NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 1900

PRELIMINARY INVESTIGATION OF THE USE OF AFTERGLOW FOR VISUALIZING LOW-DENSITY COMPRESSIBLE FLOWS

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SUMMARY

An investigation is described in which the phenomena of afterglow were utilized to make visible the low-density supersonic flows of various gases. Photographs of the afterglow in the supersonic flow about wedges are compared with schlieren photographs for densities corresponding to static pressures of from 3 to 8 millimeters of mercury. The afterglow is shown to be effective in visualizing some of the features of the flow in this range of low densities where it is difficult or impracticable to obtain comparable results with schlieren methods. It is suggested that the method employing afterglow is applicable to considerably lower densities where conventional schlieren methods are not suitable for flow visualization.

INTRODUCTION

The usual methods of visualizing flow patterns in gases become difficult to use or altogether useless when the density of the stream is decreased to the low values required for the mean free path of the molecules to become appreciable in comparison to the thickness of boundary layers or dimensions of objects in the flow. The range of densities below which new methods must be employed for visualizing the flow cannot be unequivocally specified. As the density of the stream is reduced, the optical disturbances due to the flow patterns become weaker in proportion to the disturbances caused by optical imperfections of windows and mirrors used in schlieren techniques. In a number of schlieren systems, experience has indicated that the imperfections existing in the windows imposed practical limitations on the sensitivity. Reference 1 includes estimates of the range of densities for streams in wind tunnels below which schlieren methods are impractical.

The purpose of this paper is to describe preliminary tests of a method that visualizes compressible flow by means of afterglow in a gas of low density. This method was first proposed (references 2 and 3) by Dr Joseph Kaplan, presently professor at the Institute of Geophysics, University of California at Los Angeles. Dr. Kaplan also contributed many suggestions that were an invaluable aid in this investigation. The apparatus was constructed, put into operation, and the first observations were made with nitrogen afterglow in a supersonic nozzle during his visit to the Langley Laboratory of the NACA from July 1 to August 6, 1948.

Afterglow is a term descriptive of the luminescence that persists in certain gases for an appreciable time after the gases are excited to states capable of emitting light. The afterglow of nitrogen in particular has been the subject of many investigations that have shown the phenomena to be complex. Kaplan (reference 4) applied the name "Lewis-Rayleigh afterglow" to the well-known type discovered by E. P. Lewis (reference 5) and extensively investigated by Rayleigh, whose papers are listed in the bibliography of reference 6. A striking feature of the Lewis-Rayleigh afterglow is the long lifetime, which ranges from minutes to hours. Other gases, for example, oxygen, argon, helium, and mercury vapor, are well known to exhibit afterglows for which the lifetime ranges from microseconds to minutes.

Among the many studies of afterglow by Rayleigh are two interesting papers (references 7 and 8) describing methods he used for measuring the velocity of a subsonic stream of mercury vapor by means of the afterglow. Experiments by Rayleigh (reference 9) and by Kneser (reviewed in reference 6) showed that the intensity of the Lewis-Rayleigh afterglow increases with a sudden increase in density of the glowing gas. For pressures of the order of 0.1 millimeter of mercury the intensity increased as the cube of the density. Under other conditions the increase was proportional to lower powers of the density. This variation with density permits qualitative observations of density patterns in a stream of glowing gas. Quantitative interpretations would require more information regarding the phenomena than appear to be available.

The tests of the investigation described herein were carried out principally to show the possibility of visualizing and photographing density patterns by means of afterglow in compressible flow. Special attention was directed to flow having a density that was considered low enough to be within the range where schlieren methods are of limited value although still capable of providing some information that may be compared with results from afterglow methods. These experiments in a range of density where results can be obtained with both schlieren and afterglow methods are considered to be preliminary to applications of the afterglow at low densities where conventional schlieren apparatus is ineffective. Of secondary interest in this paper are the experimental results obtained with a representative schlieren system at low densities.

APPARATUS

A schematic diagram and a photograph of the apparatus are shown as figures 1 and 2, respectively. The gas flows from a storage tank through a throttling valve and into an alternating current discharge tube where the gas is excited. In the glowing state it flows through the settling chamber and supersonic nozzle. The gas then discharges into a large vacuum tank.

The electric discharge tube is made of pyrex glass tubing of 1-inch inside diameter and 18 inches in length. Pyrex glass side arms support the electrodes by means of rubber stoppers which allow adjustment in the length of the arc path. The arms are spaced 5 inches apart. The electrodes are aluminum rods 1/4 inch in diameter. Tungsten wires 0.04 inch in diameter with approximately $\frac{1}{4}$-inch exposed length are inserted into the ends of the electrodes. These wires diminish the sputtering of the aluminum.

The arcs are powered with 60-cycle alternating-current equipment which was readily available, although higher frequencies or direct current may also be used. For the first arc two transformers rated at 3000 volts on the secondary and 300 volt-amperes output are connected in series. A capacitive impedance L_1 is used as a current limiter. The other two arcs are each supplied by a transformer rated at 7000 volts on the secondary and about 3000 volt-amperes output. A resistive load limiter L_2 is used in the primary circuit for the second arc and a capacitive limiter L_3 in the secondary circuit for the third arc.

The nozzle assembly is designed for two-dimensional flow through a channel 1.5 inches wide. It includes a settling chamber 3 inches high and approximately 16 inches long, a throat 0.5 inch high, and a supersonic nozzle with an exit 3.75 inches high. The over-all length of the assembly is 30 inches, which includes two inches of straight section at the exhaust end. The supersonic nozzle was designed by the method of characteristics for a final Mach number of 3.59. The assembly is constructed of two transparent plastic blocks contoured to form the two-dimensional channel with two side plates of the same material 0.5 inch thick. Optical glass windows are installed in the side plates for use in taking schlieren photographs. At the entrance of the settling chamber an electrically grounded fine-mesh stainless-steel screen was provided to eliminate corona effects in the flow.

Two double-wedge aluminum-alloy models were used. The leading-edge angle of one is 30° and that of the other, 15°. The models are mounted between the windows in the theoretically constant Mach number section of the nozzle.

The vacuum tank has a capacity of 12,000 cubic feet. The associated vacuum pumps could evacuate the tank to a pressure of approximately 0.5 millimeter of mercury. The pumping speed of the system was insufficient for continuous operation of the nozzle. In the tests, an intermittent type of operation was used. The supersonic nozzle discharged directly into a 10-inch pipe which connected to the vacuum tank.

The schlieren system was conventional with two parabolic mirrors 6 inches in diameter and 48 inches in focal length. The knife edges were used in the horizontal position. The optical quality of the components and the sensitivity of the assembly are believed to be representative of current practice in wind tunnels.

TESTS

The rate of flow of the gas from the high-pressure tank through the exciter tube was regulated to produce the desired pressure in the settling chamber. With the limitations of the available vacuum system, 3 millimeters of mercury was the lowest static pressure p_o at which the flow appeared to fill the test section for an adequate length of test run. This pressure indicates a test Mach number of 2.6 which is in agreement with the Mach numbers computed from the flow photographs. Under these conditions and with dry nitrogen, the afterglow was bright enough for visual observation of the patterns around the model and for photographs to be taken with an f/1.5 lens with a 20-second exposure. At higher pressures, the intensity of the afterglow produced by this apparatus was less and exposures up to 45 seconds were required. The pressure in the exciting tube ranged from 1/6 to 1/2 atmosphere. The total power dissipated in the system was measured by a wattmeter and was found to increase with the density of the stream from about 2000 to 3200 watts with the electrodes spaced about 1 inch apart. The brightness increased with increase in power for a given density of the stream up to the limit that was readily available.

A usable afterglow was first obtained with tank nitrogen designated commercially dry nitrogen. The impurities in a typical sample were reported by the manufacturer to be as follows:

Water vapor, percent by weight	0.03
Hydrogen, parts in 10^6	Less than 20
Oxygen, percent by volume	Not more than 0.3
Argon, percent	0.06

A brief trial was made with an extra dry grade of nitrogen designated Seaford grade, a typical sample of which was stated by the manufacturer to contain the following impurities:

Water vapor, percent	0.003
Hydrogen, percent	0.5
Oxygen, percent	0.002
Argon, percent	0.06

The afterglow from the dry nitrogen varied in color from orange at the low densities to bluish-white at the higher densities. Two shipments of tank nitrogen from different manufacturers differed considerably in characteristics of afterglow. Tests were made to determine the effect of varying proportions of carbon dioxide in the nitrogen on the afterglow. Its presence caused color changes and a diminution in the afterglow. Cyanogen bands have been observed (reference 4) to increase the brightness when carbon compounds are added to glowing nitrogen, but in the present tests the composition and density of the stream were not sufficiently well controlled to establish whether the intensity of the patterns can be increased markedly over the best results so far obtained by adding or removing traces of other gases to the stream of nitrogen. Of the few gases that were tried, nitrogen appeared to have the brightest afterglow and was used in surveying the possibilities of visualizing the flow.

The afterglow from the extra dry nitrogen (Seaford grade) was markedly weaker and appeared to have less blue in the color. Evidence exists (references 4 and 6) that both hydrogen and water vapor have strong effects on the afterglow, and presumably differences in concentration of one or the other impurity contributed to the differences in the afterglow.

Flow patterns were observed also in the afterglow of argon, oxygen, and air. Helium was also passed through the apparatus with the arcs operating. With this gas a bright afterglow appeared for a foot or so downstream of the arcs but decayed abruptly before reaching the settling chamber.

A limited number of measurements were made of the stagnation temperature by means of an unshrouded thermocouple in the settling chamber. A stagnation temperature of about 150° F was indicated for full power input.

Static pressures for given stagnation pressures were measured at orifices in the walls of the nozzle both with and without the discharge tube in operation. The Mach number calculated from these pressures was unaffected by the electrical discharge; however the Mach number did vary somewhat with the stagnation pressure. At 60 millimeters of mercury the Mach number was approximately 2.6 and increased slightly for higher stagnation pressures.

Schlieren photographs were made at stagnation pressures of 60, 120, and 180 millimeters of mercury and corresponding static pressures of 3, 5, and 8 millimeters of mercury, respectively, for comparison with photographs of the afterglow at the same pressures. Exposure times for the schlieren photographs were approximately 0.04 second. The schlieren photographs included runs with and without the arcs operating to determine whether the flow is noticeably affected by the arcs.

RESULTS AND DISCUSSION

The sensitivity of schlieren systems is estimated in reference 1 for representative conditions. When the results of figure 4 of reference 1 are modified for the present width of the test section and the focal length of the mirrors, it is indicated that a normal shock should be barely visible at $M = 2.6$ with a stream density of 4.4×10^{-6} grams per cubic centimeter (8.5×10^{-6} slugs per cubic foot). The density of the stream in the present tests with a static pressure of 3 millimeters of mercury in the test section just ahead of the double-wedge model was approximately 10×10^{-6} grams per cubic centimeter. A schlieren photograph at this density is compared (fig. 3) with one obtained at a higher density. The original negative from which figure 3(b) was made showed that shocks from the leading edge of the wedge were barely visible when the knife edge was horizontal. This agreement between experiment and calculation is as good as could be expected from the arbitrary assumptions involved in the calculations and the variations to be expected in experimental techniques.

Photographs of the nitrogen afterglow in the nozzle with no model are included as figure 4. The photographs were made with different pressure ratios across the nozzle, all of which were too low to fill the nozzle with the supersonic flow.

For a starting pressure ratio greater than 40 and the 15° double-wedge model in place, supersonic flow is established in the nozzle. The pattern of the flow with afterglow is shown in figure 5 for a static pressure of 3 millimeters of mercury and a Mach number of approximately 2.6 calculated from the pressure ratio.

Figures 6 and 7 include photographs of the afterglow in the flow over double-wedge models spanning the nozzle with values of the static pressures of approximately 3, 5, and 8 millimeters of mercury. Schlieren photographs of the same flow are included (figs. 3(b), 6, and 7) for comparison with the afterglow patterns. Similarities will be observed in that the afterglow shows an abrupt change in brightness that corresponds to the shock from the leading edge as seen in the schlieren picture. Examination of the photographs shows that the afterglow patterns generally resemble the schlieren photographs with the notable exception that the afterglow is more effective at the lower densities.

One of the schlieren photographs for a static pressure of 8 millimeters was made with an unexcited stream of nitrogen from the tank, the other with the nitrogen passing through the electric arcs used to produce afterglow. The two photographs appear not to differ significantly. The intensity of the light from the afterglow is very much less than that of the schlieren so that the afterglow does not show in the schlieren photographs.

A marked decrease in brightness of the afterglow is observable in the wake of the models. Rough measurements of pressure at the wall of the tunnel indicated that separation of the flow occurred near the maximum thickness. The reason for the decrease in brightness in the wake is not evident. A possibility that should be investigated is that the excitation of the nitrogen may suffer some degradation in regions of turbulent flow over the model. This possibility is suggested by experiments reviewed by Mitra (reference 6) which show a strong quenching effect due to walls unless they are suitably conditioned. A spanwise gradient in brightness of the glow along the plane of the shock was observed, the glow being weakest near the side walls.

Figure 8 is similar to figure 6(e) except that the screen over the entrance to the settling chamber was ungrounded. The model was also ungrounded and the space charges accumulated on the model sufficiently to cause a corona discharge near the trailing edge.

Figure 9(a) is a photograph of the afterglow in a stream of argon with the 30° double-wedge model in the test section. This test was run in a nozzle designed for a gas characterized by $\gamma = 1.4$, where γ is ratio of specific heats, instead of the value of γ of 1.67 for argon. Therefore, the Mach number distribution and the shock angles are different from those observed in nitrogen. Good agreement is observed in the shock pattern when figure 9(a) is compared with the schlieren photograph in figure 9(b). This schlieren photograph of the flow was taken at the same pressure but without the exciter tube in operation.

CONCLUDING REMARKS

The results of these tests demonstrate that afterglow in streams of various gases may be photographed to show general features of the flow in a manner similar to that of schlieren photography. Commercially available nitrogen produced the brightest afterglow of any of the gases tested. The intensity of the afterglow may possibly be found to be greater if other methods of excitation or other gases are employed. Since nitrogen is the principal constituent of air and has essentially the same thermodynamic characteristics as air, it appears to be well suited to aerodynamic investigations employing afterglow. Dry air exhibited afterglow sufficiently bright to be photographed. It is possible that further experimentation on the effects of water vapor and traces of impurities would result in methods for producing afterglow in air that would be at least equal to the present results with nitrogen.

The excitation necessary to cause the afterglow introduces heat and possibly disturbs the stream in other ways. These effects, including ionization and dissociation in the stream, should probably be investigated more carefully than was done in these preliminary experiments. The correlation between schlieren and afterglow photographs presented herein appears to justify the use of afterglow at least for preliminary investigations where the general features of the flow are of more interest than accurate details.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., April 5, 1949

REFERENCES

1. Rutkowski, Joseph: The Schlieren Method in Flow Observation of Rarefied Gases. Rep. No. UMM-22, Aero. Res. Center, Univ. of Michigan, June 25, 1948.

2. Anon.: Report on Conference on Flow Visualization at Low Pressures, July 7, 1947. Rep. No. HE-150-11, Eng. Res. Projects, Univ. of California, July 25, 1947.

3. Kane, E. D., and Folsom, R. G.: Problems and Progress in Low-Pressures Research. Jour. Aero. Sci., vol. 16, no. 1, Jan. 1949, pp. 46-54.

4. Kaplan, Joseph: The Preparation and Properties of Auroral Afterglows. Phys. Rev., vol. 54, no. 3, 2d ser., Aug. 1, 1938, pp. 176-178.

5. Lewis, P.: Electric Fluorescence of Nitrogen. Ann. d. Phys. 2.3. July 1900, pp. 459-468. (Reviewed in Science Abstracts, vol. 3, 1900.)

6. Mitra, S. K.: Active Nitrogen - A New Theory. Indian Press, Ltd. (Calcutta), 1945.

7. Rayleigh, (Lord): Studies on the Mercury Band-Spectrum of Long Duration. Proc. Roy. Soc. (London), ser. A, vol. 114, no. 769, May 2, 1927, pp. 620-642.

8. Rayleigh, (Lord): Fluorescent and Phosphorescent Excitation of Mercury Vapour by the Resonance Frequency and by Lower Frequencies. Proc. Roy. Soc. (London), ser. A, vol. 125, no. 796, Aug. 1929, pp. 1-23.

9. Rayleigh, (Lord): New Studies on Active Nitrogen. I. Brightness of the After-Glow under Varied Conditions of Concentration and Temperature. Proc. Roy. Soc. (London), ser. A, vol. 176, no. 964, Aug. 28, 1940, pp. 1-15.

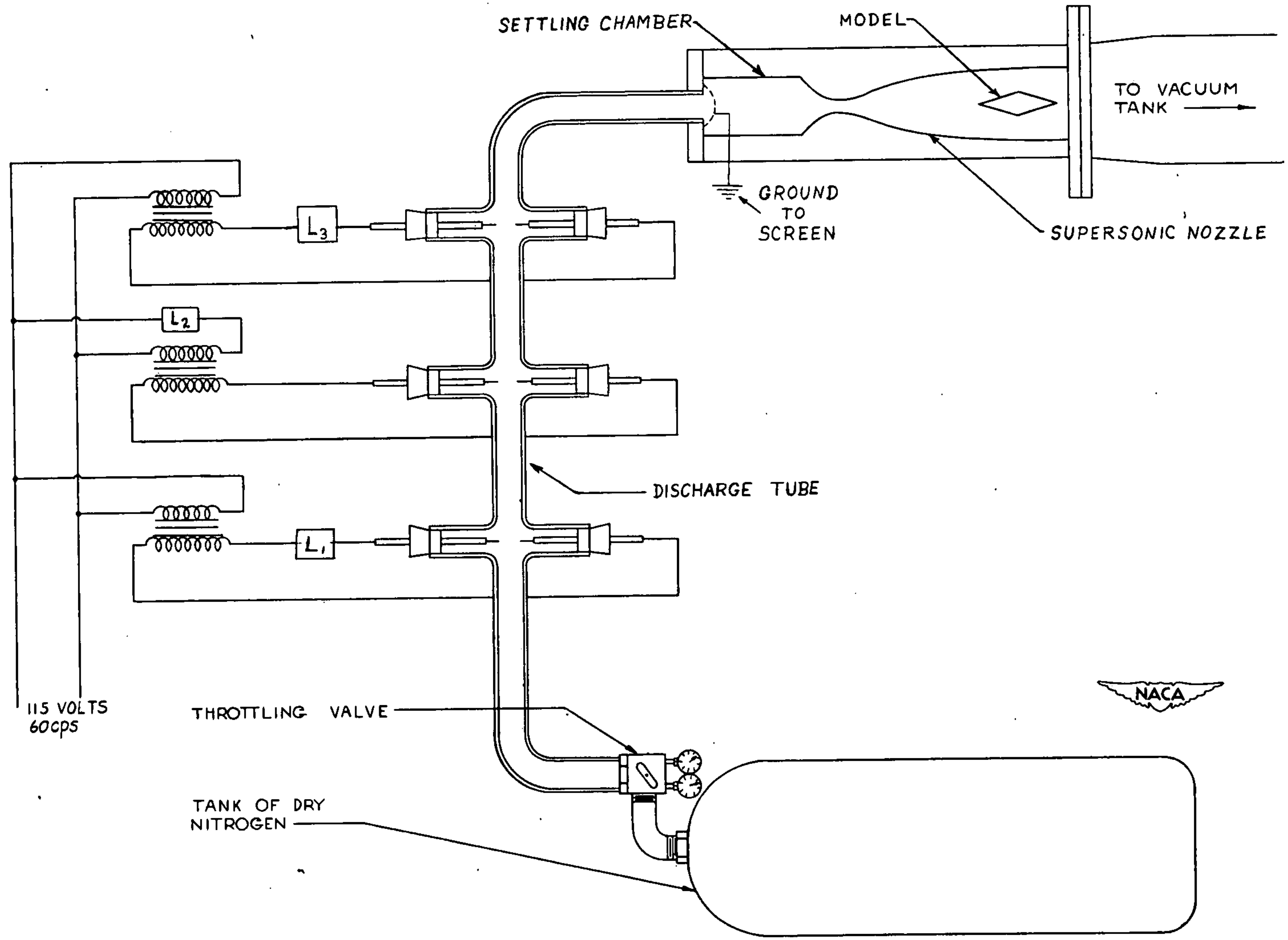


Figure 1.— Schematic diagram of apparatus for producing afterglow in a supersonic stream of nitrogen.

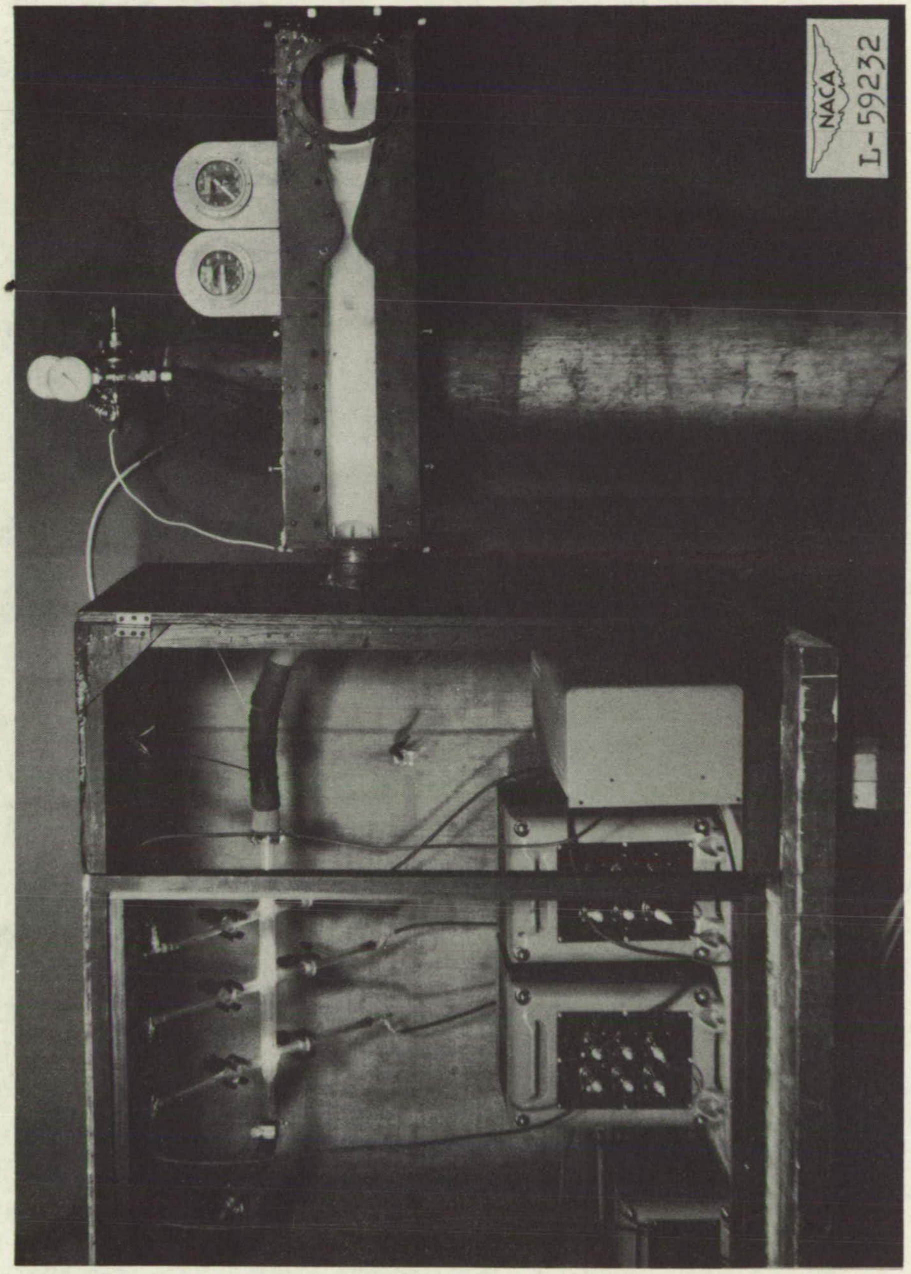
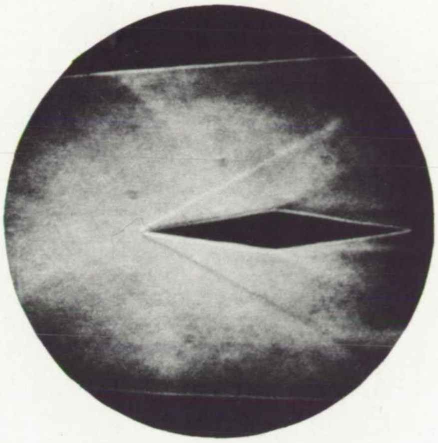


Figure 2.- Photograph of apparatus.

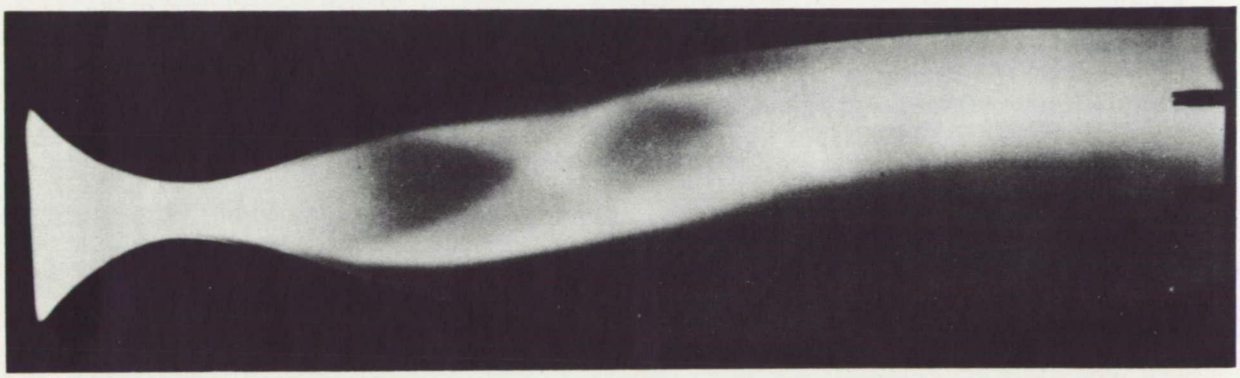


(a) p_o = 8 millimeters; $\rho = 27 \times 10^{-6}$ grams per cubic centimeter.

(b) p_o = 3 millimeters; $\rho = 10 \times 10^{-6}$ grams per cubic centimeter.

Figure 3.– Photographs at two different static pressures, showing decreased effectiveness of the schlieren system as the density in the stream is decreased.

(a) Pressure ratio approximately 9 to 1.



(b) Pressure ratio approximately 10 to 1.

(c) Pressure ratio approximately 11 to 1.

Figure 4.- Photographs of a stream of glowing nitrogen with a stagnation pressure of approximately 20 millimeters of mercury. The pressure ratios across the nozzle were insufficient to fill the nozzle with supersonic flow.

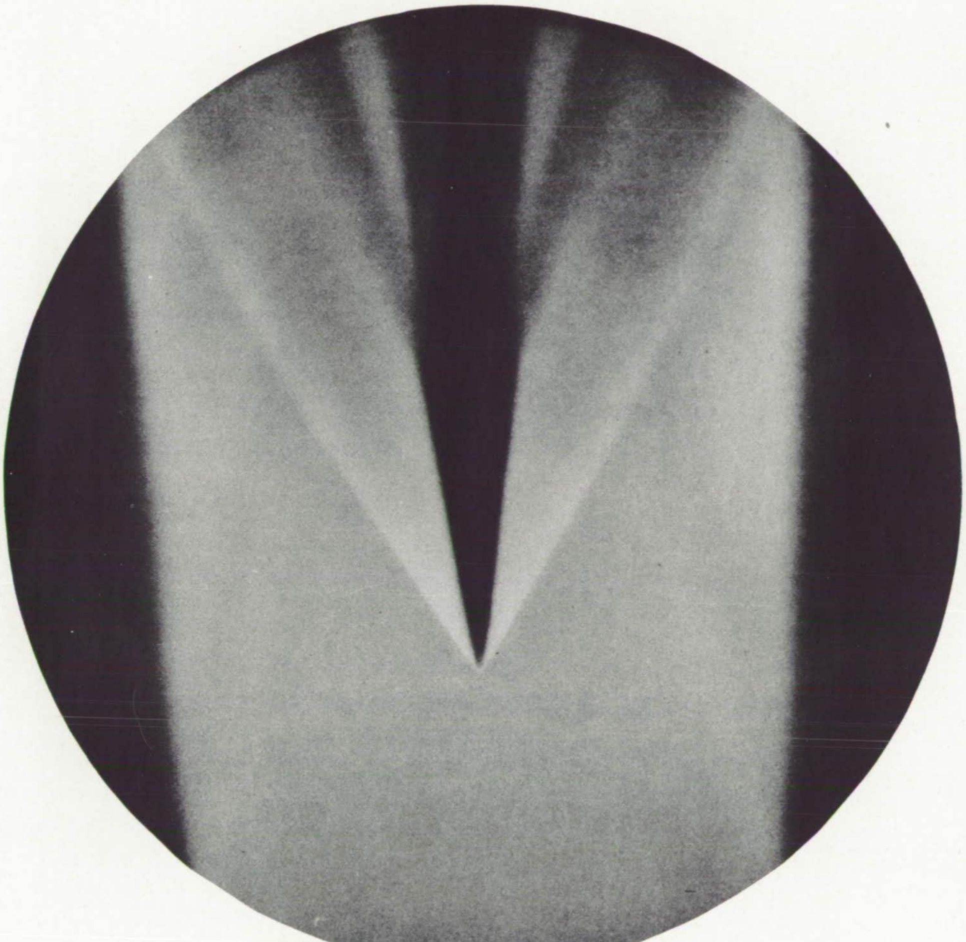
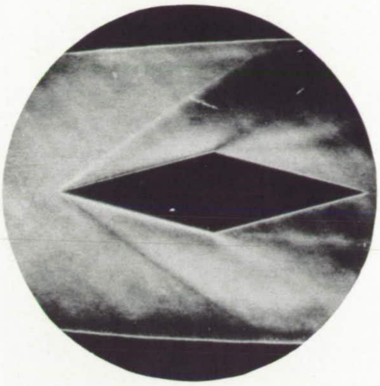
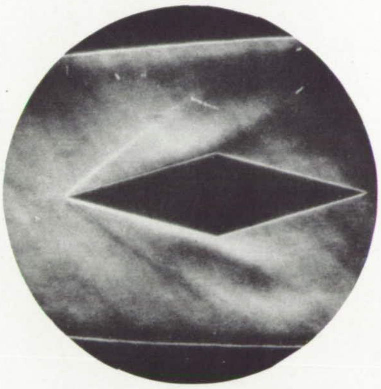


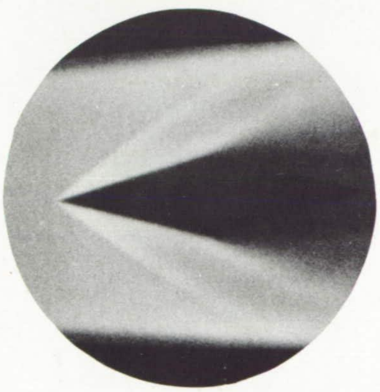
Figure 5.- Photograph of afterglow flow pattern over a 15° double-wedge model at a stagnation pressure of 60 millimeters of mercury and an indicated Mach number of 2.6.



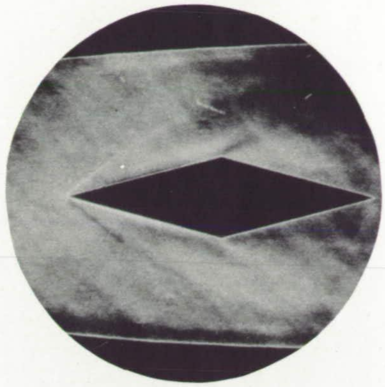
(a) Schlieren, p_o = 180 millimeters. Arcs off.



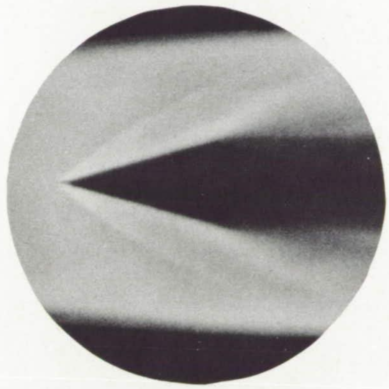
(b) Schlieren, p_o = 180 millimeters. Arcs on.



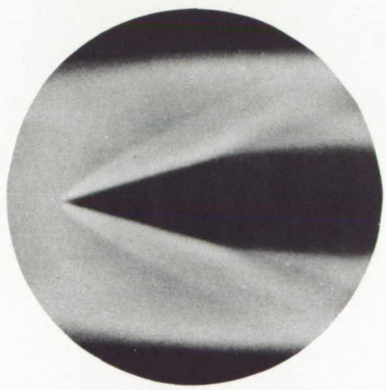
(c) Afterglow, p_o = 180 millimeters.



(d) Schlieren, p_o = 120 millimeters. Arcs off.

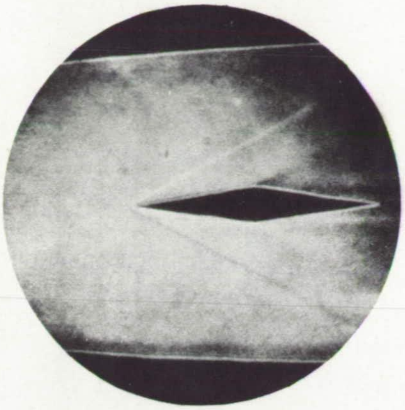


(e) Afterglow, p_o = 120 millimeters.



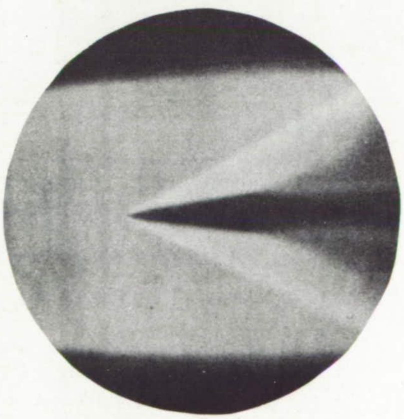
(f) Afterglow, p_o = 60 millimeters.

Figure 6.– Schlieren and afterglow photographs of flow over a 30° double wedge at three different stagnation pressures (p_o) at Mach number of approximately 2.6.



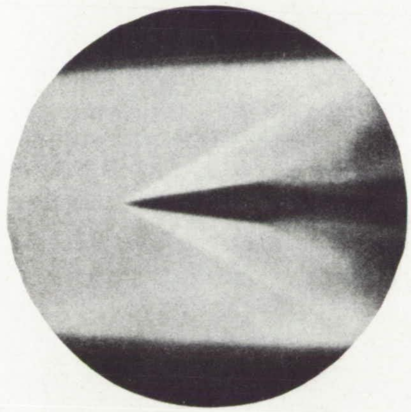
(a) Schlieren, p_o = 180 millimeters.
Arcs off.

(b) Schlieren, p_o = 180 millimeters.
Arcs on.

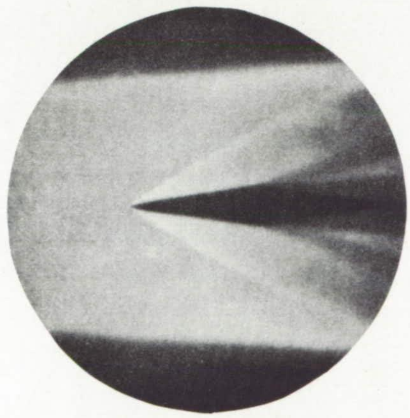


(c) Afterglow, p_o = 180 millimeters.

(d) Schlieren, p_o = 120 millimeters.



(e) Afterglow, p_o = 120 millimeters.



(f) Afterglow, p_o = 60 millimeters.

Figure 7.– Schlieren and afterglow photographs of flow over a 15° double wedge at three different stagnation pressures (p_o) at Mach number of approximately 2.6.

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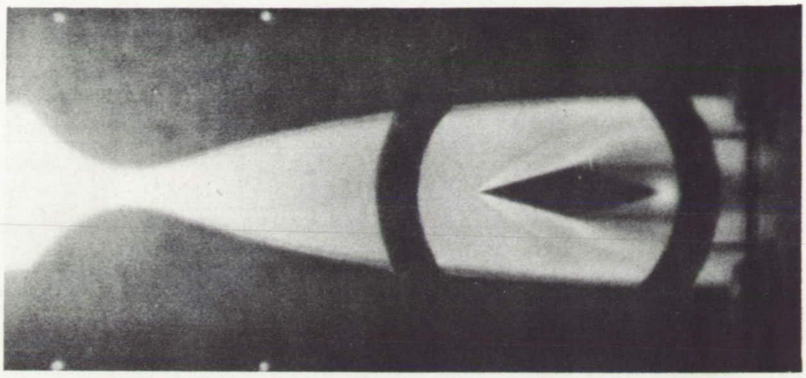
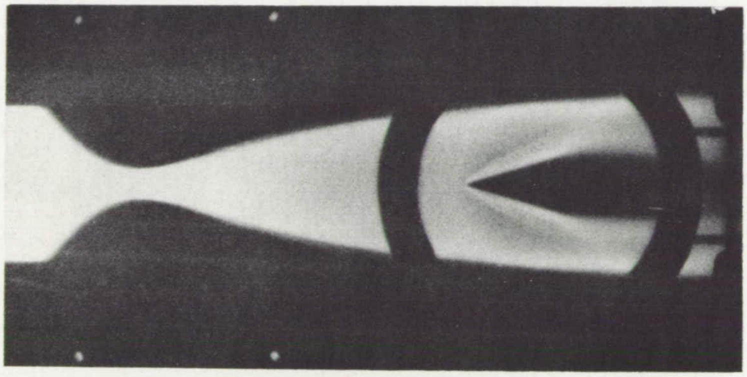
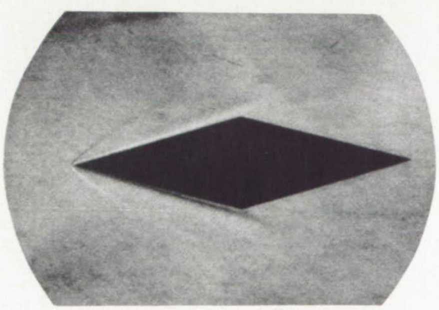


Figure 8.- Photograph of streaming nitrogen without grounded screen showing afterglow and corona off trailing edge.



(a) Afterglow.



(b) Schlieren.

Figure 9.- Afterglow and schlieren photographs of streaming argon, p_o = 120 millimeters. Afterglow photograph exposed 4 minutes with f/1.5 lens.