Development of a Flow Visualization Technique in Wind Tunnel for Hydrokinetic Turbine Application

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Abstract. A smoke wire technique was developed in a wind tunnel to visualize a drag-driven turbine flow structure for hydrokinetic application. A Nichrome wire with a diameter of 0.5 mm was initially heated and then coated with Safex oil to illustrate the streamlines that represent the turbine flow characteristics. The developed smoke wire oil coating technique was compared at airflow speeds of 3 m/s to 10 m/s to represent equivalent water flow speed corresponding to Reynolds numbers (Re) of 29, 563 to Re= 98, 543, respectively. Several parameters that influence the turbine flow patterns, such as the diameter of wire and oil coating technique, were tested in the wind tunnel to investigate the effect of these parameters to visualize the stream lines at low and high speed case. The qualitative result based on these various configurations was analyzed and discussed in this paper to identify the most practical flow visualization technique in a wind tunnel that could effectively be captured to represent the turbine flow structure for hydrokinetic application.

Keywords: Flow visualization technique, hydrokinetic, turbine, wind tunnel

1. Introduction

The flow visualization technique is commonly used in qualitative measurement. It consists of graphical details that describes the flow structure, as opposed to a quantitative measurement that consists of data and values [1]. It helps to understand the flow behaviours surrounding a model that can be used to improve the performance [2]. There are various techniques established in the literature to visualize flow. One of the most popular technique is to provide a thin and discrete smoke filament by using a smoke wire [3]. It was initially developed in 1950s by Raspet and Moore to measure a velocity profile of their model and was later used to study the flow characteristics [4]. It is a simple flow visualization technique that is widely used to capture laminar flow at a Reynolds number of below 25,000 [5, 6].

To illustrate flow motion, smoke is produced by heating a wire coated with an oil. The heated wire causes the oil to vaporize and form streak lines that represent the flow’s characteristics [7]. Wire strength, resistivity, diameter and size are important parameters that influence the capability to illustrate the flow dynamics effectively. The diameter of the wire determines the smoke intensity and thickness of the stream lines [8]. The most common materials used in this wire are stainless steel, Nichrome and Tungsten. Experimental work performed by FrisPost et al. [9] using Tungsten wire managed to capture and maintain a clear and smooth streak lines for a considerably high speed of 18 m/s. In addition, the wire can be twisted as a single or double coil to maintain sustainable streak lines for a longer duration [10].

Although the diameter and the type of the wire are some of the important aspects that contribute to a good visualization of the flow, the white smoke produced through this method is usually difficult to see with the naked eye, especially in a wind tunnel experiment. To overcome this issue, the test section of a wind tunnel is usually covered with a black cloth to minimize any reflection and to provide some contrast with the white smoke lines [11-12]. Sieverding and Van Den Bosche used coloured smoke instead of the typical white smoke by coating the wire with Waxoline dye, also known as Sudan dye [13].
The development of the smoke wire techniques has revealed various results and accuracy. One of the most challenging results to obtain in a wind tunnel experiment is to capture the flow motion at a high speed (for flow visualization), particularly beyond 3 m/s. Most smoke wire techniques are only effective at a very low speed [14]. In order to overcome this limitation, this paper aims to develop a flow visualization technique that capable to illustrate the flow motion and maintain a constant visible streak lines at a low and high-speed ranging from 3 m/s to 10 m/s, respectively. A turbine model was used to illustrate the flow structure for hydrokinetic application, and the results will be focused on evaluating the visibility of the streak lines to represent the effectiveness of the developed flow visualization technique.

2. Methodology

2.1. Wind Tunnel

The wind tunnel used for this experiment was a closed-circuit wind tunnel located at the Science and Engineering Research Centre (SERC), Aerospace Wind Tunnel Laboratory, Universiti Sains Malaysia (USM) as shown in Fig. 1. The airflow inside the wind tunnel was driven by an axial fan motor to the test section with a dimension of 1.0 m (width), 0.8 m (height), 1.8 m (length). The test section had a contraction ratio of 10:1 and a turbulence level of 0.1%, for a flow speed of up to 80 m/s.

![Fig. 1: Wind Tunnel](image)

2.2 Hydrokinetic Turbine Model

A three-bladed vertical axis drag-driven hydrokinetic turbine was used as a model to illustrate the effectiveness of the developed flow visualization technique that represents the flow behavior in the wind tunnel. It has a simple design that consists of a shaft with the blades attached to the bottom section of the shaft as shown in Fig. 2. The blade has a height of 0.085 m and a diameter of 0.14 m, with an aspect ratio of 0.61. The shaft was attached to a bearing connected to a pulley that was placed at the top of the wind tunnel test section. This has allowed the turbine to hang freely where the driven flow stream to the test section that interacts with the blades, eventually causing the turbine to rotate.
2.3 Oil Coating Techniques

The smoke wire oil coating technique requires meticulous effort, as any excessive oil applied on the wire affects the smoke clarity and intensity. In the current work, a manual technique requiring the usage of a syringe from the top of the wind tunnel test section was applied to a 0.5 mm Nichrome wire that had initially heated and coated with Safex oil, as shown in Fig. 3.

2.4 Experimental Procedure

In this experiment, the smoke wire oil coating technique was tested at different flow speeds of 3 m/s to 10 m/s, corresponding to Reynolds number of Re=29,563 to Re=98,543, respectively. At the speed of 3 m/s, the test model was positioned at a static state and as the speed increasing to 10 m/s, the test model was rotating and can be considered at a dynamic state. This was performed to evaluate the flow streak lines clarity at high speed. The test section was covered with a black cloth to minimize any reflection that could affect the results. Several halogen light bulbs were installed at the top and bottom of the wind tunnel test section to highlight the smoke flow patterns.
3. Results and Discussion

3.1 Effect of smoke wire technique at low speed

The results revealed that the streak lines were thin, clear, uniform and straight at a low speed of 3 m/s, indicating that laminar flow before it started to impinge on the turbine as shown in Fig. 4. As the airflow started to interact with the turbine blade, the flow has curled around the blade and some small circulation can be seen behind the blade. This eventually leads to a turbulence flow structure as the streak lines were no longer straight. The smoke has managed to capture the formation of some small wake vortices. The manual technique was effective at low speed using a Nichrome wire with a diameter of 0.5 mm, as clear and visible streak lines were captured which represent the turbine flow characteristics.

Fig. 4: Manual technique at low speed

3.2 Effect of smoke wire technique at high speed

The flow characteristics at a high speed of 10 m/s is shown in Fig. 5. The smoke streak lines were still visible and uniform, but started to fade as the turbine started to rotate. The usage of a Nichrome wire with a diameter of 0.5 mm managed to illustrate the flow pattern at this speed range. However, the manual method was very challenging, as the oil dripping rate could not be controlled properly, leading to rapid rate of dispersed smoke lines. Therefore, the thickness of the oil coated on the wire eventually varied and resulting in inconsistent smoke intensity. Table 1 has summarized the results at low and high speed for brief comparison.

Fig. 5: Manual technique at high speed
Table 1: Case studies and corresponding flow regimes

| Case study | Flow regime | Flow description                      |
|------------|-------------|----------------------------------------|
| 1          | Low speed   | Clear smoke intensity and large wake   |
|            | (3 m/s)     | Thick streaklines                      |
| 2          | High speed  | Smoke intensity decrease significantly |
|            | (10 m/s)    | Fade and thin streaklines              |

3.3 Future semi-automated flow visualization technique

A new semi-automated flow visualization technique is proposed to overcome the inconsistent smoke intensity observed with the current manual using syringe technique that is capable to capture the flow structure motion precisely at high speed as shown in Fig. 6. A Nichrome wire with a diameter of 0.5 mm is connected to a handle winch at the top of the wind tunnel test section, while a weight is hanged at the bottom to provide sufficient tension to pull the wire down as the handle winch is released. The wire is coated with Safex oil (filled in a box) to ensure consistency during the coating process.

![Fig. 6: Semi-automated smoke wire oil coating technique](image)

4. Conclusion

A smoke wire flow visualization technique has been developed in a wind tunnel to visualize a drag-driven turbine flow structure. The results showed that the usage of a Nichrome wire with a diameter of 0.5 mm has proven to be effective as compared to 0.36 mm (used previously) as it has managed to capture the streak lines clearly at low speed of 3 m/s and even at high speed of 10 m/s. However, the manual technique using the syringe could not capture the flow structure precisely due to poor dripping oil rate and inconsistent smoke intensity.

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