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Design and Construction of a Small Open-air Wind Tunnel without Contraction and Diffuser

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ABSTRACT

This paper presents the design and construction of a small open jet wind tunnel without the contraction and diffuser. The wind tunnel is intended for experimental testing of models in a controlled airflow environment and its design offers an affordable and practical solution for researchers and students to conduct their aerodynamic experiments on small-scale models. The paper outlines key considerations for designing and constructing the wind tunnel, including selected blower fan and design of the fan holder structure. The wind tunnel is successfully constructed and tested, and the results have shown that the airflow with an average of 4 m/s and turbulence intensity of 15%. Through its capacity to provide a wide range of turbulence intensities (i.e. 15% - 89%), this wind tunnel empowers researchers to explore an extensive spectrum of real-world conditions, ensuring that the experimental data more authentically mirrors the dynamic characteristics of outdoor environments. This enhanced versatility in turbulence intensity is of particular importance, especially given the marked variations in turbulence levels that have been evident across the different urban locales. Consequently, this study not only furnishes the practical guidance for constructing small open jet wind tunnels but also highlights the critical significance of regulating turbulence intensity, varying between 89% at a distance of 200 mm and 15% at 2000 mm from the outlet to ensure precise experimental fidelity.

Keywords: Design, Open jet wind tunnel, Turbulence intensity, Wind speed

I. INTRODUCTION

The design of cost-effective and adaptable small open jet wind tunnels addresses a fundamental need in the realm of research and education for aerodynamics and fluid mechanics. Wind tunnels have served as essential tools for conducting controlled experiments to better understand the complex dynamics of airflow over scaled models, which offers many valuable insights into various engineering and scientific phenomena. Among others, several examples of wind tunnel applications include for the study and analysis of flapping wing mechanism [1-3], wind turbines [4-7] and aircraft wing designs [8,9]. Despite their great usefulness, the cost and complexity associated with constructing traditional wind tunnels, which often include contractions and diffusers, can pose significant barriers, particularly for educational institutions and small research facilities with very limited budgets. This situation creates the demand for

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innovative solutions that can offer the benefits of the wind tunnel experimentation without the financial burden.

A comprehensive account of the design, construction, and evaluation of a blower-type wind tunnel tailored for physiological bird flight experiments is presented and discussed in [10]. Designed explicitly for studying rather large birds such as the Northern Bald Ibis the wind tunnel has a test section of 2.5 m × 1.5 m and a maximum achievable flow speed of approximately 16 m/s. The technical and financial advantages of opting for an open circuit wind tunnel have been discussed in the study, given budget constraints and the need to accommodate birds with larger wingspans. Notably, for the wind tunnel design, a well-distributed velocity within the test section is achieved, with local speed deviations of less than two percent from the mean velocity. The turbulence intensity within the test section is measured at a reasonable 1% to 2%. Wood is used as construction material, ensuring reliable functionality over at least two seasons.

In the meantime, the innovative and cost-effective design of an open-loop subsonic wind tunnel, which addresses the challenges of cost and accessibility often linked to traditional wind tunnel setups, has been presented and described in [11]. The open-loop wind tunnel has been specifically designed for the aerodynamic testing of wind turbines within the speed range of 0 m/s to 15 m/s. Key advantages of this wind tunnel design are highlighted, which include the customizable honeycomb structures to optimize fluid flow, the ease of instrumentation placement, the spacious test section to accommodate large specimens and its simple design with a low turbulence intensity. This wind tunnel configuration, equipped with a contraction chamber and a settling chamber to mitigate turbulence, allows for reliable aerodynamic measurements. In addition, a comprehensive assessment of a test chamber within an open-loop wind tunnel, which is a vital component for aerodynamic experiments, has been conducted. In this study, a series of experimental tests are conducted to assess the feasibility of a new test chamber design by examining fluid characteristics and average pressure in the chamber [12]. The obtained results indicate a significant increase in downstream velocity within the test chamber, from 8.9 m/s to 12.72 m/s, alongside a pressure gradient that ranges between 6.19 atm to 8.398 atm, and the overall turbulence intensity within the test chamber is quantified at 0.749%. Overall, the findings underscore the viability of this open-loop wind tunnel design, which features a 750 x 750 x 1200 mm test chamber, for conducting aerodynamic experiments.

On the other hand, an in-depth investigation into the construction and design of the low-speed wind tunnel for small-scale aerodynamic model testing is presented in [13]. The study has rigorously explored the effects of flow, noise and vibration on the wind tunnel's structure and performance. The wind tunnel design incorporates essential components like an axial fan, a tapered diffuser, a settling chamber with a honeycomb and mesh screens, a contraction cone and an experimental test section. The design of the wind tunnel is done through a meticulous process that adheres to the recommended rules and references, and it is shown to achieve an impressive maximum wind velocity of approximately 25.1 m/s. Furthermore, a study on design and construction of a subsonic low-speed wind tunnel is presented and discussed in [14]. The design of this wind tunnel is specifically focused on achieving a flow velocity of 35 m/s in the measurement section while ensuring a uniform velocity field at the inlet. A meticulous design process incorporating theoretical one-dimensional analysis and computational fluid dynamics simulations to optimize flow quality throughout the wind tunnel sections has been employed. The resultant wind tunnel design has been successfully validated through a direct comparison of experimental flow field measurements in the test section with the numerical simulation results.

Moreover, [15] reports on the development and testing of an open-jet wind tunnel with an extended test section to facilitate the experiments related to quadrotor flight in turbulent wind conditions. In this case, an existing open-loop wind tunnel is ingeniously modified to create a larger test section with a diameter of 2 meters, providing ample space for the quadrotor maneuvers. The characteristics of the wind tunnel are evaluated using an anemometer, revealing a maximum wind speed of roughly 8.9 m/s at the opening. The turbulence intensity is found to vary from 17% to 24% with increasing wind speed and this is taken to imply that the extended diffuser produces a laminar flow with a low turbulence intensity. This reduction in turbulence, which is achieved through the attachment of the diffuser, is vital for simulating realistic wind conditions below 100 meters, a crucial factor in testing quadrotor control algorithms. In the meantime, a cost-effective multi-fan wind tunnel capable of generating turbulence and natural wind patterns for experimental research has been introduced in [16]. This wind tunnel stands out for its capability to produce fluctuating velocity wind with mean velocities of 7 m/s and turbulence intensities of 2% and 3%. The use of 100 PC cooling fans, which are controlled by an embedded system, significantly reduces construction costs compared to traditional servo-motor-driven systems.

All in all, the commonality among previous studies in terms of the design and construction of small open jet wind tunnels without contraction and diffuser lies in their focus on tailoring wind tunnel setups to specific research needs. Each discusses the meticulous design and construction of their respective wind tunnels with unique features. While each of the previous studies addresses different research objectives, they collectively highlight the significance of a purpose-driven wind tunnel design and construction tailored to specific experimental needs, often considering cost, turbulence, flow uniformity and space requirements. In this research work, a small open jet wind tunnel without a contraction and diffuser is designed and constructed. The process involves creating a system that generates uniform and controlled airflow for testing model objects. Unlike wind tunnels with contraction and diffuser, an open jet wind tunnel allows for an unobstructed flow of air without the need for these additional components. The wind tunnel design in this study consists of nine blower fans held by three-dimensional printed parts and aluminum profile structure. It should be noted that the accuracy in measurements is crucial, so anemometers support the wind tunnel to measure the airflow velocity. While wind tunnels without contraction and diffuser might exhibit higher turbulence levels and non-uniform flow fields compared to their counterparts, they still offer some advantages in terms of cost-effectiveness, simplicity of the design and ability to accommodate larger model objects.

II. SETUP AND METHODOLOGY

The methodology that is followed for the design and construction of the small open jet wind tunnel in this study can be essentially broken down into several major steps. They are listed and described as follow:

- Design of the wind tunnel structure: Computer-aided design (CAD) software, SolidWorks 2023 is utilized to design the wind tunnel structure. The CAD model is shown in Figure 1. In this study, aluminum profiles have been incorporated as the primary framework for stability and rigidity. Several three dimensional (3D) printed parts are also designed and used to support and connect the aluminum profiles.
- Preparation of aluminum profiles: Overall, a total of 14 aluminum profiles are used for the wind tunnel design. According to the wind tunnel's dimensions, 3030 aluminum profiles (i.e. 30 mm x 30 mm) are cut into parts with one-meter lengths. Precise and accurate cuts are necessary for proper assembly later and the edges of the profiles are deburred and smoothened for safety and aesthetic reasons.
- 3D printing of parts: A 3D printer (i.e. Original Prusa i3 MK3S) is used to create the fan holders. All these 3D-printed parts must be sturdy and durable enough to withstand the wind tunnel's operational conditions. Polylactic Acid (PLA) filament material is used in 3D printing for ease of use and cost-effectiveness. The print setup is done using the open-source software PrusaSlicer 2.5.2, with a setting of print height of 0.3 mm and nozzle diameter of 0.4 mm (as depicted in Figure 2). Overall, 18 fan holders are printed for the wind tunnel.
- Assembly of the structure: Allen bolts and European standard 3030 L-shape joint brackets have been used to attach the aluminum profiles. It is crucial for the resultant assembled structure to be stable and rigid, and all parts are securely connected.
- Installation of blowers: Nine blower fans (i.e. model HF-200 with flow of 900 m^3/hr) are positioned along the three stages of the wind tunnel structure. Each of the stages holds three blower fans. 3D printed parts for the fan holders are used to securely mount the blowers, which are appropriately aligned and spaced inside the wind tunnel to provide a uniform airflow distribution across the open test section as shown in Figure 3.
- Creation of the open test section: For this wind tunnel design, there is no wall or base, which creates the open test section. This configuration enables an unobstructed flow of air. Therefore, it must be ensured that no obstruction or restriction around the test section that can disturb this condition.
- Powering the blowers: The blowers are connected to a power supply through electrical wiring. In essence, the wiring connection needs to comply with the safety requirements and precautions. The variable power supply is used to be able to adjust the speed of the blowers during the wind tunnel's operation.

Validation and fine-tuning of the airflow: In monitoring and adjusting the velocity of the airflow within the open test section, the anemometer device (i.e. Smart Sensor AR856 with wind speed accuracy of ± 3% ± 0.1 and wind speed resolution of 0.001 m/s) is used. As shown in Figure 3, the settings of the blowers' speed are then optimized to achieve the desired flow parameters such as velocity and turbulence levels.

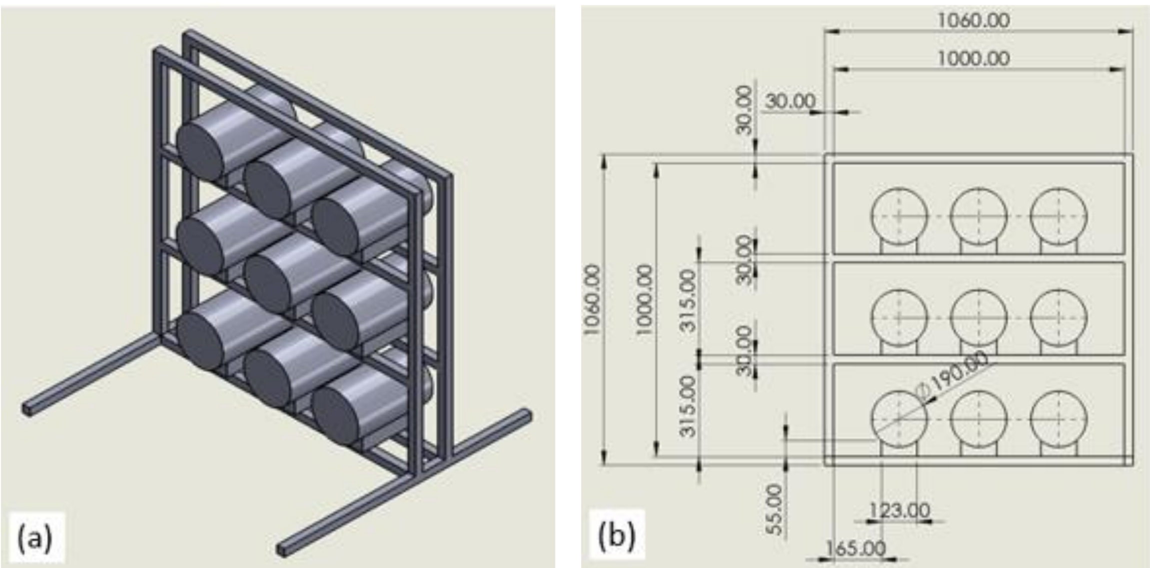

Figure 1 Design of the open jet wind tunnel's structure: (a) 3D drawing, (b) design specifications

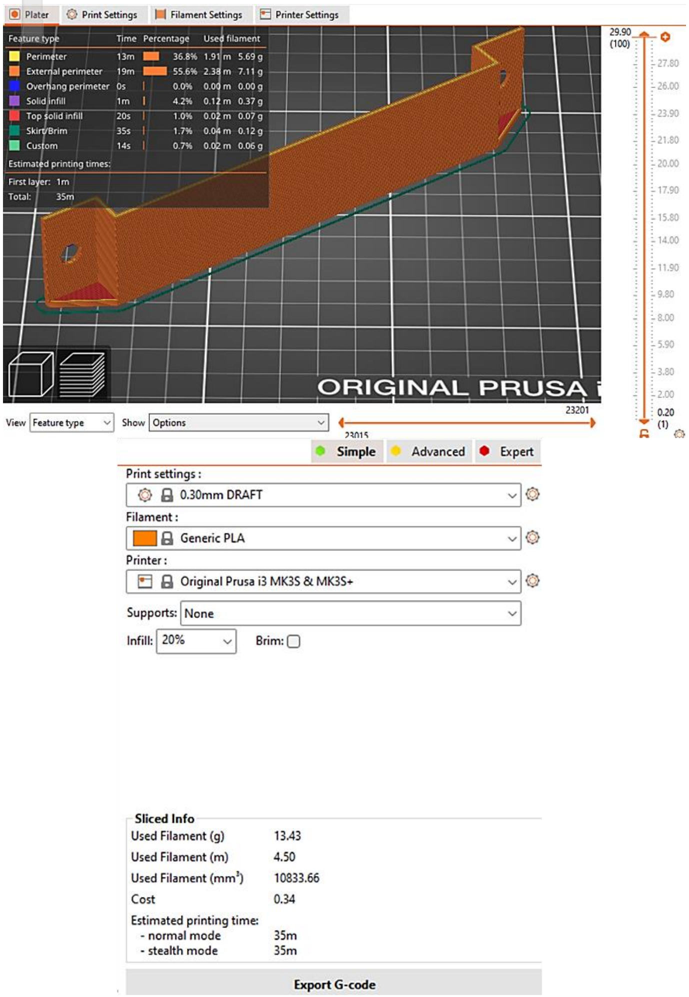

Figure 2 Print setting using PLA filament

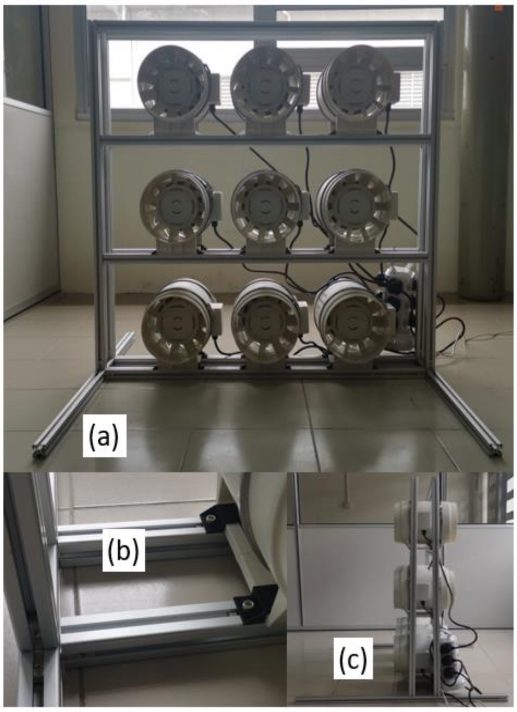

Figure 3 Open jet wind tunnel without contraction and diffuser setup: (a) front-view outlet blower fans, (b) aluminum profile connection and blower fan holder, (c) side-view wind tunnel

The distance from the inlet and outlet of fan blowers serves as an independent variable whereas the wind speed represents a dependent variable. The measurement process involves taking the wind speed data at specific distances. The distance is measured in 200 mm increments up to a maximum of 1000 mm, starting from the inlet. Similarly, for the outlet, the distance is increased in 200 mm increments up to 2000 mm. At each distance point, the wind speed is measured three times for each specific location totaling 25 measurement points. It should be noted that each of these measurements is taken at a few specific locations using the anemometer, including at the center of each fan blower and at certain points between the fan blowers. Figure 4 shows the precise location of each measurement point.

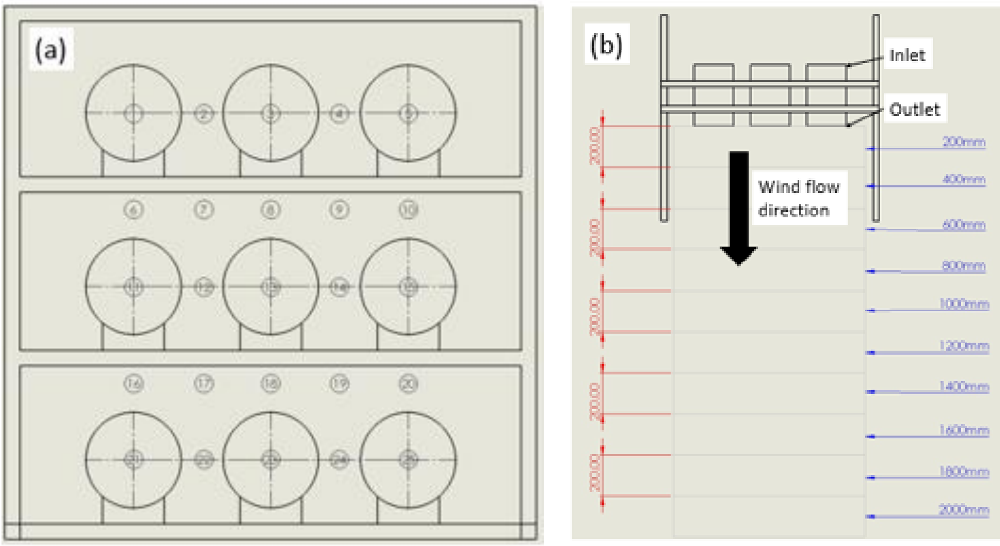

Figure 4 (a) 25 measurement points, (b) measurement distances from inlet blower

The collected wind speed data is then analyzed using the turbulence intensity formula. The formula to calculate turbulence intensity using the standard deviation is shown in Equation (1), where *TI* is turbulence intensity (expressed as percentage, σ is the standard deviation of the velocity fluctuations and U is the mean velocity.

$$TI = (\sigma/U) * 100 \quad (1)$$

III. RESULTS AND DISCUSSION

In general, the findings on average wind speed and turbulence intensity provide valuable information about the performance and characteristics of the open jet wind tunnel without contraction and diffuser. These parameters enable researchers and engineers to assess the quality of the wind flow, validate the experimental results and ensure the suitability of the wind tunnel for intended applications.

Table 1 Open jet wind tunnel characteristics by distance from outlet and inlet blowers

Outlet			
Distance (mm)	**Turbulence intensity**	**Average wind speed (m/s)**	**Average uncertainty analysis for 25 points**
0	85%	2.48	9.98%
200	89%	4.35	8.50%
400	33%	5.33	5.25%
600	19%	5.50	3.37%
800	18%	4.85	5.72%
1000	18%	4.64	3.97%
1200	19%	4.51	0.62%
1400	19%	4.32	0.49%
1600	16%	4.25	0.62%
1800	16%	4.07	0.53%
2000	15%	4.14	0.48%

Inlet			
Distance (mm)	Turbulence intensity	Average wind speed (m/s)	Average uncertainty analysis for 25 points
0	110%	4.39	6.18%
200	29%	1.78	5.35%
400	15%	1.16	1.95%
600	22%	0.68	3.03%
800	87%	0.17	3.90%
1000	0%	0.00	0.00%

Data collected is tabulated in Table 1, which is presented as well in Figure 5 and Figure 6. Observed is that the percentage average of uncertainty analysis, utilizing standard deviation for wind speed measured three times at each of the 25 measurement points, resulted in being below 10%.

At this point, the design and construction of a small open jet wind tunnel without contraction and diffuser have been successfully accomplished. The wind speed capability for the open jet wind tunnel is measured using an anemometer and it has been found to range between 0 m/s to 5 m/s. The wind tunnel outlet can produce a moderately uniform flow field with a turbulence level of 15% at an average wind speed of 4.14 m/s.

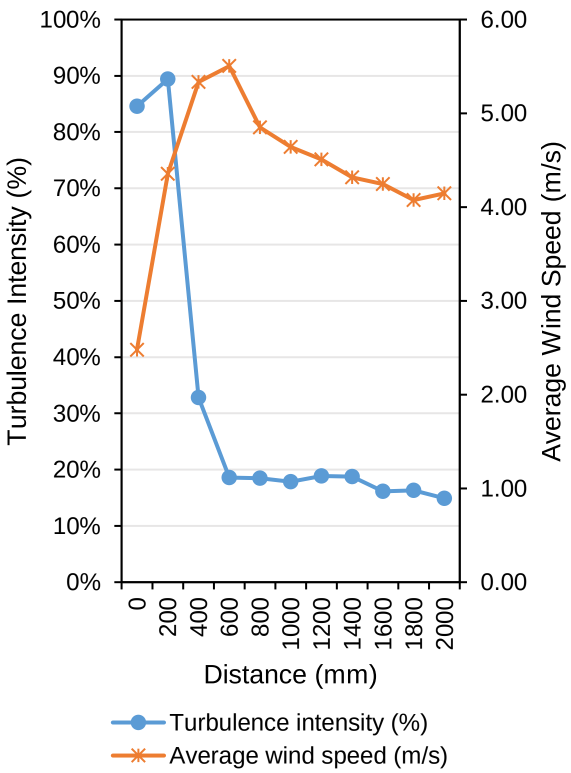

Figure 5 Turbulence intensity and average wind speed from wind tunnel outlet

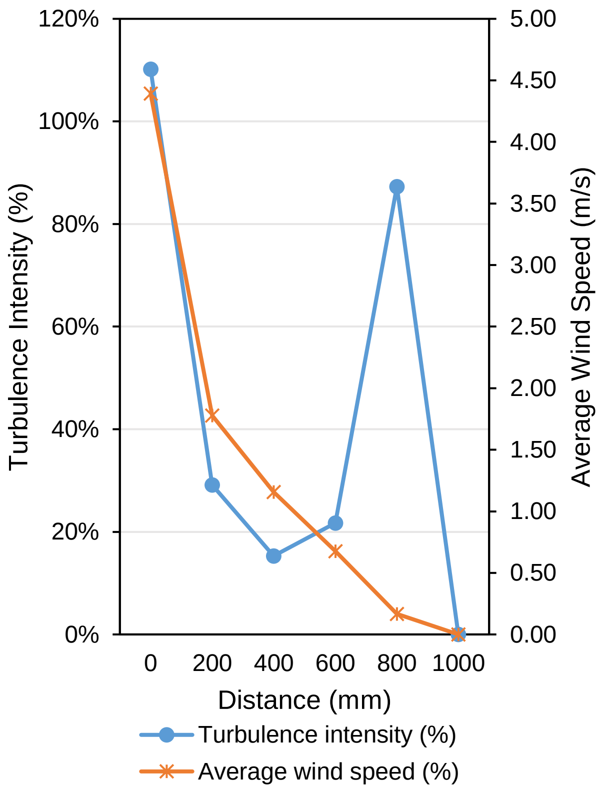

Figure 6 Turbulence intensity and average wind speed from wind tunnel inlet

It should be noted that the spacing between the blowers impacts the uniformity of the airflow, necessitating a distance of 2000 mm to achieve a turbulence intensity of 15%. On the other hand, the inlet has shown low average wind speed and high turbulence level as the distance increases. The sudden increase of the turbulence intensity at the wind tunnel inlet for a distance above 400 m can be attributed to loss of air suction. The finding on the outlet side of the open jet wind tunnel is significant in the context of Malaysia's average wind speed, which is below 2 m/s [17]. Moreover, the turbulence intensity level and its application in approximating urban wind energy is of paramount importance for effectively utilizing wind energy resources in complex urban environments [18]. Overall, these findings are invaluable for guiding the wind turbine design, siting and load eduction strategies in urban areas and other complex terrains.

Based on the established characteristics of the designed wind tunnel in this study, its suitability for applications can be discussed. An open jet wind tunnel without contraction and diffuser with turbulence intensity ranging from 15% to 85% can be used for simulating pedestrian-level wind conditions, which represents a promising and versatile advancement in wind engineering research. It is important to have a wind tunnel that can accurately replicate the complex turbulence characteristics that are often found in urban environments, as these factors significantly influence thermal comfort and convective heat loss from the human body [19]. Previously conducted research has revealed that the average turbulence intensity at the studied sites ranged from 22% to 48%, highlighting the substantial turbulence present in urban settings. Meanwhile, a study presented in [20] offers valuable insights into the influence of wind turbulence on thermal perception within urban microclimates. The research stresses the growing significance of turbulence in contemporary urban settings, where the rising roughness lengths in the atmospheric surface layer contribute toward highly turbulent wind conditions at pedestrian height. By offering a wide turbulence intensity range, such as the wind tunnel designed in this study, it can enable the researchers to investigate a broader spectrum of real-world conditions, ensuring that experimental data more faithfully reflects the actual dynamic nature of outdoor spaces. This enhanced flexibility in turbulence intensity is particularly valuable, given the substantial variability observed in the turbulence levels across different urban locations as demonstrated in the field measurements.

The small open jet wind tunnel without contraction and diffuser has several advantages over traditional wind tunnels. It is less expensive and easier to construct, and it can be used to test models that are too large for closed-circuit wind tunnels. However, the lack of contraction and diffuser can also result in non-uniform flow fields and moderate turbulence levels. The design of the settling chamber and the nozzle are critical to achieving a uniform flow field, and careful calibration of the measurement instruments is necessary to obtain accurate results. Further improvements could be made to the wind tunnel design in this study, such as adding a diffuser to improve flow uniformity and reduce turbulence levels. The addition of a diffuser will also allow for higher wind tunnel velocities and Reynolds numbers. Ultimately, the introduction of a screen can enhance uniformity by minimizing swirl and promoting a consistent, parallel flow. Nonetheless, the benefits observed when using a small open jet wind tunnel without a contraction and diffuser, such as the one proposed in this study are listed as follows:

- Uniform airflow distribution: The use of multiple small blowers that are arranged at equal spacing next to another and positioned along one side of the wind tunnel helps to achieve a more uniform airflow distribution within the test section. This arrangement can provide consistent results during the aerodynamic testing.
- Adjustable airflow velocity: The ability to control the speed of each blower independently allows for precise adjustment of airflow velocity within the test section. This flexibility will enable experimentation at various flow speeds to study different aerodynamic phenomena.
- Customizable design: The use of aluminum profiles and 3D printed parts has provided a modular and customizable design. This customizable design allows easy modifications and adjustments to the wind tunnel's structure and components as needed for specific experiments or research objectives.
- Simplified test setup: The open test section without a wall and base simplifies the setup process and allows for easy placement and removal of model objects. It also enables unobstructed access to the test section, aiding the installation of the measurement instruments and reducing interference with the airflow.
- Potential for cost-effectiveness: Using small blowers and 3D printed parts offers a cost-effective alternative compared to larger, more complex wind tunnel setups. This small blowers and 3D printed parts can particularly benefit for many research or educational institutions with limited budgets.
- Versatile research capabilities: A small open jet wind tunnel can be utilized to study various aerodynamic phenomena like lift and drag forces, flow separation, boundary layer behavior and also flow visualization. It can support research and development activities in various fields like aerospace engineering, automotive design and fluid dynamics.

IV. CONCLUSIONS

In conclusion, the design and construction of a small open jet wind tunnel without contraction and diffuser has been successfully completed in this study. The wind tunnel haves been shown to be able to produce a uniform flow field with a turbulence level of less than 15% with a wind speed average of around 4 m/s at a distance of 2000 mm from the outlet. However, the lack of contraction and diffuser can result in non-uniform flow fields and higher turbulence levels. In view of this, further improvements could be made to the wind tunnel design such as adding the diffuser to improve flow uniformity and reduce turbulence levels. Overall, it can be taken that the small open jet wind tunnel without contraction and diffuser offers a cost-effective and practical solution for testing models that are too large for closed-circuit wind tunnels.

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