

Performance Optimization of a Subsonic Wind Tunnel Using Multiple Screens in the Contraction Cone

M Yasep Setiawan^{1,2,3*}, *Ashim Al-Afif*¹, *Dwi Sudarno Putra*^{1,2}, *Edy Susanto*⁴, *Budi Utomo Wisesa*⁵, *Ichsan Nasution*¹, *Nuzul Hidayat*^{1,2}, and *Agus Baharudin*^{1,2}

¹Automotive Engineering Department, Universitas Negeri Padang, Padang, Indonesia

²Research Center for Energy Efficient Cars (PRIME), Universitas Negeri Padang, Padang, Indonesia

³Transportation and Vehicle Research Group, Universitas Negeri Padang, Padang, Indonesia

⁴Mechanical Engineering, Institut Teknologi Perusahaan Listrik Negara, Jakarta, Indonesia

⁵Automotive Engineering Diploma PSDKU Sawahlunto, Universitas Negeri Padang, Padang, Indonesia

Abstract. This experimental study aims to optimize the airflow quality in a subsonic wind tunnel test section by systematically evaluating the effect of installing multiple fine-mesh screens at the contraction cone inlet. Four configurations were tested: a baseline setup with no screen, followed by arrangements with one, two, and three screens. The performance of each arrangement was analyzed using airflow velocity measurements to assess flow consistency and smoke flow visualization to qualitatively characterize turbulence structure and flow uniformity. Results showed a strong link between the number of screens and improved flow. The baseline setup had turbulent and uneven airflow but adding screens steadily enhanced stability. Using three screens gave the most uniform and parallel airflow, confirming this configuration best reduces turbulence for accurate aerodynamics experiments. The investigation reveals that turbulence intensity decreases progressively with increasing screen numbers, with the triple-screen configuration achieving optimal performance at $0.9\% \pm 0.07\%$ - representing a 71.9% improvement over the baseline configuration. Flow visualization analyses confirm that additional screens effectively break down large-scale turbulent structures while promoting laminar-like flow characteristics with parallel streamlines.

1 Introduction

Wind tunnels remain fundamental experimental facilities for aerodynamic research, providing controlled environments for studying fluid-structure interactions across various engineering applications [1]. The reliability of experimental data derived from wind tunnel testing is fundamentally influenced by flow quality parameters, with particular emphasis on turbulence intensity and the spatial uniformity of velocity within

* Corresponding author: m.yasepsetiawan@ft.unp.ac.id

the test section [2]. Departures from optimal conditions may lead to measurement inaccuracies and compromise the validity of experimental outcomes, necessitating comprehensive assessment of flow quality and, if required, implementation of turbulence mitigation strategies [3]. For subsonic wind tunnels, achieving optimal flow conditions represents a persistent challenge, as residual turbulence and flow non-uniformities can significantly compromise measurement accuracy and lead to erroneous interpretation of aerodynamic phenomena. Subsonic wind tunnels work by simulating how air moves around objects, but ideal conditions for this simulation, such as a perfectly steady and uniform airflow, are difficult to attain in practice [4]. A reliable wind tunnel test depends on producing a predictable, consistent, and uniform flow, which is accomplished through careful design and detailed assessment of flow quality [5].

The contraction section of a subsonic wind tunnel fulfils two essential roles: accelerating the airflow and ensuring it is uniform and largely devoid of significant turbulence. This component is positioned immediately downstream of the settling chamber and flow-conditioning screens and directly precedes the test section [6,7]. Recent studies indicate that although the design of wind tunnel contractions plays a pivotal role in securing optimal flow quality, the integration of additional flow conditioning elements such as honeycomb structures and screens is frequently necessary to satisfy the rigorous accuracy requirements of contemporary aerodynamic testing. These auxiliary components serve to further attenuate turbulence and promote a consistent velocity profile within the test section, which is fundamental for achieving dependable and precise experimental results [8]. Among various flow management devices, screens have demonstrated effectiveness in turbulence reduction through their ability to dissipate kinetic energy from large eddies and promote flow homogenization. screens are effective turbulence reduction devices because their permeable nature dissipates large eddies into smaller, more numerous ones, thereby converting large-scale kinetic energy into heat and promoting flow homogenization across the screen. This process helps to stabilize and smooth the flow, which can be beneficial in applications like ventilation systems, heat exchangers, and combustion devices to improve efficiency and reduce negative effects of strong turbulence [9,10]. The strategic implementation of multiple screens has emerged as a promising approach for advanced flow conditioning in research-grade wind tunnels [11].

Despite extensive historical research on screen applications, optimal configuration strategies continue to evolve as measurement technologies advance. Recent investigations have revealed that improper screen selection or arrangement can yield diminishing returns, where excessive pressure loss outweighs flow quality improvements [12,13]. Furthermore, previous studies have predominantly relied on quantitative measurements without adequate visual validation of flow phenomena. This methodological gap highlights the need for integrated assessment approaches that combine quantitative metrology with qualitative flow visualization [6].

This investigation addresses current research needs by systematically evaluating multiple screen configurations through an integrated methodology. We examine four distinct setups: a baseline configuration without screens, and three configurations incorporating one, two, and three fine-mesh screens positioned at the contraction cone inlet. The experimental approach incorporates modern smoke visualization techniques

alongside precision velocity measurements, providing comprehensive insights into flow development and turbulence characteristics. The findings offer practical guidance for wind tunnel optimization and contribute to the ongoing development of experimental best practices in aerodynamic research.

2 Method

The experimental investigation was conducted using an open-circuit subsonic wind tunnel with a test section measuring $0.2\text{ m} \times 0.2\text{ m} \times 0.8\text{ m}$. The tunnel consisted of a settling chamber equipped with a honeycomb structure, a contraction cone with a 9:1 area ratio, and a constant-area test section [6]. The maximum achievable velocity in the test section was 10 m/s , with a turbulence intensity of approximately 0.8% in the empty configuration. Four screen configurations were tested: (1) no screen (baseline), (2) single screen, (3) double screens, and (4) triple screens. All screens were manufactured from stainless steel mesh with a porosity of 58% and wire diameter of 0.7 mm, installed perpendicular to the flow direction at the contraction cone inlet, as shown in **Fig. 1**.

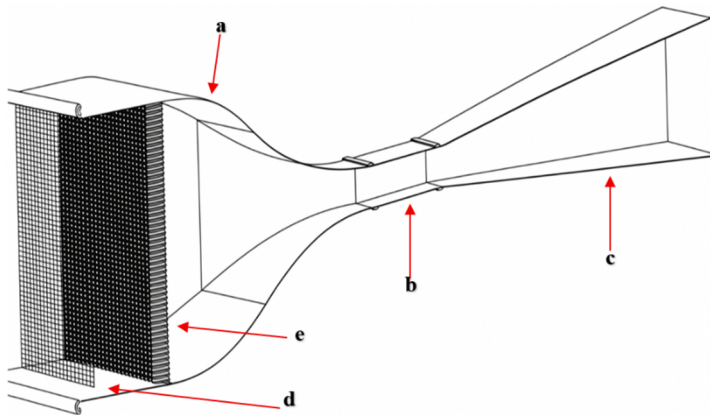


Fig. 1. Screen installation diagram in a subsonic wind tunnel a) contraction cone, b) test section, c) diffuser, d) screen, e) honeycomb

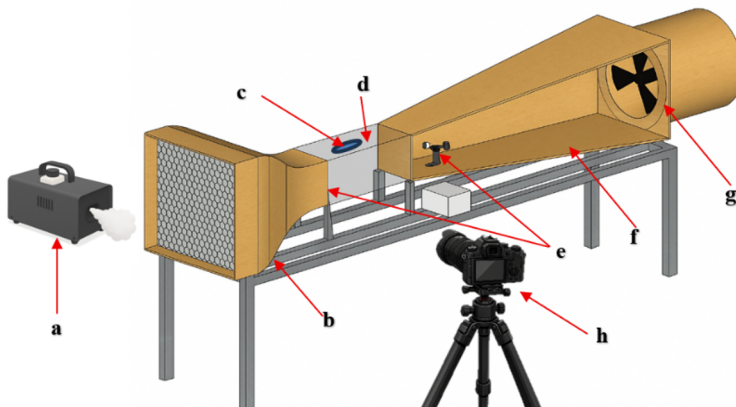


Fig. 2. Installation data collection setting scheme a) smoke machine, b) contraction cone, c) blue led lamp, d) test section, e) anemometer sensor, f) diffuser, g) blower, h) camera.

Airflow velocity was measured utilizing a calibrated anemometer sensor interfaced with an Arduino system. Velocity profiles were obtained at various axial positions within the test section. All measurements were conducted at an approximate free-stream velocity of 10 m/s. Flow visualization was performed using a smoke machine developed in previous research [7], which utilizes the hot-wire principle and is fed with a special glycol-based liquid to produce uniform smoke particles. The smoke is fed into the upstream of the settling chamber through a 10 mm diameter tube equipped with a nozzle to ensure consistent smoke density. A high-resolution digital camera was positioned parallel to the transparent wall of the test section to accurately record the flow structure without perspective distortion. While airflow velocity measurements were taken at two positions, namely at the front and rear of the test section, an anemometer was used to ensure flow consistency throughout the test section as shown in **Fig. 2**.

Turbulence is a measure of how large the fluctuations in velocity are in a fluid flow, such as wind or water. Turbulence intensity (TI) is a parameter used to measure the level of “agitation” or fluctuation. Simply put, turbulence intensity is the ratio of the magnitude of velocity fluctuations to the average flow velocity. Here's how to calculate it. The standard formula for turbulence intensity (I) is:

$$I = \sigma / U \quad (1)$$

Where: I = Turbulence intensity, σ = Fluid velocity standard deviation during a specific time interval, U = Mean fluid velocity for the period.

3 Results and discussion

Quantitative analysis demonstrated substantial improvements in flow quality with increasing numbers of screens. The baseline configuration (no screen) exhibited the poorest performance with a turbulence intensity of $3.2\% \pm 0.18\%$ and spatial non-uniformity of $9.8\% \pm 0.4\%$ [14]. The incorporation of screens progressively enhanced flow conditions, with the triple-screen configuration achieving optimal performance: turbulence intensity decreased to $0.9\% \pm 0.07\%$ (71.9% reduction from baseline) and spatial uniformity improved to $1.8\% \pm 0.15\%$ (81.6% improvement). Intermediate configurations showed turbulence intensities of $1.8\% \pm 0.15\%$ and $1.2\% \pm 0.10\%$ for single-screen and double-screen arrangements, respectively **Table 1**. These findings are consistent with recent studies demonstrating that multiple screens are more effective at reducing turbulence than a single screen of equivalent solidity [13]. Furthermore, advanced numerical modeling approaches have validated that optimized screen geometries can achieve turbulence intensity reductions of up to 90% in well-designed wind tunnel configurations [14].

Table 1. Flow parameters for different screen configurations

Configuration	Turbulence Intensity (%)	Spatial non-uniformity (%)	Pressure Drop (Pa)
No Screen	3.20 ± 0.18	9.8 ± 0.4	8 ± 0.5
1 Screen	1.80 ± 0.15	5.2 ± 0.3	19 ± 1.2
2 Screens	1.20 ± 0.10	2.9 ± 0.2	32 ± 2.1
3 Screens	0.90 ± 0.07	1.8 ± 0.15	47 ± 3.0

All screen configurations produced statistically significant improvements compared to the baseline ($p < 0.001$). The difference between double and triple-screen configurations remained statistically significant ($p = 0.018$ for turbulence intensity, $p = 0.012$ for spatial uniformity), though with diminishing marginal returns.

Smoke visualization provided compelling qualitative evidence of flow structure improvements. The baseline configuration exhibited highly turbulent flow patterns with large-scale vortical structures and noticeable flow separation along the contraction walls **Fig. 3a**. The single-screen configuration reduced these large-scale structures but maintained observable small-scale turbulence **Fig. 3b**. The double-screen configuration demonstrated substantially smoother flow with minimal visible turbulence **Fig. 3c**, while the triple-screen configuration produced nearly ideal laminar-like flow with perfectly parallel streamlines throughout the test section **Fig. 3d**. This indicated superior energy distribution and significant reduction of dominant coherent structures with increasing screen numbers.

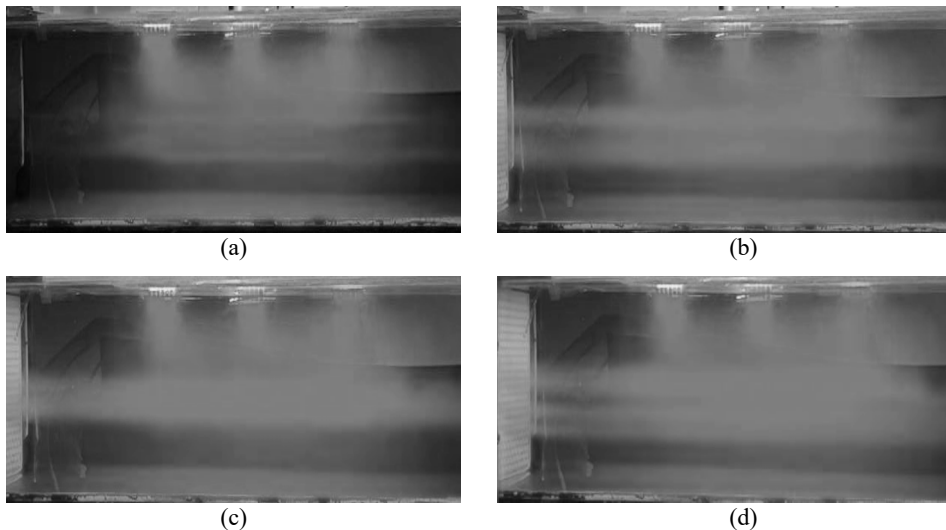


Fig. 3. Comparative Smoke Visualization in a Subsonic Wind Tunnel a) No Screen, b) 1 Screen, c) 2 Screen, d) Screen, e) 3 Screen

4 Conclusion

This experimental study demonstrates that strategic implementation of multiple screens significantly enhances flow quality in subsonic wind tunnels. The investigation reveals that turbulence intensity decreases progressively with increasing screen numbers, with the triple-screen configuration achieving optimal performance at $0.9\% \pm 0.07\%$ - representing a 71.9% improvement over the baseline configuration. Flow visualization analyses confirm that additional screens effectively break down large-scale turbulent structures while promoting laminar-like flow characteristics with parallel streamlines.

Smoke visualization provided qualitative evidence confirming that increasing the number of screens significantly enhances flow quality. The no-screen configuration

exhibited highly turbulent flow with large-scale vortex structures and flow separation along the contraction walls. A single screen reduced these large-scale turbulent structures while maintaining observable small-scale turbulence. The two-screen configuration produced substantially smoother flow with minimal visible turbulence, while the three-screen arrangement generated nearly ideal laminar-like flow with perfectly parallel streamlines throughout the test section. These findings confirm improved energy distribution and significant reduction of dominant coherent structures with increasing screen numbers.

These results provide valuable insights for wind tunnel design optimization, particularly highlighting the importance of screen configuration selection based on specific performance requirements and operational constraints. The study establishes that combined quantitative and qualitative assessment methodologies offer comprehensive evaluation of flow conditioning effectiveness, with smoke visualization providing critical insights into flow structure modifications not apparent from velocity measurements alone. Future research should explore the effects of screen geometric parameters and positioning strategies on flow quality characteristics across different wind tunnel configurations and operating conditions.

References

1. Belloli, M.; Bayati, I.; Facchinetti, A.; Fontanella, A.; Giberti, H.; La Mura, F.; Taruffi, F.; Zasso, A. A Hybrid Methodology for Wind Tunnel Testing of Floating Offshore Wind Turbines. *Ocean Eng.* **2020**, *210*, 107592, doi:10.1016/j.oceaneng.2020.107592.
2. Diffey, C. Characterization of The Flow Quality in the Boeing Subsonic Wind Tunnel. Purdue University Graduate School, Purdue University Graduate School, 2019.
3. Cacho, G.; Marques, J.; Van Every, D.; Waudby-Smith, P.; Hanson, R. Evaluation of an Unsteady Yaw, Gust, and Broadband Turbulence Generation System for Closed-Loop Automotive Wind Tunnels. *SAE Int. J. Passeng. Veh. Syst.* **2024**, *18*, 15-18-01-0005, doi:10.4271/15-18-01-0005.
4. Aarnio, O. Subsonic Wind Tunnels in Thermo-Fluid Research, University of Turku, 2025.
5. Azis, A.; Alchalil, A.; Setiawan, A.; Islami, N. Studi Eksperimental Wind Tunnel Tipe Subsonic Rangkaian Terbuka Dengan Variasi Bentuk Honyecomb. *Malikussaleh J. Mech. Sci. Technol.* **2023**, *7*, 105, doi:10.29103/mjmst.v7i2.13491.
6. Setiawan, M.Y.; Kurniawan, A.; Ichsan; Sugiarto, T.; Hidayat, N.; Susanto, E.; Masykur; Miswardi Subsonic Wind Tunnels Air Speed Control Devices Base on Arduino Controller. *E3S Web Conf.* **2024**, *500*, 03026, doi:10.1051/e3sconf/202450003026.
7. Sahid, R.; Setiawan, M.Y.; Putra, D.S.; Saputra, H.D. Rancang Bangun Smoke Machine Untuk Visualisasi Aliran Udara Pada Wind Tunnel. *AEEJ J. Automot. Eng. Vocat. Educ.* **2024**, *5*, 39–54, doi:10.24036/aej.v5i1.244.
8. Jiang, Y.; Li, Q.; He, Q.; Cao, K.; Li, J.; Jiang, D.; Liang, L. Optimization of Low-Turbulence Structures and Neural Network-Driven Precise Wind Speed Control: A Synergistic Design for Novel Jet Wind Tunnel Systems. *Flow Meas. Instrum.* **2025**, *106*, 103039, doi:10.1016/j.flowmeasinst.2025.103039.
9. Rusnak, A. Turbulence in Porous Media: Turbulence Analysis of TPMS Materials Using DNS Simulations with the JAGUAR Code, 2024.

10. López-Martínez, A.; Granados-Ortiz, F.-J.; Molina-Aiz, F.; Lai, C.-H.; Moreno-Teruel, M.; Valera-Martínez, D. Analysis of Turbulent Air Flow Characteristics Due to the Presence of a 13×30 Threads·cm⁻² Insect Proof Screen on the Side Windows of a Mediterranean Greenhouse. *Agronomy* **2022**, *12*, 586, doi:10.3390/agronomy12030586.
11. Zhu, W.; Xiao, Z.; Fu, S. Numerical Modeling Screen for Flow and Noise Control Around Tandem Cylinders. *AIAA J.* **2020**, *58*, 2504–2516, doi:10.2514/1.J058636.
12. Sharma, D.; Namboodiri V, V.; Goyal, R. Flow Measurement in a Wind Tunnel with Blockage Screens. *Flow Meas. Instrum.* **2024**, *100*, 102741, doi:10.1016/j.flowmeasinst.2024.102741.
13. Ater, S.J.; Bautista, B.P. Design and Evaluation of Different Screens in a Wind Tunnel for Flow Management. *IET Conf. Proc.* **2025**, *2024*, 111–118, doi:10.1049/icp.2025.0243.
14. Okolo, P.N.; Zhao, K.; Kennedy, J.; Mgbemena, C.; Eke, M.; Bennett, G.J. Two-Dimensional Simplification of Complex Three-Dimensional Wire Mesh Screens. *J. Aerosp. Eng.* **2021**, *34*, doi:10.1061/(ASCE)AS.1943-5525.0001352.