Design of a Supersonic Diffuser and its Effect on Shock Vector Control

The addition of a diffuser on the University of New South Wales (UNSW) - Canberra Nozzle Test Rig should allow higher mach numbers to be reached. This capability is able to provide additional capacity for experiments conducted at UNSW - Canberra as a low-cost alternative to other testing facilities around the country. This paper will explore the restrictions imposed on the diffuser by the test rig and study its effect on Shock Vector Control. It was found that a higher Mach number flow was able to be achieved with the addition of a diffuser and that a shock was able to be induced. It was found that, even with shock impingement internally to the flow, an increase in the injection pressure ratio resulted in a decrease in axial thrust and an increase in side thrust.

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Nomenclature

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<tr>
<th>Symbol</th>
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<tr>
<td>$A_e$</td>
<td>Exit Area</td>
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<tr>
<td>$A_{t,1}$</td>
<td>Nozzle Throat Area</td>
</tr>
<tr>
<td>$A_{t,2}$</td>
<td>Diffuser Throat Area</td>
</tr>
<tr>
<td>$r_{t,1}$</td>
<td>Nozzle Throat Radius</td>
</tr>
<tr>
<td>$r_{t,2}$</td>
<td>Nozzle Throat Radius</td>
</tr>
<tr>
<td>$a$</td>
<td>Speed of Sound</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$*$</td>
<td>Throat Condition</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Total Pressure</td>
</tr>
<tr>
<td>$\hat{R}$</td>
<td>Specific Gas Constant</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
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<tr>
<td>$M$</td>
<td>Mach Number ($\frac{V}{a}$)</td>
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Injection Pressure Ratio

$$\frac{\text{Injection Pressure}}{\text{Injection Pressure} + \text{Main Pressure}}$$
I. Introduction

The last few decades have seen an increase in interest for fluidic thrust vectoring, specifically shock vector control, as an alternative to mechanical thrust vectoring or standard flight controls due to the technological advancements in the field of Supersonic Combustion Ramjet (Scramjet) and other hypersonic flight vehicles. The advantages that replacing standard flight controls or mechanical thrust vectoring with a mechanism that injects fluid into the exhaust stream are numerous, such as; an increase in manoeuvrability and a reduction in overall aircraft weight. There is still a large amount of research that needs to be undertaken to investigate the viability and implementation of fluidic thrust vectoring. Most testing takes place in wind tunnels designed to sustain a high-speed flow however some experiments are able to be undertaken on a smaller scale utilising an experimental rig that is fed from numerous pressure vessels and exits into atmospheric pressure. Previous experiments of this kind conducted at UNSW - Canberra have achieved a flow speed of Mach 2. The ability to perform small scale testing on this flow is easier and cheaper to conduct than conventional wind tunnels however the maximum flow speed limits the scope of testing that can be undertaken. With the addition of a supersonic diffuser and suitably designed nozzle, the experiment apparatus should be able to reach higher flow speeds in the vicinity of Mach 3.5-4 without any additional resources.

Aim

This project aims to design a suitable diffuser and nozzle in order to determine if the experiment apparatus can produce and sustain, for a sufficient duration, a flow of approximately Mach 3.5-4. It will consider the limitations imposed by the experiment set up and determine what effect the addition of a diffuser has on shock vector control for future testing.

Review of Current Approaches

Diffusers

What are nozzles and diffusers?

The purpose of nozzles and diffusers are to either slow down or speed up the fluid through either a converging or diverging shape respectively. The relationship between change in velocity and change in area is defined as:

\[
\frac{dV}{V} = \frac{1}{M^2 - 1} \left( \frac{dA}{A} \right)
\]

(1)

As can be seen in the equation, when the fluid goes above Mach 1 the relationship reverses and you need an expanding nozzle to increase the mach number of the flow. While the nozzle contour is a major requirement, the pressure ratio from before and after the nozzle is just as important. In order to fully frame the limitations that will need to be overcome in the design of the nozzle, supersonic nozzles and diffusers will be discussed.

Supersonic Nozzles

When designing the nozzle there are multiple approaches to developing the contour, all of which have their advantages and disadvantages. The simplest nozzle configuration is the conical nozzle which uses a constant angle to increase the nozzle area until the required Ae is attained for the design Mach Number. The constant angle influences the overall efficiency of the nozzle. If the angle is small then the overall length required for the nozzle to reach its design Ae will result in a heavier vehicle mass but a higher specific impulse and efficiency. If the angle is too large then performance is affected. This trend of trying to attain an optimum level of performance for the nozzle weight is a factor that has influenced the development of nozzles.

There are a number of options for the design of a supersonic nozzle such as a bell-shaped nozzle or arc-based approximations however the most efficient thrust nozzle contour can be obtained by the determination of isentropic wall contours using the Method of Characteristics. This allows complete expansion of the exhaust gases to the ambient pressure and give a parallel uniform jet at the exit while avoiding shocks within the flow. The method of characteristics allows the design of a contour for a supersonic nozzle which is shock free and isentropic. A disadvantage of an isentropic expansion is that the length of the nozzle becomes
impractical for actual aircraft nonetheless they can become more practical through truncation and accepting a loss in performance. In the design of a supersonic wind tunnel, weight is not as much of a constraint, with the focus of wind tunnel contours to produce flow that is shockless and uniform throughout the test section.

**Supersonic Diffusers**

Diffusers are often used in the design of a wind tunnel for several reasons; primarily to increase the operating efficiency of the wind tunnel by reducing the pressure required to drive the system and by slowing down the flow with as small a loss of total pressure as possible. An ideal diffuser, similar to an ideal intake, would be able to compress the flow through an isentropic process to sonic velocity at the diffuser throat before slowing the flow to a subsonic speed. This however is incredibly hard to achieve due to the possible flow instability, the presence of the boundary layer and oblique shocks within the compression stage. In an attempt to achieve an efficient compression Busemann proposed an axisymmetric inlet that was capable of compressing the main flow without oblique shockwaves before passing through a conical shock and remain either supersonic or transition into subsonic flow.

Moelder and Szpiro conducted an analysis on Busemann Inlets and produced Figure 1.

This figure highlights several critical points, firstly the line of self-start vs no self-start and the required area ratio. The area ratio and self-start limit are inherently linked in the operation of the wind tunnel. In order for the supersonic flow to start there is a transition along the wind tunnel flow field from subsonic to supersonic which can be identified by the passage of a normal shockwave. In order for a wind tunnel to self-start the diffuser throat must be large enough to accommodate the mass flow when there is a normal shock.

The minimum area of the diffuser throat can be calculated by using the continuity equation and adiabatic relations as outlined by Liepman.

$$\rho_2 a_2^2 A_2^2 = \rho_1 a_1^2 A_1^2$$  \hspace{1cm} (2)

Using adiabatic relations and the equation of state this equation becomes:

$$\frac{A_{t,2}}{A_{t,1}} = \frac{p_{o,1}}{p_{o,2}}$$  \hspace{1cm} (3)

Applying the Normal Shock Properties, for $M = 4$, given in Annex B of Fundamentals of Aerodynamics:

$$\frac{A_{t,2}}{A_{t,1}} = \frac{1}{0.1388}$$  \hspace{1cm} (4)

This gives us the minimum required area ratio between the nozzle throat and diffuser throat in order to swallow the normal shock and start the supersonic flow.

In conventional wind tunnels the diffuser would have variable geometry, this allows conventional wind tunnels to attain a more efficient diffuser as they can initiate the flow with a throat width capable of swallowing the normal shock before adjusting the throat width to smaller width. Most diffusers also seek to utilise oblique shocks as an efficient form of compression. The total pressure loss from a number of oblique shocks before a weak normal shock is less than when compared to that of a single strong normal shock. While having numerous oblique shocks in a diffuser would prove to be beneficial, the number of shocks is constrained by both the incoming flow speed and the amount of space that is available to achieve oblique shock wave compression especially at high speed flows. With the introduction of oblique shocks within the diffuser section, shock-wave boundary layer interactions (SWBLI) will need to be considered.
Shock-Wave Boundary Layer Interaction

When designing the initial geometry of both a diffuser and nozzle, the effects of viscosity effects on the flow are typically simplified to only be present within the boundary layer\textsuperscript{12} due to the low viscosity of supersonic flows. In the design of real diffusers and nozzles the effects of this boundary layer will need to be considered due to the interactions that occur between the subsonic boundary layer and shockwaves. With the presence of subsonic flow in the boundary layer in the wind tunnel/nozzle, SWBLI can trigger large scale separation due to the shock induced adverse pressure gradient, which may result in significant total pressure loss and flow distortion.\textsuperscript{1} While SWBLI offer more problems to supersonic intakes as opposed to diffusers in terms of the importance of maintaining a clean flow downstream, the occurrences may have an impact on the forces and data gathered downstream of the diffuser. The effect of having a strong oblique shock would increase the chances of separation and a balance between slowing the flow and maintaining an attached flow needs to be considered during the design of the diffuser.

Shock Vector Control

Shock Vector Control involves the injection of a secondary flow at a point along the nozzle wall in order to alter the pressure distribution of the exit fluid and induce some a side force. Characteristics of the Shock Vector Control at the point of injection is regions of separated flow before and after the point of injection which causes a separation shock to occur in front of the injected fluid. The point at which the shock occurs in front of the point of injection is a point of interest of many studies as well as the pressure distribution along the walls of the nozzle.

Most studies have used a nozzle/experimental set up where the shock is free to exit without impinging on the opposite nozzle wall. The effectiveness of Shock Vector Control depends not only on the strength of the side force but also the maintenance of the axial thrust. The shock impingement on the opposite side of the nozzle can cause a large drop in axial thrust and most studies tend to limit their studies to the point where the induced shockwave impinges at the end of the nozzle.

The majority of previous studies have analysed parameters such as: injection pressure ratio, location of injection, state of incoming boundary layer and type of injectant gas.\textsuperscript{2} While studies into Shock Vector Control have been areas of interest for several decades, early studies struggled to properly evaluate the effect or magnitude of three-dimensional flow field effects.\textsuperscript{13} With the introduction of analytical models these 3D effects have become more readily modelled however most published articles still analyse two-dimensional injection.\textsuperscript{2} As such the majority of this study will be limited to a two-dimensional analysis due to limitations imposed by both resource availability and experimental capability.

II. Methodology

Nozzle and Diffuser Design

In order to design the nozzle and diffuser for the project there are a number of limitations that need to be taken into account. These limitations are the pressure of the fluid available, the initial temperature of the fluid and the overall length of the nozzle/diffuser. The experiment will utilise a number of pressure vessels that are attached to a regulator in order to adjust the primary airflow pressure, limiting the pressure to below 40 Bar. The initial temperature of the fluid is kept constant at room temperature as there is no heat addition capabilities within the nozzle testing facility. The overall length of the nozzle/diffuser is limited due to the size of the testing piece to 200 mm. This does not take into account the presence of the optical glass acting as the wall for the two-dimensional nozzle that acts to negate any three-dimensional transverse effects and avoids premature exposure to atmospheric pressure. The length of the optical glass wall is limited to 120 mm. Two nozzle/diffuser designs will be produced; both will have the same characteristics (number of shocks and ramp angles) however the primary primary difference between the two will be the length. The first nozzle will attempt to extend the boundary walls by using alternate materials with the second nozzle being limited to the length of the optical glass.
Nozzle Design

Considering the purpose of the project is to design a diffuser in order for a flow speed of Mach 4 to be established in order to induce a shock through a secondary flow injection upstream, the Method of Characteristics was used to develop a nozzle contour in order to avoid unnecessary shocks from forming within the nozzle and diffuser. The disadvantage to a nozzle designed by the method of characteristics is its overall length which limits the length available in the diffuser to slow the flow down sufficiently enough which in turn causes an increase in the strength of the shocks required to slow the flow.

III. Experimental Set Up

Diffuser Design

Ideally the diffuser would be designed in order to produce subsonic flow after the flow has completed its passage through the diffuser section however size restrictions imposed limit our ability to do so and as such the diffuser may have to produce supersonic flow that will still allow a sufficient amount of pressure recovery to be undertaken and allow the Mach 4 flow to be maintained in the nozzle/test section.

These size restrictions not only include the overall length restriction discussed previously but also size restrictions for the diffuser throat. In order to keep the simplistic nature of the experimental rig maintained, the nozzle/diffuser must have the ability to be self starting and remain at a fixed geometry for the duration of testing. The self starting condition of the nozzle/diffuser limits the area ratio to be that indicated in Equation 4. The number of ramps to induce oblique shocks and slow the flow down should be maximised in the space available for the diffuser. Due to the symmetrical nature of the design, all shocks produced internally should avoid impinging the opposite wall contour and the the shocks produced by the opposing ramps.

At high speed flows this leads to increased difficulties as minimal ramp angles lead to a large shock angle. Therefore a balance needs to be found between the strength and position of the shocks in order to slow the flow down through a series of shocks. Considering these limitations, it was chosen to proceed with a design consisting of two oblique shock waves. Using the the geometry available for the diffuser and the positions required for the shocks the ramp angles were calculated to be 3.65 degrees and 35 degrees.

End Product

The final design of the nozzle and diffuser can be seen in Figure 2. It should be noted that the design shown is that of the non-injection test piece, with the opposite contour being symmetrical with exception of the injection port.
IV. Numerical Set Up

An numerical analysis was performed on the nozzle and diffuser using ANSYS Fluent. The flow was modelled under two-dimensional transient conditions with the turbulence approximated using the Spalart-Allmaras Equation. This turbulence modeller was selected due to the Spalart-Allmaras model being designed specifically for aerospace applications involving wall-bounded flows, its ability to predict shock-induced separation and its relatively cheap computational requirements as it is only uses one equation as opposed to other turbulence models available in ANSYS Fluent.

V. Experimental Set Up

While the main focus of this study is to analyse the effects of adding a diffuser onto a nozzle undergoing Shock Vector Control using Computational Fluid Dynamics (CFD), in the form of ANSYS FLUENT, a validation/testing of the nozzle will be performed using the Nozzle Test Chamber at UNSW Canberra.

The Nozzle Test Chamber consists of a number of pressure vessels that are able to supply both a main nozzle flow and a secondary injection flow. Measurements on the pressure, axial force and side force produced from the nozzle will be recorded for a variety of primary and secondary injection pressures. The density gradients will also be captured utilising the Schlieren method. As the nozzle contour developed for a Mach 4 flow is longer than the nozzle utilised to establish a Mach 2.4 flow, Schlieren captures are limited to the initial expansion of the flow and the site of secondary injection due to the current set-up of the nozzle test rig.

The set-up of nozzle test rig can be seen in Figure 3. For the conduct of the testing, a main injection pressure of 30 bar and Injection Pressures of 4, 6, 8 and 14 bar were used.

VI. Results

Numerical Results

The numerical results produced are depicted in Figures 4 and 5.
Experimental Results

As stated previously a range of injection pressures for the nozzle were conducted. The data gathered was used to determine the Axial and Side Force produced by the fluid injection in the nozzle. These results are summarised in Figures 6 and 7. These show the average forces for the respective injection pressures tested throughout the conduct of the experiment.

The current set-up of the existing Schlieren system is limited in its ability to traverse vertically in order to fully capture the injection site and diffuser. This is due to higher speed flows requiring a longer nozzle to expand the flow with minimal losses when compared to previous nozzles. Improvements will need to be made in the future in order to allow qualitative analysis to be performed.
VII. Discussion

Trends

The purpose of shock vector control is to alter the thrust components in the x and y direction through injection into the main stream flow. The addition of the diffuser walls causes shock impingement to occur from the induced injection shock with the opposing wall. This may alter the strength of the side force when compared to shock vector control that occurs in standard testing where, typically, the shock is allowed to exit the nozzle without impinging on the opposite contour. Figures 4, 5, 6 and 7 all depict the changes in thrust relative to the x (axial) direction and y (side) direction. A line has been generated in each data set so that the overall trend can be observed. All of the results behaved as expected; an increase in the injection pressure ratio results in a decrease in axial thrust that is inversely proportional to the side thrust that is generated.

While the experimental pressure ratios that were tested were limited in scope, the results suggest that there is a range of pressure ratios that result in a larger change in side thrust relative to a change in injection pressure ratio. These value range between an injection pressure ratio of 0.15 and 0.4. This suggests that there will be a point at which, that an increase in injection pressure ratio will approach a limit and cease to be beneficial in terms of shock vector control. The amount of axial thrust produced relative to the side force also needs to be taken into consideration.

Due to the limitations of the UNSW - Canberra Nozzle Test Rig and lack of resources, the trends and results gathered from the experiment are unable to be compared with similar flow properties of shock vector control applied to a nozzle that exits straight out onto the atmosphere. As such the effects of Shock Impingement internally to the diffuser are unable to be quantified.

Comparison of Numerical vs Experimental

When the numerical results are compared to the experimental results, it can be observed that while the overall trends are maintained there is a difference in magnitude for both the axial and side forces for the injection pressure ratios. This difference in magnitude can be attributed to a number of factors. The numerical results are all conducted in a two-dimensional analysis with the results produced extrapolated to a three-dimensional approximation of the thrust produced. The additional affects a three-dimensional analysis that weren’t incorporated into the analysis may cause some of the discrepancies between the two sets of data to be minimised.

Another factor that affects the losses present in the experiment was the lack of sealant between nozzle test pieces and the optical glass. This exposed the nozzle test piece to atmospheric pressure and cross-wise flow.
that could have potentially altered the amount of thrust that was produced.

**Degree of Uncertainty**

The uncertainty present in the experimental results was calculated and incorporated into Figures 6 and 7. As can be seen the amount of uncertainty present relatively large. The largest uncertainty were a result of the precision of the axial and side force readings gathered. There was a significant amount of oscillations present in the electrical signals sent back to the data gathering device which resulted in the uncertainty depicted by the uncertainty bars in Figures 6 and 7.

**VIII. Conclusion**

The considerations and limitations encountered behind developing a diffuser for the Nozzle Test Rig at UNSW - Canberra have been explored and a suitable nozzle and diffuser have been produced that achieve a higher flow speed when compared to previous nozzle designs. It has been shown both numerically and experimentally that an increase in the injection pressure ratio results in a decrease in axial thrust and an increase in side thrust. The full of effects of having a diffuser attached to the nozzle have not been quantified.

**IX. Recommendations**

There are a number of recommendations that would allow for further testing and improvements to the current approach to the Nozzle Test Room at UNSW - Canberra.

1. The current Schlieren system needs to be improved in order to allow image captures to be performed at the injection site and at the diffuser.

2. Adapt existing test apparatus to allow for longer test pieces, this will allow for more space to slow the flow down more effectively.

3. Allow for the implementation of variable geometry to solve the potential issues that arise from the requirement to self-start. This will allow for increased pressure recovery and a more stable flow.

4. The extent to which shock impingement in the diffuser affects the axial and side thrust when compared to standard testing needs to be explored. This will require additional resources than those currently available within the UNSW - Canberra Nozzle Test Room.
References


6. Fluent Inc. 12.3.1 spalart-allmaras model overview, 09 2006.


