Air Breathing Chemical Propulsion: Meeting the Challenges

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From the Guest Editor . . .

Chemical propulsion had to meet several challenges over the past few decades due to changing requirements and constraints posed by the operational scenario. Improved range and speed from compact engines demand improved efficiency and performance in concert with reduced drag. Better operational maneuverability and reliability require combustion control both passively and actively over the entire flight range. The dawn of high speed computing and advanced diagnostics has opened up avenues in propulsion research hitherto considered impossible. These provide the capability of predicting performance and creating parametric characterization of propulsion systems, as well as making non-intrusive, in-situ measurements of the necessary species and other quantities.

The ONR propulsion program focuses on research to meet the above-mentioned challenges. In a nutshell, the program addresses research that generates the understanding and information required to develop propulsion systems for longer range, higher speed, better maneuverability, improved stealth, increased efficiency, minimized emission, enhanced reliability and reduced cost. The three possible scenarios of achieving this very complex goal are (i) improved mixing and control of precombustion, during combustion, and post-combustion processes, both actively and passively, (ii) utilization of fuels with higher energy density and better combustion characteristics and (iii) employment of thermodynamic cycles that are more efficient. Though all these three research scenarios are addressed in the ONR research program, the first aspect is emphasized in the articles included in this issue of Naval Research Reviews.

The scientific information generated by the ONR basic research has been successfully applied in various propulsion component designs such as ducted rockets, partially premixed combustors, and stator-rotor designs. In his article, Dr. Hukam Mongia of General Electric Aircraft Engine elucidates the challenges in the design of future gas turbine engine combustion systems. The advances made in computational combustion dynamics are being utilized together with probability density function approaches. The formulation and validation of various models used in the code are described.

The ONR propulsion program is well coordinated with other sponsoring agencies and industry so that research findings can be transitioned into applications. A balanced analytical, computational, experimental approach is pursued. It is poised to offer excellent contributions in the fundamental and applied areas with innovative concepts, simulations, diagnostics, and experimentation.

Gabriel D. Roy
Office of Naval Research

Profiles in Science

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Professor Ronald K. Hanson has been affiliated with the Mechanical Engineering Department of Stanford University since 1971, where he is the Woodward Professor and Department Chairman. Professor Hanson’s research has been in the fields of laser diagnostics, chemical kinetics, combustion, and propulsion. He is an internationally recognized leader in the development of laser-based diagnostic methods for combustion and propulsion. In the 1970s he pioneered the use of tunable IR diode laser absorption spectroscopy for non-intrusive measurements of species and temperature in combustion environments. In the early 1980’s his group established a method, known as Planar Laser-Induced Fluorescence (PLIF) and now used worldwide, for obtaining instantaneous 2-D images of combustion properties by means of laser excitation and digital camera recording. PLIF provides unique capability to observe complex flow structures which are currently beyond computation or measurement by other methods. Measurable quantities include species, temperature, pressure, and velocity. In the 1990s, Prof. Hanson and his students began to utilize room temperature tunable diode lasers (TDLs) as light sources in absorption diagnostics. These lasers offer high potential for rugged, compact, and economical diagnostics suitable for use in research and development. The potential of these diode lasers for sensing and control of practical combustion and propulsion systems was recently validated through a collaboration with Naval Air Warfare Center (NAWC), China Lake, CA. Prof. Hanson’s group designed and implemented a multiple-wavelength diode laser system which provided rapid sensing of temperature and key species in a forced combustor at NAWC. The temperature data were used in a fast, active control scheme to optimize combustor performance, with a particular objective of achieving high combustion efficiencies and minimum emissions of pollutants such as CO and unburned hydrocarbons. This pioneering implementation was highly successful, and has led to current research on sensors for other pollutant species.

A key advance in Prof. Hanson’s diode laser research was the development of measurement concepts based on the shapes and positions of absorption lines. This measurement strategy enables simultaneous determination of multiple parameters, including quantities such as mass and momentum flux, which have not been measured previously by optical means. During the past few years, under support from ONR and AFOSR, these TDL diagnostics have been applied as sensors in research on combustion control, yielding near-real-time sensing ability which has aided development of new types of forced-combustion devices of interest to the Navy. At present, Prof. Hanson’s group is working to extend TDL diagnostics to control gas turbine combustors, and to new applications in advanced propulsion systems such as pulse-denotation engines.
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The applications of thrust-vectoring are obvious. The AV-8B Harrier is a combat star, and it achieves its extraordinary performance through its thrust-vectoring engines. Short or even vertical take-off and landing capabilities are invaluable, especially to aircraft that operate from ships, or from small, damaged, or improvised airfields. Thrust-vectoring can compensate for loss of aerodynamic lift, and help a pilot keep an aircraft under control during stall conditions.

But thrust-vectoring in operational craft has always come at a high price in terms of mechanical complexity and weight. Gimbaled engines or elaborate systems of vents and louvers impose all the usual penalties of moving parts. They are also heavy, and weight is always at a premium in aerospace engineering. If there were a way of altering the direction of a reaction engine’s thrust without these mechanical impediments, that would change everything.

Strykowski and Krothapalli describe a fluidic approach to thrust-vectoring that overcomes these disadvantages. It turns out that there are indeed ways of using the fluids present in the system to direct the jets that provide thrust.

- J.P.
Vectoring Thrust Using Confined Shear Layers

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Abstract

A fluidic scheme is described which exploits a confined countercurrent shear layer to achieve multiaxis thrust vector response of high speed jets in the absence of moving parts. Continuous control of the thrust vector angle is demonstrated in jet exhaust up to Mach 2 for nozzle geometries including rectangular and axisymmetric cross sections. Studies conducted jointly between Florida State University and the University of Minnesota indicate that thrust vector angles up to at least 20˚ can be achieved at slew rates in excess of 180 degrees per second in laboratory scale nozzles. Complementary studies carried out at China Lake Naval Air Warfare Center on large scale hardware (ten fold laboratory scale) and at high temperatures (over 3000°F) suggest that scaling and temperature issues will not preclude the fluidic approach from working. In both studies, secondary mass flow requirements for control were found to be less than approximately 2% of the primary jet mass. The confined shear layer is susceptible to both attached and unattached flow regimes, the nature of which will be discussed. Finally, the performance of the fluidic approach will be examined in the presence of external coflow to evaluate the potential of the concept under flight conditions.

Introduction

The ability to redirect the thrust of an aircraft engine or rocket exhaust offers several advantages to the aerospace industry. It provides the potential for a vertical component of thrust which may be used, especially at low speeds, to augment the lift force generated by the wings. This allows the aircraft to take off in a shorter distance, and ascend at a higher rate. During landing, vectored thrust can be used to supplement the lift force generated by the wings, and approach speeds may be reduced without changing the rate of descent. The benefits of short take off and landing aircraft are especially attractive for landing on aircraft-carriers or on damaged airfields. Traditionally the wings are the sole mechanism for generating lift. However they have aerodynamic limitations, namely airfoil stall, which causes a dramatic decrease in airfoil performance and must be avoided to maintain adequate control of the aircraft. Thrust vectoring can be used to maintain or re-establish control under stalled conditions, thus enhancing the overall maneuverability of the plane. In missile applications, multiaxis thrust vector control could be employed for steering control at potentially considerably lower expense in terms of vehicle weight and cost.

There are various methods to vector the exhaust thrust of a jet engine or missile system. One way is to tilt the entire exit plane of the nozzle. While this generally requires complex actuation hardware, it has been implemented successfully on the Harrier jet for years. For vertical take-off the thrust is directed almost fully downwards, and once in flight the nozzle locks in place horizontally and the plane performs in a conventional manner. Another method which has been employed on the Lockheed X-31 and the NASA F-18 High Alpha Research Vehicle, among others, employs hinged turning vanes downstream of the nozzle exit. The exhaust impinges on these mechanically actuated vanes and is deflected. This method has proven to greatly enhance the maneuverability of the test aircraft, as well as considerably
shorten take-off and landing distances. However, these advantages come at the expense of additional weight and reduced thrust due to the wall interaction. Similar advantages can be achieved, in principle, without intricate mechanical control systems and with improved thrust recovery, by fluidically vectoring the jet.

The present study concerns a method of fluidic vector control which employs a confined countercurrent shear layer. This approach, also known as Counterflow Thrust Vector Control, or CF-TVC, attempts to combine the continuous and proportional features of mechanical based systems with the simplicity of fluidic control, and has recently been demonstrated experimentally for both subsonic and supersonic jets.\(^1\)\(^2\) Successful fluidic vectoring must achieve proportional and non-hysteretic control over a significant portion of the operation envelop, while minimizing the secondary mass flow required for actuation. The basic concept of counterflow thrust vectoring can best be illustrated by referring to the sketch in Figure 1a, where the side view of the short dimension of a rectangular jet is shown. The primary jet exhausts from the nozzle between symmetric curved surfaces called collars, placed on either side of the primary stream. To achieve upward thrust vectoring at an angle \(\alpha\), a secondary counterflow must be established in the upper shear layer of the jet. This can be accomplished by applying suction to the plenum chamber located between the upper curved surface and the primary nozzle. The action of counterflow in the upper shear layer gives rise to asymmetric entrainment and a cross-stream pressure gradient sufficient to vector the jet.

The ability of the jet to vector in the presence of a stationary surface has been commonly referred to as the Coanda effect.\(^3\) As a nominally two-dimensional jet issues from the nozzle, the shear between the jet and the surrounding quiescent fluid gives rise to lateral momentum transport which is accentuated by the turbulent mixing of the shear layer. This process leads to momentum mixing between the two fluids and is commonly referred to simply as entrainment. Because the jet is gathering fluid through entrainment, its boundaries diffuse outward and, in the process, weaken the jet’s ability to further entrain the surrounding fluid. Figure 1b depicts the two-dimensional jet with a curved surface of radius \(R\) aligned tangentially to the edge of the nozzle exit. The fluid entrained along the lower collar surface by the pumping action of the shear layer is constrained, giving rise to subatmospheric pressures in that region. This differential pressure draws the jet toward the curved surface. It is this change in the pressure field within the vicinity of a solid surface that is known as the Coanda effect. (First described by Young,\(^3\) the Coanda effect is named for the French engineer who patented the “effect” in 1932.) If the entrainment rate is sufficiently high, the pressure continues to drop until the jet becomes attached to the surface. It is this attachment process that is most often associated with the Coanda effect. However, attachment is not a necessary condition for the Coanda effect, but rather a consequence of it.

Once the flow becomes attached, the jet continues to entrain fluid between itself and the curved surface leading to further wrapping of the jet around the surface. This process continues until the shear layer structures have weakened sufficiently and can no longer entrain the fluid necessary to force the jet against the surface. The point of separation of the jet from the surface is therefore dependent on the nature of the shear layer structures and their ability to entrain ambient fluid. Once the jet has established itself in the configuration shown in Figure 1b under steady conditions, it remains stable, i.e., perturbations to this flow result in the jet reestablishing itself to the condition prior to the perturbation. While the attached portion of the jet is obviously no longer entraining fluid against the curved wall, the pressure there is kept low as demanded by the equations of motion. Under these conditions, the curved jet can be described by two-dimensional cylindrical coordinates \(r\) and \(\theta\) which, respectively, are the local radius of the curved jet and its angular position. The corresponding local velocities in the \(r\) and \(\theta\) directions are then \(u_r\) and \(u_\theta\). If we assume that the flow is nominally parallel in the vicinity of the collar, namely that \(u_\theta = u_\theta(r)\) and \(u_r = 0\), we obtain for a steady, inviscid and incompressible fluid the following relationship:
Consequently, the pressure gradient in the r-direction is seen to increase with the square of the velocity. Therefore, the pressure will increase from some minimum value at the curved surface to atmospheric pressure near the outer boundary of the jet, ensuring that the centripetal acceleration is balanced by the pressure field.

The distribution of vacuum pressure maintained on the curved surface will determine the net forces acting on the surface. However, one of the inherent difficulties of controlling the Coanda effect as described above, is its passive nature. For a given jet momentum flux and nozzle-collar geometry, a fixed pressure distribution will be created on the collar, and therefore a fixed side force will be generated. Hence, the Coanda effect leads to hysteretic jet attachment and bistable operation, which could be used for thrust vector control if the Coanda surface were designed to be movable. But this configuration would defeat the initial attractiveness of fluidic control using stationary hardware, and hence why the passive Coanda effect as shown in Figure 1b was not examined as a likely candidate for aircraft and missile control applications. However, if the jet curvature can be controlled by, for instance, manipulating jet entrainment, the cross stream pressure field can be altered continuously, and thereby generate the side forces necessary to vector thrust and avoid hysteresis.

Strykowski, Krothapalli & Jendoubi demonstrated that counterflow, when applied to the periphery of an axisymmetric jet, greatly enhanced the entrainment characteristics of the shear layer. By applying counterflow on only one side of the jet, the excited shear layer entrains mass more effectively than the opposing free shear layer. This imbalance in entrainment causes a cross-stream pressure gradient, which deflects the jet in the direction of the applied counterflow, resulting in a vectored primary flow. Van der Veer & Strykowski were able to proportionally pitch vector control a subsonic rectangular jet up to Mach 0.5 at angles up to 20°. Strykowski, Krothapalli & Forliti achieved similar pitch vectoring performance in a supersonic jet at Mach 2.

No moving parts are directly required to steer the jet when CF-TVC is employed. Consequently, reliability can, in principle, be greatly enhanced. Furthermore, there are no surfaces in direct contact with the high temperature, high velocity exhaust gases. This may eliminate the need for expensive materials or exotic cooling schemes, which would be necessary with turning vanes. Because of the potential for minimal weight addition to the vehicle, CF-TVC systems may be retrofitted to an existing aircraft’s engine without significant structural alteration of the airframe. Similar benefits are expected for the design of new exhaust nozzle concepts for both aircraft and missile applications, namely a reliable, robust system with a relatively low initial cost, and minimized maintenance costs.

Facilities

The majority of measurements were conducted in the blow-down compressed air facility of the Fluid Mechanics Laboratory located at Florida State University. (The complementary studies at China Lake Naval Air Warfare Center will only be summarized here.) The facility is driven by a high-displacement reciprocating air compressor which is capable of supplying air at a maximum storage pressure of 160 bars. Large storage tanks provide a total capacity of 10 m³ and are capable of driving the Mach 2 primary jet flow examined in this study continuously for up to 30 minutes. The supply air can also be heated by being passed through an array of resistive tank heaters having a maximum power output of 450 KW and capable of achieving stagnation temperatures in excess of 750 Kelvin. Visualization of the jets was achieved by creating laser sheet images of the vectored plane along the jet axis using frequency doubled Nd:YAG pulsed lasers. Fine condensation ice particles formed in the mixing region between the dry cold air of the primary jet and the moist ambient air scatter the laser light thus rendering the shear layers visible.

For the pitch-axis vectoring study, the blow-down facility was fitted with a rectangular nozzle having an exit aspect ratio of 4:1 (52 mm by 13 mm ). The Mach 2 axisymmetric nozzle used for multiaxis thrust vectoring was designed to have the same minimum throat and exit plane cross-sectional area as the rectangular nozzle to ensured that, for the same stagnation pressure and temperature, the flow conditions for both jets were nominally the same. Contours of both nozzles were generated by a method of characteristics for a design Mach number of two and were run at their design pressure ratios. The jets were operated at stagnation temperatures between 300 K and approximately 700 K, corresponding to exit plane Reynolds numbers from 0.4 to 1.2 x 10⁶.

Pitch Vector Control

To achieve thrust vector control, a secondary counterflowing stream needs to be established along the outer surface of one of the jet shear layers as shown previously in Figure 1a. This secondary stream is created by connecting a vacuum pump and manifold to a cavity placed along the periphery of the jet. To assure that the counterflowing stream acts along the appropriate shear layer of the jet, suction chambers must be created, the nature of which will depend on the nozzle geometry under consideration. This can be achieved quite easily in the rectangular geometry by the positioning of side plates attached to the ends of the collars, effectively isolating the secondary flow to either the upper or lower shear layer. Similar partitioning can be employed in axisymmetric jets to achieve multi-axis thrust vector control as will be discussed later.

\[
\frac{\partial P}{\partial r} = \frac{\rho u_u^2}{r} \tag{1}
\]
To demonstrate the CF-TVC concept for the pitch vectoring of a rectangular jet, a base study was conducted with flow visualization using planar laser scattering. The primary jet was unheated having a stagnation temperature of 300K, resulting in a low static temperature after expansion to Mach 2. Under these conditions, the entrainment of relatively moist air into the shear layer of the cold jet gives rise to ice crystal formation in the mixing region and thereby illuminates the jet shear layers during vectoring. The series of photographs in Figure 2 were taken over the streamwise distance of approximately \(7H\) to \(23H\), and were captured by illuminating the jet with a 10-nsec exposure of the laser sheet positioned along the jet axis. When the vacuum system, connected to the upper collar, is deactivated and air is allowed to entrain freely into both the upper and lower shear layers, the jet exhausts along its geometrical axis as shown in Figure 2a. Under these conditions the collar arrangement operates analogously to a jet ejector configuration, albeit inefficiently due to the rapid divergence of the collar walls. When the vacuum system is activated creating secondary counterflow in the gap between the jet and the collar, thrust vectoring can be achieved as shown by the photographs in Figures 2b,c. The static pressure measured on the upper collar surface in the jet exit plane (essentially the secondary plenum pressure \(P_B\)) was reduced from -0.061 bar in Figure 2b, to -0.29 bar in Figure 2c, corresponding to vector angles estimated from the photographs and corroborated using direct thrust measurements of 6˚ and 16˚, respectively. The jet could be vectored toward either the upper or lower collar by activating the appropriate vacuum system.

Due to the intense mixing which occurs in the shear layer of the vectored jet, it is not obvious whether the secondary flow drawn into the vacuum system originates primarily from ambient fluid or from the jet itself. To obtain a more complete physical understanding of the countercurrent flowfield in the vicinity of the collar, the mean velocity was captured using particle image velocimetry, a non-intrusive technique requiring that the primary and secondary streams be seeded with submicron particles and illuminated using a pulsed laser. The mean velocity-vector field and corresponding isovelocity contours obtained for a Mach 2 jet vectored at \(\delta_v = 8˚\) are shown in Figure 3. A close examination of the velocity vectors reveals that the maximum countercurrent velocity occurs near the midpoint of the collar, at \(x/H = 4\) in Figure 3, and corresponds to nearly 30% of the primary jet velocity. These high secondary velocities are due to both the vacuum system as well as the natural entrainment characteristics of the primary jet. What is perhaps most interesting is that the majority of the counterflow is eventually entrained by the jet and carried downstream, resulting in relatively small amounts of secondary flow entering the vacuum system. The maximum amount of mass drawn into the secondary plenum is less than 2% of the primary jet mass flow rate.

Casting the experimental thrust performance data into a common format, which can be used for nozzle design, requires an examination of the parameters influencing jet curvature in the proximity of the collar surface. For purposes

![Fig. 2 – Light scattering from the jet centerplane showing thrust vectoring at (a) 0˚, (b) 6˚, and (c) 16˚ using a collar geometry of \(G/H = 0.38, L/H = 6.9\), and \(R/H = 15.7\).](image)

![Fig. 3 – Velocity vector field and isovelocity contours obtained using particle image velocimetry for a jet at Mach 2 for \(G/H = 0.38, L/H = 6.9\) and \(R/H = 15.7\).](image)
of discussion, we will considering the pitch vectoring of a rectangular jet as shown schematically in Figure 1a and visually in Figure 2, and subsequently extend the scaling to other nozzle geometries, in particular the axisymmetric nozzle. The exit vector angle, \( \delta_v \), depends on the length of the collar surface, \( L \), the forward momentum of the jet per unit depth, \( \rho U_1^2 H \), and the pressure distribution on the collar surface, where the subscript 1 indicates mean quantities in the jet exit plane. Experimental work\(^1\,^{2}\) has shown that the pressure distribution on the collar surface is nominally uniform over the forward half of the collar where the majority of the side force is taken up, and may be proportionally controlled by varying the secondary plenum pressure \( P_B \). The relationship between the plenum pressure and vector angle is required for nozzle design, and has been examined over a wide range of conditions for both subsonic\(^2\) and supersonic\(^3\,^{5}\) jets. (Note that the scaling arguments and experimental results presented here are relevant for jets operated near their design pressure ratios only.)

The two-dimensional momentum equation in cylindrical coordinates provides insight into the physical phenomena affecting the relationship between \( \delta_v \) with \( P_B \). Recognizing that viscous terms are small compared to inertial effects in a free jet, and assuming that the flow is nominally parallel in the streamwise direction the momentum equation can be simplified to the expression given previously in Eqn. (1). To develop a scaling equation for CF-TVC performance, it is assumed that the jet uniformly arcs at a constant radius of curvature, \( R \). This assumption is fairly accurate as long as \( R \) is significantly larger than the jet dimension \( H \); hence, the analysis applies to small vector angles.

Integrating from one side of the jet to the other, the right hand side of Eqn. (1) represents the streamwise momentum. Since streamwise momentum is conserved in a free jet flow, this quantity is equal to the momentum flow in the jet exit plane per unit depth, \( \rho U_1^2 H \). The integral on the left-hand side is known from the boundary conditions. On the radially outward shear layer, the pressure is equal to that of the ambient, \( P_\infty \), on the inner shear layer, the pressure is approximately that of the secondary plenum \( P_B \). Thus we obtain:

\[
P_\infty - P_B = \frac{\rho U_1^2 H}{R}
\]

Upon reaching the streamwise extent of the collar, \( L \), the counterflow ceases and with it the mechanism for sustaining the cross-jet pressure gradient. As a result, the jet exits straight into the atmosphere, at an angle \( \delta_v \), as seen in Figure 1a. The jet curvature can be related to the exit vector angle and the length of the collar using the expression:

\[
R = \frac{L}{\sin \delta_v}
\]

Combining the last two expressions and solving for the vector angle in terms of the control pressure, we have:

\[
\sin \delta_v = \frac{(P_\infty - P_B) L}{\rho U_1^2 H}
\]

Experimental observations of pitch vectoring in rectangular jets, for both subsonic and supersonic conditions show that this expression holds true, to a good approximation, over a wide range of flow conditions and collar parametrics as shown in Figure 4. The data presented in the figure include a variety of studies of supersonic flow at Mach 2, where nozzle gap \( G \), collar length \( L \), radius of curvature \( R \), and jet stagnation temperature have been varied; thrust vector angles were determined using a six-component thrust stand and were corroborated with control volume analysis. The pitch vector data, indicated by the solid symbols enclosed within the hatched region, demonstrate a nearly linear relationship between normalized plenum pressure and jet response for primary stream stagnation pressures held fixed at the design pressure ratio for Mach 2. Under these conditions, weak shocks are present due to the asymmetric pressure distribution in the jet exit plane caused by underexpansion in the direction of secondary counterflow.

The scaling relationship observed in Figure 4 can be used to design nozzle-collar systems in other geometries by considering that the expression on the right hand side of Eqn. (4) is effectively the ratio of the side forces acting on the collar surface \( (P_\infty - P_B) A_{side} \) to the axial force imposed by the jet \( \rho U_1^2 A_{jet} \), where the ratio \( A_{side}/A_{jet} \) can be simplified to \( L/H \) for the rectangular geometry. Hence, the basic scaling law we want to consider for more complicated geometries is given
by Eqn. (5), valid for nozzles operated near their design pressure ratios.

\[
\delta_v = \frac{f_{cn}}{\rho_1 U_1^2 A_{jet}} \left( P_{oo} - P_B \right) A_{side}
\]

(5)

**Multiaxis Thrust Vector Control**

Extending the CF-TVC concept from pitch vectoring to multiaxis operation requires a collar design which effectively directs counterflow along the jet shear layer. Since the vacuum source alone cannot direct the flow, the collar must be partitioned to created chambers through which the secondary flow can pass and thereby establish a countercurrent shear layer. Figure 5 indicates the partitioning strategy employed for multiaxis vector control of an axisymmetric Mach 2 nozzle. When the vacuum source is connected to a particular chamber, a secondary counterflow is developed — bounded by the collar surface and a segment of the jet shear layer. This, in principle, causes the primary jet to vector in a direction normal to the shear layer along which counterflow is established. A single vacuum source was connected to the chambers via control valves allowing independent vectoring in any of the six directions as desired.

Instantaneous planar laser scattering images showing the cross-sectional view of the unvectored and vectored axisymmetric jet at x/D ≈ 2.5 are shown in Figure 6; note that the camera is positioned off-axis to avoid interaction with the high-speed jet, creating the observed oblique view. A close examination of the images reveals that not only does the jet move toward the chamber with counterflow, but the jet shape is altered considerably. We believe this is primarily due to the difference in the mixing rates of the countercurrent shear layer (upper shear layer in Figure 6b) and the shear layer regions isolated from secondary counterflow. For instance, if we compare the top portion of the jet shear layer in Figure 6b with the lower portion, it is apparent that the upper layer has diffused over a significantly larger area. This observations may allow the CF-TVC concept to be used not only for vector control but for mixing enhancement as well, which may be desirable for reducing jet noise or thermal signature. The crosshairs provide a frame of reference to compare the unvectored and vectored flow. There is a slight vertical shift in the lower shear layer, but the upper layer is considerably displaced. Thrust stand measurements indicate that the effective jet deflection is ~10°, which is difficult to detect in the oblique view of Figure 6 due to the relatively small streamwise distance where the images were captured.

A summary of the axisymmetric jet vectoring as a function of the static pressure parameter is provided in Figure 4 to allow comparison to the pitch vectoring data; multiaxis thrust vector data are shown for studies conducted at Florida State University/University of Minnesota and China Lake. Although the axisymmetric nozzle data show reasonably linear behavior, the pitch vectoring results obtained using the rectangular nozzle appear to be slightly more efficient, namely larger vector angles can be achieved with lower vacuum pressures developed in the secondary plenum. We
believe the primary reason for these differences is due to leakage between adjacent chambers of the collar assemblies for the axisymmetric arrangement. This was determined by monitoring the static pressure distributions in the chambers adjacent to the primary chamber where vacuum is applied. These measurements indicated that counterflow is not completely isolated from other parts of the shear layer, resulting in a degradation of performance due to the transverse pressure gradient across the shear layer. It is also difficult to determine the appropriate side area \( A_{side} \), which is used to develop the scaling in Figure 4; a simple projection of the active sector was used when plotting the data. The maximum vector angle of 10° achieved for the axisymmetric study compared to nearly 20° for the rectangular jet, is not due to an inherent limitation of the concept, but rather caused by the smaller side area of the axisymmetric collar compared to the rectangular collar when acted upon by the same available vacuum pressure \( (P_B - P_p) \). Although these three-dimensional effects will undoubtedly influence the collar performance, we believe that they can be minimized by improvements in collar design.

Performance Considerations

Performance of the multi-axis CF-TVC system was also documented in terms of secondary mass flow rate, jet dynamic response and hysteretic behavior. The mass flow drawn through the secondary vacuum system was determined to be consistently less than 2% of the primary jet mass for the unheated primary flow (stagnation temperature of 300 K), and significantly lower when the primary jet was heated. In the FSU/UM experiments described above, the primary mass flow rate was between approximately 0.5 and 0.75 kg/sec, for hot and cold jet conditions respectively. Dynamic performance of the multi-axis system was also evaluated for the axisymmetric configuration. A solenoid valve was used to activate and deactivate counterflow to a desired chamber and two different measurements were used to determine the dynamic response of the jet. In the first approach, the planar laser scattering images were recorded on video during this transient process and a time stamp was superimposed on this record. The video record shows the jet being deflected from \( \delta = 0° \) to 9° and vice versa in significantly less than a tenth of a second, the lowest subdivision on the time stamp. This places a lower limit of 90 degrees/sec on the jet deflection rate. A second method was then used to determine the jet dynamic response more precisely. The unsteady plenum pressure \( P_u \) on the collar surface was monitored using a fast response pressure transducer (minimum flat frequency response of 40 kHz) while counterflow was cycled on and off. These measurements indicate that the jet could be deflected from zero to 9 degrees in less than 50 ms, resulting in jet vectoring rates of at least 180 degrees/sec.

Due to the entrainment differential, a small degree of jet turning is possible, in principle, without a collar surface, however it is the addition of an extended collar surface of length \( L \) that makes CF-TVC a viable technology. First, it channels the secondary flow in parallel with the primary flow, effectively inducing a countercurrent mixing layer over a finite extent of the jet column. Second, it restricts the natural entrainment of the jet, intensifying the cross-stream pressure gradient. Finally, it gives the pressure forces a surface over which to act. A longer collar has more surface area for the pressure forces to act on thus a smaller pressure differential will impart an equal transverse force on the nozzle-collar assembly. In other words, with a longer collar, the same vector angle is achievable with a smaller amount of vacuum from the secondary flow system. The net effect is a reduction in pumping power losses.

While the collar is vital to the efficiency of the CF-TVC system, it poses a potential problem that can disrupt the continuity of the operating curve. This condition, a result of the bistable interaction between a free jet and a wall, is one in which the jet attaches to, and reaches a stable equilibrium on, the wall. It has been observed, under certain operating conditions by previous CF-TVC investigators,\(^1,2\) that the jet attaches to the collar surface during vectoring. This is unacceptable from a design standpoint as, in a flight situation, this may cause a loss of control. Furthermore, to release the jet from the collar, the differential control pressure must be reduced beyond that which was required to cause attachment. This hysteretic behavior makes a continuous vector-control system very difficult (if not impossible) to implement. Fortunately, this situation can be prevented in many instances by correctly tailoring the geometry of the collar.\(^6\)

The important thing to bear in mind when designing a CF-TVC system is that wall attachment can only occur if an equilibrium can be sustained as shown in Figure 1b. This means that the entrainment mechanisms within the jet must be able to sustain the low pressure necessary to hold the jet attached to the wall. The shorter the collar, the sharper the jet must turn in order to attach; thus a lower plenum pressure will be required. Furthermore, with a short collar, the shear layer has less contact with the secondary stream, making it more difficult for the pumping mechanism within the jet to generate the low pressure required to hold itself to the wall. Consequently, if the collar is sufficiently short, attachment will not occur.

There is a unique equilibrium location where the attaching streamline intersects the collar. This location depends on the gap width, the mixing dynamics of the shear layer, and the amount of secondary flow leaving (or entering) the recirculation zone. A large gap places the collar surface farther away from the jet, resulting in a longer attachment length. Enhanced shear layer growth rates mean the jet is more effective in sustaining low pressures along the collar surface. Likewise, counterflow being drawn from this region by a
secondary pump assists the jet in sustaining the low pressure necessary to hold itself to the wall. These two latter conditions enable the jet to turn with a smaller radius of curvature, resulting in a shorter attachment length. If the collar is longer than this equilibrium attachment length, $L_{eq}$, the jet will merely attach at the designated location, and follow the contour of the wall until boundary layer separation occurs. However, if the collar length is shorter than the equilibrium attachment length, i.e. $L < L_{eq}$, the jet will not attach to the wall. When designing a collar, it is important to be able to estimate the attachment length based on the intended operating conditions. Ultimately, designing a CF-TVC system for aircraft or missile propulsion requires that a collar geometry be found which is capable of achieving the required thrust vector angle, $\delta_v$, while minimizing external drag, secondary mass flow pumping demands, and provide attachment-free operation over the entire operating domain of the vehicle.

Flight Effects

The generally favorable characteristics of CF-TVC performance as described above are encouraging, however successful system integration of the concept requires at a minimum that the technology can be implemented during actual flight conditions. To examine this aspect of performance, the influence of a coflowing external stream was imposed on a rectangular jet (aspect ratio of 4:1) operated at a Mach number of 1.4; external coflow Mach numbers were examined between 0.3 and 0.7. A schematic of the CF-TVC system and coflow hardware is shown in Figure 7. The coflow was established by placing a rectangular duct around, and extending downstream of the nozzle-collar hardware. The duct was equipped with glass windows to allow optical access for flow visualization; surface pressures were used together with momentum flux measurements to evaluate the effective thrust vector angle using a control volume analysis. A summary of the CF-TVC performance of a rectangular jet for various counterflow and external coflow levels is provided in Figure 8 together with the pitch vector control presented in Figure 4 for comparison. Again $P_b$ represents the secondary plenum pressure measured on the collar surface in the jet exit plane. At first glance it appears that thrust vector performance with external coflow is very similar to the behavior without coflow, in that the jet vector angle increases nearly linearly with increasing vacuum pressure. However, a closer examination reveals that, albeit small, there is a systematic degradation in the performance with coflow. For a given differential pressure across the collar, the jet response indicated by $\delta_v$ decreases as the coflow Mach number increases. This effect can be understood if we consider the effect of vectoring in one direction, for instance up, on the flow regime on the opposite side, in this case the region below the curved primary jet. In the configuration used in our experiments, when counterflow is actuated in the upper shear layer, there is no flow through the lower gap between the jet and lower collar. But the lower shear layer of the primary jet and the upper shear layer of the lower coflowing stream both entrain fluid from the region bounded by these two shear layers creating a low pressure zone — essentially a wake — on the lower side of the primary jet. This in turn reduces the side force on the nozzle-collar assembly and the effective angle $\delta_v$. As the entrainment rate increases due to increased coflow Mach number, so does the wake effect and the detrimental influence on performance. However, at higher thrust vector angles the pumping action of the primary jet has a reduced impact on the surface pressures of the lower collar for a fixed coflow Mach number. Hence, as $\delta_v$ increases the difference between coflow and no-coflow experiments should diminish, which is the trend seen in Figure 8.

![Fig. 7 – Side view of a Mach 1.4 rectangular jet positioned in a coflow duct to simulate forward flight effects.](image)

![Fig. 8 – Thrust vector performance of a rectangular jet operated in the presence of an external coflowing stream.](image)
The degradation in CF-TVC performance can be alleviated, in principle, if atmospheric pressure is maintained in the regions not actively experiencing counterflow. This could be achieved by ducting some of the freestream flow into the inactive secondary plenum, and thereby “filling” this region to reduce the wake effect. Although the actual hardware used to accomplish this will depend on the overall vehicle configuration, we believe that the effect of coflow on CF-TVC performance can be implemented using this approach.

Closing Remarks

We have provided a brief overview of the issues which must be considered in the design of a thrust vector system based on counterflow. It has been shown that through CF-TVC it is possible to vector thrust in multiaxes in a continuous fashion using a fluidic approach. The performance of the nozzle system is relatively insensitive to jet stagnation temperature, at least over the range studied to date (300 to 1930 K), and the thrust vector angle is approximately a linear function of the static pressure developed in the counterflowing stream. Although many issues need to be examined further, such as the presence of shock waves within the collar region for jets operated off-design, and further study at high temperatures, the inherent simplicity of this method makes it a promising concept for vectoring thrust.

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