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An Improved Smoke-Wire Flow Visualization Technique

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Abstract: - The smoke-wire technique is a method of introducing smoke lines in flow. The objective of the work is to improve a smoke-wire flow visualization technique that can produce good quality smoke lines and have sufficient density to be visible by determining the optimum combination for wire type, size and design, voltage level, smoke fluid and lighting arrangement. It was found that for wind tunnel flow visualization, it was best to use the two-coiled 0.36 mm in diameter Nichrome wire coated with Safex smoke liquid with the voltage of about 10 V and the tunnel velocity not exceeding 4 m/s.

Key-Words: - Flow visualization, Safex, smoke lines, smoke-wire and wind tunnel

1 Introduction

Flow visualization is a qualitative measurement used to analyze flow behavior. Throughout history, flow visualization has been an important tool in fluid dynamics research. It has been used extensively in the fields of engineering, physics, medical science, meteorology, oceanography and sport aerodynamics, to name just a few. Unlike other techniques, which are limited to measuring flow conditions at discrete points within the flow field, flow visualization techniques are capable of yielding a qualitative macroscopic picture of the overall flow field.

Flow visualization can be achieved in many ways. One way is through introducing smoke into the airflow [1]. The smoke follows the air currents, allowing the observer to visualize the flow. There are several ways to introduce the smoke into the system. One such way is by using a smoke-wire. A fine high-resistance wire coated in oil and stretched across the flow field, can produce short bursts of smoke controlled electrically by resistive heating. The number of droplets per unit length depends on the diameter of the wire and the oil's surface tension, and the smoke duration depends on the current strength and droplet size [2]. This produces a sheet of smoke that flows downwind over an object of study that is placed behind the wire, as shown in Fig. 1. The smoke sheet moves with the air and deforms. This deformation allows the observer to visualize the airflow around the object. The smoke-wire technique is limited in usefulness through constraints imposed by smoke durations and low wind tunnel velocities [1]. High velocities produce unacceptable turbulence.

The objective of the work is to improve a smoke-wire flow visualization technique that can produce good quality smoke lines that are well defined and have sufficient density to be visible even at high-speed wind tunnel application by determining the optimum combination for wire type, size and design, voltage, smoke fluid type and lighting arrangement. Smoke duration is also to be acceptably long for visual observations.

2 Experimental

The experiments were performed at the wind tunnel laboratory of the Universiti Teknologi PETRONAS (UTP) in a suction-type wind tunnel with a 800 mm long working section and a 400 x 400 mm^2 cross section, as shown in Fig. 2. Hot-wire anemometry (HWA) measurements across the test section of the wind tunnel showed a uniform free-stream and a turbulence intensity of less than 5% [4].

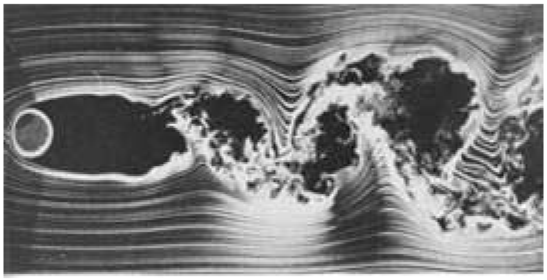


Fig. 1. Smoke-wire flow visualization of airflow around a circular cylinder [3]

Fig. 2. UTP suction-type wind tunnel

The experiments were performed to determine the best wire design, smoke fluid, voltage and lighting arrangement to produce the best result for smoke-wire apparatus. Fig. 3 shows the experimental set-up. Since the apparatus would be in the tunnel, an oil delivery system had to be designed for continuous operation. An oil reservoir was placed on the top of the nozzle-settling chamber, which was the same height as the test section roof. A tube was used to supply air from the air supply gauge while another tube was used to transport smoke fluid to the heating wire inside the test section, as shown in Fig. 4. The principal of oil delivery system was based on the gravitational potential energy. There were lighting arrangements suggested to produce clearer images for image recording. The main problem in recording the smoke lines was reflection of image in the Perspex of the test section wall. Fig. 5 (a) and (b) show those lighting arrangements. Most previous experiments used only a single resistance wire for the smoke-wire [5]. A different approach was taken for the current work. Trials were undertaken with plain wires as well as wire coiled around another wire(s). Table 1 gives all the suggested governing parameters that would affect the quality of the visualization. Each of the parameter was tested and results were discussed in the following section.

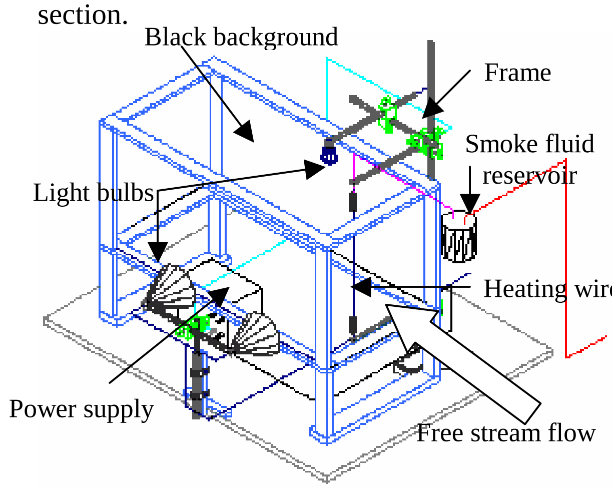


Fig. 3. Experimental set-up

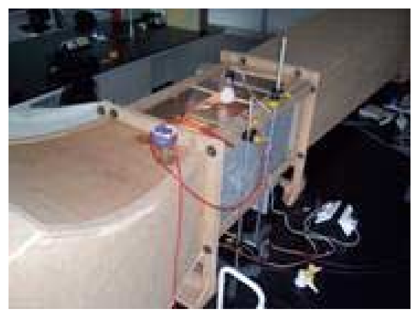


Fig. 4. Smoke fluid delivery system

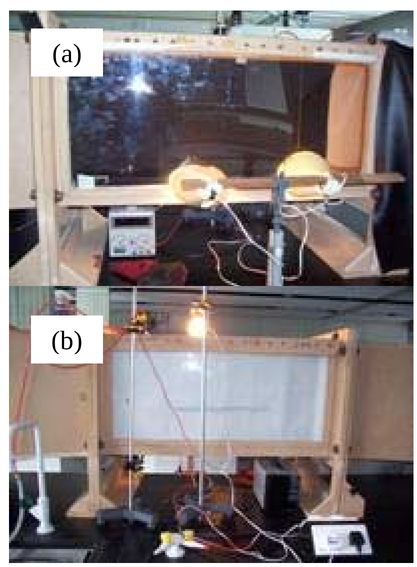


Fig. 5. Lighting arrangements (a) side (b) top

Table 1. Experiment variables

Wire (Length = 400 mm)	Wind tunnel velocity (m/s)	Voltage (V)	Smoke fluid
single Nichrome (diameter = 0.18 mm)	from 0.5 to 12.0	from 1.0 to 30.0	Safex, palm oil, diesel, gasoline, corn oil and water
2 cm-node single Nichrome (diameter = 0.18 mm)			
2-coiled Nichrome (diameter = 0.36 mm)			
3-coiled Nichrome (diameter = 0.54 mm)			

3 Results and Discussion

From the wind tunnel testing, it was found that each of the listed factors did indeed affect the quality and duration of the smoke lines produced. Using heat transfer analysis and First Law of thermodynamics, the most suitable smoke fluid for smoke generation can be chosen. The fluid, which has higher boiling flow rate, will certainly give better smoke-wire visibility at high speed. It was found that the Safex produced better results than other smoke fluids, as described in Table 2. Clear, uniform and long duration smoke lines were generated by using two- and three-coiled Nichrome wires at voltage and wind tunnel velocity of 11.8 V and 2 m/s respectively. Moreover, Safex is a non-irritant, non-flammable and non-hazardous liquid. Gasoline could also be used but it is a highly flammable liquid.

The best wires were the two- and three-coiled Nichrome wires. The best voltage to use with these wires depends on the tunnel velocity, but is generally around 10 to 12 V. At high velocity, forced convection effect becomes dominant and the wire needs more energy to surpass the smoke fluid boiling point. Table 3 summarizes the findings on each arrangement of wire. Only results from the wind tunnel velocities of 2, 4 and 6 m/s are shown because results from other velocities show similar behavior to the nearest velocity. Loss in energy due to resistance is balanced with the heat generation. Assuming the temperature coefficient is small, total resistance is only dependent on length of the wire, resistivity of the material, and the wire cross-sectional area. Experiments were also performed using copper and steel wires but Nichrome wire is the only wire that can provide enough heat to boil the smoke fluids. Nichrome wire releases more heat compared to stainless steel and copper. Due to low in electrical resistance, copper and steel wires release less heat to be absorbed by the smoke fluids. Smaller diameter of Nichrome wire has higher resistance, lower in heat loss through convection and generates higher boiling rate. Since Nichrome dissipates the highest amount of heat, it is very suitable as a heating element.

Since both the two- and three-coiled Nichrome wires can generate good quality smoke lines using the Safex smoke liquid, further experiment was performed to capture the smoke generated from those wire designs. Testing the effects of vortex shedding using objects such as circular and rectangular cylinders was done, as shown in Fig. 6. From the results, two-coiled Nichrome wire design was chosen for this smoke-wire apparatus since it generates clear, uniform white dense smoke and easy attachment of the liquid to the wire. The photograph of the smoke generated, as shown in Fig. 7 confirms this. Evolution of the vortex structure is clearly shown.

The application of top and side lighting arrangements gives sufficient illumination and reduce reflection of image in the Perspex of the test section wall for photographic purposes using digital camera.

Table 2. Selection of smoke fluid (wind tunnel velocity is set to 2 m/s for all experiments)

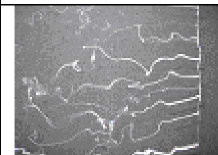
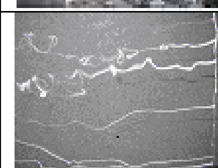
Liquid	Results	Image
Water	No smoke is generated using all type of wires. Higher heat capacity and higher latent heat of vaporization cause water needs more heat to surpass boiling point for generating smoke.	-
Palm oil	No smoke is generated by using two- and three-coiled Nichrome wires. Short duration smoke is generated by using 2 cm-node single Nichrome wire at voltage, V = 28.8 V.	
Diesel	Light smoke is generated by using three-coiled Nichrome wire. Clear and uniform smoke is generated by using two-coiled Nichrome wire but in short duration. The odor of diesel is spread in the lab.	
Gasoline	Clear and uniform smoke is generated by using three-coiled Nichrome wire at voltage, V = 12.3 V. The odor of gasoline is spread in the lab.	
Corn oil	No smoke is generated by using two- and three-coiled Nichrome wires. Light smoke is generated by using 2 cm-node single Nichrome wire at voltage, V = 25.1 V but for short duration.	
Safex	Clear and uniform smoke is generated by using two- and three-coiled Nichrome wires at voltage, V = 11.8 V. No odor is generated due to the smoke.	

Table 3. Description of smoke generated by all wire designs (Safex is used for all experiments)

Wire	Wind tunnel velocity (m/s)	Results
Nichrome (single wire)	2.0	Smoke is generated at voltage of 10.8 V. Since the wire is very thin, the liquid cannot attach to the wire. The smoke is visible but for very short duration and non- uniform. Denser smoke is generated as current increases. Denser smoke at the bottom of the wire. Smoke duration is 15 seconds.
	4.0	Smoke is generated at voltage of 14.0 V but shorter in duration. Denser smoke is generated as current increases. Smoke duration is 10 seconds.
	6.0	The liquid cannot attach to the wire due to high wind tunnel velocity. This difficulty causes this wire is unpractical to be used for wind tunnel velocity higher than 4.0 m/s.
Nichrome (2 cm-node single wire)	2.0	Smoke is generated at voltage of 16.6 V. Clear and dense smoke is generated from the nodes along the test section. The nodes are able to hold the liquid longer along the wire compared to the plain wire. Smoke duration is 12 seconds.
	4.0	Smoke is generated at voltage of 19.8 V. Clear smoke is generated from the nodes. However, the liquid is hardly attached to the wire due to high wind tunnel velocity.
	6.0	The liquid cannot attach to the wire due to high wind tunnel velocity. This difficulty causes this wire is unpractical to be used for wind tunnel velocity higher than 4.0 m/s.
Nichrome (2-coiled wire)	2.0	This wire shows the best results yet. Smoke is generated at voltage of 9.8 V. Smoke is clear and uniform. The liquid is easily attached to the wire. Smoke duration is 20 seconds.
	4.0	Smoke is generated at voltage of 11.4 V. Clear and uniform smoke is generated but in shorter duration.
	6.0	Smoke is generated at voltage of 13.6 V. The liquid flow is hardly attached to the wire due to high wind tunnel velocity. The smoke is visible but non-uniform
Nichrome (3-coiled wire)	2.0	Smoke is generated at voltage of 11.7 V. Clear, dense and uniform smoke is generated. The liquid is easily attached to the wire due to bigger surface area compared to other designs. Smoke duration is 15 seconds.
	4.0	Smoke is generated at voltage of 12.9 V. Clear, dense, uniform smoke is generated but in shorter duration. Smoke duration is 5 seconds.
	6.0	The liquid cannot be attached to the wire due to high wind tunnel velocity.

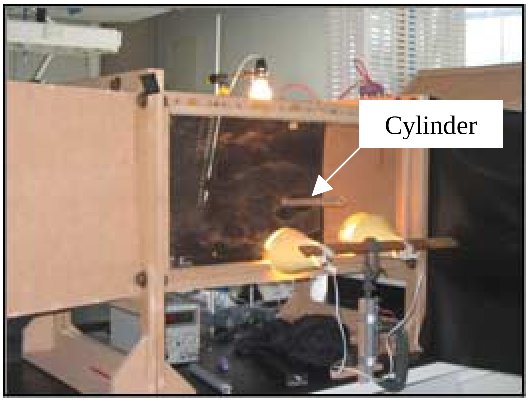


Fig 6. A circular cylinder is placed in the test section

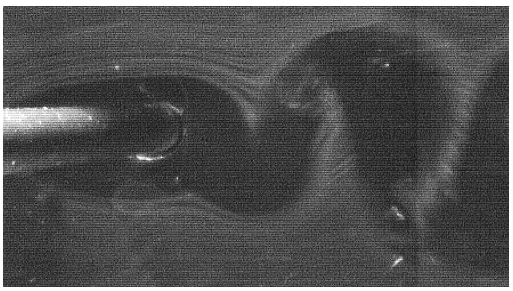


Fig 7. Smoke lines generated by two-coiled Nichrome wire coated with Safex

4 Conclusion

From the results of wind tunnel flow visualization, it is best to use two-coiled Nichrome wire as a heating element because it produces good quality smoke visibility. The applied voltage should be close to 10 V but the tunnel velocity should be just less than 4 m/s due to quick smoke dispersion at higher velocity. Generally, voltage increases as wind tunnel velocity is increased. The best smoke fluid recommended for this purpose is Safex while gasoline works very good as well but it is a highly flammable liquid.

Acknowledgement

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