AIAA JOURNAL
Vol. 47, No. 6, June 2009

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Smoke-Wire Flow Visualization in Separated Flows at Relatively High Velocities

Serhiy Yarusevych*
University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
Pierre E. Sullivan†
University of Toronto, Toronto, Ontario M5S 3G8, Canada
and
John G. Kawall‡
Ryerson University, Toronto, Ontario M5B 2K3, Canada

DOI: 10.2514/1.43539

Nomenclature

c	=	airfoil chord
d	=	smoke-wire diameter
E	=	ac voltage
Re_c	=	chord-based Reynolds number, $U_0 c/\nu$
Re_d	=	diameter-based Reynolds number, $U_0 d/\nu$
U_0	=	freestream velocity in the streamwise direction
x	=	streamwise coordinate
α	=	angle of attack
ν	=	kinematic viscosity of air

I. Introduction

A SMOKE-WIRE technique is often used for flow visualization in wind tunnels [1,2], whereby the flow of air is visualized via evaporating a smoke-generating liquid from a fine wire by means of electric heating. One of the main advantages of this technique is that, when properly implemented, it does not introduce any appreciable disturbances into the investigated flows. Over the past several decades, the technique was applied to study a wide range of both bounded and unbounded shear flows (e.g., [1–8]). Nevertheless, for a variety of fluid phenomena, flow visualization via the smoke-wire technique remains a blend of science and art.

The present Note discusses the application of the smoke-wire technique for visualizing flow over an airfoil at low Reynolds numbers ($Re_c < 200,000$). In such a flow, a laminar boundary layer separates on the upper surface of an airfoil and flow evolution is governed by laminar-to-turbulent transition occurring in a separated shear layer. Because it does not appreciably disturb the flow, smoke-wire flow visualization can be instrumental to gain new insight into key aspects of flow development. However, the application of the smoke-wire technique is usually limited to freestream velocities of about 5 m/s [1]. Also, in its common arrangement, a smoke wire placed upstream of the airfoil does not allow visualization of the flow inside the separated shear layer. In this Note, the application of a smoke-wire technique for visualizing separated flows at freestream velocities of up to 7.8 m/s is described.

II. Experimental Description

A. Experimental Facility

The flow-visualization experiments were performed in a low-turbulence recirculating wind-tunnel facility [7]. The 5-m-long test section of this tunnel has a spanwise extent of 0.91 m and a height of 1.22 m. One of the side walls of the test section is made of Plexiglas for operational and visualization purposes. The background turbulence intensity level in the test section is less than 0.1%. The freestream velocity U_0 was monitored by a pitot tube, with an uncertainty estimated to be less than 2.5%.

Flow visualization was carried out for a NACA 0025 aluminum airfoil with a chord length c of 0.3 m. The airfoil was mounted horizontally and spanned the width of the test section. The following three smoke-wire configurations were used: 1) a single wire installed 15 cm upstream of the leading edge, 2) a single wire installed 3 mm downstream of the trailing edge, and 3) a combination of configurations 1 and 2.

B. Smoke-Wire Installation

The smoke wires were installed vertically within the test section through 0.8 mm orifices in the wind-tunnel walls. To prevent contamination of pressure taps on the airfoil model, the spanwise position of the wires was offset by 5 cm with respect to the midspan plane. Also, to avoid flow interference, all electrical connections were located outside of the test section. Each smoke wire was stretched taut by attaching a small weight to its bottom end. This prevented the wires from sagging due to wind loading and heating. Because excessive tension shortens the life cycle of a smoke wire, the applied weight was chosen empirically to provide the minimum tension sufficient to prevent any measurable wire displacement due to wind loading.

C. Smoke-Wire Diameter

The wire diameter must be sufficiently small to ensure that the wire does not introduce measurable disturbances into the flowfield. This is of particular importance for flows involving laminar-to-turbulent transition. On the other hand, the wire diameter must be large enough to accommodate a sufficient amount of smoke-generating liquid. To prevent vortex shedding from a smoke wire, the Reynolds number based on the wire diameter should be kept below $Re_d \approx 49$ [6]. At air speeds of about 5 m/s, the corresponding maximum wire diameter d is around 0.15 mm. A significant reduction of the wire diameter below this upper limit was not feasible, because much thinner wires were fragile, difficult to handle, and unable to retain a sufficient amount of the smoke-generating liquid. Thus, for testing at relatively high freestream velocities, the wire diameter should be maximized within the allowable limits. Note that a wire coated with smoke-

Received 30 January 2009; accepted for publication 25 February 2009.

*Assistant Professor, Department of Mechanical and Mechatronics Engineering, 200 University Avenue West. Member AIAA.
†Associate Professor, Department of Mechanical and Industrial Engineering, 5 King's College Road. Member AIAA.
‡Associate Professor, Department of Mechanical and Industrial Engineering, 350 Victoria Street.

generating liquid has an effective diameter larger than its nominal diameter. Depending on the smoke-generating liquid employed, nominal wire diameter, and wire material, this effect can be significant and should be taken into consideration. Therefore, it is recommended that the nominal wire diameter be selected to correspond to $Re_d \leq 35$, and the size of droplets formed on the wire should be controlled closely. In the present study, a 0.076-mm-diam wire (304 stainless steel) was found to provide optimum smoke density while not introducing measurable disturbances into the flowfield.

D. Smoke-Generating Liquid

Several smoke-generating liquids were evaluated, including mineral oils, model train liquids, and liquids used in commercial smoke generators. Although model train liquids were successfully used in previous studies (e.g., [1]), they did not perform well in the present work. Specifically, only a limited amount of such liquids remained on the wire after coating, resulting in short-lasting smoke filaments at the freestream velocities studied. Similar results were observed for lighter mineral oils, such as paraffin oil. In contrast, heavier oils, such as motor oil, performed well at low freestream velocities ($\sim$2 m/s) but required a significantly higher heat flux for smoke to be generated. At the high velocities investigated, the required heat flux was so large that it resulted in wire failure. Smoke-generating liquids employed in commercial smoke generators produced the best results in the present investigation. Such liquids are typically water-based glycol mixtures, with the type of glycol determining the persistency of smoke filaments. Comparing several commercially available smoke-generator liquids, glycerol-based liquids were found to be the most effective. Also, unlike mineral oils and model train liquids, such liquids are not associated with any health-related safety concerns.

Manual coating was employed. Both smoke wires were accessed through a door located in the test-section wall, and the smoke-generating liquid was applied with a cotton swab. This approach, though relatively time-consuming, virtually eliminated any spillage of the smoke-generating liquid and provided essential flexibility for adjusting and controlling the amount of the liquid applied.

E. Wire Heating

A variable transformer was used to regulate the voltage applied to the smoke wires. For the smoke generation to begin, the coated wire has to be heated above a certain temperature, which depends primarily on a given smoke-generating liquid. The minimum electric power required to initiate smoke generation and the smoke quality were first estimated based on tests in a free-convection environment outside the wind tunnel. Specifically, experimental correlations for a vertical cylinder were used to determine the ratio of the average heat transfer coefficient in free convection [9] and that in forced convection [10], then the results of the free-convection measurements were used to obtain estimates of the minimum electric power required for flow visualization at a given freestream velocity. Given the inherent uncertainty associated with the correlations and estimating physical properties of smoke-generating liquids, the estimates were accurate to within about 20%. Nevertheless, this approach minimized contamination of the tunnel test section and significantly decreased the overall time required to evaluate multiple smoke-generating liquids. Once the most suitable liquids were chosen, an optimum voltage setting for a given freestream velocity was determined more precisely in situ. Increasing the voltage above the minimum threshold intensifies smoke generation, producing denser smoke filaments, but decreases the overall duration of smoke generation. Thus, the optimum voltage setting was selected to allow for the minimum required duration of smoke generation while not causing wire failure. For the glycerol-based smoke-generating liquid employed and freestream velocities investigated, the corresponding heat flux was 230 $\mathrm{kW/m^2}$ at 5 m/s, with smoke filaments being produced for at least 1 s ($\sim$1.5 s in most cases examined). To prevent wire failure due to overheating and to extend the wire's life span, parts of the wire located outside of the test section were sprayed with distilled water before each use.

As the freestream velocity is increased, the applied voltage needs to be increased to compensate for additional convective cooling of the wire. Using experimental heat transfer correlations for cylinders in crossflow at $Re_d < 40$ [10], the required voltage adjustment can be estimated from the following correlation: $(E_1/E_2) = (U_{01}/U_{02})^{0.2}$, where the subscripts identify parameters corresponding to different freestream velocities. The estimates were found to be accurate to within 7%, and the approach proved to be a valuable tool for effectively implementing flow visualization at various freestream velocities. Because an increase of the freestream velocity intensifies mass transfer at the surface of the wire, a slight adjustment of the voltage is still required to optimize the density of smoke filaments. However, it eventually becomes impossible to perform flow visualization at high freestream velocities, due to either insufficient duration of smoke filaments or wire failure.

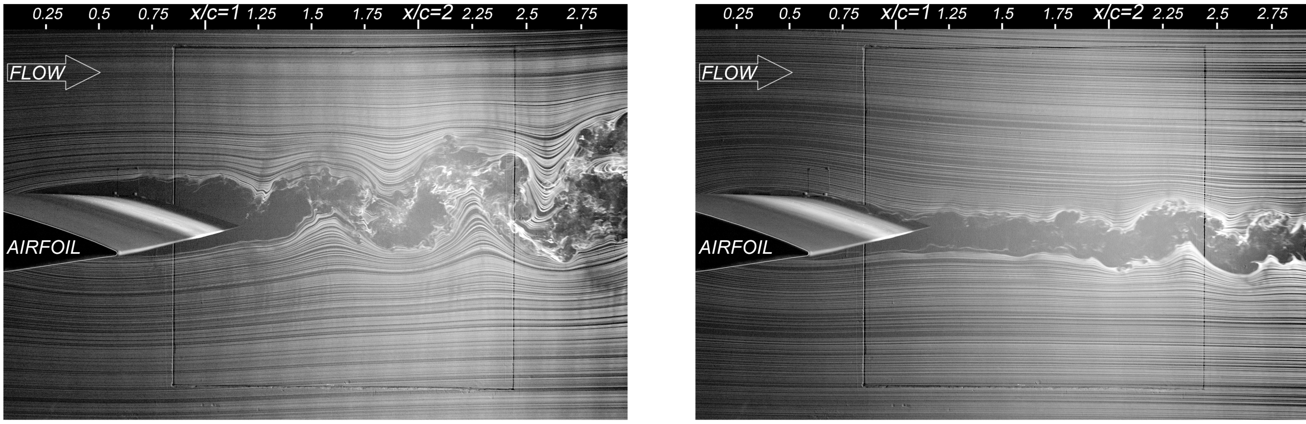
F. Imaging and Lighting

Images were obtained with a Nikon D70s digital camera, which acquired four consecutive images per second with an image resolution of six megapixels. As in any flow-visualization study, flow illumination is critical for obtaining high-quality images. It is desirable to illuminate the flow from a 90 deg angle relative to the focal axis, to limit the camera's direct exposure to a lighting source and/or light reflections. In previous investigations involving smoke-wire techniques, this was achieved by either making slots in one of the test-section walls (e.g., [1]) or using transparent test sections (e.g., [4]). In the present study, as in many other research facilities, only one wall of the wind-tunnel test section was designed to provide optical access, and any extensive modification to the test section was undesirable. Thus, the flow was illuminated with a lighting source positioned in the far wake of the airfoil model. The lighting was provided by a high-speed flash (Nikon SB 800 Speedlight), which was triggered wirelessly by the camera. It was verified via surface pressure measurements that the presence of the flash did not have any measurable effect on the flow development over the airfoil. The produced light was formed into a light sheet via a slotted attachment. There were no issues encountered with camera noise or illumination level.

III. Results

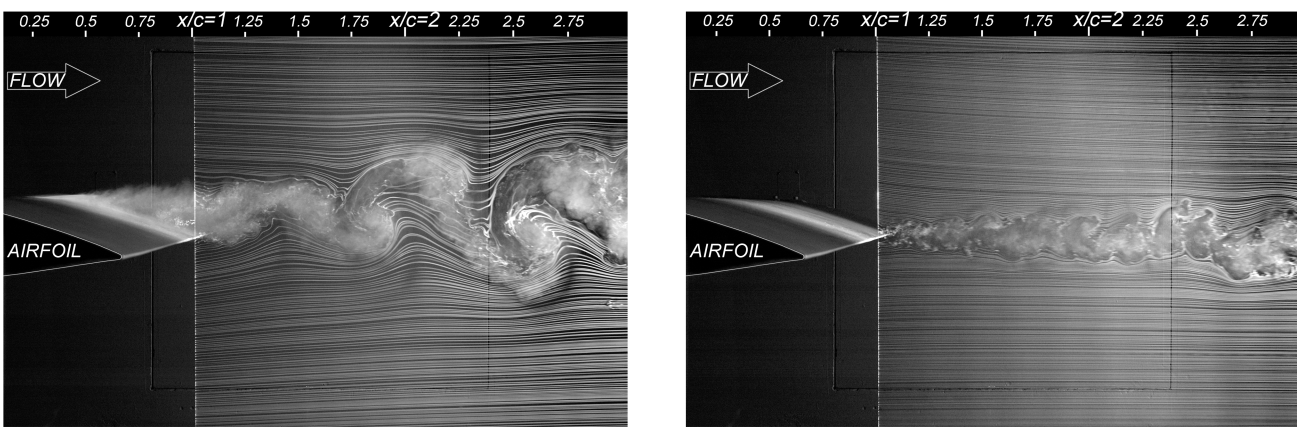
Flow-visualization experiments were performed at $\alpha = 5$ deg for three Reynolds numbers: $Re_c = 55 \times 10^3$, 100×10^3, and 150×10^3. Figure 1 shows images obtained with a single smoke wire located upstream of the airfoil, pertaining to two flow regimes: 1) boundary-layer separation without reattachment for $Re_c = 100 \times 10^3$ and 2) flow in the presence of a separation bubble on the upper surface of the airfoil for $Re_c = 150 \times 10^3$. For $Re_c = 100 \times 10^3$, the boundary layer on the upper surface of the airfoil separates at approximately $x/c = 0.25$ and fails to reattach (Figs. 1a). In contrast, for $Re_c = 150 \times 10^3$, the separated shear layer reattaches upstream of $x/c = 0.75$ (Fig. 1b). The two identified flow regimes are associated with different wake characteristics. When the separated shear layer fails to reattach, the images show large-scale structures that appear to be shed alternatively into the upper and lower sides of the airfoil wake. When the bubble forms on the upper surface, similar periodicity is observed in the wake; however, the scale of the wake structures is substantially lower.

The upstream wire arrangement allows identification of boundary-layer separation, determination of the extent of the separation region, and examination of airfoil wake development; however, it does not allow for a detailed investigation of the structures within the separated shear layer and wake. Such an investigation requires smoke to be introduced either into the attached boundary layer or directly into the separated shear layer. This was accomplished by placing a smoke wire immediately downstream of the airfoil trailing edge (Fig. 2). As can be seen in Fig. 2a, smoke produced by the downstream smoke wire is entrained into the separated region by a reverse flow and then propagates into the airfoil wake. Although this



a) Re_c**=100x10**^{3} **b)** Re_c**=150x10**^{3}

Fig. 1 Flow visualization at $\alpha = 5\,\mathrm{deg}$ **with a single upstream smoke wire.**

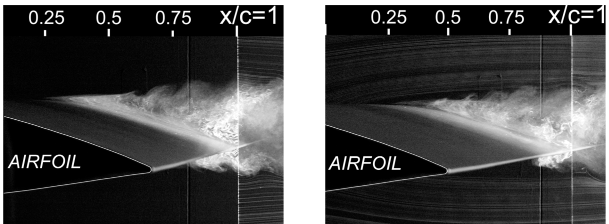


a) Re_c**=100x10**^{3} **b)** Re_c**=150x10**^{3}

Fig. 2 Flow visualization at $\alpha = 5\,\mathrm{deg}$ **with a single downstream smoke wire.**

wire arrangement is not suitable for separated-shear-layer visualization in the presence of flow reattachment (Fig. 2b), it provides both high-quality wake visualization and visualization of structures forming in the separated shear layer at the lower Reynolds numbers.

Digital imaging allows for a more detailed investigation of the images. For example, to investigate flow development in the separated-flow region, it is possible to magnify a region in an image of interest. Because of the high resolution of the digital camera, moderate magnifications did not have any apparent adverse effect on image quality. Figure 3 shows magnified images of the separated-flow region for $Re_c = 55 \times 10^3$ at $\alpha = 5\,\mathrm{deg}$, where visualization was performed with a single downstream smoke wire and with two smoke wires. The images reveal several vortices forming in the separated shear layer above the upper surface, with the first appearing at approximately $x/c = 0.5$. It is evident from Fig. 3 that the vortices form close to the interface between the reverse-flow region and the separated shear layer. These vortices originate from the rollup of the separated shear layer due to the amplification of natural disturbances [8]. A relatively small length scale makes these structures difficult to detect in the original images. It can be seen from Fig. 3b that the two-smoke-wire method allows both the separated-flow region and the outer flow to be visualized simultaneously. However, a successful application of the method requires precise coordination of the smoke production from the two wires. Also, an increased amount of smoke produced from the two wires, compared with that from a single smoke wire, is detrimental to image contrast. To remedy this, it is recommended that smoke-generating liquid be coated only on the portion of the downstream wire exposed to the reverse flow.



a) **b)**

Fig. 3 Flow visualization of the separated region for $Re_c = 55 \times 10^3$ **at** $\alpha = 5\,\mathrm{deg}$ **with a) a single downstream smoke wire and b) both upstream and downstream smoke wires.**

IV. Conclusions

Smoke-wire flow visualization on an airfoil in low-Reynolds-number flows has been examined. Focusing on flow visualization at relatively high freestream velocities, this work provides specific recommendations for selecting the wire diameter and the smoke-generating liquid, determining the optimum power-supply settings, installing the wires, arranging the lighting, and implementing the technique as a whole. The technique was applied to visualize flow development on a NACA 0025 airfoil at low Reynolds numbers. In particular, two flow regimes were investigated: 1) boundary-layer separation without reattachment and 2) separation-bubble formation. In addition to a classical smoke-wire arrangement upstream of the model, two other wire arrangements were proposed: namely, a single wire installed immediately downstream of the airfoil and a combination of the upstream and the downstream wires. The proposed wire arrangements allowed for the flow in the separated region to be successfully visualized, thereby providing valuable insight into the development of coherent structures in the separated shear layer and airfoil wake.

Acknowledgment

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada (NSERC) for funding of this work.

References

[1] Mueller, T. J., "Flow Visualization by Direct Injection," *Fluid Mechanics Measurements*, 2nd ed., edited by R. J. Goldstein, Taylor and Francis, Philadelphia, 1996, pp. 367–450.

[2] Smits, A. J., and Lim, T. T., *Flow Visualization: Techniques and Examples*, Imperial College Press, London, 2000.

[3] Batill, S. M., and Mueller, T. J., "Visualization of Transition in the Flow over an Airfoil Using the Smoke-Wire Technique," *AIAA Journal*, Vol. 19, 1981, pp. 340–345. doi:10.2514/3.50953

[4] Prasad, A., and Williamson, C. H. K., "The Instability of the Shear Layer Separating from a Bluff Body," *Journal of Fluid Mechanics*, Vol. 333, 1997, pp. 375–402. doi:10.1017/S0022112096004326

[5] Fric, T. F., and Roshko, A., "Vortical Structure in the Wake of Transverse Jet," *Journal of Fluid Mechanics*, Vol. 279, 1994, pp. 1–47. doi:10.1017/S0022112094003800

[6] Williamson, C. H. K., "Vortex Dynamics in the Cylinder Wake," *Annual Review of Fluid Mechanics*, Vol. 28, 1996, pp. 477–539. doi:10.1146/annurev.fl.28.010196.002401

[7] Yarusevych, S., Sullivan, P. E., and Kawall, J. G., "Coherent Structures in an Airfoil Boundary Layer and Wake at Low Reynolds Numbers," *Physics of Fluids*, Vol. 18, No. 4, 2006, Paper 044101. doi:10.1063/1.2187069

[8] Yarusevych, S., Kawall J. G., and Sullivan, P. E., "Separated Shear Layer Development on an Airfoil at Low Reynolds Numbers," *AIAA Journal*, Vol. 46, No. 12, 2008, pp. 3060–3069. doi:10.2514/1.36620

[9] LeFevre, E. J., and Ede, A. J., "Laminar Free Convection from the Outer Surface of a Vertical Circular Cylinder," *Proceedings of 9th International Congress of Applied Mechanics*, Vol. 4, Univ. of Brussels, Brussels, 1956, pp. 175–183.

[10] Zhukauskas, A., "Heat Transfer from Tubes in Cross Flow," in *Advances in Heat Transfer*, edited by J. P. Harnett, and T. F. Irvine, Vol. 8, Academic Press, New York, 1972, pp. 93–160.

F. Coton
Associate Editor