Supersonic impinging jet noise reduction using co-axial swirler

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ABSTRACT

Supersonic impinging jet noise reduction is an important problem, especially in STOL aircraft, VTOL aircraft and rockets. These types of impinging jets generate a larger amount of noise and highly unsteady flows, which lead to noisy environment, posing a hazard to humans and materials in the proximity. The present study is carried out on supersonic impinging cold jets for nozzle pressure ratio (NPR) values of 2 and 5 with nozzle to plate distance (x / D) of 5, at different swirl numbers. The swirl flows are generated using co-axial curved blades and the results were compared with non-swirl or free jets. The vane angles considered here are 20°, 40°, 60° and the swirl numbers ranged from 0 to 1.31. At NPR 2, the weak swirl number of 0.27 reduced the OASPL level by around 7 dB compared to non-swirl jets. The non-swirl jet emitted impinging tones at NPR 5 and the swirl jet eliminated the impinging tones. At a high swirl number of 1.31, at NPR 5, OASPL is lowered by around 12 dB compared to non-swirl jets. The flow visualization study shows that the swirl disintegrates the repeated shocks and reduces the length of the shock cell system.

Keywords: Co-axial swirl, Impinging jet, Noise reduction. I-INCE Classification of Subjects Number: 13.1.3

1. INTRODUCTION

The impingement of a jet perpendicular to a plate or ground plane is employed in applications such as heat transfer in plates, cooling of turbine blades and high speed exhaust from S/VTOL aircraft and spacecraft. The noise from theses impinging jets may have adverse effects such as a highly noise environment or highly unsteady loads on nearby structures and ground erosion. The present experimental work is carried out on supersonic jet impinging perpendicular to the plate at a nozzle to plate distance (h/D) of 5 and the nozzle pressure ratio (NPR) of 2 and 5. Co-axial swirl is employed as a tool for noise mitigation. Some introduction to the flow and acoustic aspects of the study is presented below.

1.1 Swirl Number (S)

The swirl number is used to quantify the amount of swirl introduced in the axial flow. The swirl number for the co-axial fixed vanes can be calculated (1) from Eq. (1).

$$S = \frac{2}{3}\left(\frac{1-\left(D_h/D_s\right)^3}{1-\left(D_h/D_s\right)^2}\right)\tan\theta \tag{1}$$

where, D_h and D_s are hub and swirler diameters in mm, and

θ is the vane angle in degrees.

Generally, no recirculation regions are observed in the case of weak swirl ($S \leq 0.4$), while the width of the jet increases compared to the non-swirl case. The high swirl case ($S \geq 0.6$) shows recirculation regions at the center of the jet due to the presence of strong axial and radial pressure gradients (2). For the non-swirl, no significant tangential velocity components are observed, and the swirl number is always zero ($S = 0$).

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1.2 Flow structures of supersonic co-axial swirl impinging jet

Figure 1 shows a supersonic co-axial swirl impinging jet. It consists of a free jet region, an impinging region and a wall jet region. The plate obstruction is not felt by the jet in the upstream in the free jet region. The region where the jet impinges on the plate is called as jet impinging region. Subsequently, the jet is directed radially, parallel to the plate in the wall jet region.

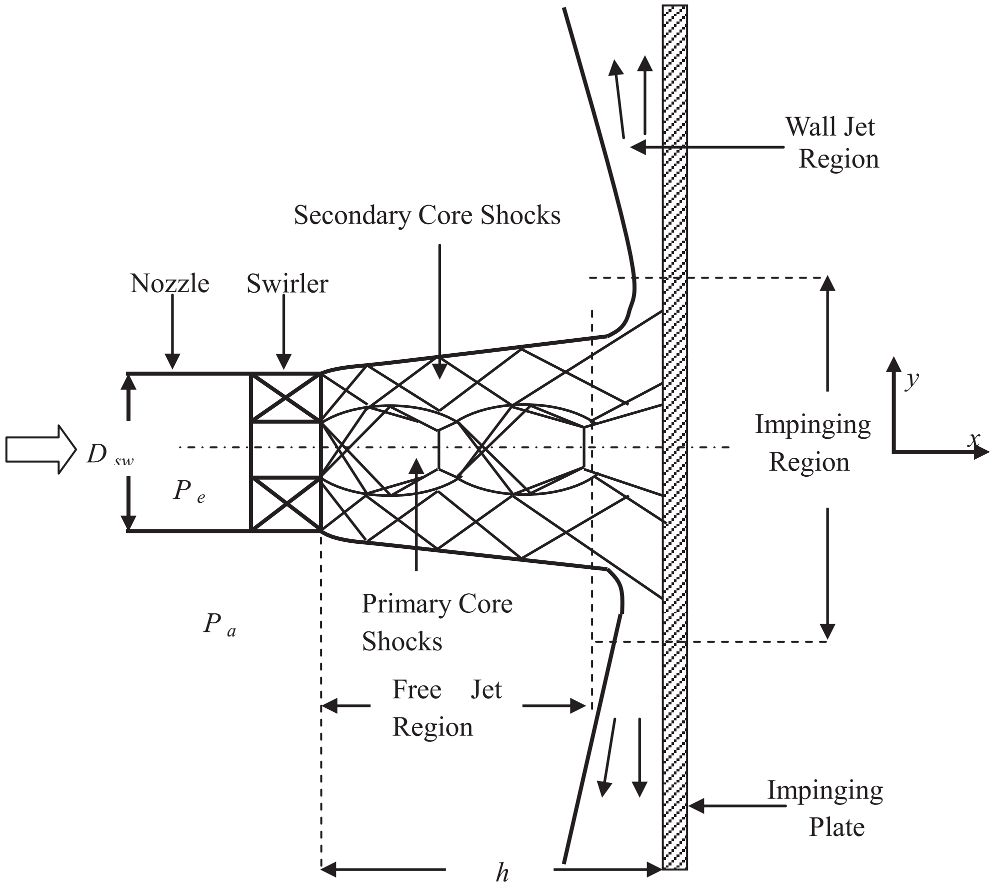

Figure 1 – Flow structures of a supersonic co-axial swirl impinging jet

The swirl jet increases the impinging region and enhances radial uniformity, in contrast to a non-swirling jet (3). The co-axial swirl jet generates shock cells in both primary and secondary core regions and these interactions depend on the vane angle and NPR.

1.3 Acoustic characteristics

In general, the noise from a free jet comprises turbulent mixing noise, shock associated noise and screech tones. However, when a jet impinges on a plate, additional tones are generated, termed as impinging tones. The turbulent mixing noise is caused by the mixing of the jet fluid with the ambient fluids and exists irrespective of the jet speed/NPR. The broadband shock associated noise (BSAN) is caused by the interactions of the downstream convecting large scale structures with the shock cells. The screech tones and impinging tones originate due to the feedback loop mechanism. The instability waves generated at the nozzle lip propagate downstream and hit the plate or a shock-cell, which causes acoustic waves that propagate back to the nozzle lip, triggering new instability waves. Thus, an acoustic feedback loop is completed, generating a tone.

However, the feedback loop mechanism can be controlled by passive or active noise control techniques. Elavarasn et al. (4) used passive techniques to control the feedback loop mechanism and 11 dB over all sound pressure reduction was achieved in the near field. Similarly, the passive control techniques using tabs also eliminates or attenuates the screech tones and shock associated noise in free jets (5). The present work employs swirl as a passive tool for noise reduction and investigates the effect of swirl number on impinging jet noise.

2. EXPERIMENTAL METHODS

The acoustic study is carried at the Thermodynamics and Combustion Engineering Laboratory, Department of Mechanical Engineering, IIT Madras. Figure 2 shows a layout of anechoic facility. The cold air is compressed by a 150 HP compressor and stored in two storage cylinders, before it is brought to the settling chamber. A condenser microphone PCB 377A01 is used for the far field measurements and a high speed digital camera Mikrotron MC1302 is used to capture the shock cell patterns.

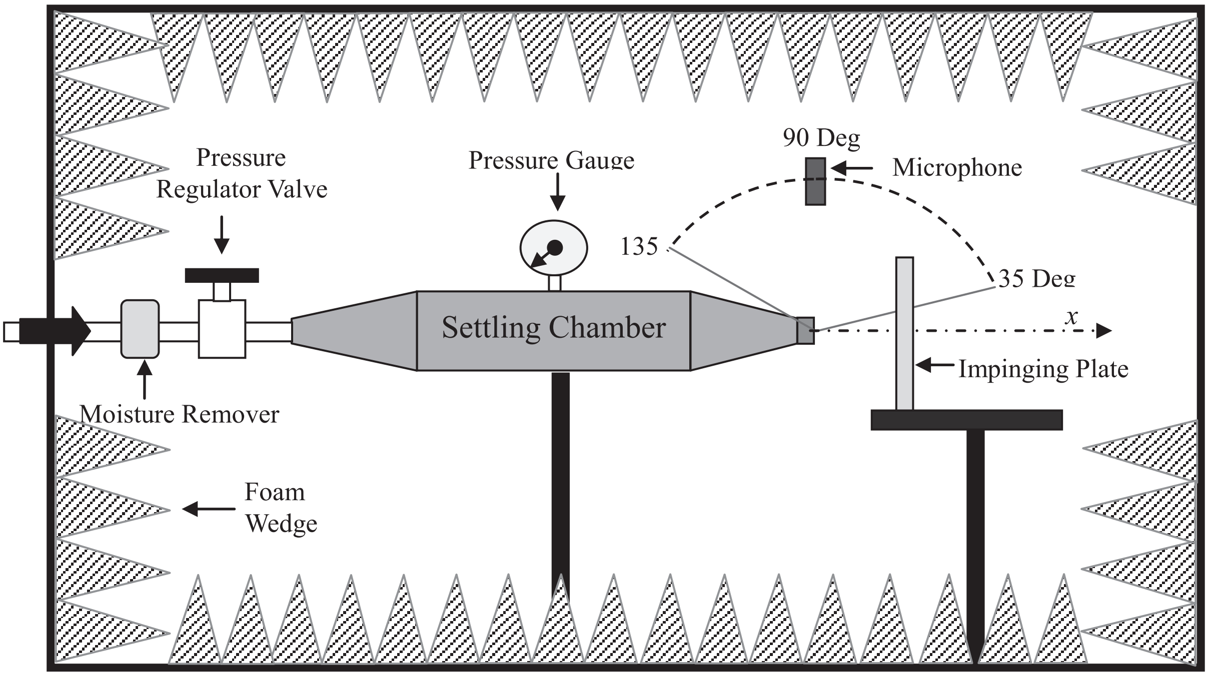

Figure 2 – Layout of Anechoic jet facility (Not to scale)

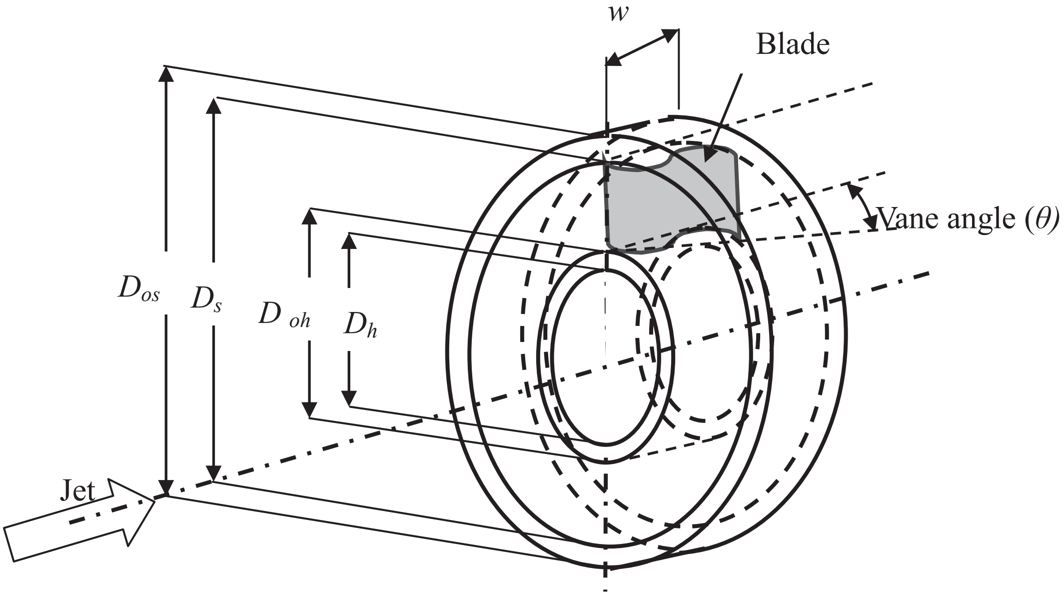

Figure 3 – Schematic of co-axial swirl jet (Only one blade shown here)

The co-axial swirl jet models are manufactured with an outer (D_{os}) and inner (D_{is}) diameter of 14 and 16 mm, respectively, and with a width (w) of 6 mm. The blade thickness (t_b) and hub thickness (t_h) are 1 mm each, and the number of blades (n) are 6. The non-swirl jet is made with a diameter (D) of 14 mm, which leads to the same equivalent area as that obtained by subtracting the frontal blocking areas of the swirler (six blades and hub frontal areas). The jet models are manufactured using Eden 350V Rapid Prototyping Machine and the material used is photopolymer resin. Figure 3 shows a schematic of the co-axial swirler and the Table 1 shows the swirl numbers used for the present work (calculated from Eq.(1)). The notation 'SCV' shown in Table 1 denotes "Swirler with Curved Vanes" followed by the vane angle. For, example SCV20 refers to a swirler with curved vanes with 20^{o} vane angle.

Table 1 – Swirl number for various curved blade vane angles

Test Model	Vane angle (θ) in Deg	Swirl number (S)	Types of Swirl
Free Jet	--	0	Non-Swirl
SCV20	20	0.27	Weak Swirl
SCV40	40	0.63	Medium Swirl
SCV60	60	1.31	High Swirl

3. RESULTS AND DISCUSSION

3.1 Spectral characteristics

The spectral characteristics of impinging jets at NPR 2 for an emission angle of 130^{o} are shown in Figure 4. It is observed that a single impinging tone exists for a non-swirl jet. However, the swirl jet eliminates the impinging tones. Also, the swirl jet radiates lowest noise at all the frequencies compared to the non-swirl jet. SCV20 swirl jet emits the lowest noise over a wide range of frequencies.

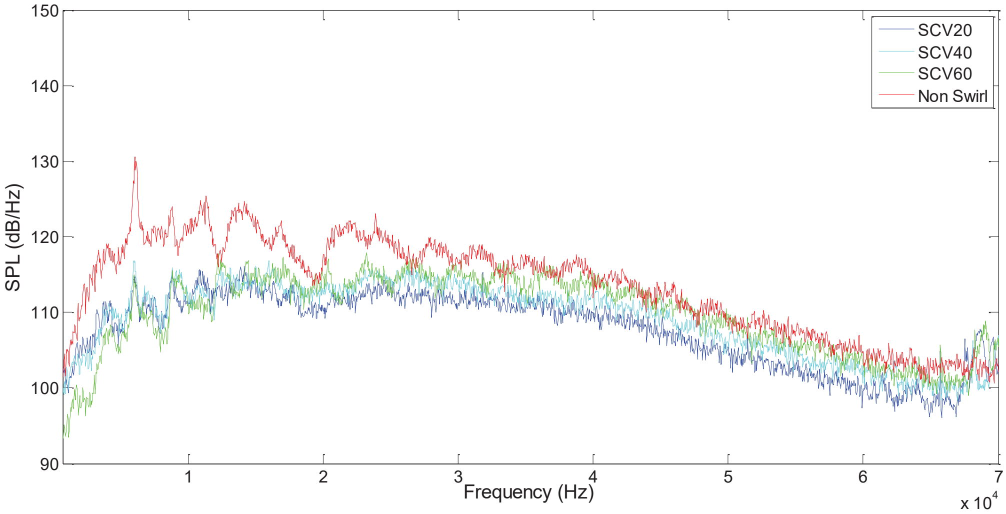

Figure 4 – Spectral characteristics at NPR 2 and emission angle 130^{o}

Figure 5 compares the spectra of impinging jets at NPR 2 for an emission angle of 110^{o}. It is observed that SCV40 and SCV60 swirl jets radiate lower levels of low frequency noise and higher levels at high frequencies due to the breaking up of large scale turbulence structures in to fine scale turbulence. Thus, the high frequency noise component is higher for high swirl number jets. The increased turbulence is brought about by the increase in vane angle and swirl number.

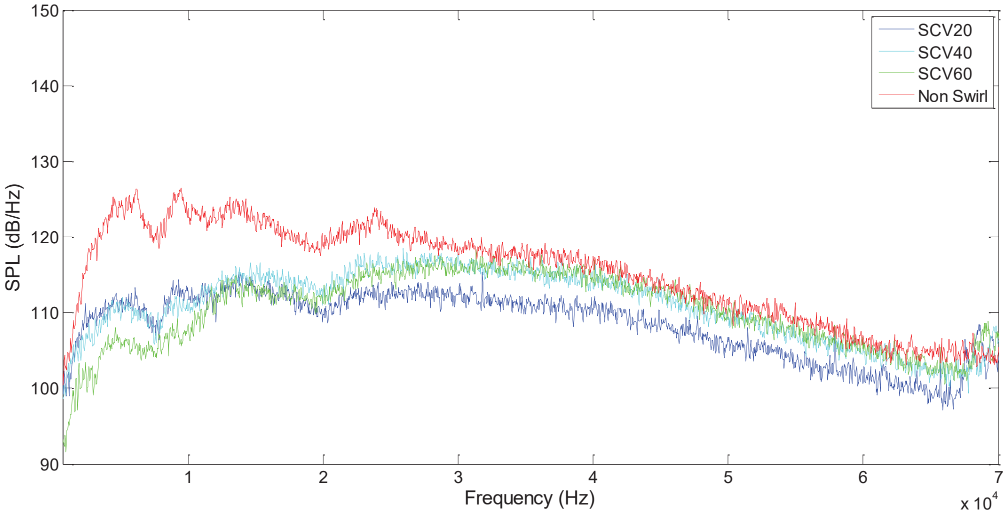

Figure 5 – Spectral characteristics at NPR 2 and emission angle 110°

Spectra at NPR 5, for an emission angle of 110° are shown Figure 6. Multiple impinging tones are observed for the non-swirl jet. However, the swirl jets entirely eliminate the impinging tones. The enhanced entrainment rates and destruction of the shock cells might be the reason to eliminate the feedback loops and consequently, the impinging tones. The emission of low frequency noise is less for SCV60 swirl jets compared to other swirl and non-swirl jets.

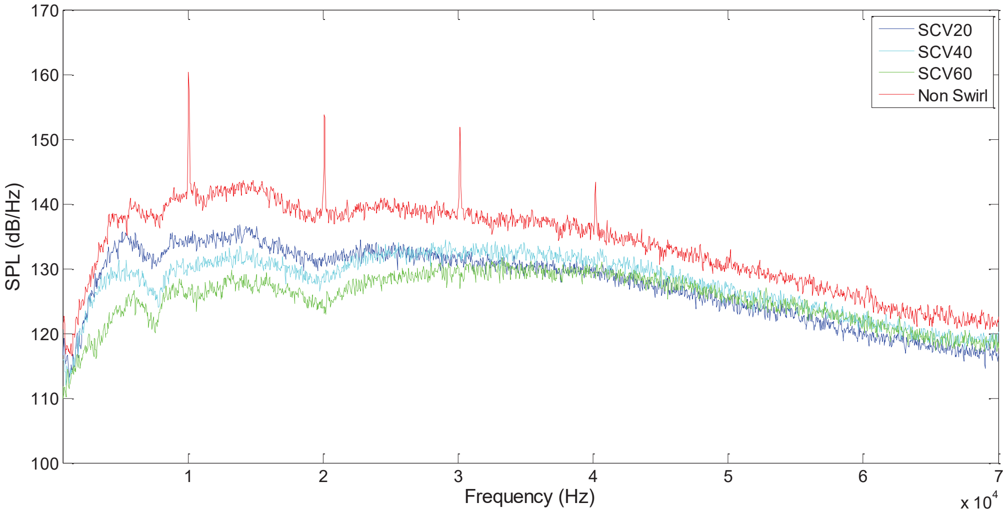

Figure 6 – Spectral characteristics at NPR 5 and emission angle 110°

3.2 Overall sound pressure level (OASPL) directivity

The non-swirl jet radiates the highest noise levels at all the emission angles for NPR 2 as shown Figure 7. However, the swirl jets radiate lower noise levels compared to the non-swirl jet. The reduction in OASPL level by SCV20 swirl jet is around 7 dB at an upstream and downstream angles compared to non-swirl jet. The increase in fine scale turbulence structure is the reason for the increase in the noise levels for SCV40 and SCV60 swirl jets compared to the SCV20 swirl jet.

Figure 8 shows the directivity of OASPL for NPR 5. It is observed that the non-swirl jet is the noisiest at all the emission angels. The presence of multiple impinging tones and strong shock cells are the main reasons for the high noise levels of the non-swirl jet. However, the swirl jets are quieter due to the disappearance of the impinging tones and weakening of the shock cells. SCV60 swirl jet radiates the least noise due to the almost complete destruction of the shock cells. However, SCV40 and SCV20 swirl jets destroy the shocks moderately compared to SCV60 swirl jet and emit higher noise levels than SCV60 swirl jet, but lower than the non-swirl jet.

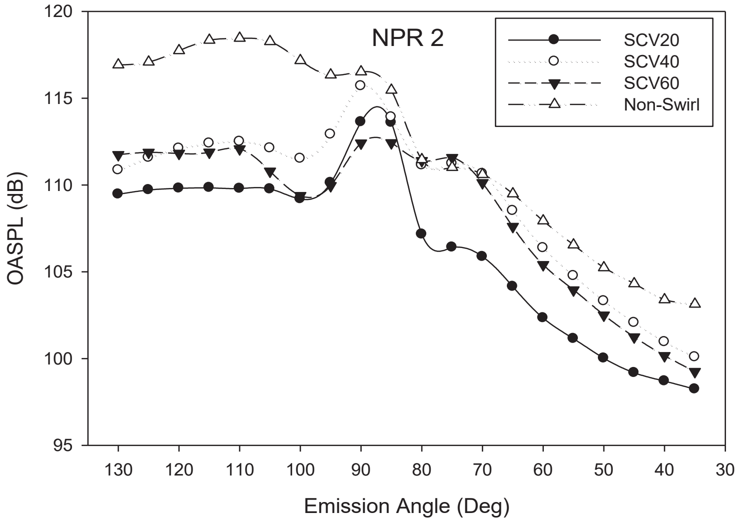

Figure 7 – Directivity of OASPL at NPR 2

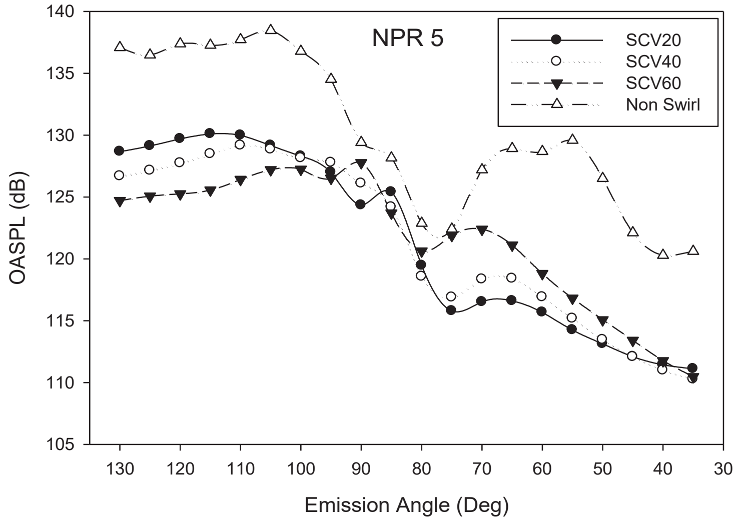

Figure 8 – Directivity of OASPL at NPR 5

3.3 Schlieren visualization study

Schlieren visualization study has also been carried out in order to capture the shock cell system, to illuminate the causes of shock associated noise. The non-swirl jet shows a Mach disk and a series of shock cells, as shown in Figure 9. The impingement of the jet and the impinging region are clearly observed. However, for the swirl jets, the increase in vane angle enhances mixing and turbulence, thus causing a mitigation of the shock system.

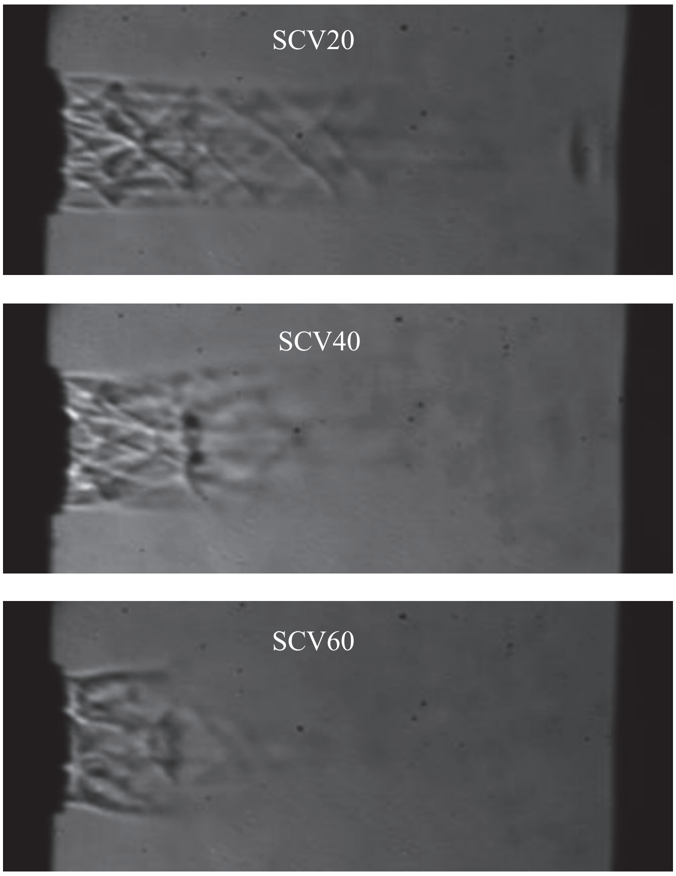

Figure 9 – Schlieren photographs at NPR 5

From, theses photographs it is evident that the swirl destroys the shock cell system and reduces the number of shock cells, compared to the non-swirl jet. This is the reason why the non-swirl jet radiates higher noise levels at NPR 5 (Figure 8) and swirl jets emit lower levels of noise. The application of swirl always results in the destruction of the shock cell system and in lowest OASPL at supersonic conditions.

4. CONCLUSIONS

The present experimental work on supersonic jets impinging on a flat plate demonstrates the efficacy of swirl in noise reduction. Weak swirl performs better at the lower NPR value of 2 while strong swirl is better in noise suppression at higher under expansions (NPR 5). The noise reduction observed is up to 7 dB. Swirl jets completely eliminate the impinging tones and weaken the shock cell structures. The swirl leads to a reduction in low frequency noise and causes a shift in the noise to the higher frequencies.

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