Design and Development of Jet Flow Setup to Determine Flow Velocity and To Visualize Flow Pattern at Nozzle Exit

R.K.Muthuraman[1*]and *P.K.Srividhya*[1]
[1]*Department of Mechanical Engineering, Periyar Maniammai Institute of Science & Technology, (Deemed to be University), Vallam, Thanjavur, India*

Abstract. Aerodynamicists use the windtunnels to test the scaled models of an Aircraft, components and other vehicles placed inside the test section of it. The flow properties, Lift and drag forces over the model can be studied. An experimental jet flow setup which is similar to a low speed open circuit wind tunnel has been designed and fabricated using mil steel material. This setup is capable of producing the flow using the exhaust fan which is placed at entry portion of it. This setup was made by keeping in mind that, the educators, students and aerodynamicists to to visualize the flow pattern and to determine the flow properties over the model placed in the test section. The laminar flow can be achieved at the downstream end of nozzleand it is passed in to the test section. In this paper, the exit velocity of the nozzle for varying rpm was determined and plotted. Also, the vortex formation inside test section can be easily visualized by passing the LASER light source.

1. INTRODUCTION

Extensive experimental and computational testing is being deployed in Aircraft and their components before its real-world applications. Wind tunnels play a crucial role in investigating the flow characteristics, visualizing flow patterns and determining aerodynamic forces such as lift and drag acting on scaled models. Based on the operating speed, wind tunnels are generally classified as low-speed and high-speed wind tunnels. Since the early development of aerodynamics, experimental studies of fluid flow over models have contributed significantly to improved aircraft performance and optimized aerodynamic designs [1]. The accuracy of wind tunnel experiments strongly depends on quality of the airflow within the test section. Consequently, efficient design of wind tunnel components such as inlets, flow straighteners, contraction nozzles, and test sections are essential to achieve uniform and low-turbulence flow. Detailed studies on wind tunnel components and their influence on flow visualization have been reported by Mehta et al [2].

---

[*] Corresponding author: rkmr.pmu@gmail.com

Open-circuit low-speed wind tunnels are widely used due to their simplicity, ease of construction and lower operational cost, which draw air from the atmosphere and exhaust it back into the environment [3]. In contrast, closed-circuit wind tunnels offer better flow control and energy efficiency but involve higher design complexity and cost [4].

Flow visualization techniques are indispensable for understanding complex flow phenomena such as jet development, vortex formation, and flow separation. Optical visualization methods using laser light sources provide high spatial resolution and non-intrusive measurement capabilities [5]. Several investigations have examined jet flow characteristics, including velocity distribution, vortex dynamics, and heat transfer behavior [6]. Smoke-based visualization techniques remain popular for low-speed aerodynamic studies when non-toxic smoke sources with low mixing rates are used [7].

Recently, experimental jet facilities have been developed specifically for flow visualization and educational research, demonstrating the effectiveness of compact laboratory-scale setups for studying jet flow characteristics and vortex dynamics **[8]**. Smoke-based visualization techniques have also been successfully applied to investigate jet flows issuing from non-circular nozzles, revealing complex vortex structures and emphasizing their suitability for qualitative flow analysis in low-speed aerodynamic experiments [9].

The present study is intended to develop and make an experimental setup of jet flow that might be utilized in identifying the nozzle exit velocity and visualizing the flow patterns. This apparatus is mostly based on the education and laboratory use and it will allow the researchers and undergraduates to comprehend the basic behavior of jet flow in a controlled environment.

2. DESIGN AND FABRICATION

The design of the jet flow setup was guided by several key considerations: (1) Cost-effectiveness and ease of fabrication for educational institutions, (2) Ability to achieve laminar flow conditions suitable for flow visualization, (3) Variable flow velocity control to study different flow regimes, and (4) Transparent test section for comprehensive flow observation. The test setup was designed using the CATIA software. It is an integrated suite of CAD, CAM and CAE Applications for digital product definitions and simulation. It also provides advanced 3-D product life cycle management solution for collaborated product development. This test setup consists of an Inlet, Hollow Cylinder, Honeycomb Structure, Nozzle and Test section. The overall length of the jet flow setup is 2.44 m (8 ft). The convergent nozzle has a length of 0.305 m (1 ft) and the nozzle exit diameter is 0.0054 m (5.4 mm). These dimensions define the geometric scale of the setup. Each section were designed separately and assembled altogether as shown in Figure 1.

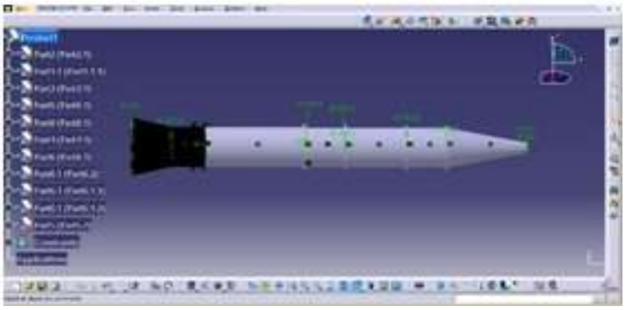
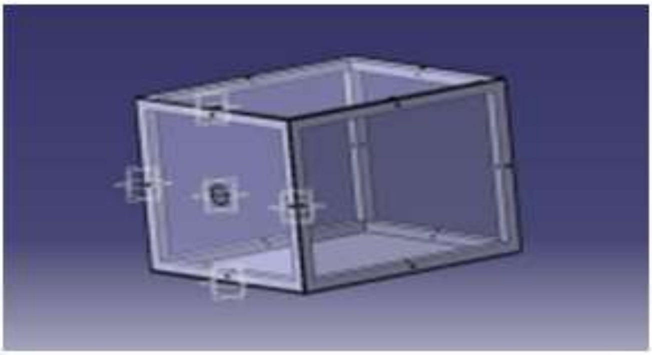


Fig.1. Assembled Jet flow setup in CATIA

The jet flow setup is fabricated using Carbon steel which is referred to as 'Mild Steel'. Mild steel was selected due to its sufficient structural rigidity, which is cost-effective and also widely available. The American Iron and Steel Institute defines a carbon steel as having not more than 2 % carbon and no other appreciable alloying element. Mild steel makes up the largest part of steel production and is used in a vast range of applications. Typically carbon steels are stiff and strong. They also exhibit ferromagnetism (i.e. they are magnetic). This means they are extensively used in motors and electrical appliances. Welding carbon steels with a carbon content greater than 0.3 % requires that special precautions be taken. However, welding carbon steel presents far fewer problems than welding stainless steels. The corrosion resistance of carbon steels is poor (i.e. they rust) and so they should not be used in a corrosive environment unless some form of protective coating is used. The acrylic sheets and iron plates has been used to make the test section model.

A ducted fan is a propulsion arrangement whereby a mechanical fan, which is a type of propeller, is mounted within a cylindrical duct at the upstream portion of the setup. The reason behind the ducted fan design was to reduce the loss of tip vortex and have a more consistent distribution of flow at nozzle entrance. The duct reduces losses in thrust from the tips of the propellers, and varied cross-section of the duct allows the designer to advantageously affect the velocity and pressure of the airflow according to Bernoulli's Principle. Ducted fan propulsion is used in aircraft, airships, airboats, hovercraft and fan packs. Ducted fans normally have more and shorter blades than propellers and thus can operate at higher rotational speeds. This fan is connected to a electrical regulator which is having 5 step controller, which enables us to regulate the speed of the flow. A honeycomb structure was installed upstream of the nozzle to make the incoming flow as streamlined and also to reduce turbulence intensity. This suppresses lateral velocity components and promotes a more uniform and steady flow at the nozzle inlet. In the present study, the honeycomb was selected to provide adequate flow conditioning for low-speed experimental operation and to avoid the entry of foreign objects into the setup.

The test section is designed using the CATIA Software as shown in Figure 2. The test section size was also optimized to be able to give sufficient optical clearance without compromising on the structure.. It is made up of Acrylic sheet, which is a transparent plastic material with outstanding stiffness and optical clarity. Thus it will be easy for the researchers to visualize the flow pattern inside the test section. The Iron rods are used in corners of the test section and it is housed together. The Figure 3 shows that entire jet test set up in which is capable of producing the laminar flow at downstream end.



Figu.2. Design of test section

Fig. 3. Jet flow test set up

3. METHODOLOGY

The experimental setup consists of the following key components: Digital anemometer with an accuracy of ±0.1 m/s for performing velocity measurements, LASER light source of wavelength 532 nm for flow visualization, Non-toxic smoke generator using incense cubes for flow tracing, the digital tachometer for measuring fan RPM, and mobile phone camera mounted on tripod for capturing flow patterns. All instruments were calibrated prior to data collection to ensure measurement accuracy.

Velocity measurements were conducted at the nozzle exit plane using a calibrated digital anemometer to quantify the flow characteristics under different operating conditions. Prior to data acquisition, the flow was allowed to warm up to ensure thermal and hydrodynamic stabilization. The anemometer probe was positioned along the nozzle centerline at the exit plane to measure axial velocity. Measurements were recorded after a 30 seconds stabilization period for each operating condition. Data were obtained for three distinct fan speed settings and repeated three times to assess repeatability and minimize random measurement uncertainty. The mean value of the three trials was considered for subsequent analysis. The fan speed was controlled using a five-step regulator, varying systematically from the minimum to the maximum setting. Corresponding exit velocities were recorded for each step and exit velocity was plotted as shown in Figure 4. The measurement has been done for 5 step of speed which is controlled using the regulator fixed. The varying RPM of the fan and the exit velocity of the nozzle is tabulated in Table 1.

The experimental measurements of nozzle exit velocity corresponding to different regulator steps and fan rotational speeds are presented in Table 1. As the regulator setting increases from Step 1 to Step 5, the fan speed rises from 976.33 RPM to 2222.67 RPM, producing a systematic increase in exit velocity from 6.27 m/s to 14.00 m/s. This monotonic trend confirms stable flow acceleration within the jet flow setup. The standard deviation of exit velocity ranges between 0.354 m/s and 0.712 m/s, corresponding to a percentage uncertainty of approximately 2.7–11.4%, with the highest uncertainty occurring at the lowest flow velocity. At higher regulator settings, the percentage uncertainty decreases to below 4%, indicating improved flow stability and reduced velocity fluctuations at elevated fan speeds.

TABLE 1 Experimental values of exit velocity for RPM

Step of Regulator	**RPM**	**Exit Velocity (m/s)**	**Standard Deviation**
1	976.33	6.27	0.712
2	1429.67	9.58	0.578
3	1778.67	11.73	0.539
4	1948.67	12.88	0.354
5	2222.67	14	0.447

To characterize the flow regime, a dimensionless Reynolds number analysis was performed. The Reynolds number is defined in equation 1

$$Re = \rho U D / \mu \quad (1)$$

For the present setup, the nozzle exit diameter is 5.4 mm (0.0054 m). Assuming standard atmospheric air properties (ρ=1.225 kg/m^3, μ=1.81×10^{-5} Pa-s), the Reynolds number varies from approximately 2.3 × 10^3 at the lowest exit velocity of 6.27 m/s to 5.1 × 10^3 at the maximum exit velocity of 14.0 m/s. These values confirms that the jet operates entirely within the low-speed, incompressible flow regime, with Mach numbers well below 0.1. Therefore, compressibility and supersonic effects are negligible and classical incompressible jet flow assumptions remain valid. The Reynolds number range also indicates that the jet flow lies in a laminar-to-transitional regime, which is well suited for controlled flow visualization and educational aerodynamic experiments [10].

Flow regime classification was performed using the Reynolds number criterion. At Step 1 of the fan regulator (Re ≈ 2,300), the flow was observed to remain predominantly laminar. As the Reynolds number increased beyond 3000, the flow began to move away from a fully laminar state and entered the transitional regime. In this range, small disturbances in the shear layer started to grow rather than dissipate. This increase in instabilities gradually gets intensified in the downstream portion, eventually forming vortex structures and introducing noticeable unsteadiness into the flow. The observed development and strengthening of these vortex structures are consistent with the flow patterns presented in Figures 5 and 6.

In comparison, typical uncertainty levels reported for laboratory-scale low-speed wind tunnel measurements range between 3% and 10%, depending on instrumentation accuracy and flow conditioning quality. The uncertainty levels observed in the present study fall within, and in several cases below, these commonly accepted limits. This confirms that the developed jet flow setup provides measurement accuracy comparable to conventional low-speed wind tunnel facilities, making it suitable for flow calibration, qualitative visualization, and educational aerodynamic experiments.

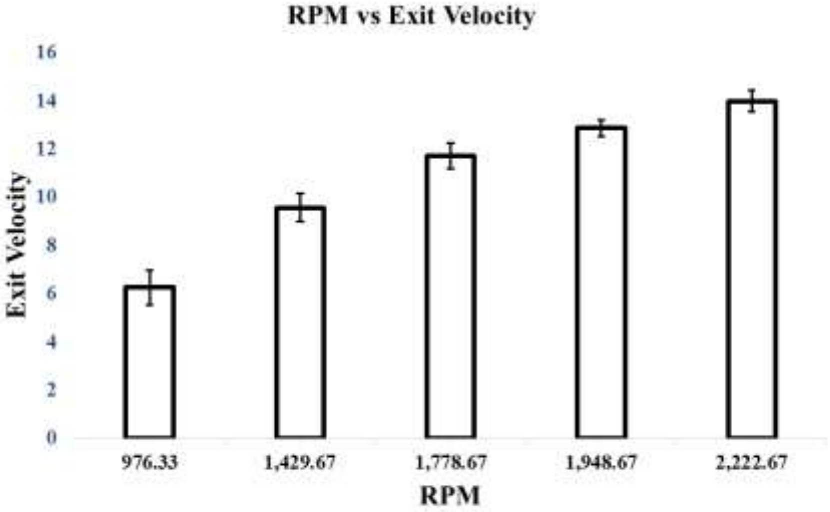


Fig.4. RPM vs Exit Velocity

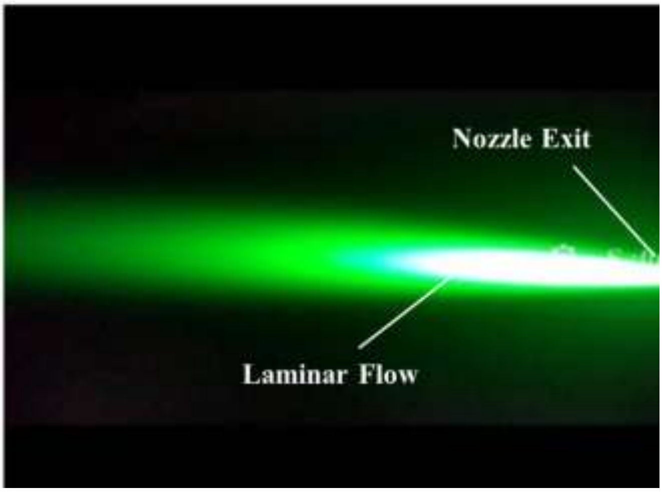


Fig. 5. Jet flow structure at nozzle exit

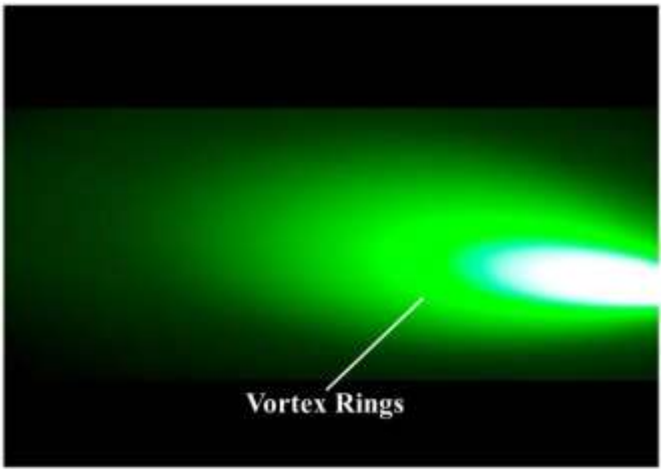


Fig.6. Development of jet shear-layer structures with increasing RPM

4. Results and Discussion

The jet flow setup was calibrated experimentally by determining the nozzle exit velocity for different fan rotational speeds controlled through a multi-step regulator. The measured exits velocities exhibit a nearly linear relationship with fan RPM, which is a well-established characteristic of low-speed open-circuit wind tunnel and jet flow facilities which correlated with the investigations done by the researchers [1] [2]. This linear trend confirms flow acceleration is likely to be within the operating range and it also demonstrates the effectiveness of the inlet section, honeycomb flow straightener, and converging nozzle in producing a stable and uniform jet.

The repeatability of the velocity measurements was evaluated through standard deviation analysis. The relatively low standard deviation values (±3-8%) across all regulator settings indicate good measurement consistency and stable flow conditions. A reduction in velocity fluctuations is observed at higher fan speeds, suggesting improved flow steadiness as jet momentum increases. The estimated uncertainty levels are within the typical range reported for laboratory-scale, low-speed wind tunnel and jet experiments

Flow visualization experiments were conducted using smoke generated from non-toxic incense cubes and illuminated using a LASER light source. This approach enabled clear observation of jet flow behavior at the nozzle exit and within the near-field region, consistent with established smoke-based flow visualization methodologies. At reduced fan speeds (Re = 3,000), the jet had a smooth and laminar flow behaviour with little turbulent mixing of the near-field area.

Overall, the experimental results demonstrate that the developed jet flow facility successfully produces a controlled, low-speed jet with predictable velocity characteristics and physically realistic flow structures. The close agreement between measured flow behavior, Reynolds number scaling, and established jet flow theory confirms the suitability of the setup for aerodynamic education, laboratory demonstrations, and preliminary experimental investigations involving low-speed jet flows and flow visualization techniques.

5. Conclusion

In the present study, a low-speed jet flow experimental setup was successfully designed, fabricated and calibrated to investigate jet flow characteristics and facilitate qualitative flow visualization. This facility was constructed using mild steel with an acrylic test section, operates as an open-circuit low-speed jet system capable of producing exit velocities up to 14 m/s. The main results of this work include establishing a linear relationship between fan speed and exit velocity, verifying the quality of the flow through Reynolds number analysis and the ability to demonstrate flow visualization using laser illumination and smoke tracing.

Dimensionless analysis indicated that the jet operates within a Reynolds number range of approximately 2.3×10^3 to 5.1×10^3, ensuring incompressible, non-supersonic flow conditions. The low standard deviation values associated with velocity measurements demonstrate good repeatability and reliability, comparable to conventional laboratory-scale low-speed wind tunnel facilities. Flow visualization using laser-assisted smoke techniques successfully captured key jet flow features. These observations are consistent with classical low-speed jet flow physics governed by Kelvin–Helmholtz instabilities.

Despite the successful development and validation of the jet flow setup, certain limitations should be noted. The maximum achievable exit velocity is limited to 14 m/s, restricting the facility to low-speed flow studies and preventing investigation of high Reynolds number or compressible flow effects. Consequently, the jet operates within the laminar-to-transitional Reynolds number regime and fully developed turbulent jet behavior cannot be examined using the present configuration.

Furthermore, the flow characterization in this study is primarily based on point velocity measurements and qualitative flow visualization. The absences of advanced diagnostic techniques such as hot-wire anemometry or particle image velocimetry (PIV) limits the ability to obtain time-resolved and spatially resolved quantitative flow data. Minor flow non-uniformities may also arise due to manufacturing tolerances and the open-circuit nature of the setup; however, these effects were minimized through the use of appropriate flow-conditioning elements.

Overall, the developed jet flow setup has been demonstrated to be a cost-effective, reliable and physically representative experimental platform for studying low-speed jet flows.The successful calibration, stable velocity control and clear flow visualization confirm its suitability for aerodynamic education, laboratory demonstrations, and preliminary experimental investigations.

Future work will also involve investigating alternative nozzle geometries to better understand their influence on jet development and stability, along with the development of CFD models to compare and validate experimental results. Also a quantitative evaluation of turbulence intensity for different honeycomb configurations can be carried out. These improvements would broaden the applicability of the setup to more comprehensive quantitative studies and establish it as a versatile platform for both research and teaching in low-speed aerodynamics.

References

1. Gad-el-Hak, M. (2001). Flow control: The future. Journal of aircraft, 38(3), 402-418. https://doi.org/10.2514/2.2796
2. Mehta, R. D., & Bradshaw, P. (1979). Design rules for small low speed wind tunnels. The Aeronautical Journal, 83(827), 443-453. https://doi.org/10.1017/S0001924000031985

3. He, R., Sun, H., Gao, X., & Yang, H. (2022). Wind tunnel tests for wind turbines: A state-of-the-art review. Renewable and Sustainable Energy Reviews, 166, 112675. https://doi.org/10.1016/j.rser.2022.112675
4. Settles, G. S., & Dodson, L. J. (1994). Supersonic and hypersonic shock/boundary-layer interaction database. AIAA journal, 32(7), 1377-1383.
5. Adrian, R. J. (1991). Particle-imaging techniques for experimental fluid mechanics. Annual review of fluid mechanics, 23(1), 261-304. https://doi.org/10.1146/annurev.fl.23.010191.001401
6. Deo, R. C., Mi, J., & Nathan, G. J. (2007). The influence of nozzle-exit geometric profile on statistical properties of a turbulent plane jet. Experimental Thermal and Fluid Science, 32(2), 545-559.
7. Westerweel, J., Elsinga, G. E., & Adrian, R. J. (2013). Particle image velocimetry for complex and turbulent flows. Annual Review of Fluid Mechanics, 45(1), 409-436. https://doi.org/10.1016/j.expthermflusci.2007.06.004
8. Rather, A. H., & Kannan, B. T. (2020, August). Design and development of impinging jet facility for flow visualization studies. In IOP Conference Series: Materials Science and Engineering (Vol. 912, No. 4, p. 042003). IOP Publishing. https://doi.org/10.1088/1757-899x/912/4/042003
9. Rajesh Kumar, S., Ramachandran, K., & Kannan, B. T. (2022). Smoke-Based Visualization of Jet Flow from a Cruciform Nozzle of Unit Aspect Ratio. In Recent Advances in Mechanical Engineering: Select Proceedings of ERCAM 2021 (pp. 29-36). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-1388-4_3
10. Zhang, Z., Huang, X., Zhang, Z., Zhu, Z., Qiu, Y., Wang, T., & Zhu, C. (2025). Effects of Ultra-High Reynolds Number and Low Mach Number Compressibility on the Static Stall Behavior of a Wind Turbine Airfoil. Machines, 13(9), 847. https://doi.org/10.3390/machines13090847