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Pressure Recovery in a Constant-Area, Two-Stream Supersonic Diffuser

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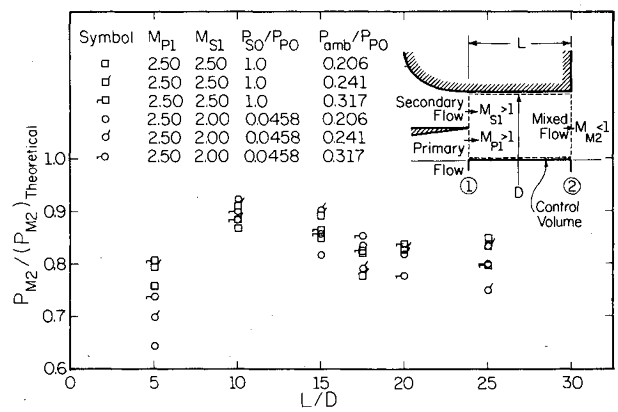

Fig. 1 Static pressure recovery factor as a function of diffuser length-to-diameter ratio for two primary/secondary Mach number cases.

Introduction

THE constant-area diffuser has long been an important device utilized for the reduction of supersonic streams to subsonic velocities. Much of the previous research concerning supersonic flow diffusion has concentrated on the case of a single entering stream and has been motivated by the desire to design more efficient wind tunnels.[1,2] The typical research effort focused on examination of the shock recompression process and the shock structure for various geometry diffusers.[3-5]

Thorough investigations of pressure recovery in single-stream, constant-area diffusers have been performed by Merkli[6,7] and Waltrup and Billig.[8] The pertinent flow variables were determined to be Mach number, diffuser length, and Reynolds number. Merkli[6,7] found that the recovery zone extended for approximately 8-12 diffuser hydraulic diameters and achieved 58-77% static pressure recovery based on normal shock-wave diffusion at the entrance Mach number. The findings of Waltrup and Billig[8] similarly indicated that the maximum static pressure rise occurred over a mixing tube length of 8-12 tube diameters.

The current investigation concerns the performance of a constant-area cylindrical diffuser with two coaxial entering streams, both of which are supersonic. This study has been prompted by current work in the field of high-energy, chemical, and gasdynamic lasers. In these applications, where multiple, high Mach number streams must mix and interact, a fluid dynamic description of the diffusion process is necessary. The basic two-stream, supersonic inflow model lends valuable insight into the multistream diffusion problem using a constant-area duct.

Theoretical Analysis

The performance characteristics of a constant-area diffuser with two entering supersonic streams were predicted by a quasi-one-dimensional control volume analysis. The primary and secondary streams enter the diffuser at location 1, shown in the inset of Fig. 1, at matched static pressures, and supersonic velocities which are not necessarily equal. The diffusion process is due to oblique shock waves and viscous interactions and not as a result of any initial pressure gradient. The mixing of the two supersonic entering streams occurs within the control volume and a uniform, subsonic stream is assumed to exit at location 2.

The quasi-one-dimensional theoretical analysis is based on the assumption of steady, uniform flow at the inlet and outlet locations. The primary and secondary streams are assumed to behave as perfect gases, and the base area between the two streams at the diffuser entrance plane is assumed to be zero. The fundamental equations of continuity, momentum, and energy are applied to the control volume shown in the inset of Fig. 1. Knowledge of the inflow conditions and manipulation of these equations produces a series of equations which determines flow properties such as static pressure and Mach number at the diffuser exit plane for the case of maximum compression. Based on the "equivalent" entering Mach number concept, the analysis provides theoretical values of the subsonic Mach number and the maximum static pressure at the diffuser exit plane for comparison with experimentally measured values. Details of the analysis are covered in Ref. 9.

Experimental Program

Experiments were conducted to obtain wall static pressure distributions along the length of the diffuser. The steady-state experiments utilized compressed air as the working fluid for the two streams. A supersonic-supersonic ejector apparatus provided the two axisymmetric and uniform supersonic streams entering the constant-area diffuser. Each of the concentrically located nozzles was designed by the method of characteristics to produce uniform exit plane flow. The diffuser was a constant-area mixing tube instrumented with static pressure taps along the wall and a total pressure probe in the diffuser exit plane.

The parameters varied in the experiments were the secondary flow entrance Mach number M_{SI} and the mixing tube length-to-diameter ratio L/D. The available experimental apparatus enabled the experiments to be conducted over the following ranges: $1.50 \leq M_{SI} \leq 2.50$ and $5.0 \leq L/D \leq 25.0$. Limited experiments were conducted for the secondary entrance Mach numbers $M_{SI} = 1.50$ and 1.75, while extensive experiments were conducted for $M_{SI} = 2.00$ and 2.50. In all cases, the Mach number of the primary stream was $M_{PI} = 2.50$.

The maximum compression experiments were performed by adjusting the primary and secondary static pressures at the confluence point at the diffuser entrance to be equal. The back pressure valve downstream of the diffuser exit was closed until the shock structure within the diffuser was positioned just downstream of the diffuser entrance plane. For this maximum compression condition, the upstream stagnation conditions, mass flow rate, diffuser exit plane stagnation pressure, and wall static pressure distribution were measured. These maximum compression experiments were conducted over the entire diffuser L/D range and for each of the four values of M_{SI}.

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Discussion of Results

The performance of a constant-area diffuser with two supersonic entering streams is now examined by comparing the collected experimental data with the theoretical predictions. Diffuser performance, especially for wind-tunnel applications, is commonly evaluated in terms of static pressure recovery and recovery zone length.[10] Minimization of diffuser length for application to chemical and gasdynamic laser systems requires a knowledge of those factors which enhance recompression and shorten the recovery zone.

The performance of the constant-area diffuser is measured by the level of static pressure recompression which occurs within the diffuser. To represent the static pressure recovery of a diffuser, an empirical "static pressure recovery factor" μ can be defined. The recovery factor μ is defined as the ratio of the experimental diffuser exit plane static pressure P_{M2} to the theoretical value $(P_{M2})_{\text{THEORETICAL}}$,

$$\mu \equiv P_{M2}/(P_{M2})_{\text{THEORETICAL}}$$

Values of the recovery factor for two primary/secondary stream Mach number combinations, namely, $M_{PI}=2.50/M_{SI}=2.50$ and $M_{PI}=2.50/M_{SI}=2.00$, are presented graphically in Fig. 1 for the diffuser L/D range investigated. Each Mach number combination was examined at three different Reynolds numbers, indicated in Fig. 1 by three sets of data varying in ambient-to-primary stagnation pressure ratio. The relatively low values of μ for $L/D=5$ demonstrate the incomplete diffusion due to the short diffuser length. The experiments with $L/D=10$ demonstrate the need for a longer diffuser for the cases where $M_{SI}=1.75$ and 1.50, as evidenced by relatively low values of μ (see Table 1). As the diffuser length becomes relatively long, namely $L/D>17.5$, the flow exhibits frictional static pressure losses.

The static pressure recovery characteristics of the constant-area diffuser were compared based on the diffuser length needed for maximum recompression. The static pressure in the diffuser is initially relatively low near the confluence point, reaches a maximum level as the flow progresses axially downstream through the shock system, and thereafter decreases in magnitude due to friction. The "optimum" diffuser length is the length which allows for maximum recompression without extending into the frictional loss range.

Table 1 Static pressure recovery factor values for $L/D=10$

M_{PI}	M_{SI}	μ
2.50	2.50	0.869
2.50	2.00	0.923
2.50	1.75	0.808
2.50	1.50	0.778

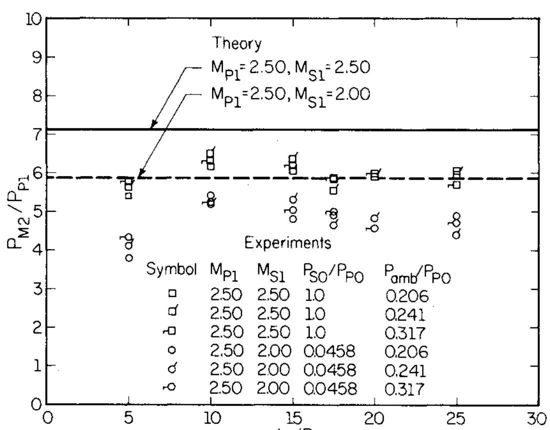

Fig. 2 Experimental and theoretical diffuser exit plane pressure ratios for the entire investigated L/D range.

The diffuser exit-to-entrance static pressure ratios are shown in Fig. 2 for the $M_{PI}=2.50/M_{SI}=2.50$ and the $M_{PI}=2.50/M_{SI}=2.00$ Mach number combinations and the $5 \leq L/D \leq 25$ range. The recompression level predicted by the theoretical analysis is also included in Fig. 2. Utilizing Fig. 2, the approximate optimum diffuser length is seen to be within the range $10<L/D<15$. The results are comparable to the length found for single-stream diffusion ($8<L/D<12$), but the two-stream data indicate longer "optimum" diffuser lengths as the secondary Mach number decreases. The incomplete diffusion process for the case where $L/D=5$ was again demonstrated by values of P_{M2}/P_{PI} which fall approximately 23% below theoretical predictions. For diffuser lengths greater than 17.5, the mixed stream was sufficiently diffused to subsonic velocities and the additional diffuser length resulted only in static pressure losses due to friction.

Since the static pressures were matched at the diffuser entrance plane, the entrance Reynolds numbers were functions only of the stagnation pressure for a given diffuser geometry. The effects of small changes in the entrance Reynolds numbers on the diffusion process were studied by conducting similar-geometry experiments where the stagnation pressure levels were different. The results showed that the changes in the stagnation pressure level (Reynolds number) influenced the diffuser exit plane pressure ratio by less than 4%.

Conclusions

The analysis of the diffusion of two supersonic streams within a constant-area diffuser showed significant differences in performance parameters when compared with the diffusion of a single supersonic stream. The data for two-stream supersonic diffusion yielded generally higher recompression (78-91% recovery) than the single-stream diffusion case of Merkli[6,7] which found only 58-77% recovery. The "optimum" diffuser length was shortest for the equivalent single-stream case ($M_{PI}=2.50/M_{SI}=2.50$), and lengthened with decreasing secondary Mach number. The recovery zone lengths for the two cases extensively examined were in a range of 9-15 mixing tube diameters for maximum recompression. The quasi-one-dimensional analysis of the diffusion process predicts the static pressure recovery for a diffuser of optimum length fairly well since the maximum experimental compression ratios were only 8.6-11.4% less than the theoretical predictions for these cases.

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