AD-A016 728

WIND TUNNEL TESTS OF A NEW DIFFUSER CONCEPT

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June 1975

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THEORETICAL AERODYNAMICS RESEARCH LABORATORY/ARL

JUNE 1975

INTERIM REPORT SEPTEMBER 1974 – MAY 1975

THEORETICAL AERODYNAMICS RESEARCH LABORATORY/LH
AEROSPACE RESEARCH LABORATORIES
Building 450 – Area B
Wright-Patterson Air Force Base, Ohio 45433

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: ARL TR 75-0198	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): WIND TUNNEL TESTS OF A NEW DIFFUSER CONCEPT	5. TYPE OF REPORT & PERIOD COVERED: Technical - Interim September 1974 - May 1975
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Dr. James S. Petty	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Theoretical Aerodynamics Research Laboratory (LH) Aerospace Research Laboratories (AFSC) Wright-Patterson AFB, Ohio 45433	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Project 7064-06-11 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: Aerospace Research Laboratories (ARL) Bldg. 450, Area B Wright-Patterson AFB, Ohio 45433	12. REPORT DATE: June 1975
	13. NUMBER OF PAGES: 35
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Gas Dynamic Lasers

Wind Tunnel Diffusers

Holography

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Tests were conducted in the ARL 3 in. by 3 in. Mach 3 wind tunnel facility of a new variable geometry diffuser concept. This gas wedge diffuser incorporates controlled large flow separation regions as compression surfaces in place of solid surfaces. Test results indicate stable flow in the device and expected pressure recovery considerably in excess of normal shock recovery.

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AIR FORCE - 7-9-75 - 200

PREFACE

This report was prepared by Dr. James S. Petty of the Theoretical Aerodynamics Research Laboratory, Aerospace Research Laboratories, Air Force Systems Command, United States Air Force, under Project 7064, entitled "High Speed Aerodynamics."

The reported wind tunnel tests were performed in the ARL 3" x 3" Mach 3 wind tunnel with the assistance of Captain James R. Cooper.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

1. BACKGROUND

High power gas dynamic lasers (GDL) presently employ fixed geometry diffusers because they are relatively simple in design and contruction and their pressure recovery performance is adequate. However, the improvement of GDL specific power output by increasing lasing cavity Mach number and decreasing cavity pressure requires diffuser performance beyond that obtainable from fixed geometry designs, which are limited to roughly "normal shock" recovery.

Variable geometry diffusers used in supersonic inlet designs can produce nearly isentropic pressure recovery, but they use massive boundary layer suction to prevent flow separation--as much as 20% of the injected flow is removed by suction. This is possible because the pressures in an inlet are all above the external ambient pressure, so no pumping of the bleed flow is necessary. Furthermore unlike the GDL there is no boundary layer build-up upstream of the diffuser.

In a GDL diffuser, as in most wind tunnel diffusers, the static pressures are all below the external ambient pressure, so boundary layer bleed by suction requires the use of some kind of turbomachine or ejector pump. While this might be acceptable for a wind tunnel, the weight and volume of such pumps could be prohibitive for a mobile GDL system. Boundary layer energization by injection is possible, but expensive in terms of the required mass flow rate of injectant.

Fortunately, research on variable geometry wind tunnel diffusers,[1,2] conducted two decades ago, demonstrated performance considerably better than that obtainable from fixed geometry diffusers could be obtained without any boundary layer suction or mass injection. Nearly twice normal shock recovery was attained at Mach 3 and, in terms of normal shock recovery, even better performance was achieved at higher Mach numbers.

In view of these results, it should be possible to design variable geometry diffusers for gas dynamic lasers which have significantly improved performance over present designs. However, because GDL systems are to be mobile, diffuser designs for them must also have the lowest weight and volume possible, consistent with the desired pressure recovery. Rapid diffuser starting is also desirable, since no laser power can be extracted from the GDL until steady supersonic flow is established in the laser cavity and working fluid from which no power is extracted is wasted mass. These constraints generally don't exist for wind tunnel diffusers.

2. THE GAS WEDGE DIFFUSER

The "gas wedge" diffuser is a variable geometry device conceived for use with gas dynamic lasers. Figure 1 is a schematic representation. Mechanically, the device consists of outer diffuser walls, an inner shock duct diffuser, movable gates, retractable stabilizer wedges, and attendant control servomechanisms. Its operation is as follows:

For GDL startup, the diffuser is configured to form a multi-channel shock duct diffuser by opening the gates and retracting the stabilizer wedges. The performance of this configuration is about the same as that of a fixed geometry diffuser with the same effective blockage, so the supply pressure required to establish supersonic flow in the laser cavity will be about the same as present GDL diffuser designs.

Once superonic flow is established, the gates are closed and the stabilizer wedges extended, causing an upstream flow separation (a "gas wedge") which deflects the flow into the central channel of the diffuser, as shown schematically in Fig. 2. In this configuration, the diffuser is essentially a conventional multiple shock diffuser and should perform similarly. The higher pressure recovery of the diffuser in this configuration then allows the GDL supply pressure to be reduced to a lower operating level.

Potential advantages of this diffuser are:

1) Significantly better pressure recovery than fixed geometry diffusers.

2) The mas of the moving parts is relatively low, permitting rapid actuation without excessive servo power.

3) No suction or injection req ents.

4) Well suited to high aspect ratio (channel width to height devices such as gas dynamic lasers.

SECTION II

ASPECTS OF THE GAS WEDGE DIFFUSER

Since the gas wedge diffuser is a rather unusual design, some comments on some of its features are in order.

The idea of using a flow separation in place of a solid surface in diffuser design is not original with this device.[3,4] It is unique, however, in using a closed separated region without any boundary layer removal.

In the following paragraphs the "gas wedge" is discussed and the means used to estimate performance presented.

1. THE "GAS WEDGE"

The behavior of a supersonic fluid flow along a smooth wall with a forward-facing step on the wall is characterized[5] by a large wedge-shaped flow separation ahead of the step, as shown in Fig. 3. After a small initial turning length, the separation streamline forms a nearly straight line to the reattachment point. The fluid trapped in the separated region has relatively little momentum and recirculates within the region, forming one or more vortices. The static pressure in the separated flow region is nearly constant.

The angle δ of the straight part of the separation streamline is a function of Mach numbers, Reynolds number, wall temperature, obstacle shape, etc. However, if the Reynolds number is sufficiently high (e.g., turbulent boundary layer) and the step height to boundary layer thickness ratio sufficient large (>2), δ depends primarily on the Mach number. Figure 4 is a representational plot of δ as a function of Mach number for this situation. The data used to construct the curve were obtained from numerous sources.[5,6,7,8,etc.]

To the external inviscid flow, the separation streamline appears as a wedge-shaped surface. The turning of the flow at the separation point generates an oblique shock wave with an attendant pressure rise. It is primarily the interaction of the boundary layer with this shock wave that determines the separation angle δ.

In order to use such a flow separation advantageously as a "gas wedge" in place of a solid wedge, one must ensure that the boundary layer flow is not seriously degraded by the separation and reattachment interactions. This can be done if the flow is steady and is reattached with as little disturbance as possible.

In experiments, it was found that the boundary layer separation point in front of a forward-facing step is not steady - it tends to "jitter" rapidly back and forth a distance about equal to the boundary layer thickness. However, this jitter is eliminated by forcing the separation to occur at a fixed point. Two simple means of accomplishing this are by placing a small wall-mounted wedge or a small rearward-facing step at the desired point. Additional benefits arise from the use of such "stabilizers": The separation shock is sharper, the separation streamline is straighter, and the separation point may be forced considerably forward of its normal position, if desired.

The flow reattachment interaction may be minimized by suitable shaping of the forward-facing step in the vicinity of the reattachment point. (A square corner is not suitable because the flow reattaches on the forward face near the corner, generating a normal shock wave and an attendent strong interaction.) Earlier experiments[9] on flow over wall-mounted cavities, conducted in the ARL 3" x 3" Mach 3 wind tunnel, have shown that a short, forward-facing sharp lip can provide stable flow reattachment with practically no reattachment interaction. Figure 5 is an interferogram of the flow over a cavity so equipped. The length of the lip is important; if it is too long, the cavity "whistles" and if it is too short, a strong reattachment interaction occurs.

2. THE STARTED DIFFUSER

Once the gates are closed and the started flow established, the gas wedge diffuser is simply a multiple shock diffuser, and its performance and design can be analyzed as such.

The desired design point is that in which the separation shocks cross the flow field and are cancelled at the expansion corner at the entrance of the central shock duct diffuser, as shown in Fig. 2. Then, ignoring viscous effects, the flow entering the shock duct section is uniform and the expected pressure recovery of the overall diffuser is roughly equal to the pitot pressure measured there.

The presence of the wall boundary layer considerably complicates the situation because of associated displacement effects and total pressure losses. However, the pressure recovery can still be estimated by assuming that the pitot pressure variation across the boundary layer is linear, and the pressure recovery is roughly equal to the average pitot pressure at the entrance to the shock duct section.

The choice of the design wedge angle is limited by how far from the natural separation angle δ the separation point can be forced to move.

SECTION III

THE EXPERIMENT PROGRAM

1. PROGRAM PLAN

In order to determine whether this diffuser concept would actually function properly, a program of relatively simple wind tunnel tests was planned. This program was to have four phases:

1) Determine whether the flow is stable over a separated region with a sharp forward-facing lip at the reattachment point.

2) Determine whether the gas wedge device can be started (the gates closed) without causing a wind tunnel unstart.

3) Compare the actual gas wedge operation with that based on the above analysis.

4) Install a complete gas wedge diffuser on a wind tunnel to determine actual pressure recovery performance and stability.

The first phase was completed and is reported in Reference 9. The second and third phases have been completed and are reported herein. The last phase was abandoned due to lack of time.

2. WIND TUNNEL MODEL DESIGN

A wind tunnel model was constructed to investigate the "gas wedge" part of the diffuser. Rather than install a gas wedge device on both the top and bottom walls of the wind tunnel a single device was mounted on the bottom wall and a flat "symmetry" plate was mounted near the tunnel center line to simulate a plane of symmetry. This "half" model differs from the full device in that there is a boundary layer build-up on the symmetry plate; however, if the separation shock doesn't strike behind the plate's leading edge, the plate boundary layer does not significantly affect the results. The model was initially designed for a gas wedge angle of 12°. Figure 6 is a drawing of this configuration. Later the model was modified for a gas wedge angle of 7°. This configuration is shown in Figs. 7 and 8. (Figure 8 is a photograph of the model mounted in the ARL 3" x 3" Mach 3 wind tunnel.)

The gate was actuated manually by means of a pushrod which is visible at the bottom of the pictures in Fig. 9. Both the gate and the splitter plate had seals of "o"-ring material to reduce leakage into the separated flow region.

3. TEST CONDITIONS

All tests were performed at stilling chamber pressures between 85 and 100 psi. Unit Reynolds numbers were about 1.5×10^{6} per inch and the wind tunnel wall boundary layer Reynolds numbers at the gate were about 15×10^{6}.

4. INSTRUMENTATION

Minimal instrumentation was used. Pulsed ruby laser holographic interferometry[10] was the principal means of collecting data. Static pressure was monitored on the tunnel sidewall forward of the region influenced by the model to detect wind tunnel unstart. Two additional static pressure parts were located on the model; one 7/8" forward of the gate and the other behind and below the gate. Both are visible in Fig. 9(b). To detect flow instabilities and oscillations in the separated region, a fast response strain-gage pressure transducer was mounted in the surface 0.7" forward of the gate and can be seen in Fig. 9. A traversable pitot probe was used to survey the pitot pressure distribution between the splitter plate and the symmetry plate.

5. RESULTS

Initial tests were conducted without the symmetry plate and stabilizer wedge installed to determine whether the wind tunnel could be started with the gate installed and whether closing the gate would unstart the wind tunnel. Figure 10 shows interferograms made with the gate in positions varying from fully open to fully closed. In Fig. 10(a), the gate is fully open and the flow is quite steady. When the gate was closed only slightly, the flow remained attached to the gate as shown in Fig. 10(b). As the gate was closed further, the flow separated from the wall upstream of the gate and reattached near the rear corner of the gate, as shown in Fig. 10(c). When this occurred, the flow became somewhat unsteady, as evidenced by the unevenness of the separation shock in the figure. This unsteadiness is due, in large part, to the separation point jitter mentioned earlier. Finally when the gate was completely closed, the flow further deteriorated with sidewall boundary layer separation and separated region flow unsteadiness as indicated by the pileup of fringes at the back of the separated region in Fig. 10(d).

These results were not discouraging since the stabilizer wedge was not installed and, without the symmetry plate, a massive shock-boundary layer interaction was expected on the upper wall of the tunnel. The test did confirm that the gate could be closed and opened without causing a wind tunnel unstart, in spite of the presence of undesirable interaction.

The next series of tests was conducted with the complete model installed. It was immediately discovered that the gate could not be closed without causing wind tunnel unstart. The cause was determined to be the fact that the effective blockage of the started gas wedge was much greater than the geometric blockage due to a large displacement thickness of the boundary layer in the central channel. (The design geometric blockage was 53%. The estimated effective blockage was 66%.)

The model was modified by raising the symmetry plate 0.20" and lowering the splitter plate 0.13" to reduce the geometric blockage to 41% and the estimated effective blockage to 55%. It then was possible to completely close the gate without causing tunnel unstart. Figure 11 shows interferograms for this configuration with three different gate positions. Of particular note was the improvement of the flow quality over the case of Fig. 10 where the stabilizer wedge and symmetry plate were not installed.

Unfortunately the above modifications moved the diffuser configuration off the design point. This can be seen in Fig. 11c: The separation shock struck the symmetry plate too far back and, as a result of the strong interaction of this shock with the plate boundary layer, two reflected shocks were produced instead of only one. The design point required a simgle reflected shock to cancel the expansion at the corner of the splitter plate. Instead, the two reflected shocks struck the splitter plate far behind the corner.

In order to regain wave cancellation at the splitter plate corner with the 41% geometric blockage, it was determined that the gas wedge angle should be 7^o instead of the natural separation angle of 12^o. To accomplish this the stabilizer wedge was redesigned with a 7^o angle, and base height of 0.18", and positioned further forward on the wind tunnel wall. This is the configuration shown in Figs. 7 and 8. (Actually, due to its size, it is probably more appropriate to think of this stabilizer wedge as a flow deflector.) Interferograms of the flow about this configuration are shown in Fig. 12. The stabilizer wedge is out of the picture to the left. The flow with the gate closed, Fig. 12(b), was quite close to the new design point. The free shear layer was well-behaved with only small fluctuations in evidence. Complete wave cancellation was not achieved at the corner of the splitter plate because the wedge angle at the front of the splitter plate was not reduced from 12° to 7°, as would have been appropriate.

Data taken with the fast response pressure transducer, which was mounted just forward of the gate, showed apparently random pressure fluctuations with the gate open or closed. With the gate open, the average peak-to-peak pressure fluctuation was about 0.5 psi with a local static pressure of 2.3 psi. With the gate closed, the average peak-to-peak fluctuation increased to about 1.3 psi with the local static pressure in the separated region increasing to 3.6 psi. The only readily discernable frequencies in either case were at about 500 Hz (presumed to be a resonance in the wind tunnel stilling chamber) and 100 kHz (possibly a transducer resonance.) Both were observed in all tests. Since the resonant frequency of the separated region would be in the range 3-10 kHz and no apparent dominant frequencies in this range were observed, the detected fluctuations are attributed to turbulence in the boundary layer and free shear layer.

6. ESTIMATING PRESSURE RECOVERY

With the completion of the above described tests which demonstrated the gas wedge principle, the question remained of the pressure recovery performance of a diffuser incorporating a gas wedge device.

Initially, construction of a complete gas wedge diffuser was planned for testing in the ARL 3" x 3" Mach 3 wind tunnel. Unfortunately, time considerations precluded doing this.

As an alternative method of estimating overall pressure recovery, the average pitot pressure in a cross section of the central duct should, at least, be indicative of the expected diffuser recovery. Accordingly, a traversing pitot probe was constructed using available equipment. The probe consisted of a 0.1" diameter steel tube mounted across the flow. The end of the tube was sealed and a small (0.015") hole was drilled in the upstream side of the tube to act as a pitot port. This port could be traversed from one sidewall of the wind tunnel to the center line of the tunnel. (Flow symmetry was assumed.)

Figure 13 is an enlargement (1 1/2 times actual size) of part of Fig. 12(b) and shows the flow in the central channel with the positions of the pitot probe indicated for the five traverses. The circles are sized to show the relative probe diameter.

This technique was not altogether successful. In particular, the pressures recorded in traverse #1 were so low as to lead one to suspect considerable interaction between the probe and the splitter plate boundary layer. As a result the data collected on traverse #1 were discarded. The integrated pitot pressures for the other traverses and the local sidewall static pressure are plotted in Fig. 14. The break in the dashed line was placed at the outer edge of the boundary layer as determined from the interferogram. The predicted inviscid flow pitot pressure was 59.5 psi, based on an aerodynamic wedge angle of 7^o and the test p_o of 100 psi.

The average pitot pressure was about 48 psi. Since the pitot pressure in the wind tunnel test section was 33.9 psi, this diffuser design would appear to offer about 40% better recovery than a conventional fixed geometry diffuser.

SECTION IV

CONCLUSION

Although the test program was not as complete as originally planned, the results obtained indicate that the gas wedge diffuser should be a viable concept. The tests did show that the natural separation angle could not be used without producing excessive blockage and forced separation at a lower angle was necessary to achieve proper wave cancellation. This is also expected to be true at higher Mach numbers. Further testing of a complete device should be undertaken to establish recovery performance and flow stability.

Application has been made for a patent to cover this diffuser concept.

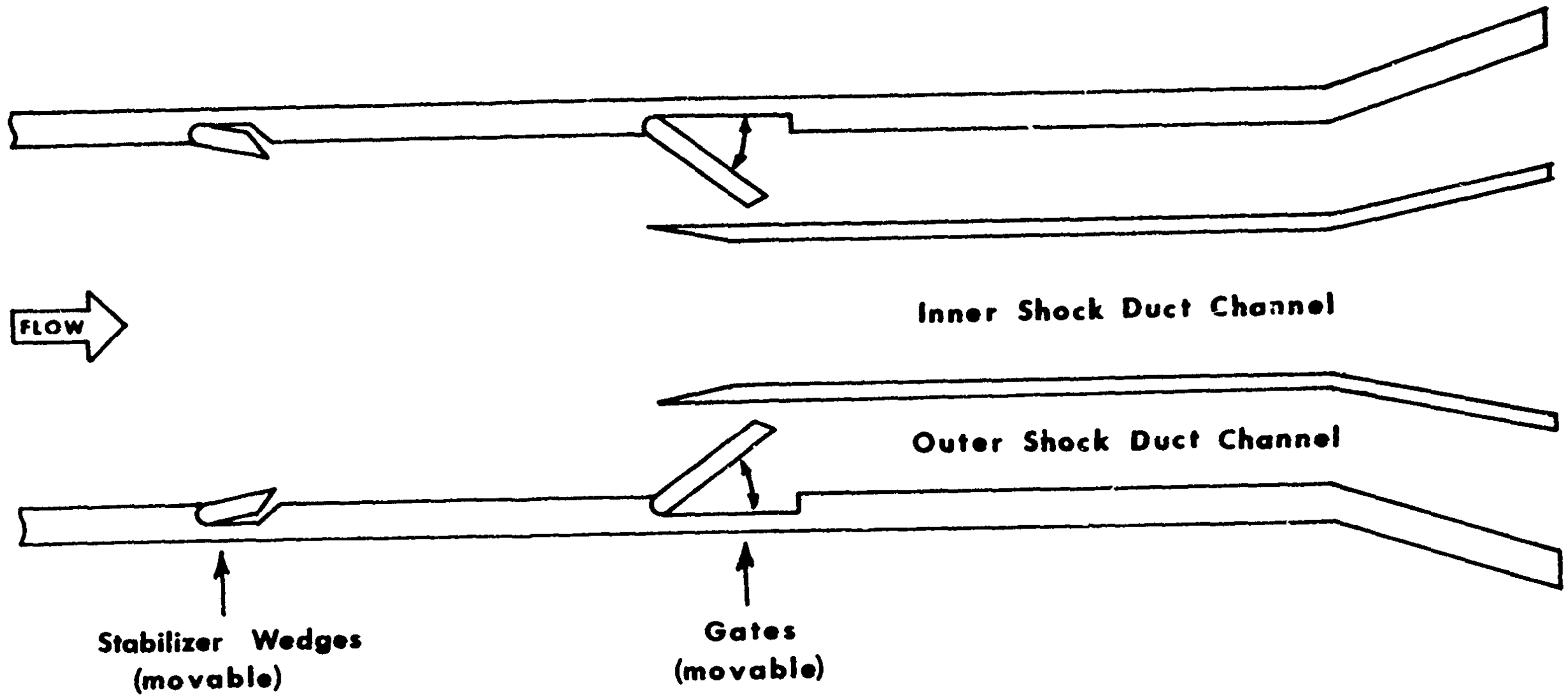


Figure 1. Schematic Representation of the Gas Wedge Diffuser

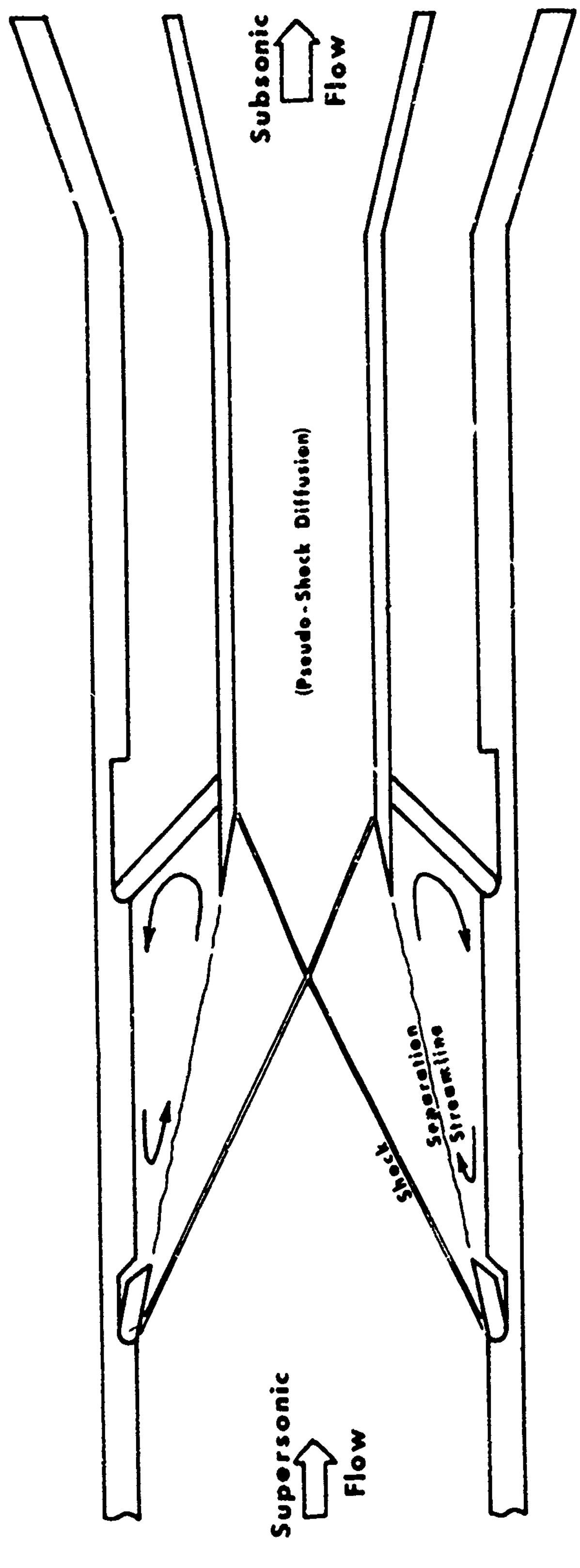


Figure 2. The Started Gas Wedge Diffuser

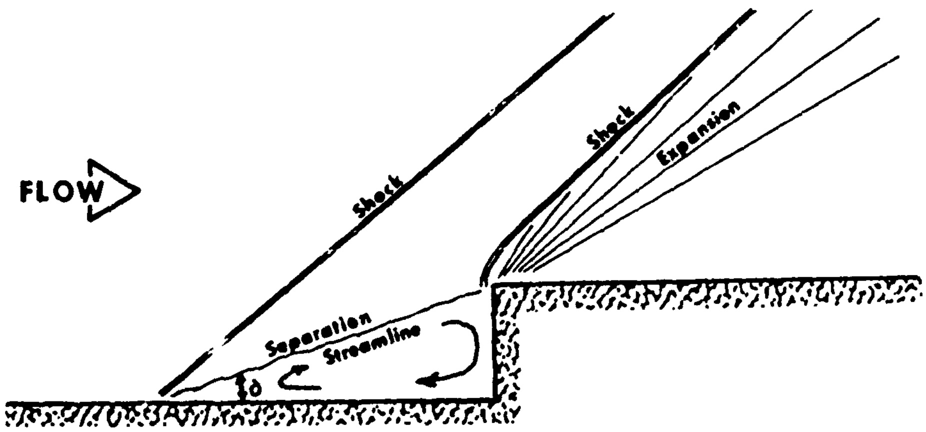


Figure 3. Flow Along a Wall With a Forward-Facing Step

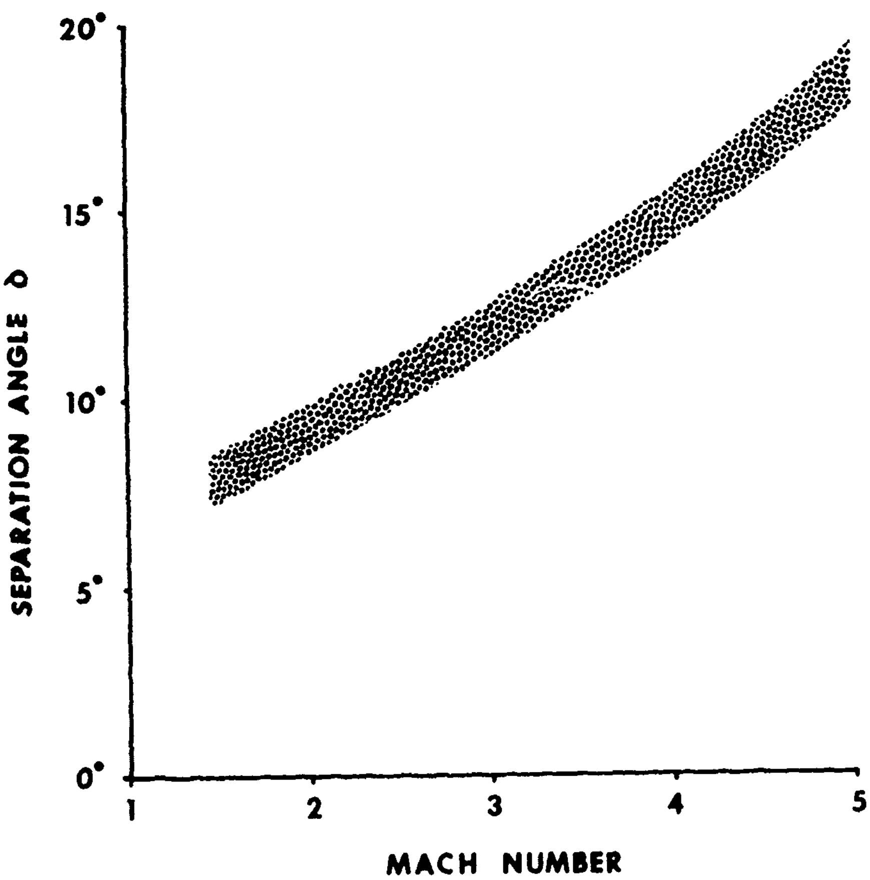


Figure 4. Separation Angle vs Mach Number

Figure 5. Interferogram of Flow Over a Shaped Cavity

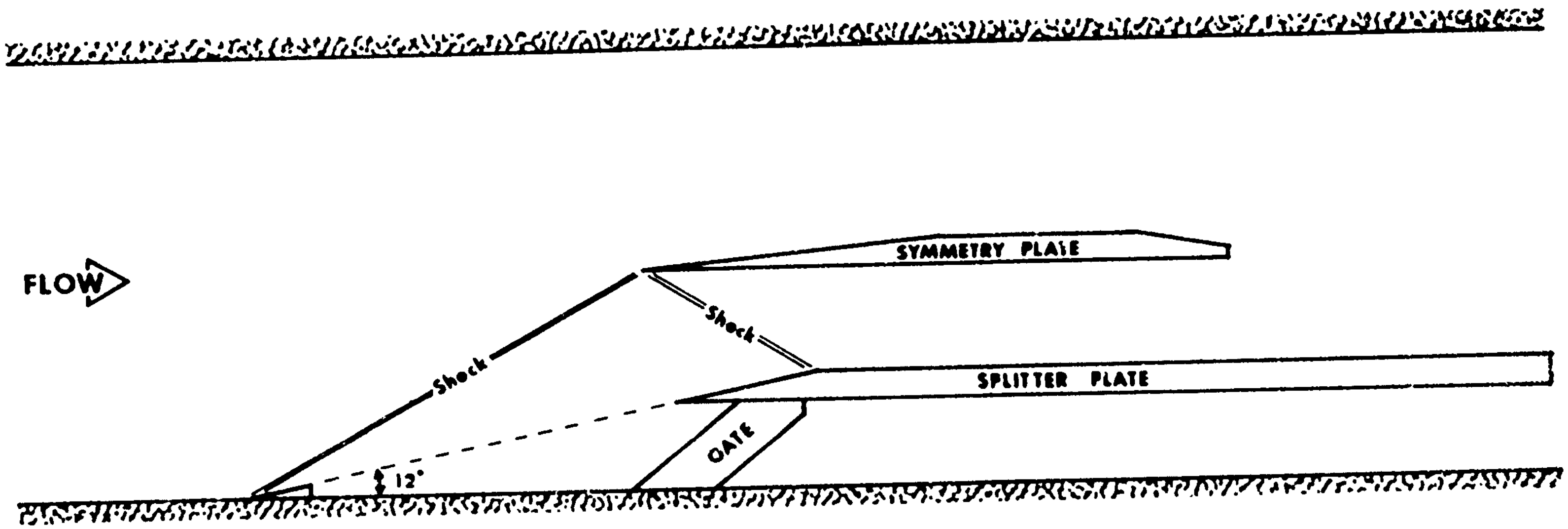


Figure 6. Initial Model Configuration

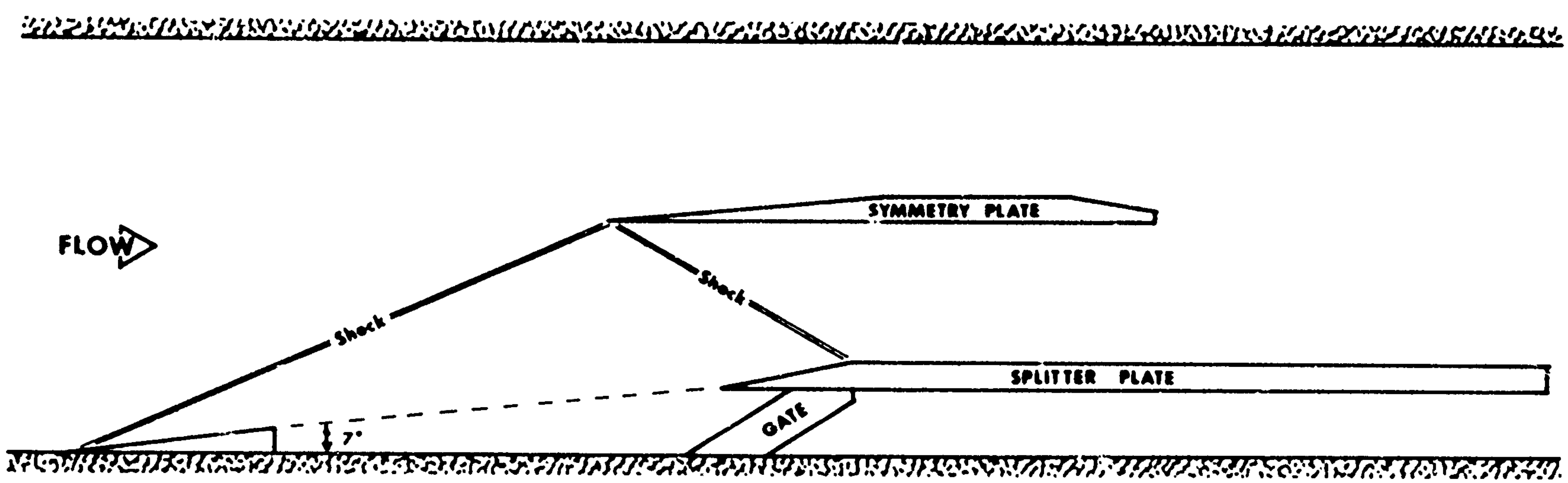


Figure 7. Final Model Configuration

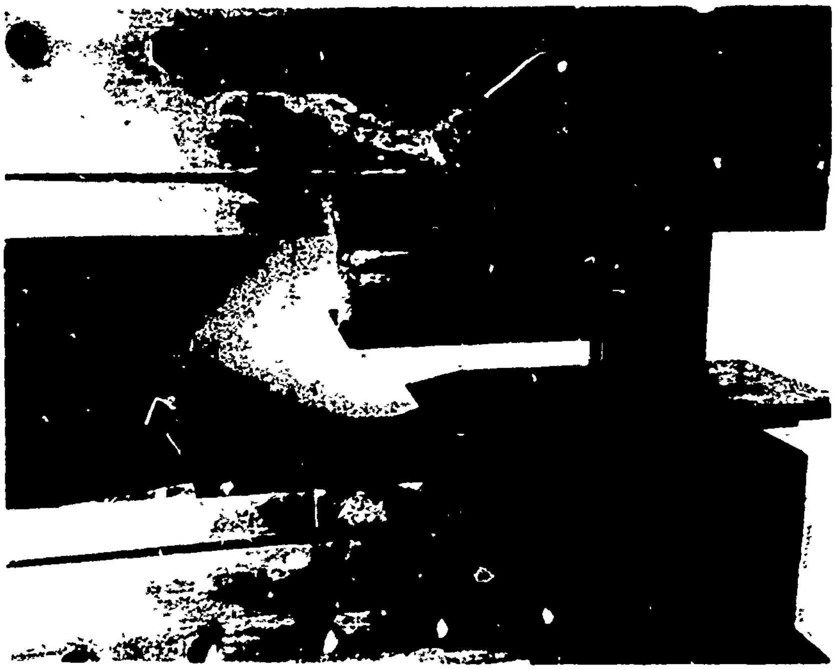


Figure 8. Final Model Configuration Mounted in Wind Tunnel

(a) (b)

Figure 9. Gate Assembly Mounted in Wind Tunnel

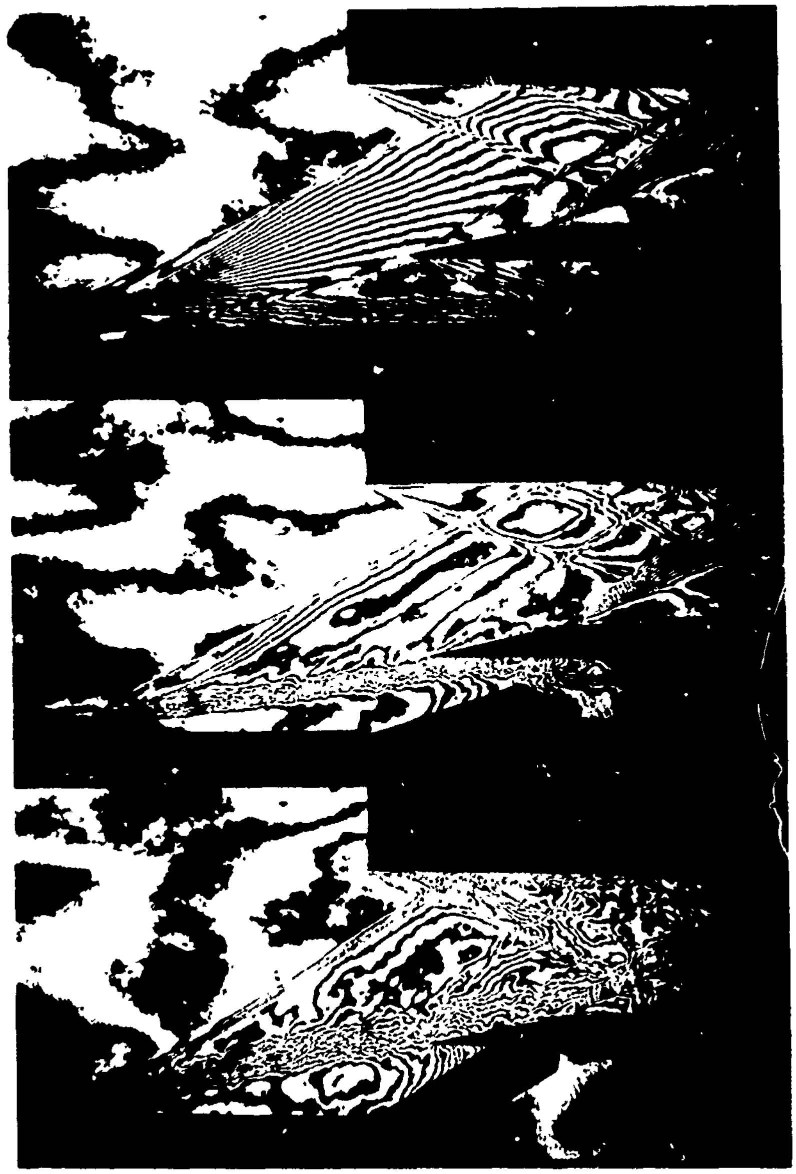
a)

b)

c)

d)

Figure 10. Interferograms of Flow Field For Various Gate Positions

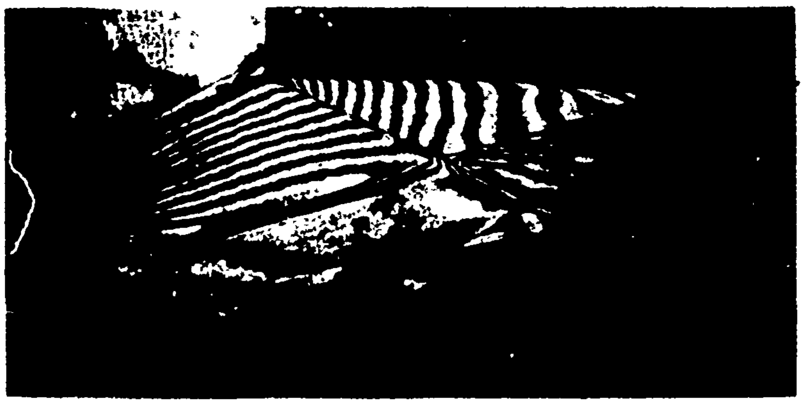


a)

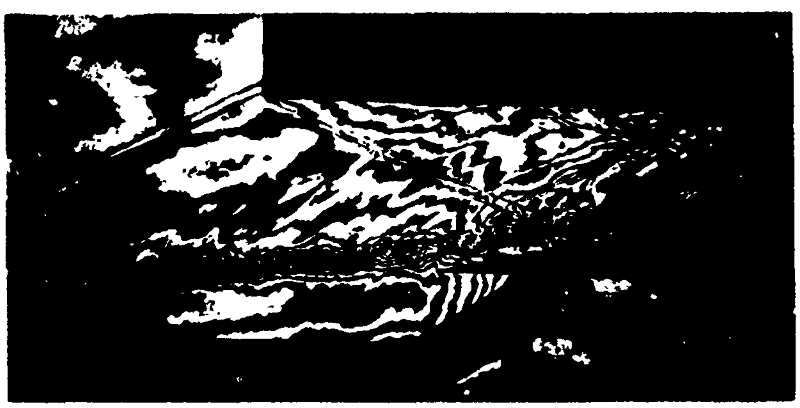
b)

c)

Figure 11. Interferograms of Flow Field of Model With 12° Gas Wedge Angle



(a)



(b)

Figure 12. Interferograms of Flow Field of Model With 7° Gas Wedge Angle

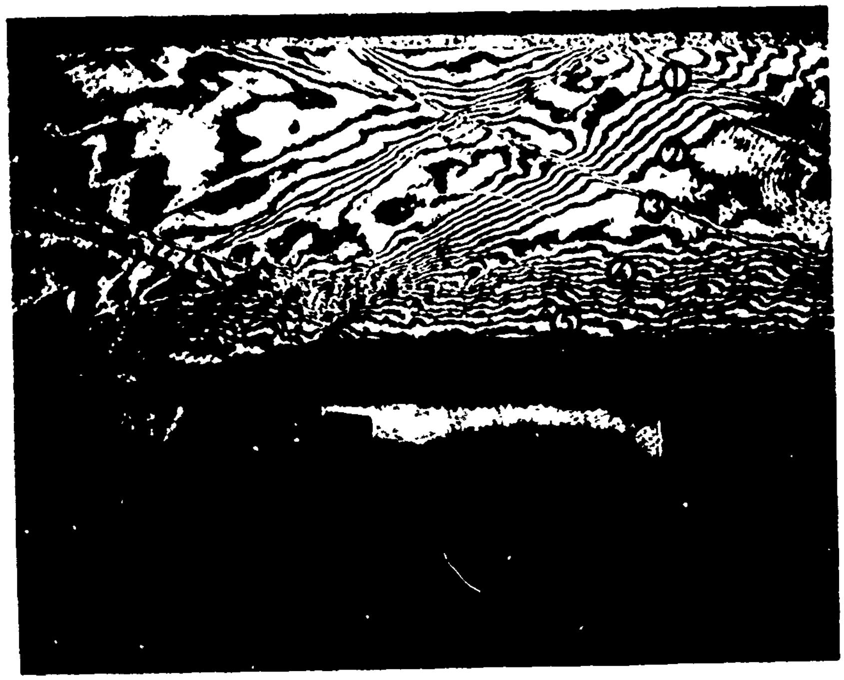


Figure 13. Locations of Pitot Probe Traverses

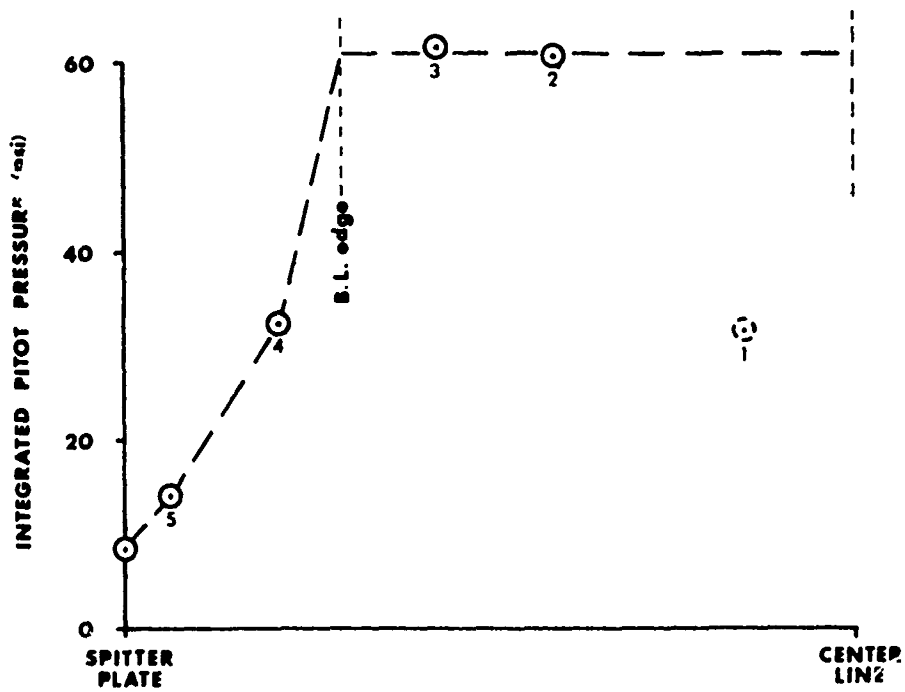


Figure 14. Integrated Pitot Pressure Distribution

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