20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Free Shear Layer Development in an Ejector: a Jet in an Axisymmetric Ducted Coflow

T. R. Cochrane[1], D. R. Buttsworth[2], B. Thornber[3] and M. Dennis[1]

[1]Research School of Engineering
Australian National University, Canberra, Australian Capital Territory, 2601, Australia

[2]School of Mechanical and Electrical Engineering
University of Southern Queensland, Toowoomba, Queensland, 4350, Australia

[3]School of Aerospace, Mechanical and Mechatronic Engineering
University of Sydney, Sydney, New South Wales, 2006, Australia

Abstract

The time-averaged development of axisymmetric compressible gas jets' free shear layer (FSL) is investigated through experiments. The research is undertaken with reference to ejectors: these devices increase the total specific enthalpy of a pipe flow and can utilise a renewable or recovered energy source. Lowering a jet's Mach number can reduce losses due to viscosity and compressibility. There is potential for ejector efficiency increases through investigation of loss mechanisms associated with FSL development. Tests characterised the FSL in terms of the pitot and static pressure fields in two spatial dimensions. A baseline experiment used nitrogen gas in the jet and co-flow, and further tests were performed with the co-flowing gas species changed to argon. The methodology and results inform future work to direct research efforts towards developing more efficient ejectors.

Introduction

An ejector is a type of compressor that can be powered using low grade heat from a renewable or recovered source. Ejectors may be applied in residential and commercial cooling applications that have traditionally relied on vapour compression systems driven by electromechanical compressors. The efficiency of the ejector is a critical factor for the commercial viability of systems based on this cycle.

Ejector inefficiency arises due to several thermofluid dynamic phenomena: (1) viscosity-induced shear stresses in wall bounded shear layers (WBSLs) as well as turbulent behaviour in both free shear layers (FSLs) and WBSLs; (2) heat may transfer between regions inside and adjacent to the ejector; (3) shock waves increase a fluid's entropy; (4) velocity profiles may be underdeveloped at the ejector outlet. The first, third and fourth of these can result in total pressure (p_T) losses, which may be overcome with a proportional increase in the energy delivered to the primary inlet. This decreases overall ejector efficiency. WBSL viscous losses can be neglected for high Reynolds number flows [7].

Viscous losses in shear layers and entropy increases across shock waves are phenomena that scale with the flow speed in an ejector. Hence, if the ejector can continue to operate at its design point conditions, reducing the magnitude of velocity should increase its efficiency. A combination of three factors can be altered to remove opportunities for flow to accelerate above the as-designed velocities, and to in general reduce the maximum velocity inside an ejector. These are: (1) boundary conditions, (2) geometry, and (3) gas species. Any such alterations must still allow the ejector to entrain sufficient secondary flow and deliver the mixed flow to the ejector exit at the necessary conditions. However, the mixing within an ejector is driven by velocity differences between flow streams, and the mixing has a significant influence on the performance of ejectors. Therefore it is not a trivial exercise to improve efficiency by reducing the flow speed.

Detailed knowledge of turbulent mixing of co-flowing jets under conditions of high compressibility is necessary for progress towards ejector optimisation through flow speed tuning. Supersonic plane mixing layers have been reasonably covered [6], and this knowledge has begun to be applied to ejectors [3]. Subsonic jets in both round and plane configurations are well documented [5]. But there are few publications for supersonic round jets in co-flow configurations that directly relate to ejectors. Hence this body of work seeks to contribute experimental data on compressible turbulent mixing of co-flowing round jets at conditions relevant to ejector operation.

Methodology

Apparatus

Experiments were performed at the University of Southern Queensland's TUSQ lab where a test rig had been developed to emulate the physical geometry and fluid fields expected in an ejector. The test rig was designed to measure the behaviour of the free shear layer between a jet and a co-flowing stream, and ideally produces an axisymmetric flow field (Figure 1).

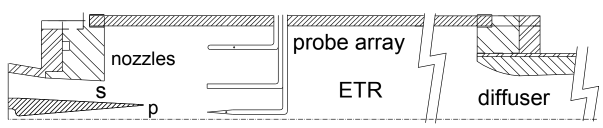

Figure 1: Nozzles, measurement region, measuring probe array and diffuser. Adapted from [4].

The system is analogous to an ejector, with a few exceptions. The region downstream of the nozzle exit plane, and upstream of any changes in cross-sectional area, has been extended in the axial and radial directions to increase the spatial extent in which the free shear layer can develop. In this paper, the region between the nozzles' exit planes and the entry to the diffuser is termed the 'energy transfer region' (ETR). The test rig operates as an open system. The pressure differential that drives the nozzle and diffuser was as follows: a low pressure dump tank acted as a receiver for gases discharged from the rig; a combination of compressed and ambient air provides the upstream pressure source for shakedown tests; bottled nitrogen and argon for the final series of tests. The operation of the test rig was an optimisation problem in terms of the following parameters: time taken to run the experiments, mass flow rate required to choke the diffuser, background pressure, and time taken to remove mass from the system between test runs.

To acquire information about the fluids' intensive and extensive properties a series of sensors at critical locations in the flow circuit provided information on pressure, mass flow rate, and temperature of the flow. Pressures were the flow property used for primary diagnosis of the flow field. A physical set of grade marks were placed along the axis of the test rig to determine the axial position of the array. A potentiometer was used to radially locate an array of three pressure probes: (1) subsonic static pressure probe; (2) pitot pressure probe; and (3) cone-static pressure probe. The probes were remotely connected to the transducers. The settling time of the pressure transducers according to their specification was $p \geq 40 \times 10^3$ Pa for $t \leq 4 \times 10^{-3}$ s, for a minimum response rate of 10×10^6 $Pa\, s^{-1}$.

Pitot static probes located in supersonic flow require a numerical solution to back calculate the flow properties upstream of a shock wave [9]. The measurement envelope of the probes in the ETR was approximately 17.4 nozzle diameters downstream of the primary nozzle (PN) exit (PNE) along the jet axis, and -0.85 to +3.0 diameters in the vertical radial axis. Ten equidistant positions at which to measure flow conditions were calculated across the axial range of the probes from 1.0 to 17.4 primary nozzle diameters.

The test rig's configuration used a PN with an exit to throat area ratio (R_A) of 18.1 and exit diameter of 13.6×10^{-3} m to output a round supersonic primary jet, and an annular low subsonic secondary nozzle for the co-flowing stream. The PN was an existing design [1]. The PNE Mach number M was calculated as $f(R_A, \gamma)$ [2]. As R_A was fixed, M varied with γ. The PN was designed for steam flow, which at the PNE has $\gamma = 1.35$ and $M = 4.34$. Air and N_2 have $\gamma = 1.40$ with $M \approx 4.6$; Ar has $\gamma = 1.667$ for $M = 6.30$. For Ar, to achieve the design value of p_{PNE} the PNs inlet pressure (p_{PNI}) is 10.2 Bar_g which was difficult to achieve in practice, resulting in $T \sim 20$ K and possibly a p_{pit} greater than the measuring range of the pressure transducer. It may produce a multiphase flow. Hence, passing Ar through the primary nozzle was not feasible for this project. Ar was instead passed through the SN and results compared to N_2 passing through the SN.

Procedure

The receiver and dump tank were connected to each other and isolated from the test rig. The power was turned on, voltage levels were confirmed, and the test rig opened to atmosphere. Atmospheric temperature and pressure were recorded with the vernier mercury barometer and thermometer. The sampling of the data acquisition system was initiated at 100 Hz. Data was recorded for 5 s at ambient conditions. The probe array was moved in the radial and axial directions. Each radial traverse required the system to be vacuumed to a common starting value, which was determined using gauge pressure transducers and hence varied with atmospheric pressure.

Data recording was started, the primary and secondary mass flow rates ($\dot{m}_p$ and $\dot{m}_s$) were supplied and a traverse initiated. Two types of traverses were made: up and down relative to the jet's centreline. Upwards traverses were made for all axial positions; downwards for the first and last axial positions. This quantified the differences in time dependency of the jet to potential increases in ETR pressure and lag in the pressures measured by the probe array. The test's design variables are outlined in Table 1. When a test was complete, the $\dot{m}_p$ and $\dot{m}_s$ isolation valves were closed and data recording stopped. The system was vacuumed back down to the starting value and the probe array was repositioned. The shut-down procedure required recording atmospheric conditions and test-specific observations.

Results

Pressure transducers attached to the probe array were observed to have a settling time across the full range used for tests ($\sim$ 100% of their design range) of: ~ 2.5 s for the pitot probe; ~ 3.0 s for the subsonic pitot static probe; and ~ 3.5 s for the cone-static probe. It was observed that the probe positioning mechanism had a variation of between negative several to zero degrees relative to the axis of symmetry of the ETR. This was due to a loose clearance fit between the vertical cylindrical sliding interface of the probes and the radial traversing mechanism. For the measurements it was expected that this would have a negligible effect on p_{pit} and a minor effect on p [8]. Figure 2 to Figure 4 describe the baseline test (60), and Figure 5 to Figure 8 describe the off-design tests (58 and 59). Constant radial position lines indicate: the test rig's axis of symmetry, the inner and outer radii of the PN, and the outer radius of the SN exit.

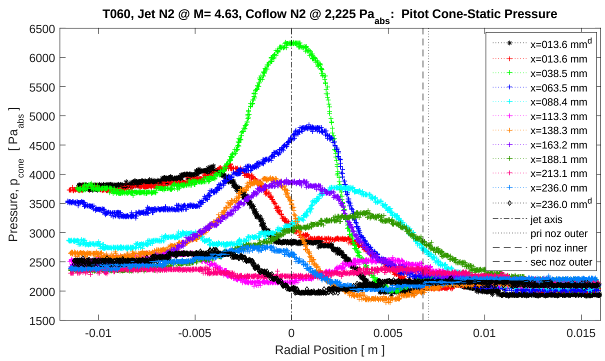

Figure 2: Ideal design, cone-static. 'd': downwards traverse.

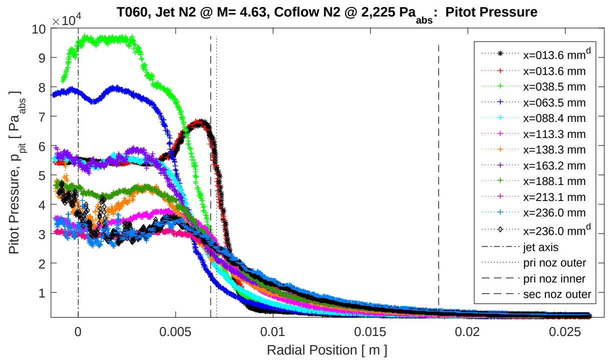

Figure 3: Ideal design, pitot. 'd': downwards traverse.

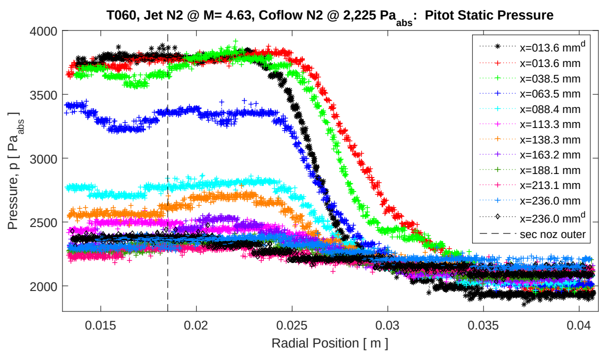

Figure 4: Ideal design, subsonic. 'd': downwards traverse.

$test\ \#$	gas_p	gas_s	$p_{T,pni}$	$p_{pne'}$	p_{pne}	p_{etr}	G_j	ρ_{pne}	$Re_{D,p}$	$\dot{P}_p$	$\dot{m}_p$	$\dot{H}_p$
$-$	$-$	$-$	Pa_{abs}	Pa_{abs}	Pa_{abs}	Pa_{abs}	$-$	$kg\ m^{-3}$	$-$	$N\ s^{-1}$	$kg\ s^{-1}$	$J\ s^{-1}$
58	N_2	Ar	4.83E+5	1.46E+3	1.86E+3	2.26E+3	O	9.31E-02	2.02E+5	6.79	9.43E-3	2.81E+3
59	N_2	N_2	4.83E+5	1.46E+3	1.82E+3	2.22E+3	O	9.31E-02	2.02E+5	6.79	9.43E-3	2.81E+3
60	N_2	N_2	7.31E+5	2.22E+3	2.22E+3	2.23E+3	I	1.41E-01	3.06E+5	10.3	1.43E-2	4.24E+3

Table 1: The data has constant values as follows: $\lambda = 0.1$, $T_{T,pni} = 288\ K$, $M_{pne} = 4.61$, $T_{pne} = 54.7\ K$, $u_{pne} = 697\ m\ s^{-1}$ (axial velocity). Key as follows. Terms: *gas* gas species, *G* geometry, *H* extensive enthalpy, *I* ideally expanded, *O* over expanded, *P* momentum, *Re* Reynolds number. Subscripts: *abs* absolute pressure, *D* diameter, *e* exit plane, *etr* energy transfer region, *i* inlet plane, *j* jet, *p* primary, *n* nozzle, $'$ design value, *s* secondary, *T* total condition. Superscripts: $\cdot$ time rate. Greek letters: λ entrainment ratio ($\dot{m}_s \cdot \dot{m}_p^{-1}$).

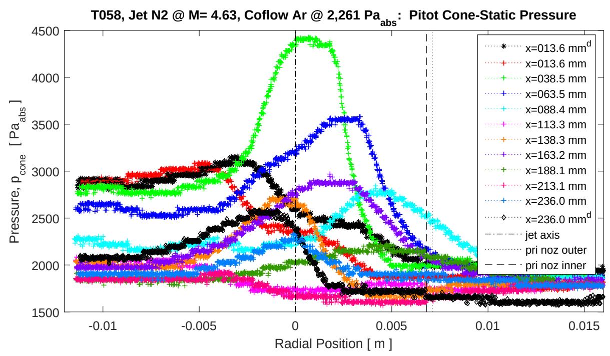

Figure 5: Off design, cone-static probe data, Ar coflow. 'd': downwards traverse.

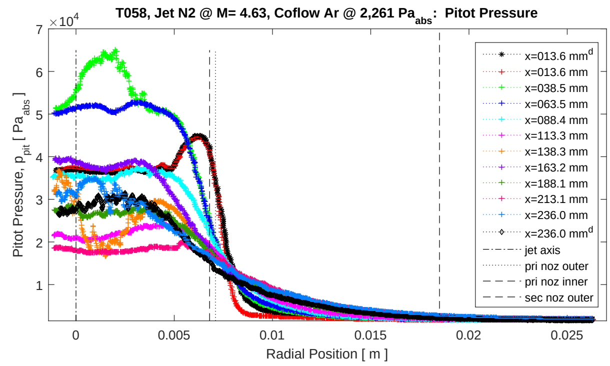

Figure 6: Off design, pitot, Ar coflow. 'd': downwards traverse.

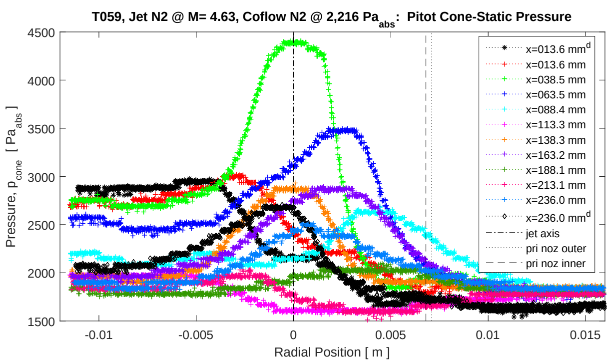

Figure 7: Off design, cone-static probe data, N2. 'd': downwards traverse.

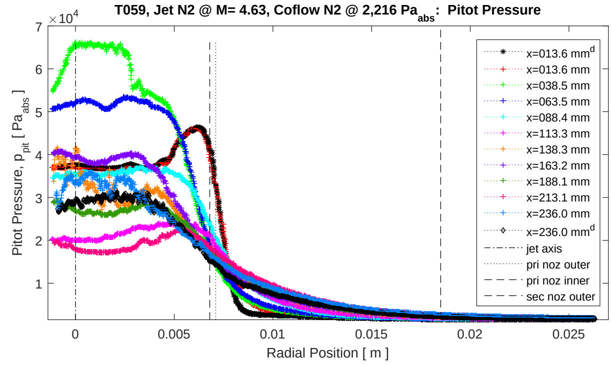

Figure 8: Off design, pitot, N2. 'd': downwards traverse.

Discussion

The measured response rate of the in situ pressure transducers was ~ 3 orders of magnitude smaller than their nominal value. This is due to viscous losses along the flow path between the inlet port (or ports) of the probes and the transducers' diaphragms. The pitot probe had an intermediate length of internal flow path with the least constrictions. The cone-static probe had the longest internal flow path and the most constrictive inlet ports. The accuracy of the radial rate of pressure change across the ejector with a moving probe array was approximately limited to $100 \times 10^3\ Pa$ divided by the response rate of each probe. The fastest response rate was $40.0 \times 10^3\ Pa\ s^{-1}$ for the pitot probe, and the slowest was $28.6 \times 10^3\ Pa\ s^{-1}$ for the cone-static probe. The response rate of the probe array could be increased by placing transducers closer to the probes' inlet ports, or by placing smaller transducers directly in the flow path.

The diffuser chokes and unchokes as a function of the radial position of the probe system (Figure 2, Figure 5 and Figure 7). The choked diffuser decreases p_{cone} as measured at the probe array. Through each individual test the background pressure is expected to rise as a function of the gas' molar mass and $\dot{m}$. Confirmation of choking is indicated by the ETRs static pressure not increasing through each test. Decreases are observed in p_{cone} measurements as a function of increasing radial distance of the probe from the jet's axis.

The phenomena of variation in centreline pressures at different radial and axial positions is likely due to converging compression waves and diverging expansion fans typically observed in supersonic jet flows. The radial variation in the pressures near the jet's axis in some traverses was unexpected, and this may indicate that the core of the jet has closed off. There are two likely time dependencies that can explain this: the mean location on the axis changing over time, and the instantaneous position over time varying about a mean value. The test data presented was measured as both a function of the time and the radial position, which cannot be separated without further testing. The jet's structure was spatially compressed as a function of time from the rising ETR p which was observable in at least a portion of every traverse of every test.

Data obtained axially near the PNE and radially near the expected near-axial side of the FSL shows an unexpected increase in p_{pit} relative to a standard top-hat profile. It is proposed that this is due to the probe moving through a region of the flow field where $M_{max} > M \geq 1$. As the probe moves out of the core flow at a nominally constant M, $M_{min} \approx 0$ when the FSL does not extend to the wall at the radial extent of the ETR. As M decreases, the pressure loss across the shock decreases non-linearly and p_T upstream along the streamline decreases approximately linearly. Hence it is possible that the observed initial increase and following decrease are purely a local function of M. This phenomenon was observed in all tests conducted with the supersonic jet which began first at test (33) and ended with the final test (60).

Additional explanations include: a proximity interaction between the probe array and the primary nozzle; an expansion fan; a compression wave; and a shock that is not aligned perpendicularly to the axis of the pitot probe. Heat transfer and viscous effects are discounted. An oblique shock that is not normal to the axis of the probe would have a lower p_T loss, as the loss across a shock is proportional to its angle of incidence relative to the original direction of the flow [2]. An expansion fan causes a greater M, but this increases shock strength and decreases p_{pit} which was not the observed phenomena. A compression wave may produce the phenomenon, but as the nozzle in test 60 was operating at approximately the correctly expanded case this is less likely the cause. Note that a correctly expanded jet for test 60 assumes idealised behaviour. In reality the nozzle's internal WBSL will displace streamlines, reducing the effective fluid dynamic area ratio of the nozzle. This results in a higher jet static pressure at the nozzle exit, causing an expansion fan in the jet downstream of the PNE. It is possible that the observed behaviour of the jet at this axial position is a combination of the above phenomena.

The current existence of a previously observed recirculation zone may be able to be deduced with further post processing from Figure 4. The behaviour displayed in Figure 2 was unexpected: the static pressure in a supersonic jet is often calculated assuming inviscid and quasi one dimensional behaviour. A reasonable explanation has yet to be developed for the stepped behaviour of p near the PNE and the pseudo-normal distribution further away from the PNE. Time-dependencies were more pronounced with the pitot static probes' measurements of p than those of p_{pit} from the pitot probe. Tests 58 and 59 are nearly identical and have similar observed properties to 60.

The pressure values are not those that would be observed while using a non-intrusive diagnostic method. The measured pitot pressure values will nominally include a normal-shock induced p_T loss for supersonic regions, and further compensations could be applied for other effects [8]. The cone-static probe that nominally operates in the supersonic flow will have a conical oblique shock upstream of its static ports, inducing a p_T loss less than that observed for the pitot probe.

Conclusions

The test rig's probe array was able to measure the pressure fields in a supersonic jets' turbulent free shear layer to a reasonable degree of accuracy in terms of spatial and pressure data. The results inform the direction and procedures required for future experiments to further characterise the total pressure losses from turbulent mixing and shocks.

To improve the utility of the rig it could be redesigned so that the nozzles, energy transfer region and diffuser can be exchanged quickly to vary geometrical parameters. For future testing of jets with variable gas species, species-specific nozzle and diffuser geometries could be designed to better control test parameters. Optical diagnostic tools could improve measurement of properties in the free shear layer, in a manner that is non-intrusive to the flow field. Use of these tools may require the following: a more compact test rig design if the test rig is to be contained in a non-reacting gas medium, and a new material to replace the acrylic polymer used in the existing test rig.

The data presented here can be used for validation of numerical simulations. Further experimental and numerical data are required to improve the ability of researchers to optimise the performance of ejectors.

References

[1] Al-Doori, G. and Buttsworth, D. R., Pitot pressure measurements in a supersonic steam jet, *Experimental Thermal and Fluid Science*, **58**, 2014, 56–61.

[2] Anderson, J. D., *Modern Compressible Flow: With Historical Perspective*, McGraw-Hill Education, New York, United States of America, 2003, 3rd edition.

[3] Ariafar, K., Buttsworth, D., Sharifi, N. and Malpress, R., Ejector primary nozzle steam condensation: Area ratio effects and mixing layer development, *Applied Thermal Engineering*, **71**, 2014, 519–527.

[4] Ariafar, K., Cochrane, T., Malpress, R. and Buttsworth, D., Pitot and static pressure measurements in a co-flowing steam jet, 2016, (unpublished work).

[5] Ball, C. G., Fellouah, H. and Pollard, A., The flow field in turbulent round free jets, *Progress in Aerospace Sciences*, **50**, 2012, 1–26.

[6] Papamoschou, D. and Roshko, A., The compressible turbulent shear layer: An experimental study, *Journal of Fluid Mechanics*, **197**, 1988, 453–477.

[7] Schlichting, H. and Gersten, K., *Boundary-Layer Theory*, Springer, New York, United States of America, 2000, 8th edition.

[8] Tavoularis, S., *Measurement in fluid mechanics*, Cambridge University Press, New York, United States of America, 2005.

[9] Taylor, G. I. and Maccoll, J. W., The air pressure on a cone moving at high speeds. I, *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, **139**, 1933, 278–297.