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6. AUTHOR(S)
Benjamin J C WU

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Yale University
Engineering & Applied Science Department
New Haven, CT 06520

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INFLUENCE OF VARIATION OF ASPECT RATIO ON THE PRESSURE RECOVERY IN SUPERSONIC DIFFUSERS

by

Benjamin J.C. Wu*

Report #8

Final Technical Report prepared for AFOSR Research Grant F49620-77-C-0068 "Supersonic Diffuser Research".

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* Presently at Brookhaven National Laboratory, Upton, New York 11973

DEPARTMENT OF ENGINEERING

AND APPLIED SCIENCE

YALE UNIVERSITY

FOREWORD

In this report we present a brief summary of the results of the research conducted under Contracts F44620-73-C-0032 and F49620-77-C-0068 "Supersonic Diffuser Research" for the period 1 January 1973 to 31 December 1978. In addition, new experimental results obtained in 1977/78 are included. This constitutes the Final Technical Report of the Contract F49620-77-C-0068.

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I. INTRODUCTION

This contract was initiated in 1973 to conduct a systematic investigation, of the gasdynamics of supersonic diffusers, In particular, diffusers applicable to gasdynamic or other types of flow lasers, (Anderson 1976, Christiansen et al. 1975) were to receive special attention.

The first phase of the research was completed in early 1974 with the publication of an extensive literature survey (Report #1 and Johnson and Wu 1975). This review covered papers from archival journals, technical reports from government and industrial research laboratories, and some technical notes and memoranda from various laboratories not widely known to the general public. In addition to U.S. literature, material from Western Europe and the Soviet Union was also included though not as completely.

The main conclusion from the literature search was that almost all the research on supersonic diffusers was performed with specific application, namely a specific wind tunnel installation or an engine, in mind. Systematic studies on the gasdynamics of diffusers even of simple geometries were scarce, making it difficult, if not impossible, to extend existing work to other configurations. Despite the fact that some of the high Mach number wind tunnels operated with known unequilibrated internal modes, there was no research on nonequilibrium flow effects in diffusers in the literature

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* Scientific Reports published under this contract are listed on p. 10.

consulted. Moreover, in most conventional wind tunnels, the cross-section of the test section is either circular or squarish. Consequently, most diffuser studies were concerned with circular, square, or rectangular cross-sections with comparable widths and heights, characterized by an aspect ratio, defined as the width to height ratio, of unity or close to unity.

Our literature concluded by recommending that a systematic study be conducted on diffusers with a simple geometry, namely a rectangular, parallel channel diffuser with constant cross-section. Primary diffuser characteristics to be examined were the pressure recovery, the starting process and the flow stability. Effects to be investigated include Reynolds number and Mach number variations, variations of diffuser length and size, addition of a throat section, etc. In addition, elementary variable geometry systems and effects of boundary layer control were to receive some limited attention. It was recognized that nonequilibrium flow effect and high aspect ratio situations are of particular importance in gasdynamic laser applications. The necessary condition that a population inversion exists in the laser cavity to produce stimulated emission of radiation means that the flow leaving the cavity is not likely to be in thermodynamic equilibrium. Thus nonequilibrium flow effects must be considered in diffusers for gasdynamic laser application. The width of the "test section" i.e., the laser cavity, is dictated by the optical requirements of the laser system and is typically much greater than the height. Therefore the diffusers needed for gasdynamic lasers will have a high aspect ratio. Since pressure recovery in supersonic diffusers is accomplished by a complex interaction of frictional (Fanno line) pressure rise, shock compression and boundary interactions, it is not clear whether a high aspect ratio cross-section, with its higher periphery-to-area ratio and accentuated multidimensionality of flow will achieve a higher or lower pressure recovery.

Having dealt with the other effects named above in previous reports, we shall outline in this report new results obtained in our laboratory regarding the influence of aspect ratio on the pressure recovery of supersonic diffusers.

II. EXPERIMENTS

The experiments in this phase of the research were conducted in a Ludwieg tube-wind tunnel whose operation principle has been described in detail before (Cable and Cox 1963, Wegener and Buzyna 1969, Johnson and Cagliostro 1971, Wegener and Cagliostro 1973, and Reports 5 and 6 of this contract). Essentially, a Ludwieg tube (Fig. 1) is simply a shock tube with a converging-diverging supersonic nozzle installed near the diaphragm section separating the high pressure driver and low pressure driven sections of the tube. A well controlled steady supersonic flow of short but useful duration is generated after the diaphragm is abruptly ruptured establishing a sufficient pressure difference across the nozzle. In this series of experiments, the diaphragm was located downstream of the nozzle.

The nozzle used in this work was the Mach number 3 nozzle which had been thoroughly calibrated and whose characteristics had been well documented in previous reports (5 and 6). The parallel flow leaving the nozzle has a cross-section of 2 in. x 2 in. To study the effect of diffuser aspect ratio, a thin vane with a sharp leading edge was installed at the center of the square (2 in. x 2 in.) cross-section diffuser, parallel to the flow direction. Thus, the square diffuser with an aspect ratio of unity as used before (Reports 5 and 6) was split evenly into two subunits, and there were now effectively two identical subdiffusers connected in parallel. Each of these subunits may be considered a separate diffuser with a flow cross-section of roughly 2 in. x 1 in. giving an aspect ratio of approximately two.

Figure (2) is a schematic drawing of the test section, showing the nozzle-diffuser assembly and the placement of the center diving vane (a) and the top and bottom deflection vanes (b). The purpose of the deflection vanes was to produce a symmetric flow in the diffusers. Moreover, an idealized static pressure distribution along the nozzle and each of the diffusers is included, giving the definition of various symbols.

For the first set of experiments, center dividing vane of 1/8" thickness, 10° total included angle at the leading edge and either 12" or 3" length was inserted. The top and bottom deflection vanes were moreover installed in some early experiments. For the second set of experiments, the center vane was replaced by a thin Mylar sheet (0.003" thick) stretched taut between the sidewalls and no deflection vanes were used. In this fashion, the effects of finite vane thickness and finite leading edge angle may be minimized and the two subunits of the diffuser would each be a parallel channel diffuser of aspect ratio two.

The experimental procedure included the measurement of static pressure variations at several locations along the wall of the nozzle-diffuser assembly as functions of the initial pressures p_4 and p_1 in the driver and driven sections, respectively, of the Ludwieg tube (Fig. 1). In addition, a schlieren system covering most of the diffuser area was utilized in conjunction with a high speed (5000 frame/sec) movie camera for flow visualization in the set of experiments with the 1/8" vane.

The driver section pressure p_4 used in these experiments was either about 750 Torr or 700 Torr, yielding $p_o \approx 725$ Torr, or 676 Torr according to well known Ludwieg tube relationships.* To quantify the diffuser performance, the most important quantities measured here are the final pressures attained at the diffuser and nozzle exits after the successful starting of the Ludwieg tube flow. The latter pressure yields information whether supersonic flow exists at the nozzle exit, or whether the flow there was disturbed by the presence of the diffuser. The pressure at the diffuser exit provides a measure of the pressure recovery achieved. Schlieren movies provided additional information about the flow, extent of the recovery zone, and in particular whether the flow was supersonic at the nozzle exit. The nozzle flow is said to be "started" if the flow at the exit is supersonic and at the Mach number obtained in calibration runs.

The variation of p_d with p_1 measured in these partitioned diffusers is displayed in Figs. 3 and 4. Here,

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* See, e.g., Cable and Cox (1963). Note the misprint in Eq. (12) in this reference. The quantity in the denominator should be $[1 + (\gamma-1)M_1/2]^2$ instead of $[1 + (\gamma+1)M_1/2]^2$.

results of the tests with 1/8" thick vanes of 3" and 12" length and those with Mylar sheet dividers of 6" and 12" length are presented. The experiments with 1/8" vane were performed without the top and bottom deflection vanes (element b. in Fig. 2) after it was found that the nozzle could not be started with the deflection vanes in place. Apparently, the thickness of the vanes combined with the boundary layer displacements reduced the effective diffuser minimum cross-sectional area below that of the minimum starting area ratio, despite the fact that the geometrical area ratio exceeded the minimum starting area ratio. We note in Figs. 3 and 4 that for a given vane, p_d first remained roughly constant when p_1 was below a certain level and the flow at the nozzle exit remained at the calibrated Mach number. In this case, it was found that the flow in the diffuser was supersonic throughout and the pressure recovery was insignificant. Next, at an intermediate range of p_1, the flow at the nozzle exit was unaffected while that at the diffuser exit became subsonic and the pressure at the latter location rose with increasing p_1. Finally, as p_1 was raised further, at a certain "critical" value of p_1, p_d increase sharply with slight increases in p_1, meanwhile the supersonic flow at the nozzle exit started to be affected and quickly broke down. The pressure p_d at the diffuser exit corresponding to this critical value of p_1 represents the maximum pressure recoverable, while maintaining supersonic flow at the nozzle exit, with the particular diffuser tested. The optimum pressure recovery is taken to be a slightly lower value of p_d/p_o than the maximum to allow a margin for safe operation. The optimum pressure recovery for the four partitioned diffuser configurations tested are indicated by the arrows in Figs. 3 and 4.

To summarize, the reciprocal of these optimum values of pressure recovery was plotted as a function of the dimensionless diffuser length L/D in Fig. 5, where D = 2" is the hydraulic diameter of the nozzle exit. Here, the circles and the curve represent the results presented by Abuaf in Report 6 in his Fig. 26. It is noted that the partitioned diffusers with 1/8" center vanes required higher values of p_o/p_d to operate, i.e., yielded poorer pressure recovery than open diffusers of equal length. However partitioned diffusers with Mylar sheet dividers produced nearly identical p_o/p_d values as open diffusers. It appears that the presence of the Mylar sheet has a negligible effect on the pressure recovery. This seems to indicate that the variation of the diffuser aspect ratio from unity to two is insufficient to cause any appreciable change in the pressure recovery. The difference between the data of the diffusers with 1/8" vane and those with the thin sheet may be attributed to the reduction in flow area when the 1/8" vane was in place, creating a throat section.

Thus, the current results suggest that the optimum pressure recovery of parallel channel diffusers is not affected by variations of aspect ratio from unity to two. However, for gasdynamic laser systems, where the diffuser aspect ratio may be many times higher than two, the pressure recovery may be significantly different.

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(1) Report #1 Joseph A. Johnson III and Benjamin J.C. Wu, "Pressure Recovery and Related Properties in Supersonic Diffusers, A Review," (April 1974).

(2) Report #2 Peter E. Merkli, "Pressure Recovery in Constant Area Supersonic Diffusers," (September 1974).

(3) Report #3 Peter E. Merkli, "Pressure Recovery in Rectangular Adjustable Area Supersonic Diffusers," (April 1975), AFOSR-TR-76-1238, ADA 033630.

(4) Report #4 Peter E. Merkli, "Pressure Recovery in Rectangular Constant Area Supersonic Diffusers," (November 1975).

(5) Report #5 Peter E. Merkli and Nesim Abuaf, "The Flow Starting in Constant Area Supersonic Diffusers in a Ludwieg Tube," (September 1976).

(6) Report #6 Nesim Abuaf, "Straight Duct Supersonic Diffuser Flow in a Ludwieg Tube with Upstream Diaphragm," (December 1976), AFOSR-TR-77-0201, ADA 037674.

(7) Report #7 Ernst Becker, "Calculation of Pressure Recovery in a Constant Area Supersonic Diffuser," (December 1978).

(8) Report #8 Benjamin J.C. Wu, "Influence of Variation of Aspect Ratio on the Pressure Recovery in Supersonic Diffusers," (February 1978) Final Technical Report.

(9) 1. Joseph A. Johnson III, "Nonequilibrium Phenomena in the Pressure Recovery of Supersonic Diffusers," (ABSTRACT) Bull. APS, Vol. 18, No. 11, p.1483 (November 1973).

(10) 2. Joseph A. Johnson III and Benjamin J.C. Wu, "Pressure Recovery in Supersonic Diffusers," Trans. ASME, J. of Fluids Engineering, Vol. 97, Series 1, pp. 374-376, (September 1975). Errata, ibid. p. 533 (December 1975).

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Figure 1

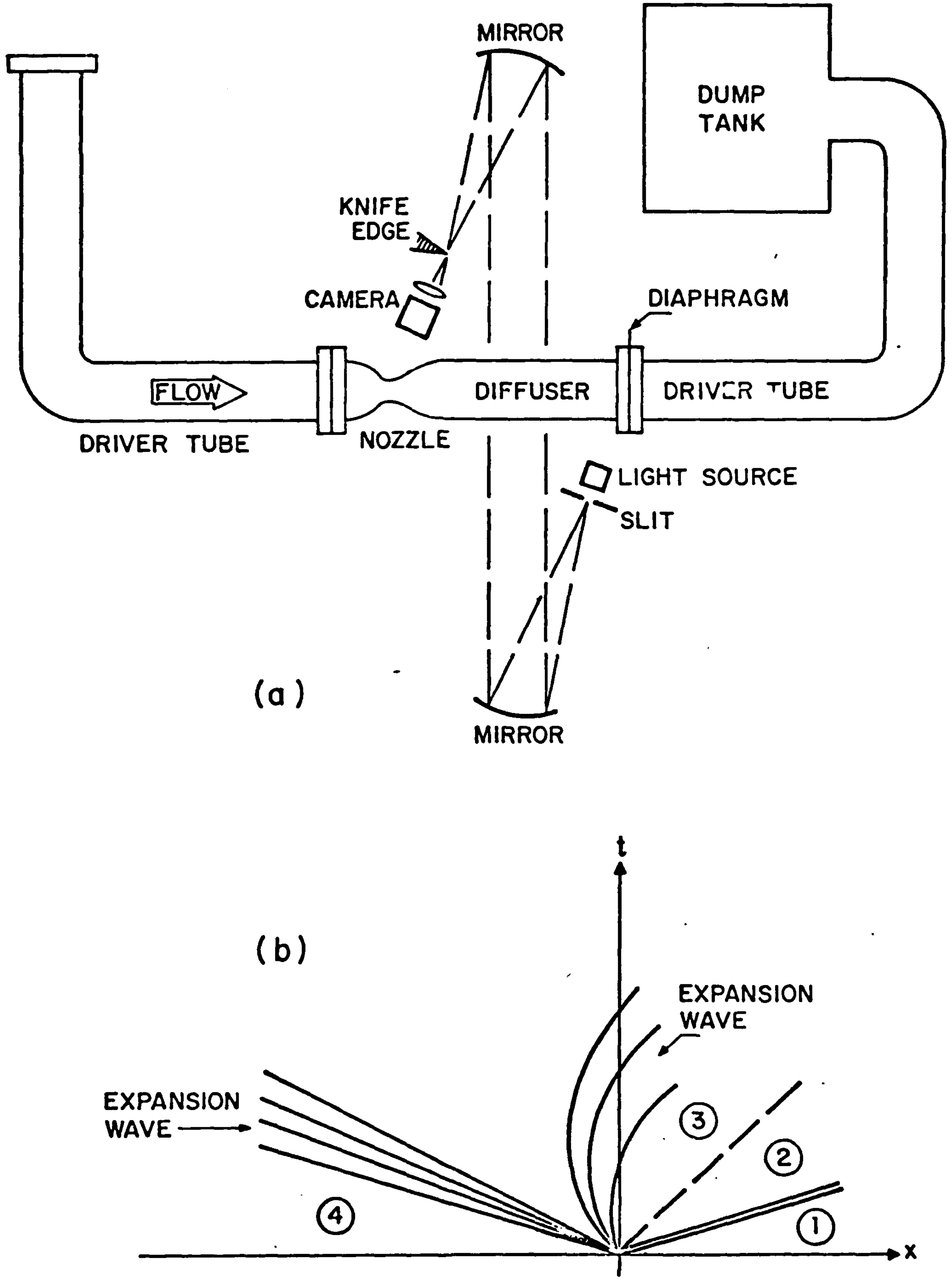
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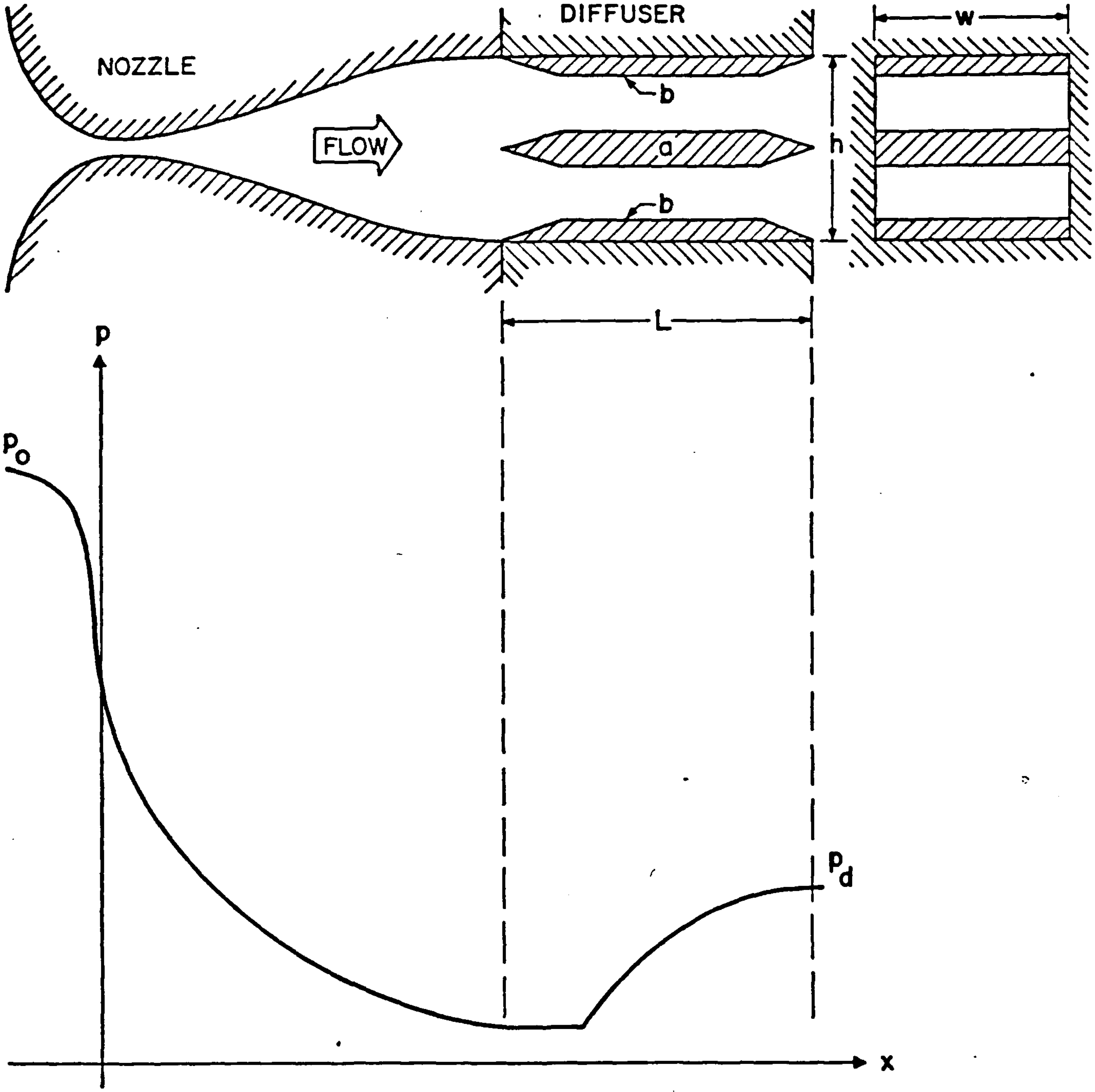
Figure 2



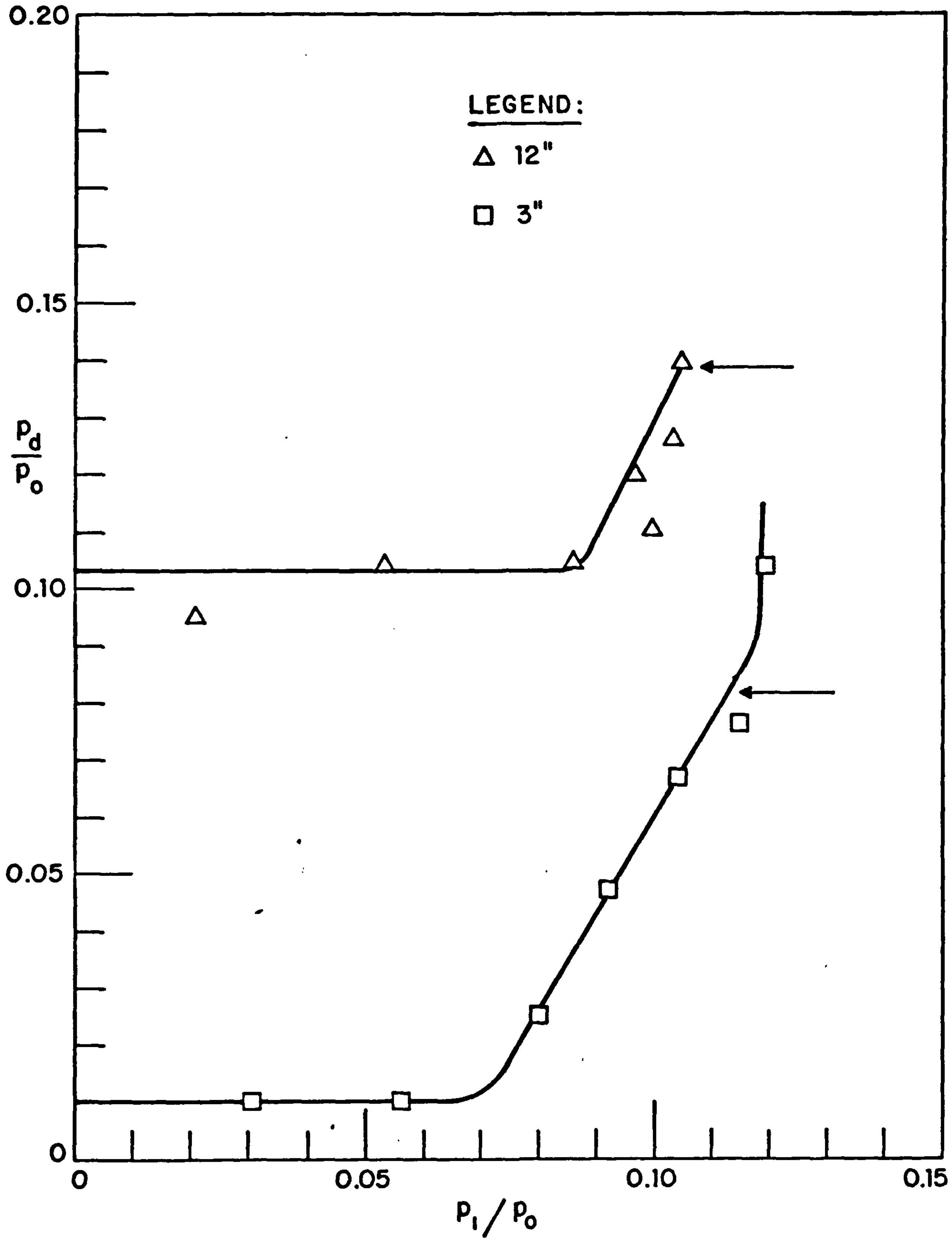

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Figure 4

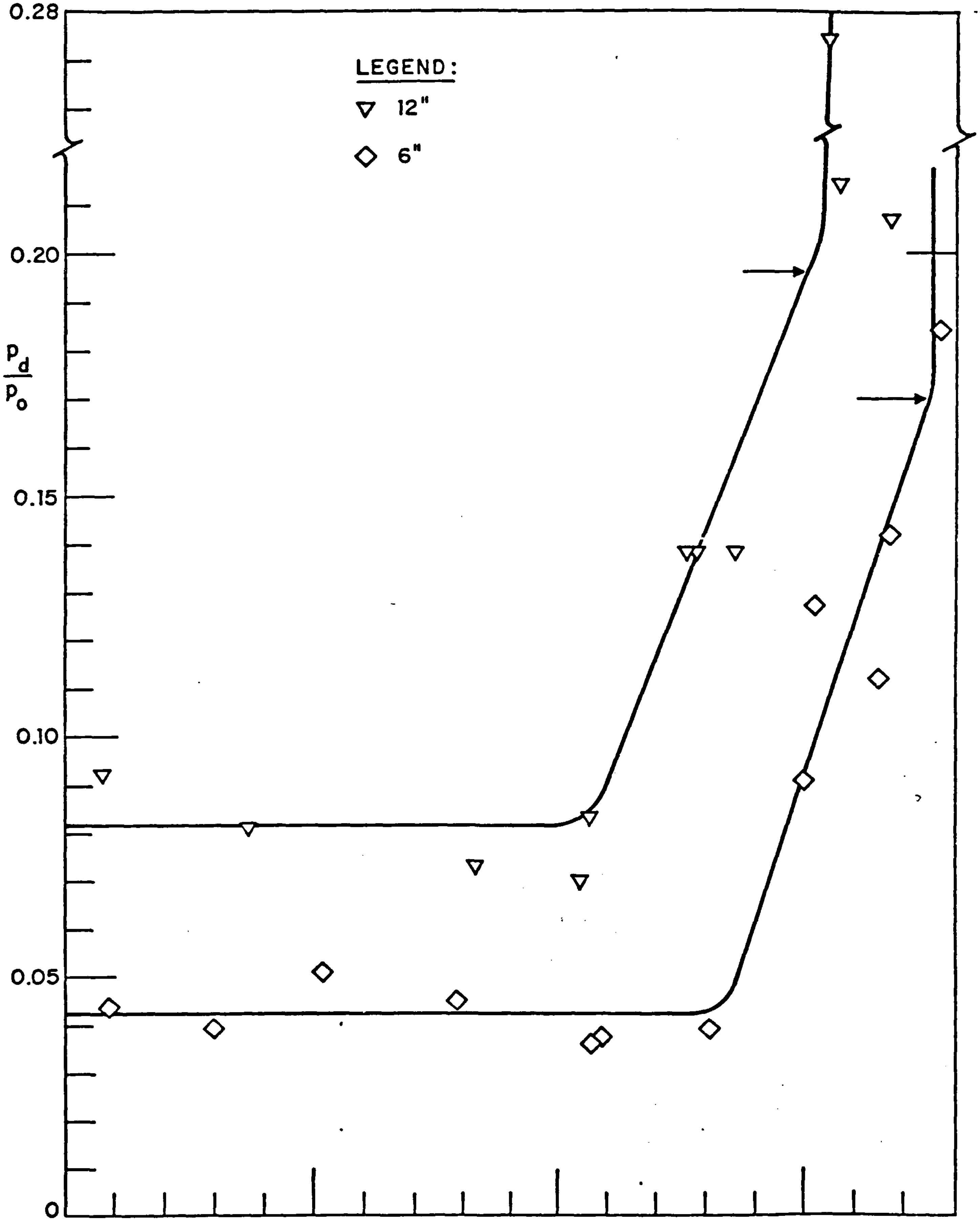

Figure 5