An improved smoke-wire visualization technique for flows with relatively high velocities

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Abstract

An improved smoke-wire flow visualization technique was proposed. Electric current discharged from capacitors was used to heat a fine metal wire suspended in the flow field under investigation. The paraffin droplets attached to the wire were vaporized and became smoke filaments which followed the flow motions. A digital camera was used to record the images of the smoke filaments. The actions of discharging and camera shutter were triggered by signals from a single chip computer. The accurate timing between the two actions allowed clear images of the streak lines to be captured at a free-stream velocity as large as 17.0m/s, much larger than the previous maximum velocity using this type of technique (7.8m/s) in the literature.

1. Introduction

Smoke-wire visualization technique can give qualitative pictures of the air flow, it is easy to implement and low in cost. The method was first proposed by Raspet and Moore in the 1950s, and improved in 70s and 80s[1-5]. Early work in developing the smoke-wire visualization techniques were reviewed by Mueller [6], Merzkirch [7] and Lim [8]. Some of the investigations using the smoke-wire visualization technique were listed in table 1.

The basic components of a functioning smoke wire system includes a metal wire, oil, a power source generating electric currents and a camera. The metal wire used in the smoke-wire visualization was usually made of stainless steel, nichrome or tungsten [8]. The strength, resistive heating characteristics and the diameter were the key factors to consider in selecting wire. The wire diameter should be small to minimize the disturbances to the flow field. The Reynolds number based on the free stream velocity and the wire diameter was suggested to be less than 20 [6]. The wire should also have a proper electric resistance to allow current of at least 0.5 amp current passing through the wire [8]. The wire was usually pre-stressed to remove the sagging or expansions after heating, the pre-stress was as much as 1.03×10^9 Pa in some investigations [6] thus the wire should also be strong enough to withstand the pre-stress. The connection of the power supply and the fine metal wire were usually using the electrodes and heavy gauge wires located outside of the test area, e.g. above and below the top and bottom walls of the test section in the wind tunnels[18-22].

Typical oil used in smoke-wire visualization includes commercial fog generator fluid (e.g. SAFEX), water based glycol mixture, kerosene, lubricating oil and mineral oil (e.g. paraffin). Oil was applied to the wire manually using a paint brush or using automatic feeding mechanisms including motors [8]. Oil beads will form after the wire is coated with oil. Smoke filaments will be generated from each of these beads when the oil is vaporized by the electric current. The size and the number of beads are related to the surface tension of the oil and the diameter of wire. It was found there were 6 to 10 mineral oil beads per centimeter on 0.11mm diameter wire [11]. Larger beads will generate longer-last smoke filaments. The smoke was found to be vaporized small liquid particles with a diameter of approximately 1-2 microns [6,15,16]. The stokes number based on the size of the particles was in an order of 10^{-3}, much smaller than unity, the particles are able to follow the air motions in most of the applications [10,15,16]. A DC or an AC power supply can be used to heat the wire. A DC power supply was found to be superior because the current was steadier [6]. It is desirable to heat the wire to a large temperature in a short amount of time, so that smoke with high density can be generated without damaging the wire. Either electric current larger than the requirement or duration of heating longer than the requirement will break the wire or shorten its life.

The recommended free-stream velocity that smoke-wire technique can be used was below 5m/s [6]. When a larger free-stream velocity was used, the convective heat flux from the wire to the air increased, larger current was needed to heat the wire to proper temperature to vaporize the oil beads. The temperature of the part of the wire outside of the flow area became so large (usually “red hot”) that the yield strength became very small. The wire is easy to break. The smoke filaments are also short-last in the flow with a larger velocity because average size of the oil beads is smaller and the smoke traveled through the test section in a shorter time. This increases the difficulties in capturing the images of the smoke filaments.

Different kinds of camera can be used in smoke-wire visualizations, including high speed video cameras [4], regular CCD cameras [15,16] and DSLR cameras[17-22]. A timing circuit was used to coordinate the actions of the power supply and camera with precision timings so that clear images of the smoke filaments can be captured even the duration of the smoke filament was small[3-5,11-13,17]. The most widely used analog timing control circuit was developed by Batill and Mueller [3] using two NE555 timer chips and solid relays. Potentiometers were used for the operators to set the time interval between the generation of smoke and camera shutter. The resolution of the time interval setting was poor and the precision of the commercially available timer chips was susceptible to changes in the ambient temperature and the supplied voltage. The largest free-stream velocity using an analog timing control circuit was 6.2m/s[12].

Recently, Yarusevych et al.[18,19] and his co-workers[20-22] studied the flow field downstream of an airfoil using the smoke-wire visualization technique. They brushed water-based glycol mixture on a stainless steel wire with a diameter of 0.076mm suspended vertically through a wind tunnel. A small weight was attached to the lower end of the wire to remove the expansions under heating. A variable transformer regulated AC was used as the power source. The voltage applied to the wire can be adjusted manually. A digital camera took four consecutive images once the power was applied to the wire. The velocity in their investigation was 7.8m/s which was the largest among the investigations using the smoke-wire visualization technique to the author’s knowledge. They noted that it was not possible to visualize the flow with a free-steam velocity larger than 7.8m/s because of the short life of metal wire and the difficulties to capture the clear image.

Table 1. Summary of smoke-wire techniques used in previous investigations

Investigators	Year	Free stream velocity, m/s	Wire diameter (d), mm	Re_d	Oil	Power source	Timing control
Mueller and co-workers [3-5]	1980	3.0	0.025,0.076, 0.152	< 30	Mineral oil	40-80V AC	NE555 timers
Kim & Park [9]	1988	4.2	0.1	27	N/A	N/A	Manual
Huang& Lin [10]	1994	1.0	0.1	20	Mineral oil	N/A	Manual
Swirydczuk [11]	1993	2.0	0.11	14	N/A	20-30V DC	A timing circuit
Prasad & Williamson [12]	1997	6.2	0.1	40	Mineral oil	N/A	NE555 timers
Lee & Lee[13]	1999	3.0, 5.0	0.1	19,32	SAFEX, paraffin	25-35V	74LS160 counter
Al-Garni et al. [14]	2000	5.0	0.1	32	Mineral oil	65V	Manual
Yen & Hsu [15], San et al. [16]	2007, 2014	3.1	0.2	40	Mineral oil	N/A	Manual
Sohn & Chang [17]	2012	3.6	0.25	57	Paraffin, lubricating oil	50V AC	NE555 timers
Yarusevych and co-workers [18-22]	2008-2013	7.8	0.076	40	Water glycol mixture	regulated AC	Manual

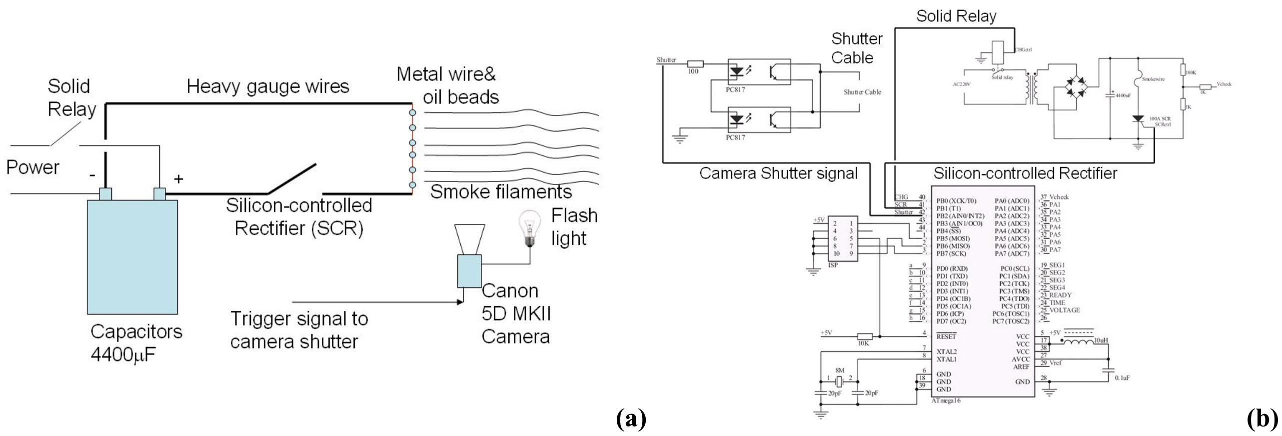
Because of the limitation of the free-stream velocity, the Reynolds number is limited. It is desired to use this technique in experiments with relative large Reynolds numbers. Here in this paper, an improved technique using a new power source and a digital timing control circuit was proposed. The technique will be discussed in details in the next section. Two examples will then be given, followed by conclusions.

2. Experimental methods

In order to visualize the flow field with free-stream velocity larger than 10m/s, a new power source utilizing capacitors was proposed. A digital timing control circuit with an ATmega16 single chip computer was also used to coordinate the actions of the power supply and camera with precision timings. The schematic of the control process and the timing control circuit are shown in figure 1.

Two 2200μF capacitors (total capacitance of 4400μF) were used as the power source. When the solid relay was switched on, the capacitors were charged by the 220V AC power source. The relay disconnects the capacitors from the power once the capacitors were charged to the pre-set voltage, typically 50V to 100V. When the silicon-controlled rectifier was switched on, electric current discharged from the capacitors, typically 10A to 20A, passed through a fine metal wire vaporizing the oil beads attached to the wire. The current discharged from the capacitors was 1 order of magnitude larger than the convectional DC and AC power supplies used in smoke-wire visualizations (0.5 to 1.0A) while the duration of the current was 1 order of magnitude smaller (approximately 30ms to 50ms depending on the voltage the capacitors were charged and the resistance of the wire). The temperature of the wire quickly rise to the temperature needed to vaporize the oil beads and then decreased quickly as the current decreased. The duration of discharging and heating was so small that the smoke density was larger than the convectional methods and the chance of wire breakage was smaller.

The actions of the solid relay (charging of capacitors), the silicon-controlled rectifier (discharging) and the camera shutter were controlled by the ATmega16 computer using digital ports. The timing sequence of the actions is shown in figure 2. When the operator pressed the control button for the first time, the solid relay switched on and the capacitors were charged to the pre-set voltage in time t_1, the solid relay then switched off. After the operator pressed the button for the second time, the silicon-controlled rectifier switched on, current was discharged through the smoke wire. Time t_2 after the start of discharging, a triggering signal was send to the camera shutter through an optical-coupler and then from camera to a flash light to record the smoke filaments. Time t_2 can be changed from -1s to 10s with a resolution of 1 ms using an interface.



(a) **(b)**

Figure 1. Schematic of (a) smoke-wire control process and (b) the timing control circuit.

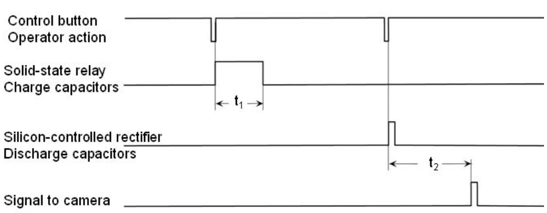
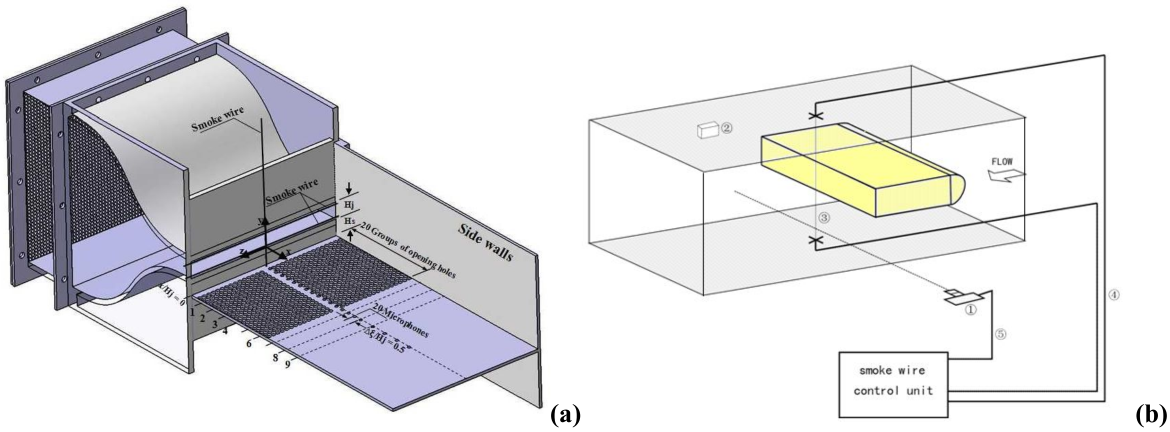


Figure 2. Schematics of the timing sequence of the smoke-wire control circuit.



(a) (b)

Figure 3. Experimental rigs for (a) offset attaching jet and (b) D-shaped body wake investigations.

The smoke-wire visualization were performed in an offset attaching jet experiment (figure 3,a). Air flow from a 0.75kW centrifugal fan goes through a diverging section, a setting chamber and a two dimensional contraction section forming a planar jet with a height of 30mm. The profile of the contraction section was a 5th polynomial with length of 300mm and a contraction ratio of 10.The turbulence at the jet exit was less than 0.5%. A 500mm long bottom plate was position in a direction parallel to the jet exit. The vertical distance from the lower edge of the jet to the plate (Hs) is 30mm. The width of the experimental facilities is 294mm. Two side panels with a height of 200mm was used to maintain two dimensional development of the flow. One side wall is 5mm acrylic. Three 304 stainless steel wires with a diameter of 0.1mm and a length of 300mm were used in the experiments. The first wire was suspended vertically across jet exit($x = 0.5H_j$, $z = 0$). The other two wires were horizontal wires stretched in the span-wise direction ($x = 0.1H_j$, $y = 0$ and H_j). The visualization were performed at a sectional averaged jet velocity U_j of 4.2 m/s, corresponding Reynolds number (U_jH_j/ν) of 7600, the Reynolds number based on the diameter of the wire (U_jd/ν) is 25. More details about the facility can be found in Gong et al.[23].

A second experiment was performed using a suction-type open-loop tunnel with a 300mm x 300mm x 700mm square test section, shown in figure 3(b). The contraction ratio is 9:1, the turbulence intensity in the test section is less than 0.5%. A D-shaped bluff body model with a height (H) of 63mm and a length of 189mm was mounted in the center of the test section. A 304 stainless steel wire with a diameter of 0.1mm and a length of 340mm was stretched vertically at 5mm downstream of the rear surface of the bluff body along in the central plane of the tunnel. The visualization were performed at free-stream velocities of U_∞=11.7m/s and 17.0m/s, the corresponding Reynolds numbers ($U_\infty H/\nu$) are 47000 and 68300, respectively. The Reynolds numbers based on wire diameter ($U_\infty d/\nu$) are 74 and 108, respectively. X is the stream-wise direction, y is the vertical direction and z is the span-wise direction. More details about this experiments can be found in Li et al.[24].

In both experiments, paraffin (70% in volume) and kerosene (30%) mixture was applied to the wire manually using a paint brush. Paraffin was chilled to 5^{o}C before experiments to increase the size of oil beads. A Canon 5DII camera and a Yongnu YN560 flash were used to record the images in both experiments. The camera sensitivity was ISO100, the aperture was F6.3 and the shutter speed is 1/200s. The background was painted with candle-soot paint to increase the contrast of the smoke filaments. The capacitors were charged to 75V, the time interval between discharging and camera shutter, t_2, was 0.01s. The peak current was estimated to be approximately 30A.

3. Results and Discussions

The visualization using the smoke-wire technique for the offset attaching planar jet with an offset distance equal to the jet height is shown in figure 4. The jet curved toward the wall from the exit and attached to the wall at 4 to 6 offset heights downstream of the jet exit. The jet curved back after re-attachment. Large scale flow structures developed in the inner and the outer shear layers. The width of the streak lines increased slightly as the structure developed downstream. A metal wire was stretched in span-wise direction at x/Hj=0.1 and y/Hj= 0 to visualize the three dimensionalities of the structures in the inner shear layer, shown in figure 5. The image showed that the structures were fairly two dimensional until the shear layer started to attach to the wall. The structures in the inner shear layer disappeared after the attachment. The structures in the outer shear layer grew in size forming 'roller' structures, the rollers were two dimensional in the region x/Hj<3, and gradually transitioned to three dimensional structures downstream of x/Hj=3.

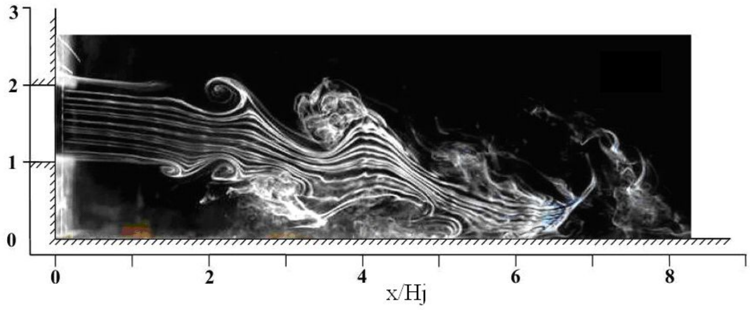


Figure 4. Visualization of an offset attaching jet issued from a contoured nozzle with offset distance equals one jet height and Re=7600 using the vertical wire.

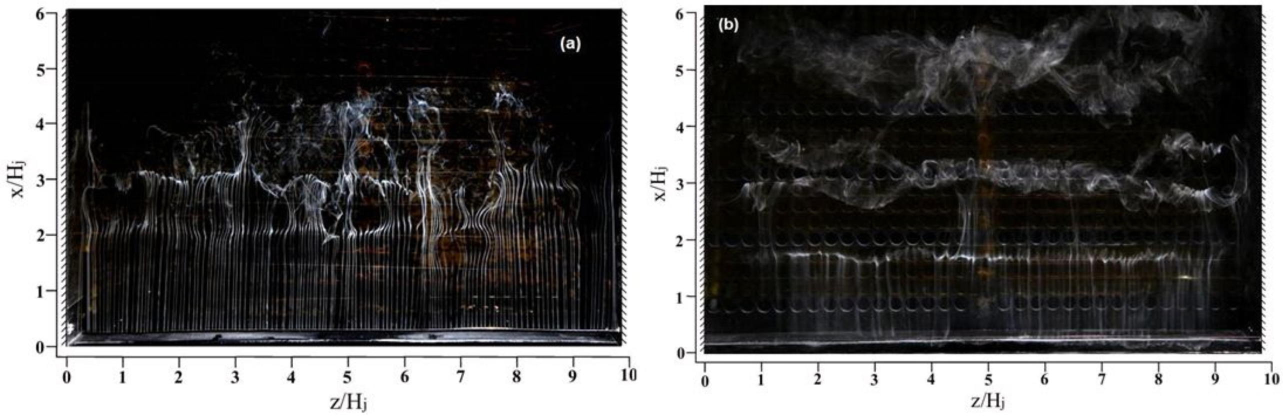


Figure 5. Visualizations of an offset attaching jet issued from a contoured nozzle with offset distance equals one jet height and Re=7600 using the horizontal wires located at x/Hj=0.1, y/Hj= (a) 0 and (b) 1.0.

The smoke-wire visualization image of the wake behind a D-shaped bluff body with a Reynolds number of 47000 and 68300 are shown in figure 5. The image for Re of 47000 case clearly showed that a separation region was formed downstream of the D-shaped body. Large scale alternating structures formed in the wake and grew in size. The width of the streak lines also increased in the stream-wise direction due to the large Reynolds number based on the wire diameter. The increase in the width of the streak lines did not have a significant effect on the observation of the large scale wake structures. The image for Re of 68300 case was not as clear as the case with small Re. This is likely due to the duration of flash light was not short enough, the motion of the filaments blurred the image. A flash light with an adjustable flash time was needed for smoke-wire visualization for relatively large velocities.

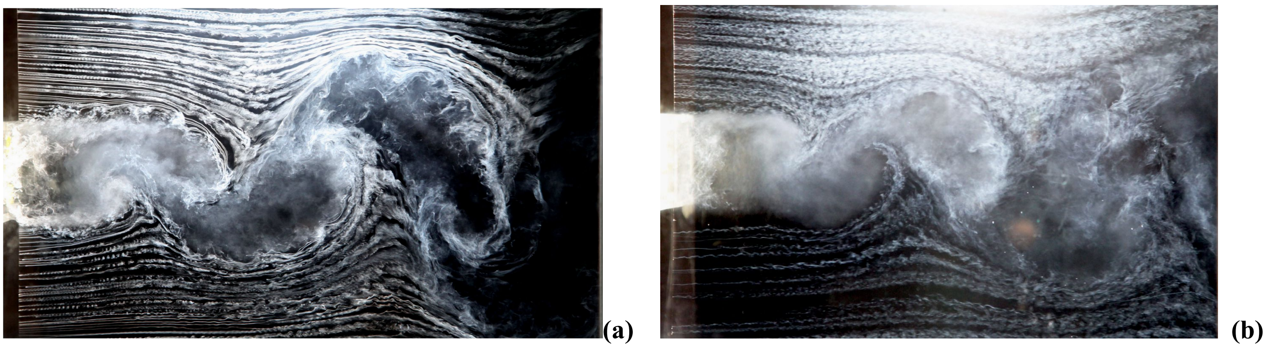


Figure 6. Smoke-wire visualization of a turbulent wake behind a D-shaped bluff body for a Reynolds number of (a) 47000 (U_∞=11.7m/s) and (b) 68300 (U_∞=17.0m/s).

4. Conclusion

An improved smoke-wire flow visualization technique was proposed in this paper. Electric current discharged from capacitors was used to heat up a fine metal wire stretched in the flow field. The oil beads attached to the wire were heated up and smoke streaks were generated. A digital camera was used to record the image. The actions of discharging and camera shutter were triggered by signals from an ATmega16 single chip computer with precise timings. The accurate timing between the two actions allow clear images of the smoke streaks at a free stream velocity as large as 17.0m/s, much larger than the previous maximum velocity of 7.8m/s in the literature. The width of the streak-lines increased as the flow evolved downstream in the cases with Re_d larger than the recommended value but this did not affect the observation of the large scale structures in the flow.

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