Smoke based visualization of turbulent swirl jet flow

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Abstract. The present study deals with the visualization of turbulent jet flow from swirl nozzles. A low-cost turbulent jet facility developed was utilized for all the experiments. Two types of vanes are considered for the present study viz. flat vanes and airfoil-shaped vanes. All the vanes are fixed to a circular hollow hub at the center. The flow is visualized by seeding smoke from incense material as tracer particles. A solid-state laser with 405nm wavelength is used for the illumination via a glass rod thereby producing a laser sheet. Cross-sectional visualizations are made at various axial downstream locations. The effect of the vane angle has a greater influence on the production of jet flow vortices due to swirlers. The present study reveals that the increase in the vane angle increases the production of vortices.

1. Introduction
The turbulent jet flows [1], are predominantly studied for their mixing and also for their flow evolution characteristics [2–4]. The non-circular jets [5,6], have shown better performances in comparison to circular jets. The usage of passive devices or control methods have helped in better mixing characteristics and noise reduction in several cases. Swirlers used in nozzles are proved to be effective in mixing and noise reduction in the subsonic regime [7]. Jet flows from swirlers became a prime interest to researchers who work in physics, engineering applications especially in aerospace industries for reaping better mixing characteristics and lesser noise generation.

The initial studies about swirling jet flow was regarding the mean flow measurements [8], and the turbulent flow measurements by various researchers by using experimental techniques like Hot-wire anemometry, Laser Doppler Anemometer, etc. The studies about swirling turbulent jet with medium ratio of swirl to axial momentum were performed to know the evolution and mixing characteristics [9]. Advanced techniques like Particle Image Velocimetry were applied to turbulent swirl jet flow and the results were matching with data from Laser Doppler Anemometer [10,11]. To study computationally, Large Eddy Simulations were employed to study the swirl jet flow evolution [12], and the physics of vortices [6]. All these studies are primarily focussed on the development of swirl jets based on the measurements of mean flow and turbulent flow parameters, imaging in a vertical plane passing through the jet axis. Hence, the present study tries to address the development of a swirl jet in a cross-sectional plane by visualization experiments.

2. Experimental Methodology
The experimental methodology for the present study is explained in this section. The jet flow setup, nozzle design, fabrication of nozzle, nozzle and its definitions, the data acquisition methodologies, and the image processing are described in detail.
2.1. Jet flow tunnel setup
The experimental setup [13], used in the present study is available at the Flow Visualization Facility, Aerospace Hangar, Department of Aerospace Engineering at SRM Institute of Science and Technology, Kattankulathur (Main Campus). The setup consists of a PVC tube with couplings. One end is fixed with a fan for driving the flow and another end is connected to a nozzle. The couplings have wire mesh in the middle for reducing the fluctuations and it also has honeycombs in one of the sections present towards the fan. The smoke is generated by an incense material for using it as a tracer. The whole setup is kept inside a dark room. The fans and exhausts are kept in off condition for the entire duration of the experiments. The maximum jet flow velocity is restricted to 1 m/s for this study.

![Figure 1. a) Jet flow tunnel – a full view from the frontal side](image1.jpg)

![Figure 1. b) Nozzle with vanes at an angle around the hub](image2.jpg)

![Figure 1. c) Source of the smoke and the fan fixed to tunnel](image3.jpg)

2.2. Nozzle design and definitions
The nozzle is purely a co-axial nozzle with a central hub (figure 2). The nozzle is designed to provide swirl flow based on the vanes. The vanes are connected to the hub and two types of vanes are used in the present study. The airfoil-shaped vane is used to provide less turbulent swirl flow and a rectangular vane is used for highly turbulent swirl flow. The nozzles are manufactured using rapid prototyping via a 3D printer available at the Fab Lab of SRM Institute of Science and Technology, Kattankulathur (Annexure Campus). The nozzles are checked for surface finish and the surface is smoothened by using sandpaper for surface undulations. The nozzle is connected to a sleeve that slides over the jet flow tunnel pipe and the entire nozzle assembly is painted with black for imaging purposes. Nozzle naming follows R-AXX-LYY (R-Rectangular or A-Airfoil, AXX-Angle, LYY-Axial location, cm).
2.3. Data acquisition system
The data acquisition consists of a vane anemometer to measure the flow velocity. A 20MP camera with f/1.7, 27mm (wide lens), 1/2.8" sensor, 1.0µm pixel size with Phase Doppler Auto Focus (Device One PLUS 5T) was used for imaging. Purple colour light from pointer LASER via glass rod was used for planar illumination.

2.4. Image processing
The acquired image is seen in figure 3a. The original image is inverted in colour to reveal the flow structures (figure 3b) and finally the image is cropped to fit the flow feature produced by the nozzle as seen in figure 3 c. The images are acquired at axial locations like nozzle exit 0cm, 5cm, 10cm and 15 cm from the nozzle exit in a plane perpendicular to the jet flow evolution.
3. Results and Discussion
In this section, the image data obtained from the visualization experiments after image processing are discussed in detail via sub-sections like airfoil vane, rectangular vane, and comparisons between two vanes.

3.1. Airfoil vane
The cross-sectional images are shown in figure 4 for jet flow from an airfoil vane. The airfoil vane kept at zero angle of incidence produces very negligent swirl flow based on the airfoil shape. As the angle of incidence increases, the vortical structures produced by the airfoil becomes prominent and the tip vortex is clearly seen away from the hub. This vortex is seen as elongated vortex from the tip to a place well off from the hub. The axial evolution of flow from airfoil vane shows lateral diffusion and as the angle of incidence increases, secondary and tertiary vortices are seen along the tip and outside the tip of the nozzle assembly. The structures become distinct with an increase in angle of incidence and become diffused with the axial distances.

![Image](image_url)

**Figure 4.** Evolution of jet flow axially via airfoil vane.

3.2. Rectangular Vane
The cross-sectional images from jet flow resulting from rectangular vane is seen in figure 5. The flow from rectangular vane kept at zero incidence shows lobes of flow around the hub with small vortices produced from the tip side and the hub side. The evolution shows that the vortices roll up and the lobes move away from the hub with downstream distances. The flow from rectangular vane kept at 15-degree incidence shows only tip side vortex followed by growth of those vortex with diffusing in the radially outward direction in the downstream locations from the nozzle. The flow from rectangular vane kept at 30-degree incidence shows only tip side vortex but the size is predominant in nature. The downstream locations show faster diffusion and chaotic state. The flow from rectangular vane kept at 45-degree incidence shows only tip side vortex but more in numbers and also predominant in nature. The downstream locations show faster diffusion than the 30-degree vane and reach a chaotic state. The flow from the hub is seen clearly unaffected for nozzles vanes with higher angles of incidence.

![Figure 5. Evolution of jet flow axially via rectangular vane.](image)

Note: In all the cases, the plain green signature in the outer parts of the image which is due to the smoke that prevails in the atmosphere/room. The slight movements towards the upper side is due to the buoyancy of smoke when it is not properly cooled while traveling via the jet tunnel.
4. Conclusions
The present study was about the visualization of turbulent jet flow from swirl nozzles. Two types of vanes are considered for the present study viz. flat vanes and airfoil-shaped vanes. Cross-sectional visualizations were made at various axial downstream locations. The effect of the vane angle has a greater influence on the production of jet flow vortices due to swirlers. The present study reveals that the increase in the vane angle increases the production of vortices i.e. primary, secondary and tertiary vortices. The usage of rectangular vane is found to be more advantageous than the airfoil-shaped vane due to the faster production of vortices and faster diffusion in lateral directions.

Acknowledgments
The corresponding author wishes to acknowledge the usage of the Flow Visualization Facility for the experiments, Advanced Computing lab for the documentation and also the help rendered by the hangar supervisor and lab assistant for the video recording reported in this paper. The jet flow setup (figure 1) was a lost cost setup designed by the corresponding author and fabricated by his student (Mr. Karar Ahmad Khan B.Tech Aerospace 2015-2019).

5. References
[1] Tennekes H and Lumley J L 1972 A First Course in Turbulence MIT Press
[2] Kannan B T 2015 Computation of an Axisymmetric Jet using Open FOAM Procedia Eng. 127 1292–9
[3] Kannan B T and Panchapakesan N R 2018 Influence of nozzle configuration on the flow field of multiple jets Proc Inst. Mech. Eng. Part G J. Aerosp. Eng. 232 1639–54
[4] Kannan B T and Panchapakesan N R 2018 Effect of momentum flux distribution on multiple round jets Aircr. Eng Aerosp. Technol. 90 452–60
[5] Kannan B T and Senthilkumar S. 2017 Numerical Simulation of Isothermal Cruciform Jet Flow. In Fluid Mechanics and Fluid Power–Contemporary Research Springer 595-604
[6] Kannan B T, Seshan P and Senthilkumar S 2016 Large Eddy Simulation of isothermal cruciform jet flow: Preliminary results Perspect. Sci. 8 10–2
[7] Balakrishnan P, Srinivasan K and Kannan B T 2018 Subsonic Jet Noise Reduction Using Co-axial Flat Vane Swirlers FMFP
[8] Rose W G 1962 A Swirling Round Turbulent Jet: 1-Mean-Flow Measurements J. Appl. Mech. 29 615–25
[9] Pratte B D and Keffer J F 1972 The Swirling Turbulent Jet J. Basic Eng. 94 739–47
[10] Facciolo L, Tillmark N, Talamelli A and Alfredsson P H 2007 A study of swirling turbulent pipe and jet flows Phys. Fluids 19 035105
[11] Kravtsov Z D, Sharaborin D K and Dulin V M 2018 Swirl effect on flow structure and mixing in a turbulent jet J. Phys. Conf. Ser. 980 012001
[12] Zemtsop C P, Stollinger M K, Heinz S and Stanescu D 2009 Large-Eddy Simulation of Swirling Turbulent Jet Flows in Absence of Vortex Breakdown AIAA J. 47 3011–21
[13] Krishna T, Akanksha K, Karar A K, Rahul S, Vinayak M and Kannan B T 2019 Experimental investigation on Laser Visualization of Flow Vortices IEEE Aerospace Conference 10 1109