approximate ratio of the measured collision cross sections for a given line is $\sigma(T_1)/\sigma(T_2) = T_2/T_1$ [46K]. Similar measurements using CO in an atmosphere of $CO_2$ at temperatures of 298, 202 and 132°K are compared with other recent experimental and theoretical results [45K].

The coupling of radiative transfer and chemical non-equilibrium phenomena behind high velocity, high altitude normal shock waves can be significant, affecting the entire flow field [7K]. An evaluation of one-dimensional approximations for radiative transport in blunt body shock layers shows that for both the radiative flux and its divergence, the tangent slab approach generally provides the most accurate results when compared with the differential approximation methods [49K]. Solutions for locally non-similar radiating shock layers about smooth axisymmetric bodies demonstrate that for the inviscid case, radiative cooling destroys the entropy layer [11K]. Radiative cooling effects behind a reflected shock wave are calculated for an absorbing-emitting gas by means of an expansion procedure in the density ratio $\varepsilon$ across the shock front. A two-band absorption model yields end-wall radiant-heat fluxes which agree well with available shock tube measurements [44K].

Measurements of the absorption of radiation in low-loss liquids at 6328 Å with a new technique show that the absorptivity of heavy water is $\frac{1}{60}$ that of ordinary water at the same wavelength [43K]. An attempt is made to predict optical properties of clear natural water. Predictions for the total attentuation coefficient compare favorably with recent data for the total attentuation coefficient obtained at several wavelengths in the Sargasso Sea [47K]. Refractive-index measurements of liquids ($NH_3$, $SO_2$, $H_2S$, HCl, HBr, OCS, $N_2O$, $Cl_2$) in the temperature range from 130 to 260°K with the 6328 Å line of a helium–neon laser indicate that the refractive indices are linear over the liquid range of these samples [51K]. The effect of thermal radiation on transient vaporization of a saturated liquid at a constant-temperature plate is analyzed and numerical solutions compare satisfactorily with data from the literature [29K]. Many simple chemical compounds exhibit pronounced changes in absorptivity between the vapor and liquid phases, particularly in the infrared [6K].

Combined conductive–radiative heat transfer in a partially transparent slab is studied introducing rigorous boundary conditions for specular-diffuse reflection [31K]. A study of radiative and conductive heat transfer in a molten glass slab results in an agreement between experimental and calculated temperatures within 5°F throughout the slab, and the measured and predicted heat fluxes agree within

10 per cent [17K]. Radiative–conductive heat-transfer studies in semi-transparent solids (molten quartz, sapphire, cadmium sulfide, selenium–arsenic glass) indicate that the gray approximation results in large errors (up to 45 per cent) for the first material whereas results for the last two materials are only by a few per cent in error [32K]. An analytical investigation of transient radiation and conduction in an absorbing, emitting, scattering slab with reflecting boundaries shows that the influence of radiation on the temperature distribution is initially negligible but becomes significant with increasing time [28K]. Transient combined conductive and radiative heat transfer in a plane gray layer confined between black walls is investigated for a layer which is intiaially at uniform temperature with one wall suddenly decreased in temperature [13K].

A different approach for calculating diffuse radiative transfer through plane-parallel particulate clouds depends on the values of two parameters which are empirically related to the optical properties of the particles and the surrounding medium [40K]. Studies of the emission properties of individual particles of silicate materials for particles sufficiently small (< 1 μm) to be optically thin at all wavelengths from 6 μm to 12 μm to particles which are large enough to be optically thick indicate that the emission behavior of small particles is dominated by scattering whereas larger particles approach the behaviour of a polished plate [23K]. The infrared refractive index of atmospheric aerosol substances is investigated for a wavelength range from 2·5 μm to 40 μm. A simple model confirms the measured transmission of a coarse dry powder of water solubles and shows that the extinction by natural aerosol should have a minimum near 8 μm and a strong maximum near 9 μm [48K]. Radiative heat transfer in gaseous suspensions of fine particles leads to high heat transfer coefficients which are of great practical interest. Analytical results are presented for laminar heat transfer between parallel, flat plates [14K] and for laminar flow in the entrance region of a pipe [15K]. The contribution to transmission measurements by scattering in percent of the incoming circumsolar radiation is evaluated for two aerosol-size distributions at different optical depths and wavelengths and for a field of view region up to 14 degrees [20K].

Properties of thin transparent or slightly absorbing surface films (optical constants, thickness of films) can be determined by using parallel polarized radiation [38K]. Optical constants of metals may be derived from the reflectance and transmittance of thin absorbing films deposited on a transparent substrate for normal and oblique incidence, s and p polarization, and different film thicknesses [34K]. Measurements of reflection, transmission, and phase shift of radiation at imbedded optical films indicates that there is a variation of absorption of the film with optical-path difference [39K]. The reflection of light by a system consisting of a non-absorbing isotropic film and a non-absorbing isotropic substrate with both boundaries (air–film and film–substrate) rough is studied and the agreement between theory and experiment is fairly good [35K].

Combined convective–radiative heat transfer is studied at the stagnation point of a body exposed to the flow of a radiating mixture of $CO_2$ and $N_2$ [26K]. Radiating boundary layers at planetary entry velocities are studied and for the particular case of earth re-entry trajectories including return from the far solar system, it is shown that convection is the dominant mode of heat transfer for vehicles of moderate size [42K]. Simultaneous heat transfer by free convection and radiation from a vertical plate immersed in an absorbing, emitting, isotropically scattering, gray fluid is analyzed by solving the non-similar momentum and energy equation [9K].

Measurements of infrared absorptivities of the transition metals, nickel, iron, platinum, and chromium at both room and liquid-helium temperatures in the wavelength range from 2·5 to 50 μm are in substantially better agreement with theory if the modification of the relaxation time due to the photon–electron–phonon interaction is taken into account [25K]. A method is proposed suitable for determination of low bulk absorption coefficients which makes use of the correlation between absorption coefficient and the temperature rise at the surface of the bulk material [50K]. A simple model for the calculation of the flux of solar radiation through the atmosphere substitutes the actual atmosphere by a model atmosphere consisting of $n$ homogeneous layers. The model offers the opportunity of determining the transmission and reflection statistics of any individual cloud type by a suitable least-square procedure [41K].

Reflection and transmission measurements for the 12·5–300 μm wavelength region are presented in graphical form for several materials [30K]. The total emissivity, total band absorptance, and Planck mean absorption coefficient of compressed oxygen are calculated for a temperature range from 100 to 1000°K. All of the total band absorptance results can be represented with a two-parameter correlation [24K]. In a study of supersonic flow over convex and concave shapes, including ablation effects, a gray gas model is introduced for the radiation field without restriction of the optical depth and without the slab approximation. Results show a significant departure from the slab approximation near surface discontinuities and large radiative energy losses near cold surfaces [3K]. In connection with zonal calculations of radiant heat transfer in industrial furnaces the error involved in determining the radiation intensity of a gray medium with non-uniform temperature distribution is estimated if different numbers of computational zones with averaged temperature are introduced [4K].

A theory for the temporal development of thermal blooming of laser beams in fluids is developed and its application to available data demonstrates good agreement [21K]. Thermal blooming of laser beams in gases is studied with and without wind transverse to the beam propagation. A general time dependent model for the interaction of a laser beam with a compressible, absorbing medium in the presence of wind is developed [2K].

*Surface radiation*

The total emittance of graphite, molybdenum, tantalum, and tungsten is reported [10L] as a function of incidence angle in the temperature range from 1000 to 3000K. The bi-directional reflectance of the moonlit earth surface measured from a satellite in the visible wave length range [7L] agrees with the model by Plass and Kattawar. The reflectance of cavities was measured with a helium neon laser [8L] and by light in an Ulbricht sphere [1L]. Analyses considered the emission of thermal radiation from a microscopically roughened dielectric surface [4L] and from roughened strongly absorbing walls [11L]. An analysis demonstrates the effect of polarization on the apparent emittance of rectangular grooves with specular walls [14L].

A 0·3 μ thick layer of alumina powder on a metallic substrate increases the spectral emittance from 0·1 to 0·6 at wave lengths from 1 to 10 μ [3L]. The spectral low temperature emittance of a thin metallic film on a dielectric substrate exhibits a minimum at a certain film thickness [6L]. The infrared radiation of thin plastic films with and without a metal substrate has been studied [15L].

Diagrams present the radiation shape factors from a plane point source to coaxial rings, isoceles triangles, and coaxial cylinders [5L]. An efficient matrix computation of shape factors was reported [12L].

The problem to analyze radiative heat transfer was formulated as a system of non-linear algebraic equations in such a way that it is well adapted to solution on a high speed computer [2L]. Six simplified models for radiative heat transfer analysis are compared among themselves [16L] and with experimental results [17L].

The unsteady state of a disk heated by a time variable radiation flux was calculated [9L] to predict the performance of a disk radiometer. Efficiencies of honeycomb absorbers for solar radiation were computed [13L] and the results were compared with the performance of plane selective absorbers.

### LIQUID METALS

Experiments [6M] established convective heat transfer coefficients for liquid potassium flowing turbulently through straight pipes made of refractory metal for Péclét numbers between 100 and 550 and for heat fluxes up to $5 \times 10^5$ $W/m^2$. Numerical calculations [11M] determined liquid metal heat-transfer coefficients using Lyon's integral equation and various expressions for the eddy diffusivity at $Pr =$ 0·001, 0·02, 0·1 and for $Re = 10\,000$. Expressions published by Deissler and Mizushina-Sasano for the eddy diffusivity gave best agreement with experimental results. The effect of wetting on turbulent diffusivity of heat and momentum was established [7M] for flow of mercury through annuli. Experiments [5M] resulted in Nusselt numbers for natural convection of mercury at a vertical flat plate which deviate from analytical values by 20 per cent at $Gr =$ 20 000. Heat-transfer coefficients for a closed thermo-syphon filled with water, mercury, or NaK were measured [10M].

The growth pattern and the vaporization rates were measured for superheated sodium in a vertical channel [12M]. The influence of a liquid metal fast breeder reactor environment on incipient boiling superheat was shown analytically [8M] to be small for the size range of cavities expected in LMFBR systems. The effect of non-uniformity of the heat supply over the length of a duct on critical heat flux during the boiling of potassium in pipes was clarified experimentally [2M]. Experiments established the transport coefficients appearing in the linear rate equations obtained from irreversible thermodynamics [3M]. The analysis was then modified to remove discrepancies between experimental results and existing theory for liquid–vapor phase change of mercury. Heat transfer during the condensation of potassium vapor in a pipe cooled by liquid sodium was measured [1M]. An analysis for film condensation of metal vapors on vertical plates and tubes [9M] resulted in good agreement with recent experiments when the presence of small amounts of non-condensable gas was postulated. The condensation of cesium vapor from argon flowing through a tube or across a tube bundle at Reynolds numbers between 1200 and 3000 resulted in deposition rates up to 45 per cent [4M].

### LOW-DENSITY HEAT TRANSFER

Measurements of accommodation coefficients of various noble gases on platinum show a clear effect of gas molecular weight [6N]. The Lees–Liu approximate moment method of solution of the Boltzmann equation has been extended to binary mixtures, and values of the thermal slip parameter determined therefrom agreed well with experiment [1N]. An analysis of the heat conduction in a rarefied gas between concentric cylinders or spheres was based on the four moment method and showed that the heat transfer ratio $Q/Q_{fm}$ ($Q_{fm}$ corresponds to free molecule conditions) is a function of the temperature difference [4N]. In an independent analysis for concentric cylinders, the ratio $Q/Q_0$ ($Q_0$ corresponds to continuum limit) was also shown to depend on the temperature ratio [3N]. When a realistic gas–surface interaction model is used, it was found that the Knudsen permeability is not proportional to $T^{-\frac{1}{2}}$ as given by traditional theory [7N].

A small particle suspended in a nonisothermal gas will experience a force which will tend to move the particle in the direction of decreasing temperature. The magnitude of such forces has been predicted for the entire range of Knudsen numbers [5N]. It has been proposed that thermal stresses can induce flow in a rarefied gas [9N].

The discrete ordinate method was employed to solve the problem of heat transfer in rarefied plane Couette flow, with good agreement being obtained with macroscopic results from computationally more demanding methods [8N]. The Langmuir expression for vaporization and the Fourier heat conduction equation formed the basis of a model for investigating the heat transfer aspects of vapor deposition in vacuo [10N]. Using a kinetic model equation with the correct Prandtl number and Eucken factor, a variational technique was used to calculate the heat transfer, temperature, and density distributions between parallel plates [2N].

## MEASUREMENT TECHNIQUES

Development of instrumentation related to heat-transfer studies continues to draw the attention of a number of investigators. The present section is primarily restricted to devices related to temperature and heat transfer measurements and fluid velocity measurements.

A review of calibration procedures for precision platinum resistance thermometry includes the effects of recent changes in the International Practical Temperature Scale [4P]. Sealed metal freezing point cells prevent contamination when used to calibrate thermometers [45P]. A transient technique enables rapid calibration of fine wire thermocouples over a range of temperature [46P]. Some carbon resistors can be used as stable thermometers over the temperature range 4–300 K [25P]. Conduction errors in temperature measurement at low temperatures have been calculated [26P]. Specially designed thermocouples help overcome the difficulties encountered due to inhomogeneity in the thermocouple wire when measuring temperature in a non-uniform field [32P]. High-temperature stable thin-film nickel thermocouples have been used up to 1000°C [37P].

The temperature error due to radiation from surroundings has been measured [40P]. Significant errors can occur when measuring the temperature of gases at low pressure because of small heat transfer coefficients between the gas and a thermometer [9P]. Serious errors can be introduced in thermocouple temperature measurements due to improper grounds in the circuit [5P]. Errors encountered in the measured temperature of an unsteadily heated body have been studied [6P]. Techniques for eliminating the effect of radiant heat transfer in measuring the surface temperature of glass have been discussed [22P].

Use of probes of different diameters helps to eliminate errors in measuring flame temperatures [30P]. Fiber optics probes have been used for taking spectral measurements in flames [17P, 41P]. A specially aligned Fabry–Perot interferometer can measure the Doppler shift in arc-heated flows [1P]. Local temperatures have been measured remotely in a flowing gas from Raman scattering [18P].

A simple differential interferometer has been constructed using a ground glass [11P] and a description of the use of Moiré fringes resulting from imperfect mirrors in a Mach–Zehnder interferometer has been given [47P]. A Wollaston prism was used to convert a standard Schlieren system to a Schlieren interferometer [44P]. A Schlieren system has been used to study temperature fields in solids [33P]. The variation of surface luminescence of suspended zinc sulphide with temperature is used to measure fluid temperature near a wall [20P].

Sweeping a calorimeter through an arc jet heater permits measurement of the high prevailing heat fluxes [39P]. Calculations show the application of Gardon type heat flux gauges of moderate thickness [24P]. An apparatus for providing a controlled temperature gas stream has been designed [21P]. A heating rate controller has been used for conductivity and thermoluminescence measurements [28P]. A survey of different methods of measuring the thermal emittance of solids at high temperatures has been presented [34P].

A small needle-like probe has been developed to measure the thermal conductivity of tissue *in vivo* [8P]. A transient technique using a laser pulse as energy input enables measurement of thermal diffusivity of liquid metals to 300°C [42P]. Another transient method has been developed for measuring thermal diffusivity of solids [23P]. By using a periodically imposed heat flux, the thermal diffusivity, conductivity, and specific heat of different solid materials have been determined [7P].

Considerable activity has been directed towards the use of hot-wire anemometers under varying conditions and with different refinements. An additional term added to the well-known King Equation for hot-wire anemometer response increases the accuracy of the relation [43P]. The effects of low pressure, natural convection and yaw angle on anemometer response have been examined [10P]. Calibration of hot-wire anemometers at low velocities where natural convection is important is considered [19P]. A modified King Equation has been used to calibrate hot wire anemometers at low gas velocities and moderate Knudsen numbers [3P]. Significant departures from standard calibrations are found when calibrating inclined and crossed hot wires by vibrating them in a steady flow [31P]. A control apparatus has been designed to maintain the temperature of a heated wire constant under changing heat removal rates [36P]. One quarter ($\frac{1}{4}$) micron diameter hot wire anemometers have been constructed for use in air up to a Mach number of 10 [12P].

Probe displacement to be used for pitot tubes near a wall has been measured over a range of tube diameters [2P]. A hot film embedded in a wall has been used for the study of biological flows [38P]. A pair of heated film gages can be used to measure flow direction and magnitude [29P].

Interest also remains high in optical measurements of fluid velocity. A report on a conference devoted to laser anemometry has appeared [13P]. A key advantage of laser anemometry is its remote measurement of fluid velocity. A $CO_2$ laser was used with a laser–Doppler system to enhance remote measurement of wind velocity [27P]. Although some of the measurements in that study were taken as far away as 300 m from the light source, most of the data was confined to a range of about 30 m. A technique for getting three velocity components in a laser–Doppler system has been developed [15P]. The analysis of a laser anemometer operating with a fringe system indicates the possibility of measuring particle size, number density, and velocity simultaneously [14P].

An optical technique has been developed to measure mean wind velocity [35P]. A flowmeter based on a ring laser has been used to measure mean flow velocity in a channel [16P].

## HEAT TRANSFER APPLICATIONS

### *Heat exchangers and heat pipes*

Studies on heat exchanger surfaces covered the effect of surface roughness [21Q], of fins [22Q], of plate heat exchangers [5Q, 13Q], of spiral heat exchangers [12Q], and of cross-inclined tube bundles [17Q]. Two-phase [3Q, 8Q] and two-component [1Q] flows in heat exchangers were investigated. Methods were developed to predict the performance of systems of heat exchangers [14Q, 16Q]. Work is continuing on the analysis of regenerators [11Q, 15Q, 18Q].

A survey [20Q] covered recent developments in heat pipes. Detailed investigations were concerned with optimization of a heat pipe [9Q], with gas–liquid [6Q], and with two-component heat pipes [19Q]. The effect of the magnetic field of a fusion reactor on heat pipe performance can be reduced by a proper heat pipe geometry [2Q]. The wick design affects the temperature distribution [7Q] and dry-out limits [4Q] of a heat pipe operating vertically against gravity. A gravity operated heat pipe can be used as a thermal switch [10Q].

### *Aircraft and space vehicles*

Papers in this section refer mainly to ablation, heat shield performance, re-entry and rocket heat transfer, especially in connection with space shuttle.

A computer program is described suitable for the analysis of the transient response of an ablating axi-symmetric body including the effects of shape changes [11R]. Studies of the reactions of the silica reinforcement fiber and ablation char of the Apollo heat shield in laboratory tests using an arc image furnace and in actual re-entry tests revealed that SiC was formed in the front surface of the char. The SiC formed was found to act as a heat sink in the ablation process and can lower the front surface temperature by 300°F [5R]. Critical defects in ablative heat shield systems (fiber-filled, honeycomb-reinforced, low-density elastomer) suitable for space shuttle were studied and the data indicate that, within reasonable tolerances, the fabrication defects are not critical in terms of re-entry performance of the heat shield [21R]. A study of the rate of damage by ultraviolet radiation to a zinc oxide–silicon coating indicates that the damage is a function of wavelength, intensity, dose, and time [2R].

An improved transpiration cooling concept for space shuttle vehicles utilizes a ceramic coating of much higher permeability than the sintered metallic structure which results in substantial reductions of the coolant requirements [18R]. Surface flow patterns and aerodynamic heating of space shuttle vehicles are investigated using suitable models. Surface oil-flow pattern and heat distributions illustrate some of the problem areas involved in understanding the conditions to which typical shuttle vehicles will be exposed [12R]. Space shuttle vehicle entry conditions are simulated using two arc-heated duct facilities which provide high temperature, supersonic, turbulent boundary-layer flows over relatively large samples of candidate materials for thermal protection systems. The ranges of heat-transfer rate, heat-transfer coefficient, and surface temperature attained are adequate to provide the desired simulation [8R]. Calculations of laminar heat transfer to the windward surfaces of straight wing shuttle vehicles at high angle of attack and with yaw based on swept cylinder theory are in general agreement with measurements in areas free of external flow interference [14R]. Laminar flow studies of a low temperature space radiator model using D-shaped tubes indicate that heat transfer and pressure drop for the radiator can be predicted within engineering accuracy with existing correlations [6R].

Turbulent base heating measurements obtained from flight tests of a very slender re-entry vehicle indicate that the effective bluntness of these slender vehicles is quite noticeable even at the aft end of the vehicle [10R]. Simulation of the conditions experienced on the conical forebody of a high-ballistic coefficient re-entry vehicle showed that mass loss from thin liquid surface films is a strong function of surface shear [17R]. Heat pipe cooling is found to be an attractive, feasible technique for limiting leading edge temperatures of hypersonic ($6 \leqslant M \leqslant 12$) cruise aircraft [20R].

Simple methods for calculating the magnitude of heat transfer are presented for a number of basic heat transfer processes which are of importance in rocket engines [23R]. In connection with the study of the effect of external radiation on the burning rate of solid propellants, it was observed that thermal radiation from the walls increases the burning rate of the propellants by as much as 100 per cent [7R]. Further evidence is presented about serious discrepancies between measured transient temperatures in solid-propellant motors and those predicted by the classical Fourier equation using independently measured thermal properties. No explanation is given for these discrepancies [15R]. Pyrometric measurements during Apollo 15 launch indicate peak exhaust plume temperatures of the Saturn V first stage of 2370°C if the plume is assumed to radiate as a black-body source [13R]. The NERVA flight engine as well as nuclear rocket engines under development utilize nozzle extensions made of a graphite composite materials. Erosion studies of this material with high temperature supersonic hydrogen flow show reasonable agreement with theoretical predictions for surface temperatures below 3000°K [19R].

A review of spectral reflectance and emittance of Apollo 11 and 12 fines (powders) confirms, in general, the measurements made by remote sensing [4R]. The spectral emittance of Apollo

12 lunar fines decreases with increasing bulk density for the shorter wavelength range (2–6 μm); and as the wavelengths become larger, the material behaves as if it were a solid body [3R]. Earth-based measurements of the infrared emission from the lunar surface reveal significant directionality effects which are associated with the topographical roughness of the lunar surface [1R].

Experimental investigations of base heating on typical Mars entry body shapes show that the angle of attack effects can result in either increasing or decreasing base heating depending upon the location of the base region [22R]. In connection with technical feasibility studies of a 1978 atmospheric probe mission to Jupiter, it is found that the thermal control of such a probe requires a number of configuration trade-offs [16R].

In order to demonstrate the influence of radiative heating on the physics of the Earth's atmosphere, monthly zonal mean global radiative heating rates were calculated which show for all seasons that radiation cools the troposphere almost everywhere [9R].

*General*

Goals and trends in present heat-transfer research were discussed [2S]. Multilayer insulations containing helium at moderate vacuum and low compressive loads were measured [4S] achieving thermal conductivities between $10^{-4}$ and $10^{-5}$ W/mC. Full-scale investigations of the heat storage capacity of buildings were carried out during two heating seasons in Moscow [1S]. The dynamic characteristics of the fluid temperature in the duct of an air conditioning system are strongly affected by the material and thickness of the duct wall but little by its insulation [3S]. Thermal effects of power plants on lakes are influenced by the heat flux at the water surface and by the diffusion coefficient at the thermocline [5S].

*Energy production*

The cooling of gas tubine blades is still attracting the attention of experimentors. Studied were impingement cooling for a variety of jet arrangements and cavity shapes [8T] and solid particles in the jets which were found to decrease heat transfer [10T].

Various refrigerants are proposed and investigated as suitable medium for power cycles [9T]. Temperature conditions in the channels of liquid metal fast breeder reactors have been analyzed [1T, 7T] as well as bubble formation in sodium [6T]. The calculated superheat was found to agree with Freon 113 experiments.

Solar energy as a power source was considered in various studies. Numerical calculations on inclined flat plate solar collectors [3T] included free convection effects in the heated tubes. A high-speed solar water heater has been described [11T]. The effects of reflecting layers of salt on the water surface of solar stills was analyzed [5T]. Direct conversion schemes utilizing the photovoltaic effect [4T] or the wave-like properties of radiation interacting with absorber-converter elements [2T] are discussed.

## PLASMA HEAT TRANSFER

Heat-transfer studies in ionized gases reported during the past year refer to fundamental investigations, as well as to applications.

An analysis of magneto-convective boundary layer flows indicates that for large Prandtl numbers, the magnetic field has little influence on the transport process while its effect is greatly enhanced for fluids of small Prandtl numbers [15U]. Analytical results of heat transfer studies in MHD flow with parallel magnetic field on a flat plate at high Prandtl numbers compare favorably with previous calculations [16U]. The effect of an elevated electron temperature on anode heat transfer for a flowing argon plasma is significant for the overall heat transfer due to the enthalpy transport by the electrons [3U].

Local heat transfer studies to a wire immersed into a highly ionized, dense argon plasma reveal that the boundary layer surrounding the wire is not in chemical equilibrium. Experimental data are correlated with a semiempirical dimensionless relationship (Nusselt number) which contains in addition to Reynolds, Prandtl, and Schmidt number the degree of ionization and a dimensionless potential existing between plasma and probe [13U]. Electric field strength and wall heat transfer measurements for the heating region of an atmospheric cascaded arc (Ar, He, $N_2$) are in excellent agreement with nonequilibrium predictions over the entire current range. Helium arcs are characterized by drastic departures from LTE [12U]. The wall heat flux in a variable area arc constrictor is significantly influenced by both the cross-sectional area and the arc current [9U]. Heat transfer from an arc plasma to a constraining tubular enclosure increases substantially if an axial magnetic field is used to rotate the arc [5U]. Anode heat transfer measurements from a constricted arc are compared with the predictions of an anode heat transfer model. The authors claim that better estimates can be obtained from empirical correlations than from this model [11U].

Wall heat transfer measurements for laminar flow in a square conducting channel with and without applied transverse magnetic fields indicate an increase in the Stanton number of a factor of as much as six for magnetic fields approaching 10 kG. These increases of heat transfer are attributed to Joule heating augmented or accompanied by magnetically induced ionization [14U]. Results of heat transfer studies in the separation, reattachment, and redevelopment regions along a tube and nozzle located downstream of an abrupt channel expansion for a flow of partially ionized argon demonstrate that up to 90 per cent of the inlet energy may be lost by heat transfer to the tube and the nozzle wall [2U].

Investigation of non-equilibrium effects present in the formation of a shock wave in a low density, slightly ionized flow (argon freejet plasma) leads to the conclusion that a precursor region of elevated electron temperature exists coinciding with the observed dark region preceding the shock wave [4U]. Hypersonic flow of a viscous, heat conducting, radiating air plasma over a blunt-nosed graphite body is considered and the influence of ablation products on the heat transfer to this body is calculated [6U].

A heat pipe is used for stagnation-point heat transfer measurements. Data from a plasma torch operated in the laminar regime are in agreement with theoretical, laminar flow predictions [1U]. A radiation gauge for measuring total radiative heat fluxes from rotationally symmetric plasma may be applied for situations in which radiation is not the dominant contribution to the wall heat flux [10U].

In connection with thermonuclear fusion, collisionless heating of a plasma by transit time magnetic pumping has been analyzed [8U]. Computer simulations of plasmas driven by large-amplitude electric fields oscillating near the ion plasma frequency reveal instabilities excited by the large fields leading to an efficient heating of the plasma [7U].

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