Int. J. Heat Mass Transfer. Vol. 11, pp. 83–116. Pergamon Press 1968. Printed in Great Britain

HEAT TRANSFER—A REVIEW OF CURRENT LITERATURE

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INTRODUCTION

THIS review is concerned with research in the field of heat transfer, the results of which have been published during 1966 or late in 1965. The total number of papers in this field continues to be so large that only a selection can be included. A more detailed listing is contained in the Heat Transfer Bibliographies published periodically in this journal.

The 1966 Heat Transfer and Fluid Mechanics Institute was held in June at the University of Santa Clara, California. One invited lecture by S. S. Penner and approximately twenty papers were concerned with heat transfer. Proceedings are available at Stanford University Press. The Third International Heat Transfer Conference was held 7 through 12 August at Chicago, Illinois. Invited lectures by R. S. Silver, Stuart W. Churchill, S. Ostrach, and S. S. Kutateladze, as well as 177 papers in the various fields of heat transfer were presented and discussed. The papers and lectures will be published in proceedings of the conference. The Max Jakob Memorial Award was given at this conference to H. C. Hottel. Tentative plans were made for the next International Heat Transfer Conference at Paris in 1970.

Several books or proceedings of conferences appeared on the market dealing with fields related to heat transfer. They are listed at the end of this paper.

Developments in research on heat-transfer problems during 1966 can be highlighted by the following remarks: In thermal conduction, attention was paid to contact resistance, to the thermal conductivity of composite materials, and to solutions of the Fourier equation for a variety of boundary conditions and geometries. In boundary-layer flow, the trend was toward the study of conditions at very high temperatures so that ionization as well as dissociation occurs. The influence of various relaxation processes was included. The increase of heat transfer by the presence of solid particles was measured. Rocket development guided research towards the study of heat transfer in nozzles and diffusors. A large number of papers was devoted to the study of various heat-transfer situations in packed and fluidized beds, indicating that this field is still far from being thoroughly understood. Combined free and forced convection as well as heat transfer in horizontal layers, heated from below, found attention. Several papers were concerned with accommodation coefficients in low density heat transfer. Supersonic transpiration cooling, utilizing air or other gases, was investigated. In boiling and condensation, the trend is toward a detailed study of the nucleation and nuclear condensation with the hope that some day this research will lead to a general understanding of heat transfer connected with change of phase. Thermal radiation processes with participating absorbing gases and on specially designed surfaces with desired angular flux distribution found attention. Discrepancies between analytic and measured heat-transfer coefficients in liquid metal film cooling were explained by the presence of an interfacial resistance. Thermocouples and resistance thermometers were developed with the goal to minimize thermal lag in the measurement of surface temperatures. Various fluid models were utilized in the analysis of heat transfer in non-Newtonian fluids. Prediction of transport properties at high temperatures, measurements at very low temperatures, and the search for improved atomic models characterized research on properties.

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

Research in conduction centers on unsteady heat flow, the use of mathematic techniques to solve problems with a variety of boundary conditions, and the heat flow associated with the moving boundaries of phase change.

Kaliski [24A] uses the phenomenological theory of heat conduction based on the thermodynamics of irreversible processes to obtain a wave-like linear differential equation of heat conduction corresponding to a finite velocity of thermal disturbances. Gurtin [16A] considers the relation between thermodynamics and the possibility of spatial interaction in rigid heat conductors.

Transient conduction in solids is considered for cases with random external temperature and/or where random internal heat generation occurs [45A]. Unsteady-state heat flow for systems of variable geometry include: diffusion of heat from a sphere to a surrounding medium [3A], heat flow in an infinite region bounded internally by a circular cylinder with forced convection at the surface [23A], heat conduction in a medium bounded internally by a cylinder with periodically varying temperature of the gas within the cylinder [39A], transient heat conduction from an infinite wedge [34A], and varying temperatures in a 30° right triangle [43A]. Watt [59A] gives general solutions of heat conduction for axially symmetric pulse heating of a cylindrical sample with constant surface conditions. Two studies treat slabs: the first [38A] presents a solution of the general problem of finding temperatures inside a slab under time-variable boundary temperature and the second [4A] studies transient heat flow in a finite homogeneous slab with one or more resistance discontinuities. At low temperatures, the thermal relaxation times of thin films on crystal substrates have been measured [57A]. Other works present an approximate method of solving nonlinear problems of heat conduction [52A] and the method of subregions for non-isotropic mediums [53A].

Khristichenko [26A] gives a method for solving one-dimensional conduction in two and three layer planes (with contact resistance at interfaces) for various geometries.

Fluid-particle heat exchange is investigated in a number of papers: measurements of heat transfer during the quenching of very small metal parts [47A]; the temperature field of a ball heated in counterflow [58A]; heat transport and temperature distributions in large single drops at low Reynolds numbers—a new experimental technique [19A]; and simple asymptotic relations for heat transfer to uniformly or nonuniformly sized clouds of particles [14A].

Steady-state heat-conduction investigations include the mixed boundary value problem of heat conduction for an infinite slab [11A], a method for the approximate solution of two-dimensional diffusion problems [54A], heat conduction in layered mediums—the half-space and sphere [42A], the steady-temperature interior to a finite or semi-infinite cylinder with a discontinuous radiation [25A], and the non-uniform cooling of a heat-generating cylinder or sphere due to arbitrarily varying heat-transfer coefficient on the surface [12A].

Contact resistance is studied experimentally and theoretically by Clausing [9A] with good agreement. The same author examines the influence of thermal strain on heat transfer at the interface of dissimilar metals [8A]. Thomas and Probert [50A] study the variation of thermal conductance of multilayer materials with applied load at cryogenic temperatures.

The moving boundary heat-conduction problem occurring with phase change receives the attention of a number of workers. Lin [35A] describes a law of similarity for one-dimensional heat conduction with phase change. Kvalvasser and Rutner [30A] use operational techniques to obtain solutions for all three basic types of boundary conditions. Other works treat freezing front motion and heat transfer outside an infinite, isothermal cylinder [51A], the freezing of spheres [31A], and heat transfer from a surface at a temperature below the fusion temperature of the surrounding medium [33A].

Fin systems are considered by Hohenhinnebusch [20A], who gives temperature distribution and heat dissipation capacity for straight composite fins. Antuf'ev [1A] studies the effectiveness of various forms of finned surfaces in transverse flow and Langston *et al.* [32A] report vapor-chamber studies of the fin concept for space radiators. Temperature distribution and heat conduction in a rod-bundle fuel element for reactors are calculated by computer and approximate formulas and compared [37A].

A miscellany of papers includes a study of thermal stresses due to prescribed temperature on the curved lateral surface of a finite cylinder with ends in contact with smooth insulating plates [5A], the heat absorption characteristics anodized aluminum [40A], heat conduction in polymer materials in thermal destruction [46A], and heat transmission in insulated masonry structures under unsteady heat flow conditions [6A].

Analog solutions are involved in the following papers: temperature field of a body bounded by conical surfaces as influenced by an instantaneous annular heat source [27A], alternating direction schemes for the heat equation in a general domain [21A], establishing a relationship between a thermal conductor of arbitrary shape and a rectangular array of electrical resistances [48A], and a presentation of particular plane heat-conduction problems with mixed boundary conditions which agree with earlier analog solutions [56A].

A variety of mathematical techniques are used to solve heat-conduction problems. Fairweather and Mitchell [13A] introduce a new alternating direction method for parabolic equations in three space variables. Surkov [49A] applies finite integral transformations to problems of non-stationary heat conduction of hollow cylinders with a movable internal boundary. A new integral equation for calculating heat flux in inverse heat conduction is presented [10A] as well as an integral method for solving the general problem of transfer of heat and matter [55A]. Kuzmin [29A] uses the method of paired integral equations to study axially symmetric heat flow in an infinite slab. Noyes [41A] examines Saint-Venant's principle in anisotropic media and Hayakawa [18A] applies Legendre functions with non-integer indices to problems of conduction of heat. Heat conduction in bodies of revolution are considered for the non-homogeneous case [36A] and the prolate spheroidal solid [17A]. Kranyš [28A] treats relativistic hydrodynamics with irreversible thermodynamics in the absence of the paradox of infinite velocity of heat conduction.

Approximations are given for: the Fourier–Kirchhoff equation for constant material density and thermal conductivity and heat capacity linear functions of temperature [22A], the general case of transient heat conduction [15A], and two-dimensional conduction where heat flow is predominantly in one direction [7A]. Bragg [2A] considers the solution structure of the radial heat problem with singular data, and Sabherwal [44A] treats some time reversal problems of heat conduction.

CHANNEL FLOW

Research on heat transfer in tubes occurs extensively by both analysis and experiment, covering entrance phenomena, laminar flow, transition flow, turbulent flow, various geometries, boundary conditions, and the effect of variable fluid properties. Turbulent heat-transfer studies continue to be primarily experiments while laminar flow studies are predominantly analytical.

Entrance region studies include the theoretical treatment of local heat-transfer effects on the developing laminar flow inside vertical tubes [27B], a rectangular passage with a non-uniform temperature distribution in the entrance cross section [43B], and a consideration of the frictional resistance to the flow of a compressible gas in the initial section of a tube with a large temperature difference between gas and wall [55B]. Stone [50B] measures local turbulent heat transfer for water in the entrance regions of tubes with various unheated starting lengths. Pauli [36B] gives special consideration to the actual entrance behavior of steam flow in tubes in calculating heat transfer.

Deissler and Presler [8B] analyze the developing laminar flow and heat transfer in a tube for a gas whose properties vary in both axial and radial directions. For a tube with non-uniform external heating (radiation) and internal cooling, Csaba *et al.* [7B] calculate the temperature distribution in the tube wall considering radial and circumferential heat transfer, convection and inter-radiation.

Bergman and Koppel [2B] measure the uniform heat flow to a gas in laminar forced convection in a circular tube. Both heat transfer and friction effect are analyzed for the laminar flow of helium and carbon dioxide in a circular tube at high rates of heating [57B]. Eraslan and Snyder [10B] give an exact but simple method for evaluating the mean viscous dissipation and bulk temperature variation for incompressible fully-developed flow in a duct of arbitrary cross section. Marek and Hlaváček [28B, 29B] treat the axial transport of heat and mass for the adiabatic tube reactor, presenting equations, methods of solution, and results of numerical calculations. Another instance of the effect of a heat source in duct flow is presented by Rothenberg and Smith [42B] in their consideration of a reacting fluid in a tube. In the work of Van Sant and Pitts [54B] the heat source is in the wall of an infinitely long tube having an adiabatic outer surface at uniform temperature. Using a new method based on boundary-layer theory Nazarchuk [34B, 35B] gives a one-dimensional analysis of diabatic gas flow in channels, yielding the conditions for heat-transfer crisis and the limits for applying the Reynolds analogy. Cheng [5B] employs a thin flat-plate analogy to produce results for laminar, uniform heat transfer in non-circular ducts by Moiré and point-matching methods. Chen [4B] presents the results for the analytical study of laminar heat transfer in a tube for the nonlinear heat-flux boundary condition imposed by radiant cooling. Heat flow in coiled tubes is considered in laminar flow [22B] and for the forced convective case [46B]. The interesting case of heat transfer to a non-Newtonian fluid in a wavy cylindrical tube is discussed by Bhatnagar and Mathur [3B].

For annular geometries there are a number of of papers: Rao [40B] considers the forced heat convection in laminar flow of a dissipative fluid for the annulus of arbitrary shape; Hsu and Huang [16B] treat heat (or mass) transfer for laminar flow of a concentric annulus with convective flux at the walls; Ratkowsky [41B] describes two friction factors defined for two space regions associated with plain, concentric annuli; Kumar [25B, 26B] treats the heat flow for the flow of Bingham material through an annulus.

The general non-circular duct convective heat-transfer problem for liquids and gases is reported by Tyagi [51B, 52B, 53B] who includes the presence of heat sources in the fluid medium, wall temperature varying linearly in the flow direction, and Neumann-type thermal boundary conditions. Sastry [44B] treats laminar forced convection in multiply-connected regions, and Sparrow and Haji-Sheikh [48B] consider ducts of arbitrary shapes with arbitrary boundary conditions.

The temperature field in a plane channel when the conducting walls are heated non-uniformly is calculated by Povarnitsyn and Yurlova [38B]. Other parallel plate investigations concern the transient effect in laminar flow of a heat-generating fluid [11B] and radial divergent flow and heat transfer of a viscous incompressible fluid [21B, 56B].

Transitional and low Reynolds number turbulent gas flow with heat transfer in the downstream region of round tubes is considered by McEligot *et al.* [30B]. Scheele and Greene [45B] consider the role of natural convection in distorting the velocity profile and inducing transition for non-isothermal flow in long and short pipes. Tube wall temperature fluctuations are studied by Kalinin and Yarkho [18B] during the constant flow of heat to water in a tube.

Turbulent flow in passages embrace a variety of conditions. Goresh [12B] considers the practical case of heat transfer in a cylindrical pipe, poorly insulated, and transferring heat from its outer surface by free convection and radiation to an environment at constant temperature. Roughness effects on heat transfer are covered by Migai [31B] who reports a 50 per cent increase of heat transfer using artifically roughened surfaces, Sheriff and Gumley [47B] who employ discrete roughness in the form of wire wound on test surfaces, and Krall and Sparrow [20B] who insert orifices in the pipe to separate the flow. Other influences on the heat transfer considered are: the presence of an electric field on gaseous coolants in a nuclear reactor [1B], the occurrence of heat transfer instabilities due to the operation of a loop near the thermodynamic critical point [6B], and the effect of heating asymetrically a rectangular duct [49B].

Presler [39B] reports an experimental investigation of heat transfer in smooth tubes for the reacting N_2O_4–NO_2 system. Kinney and Sparrow [19B] study the turbulent pipe flow of an internally heat-generating fluid.

Kubair and Kuloor [23B, 24B] consider the heat transfer in helical coils, use analogies to correlate the experimental data, and attribute the ± 10 per cent deviation to secondary flow. Gulyaev [13B] reviews the thermodynamics and fluid mechanics of vortex tubes. Supporting his case with briefly reported tests, he agrees that viscous dissipation and counter-flow heat exchange are fundamental to the system behavior but concludes that enhancement of vortex tube performance by heat exchange is limited.

Mori *et al.* [32B] report the first part of a continuing study of forced convection heat transfer in uniformly heated horizontal tubes—the experimental determination of the effect of buoyancy on velocity and temperature fields. Hendricks *et al.* [14B, 15B] give the heat-transfer characteristics of cryogenic hydrogen at high pressure (800–2500 psia) flowing upward in uniformly heated straight tubes.

For the electrically heated tube, Hufschmidt *et al.* [17B] demonstrate a simplified solution for determining the surface temperature by thermocouple. Donne and Meerwald [9B] give experimental local heat-transfer and average friction coefficients for air in an annulus at high temperatures. Mori and Uchida [33B] reports the presence of vortex rolls induced by the temperature difference between horizontal plates (lower heated, upper cooled) in a forced convection system. Pfeffer [37B] analyzes and correlates heat-transfer and friction factor data for dilute gas–solid suspensions.

BOUNDARY-LAYER FLOW

Boundary-layer theory and solutions

Forced convection heat transfer in laminar flow of a viscous incompressible fluid over a flat plate with finite length in flow direction and infinite span was analyzed in the complete range of Reynolds numbers including conditions with a thick boundary layer [7C]. Heat-transfer coefficients take on large values near the trailing edge at small Reynolds numbers. The average heat-transfer coefficient is correct within 3 per cent over the whole Reynolds number range when calculated with the results of Pohlhausen's analysis. The Reynolds analogy becomes invalid at small Reynolds numbers because pressure gradients exist along the plate. Wedge solutions have been extended for large values of the pressure gradient parameter β and for a gas with variable ρu product flowing in a laminar boundary layer over a highly cooled wall [1C]. Local similarity, using these wedge solutions, was found to describe heat transfer to a surface with arbitrary pressure variation to a good approximation. An analysis [16C] of heat transfer in a laminar compressible boundary layer along a flat plate with stepwise distribution of the wall heat flux compares well with results obtained by Sparrow and Lin. Coefficients for the Blasius series describing heat and mass transfer near a stagnation point have been tabulated for Prandtl or Schmidt numbers respectively between 0·005 and 1000 [18C]. The momentum integral and the moment of momentum integral boundary-layer equations as well as Mager's transformation are used to obtain the flow and heat-transfer characteristics in a compressible turbulent boundary layer with arbitrary pressure gradient [24C]. Correlations between the velocity and temperature field in adverse pressure gradient turbulent boundary layers are obtained from the concept of "regional similarity", subdividing the boundary-layer thickness into a number of regions and applying different laws for each of them [22C]. The effect of surface roughness and of Prandtl number was included. Heat transfer across a turbulent boundary layer with a stepwise wall variation has been analyzed [2C, 21C]. A study [30C] determined heat exchange between two fluids separated by a flat plate. Parallel flow with boundary layers both of which are laminar or turbulent results in a constant wall temperature. Other flow conditions like counterflow and laminar–turbulent boundary-layer combinations give a variable wall temperature.

Dissociation, ionization, and chemical reactions

An analysis for flow near a stagnation point with a viscous shock layer [31C] utilized a three-component gas model to investigate the effects of chemical non-equilibrium and a binary gas model to study the effects of vibrational and chemical relaxation processes. At a non-catalytic wall, the results turned out by only a few per cent larger than those obtained with a conventional binary gas model. A new binary air model was used to study the effect of dissociation and ionization in a stagnation point laminar boundary layer [9C] considering either dissociation or ionization only, depending on the temperature range. Results are obtained for velocities up to 50000 ft/s and altitudes to 250 kft. Good agreement with experiments was obtained and it was found that a nitrogen model does not adequately represent air. An analysis of laminar boundary-layer flow with surface catalysis including two reactants and two products was performed [15C]. A method was described to study laminar non-equilibrium boundary layers of a dissociating gas [28C], using an appropriate coordinate transformation normal to the wall and finite differences in flow direction. Arbitrary variations of properties, reaction rates, body shapes, and surface boundary conditions can be treated and results are presented for dissociated air up to a Mach number 25. Non-equilibrium hypersonic stagnation flow with arbitrary surface catalycity and non-equilibrium reactions through the shock layer at low Reynolds numbers were analyzed [13C]. Heat transfer to hemispheres with catalytic surfaces in low Reynolds number nitrogen flow was investigated [5C], assuming frozen shock and boundary-layer conditions. The recombination coefficient was varied between 0·01 and 0·1 for non-catalytic surfaces and was given a value one for catalytic surfaces. A heat-transfer reduction of 40 per cent was obtained by a non-catalytic coating. Transfer processes in a reacting compressible boundary layer were analyzed including ablation from the surface and assuming chemical equilibrium [26C]. The free shear layer created by helium injection into an air boundary layer at the stagnation point was studied including the thermal diffusion and diffusion thermo effect [33C]. The influence of these effects was small when the helium was injected at low temperature into a high temperature airstream. It was large for the reverse situation. The temperature field and composition field was calculated for laminar flow through a tube including a dissociation reaction [23C]. Chemical equilibrium but finite kinetics were assumed. Interferometric measurements of oxygen flow around a cone with 10000 ft/s velocity [29C] indicated that vibrational equilibrium was achieved closely behind the shock. Chemical equilibrium occurred within the shock layer. Experiments [32C] obtained a carbon monoxide–hydrogen gas mixture with a temperature of 3500°R by combustion of oxygen and acetylene. This gas mixture has a Lewis number of 3. Heat transfer to a molybdenum test plate is described by the following equation

$$\frac{qLe \neq 1}{qLe = 1} = \left[1 + (Le - 1)\frac{h_{De} - h_{Dw}}{h_e - h_w}\right]^{\frac{2}{3}}$$

$qLe \neq 1$ denotes the actual heat flux per unit area and time, $qLe = 1$ the heat flux to a gas mixture with a Lewis number equal one, h_D indicates the atomic dissociation energy and h the total enthalpy per unit mass mixture; the subscripts e and w denote conditions outside the boundary layer and at the wall respectively, and the Lewis number is based on the binary diffusion coefficient. The results of experiment [3C] on heat transfer in a system N_2O_4–NO_2 at low pressure compared well with an analysis using non-equilibrium thermal conductivity values given by R. S. Brokaw.

Effects of magnetic and electric fields

An analysis [25C] indicates that a magnetic field parallel to the surface in stagnation point flow of a partially ionized argon gas can practically eliminate electron conduction. Conditions at pressures between 0·01 and 1 atm, and 9500–12000°K total temperature were investigated. A field of 12000 Gauss resulted in 55 per cent reduction of the heat transfer. Heat transfer was also studied [12C] in MHD flow in the thermal starting region of a flat duct. Fully-developed laminar Hartman flow was assumed. Local Nusselt numbers are presented for Hartman numbers between 0·4 and 10 and for electric field factors 0·5, 0·8 and 1. Thermal free convection from the upper surface of a horizontal plate with a surface temperature larger than the surrounding was analyzed [11C] under the influence of a magnetic field normal to the plate surface. The free shear layer between two incompressible, viscous, thermally and electrically conducting fluids was analyzed [20C]. It was found that a magnetic field parallel to the flow direction thickens and stabilizes the shear layer.

Experimental studies

Experiments of heat transfer and skin friction on a flat plate with sharp and blunt leading edges at Mach number 6·8 and Reynolds numbers around 10^5 [17C] gave fair to good agreement with the theory for laminar and turbulent flow. Small and moderate blunting of the leading edge was found to delay transition. Local heat-transfer coefficients in the throat region of a nozzle with high speed laminar flow of nitrogen at 5200–6500°R total temperature and 0·9–1·5 atm total pressure gave results [6C] which agreed well with the analysis by Cohen and Reshotko. Some effects of radiation were observed. Measurements were also performed in a conical nozzle with controlled inlet velocity profile using air at 960°R total temperature and 300 lb/in^2 total pressure [4C]. Compressible boundary-layer theory predicted measured values well. A turbulence generator simulating the effect of a nuclear reactor core created upstream a turbulence intensity of 10 per cent. The value dropped, however, to 2 per cent in the throat and had no effect on heat transfer. Discontinuities in surface catalytic activity affect local heat-transfer conditions in laminar boundary layers on a sphere–cylinder model exposed to an arc-heated nitrogen stream [27C]. A non-catalytic nose, for instance, increases heat transfer to the catalytic afterbody. Finely dispersed solid particles in an air flow through a tube increase heat transfer [19C] according to the relation

$$\frac{Nu}{Nu_0} = 1 + Re_0^{-0\cdot 3}\,\mu^n$$

in which μ indicates the particle concentration, the index zero conditions with zero concentration. The exponent n differs depending on heating or cooling conditions and on the range of particle concentrations. An increase up to ten-fold in heat transfer was measured. Radial distributions of the energy flux and the current density along the surface of a copper anode exposed to a free-burning argon arc of 250–1100 A were measured [8C]. An investigation of a constricted plasma arc in an axial magnetic field with argon flow at 1 atm pressure indicated instabilities in the form of helical oscillations of the electrically conducting core in agreement with an analysis [34C]. Laminar and turbulent heat transfer was studied in the shear layers between an arc-heated argon jet of 10000–20000°R and 500 ft/s velocity injected into helium at 500°R 0–3 ft/s velocity [10C] and conditions for transition to turbulence were observed. Dimensionless correlations of the characteristics of blown electric arcs were discussed [14C].

FLOW WITH SEPARATED REGIONS

Single bodies

Experiments utilizing a thermistor measured heat transfer from a sphere to rarefied hydrogen–nitrogen and helium–nitrogen mixtures at Knudsen numbers (Kn) between 0·008 and 0·4 [20D]. The following relation represents the experimental results in agreement with an analysis

$$Nu = \frac{2}{1 + (15/2)\,\alpha^{-1}\,Kn}$$

(α = accommodation coefficient). Measurements of heat transfer from a horizontal wire with 0·008 in dia. oscillating horizontally with a frequency of 4·5 cm/s and amplitudes up to 2·5 in. in water and ethylene glycol established that previous correlations for mixed free and forced convection do not describe the present experimental results adequately [21D]. The various regimes in turbulent cavity flow and the criteria for the transition between them were studied in a rectangular groove located in the floor of a wind tunnel at velocities from 75–210 ft/s [10D]. Experiments [19D] established that heat transfer in the separated region upstream of an orifice in a tube with circular cross-section was only by approximately 3 per cent larger than in fully-developed tube flow. Heat transfer in supersonic separated flow over a two-dimensional backward-facing step is characterized by heat-transfer coefficients which are at the reattachment point from 4 to 8 times as large as corresponding heat-transfer coefficients on a flat plate provided the separation is in the transitional region [3D]. For laminar separation, the heat-transfer coefficients are only slightly higher than on the flat plate. Temperature recovery factors were found to be low (around 0·5) in the separated region and had values between 0·6 and 0·8 at and after the reattachment point. Velocity and temperature profiles were measured in turbulent jets of very low temperature (50–100°K) and of very high temperature (20×10^3 °K) ejected into quiet surrounding air at 300°K [1D].

Convection heat transfer was measured [29D] in a two-dimensional, plane wall subsonic diffusor with opening angles between 0 and 45 degrees, with a length to throat width ratio from six to eight and Reynolds number range 40000–300000. In this way the whole range of flow conditions from no separation to fully developed stall was covered. Relations are proposed for heat transfer under the various conditions. Local and average heat-transfer coefficients were measured [11D, 15D] for two dimensional and rotationally symmetric jets, single or in arrays, impinging on a flat surface. A maximum heat transfer is obtained by a certain geometry at constant power requirement.

Packed and fluidized beds

Heat and mass transfer from a single sphere to a fluid flowing through an array of spheres could be described by the relation

$$Nu = A + B\,Pr^{\frac{1}{3}}\,Re^{n}$$

$$A = \frac{2}{1 - (1 - \varepsilon)^{\frac{1}{3}}},\; B = \frac{2}{3}\varepsilon$$

$$(2 - 3n)/(3n - 1) = 4{\cdot}65\,Re^{-0{\cdot}28}$$

with ε indicating the voidage [24D]. The measurements were performed for Reynolds numbers between 130 and 2000 and ε values from 0·26 to 0·63 using air and water. For mass transfer, the Sherwood number replaces the Nusselt number and the Schmidt number the Prandtl number. An analysis [28D] treated heat transfer in parallel rod arrays and determined the necessary fundamental heat-transfer coefficients experimentally for Reynolds numbers from 7000–200000 and spacing to diameter ratios from 1·5 to 1·25 in air flow. Heat transfer from wall to fluid and particles to fluid was measured for a packed bed of glass spheres [27D]. A computer model for the regenerative bed of uniform spheres in unsteady state and with chemical reactions occurring was developed [18D]. A similar analysis is also indicated in [26D]. Local heat-transfer rates from water to a cubical bed of spheres were measured for Reynolds numbers between 3000 and 70000 [4D]. An equation was reported describing heat removal from hydrogen gas flowing through a packed bed at Reynolds numbers from 40 to 400 and temperatures from 80 to 240°K [12D]. A relation with which heat-transfer information for spherical particles in a packed bed can be transferred to irregular shapes was suggested [22D]. An unsteady method to determine heat transfer in a packed bed was described [16D] and good agreement with previous results is noted. Mixing of warm and cold gas streams in a packed bed was analyzed based on a model in which heat sources are placed into rotationally systematic flow [14D]. The results agree well with experiments, provided measured heat-transfer coefficients are introduced. A universal correlation for heat and mass transfer between particles and air reported in last year's survey was extended [17D]. The effective thermal conductivity in granular beds was found to rise linearly with gas flow rate [6D]. Heat transfer between powdered alumina and a helium gas was measured at helium temperature [7D]. The results at high pressure suggest an interfacial resistance similar to the resistance discovered by Kapitza between solids and liquid He II. Volumetric heat-transfer coefficients were determined by an unsteady experiment [8D] for flow of air through a porous matrix heated by incident radiation. Heat and mass transfer in capillary-porous materials during drying was studied when heat is applied through an electro-magnetic field [23D]. An effective thermal conductivity k_e for radial heat flux in a moving bed through which air is flowing can be described by the equation

$$\frac{k_e}{k_g} = 9{\cdot}7 + 0{\cdot}39\,\varepsilon\,Pr\,Re$$

and the heat transfer to the wall by the relation

$$\frac{hD_p}{k_g} = 2{\cdot}55 + 0{\cdot}155\,\varepsilon\,Pr\,Re$$

in which $\varepsilon = 0{\cdot}36$ is the porosity, and the subscripts p and g refer to the particle and to the gas respectively, according to measurements in [30D]. The research at Birmingham University on heat transfer to gas fluidized beds has been described [5D]. Direct heating of a fluidized phase by an electric current using the fluidized phase as a resistance heater with air flow has been investigated [9D]. An analysis of available correlations and a state of the art review is contained in [2D] and [13D]. The heat-transfer coefficient from water to a vertical wall with air bubbling through the water is described by the relation

$$h = 0{\cdot}28k\left(\frac{g\varepsilon}{\nu\alpha}\right)^{\frac{1}{3}}$$

with ε indicating the void fraction of bubbles which can be obtained from the rise of water level, ν the kinematic viscosity, k the thermal conductivity, g the gravitational acceleration, and α the thermal diffusivity [25D].

TRANSFER MECHANISMS

Thermal mixing lengths were derived from measurements of the turbulent temperature fluctuations in mercury and ethylene glycol flow through a pipe with uniform wall temperature. The results agreed well with values obtained from von Kármán's relation [14E]. Turbulent diffusivity profiles were measured for hydrogen injection into a Mach 2–3 turbulent air stream [10E]. A theory was also proposed to obtain information on the dependence of the thermal diffusivity on hydrodynamic parameters [13E]. A thermal resistance from 2·5 to 20 $cm^2\,{}^\circ K/W$ was measured for the interface between a thin metal film and liquid helium [5E]. The analogy between vorticity and energy transfer was utilized for the analysis of a two-dimensional boundary layer of a constant property fluid [9E] when a heat source is located at the leading edge of the surface. Results agreed with experiments in laminar flow; disagreed, however, in turbulent and transitional flow. An analogy between the onset of convection in a fluid heated from below and in a fluid between 2 cylinders rotating with almost the same velocity has been suggested by Chandrasekhar and is utilized in [3E]. An analysis of a horizontal disk vibrating in vertical direction and subliming at its surface has been performed [12E] and is proposed as a model to study the Leidenfrost phenomenon. Heat transfer increases by pulsation in turbulent flow according to [2E]. Experiments on free convection in a vertical cylinder with a height equal to its diameter established that heat transfer is caused by conduction only up to a Rayleigh number 2×10^3, is increased by Benard-type convection up to a Rayleigh number 8×10^6, and by turbulent convection beyond this Rayleigh number [4E]. Measurements of heavy particle and electron temperatures as well as transport properties have been performed in a two-dimensional channel [1E]. The Ranque effect has found attention in two papers [6E, 7E] reporting on experiments down to a temperature of 80°K. Heat transfer in supercritical fluids has been studied [11E]. A model of turbulent transport in shear flow has been developed which accounts for the difference in transport of mass or energy and momentum [8E]. It divides the shear layer into an inner region with continuous turbulence and an outer region with intermittent turbulence. The validity of the model is supported by previously published experiments.

NATURAL CONVECTION

Heat-transfer studies concerned with natural convection continue to hold high priority for a number of investigators. General areas of study include: variations on the boundary-layer free convection heat transfer from a vertical plate; free convection from objects of different geometry such as spheres or cylinders (and the plumes above such systems); free convection in rectangular enclosures, particularly as it might apply in problems concerned with the flow of propellants for liquid rockets; the stability and heat transfer in horizontal fluid layers heated from below; and of course combined free and forced convection.

A schlieren system has been used to study natural convection in a rarefied gas along a vertical plate [29F]. A similarity solution is obtained for the laminar free convection around a vertical surface immersed in water held at 4°C [13F]. In this study the maximum density occurs at the outer edge of the boundary layer. Similarity solutions for a class of non-Newtonian fluids in free convection flow on a vertical plate are found to exist for certain variations in wall temperature [27F]. The free convection flow of a non-Newtonian fluid on a porous vertical plate has also been studied [26F]. The heat and mass transfer from a vertical surface of a subliming material exposed to air is 10–15 per cent lower than predicted when the body forces (due to temperature difference and concentration difference) are opposing [1F]. An integral analysis predicts the natural convection heat transfer in He II [31F].

An analysis of the transient free convection on a vertical surface confirms previous studies that predict an initially pure conduction period with a possibility of overshoot of the boundary layer [40F]. Experiments on transient natural convection from a vertical cylinder also indicate the existence of an initially pure conduction heat-transfer regime [10F].

A numerical calculation [28F] for the stability of a natural convection boundary layer of air along a vertical flat surface indicates little difference in the stability criteria when a surface boundary condition of uniform heat flux is used as compared to earlier studies for an isothermal surface. The turbulent free convection heat transfer from a vertical plate in water near the critical point is found to compare well with a constant-property correlation for free convection if the properties are evaluated at the film temperature [20F].

An experimental study of the free convection from a solid sphere gives good agreement with analytical predictions of the local distribution of heat transfer up to the position of hydrodynamic separation [19F]. Under certain conditions the heat transfer by natural convection between concentric spheres leads to cellular flow [3F].

A finite difference method is used to calculate the natural convection heat transfer through a rectangular enclosure in which the top and bottom plates are insulated or assumed to have a linear temperature variation between the temperatures of the side walls [39F]. A recent experimental study is concerned with the free convection heat transfer in a rectangular channel in which heat is added from the side walls [18F]. An analysis has been reported on the temperature distribution in a vertical circular cylinder of liquid hydrogen which is heated from the walls and from which fluid is removed downwards [32F]. An experimental study on the heat transfer to an enclosure containing liquid hydrogen indicates that there is considerably less stratification if the fluid is heated from below rather than heated from the sides [14F].

Calculations have been performed on the laminar plume above a locally heated or cooled horizontal surface [24F]. Although the cooled surface gives stable flows, a heated surface apparently will produce unstable flows above a certain critical Rayleigh number. Similarity solutions are presented for the free convection heat transfer from a horizontal plate with a variable wall temperature [12F]. A study employing the von Kármán integral method for an axisymmetrical turbulent swirling natural convection plume indicates the flow depends only on the source characteristics [21F]. A companion study [22F] offers experimental verification of the analysis. An experimental investigation [5F] of the velocity and temperature fields above a heated horizontal wire shows agreement with previously reported analytical results.

Experiments [35F] on the onset of flow in horizontal layers have indicated a reproducible critical Rayleigh number approximately 5 per cent higher than the theoretical value of 1708. The application of the energy method to the stability of a horizontal fluid layer extends earlier solutions for small perturbations to the effects of larger disturbances [17F]. A recent analysis [33F] has surveyed the convective instability induced by surface tension gradients. It is found [38F] that at least for some boundary conditions surface tension driven instability can be calculated assuming the principal of exchange of stabilities is valid. Convection in a horizontal layer with volume heat sources is studied to approximate the heat transfer in Earth's mantle [37F].

A simplified analysis [23F] of the heat transfer in horizontal fluid layers gives quite reasonable predictions of the Nusselt number over a large range of Rayleigh numbers. The use of a pseudo-three-dimensional flow numerical calculation on heat transfer in a horizontal layer gives results that are similar to turbulence [9F]. Assumption must be made, however, as to the flow in one of the horizontal directions.

A schlieren study of evaporating horizontal layers of organic fluids shows that the flow pattern is strongly affected by the depth of the fluid [2F]. Measurements on the heat transfer in an evaporating water layer give a variation of Nusselt number with Rayleigh number that is quite similar to that obtained in a layer heated from below [11F]. Measurements have been reported on the mean temperature profile and the temperature fluctuation in a horizontal layer of liquid heated from below [34F]. Measurements of the heat transfer from a single horizontal heated plate facing upward in a non-Newtonian flow indicate that the Nusselt number can remain a function of a pseudo-Rayleigh number if suitable definitions of the Rayleigh number and Prandtl number are used [30F].

An experimental study shows good agreement with a mixing length analysis of thermal convection with a superimposed Couette flow [15F]. An analysis has also been presented on the horizontal internal waves in a stable fluid which is above a horizontal layer in thermal convection [36F].

An extensive review of combined free and forced convection in external flows indicates that the introduction of a suitable flow parameter permits correlation of combined free and forced convection over different external surfaces with a single curve [4F]. For flow in a horizontal tube the secondary flow produced by wall heating gives an increase in the normal forced convection heat transfer which is a function of the ratio of the Grashof to Reynolds numbers [25F]. Experiments on the combined free and forced convection with laminar flow of water in a horizontal tube do not show agreement with previous correlations [8F]. Experiments have been performed on combined free and forced convection of air in a vertical tube with both opposing and aiding flow [6F, 7F]. A perturbation analysis of the combined free and forced laminar convection heat transfer in an inclined tube indicates that the Nusselt number can have a maximum, as the tube axis varies from the horizontal, when the tube is held at some finite angle to the vertical [16F].

CONVECTION FROM ROTATING SURFACES

An analysis of heat transfer from a constant property fluid to an enclosed rotating disk was performed for laminar flow conditions [4G] and for two concentric horizontal infinite disks [1G] rotating with the same axial velocity under the assumption that the Coriolis acceleration is large compared to the inertia acceleration. Heat transfer from a shrouded rotating impeller as used in radial flow turbines is described by the equation

$$St\, Re_{fe}^{0.65} = 66.0 + 30.0\,\frac{R_{\text{rot}}}{R_{fe}}$$

for a flow Reynolds number (Re_{fe}) range and a rotational Reynolds number (Re_{rot}) range respectively between 10^5 and 10^6 [3G]. The rotational Reynolds number is based on the angular velocity and the impeller radius. The Prandtl number of the fluid is 0·7. The effect of film cooling of the disk surface has also been studied. The thermal boundary-layer equations for a rotating sphere have been solved utilizing available solutions of the laminar flow boundary equations. The relation

$$\frac{Nu}{Re^{\frac{1}{2}}} = C$$

describes the average Nusselt number with the value $C = 0{\cdot}25$ for $Pr = 0{\cdot}7$ and $C = 0{\cdot}30$ for $Pr = 1$ [2G]. The Reynolds number is based on angular velocity and sphere diameter. The stability of Couette flow between rotating cylinders in the presence of a radial temperature gradient was studied by an approximate solution of the stability equation [5G]. The critical Taylor number was found to decrease as the Prandtl number increases.

COMBINED HEAT AND MASS TRANSFER

The coolant flow rate required for transpiration cooling is strongly influenced by chemical reactions taking place either in the passage of the secondary coolant through the wall or in the boundary layer itself [10H]. An approximate technique is developed for predicting the heat transfer with transpiration cooling on a surface exposed to a hypersonic flow [3H]. The effects of transpiration cooling with a multicomponent secondary gas are studied [1H]. Use of a series expansion permits the calculation of heat transfer (assuming laminar constant property flow) with transpiration when wall blowing rate is uniform [15H]. The effect of transpiration cooling on the laminar boundary layer covering a moving continuous flat surface is analyzed [2H]. A similarity analysis is used to determine the heat transfer with a laminar boundary layer (containing a temperature dependent heat source) flowing over a flat plate through which gas is drawn [12H]. A recent review presents the results of a large number of experimental and theoretical studies of transpiration cooling including a large number of Russian investigations [9H]. Experiments on transpiration cooling in the stagnation region of a hemispherical model in an arc-jet wind tunnel show reasonable agreement with theory [16H].

Experimental measurements of the heat transfer to a turbulent boundary layer with transpiration cooling and freestream Mach numbers up to 8 are reported in one study [4H] in which air is used as the secondary gas. Another study [17H] considers nitrogen, helium and argon as secondary gas. In the latter study, measurements of the heat transfer downstream of the transpiration section show a rapid increase of heat transfer followed by a region over which the heat transfer is essentially independent of distance downstream. Transpiration cooled gas turbine blades have been studied in an experimental test rig [5H].

A film cooling experiment with air and helium injection through a rearward-facing slot into a Mach 3 air flow indicates that for a considerable region downstream of the injection (at high blowing rates) a very high film cooling effectiveness is achieved [6H]. The heat transfer following a rearward-facing step through which air may be injected into a subsonic turbulent boundary layer is found to increase (with distance downstream) to the point of reattachment and then to follow a relationship quite typical of a normal turbulent boundary layer [13H].

A film cooling study [7H] with a subsonic turbulent boundary layer shows a strong similarity between the adiabatic wall temperature distribution and the wall concentration when helium is used as the injected gas.

The von Kármán integral method is used to analyze combined heat and mass transfer in capillary porous bodies [11H]. An experimental study examines transpiration cooling with liquid flow through a porous wall, evaporation taking place in the wall or near the surface [8H]. The interaction of heat and mass transfer during evaporation is studied including effects of thermal diffusion [14H].

CHANGE OF PHASE

A marked increase is noted in the number of analytical papers dealing with aspects of heat transfer accompanied by a change of phase.

Nucleate boiling in pure liquids and in binary mixtures is considered by Van Stralen [58J, 59J] in a two-part study which extends his earlier theories on the growth rate of free spherical vapour bubbles to the more complex case of bubbles generated on a heating surface with time dependent liquid superheating. The result is a new description of nucleate boiling as a relaxation phenomenon in which the equivalent conduction layer at the heating surface is superheated due to the rapid growth of succeeding vapor bubbles on active nuclei. Kotake [23J] considers the velocity and temperature fields in the vicinity of the heating surface and discovers a relation between the period of the bubble cycle and the amount of superheat. Ruckenstein [44J] proposes a hydrodynamical model which accounts for the circulation motion caused by bubble departures. Kutateladze *et al.* [25J] continue to develop their earlier view that nucleate boiling heat transfer may be likened to heat transfer to liquid in vicinity of a stagnation point. Marto and Rohsenow [30J] present a simplified model for bubble nucleation stability and develop an approximate stability criterion.

Film boiling under forced convection conditions is considered from a two-phase boundary-layer viewpoint by Ito and Nishikawa [18J] who find that heat transfer and skin friction depend strongly on a density–viscosity parameter but weakly on superheat. Polomik [41J] treats the single component boiling flow system by a total energy balance to obtain minimum limiting values of vapor volume content, and the effect of phase velocity distributions. Zuber and Staub [64J, 65J] are concerned about aspects and characteristics of void propagation and the transient response of volumetric concentration to various parameters. In the second, related study, they derive criteria to predict the stability of dry patches forming in a thin liquid film as it flows over a heated surface. O'Loughlin [36J] predicts the thickness of a laminar liquid film draining from a vertical surface assuming that the evaporation from the film surface is a known constant. For the evaporating drop, Gardner [9J] gives the asymptotic concentration distribution of an involatile solute.

Film condensation from vapor flowing along a flat plate or over the external surface of a cylinder in transverse fashion is studied by Shekriladze and Gomelauri [48J]. Rufer and Kezios [45J] construct and analyze a physical model for stratified two-phase flow with annular laminar film condensation. Jacobs [19J] combines body force and forced convection in an integral treatment of laminar film condensation. For a tube containing a mobile liquid–vapor interface and cooled by a gas (or liquid) stream in crossflow, Schoenberg [47J] conceives a mathematical model and experimentally verifies its dynamic behavior. Madejski [28J] considers the usually neglected molecular–kinetic resistance (ΔT across interface) in an analysis of Nusselt-type condensation of vapors on flat vertical plates. Minkowycz and Sparrow [33J] give comprehensive treatment to condensation in the presence of non-condensibles, interfacial resistance, superheating, variable properties and diffusion. With a focus on design, Komarov [21J] derives a dimensionless equation for calculating the surface area required for condensing a vapor in the presence of an inert gas.

Solid–liquid phase change systems are considered by Siegel and Savino [50J] who use three analytical methods to study the frozen layer formed when a warm liquid flows over a flat plate cooled below the freezing temperature by a coolant flowing along the other side of the plates; Wilcox and Duty [62J] who determine the macroscopic solid–liquid interface shape in the solidification process; and Matula [32J] who compares exact and one-dimensional theories for incipient melting in re-entry simulation.

A series of papers attempt to generalize and correlate some of the large number of individual experimental investigations of systems undergoing phase change during heat transfer. Thus

Lienhard and Schrock [26J] formulate the displacement of the nucleate boiling heat-flux curve with pressure, Chen [6J] adds the mechanisms of micro- and macro-convective heat transfer to represent boiling with net vapor generation to saturated, non-metallic fluids in convective flow, and Seader *et al.* [46J] survey and correlate available literature on heat transfer to boiling H_2, N_2 and O_2. Alekseev [2J] contends that current theories on burn-out are inadequate to explain this complex phenomena, but give curves on burn-out for water flowing over a range of pressures and velocities both inside and outside tubes of various geometrics. Similarly, Rohsenow [43J] writes of the lack of complete understanding of nucleate boiling heat transfer but describes the procedure of idealizing conditions in order to deal with practical design problems. Pasint and Pai [39J] give an empirical correlation of factors influencing departure from nucleate boiling in steam–water mixtures flowing in vertical round tubes. For the design of devices where vapor condensation occurs, Zozulya [63J] presents equations evolved from a consideration of quantitative and qualitative aspects of the process.

Experimental work on various aspects of the boiling phenomena dominates all other research considered in this section. Nukiyama [35J] measures the quantity of heat transmitted from a metal surface to boiling water with a varying temperature difference between wall and fluid and determines a maximum heat flux condition. A series of investigations focus on bubble formation and behavior and the relationship to boiling. Tolubinsky and Ostrovsky [57J] photograph features of nucleate boiling by examining the formation and growth of vapor bubbles in a pool of saturated liquid. Gol'tsova [10J] finds the presence of a vapor formation center and the frequency of vapor bubble separation to influence the wall temperature. In related studies, Wachters and Van Andel [61J] show that a cavity can maintain bubble production only as long as it continues to be filled with vapor; Madejski [29J] notes that non-uniform liquid superheat causes non-spherical active bubble nuclei; Howell and Siegel [17J] examine photographically the inception, growth and detachment of vapor bubbles from artifical nucleation sites of known geometry and size; Cole and Shulman [7J] determine the uniform superheat model which best describes the shape of bubble growth curve over the entire range investigated.

Under pool boiling conditions, Marto and Rohsenow [31J] report results for nucleate boiling of sodium from surfaces with various finishes. Konsetsov [22J] studies heat transfer to walls and coilpipe in an apparatus representing a bubbling reactor. Using horizontal wires in pool boiling, Kovalev [24J] considers minimum heat fluxes at pressures from 1 to 100 atm, Pitts and Leppert [40J] the variation of critical heat flux with wire diameter and material, and Lienhard and Watanabe [27J] the correlation of peak and minimum heat fluxes with pressure and heater configuration.

External effects on the boiling process are considered in several studies. Heath and Costello [16J] vary geometry, orientation, and gravity field, Papell and Faber [38J] simulate zero and reduced gravity systems by using a magnetic field and a stable collodial magnetic fluid, and Simoneau and Simon [51J] study visually the buoyancy effect on nucleate and film boiling regimes of liquid nitrogen.

The Leidenfrost phenomenon (vaporization of spheroidal drops undergoing film boiling) receives consideration in a number of investigations. Gottfried *et al.* [12J, 13J] are able to verify measured evaporation times with a model: drop-suspended by vapor, evaporating due to conduction across vapor layer and radiation from heating surface, with molecular diffusion across top surface of drop. Baumeister *et al.* [4J] demonstrate that the lower limit of the plate temperature necessary to sustain Leidenfrost boiling is very near the saturation temperature of the liquid, and in reference [3J] give a generalized correlation of vaporization times required for drops of various volumes. In a related study, Wachters *et al.* [60J] examine the influence of the presence of water vapor in the surroundings on the drop evaporation rate.

In the film boiling regime there are a number of investigations. Frederking and Daniels [8J] examine the kinematics of vapor removal from a sphere during film boiling in saturated liquid nitrogen. Subbaraya and Kuloor [55J] measure heat- and mass-transfer rates for evaporation of water and a number of organic liquids and obtain heat-transfer coefficients much higher than predicted for a horizontal flat plate with the heated surface facing up. Tishina and Rychkov [56J] investigate the surface boiling of a number of aqueous solutions and determine that the principles of heat transfer are the same as those for a single component fluid. Olsen [37J] measures temperatures in the vicinity of the placid interface of two-phase hydrogen in a pressurized tank.

Styrikovich *et al.* [54J] use a technique of salt deposition (sodium sulphate) from a solution to study the mechanism of boiling at the wall of a pipe. The deposition information and wall temperature data enable the transition from nucleate to film boiling to be located. Kapitonov and Lebedev [20J] consider the effect on heat transfer of salt deposits on the heat-transfer surfaces.

A series of studies deal with special aspects of boiling. Stephan [53J] treats the high heat fluxes occurring with boiling liquids, Morin [34J] measures the variations of the wall temperature with boiling on a fire tube, and Shmelev *et al.* [49J] study a process for the continuous production of molten sodium sulphide using vacuum evaporators with forced circulation.

Hallett [15J] considers the sub-cooled falling liquid film and its breakdown during heat transfer as a preliminary to the study of burn-out in two-phase flow. Skelland [52J] considers the interesting practical case of developing relevant relationships for designing industrial melters in which the molten material is a time-dependent non-Newtonian fluid.

For the condensation phenomena there are a limited number of studies. Goodykoontz and Dorsch [11J] use temperature measurements to obtain local heat-transfer coefficients for condensing steam in vertical downflow in a $\frac{5}{8}$-in-dia. tube. Despite the condensation at the wall, the vapor core can remain superheated over the entire length of the two-phase region. The radial machine grooving of a condensing surface improves heat transfer in film-wise condensation by reducing surface resistance up to 65 per cent according to Bromley *et al.* [5J]. For liquid–liquid systems, Rao *et al.* [42J] study drop formation and develop equations which predict drop volumes to within 7 per cent. Concluding studies are those of Albers and Block [1J] who study the condensation of wetting and non-wetting mercury in uniformly tapered tubes, and Gupta and Holland [14J] who study the heat transfer from condensing steam to boiling water in a climbing film evaporator.

RADIATION

Interest in thermal radiation heat transfer continues at a high level. Much of the work is apparently motivated by the space program. General areas which have received considerable attention during the past year include: analytical study of radiation from solid surfaces which are partly diffuse and partly specular in nature, measurement of radiation properties of real surfaces, study of radiation heat transfer in media that are at least partially absorbing, and radiation effects produced by shock layers.

A Monte Carlo program is used [9K] to calculate the radiant exchange between surfaces having varying amounts of specular and diffuse reflection. The radiation heat transfer between two plates set at an angle to each other but having a common edge is shown to be greater if the plates are specularly reflecting than if they are diffuse [23K]. The radiant transfer between an outer specular cylinder or sphere and an inner diffuse cylinder or sphere has been determined [8K]. Radiant exchange is calculated [37K] in an enclosure with surfaces whose reflectance can be approximated by the sum of diffuse and specular components. A network analogue is developed [47K] to include the possibility of a specular reflecting surface. The radiation network concept for heat transfer in an enclosure is extended to include unsteady problems including conduction and convection [20K].

A shape factor for the inner surfaces of individual cones and cylinders has been calculated [1K]. Another study [33K] evaluates the radiation characteristics of diffuse cylindrical and conical cavities. An analysis [3K] shows that a non-uniform surface temperature can strongly affect the radiant emission from a spherical cavity on a surface. The effect of surface contour on the emittance from a wall with two dimensional grooves has been analyzed [30K].

Calculations [40K] of the radiation heat transfer from stainless steeel clad copper fins indicate that over a fairly large range of conditions the heat transfer can be approximated assuming a one dimensional temperature distribution in the fin and average thermal properties. The effectiveness of fin tube radiators with gray surfaces has been calculated [36K]. A finite difference calculation is used [19K] to determine the radiation heat transfer to a row of circular tubes parallel to a furnace wall. The importance of radiant heat transfer in a porous bed has been demonstrated, including the effects of simultaneous convection [28K, 44K]. Calculations of the radiant heat transfer to a moving thin plate losing heat by free convection agree well with experiment [43K].

Measurements [41K] of the biangular reflectance of thermal radiation indicate a maximum at an angle not equal to the specular angle. Other measurements of spectral biangular reflectance have been made [24K] using various rough metallic surfaces. Solar reflectances of various metallic surfaces are reported [39K], and hemispherical emittance and normal solar absorptance are determined using a steady state calorimetric method [10K]. An integrating sphere has been developed that permits absolute measurements of hemispherical spectral reflectance [46K].

Even in a relatively inert atmosphere, trace quantities of oxygen are often sufficient to form oxide layers that significantly affect the surface radiation properties of materials at high temperatures [38K]. The relatively small effect of surface roughness on the emittance of nonmetals [as compared to metals] is ascribed quantitatively to the significant internal reflections present within a non-conductor [34K].

An analysis [17K] of the radiation emitted by a layer of dielectric material coated on a conductor shows the importance of dielectric properties as well as the thickness of the layer. Calculations of the spectral emittance of a platinum–10% rhodium wire coated with fused silica indicate that at higher temperatures the emittance can be smaller for coated wires than for uncoated wires [2K]. Several coated surfaces are found [12K] to have a significantly higher total emittance than solar absorbtance. In the same study, the effect of coating thickness is also determined. The directional emittance and transmittance of a thin dielectric material has been calculated [16K]. Radiation heat transfer in solids maintained at high temperatures can play a significant role in their overall thermal conduction [13K].

There is still considerable development work being performed on high temperature bodies to be used as sources of infrared radiation. The development of a 3000°C black body will greatly increase the accuracy of the standard for short wave length radiation [15K]. A small (4-mm dia. by 1-cm long) infrared source has been developed for use at temperatures to 1150°C [4K].

A number of studies concentrate on the radiative transfer through an absorbing and emitting gas of variable optical thickness. The transfer of heat between two concentric black spheres separated by a gray gas is obtained using a numerical method [35K]. Another study on the heat transfer through a spherical shell of absorbing gas uses the temperature jump, or radiation slip, concept to simplify the calculation [22K]. Analytical techniques that have been developed in neutron transport theory are used to determine the heat transfer between parallel walls with an absorbing medium in between [27K]. A simplified method for calculating radiative transfer in gray gases in a plane geometry has been presented [14K]. Calculations of the heat transfer through a plane parallel gas layer that scatters radiation as well as absorbs and emits it indicate that the effect of scattering on the heat transfer is small [21K]. The radiative transfer between two separate absorbing gas layers has been calculated using a diffusion solution and the Monte Carlo method [25K]. The radiant heat transfer between two parallel flowing gasses is determined using the radiation slip approximation [45K].

Calculations of the interaction of radiation and convection in a laminar boundary layer on a flat plate have been extended to include the effects of viscous dissipation and incident radiation flux [31K]. A spherical harmonic analysis is used [6K] to study the effects of radiation on the flow of a gas over a wavy wall. The radiative cooling of a gray gas flowing over a flat plate is calculated assuming inviscid flow [26K]. The interaction of thermal radiation with free convection in an absorbing fluid on a vertical flat plate is treated [5K]. Calculations on the radiative heat transfer from shock layers include studies in the stagnation region behind a strong shock [7K] and the heat transfer to wedges and cones at hypersonic speeds [32K].

The possibility of injecting an absorbing gas to isolate a solid surface from radiation is described [43K]. Preliminary calculations indicate that the relative shielding decreases rapidly with higher surface reflectance. Another study [18K] considers solid particles injected with a fluid into the boundary layer and finds considerable reduction in the radiant heat transfer between the solid surface and the external flow.

Seeding a gas to increase its absorption or emission properties has also been suggested to increase radiation from a natural gas flame [11K] and to increase the heat transfer to a gas coolant flowing through a high temperature nuclear reactor [29K].

LIQUID METALS

Heat transfer to a turbulent liquid metal flow in a round tube or flat duct with heat sources in the fluid stream was analyzed [7L] assuming small turbulent diffusivity and uniform heat generation and approximating the flow as slug flow. Careful measurements [6L] established that pure mercury on pure surfaces has the same friction factor in the laminar and turbulent range as a normal fluid. A transverse magnetic field of magnitude 10000 Gauss inhibited convective heat transfer and decreased the Nusselt number by 20–30 per cent for tube flow with constant wall heat flux in a Reynolds number range 9600–137000 [5L]. Heat-transfer studies to liquid metals flowing turbulently in eccentric annuli [9L] and flowing in line through closely packed rod bundles [4L] have been reported. A perturbation extension [3L] to an analysis by Sparrow and Gregg was performed for free convection of a liquid metal from a uniformly heated flat plate with a thick boundary layer. The discrepancy between analytic and experimental values for heat-transfer coefficients in film condensation of a liquid metal vapor were clarified by experiments [8L] which demonstrated a significant thermal resistance at the liquid–vapor interface. The pressure drop of condensing non-wetting mercury in a uniformly tapered tube was measured for normal gravity and zero gravity conditions [2L]. The pressure varied from a rise of 0·9 lb/in^2 to a drop of 0·1 lb/in^2. The fog flow theory by Koestel predicted the data roughly. The experiments were also extended to wetting condition [1L].

LOW-DENSITY HEAT TRANSFER

Interest continues apace in the low density area with only a small fraction of the total activity reported in the open literature. Of this a still smaller number of papers deal with heat transfer at low density.

Lees [8M] re-examines the question of transition between gas kinetics and gas dynamics, a problem in rarefied gas flow bearing on heat transfer. Koshmarov [7M] discusses the problem of molecular gas flow between two porous plates which move at small relative velocity. Cercignani and Pagani [3M] apply a general variational approach to three typical kinetic theory problems using simple trial functions and obtain very accurate results.

Accommodation coefficients receive attention in a series of studies. Allen and Feuer [1M] use quantum theory to obtain an expression for the coefficient for the gas–solid system, in the presence of solid surface impurities, as a function of temperature, molecular and intermolecular quantities. Trilling *et al.* [10M] obtain analytical expressions for energy accommodation in the case of normal approach and tangential momentum accommodation in the case of arbitrary angle of approach. Wise *et al.* [11M] measure heat transfer through gas mixtures containing atomic and molecular oxygen in the presence of catalytic surfaces. Relative values of thermal accommodation coefficients are deduced by changes in temperature jump distances.

Heat transfer for a number of specific systems receives analytical and experimental consideration. For heat transfer between two concentric spheres at large Knudsen numbers, Brock [2M] employs a solution of the BKG model of the Boltzmann equation. For a sharp cone in supersonic rarefied gas flow, Koshmarov [6M] measures heat transfer and equilibrium temperature. Empirical formulas permit the determination of mean recovery factors for flow regimes between free-molecular-flow and continuum flow. Inman [5M] reports heat-transfer results in the thermal entrance region with laminar slip flow between parallel plates at different temperatures.

Concerned with the prediction of appreciable slip effects rather than their accurate prediction, Oosthuizen [9M] considers the effect of surface slip on laminar free convective heat transfer from an isothermal, vertical, flat plate.

Dyer and Sunderland [4M] give experimental and analytical results for bulk and diffusional flow of a binary gas mixture under steady-state conditions. The analyses are valid for the entire region between pure molecular and viscous flow.

NON-NEWTONIAN FLUIDS

Velocity profiles, boundary-layer thickness, and wall shear were calculated for a power law fluid flowing with a turbulent boundary layer over a flat plate [7N]. Reynolds analogy was used to obtain heat transfer. The boundary-layer equations were integrated for flow of a melting, glassy (thixotropic) substance near the stagnation point [8N]. The velocity and temperature fields were obtained by an analysis [3N] for channel flow and for boundary-layer wedge-type flow. A similarity situation was found to exist for a free-stream velocity proportional to the distance along the wall raised to the power one-third for Ostwalt de Waele fluids. Viscous dissipation was included in some of the calculations. Experiments with rock and lime slurries and sludge established heat transfer in transition and turbulent flow [6N]. An analysis for steady rotating flow of a Bingham material between two co-axial cylinders determined heat transfer as a function of the radius ratio, of the position of the yield surface, and of the Brinkman number (the product of Prandtl and Eckert numbers) [5N]. Heat-transfer studies in agitated pseudo-plastic solutions established relationships for the Nusselt number as a function of properly defined Reynolds and Prandtl numbers [4N]. A review of the state of art and a selection of best correlations is contained in [1N, 2N].

MEASUREMENT TECHNIQUES

Use of a pyroelectric element, which acts as a charge generator with temperature change, permits measuring temperature differences as small as 6×10^{-6}°C [24P]. A thermistor bridge permits measurement of small temperature differences, maximum scale deflection giving a difference of about 10^{-2}°C [29P]. An evaluation [42P] of thermocouple error when measuring fluid temperature includes conduction and radiation effects. Reference tables are presented [4P] for platinum–40% rhodium/platinum–20% rhodium thermocouples to 1880°C. The feasibility of measuring surface temperatures of a liquid metal using a thermocouple in which one arm is the liquid metal itself is demonstrated [41P].

Significant errors are introduced in the measurement of stagnation point heat transfer in an arc-heated stream if care is not exercised in maintaining a highly catalytic probe surface [40P]. A calorimetric probe is developed [3P] for measuring temperature and velocity in a plasma jet. By extrapolating the transient temperature response of a thermocouple, gas temperatures can be measured that are considerably higher than the normal failure temperature of the probe material [35P]. Temperature profiles in a flowing gas are obtained by passing a thermocouple through the fluid at constant speed [1P].

Transient wall heat flux is measured using a thin film resistance thermometer [22P]. A thin film resistance thermometer using germanium as a resistance element permits the use of small lead wires [9P]. The high value of the Seebeck effect for germanium also permits great sensitivity when using this material in a thin film thermocouple [30P]. By evaporating films on solid surfaces, very thin yet stable thermocouples have been made [28P]. A heat meter constructed of a very thin insulating layer between thin foils of copper and constantin has a total thickness of 0·0025 cm [18P].

A comprehensive review of the radiation properties of surfaces as they affect pyrometric measurement of surface temperature is presented [6P]. Pyrometric measurements of surface temperatures can be made using the polarized light leaving a surface [14P]. A recent work traces the historical development of optical methods for determining both solid-surface and gas temperatures [20P]. The progress in temperature measurement of inhomogeneous hot gases from infrared spectral determinations is reviewed [23P]. Gas temperatures in shock tubes [31P, 39P] and in the exit of small rockets [17P] are determined from optical measurements. From the angle of intersection of colliding shock waves the gas temperature of an arc discharge at the point of collision can be determined [5P].

Considerable interest remains in optical methods of measuring gas densities and flow. A useful review [16P] describes the design and adjustment of a precision Mach–Zehnder interferometer. Some applications of continuous wave lasers in different types of interferometers is presented [36P]. A schlieren system for high temperature experiments, in which the illumination generated in the system to be studied masks out the normal light, is developed using the light from the phenomenon under study to act as the schlieren light source [38P]. Flow visualization from afterglow indicates the streamline separating a high temperature main stream and an injected gas (nitric-oxide) [19P]. Flow visualization studies in liquids have been extended using a potential applied across a chemiluminescent solution [21P] and hydrogen bubbles generated in flowing water [2P].

A transient system is developed to determine the thermal conductivity of solid insulating materials [10P]. A comparative method using copper as a standard is refined for thermal conductivity determination of high conductivity materials [11P]. Another system for determining the thermal conductivity of metals (both solid and liquid) uses a transient system which also measures simultaneously the heat capacity and thermal diffusivity of the material in question [15P]. Another apparatus simultaneously determines the thermal conductivity, diffusivity and specific heat for moist materials [26P]. Thermal conductivity of gases can be measured using a system in which a large temperature difference is imposed between a central wire and

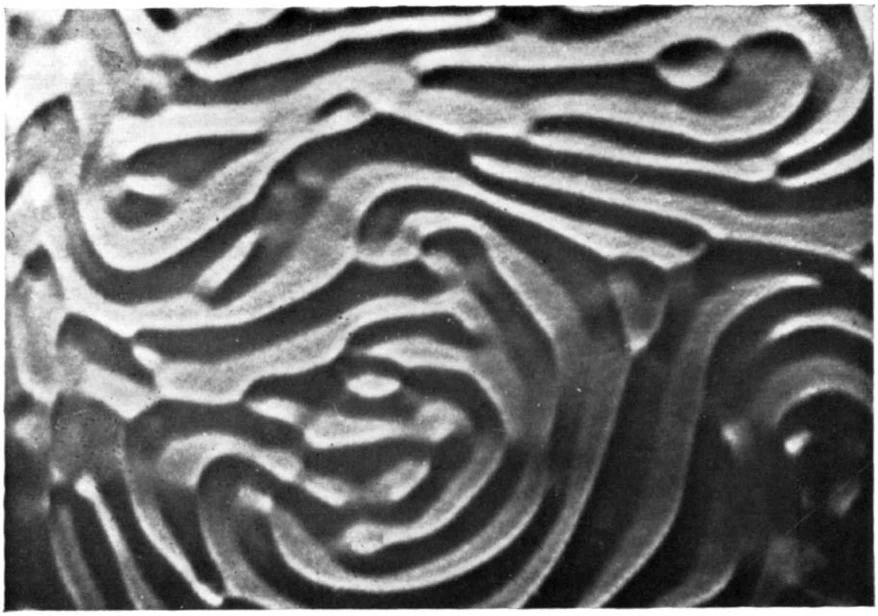

FIG. 1. Schlieren pattern in a 3-mm layer of carbon tetrachloride evaporating into still air, when the liquid surface has been contaminated with a trace amount of paraffin wax.

a surrounding circular cylinder, containing the gas under study [33P]. The assumption of thermal equilibrium in a relaxing gas is found to be valid in a normal conductivity cell [8P]. A system for measuring the thermal diffusion factor over a range of pressures is developed [34P].

A high temperature furnace for use in thermophysical property studies at temperatures up to 2900°C is described [37P]. A low frequency oscillator acts as a sinusoidal temperature wave generator [32P]. By measuring the temperature distribution in the wake of a body, the total convective heat loss from a human subject is determined [7P].

The effect of axial conduction on a thermal flowmeter, in which the downstream temperature distribution following a pulse of heat is measured to determine velocity, has been studied [43P]. An analysis [25P] shows the effects of Reynolds number and density on gas flow rates determined using a turbine flow meter. A sensitive micromanometer permits pressure measurements with an accuracy of approximately 3×10^{-5} mm of water [13P]. A rotatable wire heat meter flush with the solid surface permits determination of the direction as well as the magnitude of the local wall shear stress [12P]. A viscometer is used to measure the viscosity of liquid in layers as thin as 2 μ [27P].

HEAT-TRANSFER APPLICATIONS

Heat exchangers

Interest continues in the dynamic response of heat exchangers. Success has been obtained in analyzing simplified models of such units. An analysis [14P] of the heat exchanger dynamics for flow in a cylindrical tube or annulus indicates that the linearization assumptions often made are not always necessary. Another study [12Q] shows that the use of a Lagrangian representation for the flow down a single tube heat exchanger simplifies the calculations necessary to describe the dynamic response. An experiment on the dynamics of a simple heat exchanger shows good agreement with an exact analysis but differs substantially from the results indicated by a linearized analysis [7Q]. The limitations of a lumped parameter model used for the analysis of the dynamic characteristics of a counter-flow heat exchanger have been demonstrated [10Q].

Work on regenerative heat exchangers includes a general study [8Q] of a unit with a unidirectional flow which neglects the thermal conductivity of the matrix and a study [15Q] which considers the application of regenerators to be used in a supersonic wind tunnel. The maximum slope of the exit temperature of a regenerative heat exchanger is calculated [9Q].

A solution has been obtained for the heat transfer with laminar counterflow in a double pipe heat exchanger [13Q]. A study of helical and spiral coil heat exchangers shows an increase of heat transfer (as compared to pressure drop) with laminar flow apparently due to the secondary flows in the system [11Q]. The practicability of a flexible tube heat exchanger using thin walled teflon tubes has been demonstrated [5Q]. The performance characteristics of shell and tube heat exchangers has been reviewed [17Q]. Frost deposits formed from water vapor and carbon dioxide present in the air stream has been found to significantly affect the overall heat transfer in low temperature heat exchangers [3Q].

Several studies have concentrated on finned tube heat exchangers. Transverse fins are found to give an optimum performance in terms of heat transfer, compared to friction factor, when the spacing between the fins is somewhat greater than the height of an individual fin [21Q]. If fins are shared between individual channels in a radiator (for space application) the possibility of losing a great deal of the cooling capacity (upon meteoroid puncture) is greatly reduced [4Q]. The heat transfer and friction with different pins as surface fins has been studied [20Q]. The effect of contact resistance between fins and the base surface is found to influence the overall heat transfer for finned tubes [18Q, 22Q]. Calculations of fin effectiveness have been made with a variable heat-transfer coefficient on the fin surface [19Q] and with two-dimensional heat conduction in the fin [16Q].

Experiments indicate an improved method of calculating the pressure drop due to baffle plates in a shell and heat exchanger [6Q]. The heat transfer to a coil sitting in a tank of fluid which is agitated is found to be significantly increased by the presence of fins on the tubes [1Q]. A flow visualization study aided in indicating the characteristic dimension to use in correlating the heat-transfer results for a scraped surface heat exchanger [2Q].

Aircraft and space vehicles

Evaluations of heat-transfer measurements during the flight of Mark 2 demonstrated that stagnation point heat transfer is adequately predicted by the Fay and Riddell theory and laminar boundary heat transfer by the Kemp, Rose, and Detra analysis [11R]. Experiments in various planetary gases also confirmed analytical heat-transfer rates [10R]. Approximate equations for re-entry velocity and heating rates applicable to any atmosphere are presented in [5R]. Foamed ceramics on the outside of the skin and radiation cooling were studied as protection for a hypersonic glide vehicle [1R]. Heat-transfer and pressure distributions were measured on swept delta wings [12R] and Apollo afterbodies [9R] at Mach numbers 5·8–8·3. Charring ablators often perform differently in high and low stream enthalpy gases [15R]. Models for the analysis of charring ablators are derived from experiments [4R, 13R]. Cork insulation recently replaced other ablation materials on Minuteman missiles because of its excellent performance [7R]. Among forty ablative materials for nozzle sections of a hydrogen–oxygen rocket, silica cloth reinforced phenolic materials had least erosion [14R]. The possibility to reduce heat transfer to nozzles for gas core nuclear reactors operating at temperatures above 10000°R by seeding the propellent layer close to the wall with a radiation absorbing material was examined [8R]. The results indicate a reduction of the heat flux from 600 Btu/s in^2 to 3–5 Btu/s in^2. A method to calculate heat transfer in cooled turbine cascades is discussed [6R]. Various artificially produced surfaces with directionally dependent radiation properties are proposed for spacecraft thermal control [3R] and analyzed in their performance. Thermal modeling is indicated to decrease greatly the number of experiments which are necessary to study the heat loss from animals [2R].

THERMODYNAMIC AND TRANSPORT PROPERTIES

Thermodynamic properties

Theoretical investigations continue into various aspects of the virial equation of state for gases. Sze and Hsu [91S] calculate second virial coefficients for the Lennard–Jones [6, m] potential with parameters determined from experimental data. Levine and McQuarrie [60S] consider nonpolar axila molecules and compute both second and third ordinary and dielectric virial coefficients. In a further elaboration of this approach, Freeguard [36S] determines mixed second virial coefficients and partition isotherms. In a further extension, Cole [22S] investigates the fourth virial coefficient for a square-well potential gas. To supplement these microscopic views, Kachhava and Saxena [50S] consider the relation between equations of state and interatomic forces and Graben *et al.* [43S] treat intermolecular three-body forces and third virial coefficients. In macroscopic studies, Wolfe [100S] uses the Benedict–Webb–Rubin equation to predict phase and thermodynamic properties at nine hydrocarbons—methane through heptane—and Juza [49S] supplements a Van der Waal-type equation with additional terms to express precisely the measured values of thermodynamic properties in the immediate vicinity of the critical point for water.

Investigations of specific substances include: *steam* [3S]—the measurement of the specific enthalpy at pressures of 60–1000 bar and temperatures of 400–700°C; *octafluorocyclobutane* (Freon FS-318) [97S]—the specification of thermodynamic properties; *potassium* [21S]—a summary of thermophysical properties; *germanium* [85S]—high-temperature (300–1514°K) thermal properties as determined by a drop calorimeter; *gold and dilute alloys of* manganese, chromium, iron, and vanadium with gold [30S]—specific heat listing; *helium–nitrogen system* [61S]—experimental isobaric heat capacity and differential latent heat measurements are combined with Roebuck's Joule–Thomson data to construct charts of the pressure–enthalpy network.

In a more general vein, Allison [2S] calculates thermodynamic properties of arbitrary gas mixtures subject to ionization and dissociation effects with modified vibrational–rotational corrections for the diatomic species; Yen and Woods [103S] present a generalized equation for computer calculation of liquid densities, Bondi [11S] gives a method of estimating heat capacity of liquids using the contributions from computable components; Francesconi and Trevissoi [35S] present observations on the Gibbs–Duhem equation at isobaric conditions for liquid binary mixtures.

For thin-film polymers, Steere [87S] describes how thermal properties may be determined by a transient heating technique.

In the liquid–vapor phase boundary region, Lebowitz and Penrose [59S] deal rigorously with the van der Waals–Maxwell theory of liquid–vapor transition; Pai and Sastri [72S] correlate latent heats of vaporization; Viswanath and Kuloor [98S] generalize latent heat of vaporization and surface tension with temperature of ninety compounds with an average error of 1·8 per cent.

In the area of the critical point, Bridgeman [13S] defines a parameter based on reduced temperature which correlates data on saturated fluids and proves useful in analytical studies in the critical region. For the Van der Waals fluid, Barieau [7S] gives thermodynamic properties, with emphasis upon values near the critical point. Saksena and Saxena [81S] consider possible correlation between potential parameters and critical or boiling point constants.

Papers dealing with specific systems are: *argon–oxygen* [8S]—phase diagram; *parahydrogen* [25S]—vapor pressure and latent heat of vaporization from the triple to the critical point; *water*—the behavior at the specific heat (c_v) and entropy at the critical point [5S], and the surface tension and related properties [44S].

The Joule–Thomson effect, non-ideality and association is considered Wright [101S]. Gladun [40S] considers the Joule–Thomson effect in neon at low (cryogenic) temperature.

The concluding papers of this section deal with the velocity of sound in air [76S], the modification of Winkler's method for the determination of dissolved oxygen in water [62S], and the effect of moisture in gases [102S]. New instruments for thermophysical studies are described by Novitskii and Ergardt [70S] and Tsymarnyi and Zagoruchenko [96S] who are specifically concerned with investigating the thermal properties of gas mixtures.

Transport properties

Theoretical studies seek to improve the accuracy of the molecular models describing molecule dynamics. Following Grad, Devanathan *et al.* [26S] study the transport properties in a multicomponent assembly on the basis of a generalized BGK collision model. Melehy [66S] treats the thermodynamics of new generalized transport laws for liquids, gases, and electrons in matter and Ernst reports on hard sphere transport coefficients from time correlation functions [32S] and transport coefficients and temperature definition [33S]. Studies directed toward particular aspects of the transport mechanism include: polar gases—transfer phenomena [12S] and thermal conductivities [6S]; ionized monatomic gases—transport properties [27S]; low-energy plasmas [99S]; moderately dense gases [38S]; polyatomic fluids—a dilute gas of spherocylinders [82S]; rarefied gases—

kinetic theory of diffusion [104S]; and ablating specimens exposed to high radiant heat fluxes [29S]. Investigations of specific substances are: N_2 and CO_2—thermal transpiration and rotational relaxation numbers [63S]; and NH_3 (gaseous)—thermal conductivity [86S].

Haywood [46S] and Kestin and Whitelaw [52S] report on the Sixth International Conference on the Properties of Steam.

In the area of gaseous diffusion, Mazurenko [65S] reports a new method for investigating binary thermal diffusion in gases based on measured changes in gas luminescence. For isotopic CO and N_2 molecules, Boersma-Klein and DeVries [10S] calculate the influence of the distribution of atomic masses within the molecule. Cussler [24S] describes ternary diffusion by intrinsic diffusion coefficients, Cauwenbergh [17S] reports measurements of the thermal diffusion factor in the pressure range 1–400 torr and Kotousov in a series of studies considers both thermal diffusion effect [56S, 57S] and the diffusion-thermo effect [55S, 58S].

Great interest continues in measuring, correlating, and predicting thermal conductivities for a wide variety of substances and conditions mirroring the broad spectrum of scientific and technological activities involving heat transfer. For gaseous helium, Timrot and Umanskii [92S] report results of their investigations of helium thermal conductivity in the temperature range 400–2400°K. Israel *et al.* [48S] use porous tungsten filled with hydrogen gas to determine the thermal conductivity of that gas from 2000 to 4700°F. For interpolating the thermal conductivity of superheated steam, an equation is given by Bach and Grigull [4S]. Collins and Menard [23S] measure the thermal conductivity of noble gases in the temperature range 1500–5000°K by a shock tube. Missenard [68S] gives thermal conductivity data for pure gases of various temperatures and pressures, and Knopp and Cambel [54S] use spectroscopic means to determine the thermal conductivity of atmospheric argon plasma.

Gas thermal conductivities are also investigated for these particular conditions: at moderate density [53S] partially and fully ionized [1S], magnetic field influence on gas of nonspherical molecules [42S] and plasma with collective effects [75S]. For gas mixtures at high temperatures, Schramm [83S] gives a new formula to calculate thermal conductivity. Gandhi and Saxena [37S] correlate thermal conductivity and diffusion of gases and gas mixtures.

In the liquid region, measurements on methane are reported by two groups [15S, 67S]. Missenard [69S] gives exact values of the thermal conductivity of 300 organic [largely] compounds. Pachaiyappan *et al.* [71S] give a new correlation of the thermal conductivities of organic liquids which tests to an accuracy of 11 per cent when compared with the actual data for fifty-one liquids. Liquid and solid parahydrogen conductivities are reported by Dwyer *et al.* [31S]. In a two-part study, Reese considers amorphous polymers and reports low-temperature thermal conductivity [77S] and its temperature dependence [78S]. Rosser *et al.* [80S] give a direct, absolute, rapid small sample technique for determining the thermal diffusivity of poorly conductive materials, e.g. ammonium perchlorate.

For solid substances, experimental investigations predominate. Powell and Tye [73S] study twenty-two iron alloys having unusually high lattice components. Swift [90S] uses a transient line source method to determine the effective thermal conductivity of a number of spherical metal powder–gas systems. Chudnovskii [20S] reports on the thermal conductivity of cathode oxide coatings. In a theoretical study, Godbee and Ziegler [41S] give thermal conductivities of MgO, Al_2O_3, and ZrO_2 powders to 850°C. Other papers on solid thermal conductivities include a summary [34S] of existing relationships for determining the coefficient for two component systems, a generalization and calculation for metals by means of the law of corresponding states [18S] and a determination of the temperature dependence [88S].

Practical concerns lead investigators to a study of the following specific systems: thermal energy storage materials [19S], low density phenolic nylon char [94S], concrete [93S], single-layer walls in buildings [74S], and a quick method of determining insulating material thermal conductivity [9S].

Because the process is described analytically with greater precision and the property measured with greater accuracy than for the previous coefficients, viscosity data requirements are not as great. For the inert gases, Rigby and Smith [79S] report viscosities, and for dilute argon, Hanley [45S] gives both viscosities and thermal conductivities between 100 and 2000°K based on various molecular potentials. Kestin *et al.* [51S] report experimental viscosities for four binary gas mixtures at 20 and 30°C. Carmichael and Sage [16S] measure viscosities and thermal conductivities of nitrogen-n-heptane and nitrogen-n-octane mixtures. Svehla and Brokaw [89S] use Chapman–Enskog monatomic theory with Eucken-type corrections for thermal conductivity to calculate transport properties (and thermodynamic properties) for the systems $N_2O_4 \rightleftarrows 2NO_2$ and $N_2O_4 \rightleftarrows 2NO_2 \rightleftarrows 2NO + O_2$. For multicomponent gas mixtures of polar gases, Mathur and Saxena [64S] attempt to simplify the terms of the Sutherland expression for calculating viscosity. Using available data, including the most recent, Bruges *et al.* [14S] give new correlations and tables of the coefficient of viscosity of water and steam up to 1000 bar and 1000°C.

The critical point behavior of viscosity (and thermal conductivity) for fluids is the subject of a study by Senbers [84S]. Gegg and Purchas [39S] estimate the viscosity of gases from critical properties using charts and nomographs to assist in the solution of the Bromley–Wilke equation. Trappeniers *et al.* [95S] use the corresponding states principle to calculate noble gas viscosities up to high densities. The concluding work by Heric [47S] extends earlier binary schemes to predict viscosities for ternary mixtures.

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