Proceedings of ENCIT 2010
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13th Brazilian Congress of Thermal Sciences and Engineering
December 05-10, 2010, Uberlandia, MG, Brazil

EXPERIMENTAL CHARACTERIZATION OF THE FLOW AROUND NON-CIRCULAR CYLINDERS AND SPHERES

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Abstract. *Flow visualization is one important tool to understand complex flows around bluff bodies. In this work, using experimental hydrodynamic flow visualization, different wake configurations produced by square-section cylinders with different aspect ratio, semi-circular cylinder and spheres have been analyzed at moderate Reynolds numbers. Also, flow parameters as Strouhal number, drag coefficient, pressure distribution and velocity profiles are calculated. The experiments have been carried out in a vertical hydrodynamic tunnel and in an aerodynamic wind tunnel. Experimental visualization tests have been done, employing the dye wash and hydrogen bubble techniques. Flow parameters have been evaluated by different techniques such as hot-wire anemometry, strain gage balance and pressure transducers as well as theoretical momentum integration.*

Keywords: *flow visualization, hot-film anemometry, wake of non-circular cylinders and spheres.*

1. INTRODUCTION

For its wide application in several engineering problems, the flow around bluff bodies has been the subject of several researches in the last decades. In fact, many structures used in engineering applications have different geometric cross sections and are exposed to continuous action of several flow types.

The flow around bluff bodies is characterized by a high complexity degree, due to the simultaneous interaction of different kind of flows: the boundary layer, the separation zone and the vortex wake. Even nowadays, several aspects related to the vortex generation and shedding in the bluff bodies wake remain obscure and are focus of several types of investigations.

The intense activity of experimental research verified in this field has been based frequently on results obtained by different flow visualization techniques, which have contributed substantially to the understanding of the phenomena related to vortex dynamics. Examples can be found at Hammache & Gharib (1991) that used the smoke technique in wind tunnels, and Williamson (1989) that used dye wash technique for hydrodynamic flow visualization, among many others authors. In this work, different experimental techniques have been used as a tool for results interpretation of the bluff body’s wake.

2. EXPERIMENTAL FACILITIES AND PROCEDURES

Experimental investigation on non-circular cylinders has been carried out in a low turbulence vertical hydrodynamic tunnel (Fig. 1) operated by gravitational action, described in Vieira *et al* (1997). The test section is square shaped with chamfered corners. It has a nominal size of 146x146x500 mm, and is equipped with four transparent windows of optical quality Plexiglas, in order to allow flow visualization and image capture. Transversal area of the test section gradually increases at downstream, in order to compensate the unfavorable boundary layer growth, avoiding an expressive rise of the flow speed in the centerline region. Hot wire anemometric measurements have confirmed the adequate quality of the flow inside the test section, which combine good velocity profile uniformity, better than 0.4%, and low turbulent intensity, lower than 0.25%.

Two classical flow visualization procedures have been employed, namely, direct injection of opaque liquid dye upstream the body and hydrogen bubbles technique. In the first case, a mix of PVA pigments, ethylic alcohol, and water, having viscosity and density nearly to the tap water has been injected upstream the body by means a 0.7 mm outlet diameter hypodermic needle. In the second case, hydrogen bubbles have been generated using a Platinum wire with 250 μm of diameter. Special attention has been taken in the experiment illumination in order to obtain high contrasting images. Velocity measurements in the wake of bluff bodies have also been performed with the aid of a hot-film anemometer DANTEC, StreamLine 90N10.

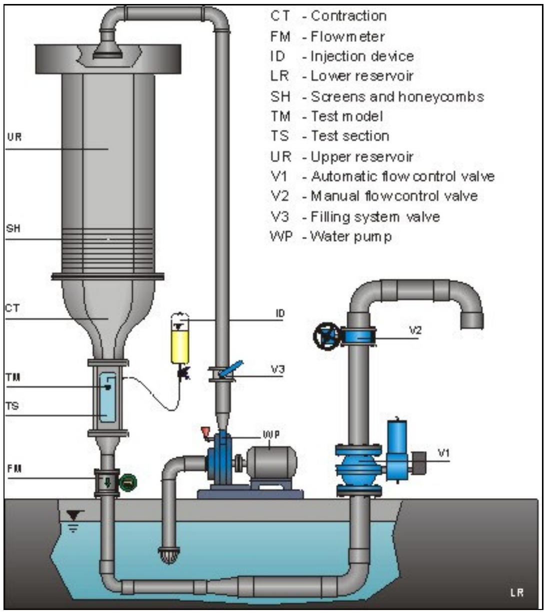


Figure 1. Vertical hydrodynamic tunnel of the Flow Visualization Laboratory (UNESP/FEIS).

The study of flow around spheres was conducted by using an aerodynamics wind tunnel which was entirely projected and built at the Flow Visualization Laboratory at UNESP/FEIS. By means of a 3kW centrifugal fan and a three-phase frequency controller, the facility can reach up to 30 m/s of free flow with a very low turbulence level. The test section has 200x200x500 mm and an easy physical access to the model is provided by means of interchangeable windows. Figure 2 depicts a panoramic view of the blower aerodynamic tunnel showing in the first level an inclined differential manometer connected to a probe of stagnation and static pressure.

Figure 2. Aerodynamic tunnel of the Flow Visualization Laboratory (UNESP/FEIS).

3. FLOW AROUND CYLINDERS AND SPHERES

Vortex shedding frequencies for square and rectangular cylinders at Reynolds numbers up to 1000 have been determined using hot-film anemometry. Flow visualization has also been used as a tool for qualitative analysis of different flow patterns and to assist the hot-film probe positioning. Flow visualizations have been used in order to highlight the shear layers developing from both sides of the cylinders as well as the vortex shedding in the wake.

There are many parameters that may affect the wake dynamics of a square or rectangular cylinder. In this paper, only the rectangular side ratio is focused. For a more in-depth study of that and other parameters the reader is referred to Lindquist (2000).

The cross-section of a rectangular cylinder can be characterized by the side ratio defined as $\phi = H/B$, where H is the height and B is the width of the cylinder. Figure 3 shows the influence of the side ratio on the Strouhal number, defined as $St = f\,H/U_\infty$, where f is the vortex shedding frequency and U_∞ is the free stream velocity. The obtained results suggest that a transition occurs on the vortex generation phenomenon for Reynolds numbers ($\mathrm{Re} = U_\infty\, B/\nu$) greater than around 250. In fact, beyond this flow regime the Strouhal curve is not continuous anymore.

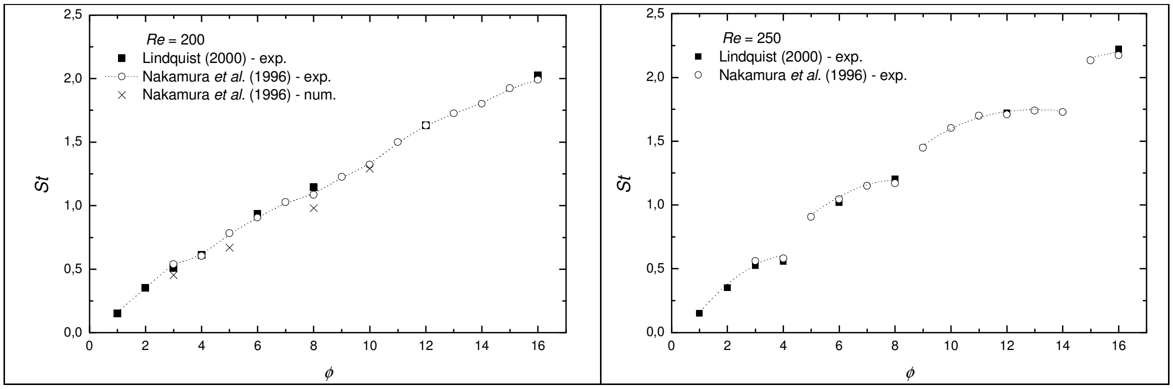


Figure 3 - Strouhal number versus side ratio of rectangular cylinders for different Reynolds numbers.

With the help of flow visualization it was found that, for Reynolds numbers greater than 250, the vortex generation migrates from the cylinder wake to the lateral surfaces, as one can see in Fig. 4. In this case, the Strouhal number increases by steps and can be approximated by $St = 0.6\, n$ where n is the number of vortices present over the cylinder lateral surface.

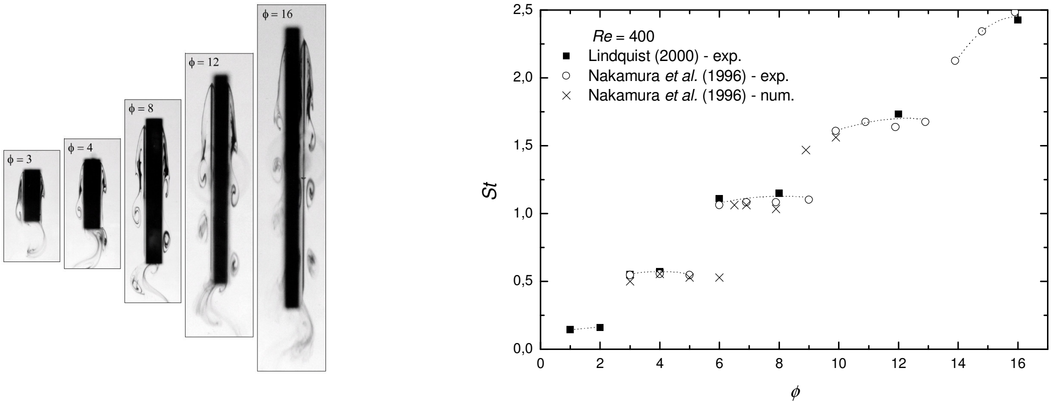
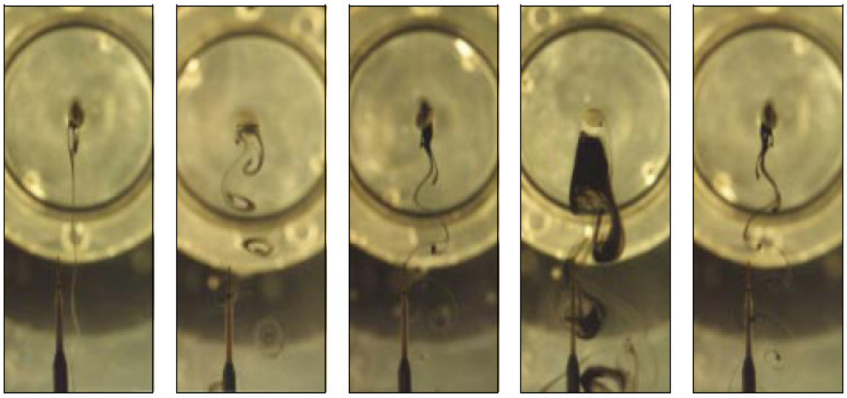


Figure 4 - Influence of the side ratio on the flow around a rectangular cylinder (Re = 400).

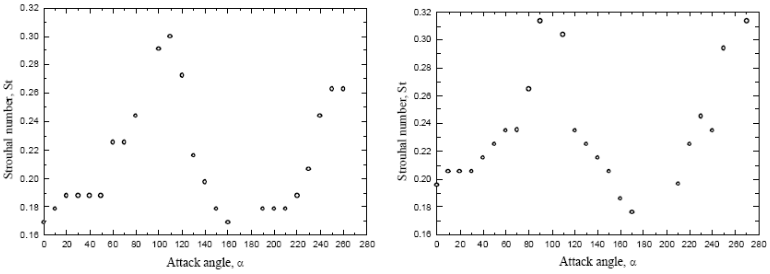
A study of semi-circular cylinders' wake at different attack angles and Reynolds numbers ranged from 100 up to 600 has been conducted in order to determine Strouhal number behavior and to identify different flow patterns. A semi-circular cylinder model with characteristic length (B) equal to 6 mm has been used, subjected to variations in the attack angle (α) in the range of 0 to 270 degrees. A Dantec probe 55R11 has been used in the hot-wire anemometry measurements. The sensor element has been placed in the wake, at position with $x/B = -0{,}75$ and $y/B = -6$, measured from the center plane base. Images of the von Kármán vortex shedding were obtained with the dye wash flow visualization technique. This procedure enables to visualize, for some seconds, the vortex street downstream the cylinder.

Figure 5 presents images of the von Kármán vortex street from the semi-circular cylinders subjected to different attack angles for Reynolds numbers equal to 100 and 200. These visualizations allow identifying some important changes in the vortex patterns in the cylinder's wake. The hot-film probe was left in the photo for demonstrates its position in the wake and its interaction with the alternate vortices. Figure 6 shows that Strouhal curves for Re = 100 and 200 present the same trend for the vortex-shedding frequency. It can be seen that at attack angles closest to 90 degrees the Strouhal curves presented a singular peak with values between 0.32 – 0.4. After 90 degrees the Strouhal number curve decreases continuously until 180 degrees, Almeida *et al* (2001).



(a) Re = 100 – α = 270° (b) Re = 200 – α = 0° (c) Re = 200 – α = 90° (d) Re = 200 – α = 180° (e) Re = 200 – α = 270°

Figure 5. Flow visualization of the semi-circular cylinder's wake for different attack angles 100 ≤ Re ≤ 200.



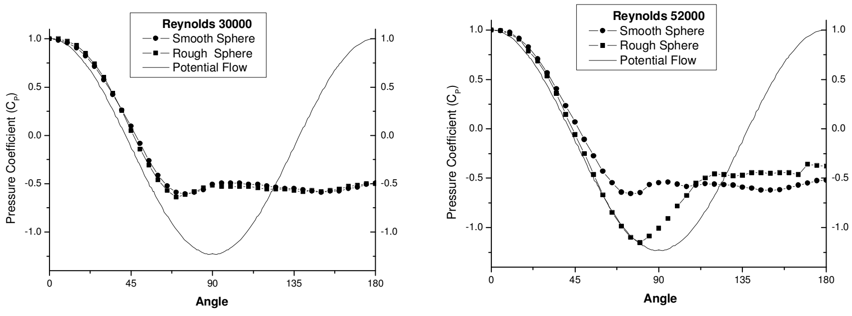
(a) Re = 100 (b) Re = 200

Figure 6. Variation of Strouhal number with attack angle at different Reynolds numbers.

The wake generated by the flow around a sphere presents a significantly different topology when compared with the wake produced by the flow around cylinders. The sphere's wake is considerably more complex, with lots of instabilities, vortex interactions and it also presents an unsteady three-dimensional structure. Although a great number of papers have been focused on the sphere wakes study, it can be noticed a great divergence from different authors which suggest that a deep understanding of the vortex formation and vortex emission are still needed. Therefore this paper also presents the results obtained for the flow around a sphere for different Reynolds numbers (ranging from 20.000 to 60.000). Extensive wind tunnel tests were conducted in order to get pressure distributions on the sphere wall for different flow conditions (smooth and rough sphere) as well as velocity profiles on the sphere wake. The smooth sphere utilized in this work is made of plastic material, with 35.5 mm of diameter and average roughness of less than 15 µm. The surface of the rough sphere was artificially controlled until a value that guaranteed enough increase of turbulence level in the boundary layer that could delay its separation.

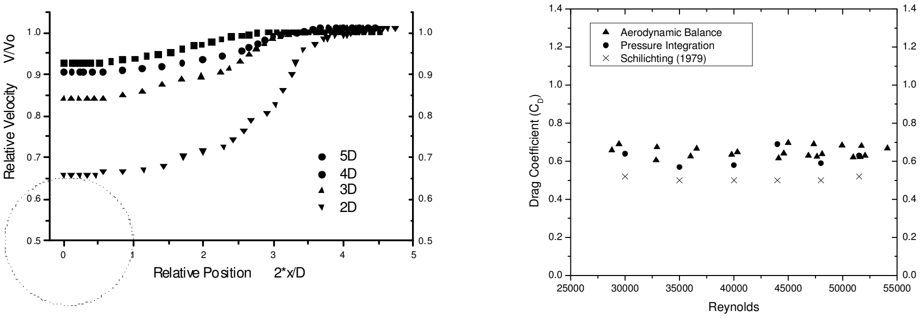
Figure 7 presents the results obtained for the pressure distribution on the sphere's surface for two different Reynolds numbers. For relatively moderate Reynolds numbers (up to 45.000) there is no significant difference regarding pressure distribution for both smooth and rough sphere (Fig. 5(a)). However, for greater Reynolds number – about 50.000 – it can be seen that for the rough sphere there is a retardation in the separation angle of the boundary layer that implicates in a sensible loss of drag force, Ilario *et al* (2005).

Figure 6(a) depicts the velocity profiles from various positions (relatively to the sphere diameter) downstream of the sphere wake. The velocity profiles were measured by using a Pitot Tube of 3 mm of external diameter. Figure 6(b) illustrates the experimental values for the sphere's drag coefficient obtained by using an aerodynamic string balance and with the theoretical momentum integration.



(a) Re=30.000 (b) Re=52.000

Figure 7. Pressure Coefficient distribution on the sphere surface for different Reynolds numbers.



(a) (b)

Figure 8. (a) Velocity distribution downstream of the sphere's wake for different positions. (b) Drag coefficient curve as a function of Reynolds number.

4. CONCLUDING REMARKS

In this work, experimental approaches have been applied for the flow characterization of some of the more common bluff bodies' wakes (cylinders and spheres). Important flow parameters were discussed, such as vortex shedding, pressure distribution and drag. Although a lot of improvements have been achieved during the years on computational fluid dynamics, experimental flow visualization still constitutes a useful tool for fluid motion understanding, contributing to improve science and technology. It was also presented some of the experimental apparatus that are part of the Flow Visualization Laboratory at UNESP/FEIS. Finally, experimental data has been gathered which may corroborate for validation of new numerical codes.

5. ACKNOWLEDGEMENTS

The authors are grateful to the financial support provided by FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) and also thankful for CAPES/PROCAD, FUNDUNESP and FEPISA for supporting the construction and acquisition of the experimental apparatus used in this study. The authors would like to express sincere gratefulness to Reginaldo Cordeiro for patience collaboration on the Plexiglas manipulation.

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