The effect of hemispherical surface on noise suppression of a supersonic jet

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ABSTRACT

High pressure gas venting operations, known as blowdowns, such as from natural gas pipelines, are known to produce significant noise. One device which has shown some potential for noise abatement is a hemispherical acoustic reflector, which has been observed to be effective for pressure ratios from 2 to 4. However, typical pipeline venting operations occur at pressure ratios far exceeding this. Therefore, the present study aims to experimentally investigate the influence of hemispherical noise reduction reflector on sonic jet flows at pressures more typical of pipeline venting operations. Results of experimental noise measurements from blowdowns with and without two different size acoustic reflectors are presented. The smaller acoustic reflector was found to strongly interact with the jet, in a manner making it unsuitable for extended use without a significant increase in structural support. The larger reflector showed levels of noise reduction on par with those seen at lower pressures. This suggests that acoustic reflectors of suitable scale, when appropriately structurally supported, are a suitable noise reduction method for the high pressure venting typical of blowdown operations.

1 INTRODUCTION

High pressure gas venting operations, known as blowdowns, such as from steam driven power plants and natural gas pipelines, and are known to produce significant acoustic noise. Noise generated by larger vents during such operations are known to reach 150 dB (Jungowski and Selerowicz, 1981). These levels of noise can be a health and safety concern for those working at the sites of such operations, and those living nearby. The simplest means of reducing blowdown noise is to reduce the jet velocity. However, this is often practically infeasible and/or undesirable. During the venting of natural gas for example, higher venting velocities allow volatile gasses to be ejected further upwards and away from potential sources of ignition (Smith et al. 2019). Therefore, the ability to design devices which allow for noise abatement without significantly influencing venting velocities is of practical interest.

Jet noise has three principle components, turbulent mixing noise, shock noise, and screech noise. These are discussed in turn. The turbulent mixing noise mechanism is explained in terms of turbulent structures distributed in the flow field of the jet. The turbulence leads to flow unsteadiness and hence sound generation. Turbulence generation will be concentrated at the jet edge, and so modifications which adjust the behaviour and characteristics of the edge flow, such as the velocity and turbulence profiles and intensity, will strongly influence turbulent mixing noise. Turbulent mixing noise typically dominates the lower frequencies for the far-field noise produced by a typical supersonic jet. In terms of spatial distribution, the large scale (Mach wave) turbulence noise is concentrated at aft angles, while the the fine-scale turbulence noise is more uniformly distributed.

Shock noise results from the interaction of turbulent structures with the shock waves caused by the turning of supersonic flow which occurs for underexpanded and overexpanded supersonic jet flows. Therefore, reducing the strength and number of shocks, as well as the amount of turbulence able to interact with existing shocks, is central to the control of shock noise. In terms of frequency distribution, shock noise tends to dominate at higher frequencies (rather than the turbulent mixing noise, or screech noise), while in terms of spacial distribution shock noise is concentrated within aft angles.

Screech noise is explained (Norum, 1983) in terms of a feedback mechanism between disturbances shed at the nozzle exit, interacting with shock cells. The interaction causes sound which travels back to the nozzle, creating additional disturbances and completing the feedback loop. It is known to be influenced by the exterior nozzle surface. Screech noise may be minimised by reducing the strength of the shock cells, or else interfering with the feedback loop which is typically achieved by reducing the azimuthal symmetry of the flow.

A number of strategies and devices have been proposed to help mitigate transonic and supersonic jet noise, including the use of chevrons (Kuo et al., 2012, Rask et al., 2007, Rask et al., 2006, Liu et al., 2009, Seiner et al., 2004, Khritov et al., 2005), bevels (Norum, 1983, Webster and Longmire, 1997, Tide and Srinivasan, 2009, Viswanathan and Czeck, 2011, Viswanathan et al., 2012, Viswanathan et al., 2011, Powers, 2012), fluidic inserts (Morris et al., 2013), corrugations and lobes (Seiner et al., 2004, Viswanathan et al., 2011, Powers, 2012, Mengle et al., 2002), post nozzle fluid injection (Brausch and Doyle, 1972a,b, Khritov et al., 2005, Greska et al., 2004), tabs (Norum, 1983, Samimy et al., 1993), the use of coflows (Dosanjh et al., 1971, Cocking and Bryce, 1975, Ahuja et al., 1990, Papamoschou and Debiasi, 2001, Rask et al., 2006), flexible filaments (Anderson et al., 1999, Bhat et al., 2000a,b, Gutmark, 2000, Lucas et al., 2013), post nozzle wires and meshes (Kweon et al., 2005), flow swirling (Yu and Chen, 1997, Neemeh et al., 1999, Balakrishnan and Srinivasan, 2017), nozzle plugs and porous nozzle inserts (Kibens and Wlezien, 1985), as well as reflection surfaces (Khan et al., 2003, 2004). Of these, the reflection surfaces have shown the capacity for the greatest noise reductions at observation angles (θ) of 90 degrees, which is usually the angle of interest for blowdown operations, as shown in Figure 1. The largest overall sound pressure level (OASPL) noise reductions achieved with reflection surfaces is approximately 24 dB (Khan et al., 2004). However, this device has only been tested for reservoir to ambient pressure ratios ranging from 2 to 4. and typical pipeline venting operations occur at pressure ratios almost two orders of magnitude higher. Thus, investigating the effectiveness of reflection surface type devices at higher pressure ratios is of potential practical interest. This paper presents the results of an experimental campaign involving field noise measurements of venting at higher pressure ratios with and without hemispherical acoustic reflectors.

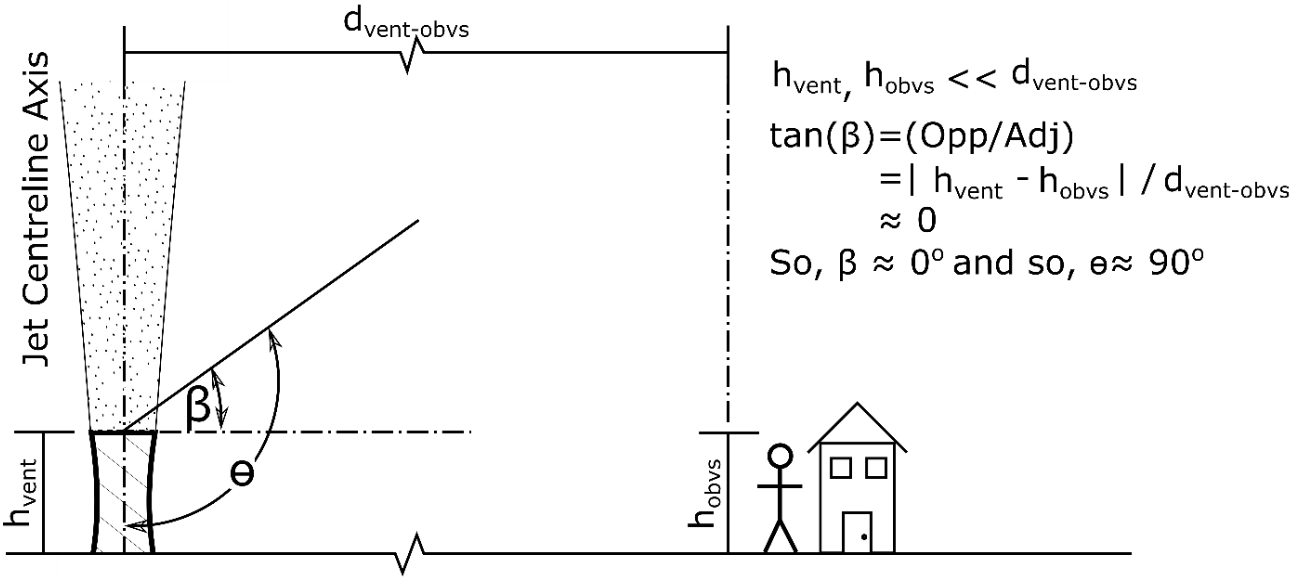

Figure 1: Typical field observation angle explanation via small angle approximation.

2 METHODOLOGY

The experiments were performed at a natural gas compressor station located near the town of Coomandook, South Australia. The blowdowns were vented from a 130 mm length of pipe with 15.78 mm internal diameter (nominal 0.5" STD Schedule). The pipe was attached to a bleed valve on a main line valve bypass supported with a structure to allow secure attachment of the acoustic as shown in Figure 2. The outlet height was 1.2 m above ground level. The main line pressure varied across the duration of the experiments, ranging between 11,244.24 and 11,238.07 kPag, or a pressure ratio of 111 relative to the ambient atmosphere, assumed to be 101,325 Pa. The jet is underexpanded and a pressure ratio of 111 corresponds to a Mach number of 3.77 assuming isentropic flow. The pipeline contained natural gas with 90% methane composition, when considered in terms of volume percent, at an initial temperature of 293 degrees Kelvin. Prevailing winds were easterly and around 15 km/hr and there had been light rain earlier in the day.

Acoustic data were taken using 3 GRAS free-field array microphones (Model 40PH CCP) recorded using a National Instruments PXI-4472B board at a sampling frequency of 102,400 Hz. Microphones were calibrated using a B&K type 4231 sound calibrator. The microphones were equipped with wind socks and mounted on 0.45 m long stings, located at a distance of 30 m from the vent stack pipe, and supported by a telescoping tripod such that the microphones were at a height of 1.2 m. The microphone arrangement is shown in Figure 3.

Considering the nominal vent pipe diameter (D) of 15.7 mm, the hemispherical acoustic reflectors had diameters of 15.7D (200 mm) and 28.3D (360 mm). The main line pressure was recorded across the course of all the tests. Full pressure venting periods ranged from 60 seconds for the pipe without any reflector, to 6 seconds for the 15D reflector. The test period with the 15D reflector installed was reduced due to oscillations threatening the structural integrity of the acoustic reflector. This is discussed in more detail in the Results section of this paper.

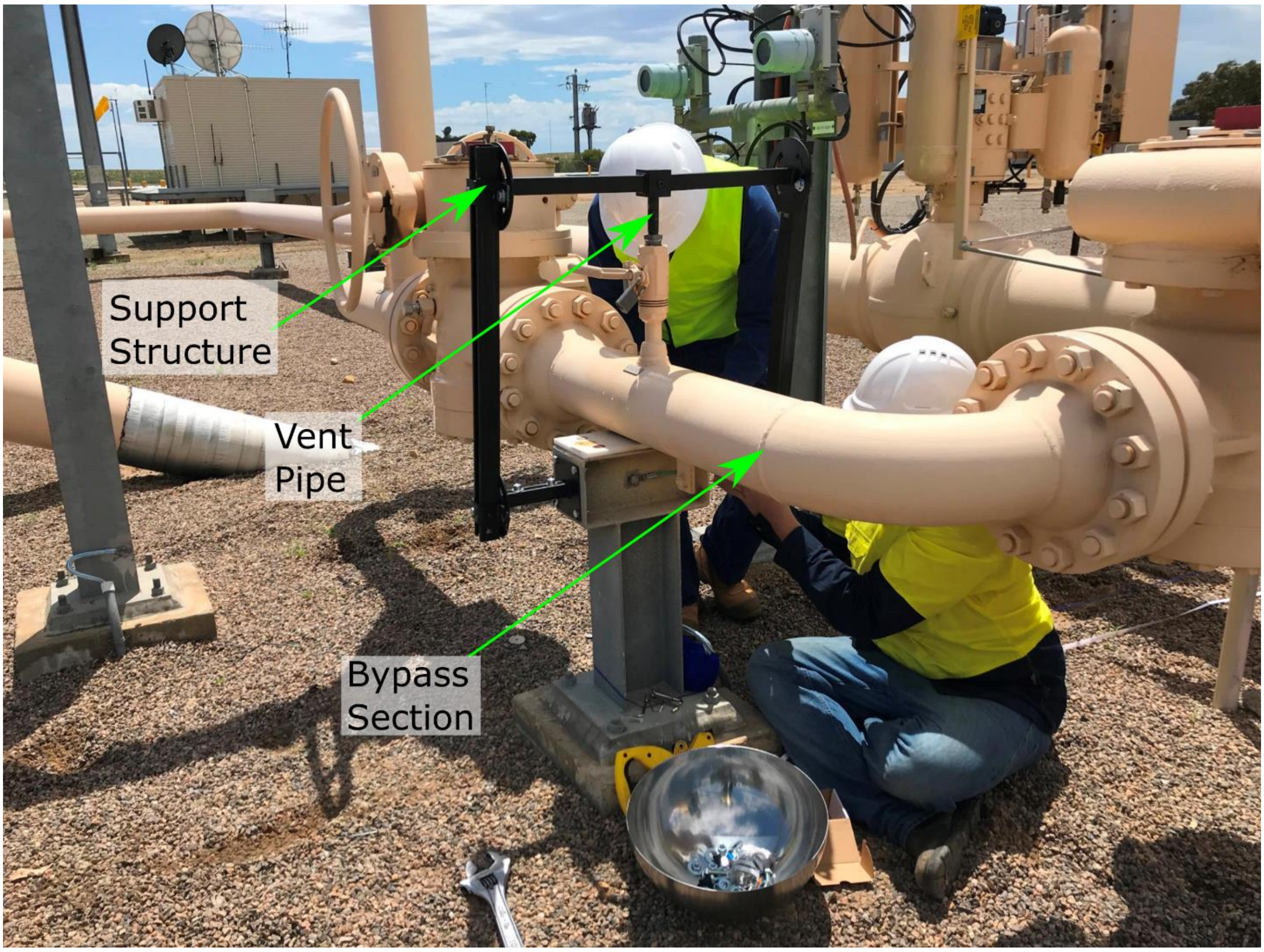

Figure 2: Blowdown vent stack arrangement.


Figure 3: Microphone apparatus arrangement. Left: without wind socks. Right: with wind socks.

3 RESULTS

Background noise levels were recorded over 160 s periods before and after the main experimental measurements. These acoustic measurements were processed into sound pressure levels relative to a reference pressure of 20 micro Pascals, the recording period divided into 0.02 second long windows and the OASPLs determined for each window. The (acoustic) average of these across the entire recording period may be used as a measure of the background noise and was found to be 48.1 dB and 49.5 dB for the background noise measurements taken before and after the main experimental measurements respectively.

The acoustic measurements for each microphone across the venting period were processed into sound pressure level (SPL) spectra calculated using Welch's periodogram, and both spectra and OPASLs were calculated using a reference pressure of 20 micro Pascals. These SPL spectra are given in Figures 4, 5 and 6 and the OASPLs in Table 1 respectively. Note that the data for the channel 1 microphone, when testing the large reflector have been omitted due to a technical fault in the apparatus. This shows that the 28.3D reflector achieves a 12.9 dB reduction in OASPL compared to venting without any reflector. In considering the difference between the spectra, as shown in Figure 7, it can be concluded that the greatest increases in noise observed for the 15.7D reflector over the levels of the 28.3D reflector occur across the frequency range 1800 to 7000 Hz and between 22,000 to 43,000 Hz, while a relatively uniform increase is observed elsewhere.

Table 1: OASPL results

Venting condition	OASPL (dB)
Pipe without reflector	109.9
15.7D reflector	110.5
28.3D reflector	97.0

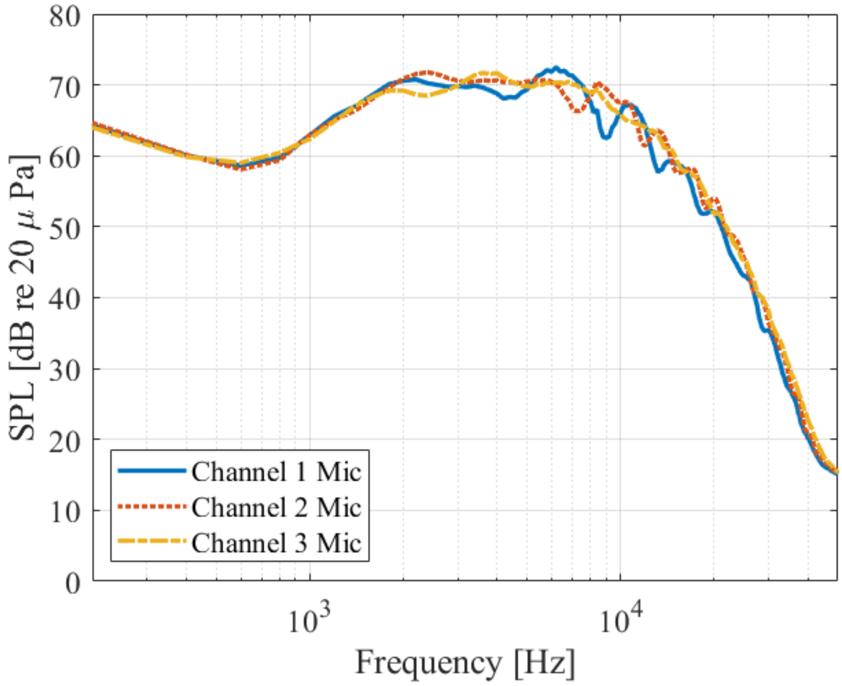

Figure 4: Venting spectra for pipe without acoustic reflector

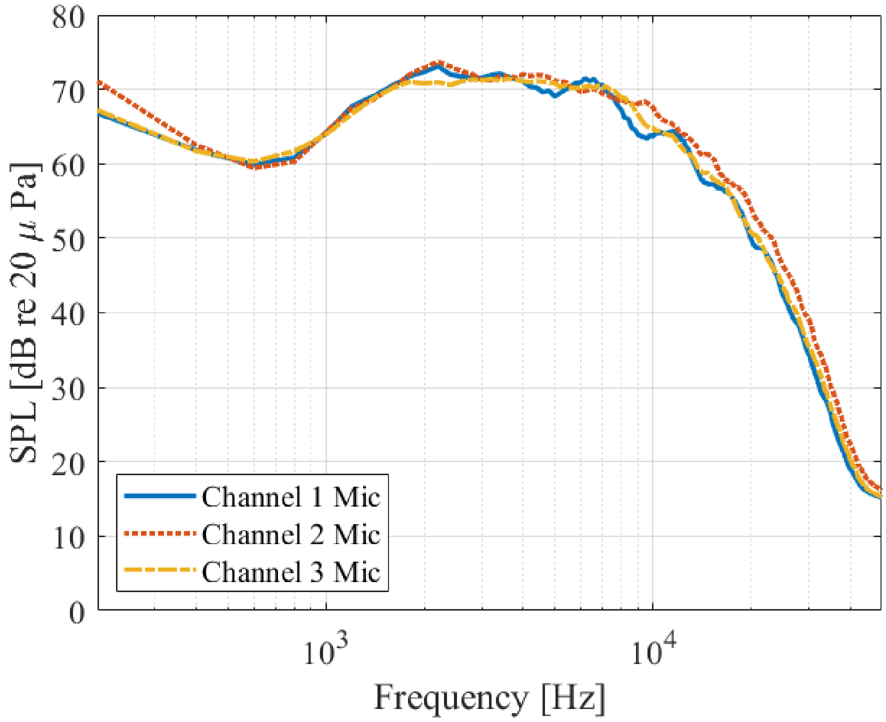

Figure 5: Venting spectra for pipe with 15.7D acoustic reflector

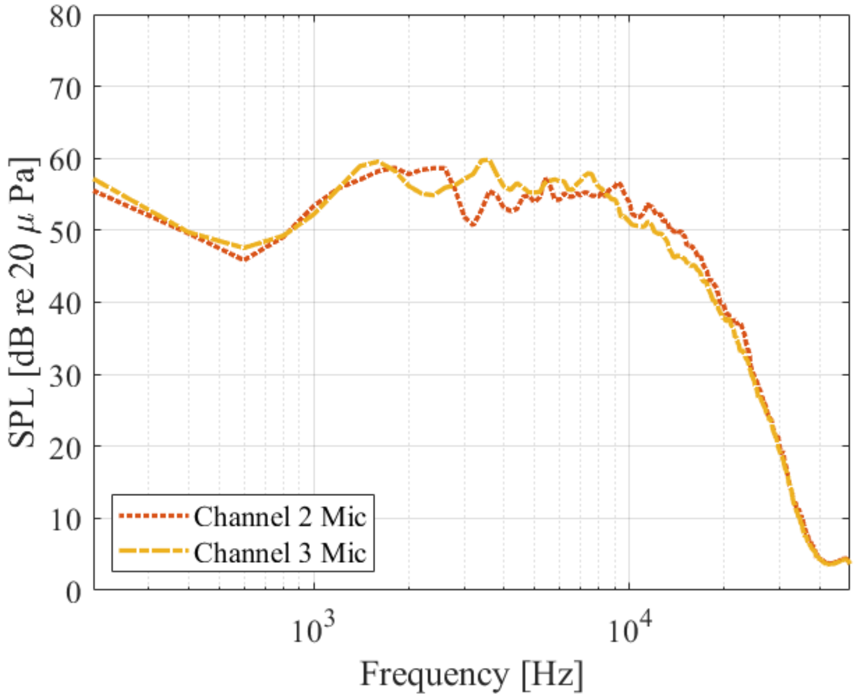

Figure 6: Venting spectra for pipe with 28.3D reflector.

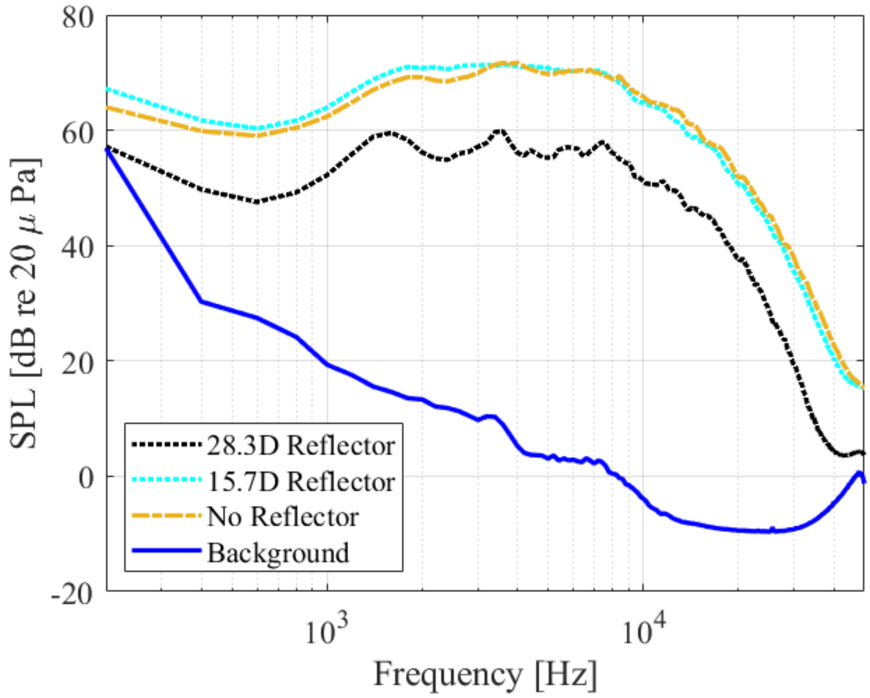

Figure 7: Comparison of spectra for Channel 3 Mic for each pipe configuration and the concluding background noise measurement.

Figure 8 compares the noise reduction results achieved in the present work to those of Khan et al. (2004) and highlights the significant difference in terms of operating pressure ratio between the results of the present work, and those from the literature, confirming the motivation for the present work and testing the effectiveness of acoustic reflectors at the high pressure ratios typical of blowdown operations.

Figure 9 shows the small reflector during blowdown in which the reflector structure was observed to couple with the jet, and for which an increase OASPL of 0.6 dB compared to the pipe without reflector. The noise due to the observed fluid-mechanical coupling could be characterised as wobble-board-like. Owing to concerns about the ability of the structure to endure these oscillations sustainedly, the blowdown period was reduced.

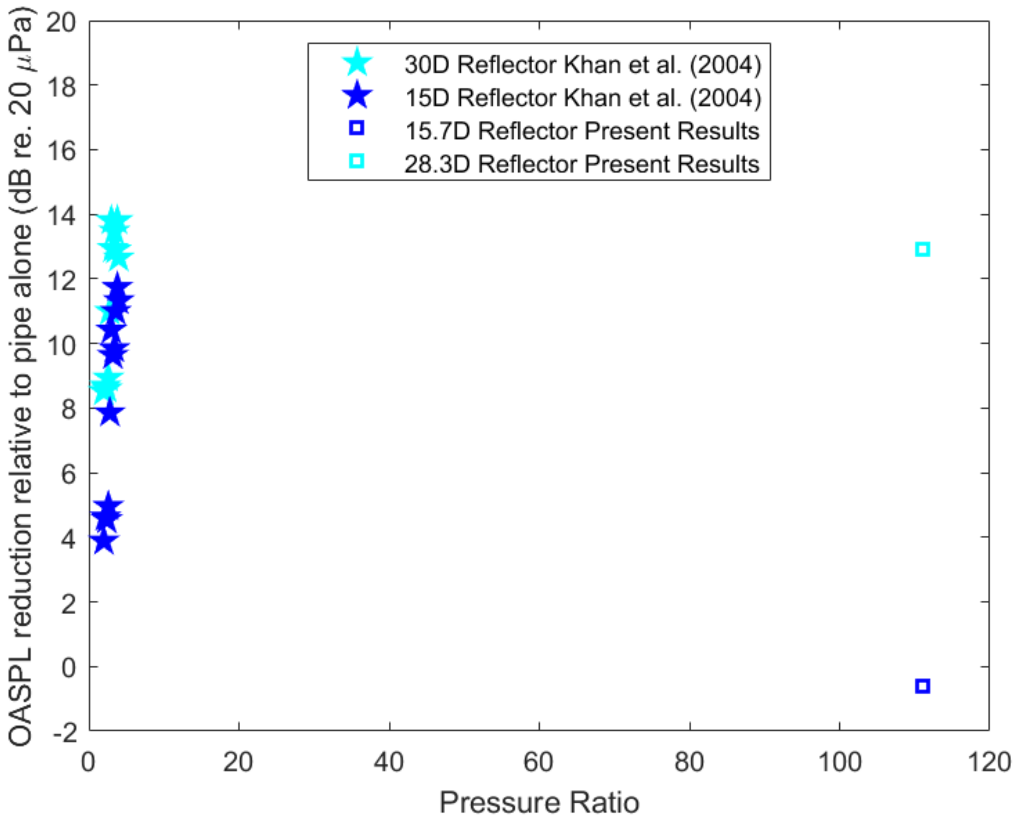

Figure 8: Comparison of noise reduction results at a 90 degree observation angle against those of the literature for a range of pressure ratios.

a)

b)

c)

Figure 9: 15.7 D acoustic reflector, a) Undeformed as jet develops, b) At approximate maximum deflection point in arbitrary direction c) At approximate maximum deflection point in approximately perpendicular direction

4 CONCLUSIONS

The results of experimental measurements of acoustic noise were presented for blowdowns venting at pressure ratios of 111. The smaller (15.7D) acoustic reflector, which had been demonstrated previously to reduce noise for lower pressure ratio jets, was seen to couple with the jet and resulted in an increase in noise relative to the pipe without any reflector. This was due to fluid-mechanical coupling between the acoustic reflector and the jet, resulting in oscillation in the reflector structure causing the reflector structure itself to radiate noise. No attempt was made to isolate these components in the current work, and further work would be needed to determine the effectiveness of a more structurally substantial 15.7D reflector under otherwise unchanged conditions. The increase in structural support may be achievable my use of a thicker material for the reflector as well as additional supporting structure, rather than, relying solely on supporting the reflector through its base. However, using a larger diameter reflector, could also be be expected to be effective at minimising any coupling and the resulting noise that this causes. The larger reflector (28.3D), was found to produce a 12.9 dB reduction in OASPL relative to the pipe without a reflector. This reduction is somewhat less, but largely consistent with the trend of results for the highest-pressure jets investigated by Khan et al. (2004) which for a 30D reflector had a 13 dB reduction at a pressure ratio of 4, the highest pressure ratio they investigated. This confirms that an appropriately scaled and designed acoustic reflector is capable of achieving marked reductions in the acoustic noise radiated at 90 degreed to the jet centreline axis, by the high speed, high pressure jets typical of typical blowdown activities.

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