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Experimental Analysis of a Linear Expansion-Deflection Nozzle at Highly Overexpanded Conditions

K. Schomberg[1], J. Olsen[1], A. Neely[2] & G. Doig[1,3]

[1]School of Mechanical and Manufacturing Engineering
UNSW Australia, Sydney NSW 2052, Australia

[2]School of Engineering and Information Technology
UNSW Canberra, Canberra ACT 2600, Australia

[3]Aerospace Engineering Department
California Polytechnic State University, CA 93407, USA

Abstract

A linear variant of the expansion-deflection (ED) nozzle has been compared to a conventional converging-diverging (CD) nozzle through an experimental analysis. Thrust coefficient calculated from axial load cells was selected to compare performance between nozzle types and schlieren imagery used to observe variations in flow structure. Both configurations were tested at pressure ratios (PR) ranging from 5-25 to represent highly overexpanded flow conditions. Thrust coefficient in the ED nozzle was 25-100% greater than the CD nozzle across the range of PR tested. Side wall loading as a result of unsteady asymmetric flow separation was evident under all conditions in the CD nozzle. Comparatively, the exhaust flow remained attached to the nozzle wall in the ED configuration, a feature of the concept previously limited to implicit verification. Flow features within the ED nozzle such as evacuation of the wake region with respect to PR and variation of effective area ratio due to a shear layer between the wake region and supersonic jet were explicitly observed. Removal of the transition between separation regimes evident in the ED nozzle would effectively remove the limit on area ratio due to flow separation at sea level. This coupled with the overall increase in nozzle thrust render the ED concept viable for application as a high area rocket nozzle.

Introduction

In a rocket engine, thrust is produced by accelerating the combustion products to high velocities using a supersonic nozzle. Optimal propulsive efficiency occurs when the pressure of the exhaust flow exiting the nozzle is equal to that of the receiver or ambient pressure [8]. This can be achieved through utilisation of local ambient conditions to limit the expansion of the combustion products, ideally resulting in high thrust efficiency at all operating conditions. The limiting behaviour of effective nozzle area in the expansion-deflection (ED) nozzle occurs through the re-direction of the exhaust flow radially outwards towards the nozzle wall [6]. This is achieved through the use of a flow deflector or pintle and results in the creation of a viscous wake region within the nozzle. At low altitudes the wake region is said to be ‘open’ to the atmosphere and will theoretically vary the effective area ratio to maintain high efficiency. As atmospheric pressure decreases with increasing altitude, the required area ratio will increase until the physical maximum is reached. At this point the shear layers will intersect, effectively ‘closing’ the wake off and restricting performance to an equivalent conventional nozzle. The flow structure of the ED nozzle is shown in figure 1.

In spite of the potential benefits of the ED nozzle, limited experimental work is currently available within the public domain. Hot and cold fire tests of an axisymmetric ED nozzle were conducted by Rao during development of the concept [6].
Rao utilised cold gas static pressure readings to implicitly evaluate nozzle thrust and feasibility of the annular combustion chamber determined using hot gas firings. Less than ten years later an experimental analysis of the ED nozzle was conducted by Wasko [13]. All results obtained by Wasko were exclusively obtained using cold gas tests; however in these experiments, thrust was measured directly using a load cell. The findings by Wasko suggested that the adaptive measures of the ED nozzle concept were flawed, returning thrust measurements consistent with a conventional nozzle [13]. This study has previously been referenced when discounting the ED nozzle concept [1].

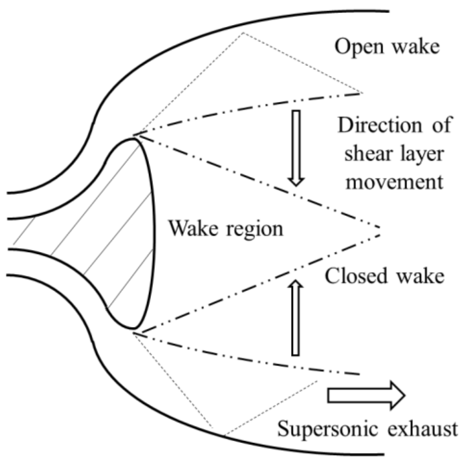

Figure 1. Flow features in the ED nozzle

A recent increase in the demand for efficient propulsion systems has led to a renewed interest in the ED concept. This has been demonstrated by Taylor through cold gas [11] and hot-fire [10] tests of an axisymmetric ED nozzle as well as cold gas tests on a planar ED nozzle [12]. Initial cold gas testing suggested ED nozzle performance was near-ideal [11]. However, these tests were performed on a low area design and thrust determined implicitly using wall pressures along the nozzle wall only. Later hot-fire and cold gas tests utilising a direct measurement of thrust suggested an off-design thrust performance in the order of 60-70% of ideal values [10]. A planar ED nozzle was tested by Wagner in an attempt to visualise the flow structure of the concept [12]. Design of the experimental rig in these tests restricted visualisation of the flowfield to downstream of the nozzle exit and thrust was not considered. The work presented in this paper experimentally compares a linear ED and equivalent CD nozzle to directly evaluate relative thrust efficiency and observe the flowfield structure within the ED nozzle.

Nozzle Design

A two-dimensional linear design was selected to enable the flow structure within each nozzle to be observed. A throat gap of 1.25mm was selected to ensure a sufficient inlet to throat area ratio (AR) and allow inlet conditions to be taken at stagnation values. An outlet to throat AR of 17.6 was chosen to represent a core stage engine nozzle i.e. an AR of 45 for LH2/LOX combustion products. Design of the nozzle divergence contour in both the ED and CD nozzles was completed using conventional techniques [5]. An expansion angle of 35° and exit angle of 4.5° was used in the CD nozzle to ensure flow behaviour similar to that in a core-stage propulsion system [4]. A maximum expansion angle of 45° and throat angle of 30° was used in the ED nozzle to provide a similar geometry to previous studies [12, 11]. The flow deflector or pintle in the ED nozzle was designed using a derivative of a method used previously by Taylor [9] and is shown (not to scale) in figure 2 below.

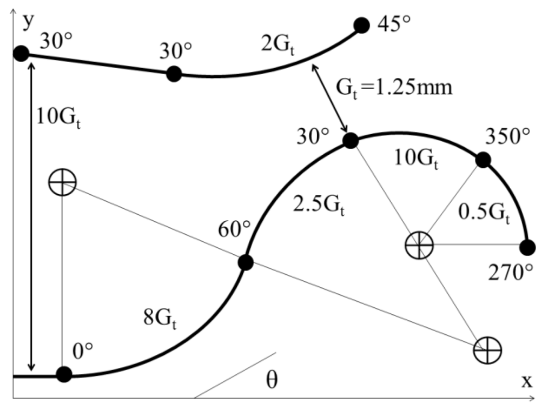

Figure 2. Flow deflector geometry

Experimental Method

All experiments were conducted within the supersonic nozzle facility at UNSW Canberra. The existing rig [3] was modified to allow testing of the ED configuration. The experimental setup used for all tests is shown in figure 3. Visualisation of the flow field was made possible using polished acrylic windows as the sidewalls and an 8mm nozzle width used to minimise the influence of the wall on the flowfield. Flow through the system was provided from G size gas bottles filled with instrument grade air at a maximum pressure of 220 bar. The pressure ratio (PR) across the nozzle was controlled using pressure regulators at each bottle up to a maximum of 30 bar. A master control valve was used to start and stop the nozzle flow and individual control valves at each bottle utilised to vary PR values safely between tests. Each test was run for a minimum of ten seconds to ensure quasi-steady conditions were achieved and testing at each PR level was repeated four times to ensure consistency between runs.

Inlet flow parameters of mass flow, pressure and temperature were recorded prior to the initialisation of each test at the nozzle inlet using a VorTek mass flow meter upstream of the master control valve. Nozzle thrust was measured directly from two axial XTRAN load cells and schlieren images captured using a Photron FASTCAM high speed camera. A monochrome in-line schlieren visualisation system [6] was used to provide insight into nozzle flow structure. The light path was produced using a pinhole light source and focused using two 100mm dia. lenses with a focal length of 500mm. Density gradients were resolved in the longitudinal direction through use of a cut-off filter with 50% of the light removed to enhance gradient contrast. Images were recorded at 8000 fps and a resolution of 896x752 pixels to capture sufficient flow details.

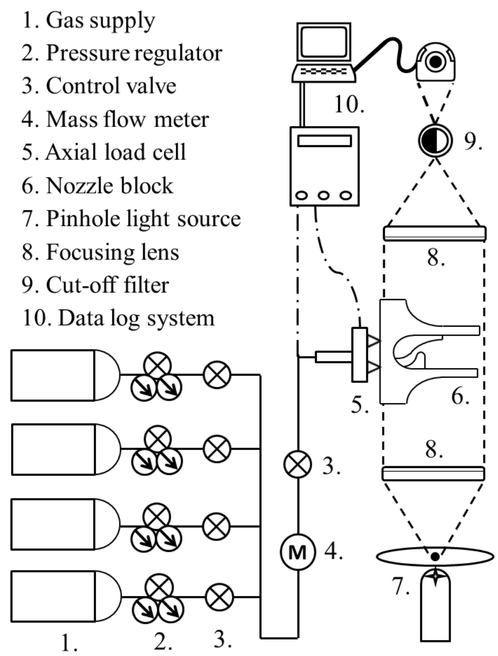

Figure 3. Diagram of experimental setup

To quantify inaccuracies due to errors in the data log system, diagnostic temperature and pressure inputs were introduced to the mass flow meter and the corresponding voltage cross-referenced with the calibration certificate provided by the manufacturer. This error was within 0.25% for both the load cell and mass flow meter. An additional source of error existed due to inaccuracy of the reported voltage. This was defined by the manufacturer at 0.25% of max rating for the load cell (250N) and 0.5% of absolute reading for the mass flow meter. Calibration of the load cells was completed using known masses and the resulting output voltage plotted using a linear regression method. This process was conducted before and after testing to remove any effects due to operation. A similar process was completed for the mass flow meter and errors due to non-linearity in both components were less than 0.15%. It is important to note that all errors could be represented as a percentage apart from the reporting error in the axial load cells. This value was fixed and would consequently result in higher overall errors at low pressure ratio.

Results and Discussion

The CD and ED nozzle were assessed across a number of highly overexpanded PR ranging from 5-25, compared to the design PR of 350 and a full-flowing but overexpanded PR of 50. Stagnation conditions were taken before each test at the mass flow meter upstream of the primary control valve. Due to the analogue gauge on the pressure regulator the exact stagnation pressure was difficult to control. However, the use of thrust coefficient (CF) as a performance variable negated this concern. All values were sampled at 1kHz and the raw data time-averaged for each 0.1s.

Thrust Comparison

Thrust was measured in the longitudinal direction for all tests to represent the useful thrust produced by the nozzle. The total thrust was taken as the sum of the force measured by each load cell. Nozzle thrust was converted to C_F using the recorded stagnation pressure and known throat area and determined using equation (1) and then plotted against PR as shown in figure 4.

$$C_F = \frac{T}{P_0 A_t} \tag{1}$$

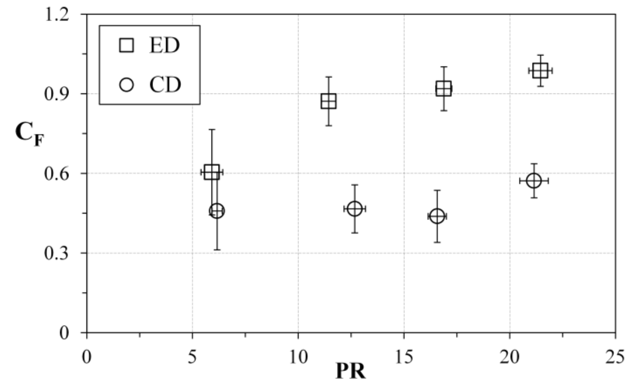

Figure 4. Comparison of nozzle thrust coefficient for individual tests

Measured C_F in the ED nozzle was greater than the CD nozzle across the entire range of pressures tested. The difference in C_F was approximately 25% at low PR and ranged between 75-100% at all other PR. The C_F increased with respect to PR in the ED nozzle in an approximately logarithmic fashion. Comparatively, C_F in the CD nozzle was approximately constant between PR values around 6-16 before increasing at a PR~22. The existence of a turning point in CD nozzle thrust would represent a transition in flow regimes within the nozzle. This was expected due to the known transition a ‘free’ and ‘restricted’ shock separation pattern occurring within in the CD nozzle [2].

Flow Structure

Schlieren imagery was used to observe the flow structure in both the ED and CD nozzle across a range of overexpanded PR. The major flow features were identified with respect to their density gradients and are shown in figures 5-8.

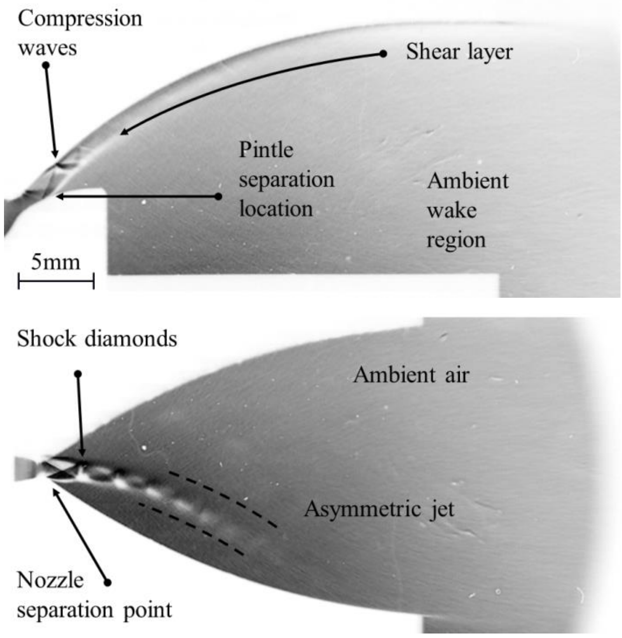

Figure 5. ED and CD flow structure at PR ~ 5

The exhaust flow remained attached to the nozzle wall in the ED configuration at a PR~5 whereas the extremely low PR resulted in an asymmetric jet forming in the CD nozzle. The separation point is clearly identifiable in the ED nozzle and the resulting shear layer clearly separated the supersonic inviscid jet from the viscous wake region as well as restricting the effective area ratio of the ED nozzle. Reflecting compression waves appear to be induced from the pintle separation shock and gradually reduced in intensity as suggested in ED nozzle concept theory [6].

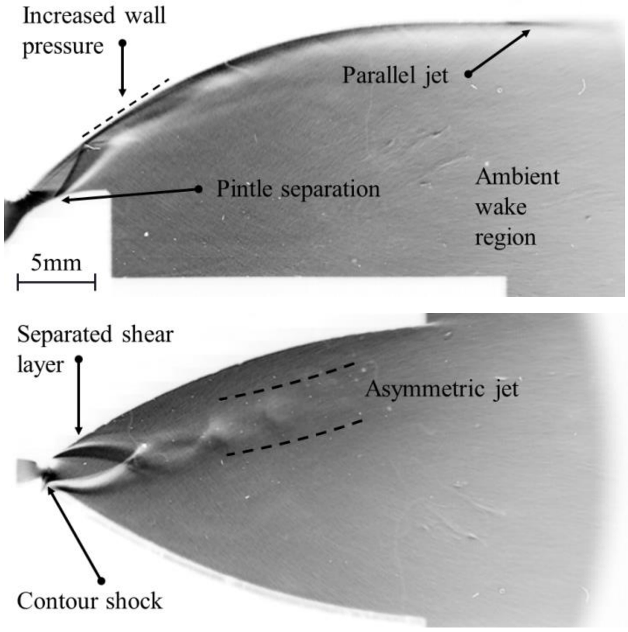

Figure 6. ED and CD flow structure at PR ~ 10

An asymmetric jet was evident within the CD nozzle at a PR~10 as shown in figure 6. The reversal in jet direction suggested considerable instability within the CD nozzle flow at low PR. A free shock separation process was observed, which was expected to occur at this PR within a conventional design [4]. Flow was again attached in the ED nozzle and the parallel jet at the exit suggested the exhaust exited the nozzle at ambient pressure.

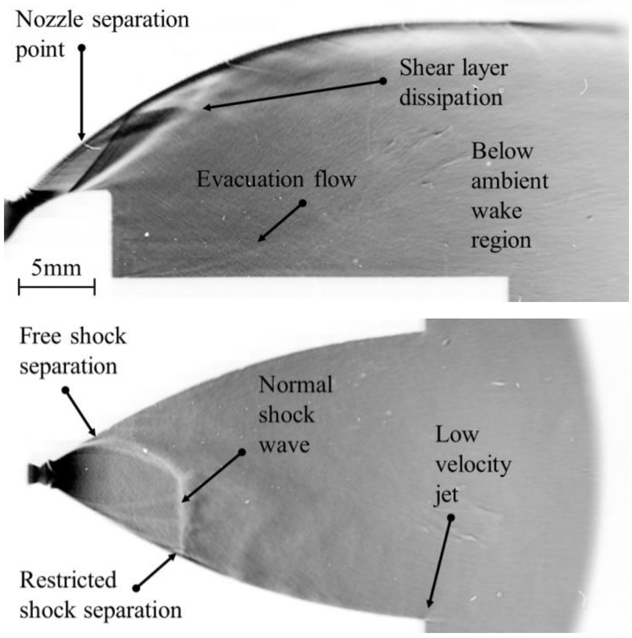

Figure 7. ED and CD flow structure at PR ~ 15

Transition between a ‘free’ and ‘restricted’ shock separation regime [2] was evident at a PR~15 in the CD nozzle. This transition process is highly asymmetric and implied the existence of high side loads on the nozzle wall [2]. Comparatively, flow remained attached in the ED nozzle independent of a small separated region between the pintle and nozzle shock. Dissipation of the separated shear layer within the ED nozzle indicated strong viscous effects within the flowfield, something previously neglected in ED nozzle analysis [11].

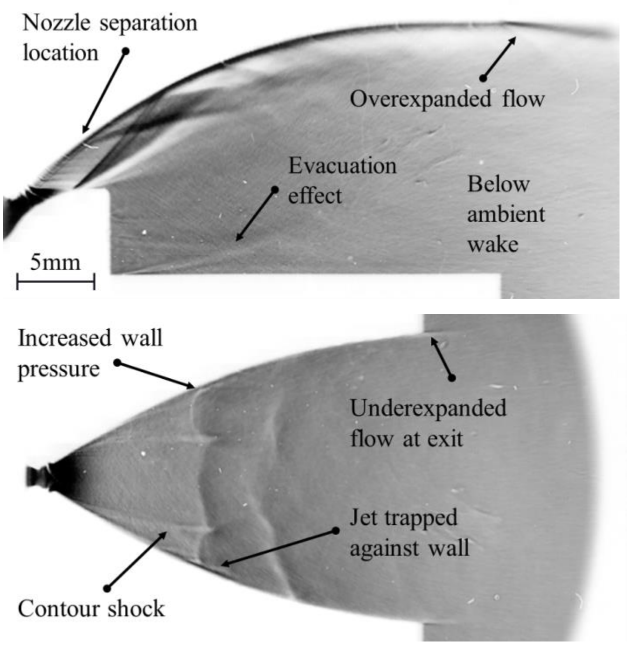

Figure 8. ED and CD flow structure at PR ~ 20

The transition to a completely 'restricted' shock separation regime in the CD nozzle was evident at a PR~20. An additional shock emanating from the non-ideal turning contour in the CD configuration was observed, as expected through use of the design method [5]. A greatly reduced exhaust velocity was inferred through low velocity jets at the nozzle outlet. A clear evacuation effect was shown in the PR~20 ED nozzle, suggesting that evacuation intensity was a function of PR. Evacuation of this region would result in a below ambient wake and was reinforced through the overexpanded jet observed at the nozzle exit.

Conclusions

The magnitude of nozzle thrust coefficient was greater in the ED configuration across all flow conditions. The performance increase at a PR~5 in the ED nozzle was within the relatively high experimental error at these conditions due primarily to the fixed error of the load cells. However, it is unlikely that operation of either nozzle at this PR would be required for any considerable length of time. Nozzle thrust in the ED configuration was 175-200% greater at all other PR values, representing a significant improvement over the CD nozzle. However, the thrust coefficient measured was far below the near-ideal performance as predicted by ED nozzle theory.

Flow structure varied greatly between both configurations at all tested conditions. Evacuation of the wake region was observed within the ED nozzle at a PR~15-20 and intensity of this process appeared to be a function of PR, as suggested in existing literature [10]. A highly asymmetric transition in separation regimes was observed in the CD configuration, suggesting high loading to the nozzle wall. Comparatively, exhaust flow in the ED configuration remained attached to the nozzle wall under all conditions. This characteristic of the ED flowfield would effectively remove the current limit on nozzle area ratio, resulting in vacuum thrust coefficient becoming a function of allowable mass. Additionally, the removal of the unsteady separation transition would result in lower transient side loading and reduce the required thickness and therefore mass of the nozzle walls.

The ED nozzle outperformed the CD configuration across all performance measures under flow conditions tested. Schlieren imagery captured within the ED nozzle confirmed the existence of flow phenomena such as: reflecting compression waves, effective area ratio control through shear layer interactions and evacuation of the wake, that have previously been supported by implicit evidence only. It is important to note that although nozzle thrust was effectively doubled in the ED configuration, a thrust coefficient of less than one is insufficient for operational use. However, the removal of a flow-induced limit on area ratio coupled with the potential for mass reduction of nozzle wall thickness warrant further investigation into the concept.

Acknowledgments

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