The 14th International Workshop on Atmospheric Icing of Structures, Chongqing, China, May 8 - May 13, 2011

EXPERIMENTAL STUDY OF FLOW CHARACT ERISTICS AROUND A CIRCULAR CYLINDER WITH DIFFERENT ICE PROFILES

H. Banitalebi Dehkordi[1]*, M. Farzaneh[1], P. Van Dyke[2]
[1]NSERC/Hydro-Québec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Atmospheric Icing Engineering of Power Networks (INGIVRE) www.cigele.ca
Université du Québec à Chicoutimi (UQAC), Chicoutimi, QC, Canada
[2]Hydro-Quebec Research Institute (IREQ), Varennes, QC, Canada
*E-mail: hamid.banitalebi-dehkordi@uqac.ca

Abstract: An experimental study was carried out to investigate the effect of ice accretion on the flow characteristics of a circular cylinder. Variations of flow characteristics such as velocity field, turbulence intensity and vorticity were studied for different ice profiles. These characteristics were used to perform detailed flow field measurements to quantify the evolution of unsteady flows around a cylinder. In order to study the effects of ice, two configurations of the cylinder model were considered: clean profile, and profile with ice accretion shapes. The velocity field and turbulence statistics of the wake behind each cylinder were measured for Reynolds numbers based on a 38-mm cylinder diameter in the range of $2 \times 10^5 - 1.2 \times 10^6$. A Particle Image Velocimetry (PIV) system, using a laser technique to capture seeding particles was used to measure velocity on the clean and iced cylinders. The experimental results show large regions of separated flow even at low incidence and for moderate amounts of ice. The results of this study will be used as input data for numerical investigations on the effects of ice accretion on aerodynamic coefficients of bluff bodies.

1. INTRODUCTION

Atmospheric ice accretion that may lead to transmission line collapses or tower damages has been observed and studied for many years. A great number of experimental investigations have been conducted to understand ice accretion process and atmospheric icing and to measure their effects on the aerodynamic performance of surfaces such as: airplane wings, airfoils, and electrical tower bars with different ice shapes [1-3].

The present study mainly focuses on the use of Particle Image Velocimetry (PIV) to perform velocity field measurements on a simple shape (cylinder profile), clean and with ice accretion. The influence of the simulated ice formation was analyzed on the cylinder velocity fields. This investigation is important for studying the effects of accreted ice on flow fields of bluff bodies and particularly for applying the measurement process to tower legs. It is also important for aerodynamic studies in order to extend them to other physical models dealing with power tower structures. This information will be part of a global study on the effect of ice accretion on the aerodynamic characteristics of tower elements. The aim of the present study is to assess the PIV applicability for the understanding of such phenomena, and to provide useful information about aerodynamic characteristics of electrical towers, more specifically the variation of the drag coefficient.

2. RESULTS AND DISCUSSION

As the flow follows a clean profile contour, the velocity near the cylinder increases to a maximum and then decreases as we move further around the cylinder. Based on the inviscid theory, a decrease in velocity results in an increase in pressure. The fluid elements experience a force opposite to the direction of the flow. At some point, the momentum of the fluid is insufficient to move the elements further into the region of increasing pressure and the flow starts to separate from the surface. With an ice accretion on the cylinder, the adverse pressure increases in a shorter distance and the onset of separation occurs closer to the front of the cylinder. The vortex shedding observed on the upper side of the clean cylinder shows the von Karman street phenomenon.

3. CONCLUSION

An experimental study on a circular cylinder covered with ice was conducted using PIV technique. Velocity measurements were performed on two different cylinder configurations; clean, and with an ice accretion profile. The main objective was to assess the use of PIV as a new tool for the study of ice accretion phenomena and also to calculate velocity field and vorticity values in order to use them as input parameters to calculate the aerodynamic coefficients. The PIV measurements gave detailed information on the flow field structure. Surveys of the cylinder upper side and wake, together with vorticity evidenced the consequences of ice formation on the velocity field; moreover, the separation, vertical structures and reversed flow regions were clearly detected. Further investigations are still in progress. They include applying this technique to calculate aerodynamic coefficients with and without ice accretion on cylinders or tower leg flanges.

4. REFERENCES

[1] C Cuerno-Rejado, G Lopez-Martinez, J L Escudero-Arahuetes, J Lopez-Diez, “Experimental aerodynamic charactristics of NACA 0012 airfoils with simulated glaze and rime ice,” IMechE, vol.215, Part G, 2001.

[2] S. Lee, M. B. Bragg, “Experimental investigation of simulated large-droplet ice shapes on airfoil aerodynamics,” J. Aircraft, Vol. 36, No. 5, 1999.

[3] X. Chi, B. Zhu, T.I-P. Shin, H. E. Addy, Y. K. Choo, “CFD analysis of the aerodynamics of a business-jet airfoil with leading-edge ice accretion,” 42nd AIAA, Reno, Nevada, 2004.

Experimental study of flow characteristics around a circular cylinder with different ice profiles

H. Banitalebi Dehkordi, M. Farzaneh
NSERC/Hydro-Québec/UQAC
Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Atmospheric Icing Engineering of Power networks (INGIVRE) www.cigele.ca
Université du Québec a Chicoutimi, Qc, Canada

P. Van Dyke
Hydro-Quebec Research Institute (IREQ)
Montreal, Canada

***Abstract*— an experimental study was carried out investigate the effect of ice accretion on the flow characteristics of a circular cylinder. Variations of flow characteristics such as velocity field, turbulence intensity and vorticity were studied for different ice profiles. These characteristics were used to make detailed flow field measurements to quantify the evolution of unsteady flows around a cylinder. In order to study the effects of ice, two configurations of the cylinder model were considered: clean profile and profile with ice accretion shapes. The velocity field and turbulence statistics of the wake behind each cylinder were measured for Reynolds numbers based on a 38-mm cylinder diameter in the range of $2 \times 10^5 - 1.2 \times 10^6$. A Particle Image Velocimetry (PIV) system, using a laser technique to capture seeding particles was used to measure velocity on the clean and iced cylinders. The experimental results show large regions of separated flow even at low incidence and for moderate amounts of ice. The results of this study will be used as input data for numerical investigations on the effects of ice accretion on aerodynamic coefficients of bluff bodies.**

Keywords-aerodynamic coefficients, circular cylinder, PIV investigations, flow measurements.

I. INTRODUCTION

Atmospheric ice accretion that may lead to transmission line collapses or tower damages has been observed and studied for many years. A great number of experimental investigations have been conducted to understand ice accretion process and atmospheric icing and to measure their effects on the aerodynamic coefficients of surfaces such as airplane wings, airfoils and electrical tower bars with different ice shapes [1-3].

Gregorio & Ragni [4] used the PIV technique in order to study the effects of different types of ice accretion on the aerodynamic characteristics of NACA 0012 airfoil section. They considered four different configurations of the airfoil model: a clean profile and the same profile with glaze rime and mixed ice-accretion shapes. The experimental results show a remarkable decay in aerodynamic characteristics due to ice formation. Among the ice types considered, glaze shows the worst performance with inversion of the lift-incidence curve and a dramatic increase of the drag coefficient. PIV measurements show the presence of large regions of separated flow even at low incidence and for moderate amounts of ice. Gregorek & Bragg [5] studied the aerodynamic effects of ice on a subsonic airfoil by means of analytical and experimental investigations. They used an analytical method to predict the size and shape of rime ice accretion, and the simulated ice shape was tested in a wind tunnel with a smooth surface and with a roughness equivalent to natural rime ice accretion. Hence, the effects of ice shape and roughness on the aerodynamic coefficients were significant. Cuerno & all [6] investigated the flow field over a clean NACA 0012 and simulated rime and glaze ice accretions at low Reynolds number ($Re = 1.4 \times 10^5$), using laser Doppler Velocimetry. Velocity profiles on the upper surface at several angles of attack were provided. They also observed the existence of separation bubbles at angles of attack much lower than in the clean airfoil, for both rime and glaze ice shapes. Addy et al. [7] compared the aerodynamic performance degradation due to different ice-accretion shapes, with rime glaze, and mixed ice types, on commercial and business jets aircraft airfoil. The different types of ice resulted in about the same decrease in lift coefficient for the business jet airfoil whereas for the commercial airfoil glaze ice had a greater effect on the lift coefficient than rime and mixed ice.

The present study mainly focus on the use of Particle Image Velocimetry (PIV) to perform velocity field measurements on a simple shape (cylinder profile), clean and with ice accretion. The influence of the simulated ice formation was analyzed on the cylinder velocity fields. This investigation is important for studying the effects of accreted ice on flow fields of bluff bodies and particularly for applying the measurement process to tower legs. It is also important for aerodynamic studies in order to extend them to other physical models dealing with power line structures. This information will be part of a global study on the effect of ice accretion on the aerodynamic characteristics of tower elements. The aim of the present study is to assess the PIV applicability for the understanding of such phenomena, and to provide useful information about the aerodynamic characteristics of electrical towers, more specifically the variation of the drag coefficient.

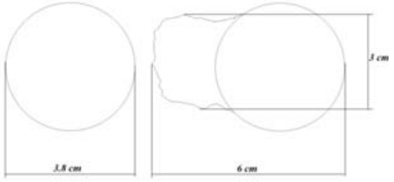
II. EXPERIMENTAL SET-UP

A. *Test facility*

The experimental data were collected in the CIGELE Atmospheric Icing Research Wind Tunnel (CAIRWT). The CAIRWT is a vertical closed-loop, low-speed icing wind tunnel with a length of 30 m, including a 3-m-long test section whose rectangular cross section measures 0.46 m in height and 0.92 m in width. The maximum velocity in the test section is 28 m/s with an accuracy of 0.01 m/s, both longitudinal and transverse turbulence is less than 0.2%. An accepted standard technique is used at CAIRWT to simulate atmospheric icing processes and involves injecting water at room temperature into a cold air stream through air-assisted nozzles located at the trailing edge of a horizontal spray bar [8].

B. *Test models*

Two cylinders having a length of 87 cm and a diameter of 3.8 cm were used in this study. The blockage ratio and aspect ratio for the models were around 8.3% and 24. The first model was a clean cylinder having a symmetric profile with a smooth surface (Figure 1a). The second cylinder had an ice accretion profile on its windward side (Figure 1b). The considered shape was obtained from measurements performed at CAIRWT.



a b

Figure 1. Accretion cylinders with a) clean profile, and b) profile with ice accretion shape

The ice profile was made of cement and a casting process was used to reproduce the ice profile on the surface of the cylinder. The profiles were covered with black, opaque paint, to minimize reflection during PIV measurements. For the PIV tests the cylinders were mounted in the middle of the test section of the tunnel.

C. *Instrumentation*

PIV is a measurement technique. One of its applications is flow field visualization. The physical principles behind this technique rely upon the illumination and capture of seeding particles that follow the streamlines of the flow. The basic concept of the PIV technique is widely described in literature [9-11]. The most commonly used method is to take at least two constructive images from small tracer particles suspended in the flow under investigation. By measuring the particle image displacement, the two dimensional projections of the local velocity vector can be calculated using the time between the two pulses from the laser.

The PIV system includes the following components: flow insemination system, light source, optics, and recording system.

The technique being based on the measurement of particle displacement, it is fundamental that the seeding accurately follows the air flow pattern [12] and that a high uniform seeding density is obtained in the region of interest. The seeding particles for the two-phase PIV investigation flows in the wind tunnel are water particles generated by means of 3 nozzles. The light source for illuminating the particles is a double cavity Nd:YAG laser and relative harmonic generator (HG) and harmonic separator (HS) supplying near-IR light into green. The Nd:YAG laser produces light with a wavelength of 1064 nm, but the HG and HS changes this to 532 nm, and the interval between the two pulses can be set between 4-10 ns.

The recording system includes a charge-coupled device (CCD) camera, a PC for image acquisition and a synchronisation unit. The camera, a full-frame interlines CCD allows the acquisition of two frames at $1\mu s$ intervals with a resolution of 1024 by 1280 pixels.

A schematic view of the PIV set-up around the test section is reported in Figure 2.

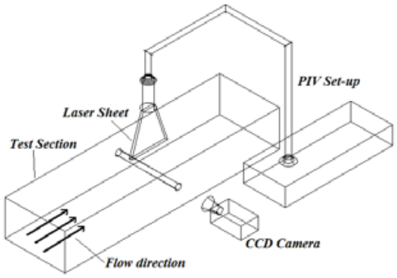


Figure 2. PIV set-up in the test section with icing object

D. *Experimental test*

The first measurements on the clean cylinder were performed in the middle of the test section at zero angle of attack. PIV measurements were done for different Reynolds number $(2 \times 10^5 - 1.2 \times 10^6)$. The region where the measurements were performed is indicated in Figure 2. For this region, a Canon lens with f =1.4 was used.

The origin was at the center of the test section.

- The *x*-axis coincided with the tunnel longitudinal center line and it was oriented in the direction of the free-stream velocity.
- The *y*-axis was placed vertically and oriented upward.

The following test parameters values are reported in Table 1: distance between the laser sheet and CCD camera, laser pulse energy, time between two exposures and number of image pairs for each area.

Five calibration images were acquired for each image series in order to calculate the magnification factor, M, and the observation area position. After the displacement data were measured, they were converted to velocity using the known magnification factor and the exposure time.

For each experimental condition, the time series of the particle images were captured to calculate the continuous evolution of the velocity fields. The velocity fields were averaged to get the statistic parameters such as mean velocity and vorticity. Typical instantaneous velocity fields for each case were introduced to show the basic flow structure of the flow separation of the wind surface. This information will be useful to calculate the drag coefficient and drag variations.

These procedures and measurements were repeated for the cylinder with ice accretion shape models to calculate the velocity field and observe the effect of ice accretion on velocity field around the cylinder.

Table 1: Test parameters of PIV investigations

Trigger Rate (Hz)	Time between pulses (μs)	Exposure Time (μs)	Number of Images	Distance between laser sheet & CCD Camera (m)	Laser pulse Energy (mJ)
500	40	50.044	500	0.85	100-500

Table 2 shows the dynamic and thermodynamic parameters of the ice accretion process and Table 3 displays the CAIRWT adjusted parameters for the PIV measurements.

Table 2: Ice accretion parameters

Air velocity during ice accretion (m/s)	Air temperature during ice accretion (℃)	Water pressure (kPa)	Air pressure (kPa)	Liquid water content (gr/m^3)
10	-10	400	400	4.5

Table 3: Velocity measurement values

Air temperature during measurements (℃)	Air velocity during measurements (m/s)
18	5-10-20

III. TEST RESULTS

In this section, the main results are presented and discussed.

Figure 3 shows the instantaneous flow field on the model upper side with zero angle of attack for both clean and ice accretion shape profiles. So the flow follows the clean profile contour, it is clearly visible that the velocity increases to a maximum (exactly before red circle in figure 3a) and then decreases as we move further around the cylinder. So based on the inviscid theory, a decrease in velocity corresponds to an increase in pressure. The fluid elements experience a net pressure force opposite to the flow direction. At some point, the momentum of the fluid is insufficient to move the elements further into the region of increasing pressure, and the flow starts to separate from the surface (red circle in both figures). This observation might also be explained by the change of direction required for the flow to follow the cylinder surface.

When there is ice on the cylinder (Figure 3b), the adverse pressure increases for a shorter distance and the onset of separation occurs closer to the front of the cylinder.

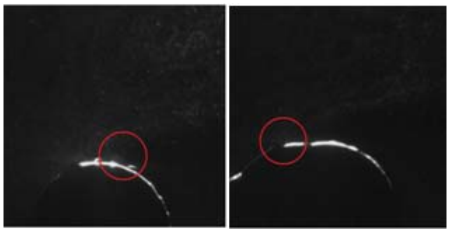

a b

Figure 3. Flow field around a a) clean profile, and an b) ice accretion shape profile; air velocity: 10 m/s

A von Karman vortex street is a repeated pattern of swirling vortices in the wake of a bluff body caused by the unsteady separation of the flow [13]. A specific Re number range ($47 < Re < 10^7$) must be considered [13] in order to shed vortices; the tests were conducted for Reynolds number range, $2 \times 10^5 - 1.2 \times 10^6$. Vortex shedding occurs in the wake of the clean profile (Figure 4) and large scale vortices are formed behind the model. The observations were made only on the upper part of the cylinder but it is expected from other experiments for the shedding to occur alternately on the upper and lower part of the cylinder. The shedding frequency may be calculated using the Strouhal relationship [14], with a Strouhal number of 0.185. The calculated shedding frequency was 48.68 Hz which agrees well with the observed period of vortex shedding of about 0.02 s.

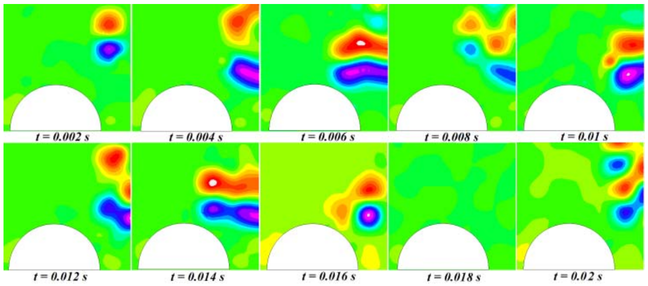


Figure 4. Vorticity contour for clean profile, air velocity: 10 m/s

Figure 5 shows a complicated vortex shedding but because of the specific geometry of the ice this shedding is unstable. Vorticity is function of the velocity field which is specified mathematically as its curl [13]. The ice accretion profile causes serious variations in pressure distribution, velocity fields, so each variation in velocity field affects vorticity.

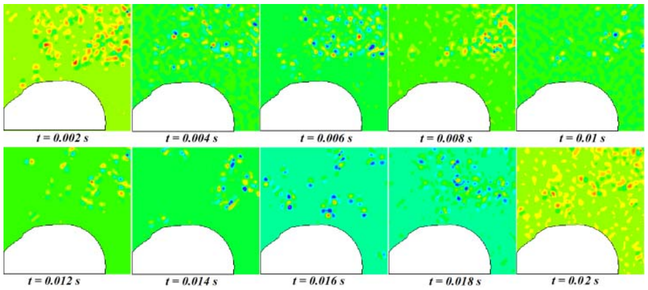


Figure 5. Vorticity contour for ice accretion profile, air velocity: 10 m/s

Figures 6 and 7 show the mean velocity field obtained by averaging 500 instantaneous velocity fields measured in the stream-wise center plane for an air velocity of 10 m/s. There is a strong reverse flow starting at x/d=1.4 in Figure 6 because of increasing pressure. The length of recirculation region extends to x/d=2.5. If the split beam is used and shuts the laser sheet on the cylinder from two sides (up and down), other recirculation vortices are formed symmetrically in respect to the wake center line (y=0), will occur in this area. When there was ice on the cylinder, Figure 7, the recirculation area was shifted in front of the cylinder. This area started at x/d=1.4 and it increased at x/d=2 when the cylinder center is at x/d=2.5. Based on the recirculation region in Figures 6 and 7, the ice profile increases in this region and causes the reverse differential pressure to increase, which has a great impact on aerodynamic coefficients.

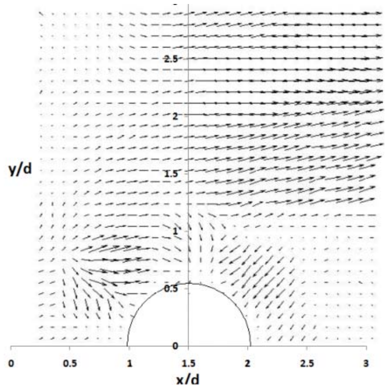


Figure 6. Average velocity field vectors for clean profile, air velocity: 10 m/s

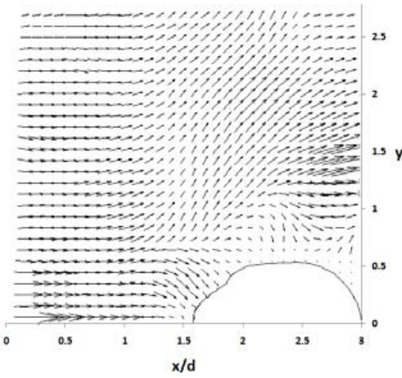


Figure 7. Average velocity field vectors for ice accretion profile, air velocity: 10 m/s

IV. CONCLUSIONS

An experimental study on a circular cylinder covered with ice was conducted using the PIV technique. Velocity measurements were performed on two different cylinder configurations; clean, and, with ice accretion profile. The main objective was to assess the use of PIV as a new tool for the study of ice accretion phenomena and also to calculate velocity field and vorticity values in order to use as input parameters for calculating aerodynamic coefficient. The PIV measurements gave detailed information on the flow field structure. Surveys of the cylinder upper side and wake, together with vorticity evidenced the consequences of ice formation on the velocity field. Moreover, the separation, vertical structures and reversed flow regions were clearly detected.

Further investigations are in progress. They include applying this data to calculate aerodynamic coefficients and effect of ice accretion on them, PIV measurements on ice accretion profile of tower leg.

ACKNOWLEDGMENT

This study was written for internal use by the personnel of the NSERC/Hydro-Québec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and the Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at the University of Québec at Chicoutimi. The authors would like to thank the CIGELE partners (Hydro-Québec, Hydro One, Réseau Transport d'Électricité (RTE) and Électricité de France (EDF), Alcan Cable, K-Line Insulators, Tyco Electronics, CQRDA and FUQAC) whose financial support made this research possible.

REFERENCES

[1] C Cuerno-Rejado, G Lopez-Martinez, J L Escudero-Arahuetes, J Lopez-Diez, "Experimental aerodynamic charactristics of NACA 0012 airfoils with simulated glaze and rime ice," IMechE, vol.215, Part G, 2001.

[2] S. Lee, M. B. Bragg, "Experimental investigation of simulated large-droplet ice shapes on airfoil aerodynamics," J. Aircraft, Vol. 36, No. 5, 1999.

[3] X. Chi, B. Zhu, T.I-P. Shin, H. E. Addy, Y. K. Choo, "CFD analysis of the aerodynamics of a business-jet airfoil with leading-edge ice accretion," 42nd AIAA, Reno, Nevada, 2004.

[4] F. D. Gregorio, A. Ragni, "PIV investigation on airfoil with ice accretions and resulting performance degradation," ICIASF, PP.94-105, 2001.

[5] G. M. Gregorek, M. B. Bragg, "Aerodynamic charactristics of airfoils with ice accretions" 20th AIAA, Orlando, Florida, 1992.

[6] C. Cuerno, R. Martinez-val, A. Perez, « Experimental diagnosis of the flow around a NACA 0012 airfoil with simulated ice," 7th Conference of laser anemometry advanced and application, Germany, pp. 747-754, 1997.

[7] H. E. Addy, M. G. Potapczuk, D. W. Sheldon, :Modern airfoil ice accretions," 35th AIAA, Reno, Nevada, 1997.

[8] L. E. Kollar, M. Farzaneh, "Spray characteristics of artificial aerosol clouds in a low-speed icing wind tunnel," J. Atom. And Spray, vol. 19, pp. 389-407, 2009.

[9] R. J. Adrin, "Multi-point optical measurement of simultaneous vectors in unsteady flow," J. Heat and Fluid Flow, vol. 7, pp. 127-145, 1986.

[10] R. J. Adrin, "Particle imaging techniques for experimental fluid mechanics," Ann. Rev. Fluid Mech., vol. 23, pp.261-304, 1991.

[11] K. D. Hinsch, "Particle Image Velocimetry in speckle metrology", ed. R.S. Sirohi, Marcel Dekker, New York, pp. 235-323, 1993.

[12] W. W. Hunter, C. E. Nichols, "Wind tunnel seeding systems for laser velocimeters," Nasa conference publication 2393, 1985.

[13] T. von Karman,"Aerodynamics," McGrawHill, 1963.

[14] Transmission line reference book, "Wind-induced conductor motion, EPRI," 1979.