# Proceedings of the American Physical Society

## Sixth Meeting of the Division of Fluid Dynamics at Urbana, Illinois, May 12, 13, 1950

### *Symposium on Hypersonic Flow and Low Density Flow*

(J. H. Bartlett, presiding)

**A1. Results of Recent Hypersonic Flow Research in the Army Ordnance-California Institute of Technology Hypersonic Wind Tunnel.** Henry J. Nagamatsu, *California Institute of Technology.*

**A2. Hypersonic Research Facilities at the Ames Aeronautical Laboratory.** V. J. Stevens, *NACA, Ames Aeronautical Laboratory.*

**A3. Recent Research at the Naval Ordnance Laboratory on Hypersonic Flow.** R. Smelt, *Naval Ordnance Laboratory.*

**A4. Hypersonic Flow.** L. Lees, *Princeton University.*

**A5. The Effect of Thermal Radiation on Hypersonic Flow in Wind Tunnels and Free Flight.** H. G. Stever, *Massachusetts Institute of Technology.*

**A6. Some Experiments in the Field of Rarefied Gas Dynamics.** R. G. Folsom and S. A. Schaaf, *University of California.*

### *Contributed Papers*

(A. T. Nordsieck, presiding)

**B1. Transonic Flow Measurements.**[1] Wayland C. Griffith, *Princeton University.*—Experimental results on the flow around two-dimensional wedges and diamond airfoils have been obtained in the Princeton shock tube. Wedge angles studied are 10, 20, 40, 60, 90, and 180° (square ended wedge). Symmetrical diamond airfoils of 10 and 15° total angle are used for a preliminary study of shock wave and boundary layer growth in the transonic region. Density contours throughout the field are found from the fringe shifts observed with a Mach-Zehnder interferometer. The Mach numbers used in these experiments are between 0.8 and 1.6. The distance between detached bow waves and the shoulder of a wedge are found to depend only on the Mach number, and not on the wedge angle as long as the flow is not near the attachment Mach number. In many cases the change in stagnation density across the chock is only a few percent. An average may be chosen and the sonic line located simply by computing the appropriate density ratio. Slides illustrating the methods used for analyzing pictures will be included.

[1] Assisted by an AEC Fellowship and ONR contract.

**B2. Diffraction of a Shock Wave through a Small Angle.**[1] C. H. Fletcher, *Princeton University.*—The theories of Bargmann[2] and Lighthill[3] for the diffraction of a shock wave near a corner which deviates the flow by only a small angle $\epsilon$ are applicable in first order whether $\epsilon$ is positive or negative. Since we have already measured[4] the density field, using a shock tube and interferometer, for $\epsilon$ of one sign, it is of interest to carry the investigations to $\epsilon$ of opposite sign as well. Shocks of small amplitude have been photographed as they suffered a diffraction through a small angle away from the flow yielding density patterns very similar to those predicted by theory. Photographs of the phenomena will be shown and comparison of the pressures on the walls and other features with theoretical predictions will be discussed.

[1] Supported by ONR contract.
[2] V. Bargmann, AMP 108.2R, N.D.R.C. (March, 1945).
[3] M. J. Lighthill, Proc. Roy. Soc. **A198**, 454 (1949).
[4] W. Bleakney and A. H. Taub, Rev. Mod. Phys. **21**, 604 (1949).

**B3. Diffraction of Shock Waves around, and Surface Pressures on, Two-Dimensional Objects.**[1] W. Bleakney and D. R. White, *Princeton University.*—The diffraction of shock waves and the resulting density field has been observed when a plane shock passes around a right-angled corner, a rectangular block, a cylinder, a triangle and other two-dimensional objects in the shock tube. Using a shock strength of $P_1/P_0=2$ the pressures $P/P_0$ at different points on the surface of the obstacle vary all the way from 0.9 to 2.3. Sharp gradients in the pressure are evident especially near corners during the early stages of the flow. The pressure behind the incident shock is sufficiently constant and of sufficient duration to establish quasi-equilibrium in the wind pressures on the object. No adequate theory of large angle diffraction of shocks has yet been proposed, but qualitatively most of the observed effects are explainable in terms of elementary notions of fluid flow. Extensive illustrations will be given.

[1] Supported by ONR contract.

**B4. Supersonic Flow in a Shock Tube.**[1] David Weimer, *Princeton University.*—The evolution of the shock tube technique for the study of shock waves, blast waves, and transonic flow problems has been well described in the literature. The purpose of this paper is to discuss some of the properties of the flow in the region behind the cold front. A number of schlieren pictures will be shown of the flow behind the main shocks in the region of mixing of the hot and cold gases and in the cold gas alone for shocks strong enough to produce supersonic flow (up to $M=3.7$). The Mach numbers of the flow in the hot and cold regions as observed by the angles of attached bow waves are consistent with each other. Considerable turbulence is observed as the cold front passes and then the flow becomes more uniform again.

[1] Supported by ONR contract.

**B5. Breaking of Waves by an Opposing Current.** Yi-Yuan Yu, *Northwestern University* (*Introduced by E. R. Peck*).—A wave beomes unstable and breaks when the forward velocity of the water particles at the crest exceeds the wave celerity. Ordinarily the criterion for breaking is given by the wave steepness, which is not to exceed 1/7 according to Michell. When waves propagate upstream against an opposing current, their breaking is further closely related to the velocity at which energy is transmitted by the wave. A criterion for their breaking may be obtained by considering the critical situation when energy can no longer be transmitted upstream by the wave. In the case in which deep-water waves propagate from still water into a moving current, the criterion comes out to be that waves break when the velocity of the opposing current reaches $\frac{1}{4}$ of the initial wave celerity. Experiments were conducted in a flume consisting of two section of different depths.

Waves were produced in the deeper section in which the water was practically still, and they propagated upstream into the shallower section against an opposing current. The $\frac{1}{4}$ ratio relation was verified, and it was further observed that partial breaking of waves had occured before the current velocity reached $\frac{1}{4}$ of the wave celerity. When the current velocity was smaller than about 1/7 of the celerity, there seemed no breaking.

**B6. Axially Symmetrical Jet Mixing of a Compressible Fluid.** S. I. PAI, *Institute for Fluid Dynamics and Applied Mathematics, University of Maryland (Introduced by R. J. Seeger)*.—The flow of an axially symmetrical jet of a compressible fluid exhausting into a uniform stream is investigated theoretically. The flow of the jet is assumed to be under full expansion from a nozzle. The pressure gradient in the jet is assumed to be negligible. The first part of the paper is concerned with the laminar flow. Ordinary assumptions of boundary layer are used to simplify the Navier-Stokes equations. A solution by the method of small perturbation is first obtained which is expressed in terms of integral of Bessel functions. Exact solution is then obtained by successive approximation from the small perturbation solution. The second part of the paper is concerned with the turbulent flow. The fundamental equation of motion of axially symmetrical jet mixing is derived by the help of Taylor's transport of vorticity hypothesis and Reichardt's assumption of free turbulence that the exchange coefficient over each cross section of the mixing zone is constant. By suitable transformation of variables, it has been shown that the equations of turbulent axially symmetrical jet mixing are identical to those of the laminar case. Hence the solution of the first part can be used to the turbulent case provided that the characteristic constant, i.e., the eddy viscosity, has been properly chosen.

**B7. Aerodynamic Behavior and Interaction of Supersonic and Subsonic Axially Symmetric Flows.** BERTRAND DES CLERS AND CHIEH-CHIEN CHANG, *The Johns Hopkins University (Introduced by F. H. Clauser)*.—This paper analyzes the linearized aerodynamic problems of the axially symmetric body in a subsonic and/or supersonic flow which may be confined in a closed or open wind tunnel, as well as the free flight condition. In order to illustrate the physical aspects of the problem clearly, the arbitrary body shape is decomposed into its Fourier components, and only one component is treated thoroughly. This component is equivalent to an infinitely long cylinder with a wavy surface traveling in a compressible fluid. First, such a wavy-walled cylinder in an axially symmetric subsonic or supersonic flow in a closed- or open-throat wind tunnel is investigated. Next, the subsonic annular flow between the cylinder and an infinite supersonic flow field is considered because of its resemblance to the supersonic boundary-layer effect on the wave drag. Some interesting results are obtained, such as wind tunnel correction and compressibility correction factors. In the supersonic flight of the axially symmetric body, the pressure distribution is not proportional to the local slope as in the two-dimensional case, but lags behind. Besides, the wave drag coefficient is finite at Mach number unity as shown by von Kármán. The thickness of the subsonic layer affects appreciably the wave drag and the pressure distribution of the body.

**B8. Explicit Representation of the Flow in the Region of Interaction of Two Arbitrary Simple Waves in One-Dimensional Compressible Fluid Flow.** R. SHAW, *New York University (Introduced by George E. Hudson)*.—The hodograph transformation is exploited to express the space coordinate $x$ and the time $t$ in the region of interaction in terms of two radially symmetric solutions of the ordinary linear wave equation in spaces whose dimensionality depends on the adiabatic constant $\gamma$ of the gas, the dimensionality for both solutions being odd integers if $\gamma=3$, 5/3, 7/5 (air), . . . . From the character of the simple waves, or, from the equations representing the arbitrary motion of two pistons at the ends of a gas-filled tube, which would produce such simple waves, initial data can be calculated along the two characteristics bounding the interaction region. In the hodograph space these characteristics are represented by forward and backward characteristic cones enclosing a spindle-shaped region which corresponds to the interaction flow. For the above values of $\gamma$ the solutions of the resulting double characteristic initial value problems are obtained explicitly in terms of the initial data and a number (depending on $\gamma$) of integrals of these data. For other values of $\gamma$, a new method of descent and ascent transforms a radial solution of the wave equation for an odd number of dimensions to a solution for any other number of dimensions (not necessarily integral). This provides general solutions analogous to the form used in the above method.

**B9. Nucleation in Very Rapid Vapor Expansions.** ARTHUR KANTROWITZ, *Cornell University*.—In the steady state Becker-Döring theory, sub-critical droplets (embryos), with vapor pressure greater than their surroundings, nevertheless grow statistically because they exist in sufficiently greater numbers than neighboring larger droplets. Thus the formation of nuclei against the thermodynamic barrier presupposes the presence of very large numbers of embryos of all sizes. An approximate lower bound for the time required for the formation of this system of embryos can be calculated readily by: (1) neglecting the thermodynamic barrier which impedes their formation; (2) assuming that when droplets contain a certain supercritical number, $G$, of molecules they grow very rapidly because their vapor pressure is considerably lower than their surroundings; (3) assuming that the formation of the embryo system begins when the vapor first becomes saturated. The equation for the rate of formation of embryos then reduces to the heat conduction equation yielding a simple solution. The lower bound sought is found to be inversely proportional to the fourth power of the degree of supercooling. Comparison with experiments indicates that in some nozzle expansions the occurrence of nucleation is determined by this process.

**B10. Effect of Variable Viscosity and Thermal Conductivity on the High Speed Plane Couette Flow of a Semirarefied Gas.** T. C. LIN, *University of Washington (Introduced by R. E. Street)*.—Schamberg has solved the problem of plane Couette flow in semirarefied gases, under the assumption of constant coefficients of viscosity and thermal conductivity. This paper extends Schamberg's solution to include the effect of variable viscosity and thermal conductivity. For the case of equal wall temperatures the effect of variable viscosity and thermal conductivity tends to increase the velocity slip and the temperature jump, as well as the friction coefficient and the heat transfer, especially at high Mach number and for decreasing density of the gas. Furthermore, at high Mach number the temperature jump plays a more important part in the friction through the coefficient of viscosity, and overbalances the reduction in friction due to velocity slip. This investigation is based on Burnett's expressions for the stresses and the heat flux and Schamberg's expressions for the slip velocity and the temperature discontinuity, as deduced from the third-order approximation to the molecular velocity distribution function of a non-uniform gas.

**B11. The Existence and Limit Behavior of the One-Dimensional Shock Layer.** DAVID GILBARG, *Indiana University*.—Designate by *shock layer* a steady one-dimensional flow of a viscous, heat-conducting fluid approaching limit values at $x=-\infty$ and $x=+\infty$ which are possible initial and final states of a normal shock wave. Rayleigh, Becker, and others have established the existence of the shock layer for ideal gases of a special type. Here the existence and uniqueness of the shock layer is proved for general fluids with viscosity and heat conductivity arbitrary functions of the thermodynamic state. It is also proved, in the same generality, that the shock layers corresponding to a fixed initial and final state converge to a shock wave if viscosity and heat conductivity approach zero (whatever the manner of approach). The limit of the shock layers as heat conductivity tends to zero, viscosity remaining fixed, is seen always to be continuous, whereas, with fixed heat conductivity, the limit, as viscosity vanishes, is discontinuous in general.

**B12. Interferometric Studies of Laminar and Turbulent Boundary Layers along a Flat Plate in Supersonic Flow.*** R. LADENBURG AND P. WATCHELL, *Princeton University.*—In continuation of our interferometric studies of boundary layers[1] it was found that refraction of light within regions of appreciable density gradients may produce errors in the evaluation. By minimizing those effects through suitable focusin the measured velocity profile near the nose of the flat plat‹ ı. at a Mach number $M\sim 2.3$ at low Reynolds number ($Re_x\sim 2\times 10^5$) in agreement with Crocco's theory[3] within the experimental uncertainties. With increasing distance from the nose of the plate the profile changes more and more and approaches a profile observed at high Reynolds numbers ($Re_x\sim 3\times 10^6$). This change can be explained by "transverse contamination" by turbulence starting near the corners of the plate.[4] The observed velocity profile at higher density in the test section, corresponding to $Re_x\sim 3\times 10^6$, follows the logarithmic law deduced recently by Kalikhman[5] for compressible turbulent flow.

* Supported by ONR.

1 R. Ladenburg and D. Bershader, Rev. Mod. Phys. **21**, 510 (1949); Proc. Symposium N. O. L. (June 29, 1949).

2 P. Wachtell, Phys. Rev. **78**, 333 (1950).

3 Luigi Crocco, Monogr. Scient. di Aeron., No. 3 (December, 1946).

4 A. C. Charters, N. A. C. A. Tech. Note No. 891 (1943). Dr. H. Liepmann informed us that he has observed such contamination also in supersonic flow.

5 L. E. Kalikhman, N. A. C. A. Memo. No. 1229 (1949).