Design and Development of a Small-Scale Wind Tunnel for Flow Visualization

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Abstract. A small-scale wind tunnel model with a length of 100 cm was designed and manufactured for flow visualization. The flow was visualized by using a mini smoke generator developed specialized for this small-scale wind tunnel and used the same principal as the conventional fog generator. To capture the flow motion, several parameters such as honeycomb screens, illumination systems, smoke liquids and fan speeds were varied to illustrate the smoke lines that represent the flow characteristics. The qualitative results based on these various configurations were presented and discussed in this paper with clear visibility for the smoke line intensity at 6 m/s with an airfoil used as the model to effectively demonstrate the flow visualization.

1. Introduction

A wind tunnel is commonly used to study the flow motion of a particular test model. It offers the ability to visualize airflow to allow further understanding of the aerodynamic characteristics of the model [1]. There are various techniques established in the literature to visualize the flow. Batil and Muellerf [2] suggested that smoke flow visualization is the most effective technique, as it is capable of producing a qualitative macroscopic picture of the overall flow field, as compared to other techniques which are limited to measuring the flow conditions at discrete point within the flow field. In addition, Martin and Mark [1] recommended the usage of a fog machine as a smoke generator device to enhance flow visualization, with the fog produced by heating a water-based liquid that has superior dispersal properties. They also emphasized the usage of a smoke rake to channel the smoke from the fog machine into the wind tunnel test section to enhance multiple smoke lines formation for better illustration of the flow.

To capture the flow motion effectively, several parameters must be considered. Wind tunnel flow velocity is one of the most common parameters that affect smoke formation [3]. The airflow velocity for each wind tunnel configurations vary ranging from 2 m/s to 10 m/s and the smoke lines can be easily dispersed based on this range. It is very important to add a screen and a honeycomb to retain the smoke lines [4-5]. A screen and honeycomb can reduce the turbulence flow caused by the air intake, resulting in smoother smoke lines. Martin and Mark [1] also studied the effect of various smoke liquid solutions for the smoke generator. They suggested a water-based solution as the best liquid for smoke generation, because the smoke is less toxic and denser compared to other liquids. In the current study, Safex oil has been used to illustrate the smoke pattern clearly.

The aim of this work is to investigate the effect of honeycomb screens, fan speeds, smoke liquids and illuminations systems as these parameters will significantly influence the quality of the flow visualization. The flow behaviour produced by the most effective configurations was discussed based on the smoke line pattern which represents the model’s aerodynamic characteristics. The final small-scale wind tunnel model produced from this work will be used for an in-house demonstration as it is very practical due to its capability to be dismantled easily, small in terms of size, portable and reasonably low cost for its capability to produce a good quality of flow visualization.
2. Methodology

A small-scale wind tunnel was designed and integrated with a smoke system to allow for flow visualization demonstration. An overview of the methodology for this work is shown in Figure 1.

2.1. Wind Tunnel

A small-scale wind tunnel was designed in CATIA R21 software and fabricated by using wood, aluminium and Acrylic Perspex. The design was based on the basic configurations established in the literature [6-8]. A contraction nozzle was placed inside the wind tunnel to eliminate the need for any attachment between the nozzle and the test section. Two rectangular supports were added to level the test section height. The wind tunnel has an overall length of 1 m, a contraction ratio of two, and a test section length of 0.56 m as shown in Figure 2.

A honeycomb made of a 6 mm circular cell with a length of 30 mm width, combined with a screen, was added to straighten the incoming flow in the test section. The size of the honeycomb was the same as the opening of the contraction nozzle. For the screen, a wire gauze of 1 mm square cell was used, stretched and sewed to a rectangular metal frame, as shown in Figure 3a and 3b. The blockage effect was less than 10% and not significant to influence the qualitative results.
Figure 2. Three-dimensional modelling of Wind Tunnel using CATIA software.

(a) (b)

Figure 3. The image of (a) honeycomb and (b) screen used in the current work

2.2. Test Model

An NACA 0018 airfoil was used as a test model for the flow visualization study due to its good stall condition and minimum effect of roughness. The length was set at 15 cm to satisfy Barlow’s [5] recommendation that a test model should be lower than 0.7 times the height of the test section. The airfoil profile points were exported from software (Airfoiltools.com) and configured into CATIA. The points were connected and linked until a solid line of the airfoil shape was formed. The airfoil model was then printed on a paper based on the real scale size. The actual model was fabricated using a polystyrene reinforced glass fibre composite via the wet layup process. The final product was then painted in black to provide contrast and better illumination, as shown in Figure 4.

2.3. Smoke System

A smoke was generated by heating a liquid fuel using a double coil 0.18 mm Nichrome wire, as shown in Figure 5a. A Nichrome wire was used as the heating element, as it has a very high electrical resistivity. The length of the wire was set at 100 mm, and a voltage of 12V was applied to heat the wire. The oil was carried to the heating coiled wire with a lamp wick. The wick acted as a mechanism to feed the oil to the heated wire through the effect of capillary action. The smoke produced by the heated oil was then stored in a closed jar to prevent it from dispersing into the surrounding environment. However, a mechanism to regulate the pressure inside the jar was required to channel the smoke into the smoke rake. A B-10200 model air pump was used to create a pressure difference and force the smoke into the smoke rake. The system works similarly to a conventional fog generator. The configuration of the smoke system and the smoke rake are shown in Figure 5a and 5b.
2.4. Image Configurations

To capture the effect of various parameters of the smoke line characteristics in the wind tunnel, a D3500 Nikon camera at 60 fps was mounted on a tripod and positioned directly in front of the test section. The camera was set to ‘automatic’ mode with ‘High Definition Image’ to clarify the generated images. Black cloth was used to cover the whole test section areas to reduce any reflections caused by the Perspex and the illumination systems.

3. Result and Discussion

3.1. Effect of honeycomb and screen configurations

The results for the smoke flow visualization system for the lab-small scale wind tunnel are shown in Figure 6. The smoke was set to be in a single line with the operating fan speed at 4 m/s, while the illumination system employed was a fluorescent lamp. The initial configuration for the small-scale wind tunnel consisted of only one honeycomb. The smoke generated for the initial configuration (Figure 6a) showed irregular and faded smoke patterns. Since the smoke entered directly from the honeycomb, a solid line was only present if the tube rake was aligned with the honeycomb cell. Otherwise, the smoke would break into several small streamlines and be dispersed rapidly later. The addition of two honeycombs (Figure 6b) appeared to improve the irregularities of the smoke line due to the synchronized alignment. However, the flow fluctuation was very significant in this case. The addition of a screen before the honeycomb (Figure 6c) resolved the fluctuation rate of the smoke. The flow became more coherent and concentrated, and the smoke line showed straighter and more streamline pattern. These results agree well with Groth [4], who showed that the usage of a screen will reduce the turbulence level of the flow and improve its streamline quality. The screen was use to break up the large-scale turbulent eddies that came along with the channelled smoke into a number of small scale eddies. The small scale eddies will subsequently have decayed, and then produced a more uniform and stable flow pattern. The further incorporation of another honeycomb (Figure 6d) however, results in a very severe dispersed flow that is not favourable. The line was observed to fade and disperse rapidly even before entering the test section. The effective smoke flow visualization
configuration for the current study has been identified as the one with the screen positioned just before the honeycomb

(a) Addition of one honeycomb
(Honeycomb > Nozzle > Test Section > Diffuser > Drive Fan)

(b) Addition of two honeycomb
(Honeycomb > Nozzle > 2nd Honeycomb > Test Section > Diffuser > Drive Fan)

(c) Addition of one screen and honeycomb
(Screen > Honeycomb > Nozzle > Test Section > Diffuser > Drive Fan)

(d) Addition of screen and two honeycomb
(Screen > Honeycomb > Nozzle > 2nd Honeycomb > Test Section > Diffuser > Drive Fan)

Figure 6. Smoke line observation at various honeycomb and screen configurations

3.2. Effect of illumination systems

It was essential to illuminate the test section of the wind tunnel so that the smoke line could be easily viewed and recorded. Comparison were made with three illumination systems: a fluorescent lamp, LED lamp, and halogen lamp. The test was conducted at a constant fan speed of 4 m/s, and multiple smoke lines were generated by using a smoke rake were used to clearly distinguish the effects of the illumination system as shown in Figure 7. The results showed the smoke lines were dim and fairly visible when a fluorescent lamp was used (Figure 7a). The fluorescent system was not able to provide adequate illumination, however, as the smoke lines could only be seen at the middle region of the test section. When using an LED lamp, the illumination of the test section was relatively better, as almost all parts of the test section were brighter. However, the smoke lines were still difficult to see clearly. Flare existed at the top region near the location of the lamp, which in turn lowering the visibility of the smoke line (Figure 7b). The final illumination system was the halogen lamp (Figure 7c). The smoke lines were visible in all parts of the test section. Signs of flare were still evident, but their intensity was reduced as compared to LED lamp. The results revealed that the halogen lamp generated the most visible smoke lines pattern, similar to the results of previous studies [9]. The lightings from the halogen system produced less flare, less haze effect, and more detailed smoke stream line patterns. These effects are important to better capture the flow around a model. The shadow from the test model will prevent an accurate observation of the smoke pattern, requiring the use of a more reliable source.
of illumination. In addition, the halogen bulb also came in a small and compact size, making modification and arrangement easier.

![Comparison between (a) Fluorescent, (b) LED, and (c) Halogen illumination system](image)

**Figure 7.** Comparison between (a) Fluorescent, (b) LED, and (c) Halogen illumination system

### 3.3. Effect of smoke liquid solutions

In general, it is important for the smoke lines to feature a good dispersion rate. In this study, the smoke was generated by heating a 0.18mm Nichrome wire using 12 Volt DC power supply. The wind tunnel operated at a fan speed of 4 m/s, and the lighting system was changed to a halogen lamp based on the previous discussion. The comparison of the smoke liquid includes; kerosene, corn oil, Safex (fog liquid), and the results are shown in Figure 8. All smoke liquids were capable of generating smoke. Kerosene (Figure 8a) smoke had a tendency to disperse rapidly as it progressed through the test section. Corn oil (Figure 8b) smoke allowed for good uniformity of streak lines. However, the intensity of the smoke was less dense as compared to the kerosene. The Safex produced the most coherent and dense smoke, as shown in Figure 8c. The smoke lines were clearly visible throughout the test section. The Safex smoke also had good disposal value, as it did not contaminate the test section with excessive leftover oil, as it, unlike kerosene and corn oil, is water-based. This resulted in a non-irritant, non-flammable, and non-hazardous fog cloud and considered suitable especially for a closed-environment and indoor usage.
3.4. Effect of fan speeds

The flow qualities of the smoke visualization system at fan speeds of 2, 4, 6, and 8 m/s were compared. The smoke was generated using Safex fog liquid, and the lighting system was fixed as halogen lamp. The smoke lines generated at 2 m/s as shown in Figure 9a indicated a dense smoke intensity, but the line was not uniform and fluctuates severely. An improved smoke line can be seen at 4 m/s (Figure 9b), where the flow showed a better streamline, although fluctuations due to the turbulence of the rake opening could still be seen throughout the test section. At 6 m/s (Figure 9c), the smoke was less dense as compared to the previous one. The lines showed no fluctuation, indicating a uniform streamline flow pattern. At higher speed of 8 m/s (Figure 9d) the line was relatively straighter. Again, no fluctuation could be seen in this case, but the smoke losses most of its coherency. Only a plume of smoke was visible at the end of the wind tunnel test section. It is important to note that in order to find the optimum velocity for this smoke visualization technique, a trade-off between the smoke intensity and the streamline pattern is necessary. Lower speeds will result in a denser and coherent smoke line, while higher speeds will result in a straighter and more uniform line. The optimum fan speed for the current studies was 6 m/s, as the smoke line could still remain thick and coherent, with no visible fluctuations throughout the test section area.

Figure 8. Comparison between (a) kerosene, (b) corn oil, and (c) Safex for smoke liquid application.
Figure 9. Comparison of smoke lines at fan speed of (a) 2 ms⁻¹, (b) 4 ms⁻¹, (c) 6 ms⁻¹ and (d) 8 ms⁻¹.

3.5. Effective Smoke Flow Visualization Configurations

The smoke flow visualization of an airfoil test model is shown in Figure 10. The airfoil was set to be at 15° angle of attack, α, to highlight its capability to capture the flow separation at the trailing edge. The configurations were set to have only a screen and a honeycomb with the illumination system consisted of a halogen lamp. The most effective setup was the Safex fog liquid solution with a fan speed of around 6 m/s. The smoke patterns were observed to be uniform around the lower half of the airfoil, as it did not encounter any disturbance. The smoke seemed to closely follow the shape of the airfoil and its streamline patterns appeared to pass through the end of the test section. The flow could be identified as laminar across the bottom part of the airfoil. However, the smoke patterns were distorted at the middle region on the upper half of the airfoil. The flow exhibited a trailing edge stall, in which the flow becomes separated from the upper surface downstream of the leading edge. The occurrence of this flow separation can be explained in terms of an adverse pressure gradient, a phenomenon in which static pressure increases in the direction of the flow, leading to a reduced kinetic energy and deceleration of the fluid motion. The detached flow then created a region of turbulent wake, taking form of eddies and swirling motion.
Figure 10. Smoke flow visualization using airfoil test model at 15° angle of attack. Red arrow indicates airflow direction

The smoke patterns visualized in this work are consistent with those found in previous studies [10-12]. The smoke technique developed in this study was able to illustrate the airflow around the airfoil. The optimized parameters were qualitatively compared based on the configuration of the current lab-scale smoke wind tunnel, and the flow visualization is considered acceptable for a lab-scale measurement. However, to fully analyse the effect of such parameters accurately, quantitative measurements would be required in future studies.

4. Conclusion

A smoke flow visualization system was developed in a small-scale wind tunnel system to demonstrate flow characteristics. It was found that the screen and honeycomb were essential, but excessive usage of these two components may result in a very thin smoke lines with a high dispersion rate. A halogen lamp can be considered to be very effective in illuminating the smoke lines. A Safex fog liquid (water-based solution) managed to produce the thickest and most stable smoke streak lines. In terms of fan speed, the smoke line intensity was clearly visible at 6 m/s. The developed smoke flow visualization system managed to successfully demonstrate smoke streak lines for an airfoil that represents classical aerodynamic behaviour.

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