18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

Altitude compensation in expansion-deflection nozzles

K. Schomberg and J. Olsen

School of Mechanical and Manufacturing Engineering
The University of New South Wales, Sydney, New South Wales, 2052, Australia

Abstract

To determine the potential of altitude compensation in the concept, a test rig capable of operating as both a conventional nozzle and as an expansion-deflection nozzle was developed. The nozzle configurations were tested at several pressure ratios to observe how performance was affected over a range of simulated altitudes. Results were taken in the form of pressure readings and Schlieren images, and then compared with theoretical and ideal values to determine nozzle performance. The performance of the conventional nozzle closely followed theoretical predictions which validated the design process and provided a performance benchmark. The expansion-deflection nozzle, while not entirely optimised at this stage, demonstrated evidence of the altitude compensation through wake area variation and higher divergence pressure, suggesting increased nozzle efficiency.

Introduction

Due to the high cost of transporting payload into orbit, any increase in launch system efficiency is highly desirable. It is widely accepted that cross-altitude rocket nozzle performance is an area where an increase in system efficiency is possible. Conventional nozzles currently utilised for orbital launchers have a physically defined area ratio, which causes the exhaust gas at the nozzle exit plane to exit at a constant pressure P_e. Optimum nozzle efficiency occurs when the P_e of the exhaust gas equals the ambient atmospheric air outside the nozzle, denoted the receiver, or back pressure P_b. As the P_b varies with altitude, losses are experienced within the system at all altitudes other than the one where $P_e = P_b$. This altitude is called the design point and nozzle performance reduces as flight altitude moves further away from this point. Flow separation at low altitudes places an upper limit on the physical area ratio of the nozzle, whereas a high physical area ratio is desirable for efficient operation in a vacuum [1].

Altitude compensating propulsion systems are not a new idea, with the vast majority of nozzle concepts developed half a century ago [2]. After an initial surge of interest, the dominance of multiple stage launch systems inevitably caused a halt to the research and development of these concepts. A resurgence of interest in reducing the cost per kilogram to orbit corresponding with the emergence of single-stage-to-orbit spacecraft has resulted in a reconsideration of altitude compensating nozzles for modern propulsion systems. Unfortunately, to date, there has been little testing of full-scale nozzles. Furthermore, as the majority of testing conducted has been in the interests of private business and the military, information on these concepts is scarce within the public domain [3].

An influential report [4] compared the altitude compensating potential of both the expansion-deflection and truncated plug nozzles. The report concluded that the potential for altitude compensation within the expansion-deflection nozzle was very limited compared to that of the plug nozzle. However, research, not available in the public domain at the time [5] demonstrated the great potential of the expansion-deflection nozzle. As this study was classified for many years, the general perception was that the expansion-deflection concept was flawed. However, recent research has reinforced that increased efficiency through altitude compensation is obtainable for expansion-deflection nozzles [6].

Within the expansion-deflection nozzle, continual adjustment of the nozzle area ratio enables the nozzle to compensate for the effects of changes in altitude. The variation in the nozzle area ratio is achieved through the nozzle deflecting gas radially outwards towards the nozzle wall, creating a wake area in the diverging section of the nozzle. The wake area behaves similar to a physical boundary. A centrebody (commonly referred to as a pintle) is responsible for this deflection of gas.

The nozzle area ratio can be varied up to the physical limit of the nozzle itself. However, at low altitudes, as flow separation does not occur, the physical limit of the nozzle area ratio is instead determined by weight and manufacturing constraints. While area variation is occurring within the nozzle, it is said to be operating in ‘open mode’. When the optimal area ratio is equal to that of the physical area ratio, operation switches to ‘closed mode’. In closed mode, the nozzle ceases to be altitude compensating and behaves similar to a conventional design. A diagram of these two modes of operation can be seen in [6]. In this work, the altitude compensating behaviour of an expansion-deflection nozzle is compared to a conventional converging-diverging nozzle.

Experimental methodology

All experiments were conducted in the aerodynamics laboratory at the University of New South Wales. To measure nozzle performance, the test rig was fixed to a pipeline connected to the compressed air tanks used for the Mach *3* wind tunnel. The maximum rated air pressure within these tanks was *8* bar (*120* psi). For safety reasons, maximum inlet pressure was restricted to *7* bar. The design specifications of the test rig were:

- its functionality as both a converging-diverging and expansion-deflection nozzle,
- the means by which to vary of pressure ratio to simulate altitude change, and
- the means to observe nozzle efficiency and altitude compensating effects.

A digital panel mounted on the compressor enabled us to control the pressure of air within the tanks that fed the nozzles and therefore the nozzle pressure ratio. Such control enabled us to simulate the effects of altitude change.

Both a convergent-divergent and expansion-deflection nozzle could be tested by varying the pintle geometry. This was determined to be the most effective method of testing both nozzle configurations quickly, using the same rig. The pintle attachments were positioned upstream of the nozzle itself to minimise adverse effects on the flow field. A streamlined support structure held the attachments in position.

All conventional assumptions for supersonic nozzle design were used [1]. The nozzle pressure ratio was taken to be five to allow an increase and decrease in operational pressure ratio, and therefore, altitude to be observed. The divergence contour was sized using standard tables for isentropic flow. As it was desirable to show increased efficiency over an industry standard converging-diverging nozzle, the nozzle was designed to be on the limit of flow separation. After applying Summerfield's criteria [7], the design pressure ratio used for nozzle sizing was taken to be *12.5*. The corresponding nozzle area ratio was found to be *2.19*.

Although the standard inlet to throat diameter contraction ratio is *3* [6], the throat area was determined from the compressor flow rate to ensure that the pressure ratio could be maintained. The required effective throat diameter was calculated and rounded to *30*mm. As the inlet diameter was fixed, the effect of this throat area on the inlet flow could be determined. Using the isentropic tables, the difference in parameters of the inlet flow from their stagnation values was found to be less than *0.2*%. The stagnation values were taken to be a good representation of the inlet flow and a throat diameter of *30*mm accepted.

To shape the nozzle, curves were required for both the convergent and divergent sections. As any smooth curve is sufficient for the convergent section [1], a quarter circle of radius *40*mm was used. A conical divergence section was used since only relative efficiency was required for a positive result and to simply the design and manufacture. To ensure that enough pressure tapping points could be installed and a sufficient pressure curve generated, a minimum divergence length of *40*mm was selected.

As the weight of the rig would not affect performance, a factor of safety of *10* was used as a minimum for all connections. The critical connection was the pintle attachments to the support structure via a screw thread. To achieve the required factor of safety, a pintle diameter of *12*mm was used. This resulted in a nozzle throat diameter of *32*mm to give the required effective throat diameter. Following the throat area, the cross-sectional area of the converging-diverging pintle attachment was gradually reduced to a point. The expansion-deflection attachment followed the nozzle contour to generate a wake area downstream of the pintle base. A minimum attachment base to nozzle area ratio of *10*% was deemed to be sufficient; resulting in a minimum post throat length of *20*mm. Sectioned views of both configurations can be seen in Figure 1.

To evaluate nozzle performance, pressure readings were obtained through tapping points on the nozzle wall and shock wave images were captured at the exit to the nozzle using Schlieren photography. Due to the pressure rating, analogue gauges were used instead of electronic pressure transducers. The Schlieren system utilised a mercury lamp and *60* inch focal mirrors. To enhance the density gradient across the shockwave, a *50*% cut-off filter was used and image was captured on a Nikon *D70S* camera.

Before conducting the experiments, theoretical and ideal pressure values for each pressure tapping point location were calculated. The theoretical values were interpolated from the standard isentropic tables and plotted to give a predicted pressure contour for a converging-diverging nozzle. The ideal values were found by calculating the divergence angle corresponding to an ideal nozzle exit area ratio. Using this angle and the known locations of the tapping points, ideal pressure values could be found from the tables. The predicted shock wave at the nozzle exit was determined using the normal shock tables.

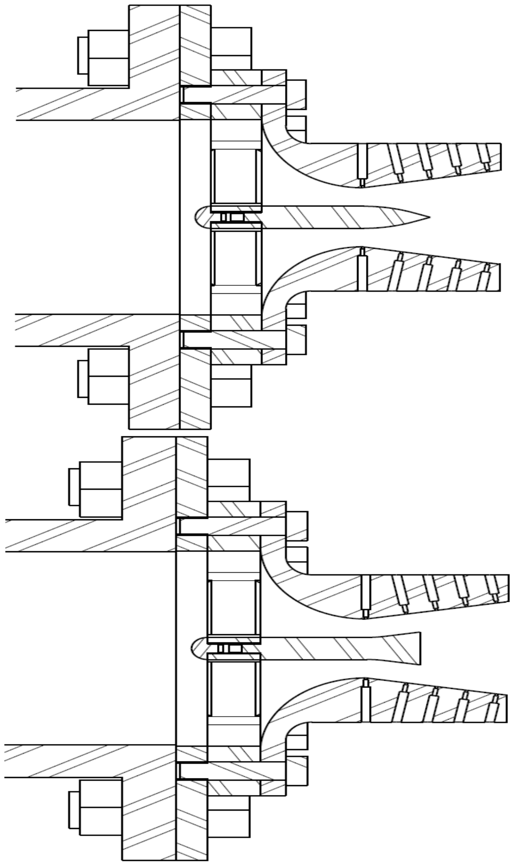

Figure 1: Section views of the converging-diverging and expansion-deflection nozzle configurations.

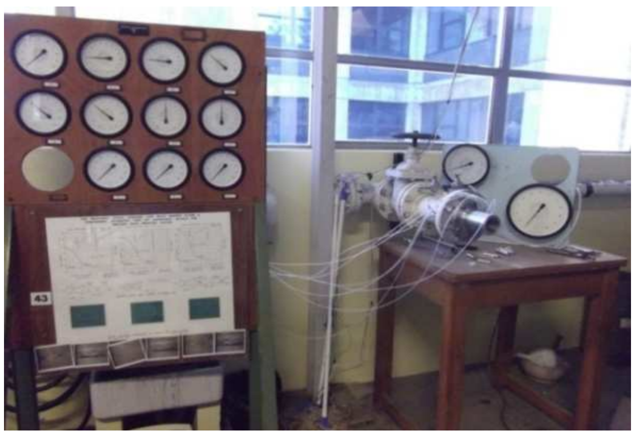

Figure 2: The experimental setup.

Results and Discussion

The converging-diverging and expansion-deflection nozzles were tested over a range of inlet pressures. As the ambient pressure would be fixed at atmospheric, inlet pressure was manipulated to vary pressure ratio across the nozzle.

Conventional nozzle

The objective of the convergent-divergent nozzle testing was to ensure that it performed similar to the predicted theoretical calculations. This result would validate the design process and confirm that the test rig was capable of representing conventional supersonic nozzle operation. Figures 3, 4 and 5 show the pressure contour and a Schlieren photo for both configurations at each inlet pressure used.

The pressure distributions show a strong correlation between measured and theoretical values. Although Summerfield's criteria would suggest that flow separation should not occur within the nozzle if the pressure ratio is above five, it is known that cold gas flow at low pressure ratios will tend to separate more readily [8]. Additionally, as the nozzle length and therefore, area ratio was increased slightly to accommodate an additional pressure tapping point, the chance of flow separation was higher.

The Schlieren images show clear shock patterns for all pressure ratios. As the inlet pressure was increased, the length of the shock diamonds in the stream-wise direction increased. Similarly, the Mach disk area can be seen to be decreasing with an increased pressure ratio. This is in accordance with the reduced oblique shock angle associated with a higher pressure ratio. As a definitive shock was visible in the *5.5* and *6.5* bar inlet tests, the shock angle was measured and compared to the theoretical values as shown in Table 1 below.

Table 1: Oblique shock angle measurements

NPR	θ_{ideal}	θ	*% difference*
5.5	*41*	*39*	*4.88*
6.5	*36.5*	*35*	*4.11*

Overall, the results from the converging-diverging nozzle experiment were positive. Pressure contours closely matched theoretical values in all tests up to the flow separation point, where values all returned to ambient, as expected. Furthermore, the shock behaviour was consistent with theory and the shock angle within *5*% of predicted values.

This meant that the test rig could be accepted as a reasonable representation of a conventional converging-diverging nozzle. Additionally, any future projects involving a similar design method can safely neglect the requirement for a converging-diverging nozzle basis, as the theoretical values were shown to be a sufficient representation.

Expansion deflection nozzle

The results of the converging-diverging nozzle experiments provided a performance benchmark to which the expansion-deflection nozzle could be compared. The objective of the expansion-deflection experiments was to observe an increase in nozzle efficiency that could be attributed to the altitude compensating behaviour within the expansion-deflection nozzle. This would be represented by a pressure contour closer to the ideal values, in addition to a wake area proportional to the required nozzle exit area for ideal expansion visible in the Schlieren images. The experimental parameters were kept consistent between both nozzle configurations. Similarly, Figures 3, 4 and 5 show the results from the expansion-deflection nozzle tests.

Flow separation did not occur at any pressure ratio for the tests and the pressure gradient was much closer to the ideal case than for the conventional nozzle. However, the pressure at the nozzle throat was higher than the ideal value, indicating that the expansion-deflection nozzle experienced some degree of choking at the throat.

The Schlieren imagery in the expansion-deflection nozzle tests was highly encouraging due to strong evidence of the wake area being formed within the exhaust flow. The figures show that this wake area decreased as the pressure ratio across the nozzle was increased. As the nozzle exit area was known, the wake area could be measured to determine the effective area ratio in the nozzle. These results are detailed in Table 2:

Table 2: Effects of wake area in the expansion-deflection nozzle

NPR	AR_{ideal}	AR / AR_{ideal}	AR_{eff}	AR_{eff} / AR_{ideal}
4.5	*1.129*	*2.119*	*1.564*	*1.385*
5.5	*1.176*	*2.034*	*1.808*	*1.537*
6.5	*1.248*	*1.917*	*2.018*	*1.617*

The wake area was beneficial across all tests, reducing the effective area ratio. The Schlieren images suggest the wake boundary acted as a physical boundary by deflecting the oblique shock waves produced at the nozzle exit.

The results for the expansion-deflection nozzle were encouraging. Formation of the wake area was observed, and the physical behaviour of this area was in accordance with current theory. Additionally, the wake area decreased with increasing pressure ratio, although the rate at which this occurred was greater than required for ideal expansion. Pressure readings were much closer to values required for ideal expansion than in the conventional nozzle. Increased pressure at the nozzle throat may be a result of choking. This is undesirable and will need to be further investigated, as it may have influenced the result.

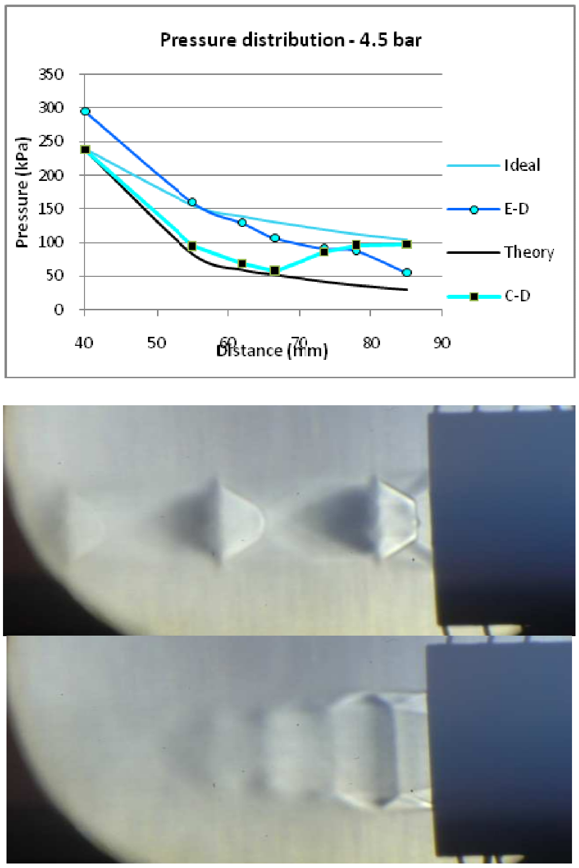

Figure 3: Distribution and Schlieren images at a 4.5 bar inlet

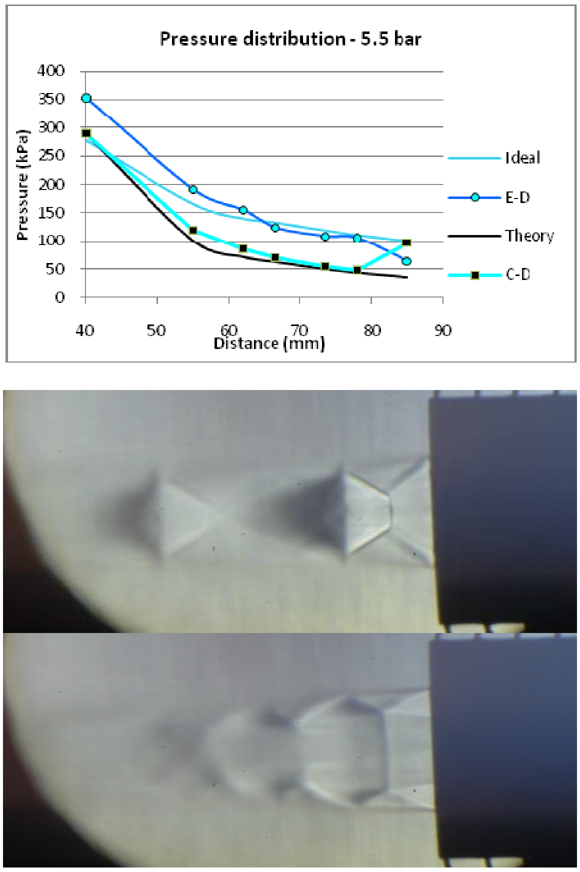

Figure 4: Distribution and Schlieren images at a 5.5 bar inlet

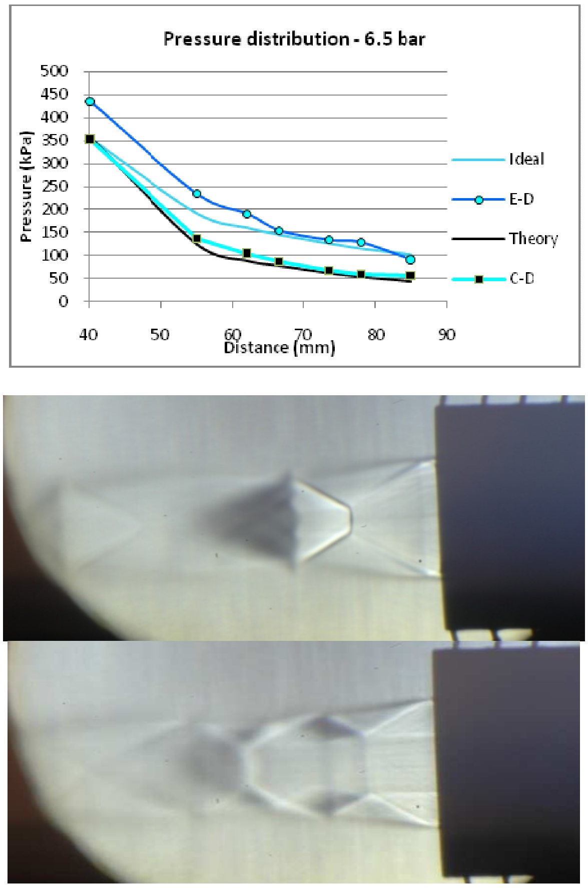

Figure 5*: Distribution and Schlieren images at a 6.5 bar inlet.*

Conclusions

A converging-diverging and expansion-deflection nozzle were designed and tested at various pressure ratios to represent operation over a theoretical altitude range. The design process was validated through the converging-diverging nozzle experiments, as all performance parameters closely followed theoretical predictions. Characteristics of flow specific to expansion-deflection nozzles were observed. Divergence pressures were much closer to ideal values within the expansion-deflection nozzle, and a wake area was not only visible in the Schlieren images, but also behaved in a manner consistent with current theory. The result was highly encouraging as it demonstrated that nozzle efficiency within the expansion-deflection nozzle was greater than the converging-diverging design in these experiments

Although the overall result was positive, further research is required to verify the results and increase understanding of expansion-deflection nozzle behaviour. Wake areas were smaller than required for an ideal effective area ratio, and choking at the throat may have influenced the pressure contour. To address these issues, a greater understanding of the effect of pintle geometry on flow behaviour and nozzle performance is required and will be the focus of future research.

Acknowledgements

The authors would like to thank the aerodynamics laboratory at UNSW and in particular, Mr Terry Flynn for his assistance during the experiments. Gratitude must also be extended to Mr Ian Cassapi, Mr Andrew Higley and Mr Radha Kottieth Pullambil for manufacture of the test rig components, and Mr Seetha Mahadevan and Mr Subash Puthanveetil for their assistance in drilling the pressure tapping points.

References

[1] Sutton, G. P. & Biblarz, O. *Rocket Propulsion Elements.* 8th. New York : John Wiley and Sons, 2010.

[2] Rao, G.V.R., Analysis of a New Concept Rocket Nozzle, *Journal of Liquid Rockets and Propellants*, 1960, 669-682.

[3] Stitt, L.E. *Exhaust nozzles for propulsion systems with emphasis on supersonic cruise aircraft*. National Aeronautics and Space Administration, 1990.

[4] Wasko, R. A. *Performance of Annular Plug and E-D Nozzles.* National Aeronautics and Space Administration, 1968.

[5] Hawk, C. W. *Air Force altitude-compensated nozzles.* Edward Flight Test Centre : United States Air Force, 1963.

[6] Taylor, N.V., Hempsell, C.M., Macfarlane, J., Osborne, R., Varvill, R., Bond, A., & Feast, S., Experimental investigation of the evacuation effect in expansion deflection nozzles. *Acta Astronautica*, 66, 2010, 550-562.

[7] Summerfield, M., Foster, C. & Swan, N., Flow separation in overexpanded supersonic exhaust nozzles, *Journal of Propulsion*, 1954, 319-321.

[8] Mueller, T.J., Sule, W.P. & Hall, C. R., *Characteristics of separated flow regions within altitude compensating nozzles.* Notre Dame : National Aeronautics and Space Administration, 1971.