The fluidic thrust vectoring experimental apparatus at the Australian Defence Force Academy was improved in order for meaningful research to be conducted in the future. This was accomplished by the design of a parametric nozzle and by the installation of new instruments. The new nozzle design allows variation in nozzle geometry and avoids errors in force measurement typical of the old nozzle, by positioning the secondary flow hose axial to the primary flow instead of transverse. The instruments installed were mass flow meters on the primary and secondary lines and a fast acting solenoid valve on the secondary line. The mass flow meters were required to measure flow directly in order to avoid error associated with using the assumption of isentropic flow. The fast acting solenoid valve was installed for transient response experiments where rapid and repeatable flow switching is required. Preliminary experiments were conducted incorporating the new instrumentation. The first experiment compared mass flow in the primary line measured by the mass flow meter, to mass flow calculated using the isentropic assumption. It was found that real mass flow is approximately 65% of isentropic. The second experiment tested the response time of the primary flow to injection of secondary flow. Response times of 20 ms to starting injection and 125 ms to stopping injection were recorded.

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Final Thesis Report 2008, UNSW@ADFA
The emergence of thrust vectoring has enabled significant improvements in combat aircraft performance. It has improved dog-fighting capability by allowing a condition known as super-maneuverability, where the conventional flight envelope is extended into the post-stall region. Aircraft range has been extended by vectoring to alleviate trim drag caused by elevator deflection (Mason 2002). Take-off distance has been reduced by vectoring thrust downwards on rotation. Thrust vectoring can also be used to reduce the radar cross-section (RCS) of very low-observable aircraft by removing the need for conventional aerodynamic control surfaces (Gal-Or 1989). These factors combine to give thrust-vectored aircraft a significant tactical advantage.

In the past, all jet aircraft to apply thrust vectoring have used mechanical thrust vectoring techniques. This is done by mechanically deflecting the engine nozzle to direct the flow. Whilst effective, a mechanical thrust vectoring system is heavy and complex. Indeed, the thrust vectoring nozzle on the F-22A Raptor accounts for approximately 30% of the total engine weight (Chalmers 1999). To avoid these problems, fluidic thrust vectoring (FTV) methods have been proposed. FTV is achieved by injecting air from the nozzle side wall, into the primary flow to create asymmetric flow. It has the advantage of reduced weight, reduced cost and improved reliability. FTV can also improve stealth characteristics when compared to MTV by completely removing the need for external moving surfaces (Gamble 2004).

A. Methods of Fluidic Thrust Vectoring

The methods of FTV that have been researched include shock vector control (SVC), throat shifting (TS), co-flow and counter flow. This thesis will primarily focus on the SVC method, with the option to modify the experimental apparatus to incorporate TS at a later date.

1. Shock vector control

The SVC method shown in Fig. 1 creates an asymmetric vectoring force by injecting a secondary flow at the wall of the diverging section of a converging-diverging (CD) nozzle. Flow is supersonic in the divergent section under the conditions a CD nozzle is designed to operate. The injected flow behaves like a compression ramp in the primary flow, creating an oblique shock-wave. As the flow passes through this shockwave it turns away from the injection port, creating a vectoring force. The greatest thrust vectoring force is obtained when the oblique shock just impinges on the nozzle exit. At a greater shock angle the shock reflects off the opposite wall and turns the flow back towards the centreline. At lower shock angles the flow is turned through less angle (Deere 2003).

2. Throat shifting

In the throat shifting method secondary flow is injected at or just prior to the throat. This has a distinct advantage in efficiency over SVC because it is effectively isentropic due to the absence of shock waves. Research on TS at NASA Langley Research Center (LaRC) suggests that TS is the most promising form of FTV (Deere 2003).
3. Co-flow and counterflow

The co-flow and counter-flow methods use secondary flow injected or removed respectively, parallel to the nozzle wall. This entrains the primary flow to the wall which is designed with a curved surface that flares away from the nozzle axis at the exit. Air stays attached to the curved exit due to the Coanda effect, creating a vectoring force. The Coanda effect can be seen by blowing over the top of a piece of paper. The paper will rise due to a reduced static pressure on the top because of the higher velocity. Previous research conducted at NASA LaRC has shown that co-flow and counter-flow methods are unreliable because of sudden and unpredictable separation from the walls (Deere 2003).

B. Background – NASA Langley Research Center

FTV has been investigated at a number of institutions, but the most extensive research has been done at the NASA Langley Research Center (LaRC). For this reason the research at LaRC will be used to summarise the topic.

Research into FTV at LaRC began in 1987 with the SVC method on a 2D CD nozzle similar to the one used at ADFA. This experiment concluded that SVC has the potential to produce large thrust vectoring efficiencies up to $\eta_s = 4.4\%$-injection but at low thrust ratio of $C_{fg,sys} = 0.89-0.93$ (Wing 1994).

In order to be practically applied to low-observable aircraft with no aerodynamic control surfaces, as ultimately envisaged, FTV must be effective in pitch, yaw and roll. This requires multi-axis thrust-vectoring (MATV) with two engine differential vectoring for roll. LaRC began to research this in 1992 with a MATV experiment combining the SVC method in pitch with the co-flow method in yaw. The experiment concluded that co-flow was not a practical method of thrust vectoring because the flow separated from the Coanda surface at a Nozzle Pressure Ratio (NPR) greater than 4 (Deere 2003).

The throat shifting concept was investigated by the LaRC in 1995. The experiment showed TS to be very promising with thrust vector efficiency $\eta = 1.8\%$-injection and thrust ratio $C_{fg,sys} = 0.95$ (Deere 2003). An innovative TS method developed at LaRC utilises separation in a recessed cavity. The recessed cavity nozzle concept manipulates flow separation in the recess by injecting air at the throat. Through this method researchers at LaRC were able to achieve large thrust vector angles at high thrust vector efficiency $\eta_s = 2.15\%$ and high thrust ratio $C_{fg,sys} = 0.96$ (Deere 2003).

Through the investigation done into SVC, TS and co-flow methods of FTV at LaRC, researchers have concluded that TS shows the most potential for application on aircraft. It was found that TS produced the best thrust efficiency but with slightly lower thrust vector angles than SVC. The SVC method was effective but it had poor thrust efficiency because of energy loss through the shock. TS has better efficiency because flow is diverted when it is subsonic. Vector angles achieved through TS are improving with new approaches such as the recessed cavity nozzle.

C. Fluidic Thrust Vectoring at the University of New South Wales - Australian Defence Force Academy

Following on from the research done at the NASA LaRC, the School of Aeronautical, Civil and Mechanical Engineering (SACME) at the University of New South Wales at the Australian Defence Force Academy (UNSW@ADFA) began research into FTV in 2005. A SVC experimental rig was constructed for an undergraduate thesis project (Chia 2005). A computational fluidic dynamics (CFD) investigation into supersonic nozzle flow was also conducted in parallel (Chittleborough 2005). The SVC method was chosen for the ease of visualisation using a schlieren optical system. Four 15 MPa compressed air gas bottles provided the primary flow to the nozzle and a fifth air bottle was used to supply the secondary flow as shown in Fig. 2. The nozzle was a 2D convergent-divergent type with throat area of 20mm² and a nozzle area ratio of 3.6. The secondary flow was injected through a slot in the wall of the divergent section. The thesis by Chia (2005) successfully recorded schlieren images of the nozzle with an oblique shock at various angles dependant on NPR and secondary injection pressure. Thrust vector angles were calculated from the schlieren photos using a MATLAB code developed for the purpose and mass flow was calculated using isentropic flow equation. It was found that the best thrust vectoring angles were achieved when the oblique shock just impinged on the nozzle outlet. Beyond this point the shock reflected off the nozzle wall and turned the flow back towards its original direction (Chia 2005).
Load cells were added to the rig in 2007 to measure forces directly, precluding the need for the MATLAB code for force calculation (Fig. 3) (Neely 2007). Another series of experiments were conducted with the new apparatus and the results were presented in the paper ‘Performance Studies of Shock Vector Control Fluidic Thrust Vectoring’ by Neely, Gesto and Young (2007). A maximum thrust vector angle of $\delta = 5^\circ$ was achieved which was significantly less than the thrust vector angles reported in other SVC investigations of up to $\delta = 15^\circ$. Numerical simulations agreed with the maximum degree of thrust vectoring achieved in experiments but over-predicted the mass flow ratio required to achieve optimum thrust vectoring. It was concluded that the thrust vectoring force achieved was not sufficient to justify the use of FTV when compared to the same secondary flow being used for manoeuvring thrusters. The recommendation was made that better performance could be achieved through the use of a nozzle with a lower expansion ratio (Neely 2007).
D. Rationale and Scope of Thesis

Previous research done using the ADFA FTV experimental apparatus has revealed a number of shortcomings in the design. In the paper by Neely, Gesto and Young (2007), two problems in particular were identified that this thesis aims to address.

The first problem was the installation of instruments to accurately measure mass flow and control secondary flow. In the past mass flow had been calculated for both the primary and secondary flows using isentropic flow equations. This was done by recording the total pressure in the lines before and after each experiment, when there was no flow. Mass flow was over-predicted using the assumption of isentropic flow because losses were not accounted for. This problem was overcome by installing a mass flow meter on the primary and secondary supply lines, allowing mass flow to be measured directly. Additionally, a fast acting solenoid valve was added to turn secondary flow on and off in a rapid and repeatable manner.

The second problem this thesis addressed was the construction of a parametric nozzle. There were a number of deficiencies with the previous nozzle:
1. The inability to vary nozzle geometric parameters such as throat area, area ratio and injection location.
2. Errors in force measurement caused by the secondary flow hose attachment on the side of the rig.
3. Separation at the throat caused by sharp throat geometry.
4. Poor optical clarity of the acrylic window.

The ability to vary nozzle geometric parameters is necessary to investigate the optimum geometry required to maximise thrust vectoring efficiency. It also resolved the problem with flow separation by allowing different throat geometries. The error in transverse force measurement can be fixed by locating the secondary flow hose attachment parallel to the primary hose.

Future research in FTV at ADFA will be advanced through a PhD scholarship offered by the Defence and Security Applications Research Centre (DSARC) and BAE Systems Australia. This scholarship was the result of contact this author made with members of BAE Systems Australia who specialise in thrust vectoring. This contact was made while I was doing work experience at the Defence Science and Technology Centre (DSTO) in Melbourne. I was researching Unmanned Combat Aerial Vehicles (UCAVs) for DSTO when I discovered development being conducted by BAE Systems Australia on the Taranis autonomous, low-observable UCAV. I knew that FTV had promising applications on low-observable vehicles according to the literature available on FTV. So I contacted BAE Systems in Melbourne regarding a report I was preparing for DSTO on BAE Systems UCAVs. During this discussion I mentioned the research on FTV being conducted at ADFA. This resulted in a visit to ADFA by 3 members of a team responsible for the development of the Nulka hovering rocket to discuss our FTV research. The Nulka hovering rocket is an Australian designed missile decoy that is launched off the back of ships. It uses mechanically actuated SVC to hover and remain upright. As a result of this meeting, DSARC has offered a 3 year scholarship of $21,000 per year in conjunction with the BAE Systems Australia who has offered an additional $7000 per year for 3 years for FTV research at ADFA.

The objective of this thesis is to make improvements to the FTV experimental apparatus operated by SACME at the UNSW@ADFA. The purpose is to allow meaningful experiments to be conducted in the future. There were two primary tasks involved in achieving this objective. First, instrumentation was added to allow direct measurement of mass flow and fast activation of the secondary flow. Second, a new nozzle block was designed to allow variation of the nozzle geometry, axial location of the secondary hose and replacement of the acrylic window with glass.
II. Fundamental Concepts

The SVC method of FTV relies on shock-waves to turn the flow. Shock-waves are a feature of compressible flow that only occurs when the flow is supersonic. Therefore, SVC requires a convergent-divergent nozzle to achieve a supersonic flow.

A. Isentropic Flow

Isentropic flow is a flow that is adiabatic and reversible. That means that no heat is added or taken away from the system and no energy is dissipated through an increase in entropy. In the context it is used in this report, it is taken to mean that there is no pressure loss through the pipe. However, flow through a shock wave cannot be analysed as isentropic.

B. Convergent-Divergent Nozzle Flow

Pressure ratio \( \frac{p_1}{p_2} \) is the ratio of pressures between two stations in a nozzle and can be found from Eq. (1).

\[
\frac{p_1}{p_2} = \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{\frac{\gamma - 1}{\gamma}}
\]

If density and temperature are known then \( p \) can be found using Eq. (2), where \( R \) is the gas constant (\( R_{\text{air}} = 287.05 \text{ Nm/kg·K} \)).

\[
p = \rho RT
\]

If pressure ratio is known then temperature (\( T \)) and density (\( \rho \)) ratios can be found from Eq. (3).

\[
\left( \frac{p_2}{p_1} \right)^{\frac{\gamma - 1}{\gamma}} = \frac{\rho_2}{\rho_1} = \frac{T_2}{T_1}
\]

For supersonic flow in a convergent-divergent nozzle, the flow will first become sonic at the throat. This condition is known as choking and it occurs at and above the critical pressure ratio \( \frac{p_0}{p^*} \). Critical pressure ratio can be found from Eq. 1 by letting \( M = 1 \), \( \gamma_{\text{air}} = 1.4 \) as shown in Eq. (4). Where, \( p_0 \) is the inlet static pressure and \( p^* \) is throat static pressure as shown in Fig. 4.

\[
\frac{p_0}{p^*} = \left(1 + \frac{1.4 - 1}{2} (1)^2 \right)^{\frac{1.4}{14-1}} = 1.893
\]

Figure 4. Nomenclature of a converging-diverging nozzle (Anderson 2007)

As the pressure ratio is increased beyond this critical pressure ratio, the Mach number at the throat stays at 1 because it cannot exceed this value in a convergent duct. However, velocity at the throat can change. It is dependent on temperature as can be seen in Eq. 6.
Pressure ratio can be used to find the Mach number at the exit, which can be used in Eq. (5) to find the area ratio \( \frac{A_e}{A^*} \) required for complete expansion.

\[
\left( \frac{A_e}{A^*} \right)^2 = \frac{1}{M^2} \left[ \frac{2}{\gamma + 1} \left( 1 + \frac{\gamma - 1}{2} M^2 \right) \right]^2
\]

(C. Supersonic Compressible Flow)

The mechanism for vectoring the flow in the SVC is an oblique shock. An oblique shock is produced when a supersonic flow experiences an obstruction such as a ramp, causing an instantaneous change in direction, pressure, density, temperature and velocity. The change is instantaneous because ‘information’ can only travel upstream at the speed of sound. To begin analysing supersonic flow, some fundamental values must be calculated such as the speed of sound Eq. (6) and the Mach number Eq. (7).

\[
a = \sqrt{\gamma RT}
\]

Where, \( R \) is the gas constant (\( R_{\text{air}} = 287.05 \text{ Nm/kg·K} \)), \( c_p \) and \( c_v \) are specific heat at constant pressure and temperature respectively.

\[
M = \frac{V}{a}
\]

The equations for an oblique shock are:

\[
\tan \theta = \frac{2}{\tan \beta} \frac{M_1^2 \sin^2 \beta - 1}{M_1^2 (\gamma + \cos(2\beta)) + 2}
\]

\[
\rho_2 = \frac{u_1}{\rho_1} = \frac{(\gamma + 1)M_1^2 \sin^2 \beta}{2 + (\gamma - 1)M_1^2 \sin^2 \beta}
\]

\[
\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma + 1} \left( M_1^2 \sin^2 \beta - 1 \right)
\]

Where, \( \theta \) is the ramp angle or flow deflection angle and \( \beta \) is the shock angle as shown in Fig. (5). Tables have been published to find these values at particular Mach numbers (Anderson 2007).

![Figure 5. Shock angle \( \beta \) for a ramp angle of \( \theta = 10^\circ \) at \( M = 1 \) (Anderson 2007)](image_url)

(D. Pipe Flow)

Flow through a pipe is non-isentropic. The loss due to friction and local flow factors is known as head loss and can be calculated from Eq. (11). A sample pipe flow calculation was conducted (Appendix E).

\[
\left( \frac{p_1}{\rho} + \alpha_1 \frac{V^2}{2} + gz_1 \right) - \left( \frac{p_2}{\rho} + \alpha_2 \frac{V^2}{2} + gz_2 \right) = f \frac{L V^2}{D} + \frac{f L e V^2}{D} + K \frac{V^2}{2}
\]

- \( p_1 \): pressure (Pa)
- \( \rho \): density (kg/m\(^3\))
- \( \alpha \): kinetic energy coefficient
- \( V \): average velocity (m/s)
- \( g \): acceleration due to gravity (m/s\(^2\))
- \( z \): height (m)
- \( f \): friction factor
- \( L \): length (m)
- \( D \): diameter (m)
- \( L_e \): equivalent length (m)
- \( K \): loss factor
III. Instrumentation

Instrumentation was used to measure the flow conditions, measure the forces generated by the nozzle, visualise flow features and to control the flow. New instrumentation was added to the FTV rig to rectify a number of problems that were encountered in the original experiments. Mass flow meters were added to remove error caused by the isentropic flow assumption and a fast acting solenoid valve was added so the secondary flow could be turned on in a rapid and repeatable way.

A. Mass Flow Meters

Mass flow meters were required to measure the primary and secondary mass flows directly. This was necessary in order to avoid the errors caused by calculating mass flow using the isentropic expansion assumption, as was done in past experiments.

The selection and installation of mass flow meters was a lengthy process. First, a mass flow meter had to be found that could handle the particular flow conditions in the experiment. Once ordered, the mass flow meters took approximately 6 weeks to arrive. In the meantime the fittings required to install the meters had to be determined and acquired. Finally, once all parts had arrived a new piping configuration was designed and built.

1. Isentropic mass flow calculation

An approximate mass flow calculation was done assuming isentropic flow, to determine the appropriate range of the meter. Mass flow in a pipe of cross sectional area \( A \) can be calculated if density \( \rho \) and velocity \( U \) are known (Eq. 12).

\[
\dot{m} = \rho U A
\] (12)

In this case, mass flow will be calculated at the throat because velocity here is known to equal to the speed of sound in the choked condition and area is known to be 20 mm\(^2\). To determine the conditions at the throat, the conditions upstream must be known. In order to find the maximum flow rate the maximum operating pressure of 3 MPa will be used. Initial temperature will be assumed to be 288 K.

\[
\rho_0 = \frac{p_0}{RT_0} = \frac{3 \times 10^6}{287.05 \times 288} = 36.3 \text{ kg/m}^3
\] (13)

For isentropic flow in a nozzle, density and temperature at the throat can be calculated using the following formulas (Anderson 2007).

\[
\rho^* = \rho_0 \left( \frac{2}{\gamma + 1} \right)^{\gamma/(\gamma - 1)} = 36.3 \left( \frac{2}{1 + 1.4} \right)^{0.4} = 23.0 \text{ kg/m}^3
\] (14)

\[
T^* = T_0 \left( 1 + \frac{\gamma - 1}{2} M^2 \right)^{-1} = 288 \left( 1 + \frac{1.4 - 1}{2} \right)^{-1} = 240 \text{ K}
\] (15)

The speed of sound changes with temperature and can be calculated using the following formula (Anderson 2007).

\[
U = a = \sqrt{1.4 \times 287.05 \times 240} = 310.6 \text{ m/s}
\] (16)

Thus, mass flow can be calculated by knowing the density, velocity, and area of the throat using Eq. (12).

\[
\dot{m}_{\text{max}} = 23.0(310.6)(20 \times 10^6)
\]

\[
\therefore \dot{m}_{\text{max}} = 0.143 \text{ kg/s}
\]
2. Meter selection

The meters selected were Vortec M22-VTP models as shown in Fig. (6). The primary flow was a 300 psi class unit and the secondary flow was a 150 psi class unit. Table 1 and Table 2 show the comparison of flow condition requirements of the FTV rig to the Vortec M22 operating limits. It can be seen that the meters satisfy most requirements but a number of compromises had to be made. First, the operating pressure of the primary line meter is limited to 20 Bar according to the literature. Ideally, the FTV rig operates at up to 30 Bar. Secondly, the minimum flow rate of the secondary meter is 0.0033 kg/s, but the required mass flow rate is 0.0017-0.015 kg/s (Neely 2007). This deficiency will be discussed in the Validation Experiments chapter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Vortec M22 operating limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum mass flow rate, kg/s</td>
<td>0.143</td>
<td>0.304</td>
</tr>
<tr>
<td>Minimum mass flow rate, kg/s</td>
<td>0.028</td>
<td>0.0057</td>
</tr>
<tr>
<td>Pressure, Bar</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Temperature, ºC</td>
<td>-5 to 25</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>Response time, s</td>
<td>&lt; 5</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 2. Secondary flow conditions required compared to 150 class Vortec M22 operating limits**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
<th>Vortec M22 operating limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum mass flow rate, kg/s</td>
<td>0.015 (MFR = 0.11)</td>
<td>0.107</td>
</tr>
<tr>
<td>Minimum mass flow rate, kg/s</td>
<td>0.0017 (MFR = 0.012)</td>
<td>0.0033</td>
</tr>
<tr>
<td>Pressure, Bar</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Temperature, ºC</td>
<td>-5 to 25</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>Response time, s</td>
<td>&lt; 5</td>
<td>1</td>
</tr>
</tbody>
</table>

The meter uses pressure, temperature and velocity to determine mass flow according to Eq. (12). The meter measures pressure with a pressure transducer, temperature with a thermocouple and velocity by utilising the principal of Von Karman vortex shedding. Vortices are shed from a bluff body at a particular frequency depending on the velocity of the flow. This frequency is sensed by a piezoelectric element to determine velocity.

The meter is powered by a DC power supply providing 12-36 V. The output is a current of 4-20 mA which is sent to a National Instruments SCC data logger which is connected to a computer running data acquisition software developed in house at SACME by Andrew Roberts.

The display can be scrolled by removing the cover and pressing the up and down buttons or by using the magnetic selector on the outside of the cover to activate these buttons. The display options include mass flow, volume flow, temperature, pressure and density.

The setup menu can be accessed by activating the enter button which brings up the password screen. Enter the password (set to 0) to access the setup menus. The menus are output, display, alarms, totalizer, fluid, units, time & date, diagnostics, calibration, and password. The settings should already be appropriate for thrust vectoring experiments.

3. Meter installation

The installation of the mass flow meters proved to be the most difficult step. In order to obtain reliable mass flow measurements a straight pipe run was required before and after the meter. This was to ensure the flow was steady through the instrument. The requirements were:

- The inside diameter (ID) of the pipe must be larger than the ID of the meter.
- For an expansion in the pipe there must be a straight pipe run of 20 diameters (D) before the meter and 5D after.

The ID of the meter was 15 mm. Ideally, pipe with the same ID as the meter would be used with a straight run before and after. This was not practical because pipe and tube sizing conventions are different as explained below. So ¼” tube with an ID of 16.65 mm was used. This required a straight run of 20D = 300 mm before the meter and 5D = 75 mm after.
The reason it was not practical to use 15 mm ID piping was that the meter was sized according to the Nominal Pipe Sizing (NPS) standard and the FTV rig was set up using ½’’ tube. To describe a pipe in the NPS system, a nominal size and a schedule are stated. The nominal size is neither the OD nor ID. For example, the ½’’ NPS schedule 40 pipes recommended for the meter have an ID of 15.8 mm which is greater than ½’’ (12.7 mm). This system is a remnant of an old system where NPS was intended to represent OD. Schedule gives an indication of wall thickness and was originally intended to represent pressure rating. Conversely, tube is described by a simple system where OD and wall thickness are stated.

The primary flow meter came with American National Standards Institute (ANSI) 300 class flanges and the secondary flow meter came with ANSI 150 class flanges. Both were sized according to ½’’ NPS schedule 40 pipe with 15.8 mm ID. The existing ½’’ tube on the FTV rig had an ID of 10.3 mm. The rig was already set up with Swagelok™ tube, so it was decided that ¾’’ tube with an ID of 16.65 mm was to be used before and after the meter to satisfy the requirement of greater diameter than the meter.

Swagelok™ does not stock ANSI flanges that adapt to ¾’’ tube in the same size as the meter. In order to get these flanges from Swagelok, they would have to be specially made in the factory in the US. This would involve a lead-time of 10-11 weeks, which would be outside the time-frame of the project.

A number of alternative solutions were investigated, such as welding straight sections of pipe to blank flanges. This would have been a suitable solution except that we would have been required to find a welder certified to weld pressure vessels. In the end it was decided that the best solution was to make the flanges in the school workshop with the centre hole tapped and mate them with Swagelok fittings that joined ¾’’ National Pipe Thread (NPT) (Fig. 7).

Figure 7. (a) Swagelok ¾’’ tube to ¾’’ NPT fitting (b) ANSI 150 class ¾’’ flange

B. Solenoid Valve

The installation of a fast acting solenoid valve was necessary in order to conduct transient response experiments. The time taken for the vectored flow to respond to the injection of the secondary flow is of interest for the design of control systems. This is a critical step in the development of thrust vectoring technology if it is to ever be applied in real aircraft.

The selection of a fast acting solenoid valve was primarily driven by two competing factors: response time and operating pressure limit. A reaction time in the order of 20 ms was desired and the valve had to operate at pressures up to 3 Bar. These factors were in conflict because generally, direct lift valves have faster response times but pilot operated valves are capable of operating at higher pressures.

The solenoid valve selected was an ASCO 262 series, 240V AC, normally closed, direct lift valve shown in Fig. 6. It has a response time of 5-25 ms and an operating pressure of up to 6 Bar. After purchasing the valve it was discovered that a 12V DC solenoid would have been more suitable for triggering with the data logger. The method of triggering the solenoid with a relay as envisaged is not practical because relays have an inherent delay due to their mechanical nature. A replacement solenoid head can be purchased from Ascomation without having to replace the solenoid body.

Figure 8. ASCO 262 series solenoid valve
C. Piping

The experimental apparatus had to be re-plumbed to accommodate the new mass flow meters and the solenoid valve. The primary consideration in the new design was to provide straight sections of ¼” tube for 300 mm before and 75 mm after the meters. It was decided that the mass flow meters would be mounted on brackets attached to the vertical members of the frame. In order to provide a sufficient straight run, the primary line was extended to the far left end of the frame and the secondary line was directed as far left as possible without obstructing the primary flow meter as shown in Fig. (9).

The tube had to be moved out from the frame because the flanges on the mass flow meters were too wide to fit into the line in its original location. This was achieved on the primary flow line by adding two 90º elbows at the bottom left of Fig. (9) and inserting spacers to move the Stauff™ pipe clamps and Swagelok tap away from the lower horizontal of the frame. Space was made for the flanges on the secondary flow line by moving the pipe above the lower horizontal bar. The tube was secured with a Stauff clamp welded to a flat piece of steel.

The new plumbing configuration has the added advantage of positioning the primary and secondary flow lines in such a way that minimal modification will be required to install the new parametric nozzle discussed in this report. A feature of the new nozzle is the secondary flow lines entering the nozzle axially, in order to avoid applying unwanted forces on the nozzle block. The secondary flow lines will be attached symmetrically, both sides of the primary line so that any moment is cancelled out. With the primary line between the two secondary lines and in the same plane as the frame mounted plumbing, the primary line must be directed out of plane. This is already achieved with the new plumbing design because the primary line has been moved out to allow room for the mass flow meter as shown in Fig. (10).

D. Load Cells

Early in the project the benefit of replacing the load cells to improve sensitivity was considered. The original configuration had 4 XTRAN load cells. In the axial direction there were two S-beam type load cells of 250 N and 350 N which shared the load equally. These load cells were co-linear and supported the nozzle with a fulcrum to allow it to move in the transverse direction. The two load cells in the transverse direction were shear-beam type of 35 N and 100 N respectively. The 35 N cell was in the vectoring direction so the 100 N cell effectively measured zero load.

It was decided that replacing the load cells would not be necessary because the current sensitivity was satisfactory and scope was needed to increase nozzle thrust in the future. Also, the nozzle rig had been designed to fit particular types of load cells and to gain significant improvement in sensitivity in the axial direction the S-beam type load cells would have to be replaced by shear-beam type. This was because the lowest load rating available in the S-beam type is 250 N. There was little margin for improvement in transverse sensitivity because the lowest load rating available is 25 N which is only 10 N lower than the original load cell. For these reasons it was decided not to change the load cells.

The 250 N load cell was lent to another thesis student who was testing model rocket motors. Unfortunately, one of the rockets exploded during a test which destroyed the load cell. So two new 250 N load cells were purchased for the FTV rig and the 350 N cell was used to continue the rocket testing. The new load cells took 6 weeks to arrive, which severely delayed the project schedule.
E. Data Logging

A National Instruments data logger was set up to record the 6 outputs from the mass flow meters, 4 outputs from the load cells and 1 output from a pressure transducer. The outputs from the load cells were in Volts so 2 SCC-SG24 cards were required to interface with the data logger. Whereas, the outputs from the mass flow meters were 4-20 mA so 3 SCC-C120 cards were purchased to convert the signal to Volts. The signals from the data logger were sent to a computer running data acquisition (DAQ) software developed ‘in house’ at SACME by Andrew Roberts.

Calibration was done by incrementally setting known output values for each instrument, then entering this value in the calibration window of the DAQ software for each channel. For the load cells, these known values were set by attaching weights to cables attached to the load cells. For the mass flow meters, these values were set in the Diagnostics menu of the meter.

Synchronising the data logger with the camera recording schlieren images was difficult. In previous experiments the data logger was triggered by the High Speed Redlake camera, which sent a pulse to the data logger. The Low Speed Redlake camera used this year did not have the function to output a pulse, so an alternative had to be found. In the end synchronisation was done by placing a small LED near the nozzle so it would be in the frame of the schlieren images. The DAQ software was programmed to send an output pulse to light-up the LED when data logging was initialised. By finding which frame the LED first turned on, it could be determined which schlieren frame the data logging started. It is recommended that when the High Speed Redlake camera is repaired it would be best to reverted to the original method of synchronisation.

F. Schlieren Flow Visualisation

Schlieren imaging is used to visualise the density changes in the nozzle flow. Schlieren works by recording changes in the refractive index (n) of a fluid due to changes in its density. For most gases the refractive index is the linear relationship shown in Eq. (17).

\[ n = k\rho + 1 \]  

(17)

Where, \( k \) is the Gladstone-Dale coefficient (\( k =0.23 \text{ cm}^2/\text{g} \) for air) and \( \rho \) is density.

Figure (11) shows the configuration of the schlieren optical system used. Light is projected from the source through a convex lens so the light is travelling parallel. As it passes through the test area the light is bent by changes in the refractive index of the fluid due to variations in density. This refracted light is then focused by another convex lens to a knife edge at the focal point. If the light is not refracted, approximately half of it will hit the knife edge. The amount of light that is blocked by the knife edge depends on the degree and direction or refraction. The light is then focused by a third lens onto a camera. So areas of different density show up as dark or light areas on the display (Settles 2001).

![Figure 11. Components of a schlieren flow visualisation system](image)

1. Schlieren set-up

The schlieren optics used in this experiment are mounted on two optical rails. These rails are supported by four heavy optical stands that were built in the ADFA workshop. Ideally, the light should be a point source. In order to achieve this, a screen with a small hole in it is positioned in front of the light. A diffuser is placed behind this screen to ensure that the light emerging is homogeneous. The first lens is positioned so that the point source is at the focal point. In this case, the lens used has a focal length of 500 mm. To test if the lens is positioned correctly, a sheet of paper can be moved back and forth between the lens and the test section. If the projected circle of light remains the same size then the light is travelling parallel. The second lens which refocuses the image is placed on the other side of the test section. Its position relative to the test section is not critical but its position relative to the knife edge is. The knife edge must be at the focal point of the second lens. This can be tested by moving the knife edge in and out of the light. If the knife edge is positioned correctly the image will darken evenly. If it is positioned incorrectly the image will darken from one side. The third lens is used to focus the image on the camera. The degree of magnification can be changed by moving this lens and the camera.

Final Thesis Report 2008, UNSW@ADFA
IV. Design of Parametric Nozzle

A. Nozzle Block Design

The design of a new nozzle block was required to address the problems encountered with the previous design. The nozzle design on which previous experiments were carried out was deficient in a number of aspects. Firstly, the nozzle geometry was fixed which prevented any modification required to optimise efficiency and thrust vectoring performance. Secondly, the position of the secondary flow supply hose on the side of the nozzle was causing unwanted transverse load, which was difficult to de-couple when analysing force measurements. Thirdly, the acrylic windows on the original nozzle had poor optical clarity and scratched easily. Consequently, the schlieren images taken had a number of flaws.

The new design shown in Fig. (12) has addressed the above problems in the following ways: A removable nozzle was designed to allow changeable geometry; a window retaining plate was added to accommodate the new glass window and the secondary flow hose attachment has been moved to the bottom. The nozzle block was made using a sandwich construction. The nozzle block walls clamped against the removable nozzle section and the manifold walls.

![Figure 12. Components of the parametric nozzle](image1)

2. Parametric nozzle

The problem of allowing change in nozzle geometry was addressed with the design of removable nozzle section. The nozzle is split into two halves which are inserted from the top of nozzle block as shown in Fig. (13). They are secured by a slot at the bottom and a cap screw at the top. The secondary flow is supplied from a manifold which seals against the back of the nozzle section. The secondary flow is injected through a series of 1 mm holes across the diameter of the nozzle. Research at NASA LaRC has shown that a series of small holes is a more efficient method of injection than the slot used in the previous nozzle design (Deere 2003). The manifold allows the injection position to be varied from just before the throat to approximately two thirds of the way along the diverging part of the nozzle. This will allow for throat shifting and fluidic throat area control experiments to be conducted in the future. The complete rig set-up can be seen in Fig. (2)

To change the nozzle, the bolts clamping the nozzle block walls together and the bolts attaching the nozzle block to the plenum are loosened. Then the cap screws holding the removable nozzle section in place are unscrewed 10 mm so they are only in the thread of the removable nozzle. At this point it should be possible to grab the cap screw and pull the nozzle out the top of the nozzle block. The new nozzle section is then inserted by utilising the cap screw in the same manner. Finally, all bolts are re-tightened.

![Figure 13. Front view showing removable nozzle](image2)
3. **Replacement of window**

The design of the nozzle block to accommodate a glass window was driven by a number of conflicting requirements. Only simple shapes can be ground out of glass so significant design must go into securing and sealing it. The shape of the window in this design is a cylinder with a diameter of 36 mm, a length of 22 mm and a chamfer of 3 mm on the outer edge.

The window is held in position with a retaining plate on the outside and by the nozzle on the inside. A size 124 o-ring is used between the retaining plate and the chamfer in the glass to seal and avoid metal to glass contact. On the inside, a cardboard gasket material of 0.03 mm thickness is placed between the glass and the nozzle for the same reason.

It is desirable to maximise viewing area, but this is restricted by the space available. The largest window diameter that could be achieved with this design was 36 mm. Any larger and the window would interfere with the inset of the nozzle block wall. The retainer plate must overlap the window so the viewing area is reduced by a further 8 mm. So the final viewing diameter is 28 mm which is sufficient to view the nozzle from the throat to beyond the exit.

4. **Secondary flow hose location**

The secondary flow supply hose was moved to the bottom of the nozzle as shown in Fig. 12 to avoid transverse forces generated by the pressurisation of the hose. A plenum was designed in which the secondary flow lines entered axially on both sides of the primary line. For thrust vectoring experiments only one secondary flow line is used. The other is blocked off to balance any moment caused by the hose. Having secondary flow available on both sides will allow fluidic throat area control experiments to be conducted. The method of directing the primary and secondary lines to connect to the piping is discussed in the previous chapter and is shown in Fig. (14).

5. **Sealing**

Sealing was critical part of the design that had to be overcome in the design process. The nozzle block experiences a maximum operating pressure of 34.7 Bar in the primary line with a 35 Bar pressure relief valve and isentropic flow. The secondary flow line has a typical maximum operating pressure of 7 Bar but it does not have a pressure relief valve. Therefore, it was designed to handle 10 Bar to allow a factor of safety.

The three primary methods of sealing high pressure air are o-rings, gaskets and machined labyrinths. Each method has advantages and limitations. O-rings protrude from a groove machined in one face and seal against the opposing face, so space is required for the o-ring groove. Gaskets rely on clamping force between the two faces to seal. Therefore, tension on the bolts has to be correct. Gasket material can also yield due to repeated clamping action. A labyrinth works by increasing the distance the air has to travel to escape, thus increasing the resistance. Labyrinths are usually used in conjunction with grease. The main drawback with labyrinths is the increased machining time due to the high tolerances required.

Initially, the nozzle block was designed with gaskets to seal the side walls and the removable nozzle section. This design was changed on the recommendation of Paul Walsh from SACME because the amount of compression of the gasket is dependent on the tension on the bolts. If one bolt is tighter, the nozzle sections can be misaligned. With such a small nozzle, a slight asymmetry can cause significant flow disturbance. The drawback of using gaskets on the side walls is that the repeated clamping and loosening when changing the removable nozzle could deform the gasket material and cause a leak. The only feasible way to seal the nozzle against the glass is with a gasket. To do this the gasket is glued to the nozzle section using 518 loctite, clamped and allowed to set before installation.

The next method of sealing investigated was o-rings. The design of the o-ring groove in the nozzle block wall posed a number of problems. Firstly, there was not enough space available for the groove path, particularly between the secondary flow duct and the window. Secondly, sealing was difficult where the o-ring passed a join, like at the removable nozzle. Thirdly, it was not possible to put an o-ring groove in the nozzle sections because the secondary injection holes intersected the groove. The secondary injection holes need to be close to the surface so air is injected evenly across the nozzle.

O-rings were used to seal the window as shown in Fig. (15). A 3 mm chamfer was put on the outer edge of the glass and the window retaining plate was designed to give a further 0.48 mm clearance. This gave the 3.48 mm clearance specified for a 2.62 mm o-ring in triangular housing. The o-ring chosen to fit this application was size number 124. A second o-ring was required to seal between the retaining plate and the wall.
O-rings were also used to seal the nozzle in the axial direction as shown in Fig. (15). O-ring cord of 1.5 mm diameter was placed in the corners of the removable nozzle section, spanning the entire diameter of the nozzle. It sealed against a corner radius of 3 mm which was required due to minimum tool size for machining. The 3 mm corner radius is approximately equivalent to a 2 mm chamfer for triangular o-ring housing.

The final method of sealing investigated was the use of a labyrinth. This was done by machining a step in the nozzle block wall to allow the manifold to be inset into the block wall. The main drawback of this method is that all inner diameter corners machined into the face must have a radius of at least 2 mm because of the tool size. This meant that a small discontinuity was unavoidable in the join between the removable nozzle section and wall of the primary flow chamber as seen in Fig. (15). This could potentially cause a disturbance in the flow that might be detectable at the throat. The impact of this disturbance was found to be negligible as the flow velocity prior to the nozzle is only approximately 20 m/s compared to approximately 350 m/s at the throat.

6. Design concepts
A number of conceptual designs were considered before the final design was chosen.

![Figure 15. Position of o-rings used to seal nozzle block](image)

![Figure 16. Progression of design concepts: (a) Concept 1, (b) Concept 2, (c) Concept 3, (d) Concept 4](image)

The first concept shown Fig. 16(a), utilised the one piece nozzle in the original design with additional surrounding structure. The intention behind this was to simplify sealing of the high pressure air between the nozzle walls and the immediate structure. The concept was to slide the block containing the nozzle in from the top and tighten bolts on every side to seal it.

This concept had a number of problems. The entire nozzle rig had to be dismantled every time the nozzle was changed, the manufacturing of each nozzle was complex and sealing between the nozzle block and the plenum was difficult. Due to these problems it was decided that this concept was not feasible.

The limitations in a one piece nozzle prompted concept 2 which featured a nozzle split in two separate halves. In the first iteration of this concept the nozzle halves would be inserted by removing one of the side walls of the rig and positioning the nozzle sections by sliding them onto two bars as shown in Fig. 16(b).

Concept 3 shown in Fig. 16(c) utilised the split nozzle feature but improved on it by securing the removable nozzle sections with a bolt through the top into underlying frame. This allowed the nozzle sections to be inserted and removed from the top without disassembling the entire nozzle block.

This concept was further improved on in concept 4 shown in Fig. 16(d) which added tabs to grab the nozzle for removal. The sides of the nozzle were angled to allow room for the hose attachments at the bottom while still fitting in the current rig at the top with only minor modification.

The final concept did away with the tabs because of limited space. The top of the nozzle block was also lopped off to prevent the shock wave from impinging on the structure after the nozzle exit and causing errors in force measurements.

Two designs of the final concept were sort listed with different sealing methods (Fig. 17). The first design used gaskets to seal the wall, the manifold and the nozzle section on both the axial and transverse faces. After discussion with workshop staff a second design was developed which used a combination of gaskets, o-rings and an inset labyrinth.
The final design chosen was design 2. It was chosen because it was determined to be the safer design with regard to sealing, despite being significantly harder to manufacture. This decision was arrived at after consultation with Michael Jones from the SACME workshop and Paul Walsh who is an expert on high pressure design. The detailed drawings of the final design were produced (appendix A).

B. Nozzle Geometry

The old nozzle geometry used for previous experiments was not optimised. The geometry was decided upon by selecting the maximum throat area then choosing the divergence angle so that the best axial component of thrust was achieved. The nozzle length was arbitrarily chosen to give good optical access for the schlieren so the divergent section ended up being long. The long nozzle at a divergence angle of 13º resulted in a area ratio of 3.6 which causes the flow to be overexpanded at supply pressures below 30 Bar (Neely 2007).

To select the optimum nozzle geometry, three primary steps must be completed. First, the throat area must be determined. Once this is known, the dimensions of the rectangular throat can be calculated if the aspect ratio is known. The aspect ratio is the width to height ratio of the throat and its value will depend on the two-dimensionality of the flow. Finally, the exit area can be calculated for the desired pressure at the exit of the nozzle.

1. Throat area

The throat area is selected to ensure choking occurs at the throat. To achieve this, the throat must be the smallest orifice in the system. The old nozzle had a throat area of 20 mm$^2$. It would be desirable to increase this to allow better optical access and reduce asymmetry caused by small disturbances.

The smallest restriction in the piping occurs at the regulator. At 10 Bar the regulator orifice diameter is approximately 3 mm and at 30 Bar it is approximately 5 mm (Chia 2005). With 4 bottles in parallel the orifice area varies from 28.3 mm$^2$ at 10 Bar to 78.5 mm$^2$ at 30 Bar.

A test was conducted with one bottle to see what pressure was required to attain supersonic flow. A new bottle could supply a maximum of 13 Bar with all valves open. This was sufficient to attain choking but not to maintain supersonic flow at the exit. One bottle has an orifice area of approximately 20 mm$^2$ at 30 Bar. This indicates that choking can still occur at the nozzle when the minimum restriction in the system is smaller than the throat. This is a phenomenon known as multiple choking and it is not properly understood in this test.

It was concluded from the above test that the throat area could be much larger and choking would still be achieved. The drawback of increasing throat area is that the air bottles will get expended quicker. Balancing these factors a new throat area of 30 mm$^2$ was selected. This is 50 % increase on the previous throat area.
2. Two-dimensionality

The experiment is designed so that the flow in the nozzle can be idealised as two-dimensional (2D). In order for this assumption to be valid the nozzle has to be sufficiently deep in the z-direction (Fig. 18). The value used to represent nozzle depth in the z-direction to width in the y-direction is called aspect ratio (AR). The throat of the previous nozzle was 8 mm x 2.5 mm so the AR can be calculated as shown in Eq. (18).

\[
AR = \frac{\text{depth}}{\text{width}} = \frac{8}{2.5} = 3.2
\]

(18)

To determine what aspect ratio is required to achieve two-dimensionality, a three-dimensional numerical simulation was conducted using the old nozzle geometry. The two-dimensionality observed with an AR = 3.2 will be used to inform the AR required for the new nozzle. A computational fluid dynamics (CFD) simulation was conducted by Dr. John Young using FLUENT CFD software and analysed by the author using TechPlot fluids analysis software. The computational domain shown in Fig. 16 includes the convergent nozzle section, divergent nozzle sections, the secondary flow plenum, injection slot and the downstream flow for a limited distance. The flow conditions were set at primary inlet pressure \( p_0 = 20 \) Bar and secondary inlet pressure \( p_0' = 1.4 \) Bar. These values were determined from the results of the simulation by taking a slice of the xy-axis at the centre of the z domain (\( z = 0.04 \)m). The inlet pressure (\( p_0 \)) was calculated by taking the average pressure of 50 points sampled along the slice at the inlet. This gave an average of 2012.485 kPa. The exit pressure (\( p_\text{ex} \)) was assumed to be the international standard atmospheric pressure at sea level of 94.5 kPa. This gave a nozzle pressure ratio (NPR) of 21.3.

\[
NPR = \frac{p_0}{p_\text{ex}} = \frac{2012.485}{94.5} = 21.3
\]

(19)

The 3D simulation conducted at a NPR = 21.3 was compared against the 2D simulation done previously at NPR = 20 and mass flow ratio (MFR) equal to 0.07 (Neely 2007). MFR is the ratio of mass flow of the secondary flow on the primary flow. The plot of Mach contours for the 2D simulation is shown in Fig. 19(a) and the Mach contours for the 3D simulation is shown in Fig. 19(b). It can be seen that the flow structures are similar except that the Mach numbers calculated in the 3D model are much higher. The maximum Mach number recorded in the 3D model was \( M = 59.5 \), which is completely unrealistic but the velocities are still accurate. So it was concluded that the reason for the unrealistic values of Mach number was an error in converting from temperature in Kelvin to degrees Celsius when the data was transferred from Fluent to TechPlot. Temperature was calculated at approximately 120 K which caused the speed of sound calculation to be wrong. This problem was not encountered when the properties were checked in Fluent, so it was concluded that the fault was in TechPlot. This conclusion is supported by realistic values of velocity magnitude in the region of 600 m/s in the domain.
In the 2D CFD investigation, plots were made of the axial (x) velocity (Fig. 20), normal (y) velocity (Fig. 21) and pressure (Fig. 22) across the exit plane as a measure of nozzle performance (Neely 2007). Equivalent plots have been created for the 3D model and compared against data extracted from the 2D model plots using data extraction software available for free off the internet called XYplot.

Figure 20. Plot of x-velocity across the exit plane.

Figure 21. Plot of y-velocity across the exit plane.
Momentum thrust was calculated by multiplying local density and local velocity squared at discrete points then integrating across the exit plane. This was done for the axial and normal directions to give momentum thrust and momentum vectoring force respectively. The pressure thrust was also calculated by integrating the product of pressure and area across the exit plane (Neely 2007).

It can be seen that the 2D model approximates the 3D model reasonably well except for in the case of normal momentum thrust. In this case the 2D curve is below the 3D curve, resulting in a more negative total area between the curve and the axis. This means the 2D model will give more normal momentum thrust than the 3D model.

Figure 23 shows contours of axial velocity parallel with the nozzle exit plane overlayed with a plot of axial velocity (note the false zero on the vertical axis). This view is very informative when analysing the 3D effects of the side walls. A thin boundary layer can be seen on each side wall which is much thinner than the boundary layer at the top. The flow is close to symmetrical about the vertical centreline.
The values in the plot in Fig. (23) show that axial velocity only varies by 3.4 % across the exit plane. Thrust is the integral over the area so any thrust calculation based on the velocity at the centreline where the value is 505 m/s would have an error of approximately 8%.

From this it was concluded that an AR equal to or greater than 3.2 is sufficient to achieve flow through the nozzle that can be analysed as two-dimensional with minimal error. Given a throat area of 30 mm² for the new nozzle, an AR of 3.33 was chosen to give dimensions of 3 mm × 10 mm.

3. Area ratio

The area ratio was calculated so that the flow would be fully expanded with an inlet total pressure of 20 Bar. To be fully expanded, the static pressure at the nozzle exit must be equal to atmospheric pressure. Full expansion gives the best thrust efficiency.

The first step was to calculate the critical pressure ratio \( \frac{p_0}{p^*} \) as shown in Eq. 4.

\[
\frac{p_0}{p^*} = \left(1 + \frac{1.4 - 1}{2} (1)^{2} \right)^{\frac{1.4}{1}} = 1.893
\]  

(4)

The critical pressure ratio was used to find the static pressure at the throat as shown in Eq. (20).

\[
p^* = \frac{p_0}{\frac{1.893}{1.893}} = 1056 kPa
\]  

Then the pressure ratio from the throat to exit was found as shown in Eq. (21).

\[
\frac{p^*}{p_e} = 1056.0 \times 101.3 = 10.42
\]  

(21)

The pressure ratio was used to find Mach number at the exit using Eq. 1 by rearranging to solve for \( M \) as shown in Eq. (22).

\[
M = \sqrt{\left(\frac{p^*}{p_e}\right)^{\frac{\gamma - 1}{\gamma}} - 1} \times \frac{2}{\gamma - 1} = \sqrt{(10.42)^{\frac{0.4}{1.4}} - 1} \times \frac{2}{0.4} = 2.184
\]  

(22)

Once the Mach number at the exit for complete expansion is known, the area ratio required to achieve this can be determined by rearranging Eq. 5 to solve for exit area as shown in Eq. 23 and Eq. 24.

\[
\left(\frac{A_e}{A^*}\right)^2 = \frac{1}{M^2} \left[ \frac{2}{\gamma + 1} \left(1 + \frac{\gamma - 1}{2} M^2 \right) \right]^{\frac{\gamma + 1}{\gamma - 1}}
\]  

(5)

\[
A_e = A^* \sqrt{\frac{1}{M^2} \left[ \frac{2}{\gamma + 1} \left(1 + \frac{\gamma - 1}{2} M^2 \right) \right]^{\frac{\gamma + 1}{\gamma - 1}}}
\]  

(23)

\[
A_e = 30 mm^2 \sqrt{\frac{1}{2.184^2} \left[ \frac{2}{2.4} \left(1 + \frac{0.4}{2} \frac{2.184^2}{2.4^2} \right) \right]^{\frac{0.4}{2}}} = 93.4 mm^2
\]  

(24)

In conclusion, it was found that an exit area of 93.3 mm² was needed for the flow to be fully expanded. In order to ensure complete expansion and to simplify construction the nozzle exit width was rounded up to 10 mm² which gave an exit area of 100 mm².

4. Rounded throat geometry

The throat was designed with a significantly larger radius of curvature in order to avoid separation and water condensation forming at the throat, due to rapid expansion. This phenomenon was observed in previous experiments (Neely 2007). It made it difficult to visualise some flow structures and invalidated assumptions made in calculation due to the two phases present.
5. **Final nozzle geometry**

The final geometry of the nozzle is shown in Fig. (24). Detailed drawings of the final nozzle design can be found in appendix A.

![Figure 24. Dimensions of nozzle](image)

- Throat width ($w_t$): 3mm
- Throat area ($A^*$): 30mm$^2$
- Throat aspect ratio (AR): 3.33
- Exit width ($w_e$): 10 mm
- Exit area ($A_e$): 100 mm$^2$
- Area ratio ($A_e / A^*$): 3.33
V. Preliminary Experiments

A limited set of experiments were conducted using the old nozzle to verify that the new instruments were functioning as intended and to justify the addition of mass flow meters. The first set of experiments conducted were mass flow tests. The conditions were set for optimum thrust vectoring where the shock just impinges on the nozzle exit. Mass flow of the primary and secondary lines were measured directly using the mass flow meters and compared to the mass flow calculated using the isentropic assumption in previous experiments. The second set of experiments were transient response tests. Once again the optimum thrust vectoring conditions were set and then the secondary flow was turned on rapidly using the solenoid valve. The response time and the dynamic behaviour of the shock were investigated.

A. Experimental Procedure

In order to obtain accurate and meaningful results, the correct experimental procedure must be followed (appendix B). The primary flow is supplied by four air bottles in parallel. Therefore ensuring that each bottle supplies the same pressure and mass flow is important. This can be achieved by following these steps:

1. Close all valves
2. Ensure all regulators are closed (anti-clockwise)
3. Open all air bottles
4. Adjust each regulator to slightly below desired pressure (regulator gauge is only approximate)
5. Change display on mass flow meter to pressure
6. Open valve 1 in primary line to let pressure through to mass flow meter
7. Adjust regulator so that the desired pressure is displayed on mass flow meter
8. Close valve 1
9. Vent air in line by opening main valve
10. Repeat for lines 2, 3 and 4
11. Open all sub-valves
12. Record pressure displayed on the primary mass flow meter
13. Change display on mass flow meters to mass flow
14. Open main valve to start primary flow
15. Open secondary valve and turn on power to solenoid to open valve
16. Start schlieren recording and data logging
17. Adjust secondary flow regulator until the shock wave impinges on the nozzle exit in schlieren image
18. Record primary and secondary mass flow
19. Turn off solenoid valve
20. Close primary flow main valve
21. Close all bottles
22. Vent primary and secondary lines
23. Ensure all regulators and valves are closed

B. Mass Flow Comparison

A mass flow test was conducted on the primary line with the new mass flow meter. The results were compared to mass flow calculated using the isentropic assumption and mass flow calculated with head loss using Eq. (11). The spreadsheet in appendix C was used to perform the pipe flow calculations and a sample calculation is provided in appendix D. The results are shown in Table. 3 and plotted in Fig. (25).

Secondary flow mass flow tests could not be conducted because the secondary mass flow meter was not working. Initially it was thought that the 50 Hz vibration from the solenoid valve alternating current could be interfering with the piezoelectric sensor used to measure velocity of the flow. The sensor measures the frequency of vortices shed from a bar in the flow. So the solenoid valve was removed and the meter tested again but there was still zero mass flow registered. Next the secondary supply hose was disconnected which allowed the air to exhaust directly out of the pipe. Without the restriction of the 8 mm² slot, the meter registered mass flow. It was concluded that the flow rate through the 8 mm² slot was below the threshold of the meter. In the end secondary mass flow tests had to be abandoned because of time limitations.

It can be seen from Fig. (25) that measured mass flow is significantly lower than mass flow calculated by adding up head loss through the pipe work. This is because the value of minor loss coefficient (K) is not accurately known for the nozzle. It was higher than predicted because the sharp throat in the old nozzle caused separation and shock waves.
Table 3. Calculated mass flow compared with results of mass flow test

<table>
<thead>
<tr>
<th>Pressure (Bar)</th>
<th>Mass flow calculated using isentropic assumption (kg/s)</th>
<th>Mass flow calculated including head loss (kg/s)</th>
<th>Measured mass flow (kg/s)</th>
<th>Discharge coefficient</th>
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<tr>
<td>30</td>
<td>0.1442</td>
<td>0.11286</td>
<td>0.0920</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Figure 25. Plot of mass flow at different pressures for calculations using isentropic assumption, calculations including pipe viscous loss and measured directly with mass flow meter.

Figure 26. Plot of ratio of measured mass flow to isentropic mass flow

The discharge coefficient was calculated for each pressure setting and plotted in Fig. (26). Discharge coefficient is the ratio of actual mass flow to isentropic mass flow. It is a function of losses in the pipe and loss due to the nozzle. It can be seen from Fig. (26) that the discharge coefficient approaches 0.65 as the pressure increases. This means that measured flow is approximately 65% of flow predicted using the assumption of isentropic flow.
The response time of the shock wave to the initialisation of the secondary flow was investigated. The new solenoid valve allowed the secondary flow to be turned on in under 20 milliseconds. The response of the flow was recorded using schlieren with the school’s old Redlake™ camera at 48 frames a second (fps) and the vector forces measured by the load cells were logged. Unfortunately, a method of synchronising the data logger had not been set up so transient response results difficult to interpret. This was because the high speed Redlake camera used in previous thrust vectoring experiments was broken. The low speed Redlake camera does not have the ability to send out a triggering pulse to synchronise the data logger.

The response time could be determined by the number of frames it took for the shock wave to settle in its new position after the solenoid valve was opened or closed. At 48 fps the Redlake camera takes a photo every 0.0208 seconds. The nozzle started in the open position and the flow took 6 frames to respond when secondary injection was stopped. This equates to a response time of 0.125 s. When the secondary valve was re-opened the shock only took one frame to settle in its position impinging on the nozzle exit. From this we can deduce that the response time to the injection of secondary flow is less than 20 ms. It can be assumed that the fluid response is better than this because the response time of the solenoid valve is approximately 20 ms.

The shock structure when secondary flow is off is shown in Fig. 27(a) and when secondary flow is turned on is shown in Fig. 27(b). The conditions of best thrust vectoring performance were chosen, at which the shock just impinges on the nozzle exit. This creates the greatest possible change in flow direction. A greater shock angle would cause the shock to reflect off the nozzle wall thus turning the flow back in the opposite direction. A weak shock can be seen when there is no secondary flow because of the effect of supersonic flow passing over the cavity created by injection slot.

![Schlieren images of (a) flow without secondary injection and (b) flow with secondary injection](image)

The schlieren was done with the knife edge facing up in the horizontal position, showing density gradients in the axial direction. In future it is recommended to have the knife edge facing down so that the shock comes out dark and the expansion at the throat is light. Otherwise, the knife edge could be positioned vertically to visualise density gradients across the nozzle.

It is recommended that the 240 V AC solenoid head be replaced with a 12 DC head to allow triggering of the solenoid and make valve response times more repeatable. The response time of an AC solenoid depends on where the current is in its cycle. If the current is in between peaks the valve will take longer to open than if it is at the top. Using a relay to trigger the solenoid valve is not a good solution because relays have a time delay due to their mechanical nature. A DC solenoid head can be ordered from ASCO to fit into the valve body already installed.

The implication that the transient response times observed has on the design of a control system is that there is more lag when turning off the vectoring. So the control system will need less gain when vectoring is being initialised. A response time of 20 ms when opening and 125 ms when closing is quite good and a sufficient control system should be able to be designed.
VI. Conclusions

The fluidic thrust vectoring rig at ADFA was improved in order for meaningful research into FTV to be conducted in the future. This was achieved by the installation of mass flow meters into the primary and secondary flow lines to measure mass flow directly and the addition of a fast acting solenoid valve to allow transient response experiments. The validity of future FTV research was also improved by the design of a parametric nozzle. The design will eliminate errors from transverse forces caused by the secondary supply hose location and allow for higher quality schlieren images to be produced because of the improved clarity of the window. Additionally, the scope of future FTV research will be expanded by allowing for variation of nozzle geometry to include fluidic throat shifting and fluidic throat area control. Detailed drawings of the final design were produced to allow a future researcher to manufacture the nozzle by simply giving the drawings to the SACME workshop.

Preliminary experiments were conducted to verify that the new instrumentation was working correctly and to validate the rationale for installing new instruments. It was found that the secondary mass flow meter was not working because the mass flow rate was below the range of the meter. Despite this, the rationale for installing mass flow meters was justified by the results from the primary flow, which showed that the measured mass flow rate was 65% of the isentropic flow rate. This correction can be applied to previous experimental data to obtain valid results. The transient response experiments conducted indicated an initialisation response of 20 ms and a stopping response of 125 ms. More accurate results could be obtained with the use of a high speed camera and synchronised data logging.

VII. Recommendations

The work done in this project has provided the foundation for cutting-edge research to be done into shock vector control and throat shifting methods of fluidic thrust vectoring at UNSW@ADFA. Additionally, the new nozzle allows for scope to conduct research in fluidic throat area control.

The first task is to repeat the experiments conducted by Neely et al in 2007, with the addition of mass flow measurement. In order to do this, the secondary mass flow meter needs to be replaced with a meter with lower mass flow range. It is suggested that a mass flow controller is purchased so that secondary mass flow rate can be controlled as discussed below. A method of synchronising the data acquisition software with the camera recording the schlieren images must be found. In past experiments this was done with a pulse output from the high speed Redlake camera. The Redlake camera is currently broken and until it is fixed a LED put in the corner of the schlieren image frame can be used to indicate when data logging starts.

The second task is to conduct transient response experiments to determine the feasibility of integrating FTV into a control system of a real aircraft. In order to do this, the high speed Redlake camera is required and the 240V AC head on the solenoid valve should be replaced with a 12V DC head. This will permit the valve to be triggered from the data acquisition software. The solenoid head can be ordered from Ascomation Pty. Ltd. without having to order a new valve body.

The third task is to build the new nozzle. This will open up many opportunities for further research, such as optimising the shock vector control method, examining the throat shifting method and investigating fluidic throat area control. The SVC method could be optimised in order to achieve vectoring angles comparable to those found in the literature. This could be achieved by incrementally varying expansion ratio and injection position. Experiments using the TS method could be conducted by drilling the secondary injection holes just upstream of the throat. Throat shifting could also be conducted with nozzles featuring recessed cavities, which showed significant potential in experiments conducted at NASA LaRC. Finally, the new nozzle could be used to conduct experiments with fluidic throat area control. Fluidic thrust vectoring is redundant if an engine still requires mechanical throat area control. So an effective method of controlling throat area by injecting fluid is needed before FTV can be applied on real aircraft. The use of a mass flow controller for fluidic throat area control experiments will provide scope to program secondary flow rate, so that the throat area can be changed to optimise thrust with variation in primary pressure.

The ambitious nature of these recommendations is justified by the fact that a scholarship has been offered by the Defence and Security Applications Research Centre (DSARC) and BAE Systems Australia towards fluidic thrust vectoring at ADFA. This will allow fluidic thrust vectoring research to thrive at ADFA for years to come.

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