Acoustic characteristics of annular jets

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ABSTRACT

Annular jets are widely used in gas turbines and burner due to stability over free jet; it introduces highly strained, recirculated turbulent flows and low NO_x emissions. Present article compares acoustic features of annular jets formed with different blockage area and free jet. This study is carried out for nozzle pressure ratio (*NPR*) varying from 1.5 to 5. Various noise parameters such as turbulent noise, broadband shock associate noise and screech are compared separately. It is found that increase in blockage area reduces the overall noise except small region and occurrence of screech shifts to higher *NPR*. Addition to this directivity study is carried out for specific *NPR*. Further flow visualization is carried out to support acoustic data.

Keywords: Annular Jet, Acoustic Power, Screech   I-INCE Classification of Subjects Number: 21.6.1

1. INTRODUCTION

Annular jets are extensively used in industrial treatment processes, glass fiber processing and in combustion as burners. Apart from this annular jets have large scope in aviation industry for the thrust production. High rate of thermal and fluid properties exchange makes jet flows very fruitful in many applications. However these same features are responsible for broadband noise generation, such as high rate of turbulent mixing, Mach wave radiations at high speeds. From Second World War jet noise has been investigated very extensively due to its application in high speed air transportation. Lighthill's (1, 2) theoretical work followed by Powell's (3, 4, 5) extensive experimental work during mid of 20th century made the foundation of aeroacoustic. There is lot of literatures available, which describes various jet noise components for different configuration of nozzles from simple orifice, pipe to convergent and convergent divergent nozzles with various contours, from circular to non circular (triangle, rectangle, ellipse etc,). To enhance the payload capacity or to optimize the efficiency with altitude aerospike nozzles are employed in which overexpansion process losses are controlled by exposing the inner wall of the nozzle to an ambient pressure. During last 5-6 decades many researchers demonstrated that jet noise varies very drastically with nozzle exit conditions. Recently Karthikeyan et. al. (6) and Frendi et. al. (7) deals with aero acoustical experiments of aero spike nozzles. However very less aeroacoustic study of annular jet (truncated spike nozzles) is carried out. This article deals with various acoustic parameters of annular jets in both subsonic and supersonic regime.

Generally annular jet is consists of circular jet with bluff body or cylinder at centre which is responsible for recirculation zone near the jet exit. Figure 1 shows the basic structure of subsonic annular jet. Annular jets are classified as small diameter ratio (d_i/d_o where d_i is diameter of solid plug or internal diameter and d_o is outer diameter) and large diameter ratio (larger than 0.7). Recently Danlos et al. (8) carried out flow analysis of annular jets of large diameter ratio. Present article compares free jet with three annular jets having diameter ratios of 0.4, 0.6 and 0.8. The main objective of our work is to find the acoustic power of annular jet and compare with free jet and variation of screech frequency.

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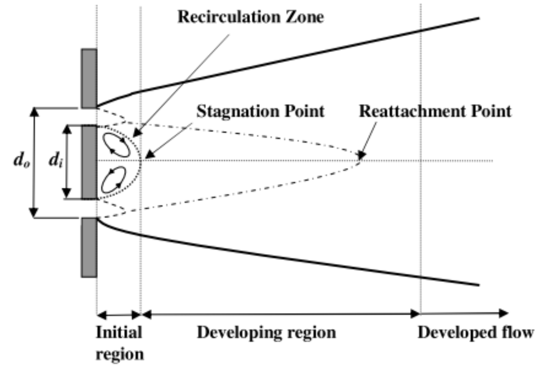

Figure 1 – Basic structure of subsonic annular jet

2. EXPERIMENTAL SETUP

2.1 Anechoic Chamber and Jet Facility

Experiments are carried out in a semi-anechoic room of size 2.5m x 2m x 2m (wedge tip-to tip) as shown in Figure 2. Polyurethane square pyramidal wedges of 6 and 3 inches are fixed to all inner surfaces except the floor. The chamber floor lined with carpet. The chamber is anechoic for frequency above 700 Hz.

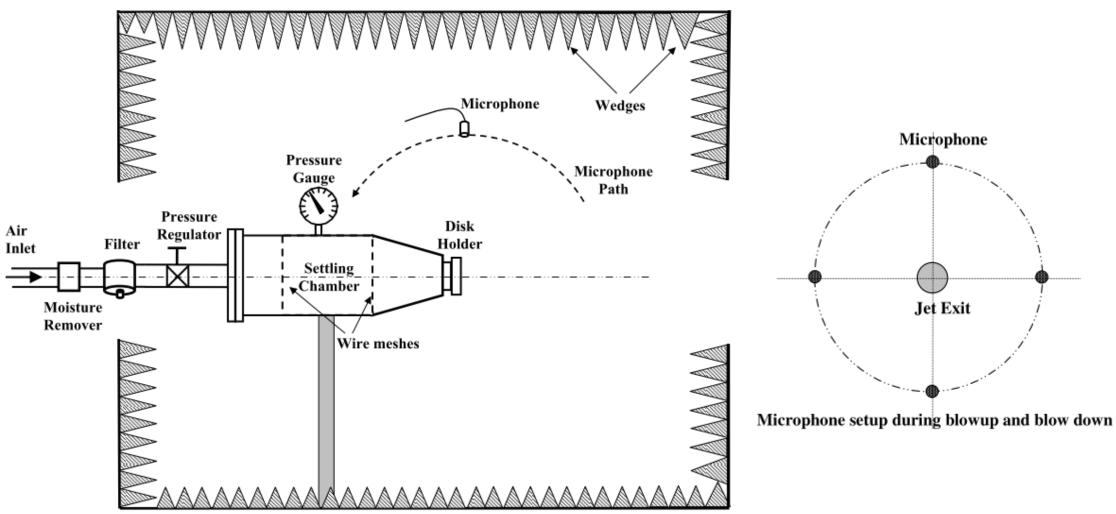

Figure 2 – Schematic view of the jet facility inside the anechoic chamber with Microphone setup

The cold free-jet test facility consists of settling chamber fixed inside anechoic room. The settling chamber has the dimensions of internal diameter of 380 mm and the length of around 700 mm connected to pressure regulating valve by pipe at one end and convergent opening at another end to fix orifice or nozzle. The settling chamber is converged from 380 mm to 43.5 mm in 100 mm distance where the required nozzles can be mounted easily. Initial disturbances such as turbulence and structure borne acoustic perturbations are mitigated by fixing progressive meshes and coating inner wall with foam respectively.

The air is compressed using a reciprocating air compressor and stored in the two reservoir of total capacity of 20 m^3. The compressor compresses the air up to 7.5 bar gauge. 4-inch pipe is used to supply the compressed air from the reservoir to the settling chamber. Moisture separator and filters are fixed in pipe line to make air moisture and dust free respectively. To lessen the internal acoustic reflections from metallic surfaces are layered with acoustic foam.

2.2 Measurement and Instrumentation

A quarter inch Bruel and Kjaer microphones are used for the entire acoustic measurement. Signals are acquired by filtering at 70 KHz using low pass analog filter (Krohn-Hite Model No. 3364), and sampling at the rate of 150000 samples/sec. A piezo-resistive pressure transducer (Endevco model no. 8510C-100) mounted inside the settling chamber is used to measure settling chamber pressure. Data acquired during the experiments, is taken to frequency domain using a Matlab based FFT algorithm and overall sound pressure level ($OASPL$) and sound pressure level (SPL) is analyzed.

2.3 Blowup and Blow down Study

Blowup and blow down tests are executed to reveal the noise variation with respect pressure ratio/Mach number and also helps to find hysteresis effect if present. For these tests, 10 mm diameter orifice and annular are used and three microphones are placed at a distance of $20d_o$ from the centre of the jet exit at an emission angle of 90^{o} and one microphone at $40d_o$ at an emission angle of 90^{o}. The pressure regulating valve is fully opened and the compressor is started so that pressure is built in the reservoir as inflow is larger than outflow. When the reservoir pressure is crosses 6 bar, the compressor is stopped. The stagnation pressure and acoustic pressure are obtained continuously using Endevco piezo-resistive pressure transducer and Bruel and Kjaer microphones respectively. The data collected in between starting and stopping the compressor is called blow up study and the data collected after stopping the compressor still complete draining of reservoir through the orifice is called blow down study. The acoustic measurements are carried out for the nozzle pressure ratio ranging from $1.4 \leq NPR \leq 6$.

2.4 Annular Jet Models

Free Jet and three annular jets with diameter ratios of 0.4, 0.6 and 0.8 are studied extensively. Schematic views are shown in Figure 3. Free jet consists of 10 mm orifice with 3mm thickness where as annular jets are made of same orifice as that of free jet with solid cylinder of different diameters (4, 6 and 8 mm) at the centre.

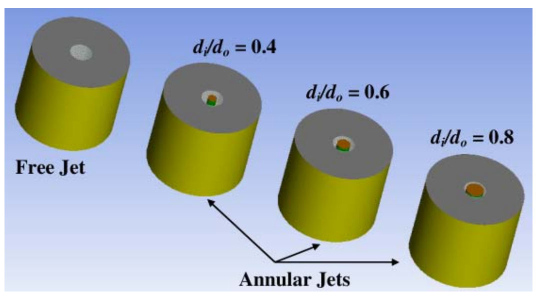

Figure 3 – Schematic view of the Annular jets

2.5 Flow Visualization

To reason out in the variation of acoustic power of annular jets and free jet, flow visualization is carried out. High speed schlieren technique which is based on the refractive index variation due to density gradients is used for the flow visualization. Schlieren setup schematic is shown in Figure 4 which is consists of light source, condenser lens, expander, beam splitter, two biconcave lens, knife edge and camera.

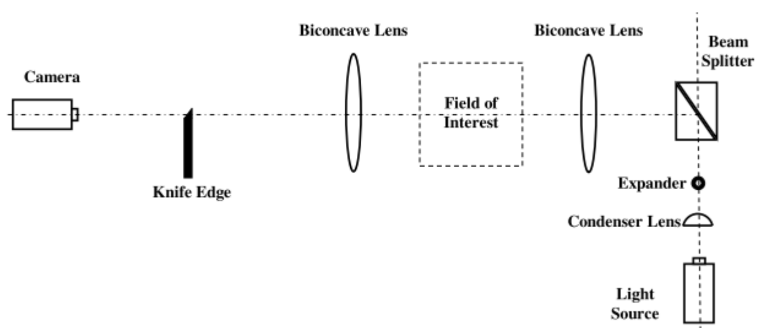

Figure 4 – Schematic view of the schlieren setup

2.6 Uncertainty Analysis

The microphones are calibrated using the piston-phone calibrator of frequency 250 Hz and 124 dB power. The piezo-resistive transducer used in blow up and blow down test to obtain the stagnation pressure data has an uncertainty of ±0.2 % of full scale. The anechoic room temperature is almost constant with a maximum temperature variation of $\pm 1^{o}$ C for each trial of experiment. The sound pressure level reported here is relative to the reference pressure of 20 μPa. The error in microphone positioning is ±1 mm. The frequency resolution based on the FFT size is 37 Hz over the range of frequency from 630 Hz to 70 KHz. The noise level was repeatable within ±1 dB.

3. RESULTS AND DISCUSSION

3.1 Acoustic Study

3.1.1 Acoustic measurements during blowup and blow down study

To understand the effect of hysteresis and effect of *NPR* on *OASPL* blowup and blow down study is carried out by keeping 4 microphones at different locations. It is observed that the *OASPL* does not vary during both processes for all the nozzles indicating there is no hysteresis. *OASPL* variation with respect to *NPR* observed by microphone placed at $16d_o$ for annular jets with d_i/d_o = 0.4 and 0.6 are indicated in Figure 5 and then blow down *OASPL* of all nozzles are compared in Figure 6. It is clearly seen in Figure 6 that the *OASPL* decreases with increase in diameter ratios except in some region it is also seen that this drop off in *OASPL* increases with *NPR*. In supersonic regime for all nozzles one *OASPL* sudden jump appears except d_i/d_o = 0.8 and this jump shifts with diameter ratio. For instance for free jet it occurs at *NPR* = 2.6, for d_i/d_o = 0.4 it occurs at *NPR* = 3.4 and for d_i/d_o = 0.6 it occurs at *NPR* = 4.2 and 5.4. To identify jump in *OASPL* spectral analysis is carried out, which is discussed in next section.

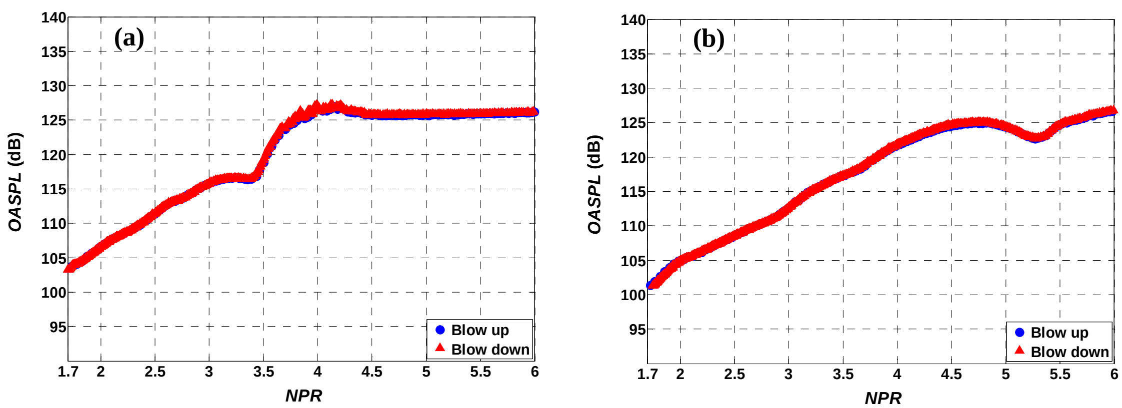

Figure 5 – Variation of *OASPL* with respect to *NPR* for (a) d_i/d_o = 0.4 and (b) d_i/d_o = 0.6

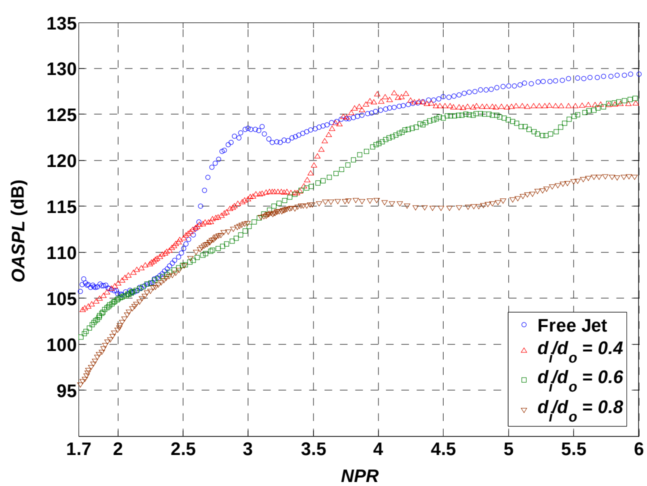

Figure 6 – Comparison of *OASPL* for free and annular jet at different *NPR*

3.1.2 Spectral Analysis

Detail analysis of amplitude of all frequencies in the range of 1000 Hz to 50000 Hz for *NPR* varying from 1.7 to 6 is carried out. It shows that the jump in *OASPL* is due to the presence of screech and its harmonics. For instance free jet it occurs at *NPR* =2.6 to 3.2 both screech and its harmonics are present and then harmonics diminishes while screech is present up to *NPR* = 6.0, while for annular jet with d_i/d_o = 0.4 and 0.6 it occurs at *NPR* = 3.8 and 4.2 respectively. However for high diametric ratio annular jet i.e; d_i/d_o = 0.8 screech is absent. It is clearly visible in Figure 7. To illustrate the effect of broadband noise spectra of free and annular jets at *NPR* = 3.0 and 5.0 are compared in Figure 8 (a) and (b) respectively. Apart from screech the broadband shock associated noise enhances the *OASPL* of free jet at *NPR* = 3.0 and 5.0, where as for annular jet with d_i/d_o = 0.4 this noise parameter is responsible at *NPR* = 5.0. Further the directivity and acoustic power of these jets is measured for *NPR* = 2.0, 3.0, 4.0 and 5.0.

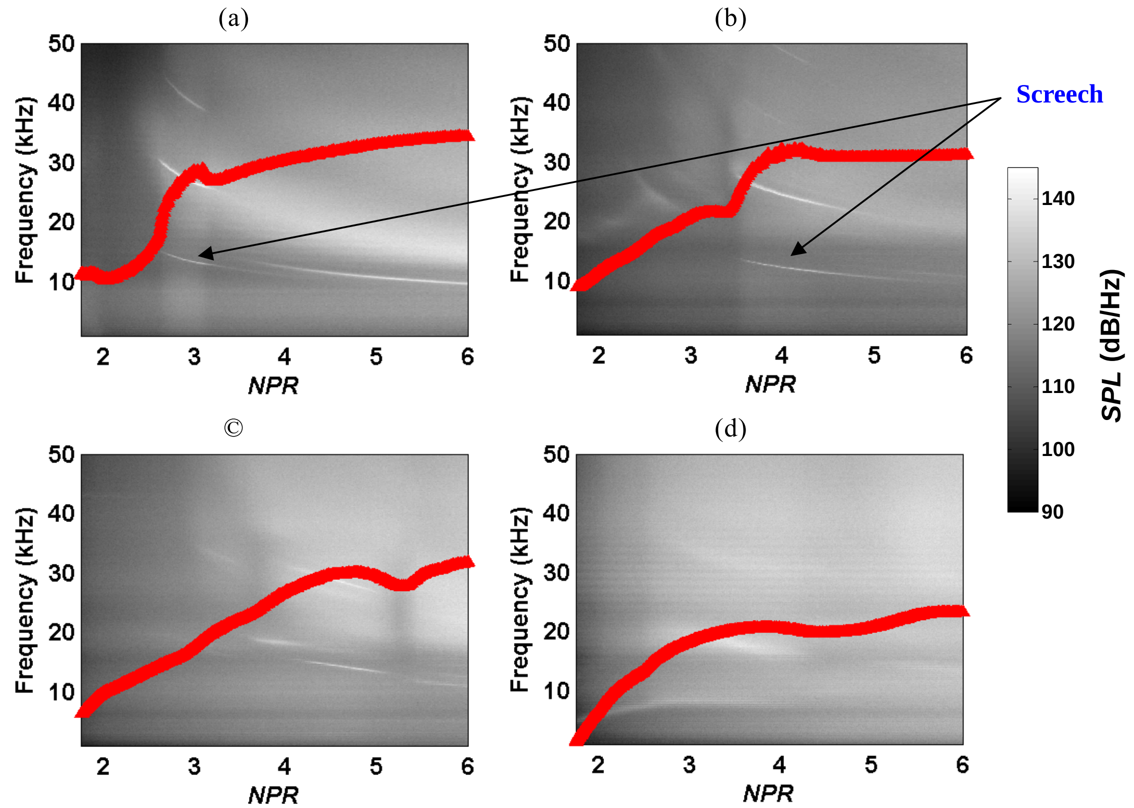

Figure 7 – Spectral Analysis of (a) free jet and annular jets with d_i/d_o (b) 0.4 (c) 0.6 (d) 0.8

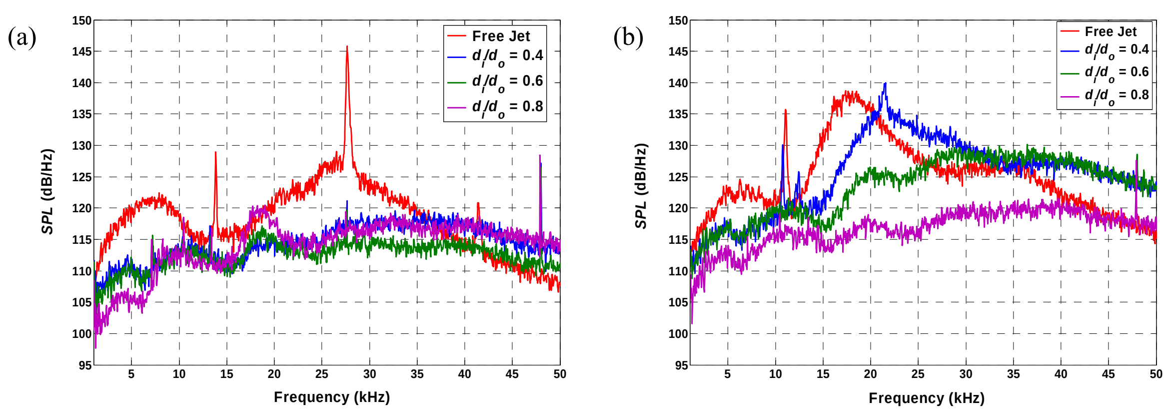

Figure 8 – Spectral Analysis of free and annular jets at (a) *NPR* = 3.0 and (b) *NPR* = 5.0

3.1.3 Directivity and Acoustic Power

Microphone is fixed to angular traverse and moved in the arc of radius = $40d_o$ from jet exit and starting 45^o to the jet axis and ends at 130^o. For free and small diameter ratio the directivity is similar but for high large diameter ratio is *OASPL* is more in upstream direction. Directivity pattern for free and annular jets is shown in figure 9, for *NPR* = 4.0 and 5.0. Acoustic power of all nozzles are calculated from directivity, it is found from Figure 10, that the acoustic radiations are more for annular jet in subsonic case and variation is small but in supersonic cases free jets are more noisy compared to annular jets. Further as diameter ratio increases annular jets radiates less acoustic power. Next section deals with flow structure, which causes these effects.

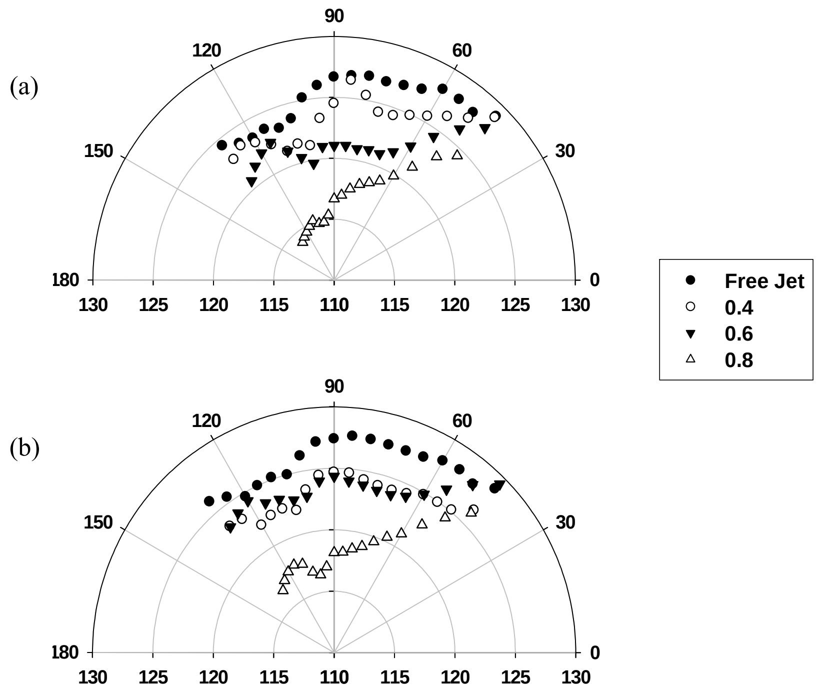

Figure 9 – Directivity of free and annular jet at (a) *NPR* = 4.0 and (b) *NPR* = 5.0

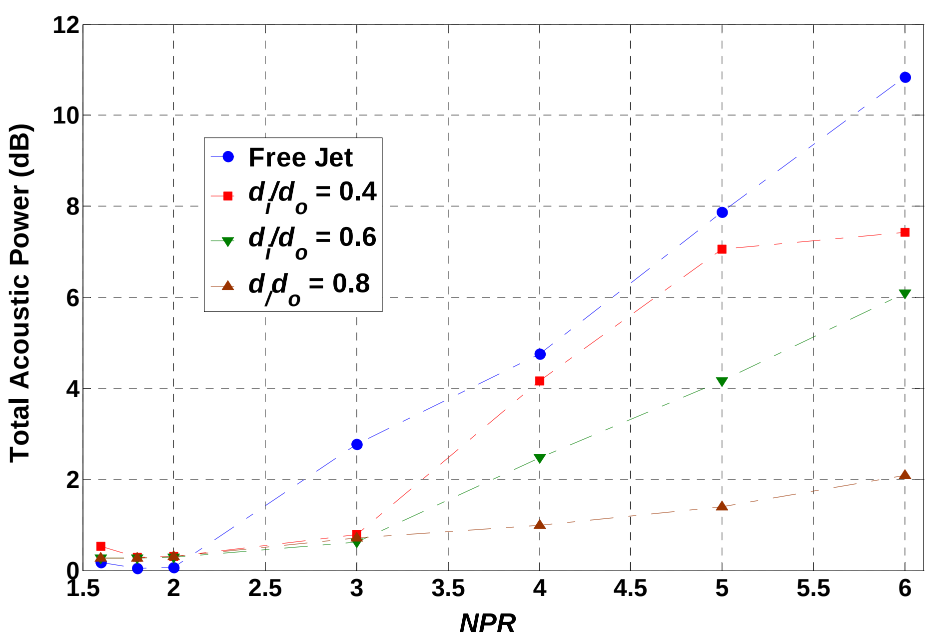

Figure 10 – Acoustic power comparison of free and annular jet

3.2 Flow Visualization

Variation in acoustic power is more at high *NPR* so high *NPR* = 5.0 is selected to demonstrate the flow structure difference. Figure 11 shows schlieren of free and annular jets at *NPR* = 5.0. Figure 10 clearly indicates that shock cells are strongly affected by bluff body present at the centre of annular nozzles. For free jets shock cells are stronger compared to annular jets. First shock cell length decreases as the diameter ratio increases. Thus causes reduction in broad band shock associated noise and delay in screech which is observed in previous subsections.

Free Jet

$d_i/d_o = 0.4$

$d_i/d_o = 0.6$

$d_i/d_o = 0.8$

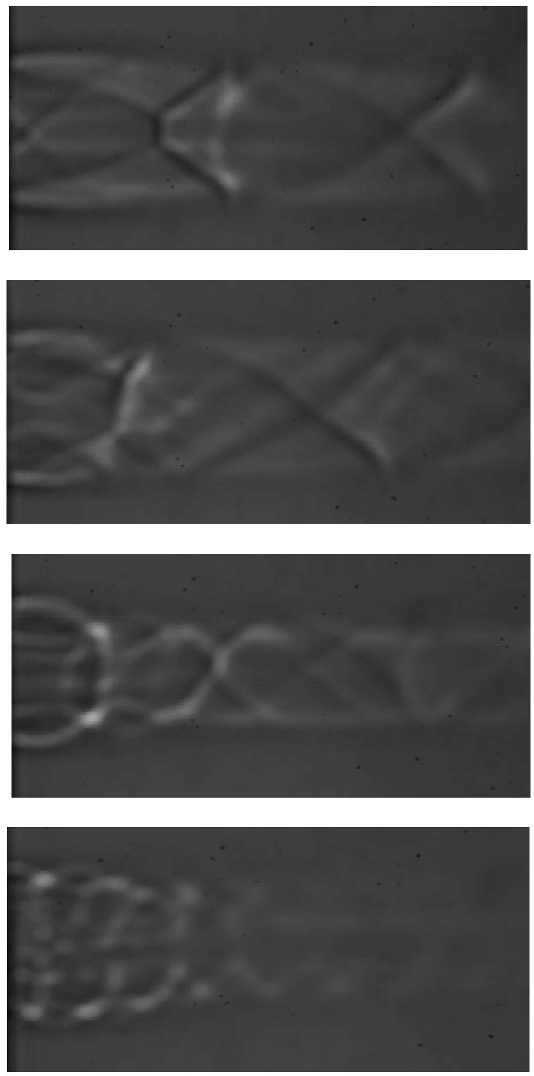

Figure 11 – Flow Visualization (schlieren) of free and annular jet at *NPR* = 5.0

4. CONCLUSIONS

Detail acoustic and flow visualization study of free and annular jets reveled that acoustic power of annular jet for low *NPR*, but not significant. As *NPR* free jet radiates more acoustic power compared to annular jets and as diameter ratio of annular jet increases the acoustic power decreases. In case of annular jets screech delayed compared to free jet and this delay increases with increases in diameter ratio due to decrease in shock strength and size which is the main cause of both broadband shock associated noise and screech.

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