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Minutes of the Meeting of the Division of Fluid Dynamics at the University of Virginia, Charlottesville, Virginia, December 28–30, 1949

The fourth meeting of the Division of Fluid Dynamics was considered a great success by more than a hundred members who attended the three-day session at the University of Virginia. A program, which emphasized the field of "Irreversible Processes in Fluid Dynamics," was arranged by a committee under the chairmanship of J. O. Hirschfelder. Local arrangements and accommodations were provided by a committee under J. W. Beams. Four symposia, two sessions of contributed papers, and two evening lectures comprised the program.

WALKER BLEAKNEY, *Secretary*
Division of Fluid Dynamics
Princeton University
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Symposium on Fluid Flow

The Thickness of the Transition Region in a Shock Front. DONALD F. HORNIG, *Brown University.*
Relaxation Theories of Viscous and Plastic Flows. HENRY EYRING, *University of Utah.*
Preliminary Study of a Converging Shock Wave. ARTHUR R. KANTROWITZ AND ROBERT W. PERRY, *Cornell University.*

Symposium on Energy and Entropy Changes

Entropy Changes in Fluid Flow. CHARLES F. CURTISS, *University of Wisconsin.*
Maxwell's Demon Cannot Do It—Information and Entropy. L. BRILLOUIN, *Columbia University.*
On the Heat Flux Vector in Moderately Rarefied Gases. C. A. TRUESDELL, *Naval Research Laboratory.*
Interchange of Translational and Vibrational Energy in an Asymmetric Molecular Potential Field. H. M. HULBURT, *Catholic University of America.*

Symposium on Non-Equilibrium Statistical Mechanics

The Relation of the Macroscopic to Molecular Viewpoint in Non-Equilibrium Processes. K. F. HERZFELD, *Catholic University of America.*
Recent Advances in Non-Equilibrium Statistical Mechanics. ELLIOTT W. MONTROLL, *Office of Naval Research.*
The General Theory of Irreversible Processes. JOHN M. RICHARDSON, *Central Experiment Station, Bureau of Mines.*

Symposium on the Theory of Flames

Stability and Transport Characteristics of Flames. BRUCE L. HICKS, *Ballistic Research Laboratories.*
Thermo Reaction Propagation in Flames. HOWARD W. EMMONS, *Harvard University.*
Combustion in Long Closed Tubes at Low Pressure. LELAND B. SNODDY, E. E. HACKMAN, AND J. W. BEAMS, *University of Virginia.*

Evening Lectures

Rockets and Ram Jets. R. E. GIBSON, *Johns Hopkins University.*
Problems in Newer Fields in Fluid Mechanics. JOHN W. BECKER, *Langley Field, Virginia.*

Contributed Papers

1. On the Three-Shock Configuration.* G. RAWLING AND H. POLACHEK, *Naval Ordnance Laboratory, White Oak, Silver Spring 19, Maryland.* (Introduced by F. N. Frenkiel.)—An initial report of investigations of three-shock configuration is presented. The numerical values for isopycnals and isobars are graphed for various strengths of shock wave on the basis of theoretical results of Bargmann.** In particular, the effects of increasing strength of the shock wave on density and on pressure are discussed. Experimental three-shock configurations are illustrated by interferograms and schlieren pictures obtained in the wind tunnel and in the shock tube.

* Under the sponsorship of the ONR.
** V. Bargmann, "On the nearly glancing reflection of shocks," National Defense Research Committee AMP Report 108.2 R (March, 1945).

2. Vibrational Relaxation Times in Polyatomic Gases. R. N. SCHWARTZ, *Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland.*—The method of Zener[1] is extended to treat collisions between molecules with s internal degrees of freedom. Using a one-dimensional model and approximating the field between two colliding molecules by an exponential, one may write the probability of simultaneously exciting the x-internal coordinate of either molecule from the n_1th to the t_i vibrational state, the x_2-internal coordinate from the n_2th state, etc., while the relative velocity of the molecules change by ΔV, in the form

$$p_{t_1\cdots t_s}{}^{m_1\cdots m_s}=[\mathrm{V}_{t_i}{}^{n_1}(x_1)\cdots\mathrm{V}_{t_s}{}^{n_s}(x_s)\mathrm{R}(\Delta V)]^2.$$

This conceptually simple result is applied (a) to experimentally available data on the effect of foreign gases on relaxation times, and (b) to the question of the possibility of detecting more than one relaxation time in certain polyatomic gases.

[1] C. Zener, Phys. Rev. 37, 357 (1931).

3. A Modification of the Theory of Kinetics of Condensation and Its Application to Air Condensation in Hypersonic Wind Tunnels. H. GUYFORD STEVER, *Massachusetts Institute of Technology*.—The relationships describing the kinetics of condensation of a vapor involve the liquid phase surface energy as an important property. Generally this surface energy is assumed dependent on temperature but independent of the surface curvature of the liquid phase. In condensation phenomena, the nuclei of condensation often have such small radii of curvature that the surface energy cannot be considered independent of surface curvature. In a project sponsored by the National Advisory Committee for Aeronautics to investigate the possibilities of air condensing in hypersonic wind tunnels, the theory of condensation has been modified to incorporate this surface curvature dependence. The results show that extremely high supersaturation ratios, much higher than predicted by the unmodified theory, can be obtained without getting appreciable condensation rates. The modified theory was applied to nitrogen and oxygen, with results indicating that air condensation should not occur in present hypersonic wind tunnels (stagnation pressures up to 150 atmos., stagnation temperatures down to 240° K) unless higher stagnation pressures or lower stagnation temperatures are used.

4. Dissipation of a Shock Traveling in a Tube.* R. J. EMRICH AND C. W. CURTIS, *Lehigh University*.—The measured strength of a shock produced in a shock tube is always somewhat smaller than predicted by the usual theory which ignores all dissipative effects except those within the shock front itself. Since the measuring station is some distance from the diaphragm, the decrease in strength (and velocity) during travel along the tube has been investigated as a possible explanation of this discrepancy. Using timing techniques similar to those previously described,[1] velocity loss measurements have been carried out in a tube of 3.5-cm diameter for shocks ranging in Mach number from 1.04 to 1.35. The losses in this tube were greater than those in a 15-cm tube by about the inverse ratio of the diameters; the losses in both tubes were considerably larger than predicted by a laminar flow theory attributing dissipation to the effect of wall friction.[2] The measured losses are sufficient to account for a large part of the discrepancy between experimental and predicted shock strengths.

* This work was supported by the ONR under contract N7 onr-39302.
[1] R. J. Emrich and F. B. Harrison, Phys. Rev. 73, 1255 (1948).
[2] C. duP. Donaldson and R. D. Sullivan, N.A.C.A. Tech. Note 1942 (1949).

5. Some Circular Schlieren Pictures of Shock Wave Reflections.* EDWARD M. LITTLE, *University of Maryland*.—With circular schlieren the change in illumination on the photographic plate is independent of the direction of the gradient of the fluid density. This is valuable here as many shock directions occur in the same picture. A calibrating schlieren lens is in one corner of each picture. This shock tube has a special reflector with its leading edge always exactly in one face of the shock tube, thus eliminating spurious reflections from the underside of the leading edge. The pictures obtained are under conditions varying continuously from diffraction (reflector 13° below sidewall) through "Bargmann?" reflection and Mach reflection to regular reflection (reflector 40° above sidewall). The shock "weakness" varies from 0.77 to 0.86 (weak shocks). The reflected rarefaction from the leading edge is clearly visible in the case of regular reflection. In the cases where it overtakes the shock intersection (some regular reflection and all Mach reflections) there is seen a non-uniform-density region behind the shock intersection as discovered by Bleakney with the interferometer. It also causes a bending backward of the Mach shock at the "triple point" (besides the usual steady-state effect). It also bends back the shock in the diffraction cases.

* This work was performed at the Naval Ordnance Laboratory at White Oak, Silver Spring, Maryland, and is unclassified.

6. Virtual Mass of a Sphere Entering Water Vertically.* ALBERT MAY AND JEAN C. WOODHULL, *Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland*.—The accelerated underwater motion of a body is affected by the "apparent additional" mass of water which shares the acceleration. The adaptability of the concept of virtual mass to water-entry has been discussed frequently and reported in literature under security restrictions, always assuming no variation of drag coefficient with speed or depth of sphere. The authors have determined virtual mass by comparing vertical entry drag forces of half-inch tungsten and steel spheres with others of dural, magnesium and polystyrene, a density range of 16 to 1. Instantaneous C_D values were found at the same speed and depth. Surface-closure of the entry cavities was prevented by using reduced air pressure above the water. This removes the effect of cavity pressure but changes the flow pattern slightly. Compared with previous, roughly estimated added-mass values of about 0.45 that of the displaced water, the authors obtain values less than 0.2; actually, values range from zero to 0.16, near the limit of accuracy. The virtual-mass concept is apparently unimportant for water-entry work over the range investigated.

* Supported by the ONR, Fluid Dynamics Branch (Project NR-062-024).

7. Oscillations of a Cable in a Stream. A. E. SEIGEL, *Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland*. (Introduced by A. May.)—In the flow of a fluid past a straight flexible cylindrical cable an alternating side force perpendicular to the flow velocity is exerted on the cable; this force is a result of the shedding of vortices alternately from side to side of the cylinder. The ratio of the side force to the drag force is a function of Reynolds number only. From experimental results and theoretical considerations the function is completely determined for Reynolds numbers in the range of 20 to 0.5×10^6. The periodic side force tends to vibrate the cable. The partial differential equation of motion which includes the inertia force of the cable, the fluid damping force, and the cable tension force, as well as the side force, is solved. The amplitude of cable vibration is obtained with special attention to resonance conditions.

8. Photographic Observations of Air Flow around Moving Bodies at Mach Numbers up to 9.6. P. A. THURSTON, *Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland*. (Introduced by J. H. McMillen.)—Observations of the flow around projectiles at extremely high Mach numbers have been made by firing bullets at high velocities into gases at reduced temperatures. Both standard and special small bore projectiles moving at speeds up to 7000 ft. per sec. in air and nitrogen at temperatures down to 120° K were observed by means of spark shadowgraphs. The spark system used coaxial cable energy storage as originally proposed by Beams, and gave an effective light duration of about 10^{-7} sec. From the observed configurations of shock wave and wake, the wave drag and base drag have been calculated, and typical results are presented.

9. Density Measurements in Supersonic Flow by an X-Ray Technique.* EVA WINKLER, *Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland.* (Introduced by R. J. Seeger.)—Air density measurements have been made in the free stream of a supersonic flow by means of the x-ray absorption method. The measurements were made at a Mach number of 2.83 in the NOL 18×18 cm wind tunnel. Excellent agreement has been found with Pitot tube measurements of the same nozzle. The accuracy of the present equipment is limited, for this Mach number, to 5.5 percent. The equipment consists of a Machlett AEG-50 x-ray tube having a beryllium window and two G-M counters one of which measures the initial x-ray intensity for comparison. The results and the general arrangement of the equipment at the wind tunnel will be described.

* Sponsored by the ONR.

10. A Simple Interferometric Test for Conical Flow. J. H. GIESE, F. D. BENNETT, AND V. E. BERGDOLT.—In conical flows the velocity components, pressure, and density do not vary on lines through the vertex of the cone. In this paper it is shown that for interferograms of general conical flows $\delta(y, z)/z = f(y/z)$, where y and z are any set of Cartesian coordinates with origin at the image of the vertex of the cone, and δ is the fringe shift at y, z. Thus, for strictly conical flow, a graph of $\delta(y, z)/z$ *versus* y/z should be a single curve. This suggests a test for approximate conicity that requires very little computation. This test is applied to interferograms obtained from a number of approximately axisymmetric flows at various Mach numbers about cone-cylinders in free flight. Plotted fringe shift data from the region near the nose fall into a narrow band, an indication of approximate conicity. They also closely check the corresponding theoretical fringe shift curve calculated for Taylor-Maccoll flow.

11. On Turbulent Jet Mixing in Two-Dimensional Supersonic Flow. D. BERSHADER AND S. I. PAI, *Institute for Fluid Dynamics and Applied Mathematics, University of Maryland.*—Distributions of mean density in several sections of the mixing region of a rectangular, uniform, fully expanded jet of Mach number 1.7, discharging into the atmosphere, have been calculated from measurements made with the Mach-Zehnder interferometer.* The results thus obtained have been compared with predicted density distributions, calculated by use of a theory somewhat modified from that developed by the second author,[1] which makes use of Reichardt's theory of free turbulence. The theory involves as an unknown parameter the coefficient of eddy kinematic viscosity ϵ, whose value is to be determined from experimental results. Under the present experimental conditions ϵ is assumed constant, corresponding to the assumption of the similarity of the velocity profile over various sections. The value of ϵ which gives best agreement with experiment is $\epsilon = 164$ cm²/sec., over 1000 times the value of the coefficient of laminar kinematic viscosity. The existence of a 1-mm boundary layer[2] at the exit of the nozzle differs from the assumption used in the theory of a zero-thickness mixing region at this point. However, the experimental and theoretical curves fall very close together, except at the ends, if the former curve is plotted using a line 0.16 mm in from the nozzle wall as the axis $y=0$ (y is the coordinate perpendicular to flow). The theoretical density distribution has also been calculated for the laminar case.

* The experimental data used herein was obtained by the first author in research performed with R. Ladenburg at Princeton University.
[1] S. I. Pai, "Two-dimensional jet mixing of a compressible fluid," J. Aero. Sci. 16, 463 (August, 1949).
[2] D. Bershader, "An interferometric study of supersonic channel flow," Rev. Sci. Inst. 20, 260–275 (1949).

12. On the One-Dimensional Theory of Flame Structure. RAYMOND FRIEDMAN AND EDWARD BURKE, *Westinghouse Research Laboratories.* (Introduced by R. C. Mason.)—The variations of temperature and concentration throughout a premixed gas flame are calculated from the fundamental equations in terms of the burning velocity, the reaction zone thickness, the thermal diffusivity, the diffusion coefficient, the heat release pattern, and the rate of formation pattern of a particular species. Four arbitrary patterns are treated. The magnitude of the error introduced by assuming transport coefficients to be independent of temperature is computed. The influence of cylindrical flame curvature is treated. The Mach number is shown to be a pertinent variable in deflagration. Certain experimental data are analyzed in the light of the relations given herein. This is not a new theory of burning velocity, but rather an exposition of the necessary relations which hold between the pertinent variables by virtue of the conservation of matter and energy.

13. Investigation of Turbulent Flames.* BELA KARLOVITZ,** *Bureau of Mines.* (Introduced by Bernard Lewis.)—An extensive study of turbulent flame phenomena was undertaken in order to find a basic understanding of the effect of turbulence, especially of large-scale turbulence, on flame propagation. Bunsen-type turbulent flames were produced under controlled, variable experimental conditions, with flow velocities ranging up to 50 meters per sec., Reynolds numbers up to 100,000, and burner-tube diameters from $\frac{5}{8}$ in. to 2 in. Instantaneous shadow photographs of the flames confirmed the results of previous investigators, according to which the main effect of the large-scale turbulence consists in the random displacement of small portions of the combustion wave. Starting from this observation, a theory of turbulent flame propagation was developed. The theory explains the mechanism of turbulent flame propagation and the peculiar shape of the flame surface and permits calculation of the turbulent burning velocity from known values of turbulence intensity and normal burning velocity. To test this theory, a program for the measurement of the intensity and scale of turbulence was initiated, and a method was developed for accurate measurement of the turbulent burning velocity. The measurements are in progress; data obtained up to date will be presented.

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