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# HEAT TRANSFER—A REVIEW OF CURRENT LITERATURE

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## INTRODUCTION

THIS REVIEW is concerned with research in the field of heat transfer, the results of which have been published during 1964. The total number of publications 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 Second All-Union Conference on Heat and Mass Transfer was held at Minsk, BSSR, during May 1964. Scientists from Great Britain, France, Germany, Japan and the United States participated upon invitation. A large number of papers was discussed dealing with basic as well as applied aspects of heat and mass transfer. *Proceedings* of the conference will be available in book form in the Russian language and in English translation. The 17th Heat Transfer and Fluid Mechanics Institute took place during June at the University of California, Berkeley, and a major portion of the papers on the program dealt with convective and radiative heat transfer. The *Proceedings* are available from Stanford University Press. The 7th National Heat Transfer Conference was held at Cleveland, Ohio on 9 to 12 August. Two invited papers and 85 contributed papers constituted the program, together with a panel discussion on modern trends in heat-transfer education and with a forum of short presentations which again enjoyed a large attendance. The papers are, or will be, published in the *Journal of Heat Transfer* or in journals of the American Institute of Chemical Engineers. Papers presented at A.I.Ch.E. meetings will also be found in the Symposium Series of that Society.

Several books dealing with heat transfer have appeared on the market. They are listed, together with books in related fields, at the end of this paper.

The literature in channel flow emphasized non-circular geometries and the effect of variable fluid properties. The analysis of turbulent boundary layers was refined and generalized in a number of papers. The study of heat transfer in boundary layers with chemical reactions tended also toward refinement of available methods. The effect of variable properties, especially of the Lewis number, and errors caused by approximation of multicomponent mixtures by two-component ones, has been studied. In experiments on boundary-layer heat transfer, special attention was devoted to the effect of surface roughnesses and of fin-body interactions. Gases used in such studies simulated the atmospheres of Venus and Mars. The effect of thermal diffusion and diffusion thermo on combined heat and mass transfer found considerable attention. The stability problem in natural convection was analyzed for various geometrical configurations.

Many papers describe experimental studies on heat transfer with phase change. Visual observation or photographs revealed the details of nucleate and film boiling processes. The effect of promotors to establish or maintain nucleate boiling is described. Application of an electric field of 500–1500 V was, for instance, found to delay film boiling or even to break it up and change it to nucleate boiling. In boiling on a mercury surface, the nucleation sites were found to move around, whereas they are fixed on solid surfaces. Interest in low density heat transfer was much larger than indicated by the number of published papers. Many investigations are described only in research reports. The study of thermal radiation in gray or nongray absorbing gases continued during the past year. The development of the gas turbine obviously instigated a number of investigations on regenerative heat exchangers.

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

Conduction, A
Channel flow, B
Boundary-layer flow, C
Flow with separated regions, D
Transfer mechanisms, E
Natural convection, F
Convection with rotating surfaces, G
Combined heat and mass transfer, H
Change of phase, J
Radiation, K
Liquid metals, L
Low-density heat transfer, M
Measurement techniques, N
Heat exchangers, P
Aircraft and space vehicles, Q
Thermodynamic and transport properties, R

## CONDUCTION

Heat conduction across metallic surfaces in mechanical contact receives attention by several investigators. Shvets and Dyban [34A] determine by analysis the dimensionless quantities and relationships characterizing heat transfer between metallic surfaces in contact and find good agreement with experimental results. Shiykov and Ganin [33A] predict thermal resistances between two rough metal surfaces for different compressing forces and surface finishes in good agreement with experimental data. Analog computers are used [15A] for determining surface parameters required for predicting thermal contact resistance by the Fenech–Rohsenow scheme. Contact heat transfer between a single drop moving freely in an immiscible liquid is reviewed by Sideman and Shabtai [36A], both experimental and theoretical data being used to determine inside and outside transfer coefficients for the drop.

Heat conduction in nonisotropic mediums is considered by Sicard [35A] and Heaps and Srivastava [14A]; the latter give solutions as infinite series, the first term being the solution for the homogeneous case, the additional terms giving the influence of nonhomogeneity. Wells [41A] considers the case where the thermal conductivity varies linearly with distance below the surface of a finite slab, a situation of interest in the initial phase of vehicle re-entry. Rowley and Payne [31A] consider the interesting problem of steady-state temperature distribution in a heat-generating circular cylinder pierced axially by a concentric ring of identical holes.

Unsteady-state conduction is considered for a variety of geometries. Norminton and Blackwell [25A] give formal solutions for heat flow from initially isothermal oblate and prolate spheroids and the thin circular disc. Touryan [40A] considers the case of the two-dimensional conduction in a thin, anisotropic cylindrical shell, and Richardson [30A] notes the asymptotic solution for one-dimensional conduction in a semi-infinite slab with surface heat flux proportional to $n$th power of surface temperature.

For describing time-dependent heat transfer, Li [22A] proposes a thermokinetic potential in place of the entropy production. Various orders of heat-conduction laws are obtained for materials with various symmetries by applying axiomatic thermodynamics to rigid, continuous media [9A]. Ölcer [26A] applies finite integral transform techniques to solve three-dimensional heat-conduction problems with time-dependent heat sources for all three boundary conditions (i.e. prescribed temperature, prescribed heat flux, and Newton cooling). Conformal mapping is noted [20A] as an approximate method for treating heat conduction in bars of arbitrary cross-section.

Phase change during heat conduction and moving sources and sinks receive wide interest. Lin [23A] treats unsteady heat conduction in one-dimension with simultaneous phase change for bodies with cylindrical or spherical symmetry. Berlad [3A] uses an iterative procedure to analyze a crystallization front propagating into a subcooled liquid. Hamill and Bankoff [12A] use numerical integration to solve the plane-melting problem with temperature dependent properties.

Biot and Agrawal [4A] apply variational and Lagrangian thermodynamics to the ablation process with variable material properties, and Boley [5A] considers the upper and the lower bounds of melting or solidifying slabs, also with variable properties. The peak temperature caused by the moving heat source of submerged-arc welding attracts the attention of Paley *et al.* [27A] while Emery [10A] considers the temperature distribution in a metal plate due to a small "spill" and spreading of a cryogenic liquid. The novel problem of temperature variation in a cylindrical rod moving between chambers at different temperatures is treated by Horvay and Dacosta [16A].

Further geometrical considerations enter when Lebedev and Skalskaya [21A] use integral transforms to treat conduction in wedge-shaped bodies and Allard [1A] proposes a replacement of the relaxation, shape factor to estimate the steady-state conduction in walls of an infinitely long, square, tunnel. Steady-state heat dissipation from thin-film strips to liquid helium is the subject of study by Seki and Ames [32A].

Analogs prove useful in solving several heat-conduction problems. Sotiriadès [37A] and Forray and Newman [11A] note similarities between stress and temperature fields in a medium. Electrical circuit models are used by Ball [2A] for treating distributed-parameter heat-transfer systems and by Chan and Rushton [8A] to simulate boundary conditions in heat-conduction problems. Electrically conducting paper is used [17A] to determine two-dimensional temperature distribution and heat transfer in bodies subjected to convective-boundary conditions.

Fin characteristics are considered in a series of notes treating the temperature distribution in a thin circular fin of rectangular profile [24A], fin efficiency for an infinite array of tubes arranged in square configuration in a sheet fin [19A], and polygonal and plate fins [39A].

The inverse problem in heat conduction is considered by Sparrow *et al.* [38A], and Burggraf [6A], the results being applied to semi-infinite and plane slabs, sphere, cylinder and transpiration-cooled slab. Cannon [7A] shows for homogeneous conductors that knowledge of the heat-flow rate on boundary at one time uniquely determines the unknown physical property of the conductor and the temperature distribution. Other mathematical aspects of the conduction problem are the calculation of timelag in constant property media [28A] and a note of the errors attending finite difference solutions [18A].

Finally, the thermal conductivity of rigid foams is analyzed in detail, including its time variation, in a study by Harding [13A]. Probert [29A] notes measured thermal conductivities for two types of stainless-steel tubes at cryogenic temperatures (1K–4K).

## CHANNEL FLOW

Turbulent heat transfer in tubes and ducts has been explored in a wide range of experimental studies. Constant-property Nusselt numbers were deduced from experiments in which the local Reynolds and Prandtl numbers were held fixed while the wall-to-bulk temperature difference was varied [1B, 28B]. The tests, covering the Prandtl number range from 3 to 75, showed that the Dittus–Boelter equation predicted constant-property Nusselt numbers that were low. Furthermore, both the Sieder–Tate and the Colburn equations over-predicted the variable-property effects. The difference between local heat-transfer coefficients for airflow under conditions of uniform wall temperature and uniform wall heat flux increases as the Reynolds number decreases [17B]. The famous paper wherein the *j*-factor correlation is set forth by A. P. Colburn has been reprinted [7B].

Nusselt numbers, measured for airflow in rectangular ducts with aspect ratios of 1:1, 1:5, and 1:10, were bracketed by analytical predictions for the parallel-plate channel and the circular tube (34B). On the other hand, for water flowing in flat ducts of aspect ratio 1:10 to 1:25, the Nusselt numbers fell above the Sieder–Tate correlation by as much as thirty per cent [14B]. The effect of heat transfer on the fully developed friction factor was investigated in experiments with water flowing in a 1:12 aspect ratio rectangular duct (29B). These data, taken together with other information in the literature, were correlated by an expression relating the isothermal and non-isothermal friction factors for both air and water; the correlation purports to hold for tubes and ducts. The heat-transfer coefficient and pressure drop for a helically coiled tube exceed that for a straight tube. New data have been published for turbulent flow of water in coils wherein the ratio of coil diameter to the tube diameter ranged from 10 to 20 [37B].

The effect of hydrodynamic inlet conditions on heat transfer in a tube [38B] and in a bell-shaped nozzle [13B] was investigated. The local heat-transfer coefficient in a convergent-divergent nozzle was found to be a maximum at the location where the mass flow per unit area was a maximum [2B]; a substantial decrease in heat transfer was observed downstream of the point of flow separation. Average heat-transfer coefficients for a high-temperature combustion gas contained in a cylindrical chamber were sharply increased by flow oscillations [22B]. The effects on heat transfer of two-dimensional roughness elements in an annular channel was explored for both water and for transformer oil [15B].

Variable fluid properties can play an important role in gas flows in a variety of physical situations; for instance, for large wall-to-bulk temperature ratios, for dissociating conditions, and for thermodynamic conditions near the critical point. Investigations involving helium [52B] and hydrogen [45B] have yielded heat-transfer coefficients and friction factors corresponding to wall-to-bulk temperature ratios as high as 5·6; maximum wall temperatures ranged above 5000°R. Data for air and $CO_2$ were correlated by introducing into the Nusselt–Reynolds–Prandtl expression a multiplicative factor depending linearly on the wall-to-bulk temperature ratio [8B]. Velocity and temperature profile measurements were made in the dissociating gas $N_2O_4 \leftrightarrows 2NO_2$ flowing in a parallel-plate channel [5B] and in a circular tube [6B]; eddy diffusivities were deduced and suitably defined universal profiles compared with theory. Corresponding measurements for $CO_2$ near the critical point revealed a severe flattening of the radial temperature profile and a maximum in the velocity profile between the tube axis and the wall [55B].

An electrochemical method was successfully applied for the measurement of the mass-transfer rates in the entrance region of a tube [43B]. Tests in vertical concentric and eccentric annuli spanned the laminar and the low turbulent regimes and included a variety of heating conditions at the inner and the outer bounding walls [4B].

Several papers have dealt with analytical aspects of turbulent heat transfer in tubes and ducts. Fully developed heat and mass-transfer results for circular tubes have been calculated employing models somewhat different from those in the literature [47B, 48B, 54B]. The thermal entrance region in a tube with uniform wall temperature was solved once again [50B]. The parallel-plate channel with asymmetric thermal boundary conditions at the bounding surfaces was analyzed by applying several slightly different assumptions for the eddy diffusivity [3B, 18B, 19B]; both entrance-region and fully developed results are presented. For the thermally developed regime in the asymmetrically heated channel, a characteristic heat-transfer coefficient was proposed that is independent of the asymmetry [26B]. Fully developed Nusselt numbers for the concentric annulus were computed for turbulent flow with turbulent heat transfer, for turbulent flow with molecular heat transfer, and for various other transport conditions [10B].

For high temperature gas flows in tubes, longitudinal transport of heat by radiation is superposed on the convective transport [44B]. An analysis of the aforementioned situation was carried out for turbulent flow; axial heat conduction in the tube wall was also included. Circumferential variations in heat flux at either or both walls of a concentric annulus can lead to significant circumferential variations in wall temperature, even for turbulent flow [51B].

Investigations of laminar heat transfer in tubes and ducts tend to be primarily analytical. The thermal entrance region for a concentric annulus was analyzed for the cases of a hydrodynamically developing flow [20B], and a hydrodynamically developed flow [53B]. The latter hydrodynamic condition was also applied in studying the thermal development in a rectangular duct [27B]. The transient problem wherein a step change in wall temperature is impressed upon an initially isothermal laminar tube flow was attacked by double Laplace transformation [21B]. The effect of temperature-dependent viscosity on laminar heat transfer for water flowing in a circular tube or in a parallel-plate channel has been determined [49B].

Several papers dealt with fully developed laminar heat transfer. The circumferential temperature maxima on the wall of a rectangular duct have been investigated for a range of wall heating conditions [40B, 41B]. Nusselt numbers were derived for both laminar and slug flow in concentric annuli for a variety of thermal conditions at the two bounding walls [9B]. Transient development of the fully developed temperature field was investigated for laminar tube flow wherein the internal heat source is viscous dissipation [16B], and for an annulus flow wherein the wall temperatures and the internal heat source vary exponentially with time [24B].

Both numerical [56B] and closed-form solutions [57B] for heat- and mass-transfer in logarithmic-spiral channels have been presented. The Erdelyi theory for the vortex tube was critically discussed [42B]. It was demonstrated that the vortex tube is capable of separating two components of a gas mixture [25B]. The flow in a horizontal duct in which the temperature of the lower bounding wall exceeds that of the upper bounding wall is analyzed to determine the conditions marking the onset of instability [39B].

Magnetohydrodynamic effects were analytically explored by several investigators. It was demonstrated that the fully developed heat transfer in a parallel-plate channel can, under some conditions, be affected by finite electrical conductance of the bounding walls [23B, 46B]. Solutions for the parallel-plate channel were also carried out for the thermal entrance region [11B, 31B]. The fully developed Nusselt number for a uniformly heated circular tube subjected to a transverse magnetic field varies circumferentially [33B].

Non-Newtonian flows hve also been the subject of study. For hydrodynamically developed flow, the thermal entrance region of a circular tube was analyzed for conditions of internal heat generation within the fluid [12B, 32B]. The simultaneous development of the velocity and the temperature fields has also been determined, but without internal heating [30B, 36B]. An experimental study involving pseudoplastics revealed heat-transfer increases of up to twenty per cent due to the non-Newtonian nature of the fluid [35B].

## BOUNDARY-LAYER FLOW

### *Boundary-layer theory and solutions*

Analytical methods and experimental data have been reviewed for the compressible turbulent boundary layer over a flat plate with and without heat transfer. An alternate analytical procedure for computing the drag is proposed [44C]. It has been demonstrated that the Spalding function facilitates turbulent heat-transfer calculations. The available numerical information for the Spalding function is brought together and generalized [43C]. An analysis of the turbulent boundary layer focused special attention on cases where the thermal boundary layer extends beyond the velocity boundary layer (i.e. low Prandtl number flows). However, the assumption of equal turbulent diffusivities for heat and momentum places considerable uncertainty on the results [24C]. Crocco has proposed a transformation that converts the integral boundary-layer equations for turbulent compressible flow to those for low-speed turbulent flow; effects of pressure gradient and heat transfer are included [12C].

Several papers have dealt with the laminar boundary layer. Fundamental solutions were obtained for a discontinuous variation of surface heat flux on a flat plate, and these were generalized to accommodate any surface distribution of heat flux [23C]. The recovery factor for laminar flow longitudinal to a cylinder is smaller than that for the flat plate when $Pr < 1$; the relationship is reversed for $Pr > 1$ [45C]. The stagnation point heat-transfer solution for low-speed incompressible flow was modified to take account of internal heat generation and of suction at the wall [40C].

Vorticity generated by a curved bow-shock wave is shown to interact with the compressible boundary layer in the stagnation region of an axisymmetric body [13C]. Laminar heat-transfer computations for high-speed airflow in chemical and thermodynamic equilibrium were facilitated by applying the Crocco equation as a first approximation [9C]. A transformation was devised for reducing the equations of the laminar three-dimensional compressible boundary layer with small cross flow, adiabatic wall, and normal wall velocity to those of a corresponding incompressible problem [20C]. A procedure for finding the minimum description of a problem both in terms of independent variables and assignable parameters is illustrated by application to several boundary-layer problems [25C].

The transient response of a flat-plate boundary layer to a step change in energy input to the plate was computed; experiments in air verify the solution for the quasi-steady limit [1C]. The initial portion of the thermal transient following a step change in surface temperature is pure conduction, provided that the velocity distribution is independent of the streamwise coordinate [26C]. The influence of the laminar boundary layer on the testing time in shock tubes was analyzed by an improved model [4C]. A solution has been obtained for a cylinder that is accelerated impulsively from rest with a simultaneous impulsive change in surface temperature [6C].

Consideration has been given to fluid flow aspects. For the turbulent incompressible boundary layer with streamwise pressure gradient, a two-layer model has been proposed to accommodate the law of the wall and the law of the wake [35C]. The conditions which permit similar-type boundary-layer solutions were determined for laminar flows in certain three-dimensional orthogonal coordinate systems with irrotational free streams [36C] and for non-Newtonian power-law fluids [29C, 50C].

A class of wake-like solutions of the Faulkner–Skan equation have been uncovered and numerical results tabulated for a range of values of the pressure gradient parameter $\beta$ [30C]. Pohlhausen's method was applied for determining the flow adjacent to the edge of an infinite half plane that is moving in a direction parallel to the edge [42C]. By subdividing the laminar boundary layer into two strips, an improvement was achieved in the Pohlhausen method for computing the two-dimensional laminar boundary layer with pressure gradient [33C].

*Dissociation, ionization, and chemical reactions*

In a previous paper, Anderson had found that use of an average Lewis number in a constant property analysis predicts stagnation point heat transfer in a binary gas boundary layer with varying Lewis number within five per cent. An analysis [17C] for Couette flow results in the following reference Lewis number for equilibrium flow

$$\overline{Le} = 0{\cdot}273\, Le_w + 0{\cdot}727\, Le_\delta - 0{\cdot}156\, Le_\delta\, (Le_w - Le_\delta)$$

and one for frozen flow

$$\overline{Le} = 0{\cdot}419\, Le_w + 0{\cdot}581\, Le_\delta - 0{\cdot}0558\, Le_\delta\, (Le_w - Le_\delta)$$

which, used in a constant property analysis, gives the same heat-transfer rate as an analysis with the actually varying Lewis number. Heat transfer from a non-equilibrium ionized argon gas was studied for temperatures between 4000 and 12000°C [37C]. Ablation of graphite was studied [2C] as caused by surface reaction at moderate temperatures and by sublimation at high temperatures. An analysis [27C] of a nearly frozen four-component gas boundary layer for stagnation point, cone, and flat-plate flow over catalytic or non-catalytic surfaces gives the result that an approximation by a binary mixture (atoms and molecules) can overestimate the recombination rate by a factor of 2. Another study of a many-component laminar boundary layer on a chemically active surface is reported in reference [48C]. Similar solutions are obtained [8C] for the laminar mixing of two parallel streams of reactive gases with a pressure gradient in stream direction, under the condition $\rho\mu$ = constant and

$$Pr = Le = 1,$$

for frozen and equilibrium state. As an example, the mixing of combustion products with air at a Mach number of 8·5 is analyzed.

*Effect of magnetic and electric fields*

Heat transfer in two-dimensional magnetohydrodynamic channel flow has been analyzed in several papers [18C, 28C, 31C], including a study of the thermally developing region after a step in the wall temperature and in the presence of a transverse magnetic field [31C]. The local

Nusselt numbers are higher in this region when the walls are electrically conducting. Various boundary-layer situations are treated in [16C, 41C, 38C]. An exact solution [38C] for free convection flow over a heated vertical plate, with a magnetic field normal to the surface, compares well with Pohlhausen's approximate method. An unsteady boundary layer in incompressible flow over a non-conducting, infinite plate with suction and a transverse magnetic field have been analyzed [41C], assuming a magnetic Prandtl number equal to one and Alfven wave velocities less than the suction velocity. The temperature field in a plasma slab between two parallel electrode surfaces and with a magnetic field normal to the velocity vectors has been derived [34C] from a heat and momentum balance including the effect of viscous dissipation. At a temperature of $10^6$ degrees, the energy losse sby conduction were found to dominate in a hydrogen plasma. Equations describing the temperature characteristics of an arc jet are published [19C]. A continuum approach was used [10C] to study the electrical interaction between the gas and a surface for Couette and stagnation flow of a weakly ionized gas. Use of this method is suggested for diagnostic purposes. It is proposed to reduce heat leaks through a structure by the use of semi-conductor thermocouples as structural elements, utilizing the thermo-electric effect [47C].

*Experimental studies*

Experiments [49C] on stagnation-point heat transfer at Mach numbers between 2 and 6 and Reynolds numbers between 18 and 1500 resulted in good agreement with boundary-layer theory for Reynolds numbers above 300. Similar measurements [21C] of laminar heat transfer to spherically blunted cones at Mach number 20 and free-stream Reynolds numbers from 8000 to 15 000 per inch, checked the theory by L. Lees. The reference temperature concept was found to predict the displacement thickness for laminar boundary layers with good accuracy [39C]. Free-stream turbulence increases heat transfer in a laminar boundary layer on a flat plate only when the turbulence intensity is above 1% [7C]. The increase is moderate and amounts to 5–10% for 5% turbulence intensity. Experiments [5C] on stagnation-point heat transfer in an arc-heated supersonic stream resulted in Nusselt numbers which did not follow those predicted by Fay and Riddell. This is attributed to the effect of free-stream turbulence. The transition Reynolds number on a sphere with two-dimensional roughnesses in hypersonic flow was found to be a function of the ratio roughness height to boundary-layer displacement thickness [32C]. It occurred at ratios of absolute wall temperature to free-stream total temperature between 0·5 and 1, approximately at 45 degC from the stagnation point. Protruding rivets on a Lockheed Agena model decreased the transition Reynolds number to one third of the value on a smooth surface [15C]. Heat transfer in the turbulent boundary layer was not influenced. Heat transfer was also studied on a flat plate with corrugated surface at Mach numbers between 2·6 and 4·5 [46C]. Universal temperature profiles were derived from measured velocity and temperature profiles on four plates with homogeneous roughnesses at a Reynolds number of $2 \times 10^6$ [14C]. Heat-transfer coefficients were then calculated from the universal profiles. Stagnation-point heat transfer was measured [11C] for three gases simulating the atmosphere of Venus and Mars (I: 9% $CO_2$, 90% $N_2$, 1% A; II: 100% $CO_2$; III: 65% $CO_2$, 35% A). The results in case I agreed well with the prediction by Fay and Kemp, in case II they were by 10% larger, and in the case III about twice as large. Dissociation of $N_2O_4$ gas connected with heat transfer on a cylinder with its axis normal to the upstream velocity vector at Reynolds numbers between 6000 and 10 000 resulted in heat fluxes nine times as large as for heat transfer without dissociation [3C]. A calorimetric method was devised to measure the temperature field around the cylinder. Experiments [22C] in an electrically driven shock tube determined the heat transfer in planetary atmospheres ($CO_2$–$N_2$ mixtures) at velocities between 30 and 45 kft/s. Radiative and convective heat transfer was measured and compared with predictions.

## FLOW WITH SEPARATED REGIONS

*Single bodies*

Heat-transfer measurements [19D] between water and a uniformly heated cylinder with its axis normal to the upstream velocity and its Reynolds numbers between 2000 and 120 000 could be expressed by the following equation

$$Nu \left(\frac{\mu_w}{\mu_b}\right)^{0.25} \Big/ Pr^{0.4} = 0.31\ Re^{0.5} + 0.11\ Re^{0.67}$$

The turbulence level in the free stream was found to increase the Nusselt number at the stagnation line for values above one per cent. The turbulence level in the present channel was approximately three per cent. Heat-transfer coefficients on a circular cylinder exposed to free jet flow were by about twenty per cent larger than those in an unlimited stream when the jet was $\frac{1}{8}$ diameter high and two to eight jet heights distant from the cylinder [21D]. The occurrence of this maximum is explained by the Coanda effect and by the turbulence in the jet. The unsteady equations of motion and energy of a viscous, heat conducting, incompressible fluid were solved numerically [8D] for the flow past a rectangular cylinder resulting in a von Kármán vortex street. The thermal recovery factor behind a cylinder in oblique supersonic flow [30] and heat transfer for transverse flow with periodically varying velocity over a cylinder [18D] were analyzed.

Investigations [20D, 22D] considered heat transfer to a surface downstream of a backward-facing step, and to the downstream side of blunt objects [24D]. Suction or injection through a slot at the base of a step was found to have only a small effect on heat transfer [22D]. Laminar heat transfer in the separated region from a high enthalpy supersonic flow was larger than on a flat plate when the ratio boundary-layer thickness to step height was below a certain limit. An analysis [28D] for laminar, transitional, and turbulent heat transfer after a sharp, convex corner utilized a model considering inviscid expansion around the corner, and a viscous sublayer starting at the discontinuity further downstream. Momentum integral methods [14D] are discussed for the laminar free shear layer at constant pressure.

Experiments [11D, 12D] on flow through rows of tubes, with their tube axes alternately normal to each other, resulted in Nusselt numbers and pressure drop coefficients differing little from the values on staggered rows of parallel tubes. Heat transfer due to oscillations of a hot gas in the cylindrical chamber doubled with an increase in the frequency by 1000 c/s below 10 000 c/s, but did not increase beyond that value [9D]. A review paper [23D] discussed direct contact heat transfer between a single drop and an immiscible liquid utilizing a rigid drop model, or a model with internal circulation. Numerous relations for outside and inside heat coefficients are tabulated.

*Packed and fluidized beds*

Studies [17D, 27D] were undertaken on heat transfer to water flowing through a packed bed and resulted in the following equations for the effective conductivity $k_e$ and the heat-transfer coefficient $h_w$ to the wall [17D] in the Reynolds number range from 100 to 1000

$$k_e = 4.75 \left(\frac{d_p\, G}{\mu}\right)^{0.27}$$

$$h_w = 5.53\ G^{0.434}$$

with $d_p$ representing the diameter of the spherical particles and $G$ the approaching mass flow per unit area. An equation of similar form, but with an exponent varying with the dimensionless parameters, was found in experiments [25D] at $0.3\ Re < 2500$ and $6 < Pr < 1300$. Effective conductivities between 0·16 and 1 Btu/h ft degF) were measured [26D] in flow of superheated steam through a packed bed of calcium orthophosphate pellets. Pressure drop and heat-transfer coefficients were also measured [15D] for gas flow through a bed of steel spheres, sand, and rock particles. $j$-factors, describing simultaneous heat and mass transfer of gases to a bed of spheres, exhibited a peculiar transitional behavior in the Reynolds number range between 4000 and 5000 [7D]. Unsteady heat transfer in a packed bed with suddenly varying entrance temperature was analyzed [6D].

Several papers discussed heat transfer between objects and a fluidized bed [1D, 5D, 10D, 29D]. In such a bed in which the fluidized particles have the capacity to transfer heat but not mass, the heat transfer increased ten to twenty times compared to heat transfer in a one-component fluid, whereas the mass transfer increased only one and a half to two times [29D]. It is therefore concluded that 80–90 per cent of the heat transfer is caused by the solid particles, only the rest by the gas. The height of a fluidized bed was found to have no effect on heat transfer to an object provided it is located at a sufficient distance from the grid [5D]. Heat transfer between a fluidized bed and a surface is analyzed [1D] as caused by density pulsations. Heat transfer between a packed bed of ceramic spheres with 8–15 mm diameter and fluidized alumina particles was measured [2D]. Heat transfer between an agitated bed of dispersed material in vacuum was found to be mainly caused by radiation above room temperature and by conduction below room temperature [4D]. Heat transfer was studied in a spouted bed [16D] agitated by an air jet and for liquid–solid suspensions flowing in pipes [13D].

## TRANSFER MECHANISMS

Exact solutions for the diffusion equations of momentum, heat, and mass in spiral viscous flows of an incompressible fluid have been reported [15E]. The transition process to turbulence was studied experimentally in oscillating boundary-layer flows [7E]. A periodic velocity variation was impressed on the main flow by a shutter valve. The transition Reynolds number was found to depend on the ratio of the velocity fluctuation to the mean velocity only, and not on the frequency. Turbulence bursts were closely connected with the fluctuations. The development of turbulence in the presence of heat flow was investigated in helium II [12E]. An analysis [9E] of the turbulent temperature field on a flat plate with a turbulent Prandtl number, which varies with wall distance, gave the result that heat transfer and temperature recovery are mainly influenced by the turbulent Prandtl number close to the wall. A turbulent wall Prandtl number of 0·9 gave results in best agreement with experiments. The distribution of temperature and eddy diffusivity for heat in turbulent flow near a wall was studied in [11E]. Local time mean and fluctuating concentrations were measured in turbulent flow through a pipe by dye injection [4E]. A new method [13E] utilizing small nickel electrodes imbedded in a pipe wall, recorded the fluctuations in the local rate of turbulent mass transfer to the wall. The influence of Mach number and heat transfer on the laminar sublayer thickness of a turbulent boundary layer was calculated [2E] and offered as a means to estimate the influence of roughness on friction and heat transfer. A transformation of the two-dimensional boundary-layer equations for turbulent flow of a compressible fluid to the incompressible form was achieved [1E]. Measurements [3E] on an argon plasma jet with a temperature of 23 000°R showed that the core of uniform velocity downstream from the nozzle exit extends through a length equal to one diameter. In the mixing region, mass was found to spread more rapidly than energy and this more rapidly than momentum. Analyses were published on laminar and turbulent mixing of two co-axial streams with different velocities [14E] and of the heat diffusion from a line source into the turbulent mixing region of two parallel streams [6E]. A survey paper [8E] discusses the use of a forced-flow system for the study of kinetics of fast homogeneous reactions. Second order fluids have a stress tensor which depends on the local acceleration field as well as on the velocity field. For such a fluid, the recovery temperature was calculated [10E] considering the flow between a stationary and a parallel rotating disc of infinite extent. Diagrams were presented [5E] which show for mixed free and forced convection the regimes in which free convection or forced convection effects can be neglected and in which both have to be considered.

## NATURAL CONVECTION

A range of problems has been investigated for natural convection boundary layers. Heat-transfer coefficients corresponding to either prescribed surface temperature or prescribed surface heat flux were computed for the sphere [6F] and the horizontal cylinder [17F]. The three-dimensional natural convection boundary layer near the stagnation point on a general curved surface depends on the ratio of the two principle radii of curvature as well as on the Grashof and Prandtl numbers [32F]. Arbitrary surface temperature variations along a vertical flat plate were treated by an integral method [36F]. The temperature and flow fields adjacent to a vertical plate subject to a spatially discontinuous surface temperature were respectively visualized by an interferometer and by the Schlieren and tellurium methods [37F]. Some of the tests were carried out with a portion of the plate maintained at a temperature above ambient and another portion maintained at a temperature below ambient.

When the buoyancy force varies linearly with the distance from the leading edge, and the flow is laminar, the surface heat flux is uniform when the surface temperature is uniform. A similar correspondence does not hold for turbulent flow. Heat-transfer results for the aforementioned problems were computed both by integral and by finite difference methods [19F, 20F]. The first order correction to the boundary-layer solution for the isothermal vertical plate leads to better agreement with velocity profile data [46F]. The laminar wake above such a plate does not yield similarity-type solutions [45F]. The same state of affairs applies for the effects of buoyancy on a rotating cone [10F]. A series solution for the latter problem provided Nusselt numbers that are in satisfactory agreement with experimental data.

A computation method is proposed for estimating the heat transfer from plane vertical (and slightly inclined) surfaces of arbitrary contour [21F]. It is once again demonstrated that a gas having properties $\mu \sim T$, $Pr =$ constant, and $c_p =$ constant yields laminar boundary-layer equations identical to those for a constant property gas [13F]. The problem of blowing and suction on nonisothermal vertical plates has been added to the store of similarity solutions [22F], as has an unsteady problem in which the plate temperature varies in a rather special way with time and position [33F]. The transient natural-convection cooling of a previously heated vertical surface was studied [11F]; it was demonstrated that the quasi-steady assumption underestimates the time required to cool down to a given temperature.

The effect of buoyancy on a forced-convection flow and the effect of a non-zero free stream on a natural-convection flow have been investigated by series expansion methods for the vertical isothermal plate [9F, 43F]. Suction and blowing were included in an analysis of combined forced- and natural-convection flows in horizontal and vertical channels and in vertical tubes [5F]. On the basis of the latest available experimental information, conditions are set forth delineating forced, natural, and mixed convection in horizontal and in vertical tubes [24F]. Experimental data are reported for combined forced- and natural-convection flow in vertical concentric and eccentric annuli with oil as the working fluid [1F].

It was demonstrated experimentally that the nature of the inlet to an open thermosyphon tube can affect the heat-transfer characteristics of the system [23F]. An interferometer was employed to study the transient and a steady natural convection in a vertical parallel-plate channel containing an internally heat-generating fluid [27F]. Analysis has provided upper bounds for the heat transfer across a horizontal fluid layer that is heated from below [16F]. The buoyancy-induced flow within a horizontal cylinder whose wall temperature varies sinusoidally around the periphery was also subjected to analysis [44F].

Transverse oscillations of either finite or infinite vertical plates lead to a slight reduction in the steady-state natural convection Nusselt number [2F, 3F]. These analytical predictions were in accord with experiment as long as the flow regime was laminar [4F]. Natural convection may be set up in a chamber due to compressive heating of the gas within the chamber [12F]. An empirical procedure is outlined for determining the temperature profile due heating [35F].

There has been considerable interest in problems of convective instability. The onset of convective motion in a horizontal fluid layer heated from below is usually characterized by the critical Rayleigh number. Values of this parameter were calculated for a wide range of thermal boundary conditions and for nonlinear temperature profiles [41F]. A method is outlined for finding lower bounds on the critical Rayleigh number for fluids contained within vertical cylinders of arbitrary plan form [30F, 31F]. The role of surface tension in creating cellular convection in horizontal fluid layers has been subject to analysis [26F, 38F].

Consideration has also been given to the patterns of cellular convective motion and to the development of other flow patterns at higher Rayleigh numbers. The relationship between the periodic solutions of linear theory and the cells observed in experiment is clarified [42F]. It is demonstrated that the variation of kinematic viscosity with temperature is the dominant factor in establishing the hexagonal form of the celluar motion [29F]. Turbulent convective motions in horizontal fluid layers have been investigated by numerical integration of the time-dependent form of the conservative equations [7F, 15F]. Convective growth rates in the atmosphere and in the solar environment have also been subjects of analytical interest [28F, 39F].

Convective instability in various other flow configurations were analyzed. Among these are the boundary layer on an isothermal vertical plate [25F], the vertical parallel-plate channel with an applied transverse magnetic field [8F], Couette flow of a non-Newtonian fluid in a horizontal channel heated from below [14F], a plane-parallel flow of a thermally stratified fluid under the influence of a body force acting normal to the plane of stratification [18F].

A few papers were devoted to magnetohydrodynamic natural convection. The following topics were considered: the effects of external electric circuit and wall conductance on fully developed flow in a vertical channel [47F], the boundary layer adjacent to an isothermal vertical plate subjected to a strong magnetic field [34F], the doubly infinite vertical plate subjected to a horizontal magnetic field and time-varying surface temperature or heat flux [40F].

## CONVECTION FROM ROTATING SURFACES

When a free-stream flow impinges against a rotating disc, the heat transfer exceeds that for a disc rotating in a quiescent environment [10G]. The latter problem is treated within the framework of boundary-layer theory and limiting solutions are obtained for small and large Prandtl numbers [4G]. A fundamental solution corresponding to a spatially discontinuous temperature on the surface of a rotating disc was generalized to accommodate arbitrarily variable surface temperatures [6G]. A correlation of experimental heat-transfer data for a disc in vertical orientation took account of both rotation and buoyancy [5G]. The same study investigated the effect of heat transfer of nearby stationary objects. The transfer across the gap between a rotating and a stationary disc was investigated analytically for cases in which the fluid is non-Newtonian [7G] or is electrically conducting and subjected to a transverse magnetic field [8G].

For the case of throughflow in an annulus wherein the inner surface rotates, it was possible to predict heat-transfer rates to fluids with $Pr = 1$ for the Taylor number range slightly above the critical. For other Prandtl numbers and a wider range of operating conditions, a semi-empirical Nusselt number correlation was devised [1G]. In a series of experiments involving several fluids it was found that, for a wide range of conditions, the heat-transfer rates for combined rotation and throughflow were the sum of those for rotation alone and for throughflow alone [9G]. Tests were also carried out to determine the heat transfer between two fluids flowing in counterflow through concentric annuli, the separating wall being a rotating tube [3G].

The effect of rotating a solid cylinder moving at high speed normal to its axis was to eliminate thermal hot spots on the surface [2G].

## COMBINED HEAT AND MASS TRANSFER

Interest continues in the effects produced by thermal-diffusion and diffusion-thermo in binary boundary layers. The initial impetus for this concern stems from the use of a secondary gas different from the main-stream gas (usually air) in transpiration cooling. Recent theoretical studies concentrate on transpiration with stagnation-point flow. One of these [1H], obtains results with injection of helium and Freon-13. With helium injection, large changes in the stagnation point adiabatic wall temperature are found. Another study of helium injection into a plane or axisymmetric stagnation flow of air finds qualitatively similar results [18H]. Diffusion-thermo plays a key role in transpiration-induced buoyancy when helium is injected at the stagnation-point region of a horizontal cylinder [16H]. Comparing the calculations of different gases (injected into air) in both forced convection and buoyancy-induced stagnation-point flows, diffusion-thermo effects are found to be most important when using hydrogen or helium [17H]. It is also found that defining the thermal driving force as the difference between the wall temperature and the adiabatic wall temperature permits the use of heat-transfer coefficients derived for flow with a single component. A similar result has been presented for one-dimensional heat and mass transfer with either hydrogen or carbon dioxide injected into air [22H]. Failure of the analogy between heat and mass transfer, when they occur simultaneously, has been demonstrated [5H], as being due to thermal-diffusion effects. The equations for simultaneous heat and mass transfer, without thermal diffusion, with a laminar three-dimensional boundary layer have been examined to demonstrate the conditions required for similarity solutions [2H].

An experimental study with injection of either helium or Freon-13 at the stagnation point of a hemisphere in a high speed air stream shows the significance of thermal diffusion effects [4H]. Two reports [12H, 13H], have been presented describing experiments in which helium, air, and Freon-13 have been used in the transpiration cooling of a cone at Mach numbers up to 4·35. With large blowing rates, recovery temperatures were obtained in the experiments that were higher than the main stream total temperature.

The downstream influence of transpiration cooling in an axisymmetric nozzle has been measured [7H]. In that study, helium and nitrogen were injected into a main stream of combustion products. Hydrogen was found to be more effective than helium in protecting a conical surface, when injected at the apex of the cone into a Mach 7 air flow [6H].

When a liquid is used in film cooling, the vapor formed is found to provide an effective insulating layer [23H]. This layer can extend a considerable distance downstream from the region where the coolant has evaporated. Film cooling with water injected on a conical surface exposed to a high temperature Mach 2 airstream is found to be less effective than transpiration cooling [3H]. Transpiration cooling through the porous graphite anode of an electric arc greatly reduces the heat transfer to the anode [15H]. Using known correlations, film cooling and transpiration cooling are compared when regenerative convection cooling is also present [9H].

One-dimensional combined heat and mass transfer between a gas and a liquid has been analyzed in the case of unsteady [20H] and steady [21H] state transfer. In the latter paper, application is made to a specific air–aqueous solution system which is related to problems in dehumidification. Heat and mass transfer in vapor–gas mixtures has been studied [11H] and relations for evaporation from a liquid layer into a still gas and into a moving gas have been presented [14H].

The diffusion of mass, from a point source on a plate into a two-dimensional turbulent boundary layer when heated from below and when unheated, has been measured [8H]. Universal velocity laws, for turbulent boundary layers with transpiration, have been obtained using either the maximum shear stress in the flow [10H] or the wall shear stress [19H] as the reference friction velocity.

## CHANGE OF PHASE

Activity, largely experimental, continues unbated in the area of boiling, condensation, bubble inception and dynamics, and aspects of burnout.

Satō and Matsumura [66J] consider incipient subcooled boiling with forced convection. Ruckenstein [65J] proposes a physical model for nucleate boiling heat transfer, deriving coefficients for a horizontal surface and a boiling liquid. Maximum nucleate boiling heat fluxes and transfer coefficients are studied experimentally using cylinders (of various metals coated with chemical films) in liquid $N_2$, liquid $O_2$, and their mixtures [49J]. A group of investigations consider a variety of effects on the nucleate boiling process: surface tension [63J], pre-treatment of heating surface with Teflon spots [84J], gravitational field [69J], and flow vibrations [2J]. For refrigerants (Freon-11 and -113) Blatt and Adt [5J] study experimentally boiling heat transfer and pressure drops.

Grassmann and Hauser [29J] experiment on a single nickel wire range over nucleate and film boiling regions and the coexistence of these regions is studied by Nishikawa and Shimomura [56J]. The transition from nucleate to film regimes receives attention from Beurtheret [4J] and Vliet and Leppert [78J, 79J]; the latter propose a physical model of the transition mechanism based on photographs and cite the marked effect of subcooling on the flow mechanism. Gravitation influence is studied experimentally over both regimes by Merte and Clark [52J].

Heat transfer in surface boiling under free convection is studied by Nishikawa and Kusuda [55J], and under forced convection by Bergles and Rohsenow [3J]. Gambill [24J] conducts 234 tests on saturated water to determine the inherent uncertainty of the critical heat flux in pool boiling. Increases in pool boiling heat transfer by delay or destabilization of the vapor film are obtained by applying a voltage according to Markels and Durfee [50J].

Film boiling is investigated by Ledinegg [45J] and by Hamill and Bankoff [33J], the latter theoretically determining the upper and the lower bounds for the growth of a vapour film at the surface of a rapidly heated plate. Frederking and Hopenfeld [23J] report on laminar, two-phase, boundary layers in natural convection film boiling of subcooled liquids. In annular flow, Polomik *et al.* [60J] measure film boiling heat-transfer coefficients beyond "burnout" for steam–water mixtures. Various effects on this regime of boiling are considered: gravitational field [61J], film stability [48J], radiation [71J], and pulsating pressures [20J].

For boiling in channels, Tippets [75J] examines critical heat fluxes and flow patterns in high pressure boiling water flows; Hudson *et al.* [40J] study by analog, the response to power or inlet flow modulations.

Evaporation of hydrocarbon drops in sea and distilled water is studied by Sideman and Taitel [68J]; Schlünder [67J] investigates pure and salt solution droplet evaporation into gas for steady and unsteady conditions. Fedorov [22J] studies experimentally the evaporation of water from a porous wall into a nonisothermal, turbulent boundary layer. Cary [11J] considers the irreversible thermodynamics aspects of normal drying of porous materials. Control of evaporation by monomolecular films is reported by Katti *et al.* [43J]. The flash distillation method of producing fresh sea water is analyzed thermodynamically by Knuth [44J] for optimum performance. Additional evaporation studies deal with condensation coefficients of water and ice [18J], molten metal vaporization into much colder surroundings [38J], and the inception of vaporization in adiabatic flow [53J].

Specific attention is directed toward bubble characteristics because of their intimate involvement in the boiling mechanism. Rallis and Jawurek [62J] measure latent heat transport by bubbles to be significant at all states of boiling and Rogers and Mesler [64J] observe surface cooling by bubbles during nucleate boiling. Photographic studies give insight into such details as: bubble dynamics from a single nucleation site [16J], bubble departure from capillaries [81J], and the growth of electrolytic bubbles [27J]. Bankoff [1J] treats the asymptotic growth of a bubble in a liquid of uniform, initial superheat. Clark *et al.* use the source theory to treat growth and collapse of bubbles [82J] and investigate the "bubble boundary layer" for forced convection boiling in channels [42J].

Heat transfer at "burnout" conditions is considered for the systems used in engineering practice. Becker and Persson [7J] report agreement between predictions and experiment for boiling water in vertical round ducts; Mayersak *et al.* [51J] note confirmation of burnout heat flux equation at higher flow velocity; Doroshchuk and Lantsman [21J] study pressure and mass-flow rate effects for water and water–steam mixture flow in tubes; Bernath *et al.* [9J] treat rod bundles in forced convection of water at high pressures, and Becker and Hernborg [6J] compare results for boiling water in a vertical annulus with published annuli and rod cluster data. Gambill and Bundy [25J] consider thin rectangular channels containing low-pressure water in natural circulation. Capillary wicking and surface deposits appear significant to Costello and Frea [15J] in attempting to evolve a correct burnout model.

Following a review of two-phase flow with heat transfer, Oliver and Wright [57J] work with gas–liquid slug flows because of the promise of high heat-transfer rates. Collier *et al.* [14J] experiment with steam–water mixtures flowing vertically upwards in various annuli. A slip model [17J] is used to obtain an empirical correlation for gas–liquid convective heat transfer accurate between six and seventeen per cent.

Tippets [76J] uses high-speed photographs to relate critical heat flux to local flow parameter and fluid properties for high pressure, bulk boiling of water in forced convection. For horizontal tubes, Pike and Ward [58J] employ nonlinear differential equations to successfully describe adiabatic, evaporating flow of steam and water; Zahn [85J] studies two-phase single component flow under conditions simulating those of a small air-conditioning coil. Prediction of voids is the concern of Griffith [30J] who uses slug flow theory to predict density in heated channels of various shapes, and Zivi [86J] who estimates steady-state steam-void fraction by the principle of minimum entropy production. Bentwick's and Sideman's study [8J] of annular liquid–liquid flow has interesting practical consequences, i.e. a viscous oil is better heated if allowed to flow inside a thin water annulus.

Condensation studies cover both discrete and gross aspects of the phenomenon. Heiskala [36J] views the process from an irreversibility viewpoint; Lee [46J] calculates the heat-transfer coefficient for the turbulent Nusselt's model; and Stewart *et al.* [74J] consider the influence of mixture composition, gas phase turbulence, and liquid layer thickness on overall coefficient of heat transfer. A refinement of an earlier work is the removal of condensate through the pores of a vertical, isothermal wall on which laminar film condensation occurs [41J]. Particulars of the process consider the kinetics of capillary condensation in wedge-shaped pores [59J] and on inside surface of glass section of shock tube [28J]. Visual and photographic study [37J] shows condensation occurring in the mixing zone between jet and ambient air. Hasson *et al.* [34J, 35J] by theory and experiment study vapor condensation on laminar liquid jets. Further aspects of condensation heat transfer reported are: influence of a noncondensible gas [72J] inclination of the cylindrical condensing surface [26J], rotation of cooled cylinders [39J], the effectiveness of condensation promoters [19J, 47J], and homogeneous nucleation in nozzles [80J].

Related topics include an application of the source theory to solve phase change problems [83J], the pressure dependence of ultimate superheating of a liquid [70J], and gas absorption accompanied by large heat effect and volume change of the liquid phase [13J].

Studies closely related to engineering practice consider: the various influences on the condensation of steam in coils [10J] and on stainless steel [77J], commercial and industrial aspects of the thin film evaporation [54J], effect of oil on heat transfer to boiling refrigerants (F-12 and F-22) [73J], effect of internal frost deposits on the performance of a heat exchanger tube [12J], and the use of latent energy of vaporization in energy reservoirs [32J].

## RADIATION

Judging by the number of articles devoted to the subject in the past year, there is great interest in the radiant heat transfer between solid surfaces and adjacent gases (stationary or flowing). Calculations of radiation exchange within an absorbing and emitting gas were initiated, historically, by astrophysicists interested in the heat exchange in stellar bodies. Engineering interest goes back to furnace applications where high temperatures or entrained dust or ash causes the gaseous medium to absorb thermal radiation. Recently, interest seems to have been stimulated by the high temperatures encountered in high-speed objects entering the atmosphere and general problems in flow of high-temperature gases.

Use of a "temperature-jump" or "radiation-slip" boundary condition at a solid interface with a radiating gray gas has been explored [12K, 29K]. When this boundary condition is used, the radiant exchange within the gas can be approximated by the diffusion equation even when the gas is not optically thick. The temperature jump boundary condition has also been used in determining the heat transfer in an inviscid optically-thick gas flow [43K]. Other approximations have been made for a two-dimensional radiating gas flow to enable the use of transport theory [10K]. A Monte Carlo solution has been obtained for heat transfer through a gray gas (of varying optical thickness) between two plane parallel gray walls [20K] and between two concentric gray cylinders [31K]. A differential equation has been obtained from the normal integral equation for radiation from a volume gas source [44K]. Approximation of the heat transfer through an absorbing gray gas between walls of a rectangular duct [27K] and several other geometries [13K] have been obtained. Contour integrals have been used to calculate some special cases of radiation heat transfer in gases [11K]. Possible definitions of a mean absorption coefficient to use with a nongray gas have been described [45K]. The Monte Carlo method mentioned above has been extended to the case of heat transfer through a specific nongray gas with a temperature dependent absorption coefficient [21K].

The relative importance of conduction and radiation in a stationary absorbing gas has been described for varying optical thickness [41K]. Another analysis studies the effect of a nongray gas with conduction present [42K]. Calculations performed for one-dimensional transfer of heat through a gray and a specific nongray gas includes the effect of variable conductivity [18K]. The importance of optical thickness on heat transfer to a turbulent boundary layer of a gray has been demonstrated [23K]. In a laminar boundary layer the combined radiation and convection heat transfer are found to differ greatly in a comparison between a gray and a nongray gas [7K]. The absorption of radiation in a high-speed laminar boundary layer reduces the recovery factor [8K]. For slug flow between parallel plates, radiation scattering under certain circumstances (e.g. dust-laden air) can have a much greater effect on heat transfer than absorption and emission [9K]. The mean-free path for scattering of radiation in fogs has been calculated [6K]. Calculation of the temperature distribution in a real absorbing gas (ammonia) layer agrees with experiments [16K]. In the same study, the onset of convection in a horizontal layer of the conducting–absorbing gas is determined. The speed of propagation of small disturbances in a radiating gas is, at various times, either the isothermal or isentropic speed of sound [25K]. A simplified analysis of radiation from a detached shock layer shows the importance of the optical thickness in determining the radiant heat loss [17K].

The effect of roughness on the reflectance of a solid surface has been studied theoretically [33K]. It was found that the reflectance of the surface may be used to determine the distribution of the heights of the surface irregularities. An experimental study indicates that the minimum wavelength for appreciably specular reflectance, with normal incidence on an aluminized ground glass plate, is roughly one-fourth the average particle size used in grinding the surface [1K]. With incident black-body radiation, the roughness of a metal surface has a much greater effect on the specular reflectance than on the total hemispheric reflectance [3K]. The emission and reflection properties of solid surfaces with regular sinusoidal [14K] and sawtooth [30K] two-dimensional roughness elements [much larger than the wavelength] have been calculated for gray surfaces.

Calculations for combined radiant interchange and convection with a transparent gas have been performed for flow in an asymmetrically heated parallel plate channel [22K] and in the entrance region of a circular tube [36K]. In both geometries there are many situations when the radiation heat transfer cannot be neglected. The combined radiant and conduction heat transfer through a plane layer of a transparent quiescent gas has been determined when a radiation shield is placed in the gas [40K]. The transport of radiation between two isothermal containers connected by a tapered tube with gray diffuse walls has been calculated [37K]. Application of the method of images in radiation heat transfer in enclosures has been extended to some special classes of nongray surfaces [5K]. Shape factors between surface elements and paraboloidal and other axisymmetric surfaces have been determined [28K]. Possible use of the concept of exergy in radiation calculations has been explored [32K].

The effects of variable thermal conductivity and emissivity [39K] and variable root temperature [34K] on the performance and optimum design of single radiating fins has been calculated. For radiating fins connected between two walls or tubes, the effects of variable fin thickness [19K] and asymmetrical temperature distribution [38K] have been studied.

An apparatus for simulating high radiation flux inputs to a solid surface using an electric arc has been described [26K]. Measurements of the normal spectral emittance of refractory materials have been made at temperatures up to 1000°C [4K]. With a solar furnace, simultaneous measurements of the emittance and sample temperature (inferred from radiation measurements) have been made up to a temperature of 2000°C [24K]. Theoretical calculations [35K] which relate the emissivity and absorptivity of metals to their thermal conductivity agree well with previous experimental studies.

The emittances of the skins of a number of different animals species are all very close to unity [2K]. The total radiant energy emitted by a human, gender unspecified, was found to be more than fifty per cent greater when the sample was unclothed as compared to fully clothed [15K].

## LIQUID METALS

A review of available information on liquid metal heat transfer included such topics as forced-convection single-phase flow, pool and forced-convection boiling, and condensation [4L]. Special reference is made to applications in space technology.

Experiments involving sodium flowing in a circular tube [2L] and NaK flowing in a parallel-plate channel [6L] have provided additional heat-transfer data and corresponding correlation equations. Compared with the circular tube, there is relatively little experimental information in the literature for longitudinal flow between rods arranged in regular array. New data for the latter flow situation have recently been reported for sodium [3L] and for mercury [8L]. By applying an inviscid flow model, improved analytical Nusselt number predictions have been obtained for cross flow of liquid metals through rod bundles [7L]. It was demonstrated that adding a small amount of helium or nitrogen gas to mercury flowing in either vertical or horizontal tubes caused a remarkable decrease in heat transfer [9L].

Two distinct flow regimes were observed in a heated thermosyphon tube containing mercury [1L]; the temperatures of the system were generally unsteady. When mercury confined between two horizontal plates was heated from below, and the apparatus spun on its vertical axis, the heat transfer was found to depend on both the Rayleigh and the Taylor numbers; however, at small rotational speeds, the dependence on the Taylor number vanished [5L].

Forced-convection boiling studies were carried out with two potassium amalgams: 14·7 per cent K and 44·7 per cent K [13L]. Mercury was used as a surface on which boiling studies for water and alcohol were performed [11L]. Nucleation was observed to take place at sites which are mobile and move irregularly. Measurements of void fraction in a two-phase mercury flow were correlated with the slip velocity [12L]. A method of preparing droplets of liquid metal using flash heating is described [10L]. The tests produced single droplets of molten zirconium with highly reproducible diameters between 100 and 500 $\mu$.

## LOW-DENSITY HEAT TRANSFER

Interest in this area increases, but for the past year publication occurred primarily through reports of limited distribution. Open literature articles are only a small fraction of these.

Wise [12M] considers the accommodation coefficient for collisional energy exchange between gas and solid surface to be a non-isothermal desorption process. The predicted absence of pressure influence on the accommodation coefficient agrees with experimental evidence. The related problem of condensation coefficients is approached by Kochurova [4M] using the "hole-potential" quantum-mechanical model for the liquid. Limited comparisons of theory with experiment are made for four substances.

Heat transfer and flow under rarefied gas conditions receives attention by a number of investigators. Rebrov [7M] gives an improved equation for calculating heat transfer near a wall with emphasis on the condition where the accommodation coefficient is near unity. Inman [3M] extends an earlier procedure of obtaining heat-transfer coefficients based on generalization of constant wall temperature results to the case of fully developed laminar tube slip flow. Deissler [1M] analyzes the effect of second-order slip flow and temperature-jump boundary conditions, finding agreement with experiment at somewhat lower densities than the usual first-order analysis, which differs from the second-order analysis by as much as twenty per cent in some instances.

Specific geometries considered are: (1) parallel plates—here Sparrow and Kinney [9M] vary the thermal accommodation and reflection coefficients for infinite, isothermal plates, and calculate the heat transfer; (2) sphere and cylinder—Springer and Tsai [10M] determine the effect of thermal accommodation on drag, Touryan and Maise [11M] calculate the heat transfer to a sphere from a nonuniform gas; (3) fine wire—Hurlbut [2M] extends the conductive heat-transfer analysis of Lees and Liu, originally done for complete thermal accommodation of gas molecules at the surface, to case where arbitrary accommodation holds; (4) concave cylindrical surface—Sparrow *et al.* [8M] calculate heat-transfer rates, wall temperature, and forces on inside surface of a concave cylinder.

Probert and Thomas [6M] consider heat conduction through residual gases during the low-temperature measurement of thermal properties with particular interest shown to the transition region between free-molecule and continuum flow.

Maise and Fenn [5M] measure stagnation point recovery factors in the supersonic flow of argon (20%)-helium (80%) mixture at low density. Results exceed substantially those for either pure gas and are attributed to partial separation of molecular species in the shock layer.

## MEASUREMENT TECHNIQUES

A description of the highlights of a recent conference on high temperature measurements has been presented [3N]. Basic techniques and problems in precision thermometry have been reviewed [33N]. Several studies have explored the use of thermocouples at high temperature. Platinum 20% rhodium vs. platinum 5% rhodium thermocouples were found [4N] to be quite stable in use at temperatures up to 1800°C. Tungsten–rhenium thermocouples have been used up to 2000°C, but variations in wire samples require the calibration of each spool of wire [14N]. Refractory thermocouples have also been used at high temperature [5N]. A pulse technique, wherein the time rate of change of a thermocouple is measured, allows one to infer gas temperatures up to 7000°F [43N]. The thermocouple itself never reaches a high temperature; a gas coolant directed on it can be turned on and off rapidly.

The effects of stress, temperature gradient, and annealing history are found to be significant on some samples of copper–constantan thermocouples [15N]. The output of a thermocouple made of elements in sliding contact with each other (as in measurements of tool interface temperatures) has been related to the surface temperature distribution [39N]. The manufacture of fine (0·001 in diameter) thermocouples has been described [20N]. Small (0·0005 in. diameter) thermocouples mounted at the stagnation point of a support have been used to measure the local total temperature in a high-speed air flow [8N]. Use of very thin thermocouple junctions embedded in a solid surface have been found to respond rapidly to changes in surface heat input [34N]. A thermocouple has been used to measure the surface temperature of a burning solid [42N]. Thin films of copper and nickel evaporated onto a glass surface were used as a thermocouple to obtain the surface temperature [10N].

Surface temperature can be measured [11N] using a luminescent coating on a surface. The coating is irradiated by a mercury vapor lamp and the emission, at two wave lengths, is measured by a photomultiplier. A resistance bridge has been designed to give a linear output with temperature change when connected to a platinum resistance thermometer [24N]. Instruments for precise measurement of small temperature changes have been described [35N, 36N]. One of these [36N] is a thermistor-AC bridge construction which permits measurements with a standard deviation of 14 μdegC. Averaging of the output of a radiation pyrometer used in measuring gas temperatures can cause significant errors due to the nonlinear relation between emission and temperature [9N].

A number of studies have been concerned with devices for direct measurement of heat flux. Thin film resistance thermometers are often used for this purpose in transient studies. The feasibility of a direct calibration of thin film thermometers by putting in an electrical energy input when the thermometer is immersed in a liquid has been demonstrated [1N]. A small value of the Biot number is required for the best utilization of thin film heat-transfer gages [25N]. A thin film thermometer for use at high temperatures (to 1000°F) has been constructed [6N]. The use of several different gage materials for the resistance elements was found to have negligible effects on the performance of a heat-transfer gage [13N]. In measuring combined radiation and convection heat transfer, however, the spectral characteristics of the thin film must be determined [7N].

Direct measurements of heat transfer and heat-transfer coefficients are possible in a steady-state experiment if the wall heat flux is provided by a thin metallic film in which there is Joule heating [22N]. Coatings which change phase at different temperatures may be used to measure surface temperature [31N]. Various types of heat-flux meters have been reviewed [41N] and the perturbation of a heat-flux meter on the wall conditions has been described [28N]. Solutions of the conduction equation permit measurement of the surface heat transfer in a transient experiment [37N]. The dimensions and properties of an aerodynamic heating rate probe can be adjusted to give the maximum time for linear response when determining the heat flux [32N].

An infrared radiation detector in the form of an evaporated thermopile has been described [2N]. A surface with a blackened conical contour has been developed to act as a black radiation detector out to very long wave-lengths (40 $\mu$) [16N]. An absolute reflectometer has been designed for use at very low temperatures (near-liquid helium) [27N].

A number of papers concerned with the measurement of thermal conductivity have been presented. A steady-state radial heat flow system has been used with granular materials at temperatures to 1000°C [19N]. A transient system using a line source has been developed for use with cylindrical specimens of rocks and other poor conductors [30N]. Further discussions have been presented on transient methods of thermal conductivity determination with a line source in a fluid [26N] and with a one-dimensional heat flow in a solid [18N]. Because of the reproducibility in measurements of its thermal conductivity over a large range of temperature, platinum has been suggested as a standard for conductivity measurements [40N].

The feasibility of using a Mach–Zehnder interferometer illuminated by radiation at two wave lengths for simultaneous measurements of temperature and concentration has been demonstrated [17N]. Losses due to electrical heater leads have been compensated by judicious placement of the potential taps [21N]. Wall shear stress measurements can be made using an impact tube adjacent to the wall surface. This technique, originally developed by Preston, has been used on rough walls [29N] and it has been compared to other methods of wall shear stress measurement [38N]. In measuring fluid velocities with an impact tube along the centerline of a tube in turbulent flow, the diameter of the probe has been found to have a significant effect [23N]. Measurement of the heat loss from a probe has been used to determine low fluid velocities [12N].

## HEAT-TRANSFER APPLICATIONS

### *Heat exchangers*

Heat exchangers used with gas turbines operating on a regenerative cycle are often of the periodic-flow type. The hot and cold fluids alternately flow through a packed bed of finite heat capacity which acts as a thermal reservoir, alternately exchanging heat with the hot and cold fluids. Finite difference methods for determining the performance and temperature distribution in periodic-flow heat exchangers exchangers have been reported. Two papers [1P, 18P] include the effects of longitudinal conduction on the steady-state temperature distribution and one work [22P] is specifically directed towards transient effects. Experiments using various packings in a regenerator found spiral wire rings give the best hydraulic and thermal characteristics [8P]. The effect of variable fluid properties at high temperature on regenerator performance has been calculated [11P]. Some solutions for transient performance of periodic-flow and direct-transfer type heat exchangers for gas turbine use have been reported [16P].

A three-part paper [15P] reviews recent developments in compact heat exchangers (in which a large surface area for heat transfer is contained in a small volume). Methods for designing optimized shell and tube exchangers have been reported for tubes with fins [5P] and for plain tubes [9P]. The performance of shell and tube heat exchangers where the shell flow is divided into two parallel flows at the entrance has been calculated [14P]. A simple analytical relationship has been developed for the overall performance of cross-flow heat exchangers [12P]. Cross-flow heat exchangers with finned tubes have also been studied [4P]. Two recent papers [2P, 3P] consider the thermodynamic availability as a measure of efficiency in counterflow heat exchangers, and also include the effects of variable fluid specific heats. Equations have been derived for determining the temperature distribution in a parallel flow multichannel heat exchanger in which each channel interacts with every other channel [23P]. Assuming scale formation in tubular heat exchangers to be caused by nucleation of a supersaturated solution, the time rate of change, due to scaling, of the overall heat transfer is determined [19P].

The frequency response of counterflow heat exchangers to several different variations of inlet temperature has been calculated [21P]. Flow transients of a periodic nature, which affect the heat-transfer coefficient, are found to lead to possible resonances in heat-exchanger response [18P]. The transient response of a concentric tube heat exchanger, when the flow rates are changed suddenly, has been determined theoretically and experimentally [20P].

A simplified method for calculating the performance of a condenser has been used when there is a multicomponent vapor present [17P]. A hydraulic analog can be used to determine the effect of pressure drop of steam flow on overall heat transfer in a low pressure condenser [10P].

Scraped surface heat exchangers have been tested for possible application in the food industry [7P]. In this study, ice frozen from solutions of water was physically scaped off the heat exchanger walls. Plate heat exchangers have been tested with viscous fluids in laminar flow [13P] and with non-Newtonian fluids [6P].

*Aircraft and space vehicles*

Several papers [3Q, 10Q, 12Q, 16Q, 18–20Q] deal with heat transfer in supersonic flow to various shapes simulating aircraft, especially with interference effects between fins and base surfaces [3Q, 10Q, 12Q, 16Q] with delta wings [20Q] and with recessed surfaces [18Q, 19Q]. Interference caused peak heat-transfer coefficients [3Q]. Data on meteor flight are utilized [1Q, 6Q] to study the effects of aerodynamic heating. Radiative heat transfer was found [6Q] dominating at altitudes above 25 km. Convective and radiative heating to bodies of various shapes entering planetary atmospheres are discussed [5Q, 14Q]. In the Venus atmosphere radiation is dominating, in the Martian convection [5Q]. Numerous papers are devoted to ablation cooling in the re-entry process [11Q, 21Q, 22Q] to the performance of cork as a thermal protection material [8Q], to gaseous film cooling of a rocket motor [13Q], and to heat transfer in a rocket through which a gas with solid particles is moving [4Q].

The thermal radiation process for heat shields of space vehicles is discussed [2Q, 15Q] and space radiators are studied and optimized [9Q, 17Q], including a moving belt radiator system [7Q].

## THERMODYNAMIC AND TRANSPORT PROPERTIES

*Thermodynamic properties*

As in the past, experimental investigations are greatly outnumbered by theoretical studies, the latter centering on the critical state, intermolecular potential models, and thermodynamic data of systems at high temperature.

Using a Beattie-type apparatus, Hsu and McKetta [40R] report P-V-T measurements on methyl chloride. Lichtblau *et al.* [59R] measure compressibilities of ammonia and its mixtures with nitrogen and hydrogen to 2500 atm and 500°C. Measured virial coefficients are obtained for n-butane by Bottomley and Spurling [10R] and for carbon dioxide and ethylene by Butcher and Dadson [13R]. Additional properties reported are isothermal bulk modulus of selected fluids to 700°F and 10,000 psig [39R], temperature dependence of liquid metal densities [97R], and Joule–Thomson effects for nitrogen–ethane mixtures [96R]. Herington [33R] reports on the measurement of thermodynamic properties at the National Chemical Laboratory.

Equations of state for specific substances are reported for propyne [95R], hydrogen sulphide–hydrocarbon mixtures [89R], and neon [65R]. For the virial equation of state, second virial coefficients of vapors and their mixtures are given [112R], second and third virial coefficients for hydrogen [25R], and calculated coefficients for argon, methane, nitrogen, and xenon based on experimental compressibility data [27R]. The latter analytical approach is subsequently generalized [28R]. Connolly [18R], determines virial coefficients for carbon monoxide–hydrocarbon mixtures.

Theoretical investigations consider the fifth virial coefficient for a fluid of hard spheres [80R], the fourth for the square-well potential [67R], the third for the Kihara, exp-6, and square-well potentials [87R], the general superiority of three-parameter to two-parameter intermolecular potential functions in calculating virial coefficients [86R], and inter-molecular forces between unlike molecules [36R]. Lebedeff [55R] determines Lennard–Jones parameters from total scattering cross-section measurements and Smith [91R] the influence of intermolecular force effects on the thermodynamic properties of nitrogen.

The critical state is considered from the theoretical viewpoint by Azbel *et al.* [2R] and Temperley [104R]. Equation of state description in this region is explored for water [73R]; Hansen [30R] proposes an equation containing the critical temperature as an explicit factor; and Fisher [22R] gives deviations from Van der Wall's behavior on the critical isobar. Using sealed tubes, Cheng [17R] considers the effect of gravity on material distribution near the critical state.

Vapor pressure data include measurements, correlating equations, and estimating procedures. Miller [70R] measures liquid methanol vapor pressures near the melting point. For the salt water–fresh water process, Forrest and Worthley [23R] measure the vapor pressure of concentrated sea water. A simple, single relationship is developed permitting rapid vapor pressure calculations for normal paraffins [90R] and a Clausius–Clapeyron type equation particularly suited for computer use is described by Hall [29R]. For estimating vapor pressures, Miller compares a number of existing equations [68R] and derives two others [69R]. Minkoff [72R] describes an approximate determination of binary equilibrium data from single component isotherms. Theoretical considerations by Hemmer *et al.* of vapor–liquid equilibrium are directed toward equation of state and long-range forces [31R] and the critical region [32R]. Vapor pressure tables for water are reported by Bridgeman and Aldrich [11R] and heat-capacity data for supercritical conditions by Amirkhanov and Kerimov [1R]. Lu [60R] reports a theoretically based method for estimating latent heat of vaporization. Spalding [92R] provides a useful transformation of the Mollier, enthalpy-composition diagram. Other theoretical considerations concern the equation of state and adiabatic processes [47R] and the calculation of compressibilities and heat capacities from a rigid sphere equation of state [111R].

In the high temperature area the physical properties of gases are investigated [54R] and the calculation of real gas thermodynamic properties discussed in [101R]. Specific investigations deal with imperfect air and nitrogen to 15000°K [53R, 58R], helium [35R], carbon dioxide dissociation at 3500–6000°K [20R], dissociating combustion gases [3R], and their exergy [4R] The effect of partition function cutoff on the thermodynamic properties of atomic hydrogen and helium to 100000°K is determined [34R] and carbon monoxide vibrational relaxation in mixtures with helium, neon, and krypton measured spectroscopically [71R].

*Transport properties*

Diffusion coefficients, their measurement and prediction receive considerable attention. Holsen and Strunk [38R] report measurements for five binary mixtures of nonpolar gases by the Loschmidt Method; Mason *et al.* [63R] use radioactive tracers to measure thermal diffusion factors and mutual diffusion coefficients for several binary gas mixtures; Ivakin and Suetin [42R] use an optical method to measure diffusion coefficients for 22 gas pairs and compare with predictions based on the Lennard–Jones 6–12 and Buckingham exp-6 potentials; Unver and Himmelblau [106R] use the absorption of gases by a water jet to measure diffusion coefficients.

Other diffusion studies consider a line source in a turbulent boundary layer [76R], effective coefficients in a laminar, multicomponent boundary layer [103R], the pressure effect of gas interdiffusion [99R], temperature dependence of diffusion coefficients [41R], and the estimation of diffusion coefficients from viscosity measurements for polar and polyatomic gases [110R]. Van der Valk [107R] calculates thermal diffusion factors in ternary mixtures using the Lennard–Jones 6–12 potential and Mason *et al.* [62R] examine thermal and ordinary diffusion data over the temperature range 195–580°K to obtain intermolecular force and test combination rules. An earlier paper by Chen and Othmer [16R] provokes a lively exchange [15R, 84R, 88R].

Thermal conductivity of liquids, gases, and vapors is measured experimentally and predicted by kinetic theory. Leidenfrost [57R] describes an apparatus designed for precise measurements over the range −180–500°C and to 500 atm. Other measurements are reported for steam [51R], neon between 25°C and 75°C and to 2600 atm [85R], organic liquids by an absolute unsteady-state method [45R], aluminum and zinc powder suspensions [64R], saturated hydrocarbons by the hot wire method [26R], and ammonia [79R]. Blum and Deaton [9R] join theory and experiment to determine thermal conductivity and phase boundary at elevated pressure and temperature. Liquid and dense gas thermal conductivity is considered generally by McLaughlin [66R] and specifically for nonpolar substances by Stiel and Thodos [94R]. Special consideration is given to the determination of polyatomic gas thermal conductivity [19R, 74R, 83R] and their mixtures [5R, 74R]. High temperature studies consider the thermal conductivity of a fully ionized gas [100R], and measurement of plasma conductivity [102R].

Viscosity determinations were carried on over a wide front involving several experimental methods. Barus *et al.* [7R] use a capillary viscometer for the gases ($H_2$, $D_2O$, $CH_4$, $CO_2$) between −50° and 150°C to 200 atm. Using the oscillating disc method, Kestin *et al.* report results for isotopes of hydrogen [49R], dry and humid air [50R], argon–helium mixtures [43R], neon–helium and neon–argon mixtures [48R], and argon–ammonia mixtures [44R]. Trappeniers *et al.* [105R] use transpiration method to study neon up to 1800 atm and corresponding states to generalize the viscosity of noble gases at high densities. Steam viscosity is measured at high temperatures and pressures [78R, 81R]. Petker and Mason [75R] measure $N_2O_4$–$NO_2$ gas viscosity with a rolling-ball viscometer but Carmichael *et al.* [14R] cite this technique as being entirely unsuited for gas phase measurements. Ramakrishna [77R] employs an oscillating cylinder for liquid determinations and Browning and Fox [12R] the pressure drop and level in a U-tube for viscosity and diffusion measurements on atomic and molecular hydrogen.

Theoretical studies concern the foundation of transport theory [61R], transport coefficients and cross-sections in argon [6R, 21R] and hydrogen–argon mixtures [21R], and viscosity variation with temperature for heavy water [8R]. Kingston [52R] considers Van der Walls forces for unlike pair interactions for the noble gases (He, Ne, Ar, Kr and Xe). Hard sphere [108R] and Morse potential [82R] models are also used for viscosity predictions, and new combining laws proposed for nonpolar gas mixtures [98R]. Other mixtures studies include viscosity and translational thermal conductivity of multicomponent gas mixtures [24R] and liquid ternary mixtures [46R]. Lee *et al.* [56R] correlate the viscosity for light hydrocarbons, Stevens and Guirao [93R] comment on the scaling of apparent viscosity, and Waldmann [109R] is concerned with gaseous isobar mixtures. Holmes *et al.* [37R] consider the problem of combined viscothermal and thermal relaxation in polyatomic gases.

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*Boundary-layer Flow*

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