Design and Development of Low-Cost Wind Tunnel for Educational Purpose

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Abstract. The presence of wind tunnel is undoubtedly bringing infinite possibilities to studying and understanding complex fluid flows. However, commercial wind tunnel is expensive and only limited to highly-focus researchers or exclusive institutions. This paper discusses the design and development of a low-cost, educational-purposed, open-typed subsonic wind tunnel. In this work, an open-typed subsonic wind tunnel is designed with the aim of achieving turbulent intensity (in the working section) below or equal to 5%, within the budget of RM 1500 and a working speed of 6 m/s – 8 m/s to meet the Reynolds number in the order of 10^5. The conceptual design was studied using Ansys Fluent 14.5 and the optimal design was then developed and experimentally verified.

1. Introduction

The phenomenon of turbulent flow has been long studied and intrigued scientists and researchers. It was Dr. Price's [1] of Monash University belief that Leonardo Da Vinci was one of the first to be intrigued by turbulent flows. Due to his insightful observations, significant works were able to carry out easily and led to the development of the basic dynamics equations. Unfortunately, the knowledge of turbulent flows is too vast and is still fairly immature to date. There are limitations on numerical approach as it involves approximations and it lacks physical understanding to researchers. The invention of wind tunnels gave researchers an idea how flows behave in actual.

There are various different design types of wind tunnel for different applications as no single tunnel fits for all purposes. Wind tunnels can be classified based on air flow speed in test section or based on design. Open-typed wind tunnel and close-typed wind tunnel (see figure 1) are wind tunnels based on design while wind tunnels based on speed are subsonic, transonic, supersonic and hypersonic. An advanced commercial grade wind tunnel is very expensive and exclusively available only to research-focused universities.

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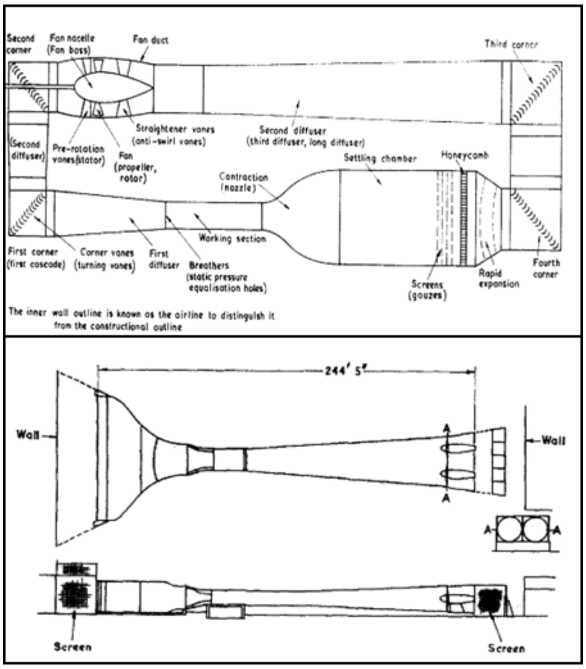

Figure 1. Closed Type Wind Tunnel proposed by National Physical Laboratory (NPL) (above) and Open Type Wind Tunnel of Indian Institute of Science (below) [2].

Thus, this project aims to design, develop, and construct a cost-effective open-circuit wind tunnel which is able to conduct small-scale experiments to visualize flow passing through fundamental objects for educational purpose. This wind tunnel mainly focuses on testing any scaled-down model, roughly giving a width based Reynolds number of the order of hundred thousand at approximately 5% blockage based on frontal area. A fourth to sixteenth times scale was deemed adequate for investigations of the underlying flow mechanisms and for basic research and study on simplified bluff and quasi-streamlined bodies. Turbulence intensity of less than 5% at working speed of 6 m/s to 8 m/s would be considered reasonable for testing without compromising the integrity of the results [2]. A 120 V gable fan was used to achieve the working speed. The budget for this project was allocated RM 1500.

2. Design methodology

This project can be divided into three components namely: Designing and Simulation, Construction, and Experimentation. The design of educational-purpose and cost-effective subsonic wind tunnel is verified and improved using Ansys Fluent 14.5 CFD simulation. In order to achieve the goal of designing a subsonic wind tunnel with working turbulent intensity of less than 5%, the relationship between the relevant parameters and components were studied. A detailed list of the parameters and the components are studied by [3].

All designs were simulated using Ansys Fluent 14.5 simulation software. The Computational Fluid Dynamics (CFD) model and setup can be referred to [3]. Table 1 show the final design of the subsonic wind tunnel which has a blockage ratio of 4.8% and a turbulence intensity of 2.72% - 3.39% at the flow speed of 6.28 m/s (see also figure 2).

Table 1. Dimensions of components for final conceptual design

Module	Width (m)	Height (m)	Length (m)	Area (m^2)	Area Ratio
Contraction Cone	0.81	0.81	0.610	0.656	7.28
Working Section	0.30	0.30	0.610	0.090	-
Diffuser	0.43	0.43	1.218	0.185	2.05

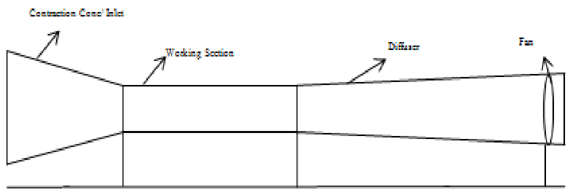

Figure 2. Schematic sketch of designed wind tunnel.

3. Wind tunnel construction

The wind tunnel was vastly of wood construction due to its affordable price compared to metal sheet or fibre glass of smoother surface but more expensive. Due to its nature of the wood, it is also relatively easy to handle for construction as well. The chosen material was standard 0.9 cm plywood. The working section had to be transparent to gain clear view of the internal of working section. Also, a working section is the most important part of the wind tunnel as experiment is carried out in the working section; thus, a smooth surface (see figure 3) was necessary to maintain the accuracy of results. A rough surface could induce unwanted development in boundary layer and stress and was experimentally demonstrated by Bradley [4]. At large surface roughness, the flow may be excessively clogged by the tunnel walls leading to increased pressure gradient and consequent acceleration of flow at the blockage. The blockage ratio of 5.0% - 5.3% is generally accepted as sufficiently low to avoid significant low wall interference effects [5].

Figure 3. Photograph of actual test section made from plexiglass.

3.1. Contraction cone

The contraction cone, with a contraction ratio of 7.28, which was in between the range of 6 and 9 proposed by Bradshaw [2] has a huge influence on working section turbulence intensity. A contraction cone is used to improve uniformity of the air flow and increases the mean velocity. The power factor contribution of screens in the settling chamber varies as $\frac{1}{c^2}$ [2 and 6]. However, if the contraction part of the wall along the flow direction is too large at certain points, the uniformity of velocity will be disturbed at the end of contraction cone [7]. It is therefore very important to achieve a perfect balance between the size of the test section and contraction ratio. The contraction cone was a perfectly straight without any curve as it was easier to construct with plywood. The trapezium shaped plywood were connected using 5 cm long, 0.4 cm diameter nails. The gap between joints (see figure 4) was filled with silicone glue to strengthen the structure and minimize exfiltration. The end which connect the cone to the test section was filled with rubber gasket and silicone glue (see figure 5 and 8).

Figure 4. Joint filled with silicone glue (top view).

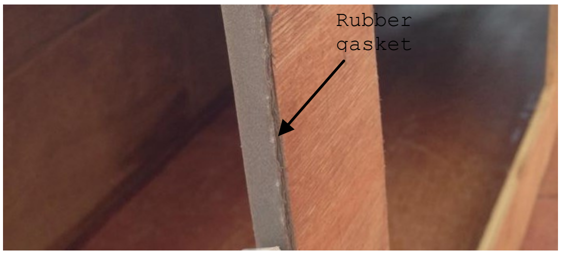

Figure 5. Rubber gasket adhere to the side of diffuser.

3.2. Honeycomb

A proper honeycomb is very expensive to acquire. The initial plan of improvising by using 1.2 cm diameter thick straw, which met the minimum requirements suggested by Metha [6] and Bradshaw [2] was time consuming to construct. Therefore, a wire mesh of 0.5 cm diameter was used as substitution (see figure 6) due to the consideration that a proper honeycomb was not accessible locally and would be expensive. The wire mesh was fitted to the contraction cone by stapler bullet. The performance of substituted honeycomb would be greatly reduced as it had no depth.

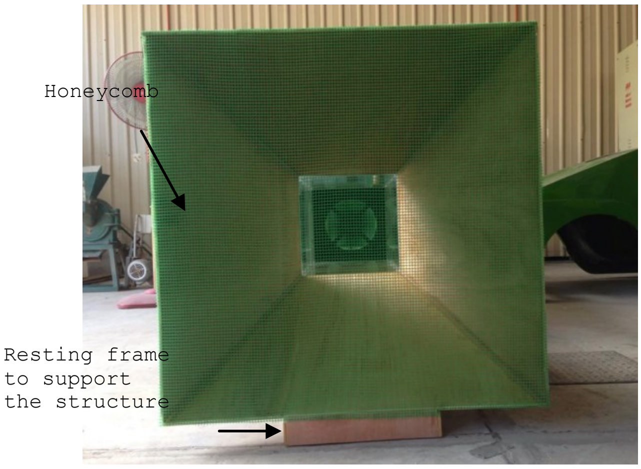

Figure 6. Contraction cone fitted with honeycomb made by mesh wire.

3.3. Diffuser

The diffuser is arguably the least important part in a suck down open circuit configuration because of its position at the downstream of test section. The diffuser (see figure 7) was a trapezium shaped with exit slightly larger than the entrance of an area ratio of 2.05 which was less than 2.5 [8]. The three components: contraction cone, test section and diffuser were assembled together by sitting on a frame (see figure 9) which provided a firm and stable structure for the wind tunnel. The assembly was as equally important as constructing the separated parts because if the structure was not strong and stable, the wind tunnel would vibrate when operating due to the vibration from the fan.

Figure 7. Trapezium shape diffuser made of plywood.

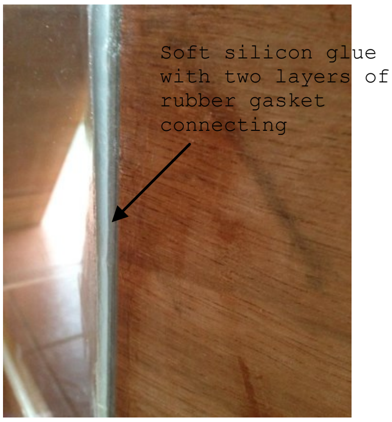

Figure 8. Joint between contraction cone and test section.

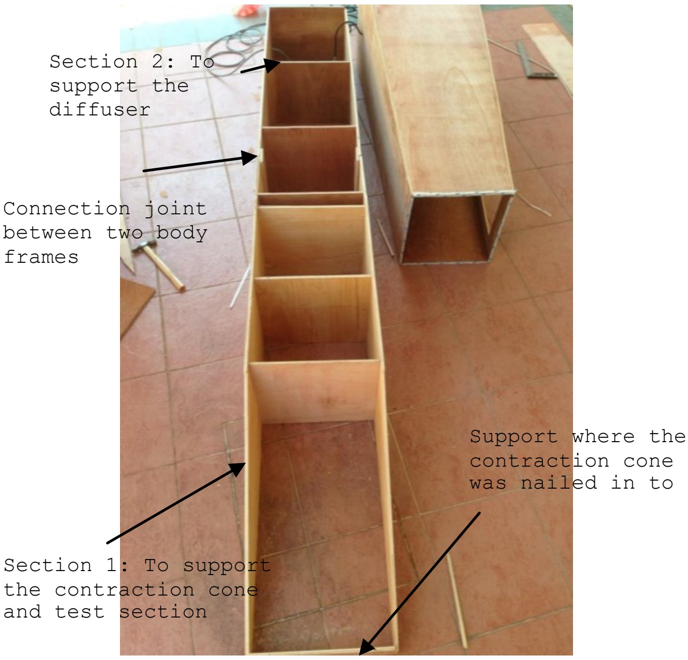

Figure 9. Body frame to support the wind tunnel.

4. Experiment

The prototyped wind tunnel had to be verified experimentally to know its specification. Due to the limited budget and equipment, a simple air flow anemometer accompanied with a data logger with RC-232C interface were used to check the oncoming wind speed. The air flow anemometer used has an accuracy of ± 3% at the range of 0.1 m/s - 45.0 m/s. The turbulent intensity is given in the equation below:

$$Tu = \frac{\sqrt{\overline{u^2}}}{U_{mean}} \qquad (1)$$

With the goal of achieving within 5% of turbulence intensity, the air flow anemometer was placed at two positions (see figure 10 marked 1 and 2) in the region of developed boundary layer over a consistent of 130 seconds.

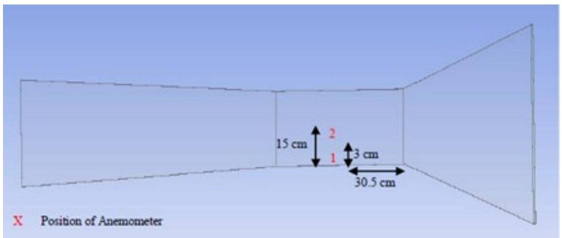

Figure 10. Position of anemometer.

Experiments were conducted for completed wind tunnel (figure 11) under 3 different conditions as shown in table 2.

Table 2. Detailed sets of experiments conducted

Experiments	Conditions	Positions (see figure10 for picture illustration)
1	Right after the fan was initiated	1
2	10 minutes after the fan was operated	1
3	10 minutes after the fan was operated	2

Figure 11. Completed wind tunnel.

5. Results and discussion

5.1. Simulation results

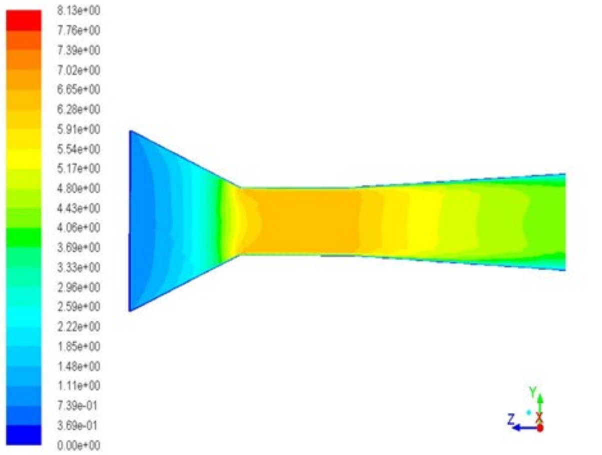

Figure 12. Contours of velocity magnitude for final conceptual design.

Figure 12 shows the simulation results of the final conceptual design, which simulation settings can be referred to [3]. The color bar indicates the velocity in m/s. It can be seen that the velocity at the working section has a uniform pattern peaked at 6.65 m/s and in the general region of 6.28 m/s. The velocity decreased gradually in the diffuser and satisfied the conversation of mass equation for subsonic flow.

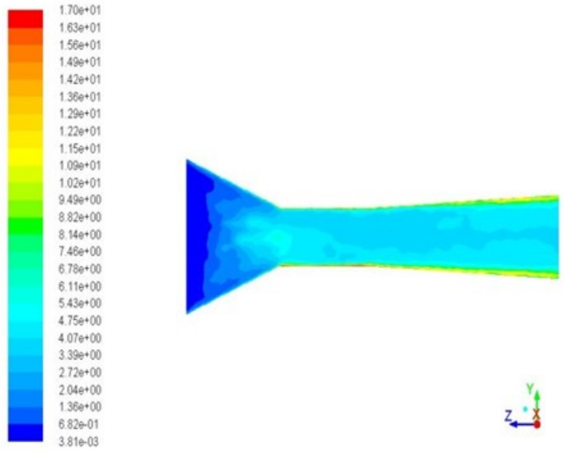

Figure 13. Contours of turbulence intensity for final conceptual design.

Figure 13 shows the simulation results of the final conceptual design. The color bar indicates turbulence intensity in percentage. The data shows the turbulence intensity within the working section ranged from approximately 2.72% - 3.39%. In consistence with the figure of velocity contours, the flow near wall was unstable due to the boundary layer thickness and skin friction. However, the usable area, which was approximately 3 cm off the working section floor, had a blockage ratio of 4.8% [3] in comparison to the 5.0% - 5.3% which was generally accepted as sufficiently low to avoid significant wall interference effects [5].

5.2. Experimental results

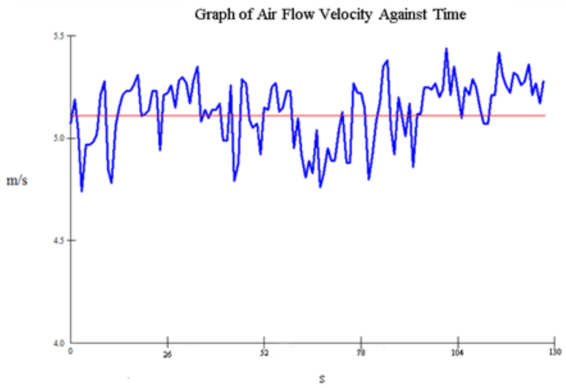

Figure 14. Graph of air flow velocity against time for experiment 1.

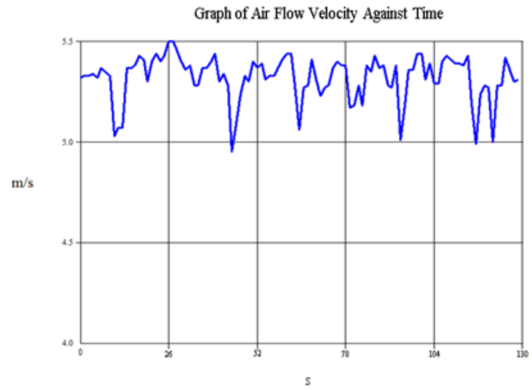

Figure 15. Graph of air flow velocity against time for experiment 2.

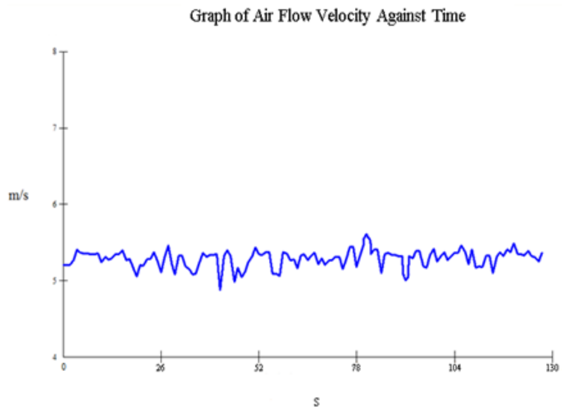

Figure 16. Graph of air flow velocity against time for experiment 3.

Figure 14 shows the graph of air flow velocity against time for experiment 1. The mean velocity was 5.12 m/s. The stream-wise turbulent intensity was 3.073 % at that position. Figure 15 shows the graph of air flow velocity against time at for experiment 2. The mean velocity was 5.32 m/s. The stream-wise turbulent intensity was 2.055% at that position. The mean velocity appeared to be slightly higher than in experiment 1 after the surrounding flow was steady. The flow inside the test section also appeared to be slightly more steady than in experiment 1 as the turbulence intensity of 2.055% was slightly less than 3.073%. Figure 16 shows the graph of air flow velocity against time for experiment

3. The mean velocity was 5.29 m/s. The stream-wise turbulent intensity was 2.028% at that position. The mean velocity appeared to be near the mean velocity in experiment 2 which was in position 1. The velocity appeared to be uniformly distributed in the boundary-layer-free region once the flow was steady.

Based on the experimental and simulation results, it is safe to say that they are close. The overall mean velocity in experimental data shows a 5.32 m/s in position 1 of condition 2 to 5.29 m/s in position 2. In contrast to that, the overall mean velocity generated by Fluent was 6.5 m/s (see figure 12). A velocity of ± 1.2 m/s was higher than experimental results. The reason could be due to the friction which was caused by wall surface roughness. Since the rough flow is dominated by the drag of the roughness elements over shear stress as compared to smooth flow where the shear stress is dominated by viscosity [9 and 10], the drag produced induces energy loss in the flow.

The turbulence intensity simulated by Fluent showed a region of 3.67% at the position 1 and a region of 2.93% at the upwards of position 2. The experimental results which were surprisingly lower than simulation results. This could be because the experimental results showed were only stream-wise turbulent intensity. The overall turbulent intensity should be added up from the longitudinal, transverse and vertical turbulence intensity instead of just stream-wise turbulent intensity as shown by the experimental results.

6. Construction cost

Table 3. Costs breakdown for materials bought

Materials	Price per unit (RM)	Total amount (RM)
Aluminum mesh wire 50 cm x 50 cm	15.00	15.00
Wington 12 inch gable fan	290.00	290.00
Silicone glue small	11.00	11.00
Wood glue small	10 .00	10.00
½ inch square x 3 ft PVC netting	13.00	39.00
Plexiglas 1cm thick (30 cm x 61cm)	155.00	310.00
Plexiglas 1cm thick (32 cm x 61cm)	155.00	310.00
Plywood 10 mm x 1 m x 2 m	95.00	745.00
1 inch adhesive double side tape	36.00	36.00
Total		1766.00

Table 3 shows the detailed cost of materials purchased to building the wind tunnel. An invoice of the purchase order can be referred to [3].

7. Conclusion

Several studies have provided brief guidelines on the relationships between the components and the reliability of the flow. The simulation model used was the *k-ε* model with the assumption of incompressibility. The materials used to construct the wind tunnel were mainly plywood and Plexiglas as the working section. The cost of the wind tunnel was relatively affordable despite the RM 266 more than the budget. The prototyped wind tunnel shows good agreement with the simulation results. The experimental results showed that the mean velocity was ± 1.2 m/s slower than simulation results but the turbulent intensity was as suggested by Fluent. However, due to the simplicity of the RC flow anemometer, only stream-wise turbulent intensity was tested. Overall this project has achieved its objective and was able to test small scale test specimen to study the flow around the object although if possible, is better to further refine the performance of the wind tunnel.

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