Proceedings of ENCIT 2010
13th Brazilian Congress of Thermal Sciences and Engineering

December 05-10, 2010, Uberlandia, MG, Brazil

FLOW AROUND SQUARE CYLINDERS IN SEVERAL ATTACK ANGLES

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Abstract. *Since the historic Strouhal's work of 1878, many experimental works have been carried out in order to determine the relationship between the vortex shedding frequency and the flow regime. In this work a square cylinder has been tested in order to determine the relationship between the Strouhal number and the Reynolds number for different attack angle (*$0^o < \alpha < 45^o$*). The experiments have been carried out in a vertical low turbulence hydrodynamic tunnel with 146x146x500 mm of test section operating in continuous mode. Flow visualization by direct liquid dye injection has been utilized in order to produce flow images. A hot-film probe has been adequately positioned in the vortex wake to determine the temporal velocity flutuations and consequently the Strouhal number. Results obtained for Strouhal number have a good agreement when compared with data avaliable..*

Keywords*: Flow visualization, Vortex shedding, Hot film anemometry, Strouhal number*

1. INTRODUCTION

An experimental study of the flow around a square cylinder was made by Vickery, (1966) analyzing the influence of the free stream turbulence and incidence angle of the flow over several parameters including the Strouhal number. Pressure oscillations in the test body surface have been obtained utilizing a strain gage probe. Vickery's results, obtained for Reynolds number between 4×10^4 and 1.6×10^5, show no appreciable influence of the Reynolds over Strouhal number.

Obasaju, (1983) studied, for Reynolds number of 10 000, the flow around a square cylinder with attack angle from 0^o to 45^o utilizing a pressure probe mounted in the surface of the test section and a hot film probe positioned in the wake. Obasaju's results show a maximum value for Strouhal number around 13.5^o for attack angle. Several differences can be observed in the Obasaju's results when compared with others authors, probably due to turbulence level and tip effects of the cylinder.

Norberg (1993) was studied the flow around rectangular (included squares) cylinders with attack angle varying from 0 to 90 degrees in Reynolds number between 1 000 to 10 000. Hot wire anemometry was utilized in order to obtain the vortex shedding frequencies. Forces and moments was also measured by means of static pressure distribution on the surface of the test models. The maximum Strouhal number obtained for Reynolds equal to 1 000 was to attack angle equal to 15 degrees.

Experimental results of the Strouhal mumbers produced by square cylinders positioned perpendicularly to free stream flow was also obtained by Lindquist *et al.*, (1997). Only two attack angles ($\alpha = 0°$ and $45°$) was tested in a water flow for Reynolds numbers limited up to 300. The vortex shedding frequency was measured by processing of the visualized flow images showing considerable alterations of the flow due to two attack angles studied.

Other experimental results of the Strouhal number variation obtained by Lindquist *et al.* (1999) for square cylinders for Reynolds number up to 500 and attack angle between 0 to 45 degrees are available. In this work, the authors measured the vortex shedding frequency by means of the spectral analysis of the temporal velocity variation obtained in the wake cylinder with help a hot film anemometry. A hard influence of the Stouhal mumber can be observed for a square cylinder with the variation of the attack angle. The measures show the maximum Strouhal occurring for attack angle between 10 to 15 degrees, in agree with others authors.

The present work represents a contribution to Strouhal evaluation for flow transversally a square cylinder, using experimental hydrodynamic flow visualization and hot film anemometry for Reynolds number up to 1 000 and attack angle between 0 to 45 degrees. . In the following sections, the steps involved the experimental apparatus, hot film anemometry and photographic techniques, are described. Results from the flow visualization around a square cylinder are presented and discussed. Additionally, the non dimensional vortex shedding frequency behavior is showed in function of the Reynolds number and attack angle.

2. EXPERIMENTAL APPARATUS

2.1. Low Turbulence hydrodynamic tunnel

All experiments have been carried out in a vertical open circuit water tunnel with a $146 \times 146 \times 500$ mm square cross test section, shown in Fig. 1. The water tunnel has a free stream velocity range of 30 to 300 mm/s with a turbulence intensity level always less than 1%. All tests were run over the Reynolds number range, based on approach flow velocity (*V*) and cylinder diameter (*D*), of $50 < Re < 1\,000$. The water tunnel is operated by gravitational action, and can be used in continuous or blow-down mode. Continuo mode has been used in this work. The free flow velocity has been determined utilizing a Yokogawa electromagnetic flowmeter ADMAG AE208MG. The uncertainty in the free flow velocity determination is estimated in less than ±3%, producing a maximum uncertain less than 5 % for the Reynolds number. For further information on the water tunnel characteristics, reference may be made to Mansur *et al*. (1996).

In the present work, the free stream turbulence level was measured in the center line of the test section with the hydrodynamic tunnel operating in continuous and intermittent mode. In all measurements the velocity signal was obtained with an acquisition rate of 1 kHz in 10 blocks with 1024 points each. Intensity level is calculated utilizing RMS procedure. With the tunnel operating in blow-down mode the relative turbulence level is approximately twice times less than the turbulence for continuous mode, in accord to shown in Fig. 2.

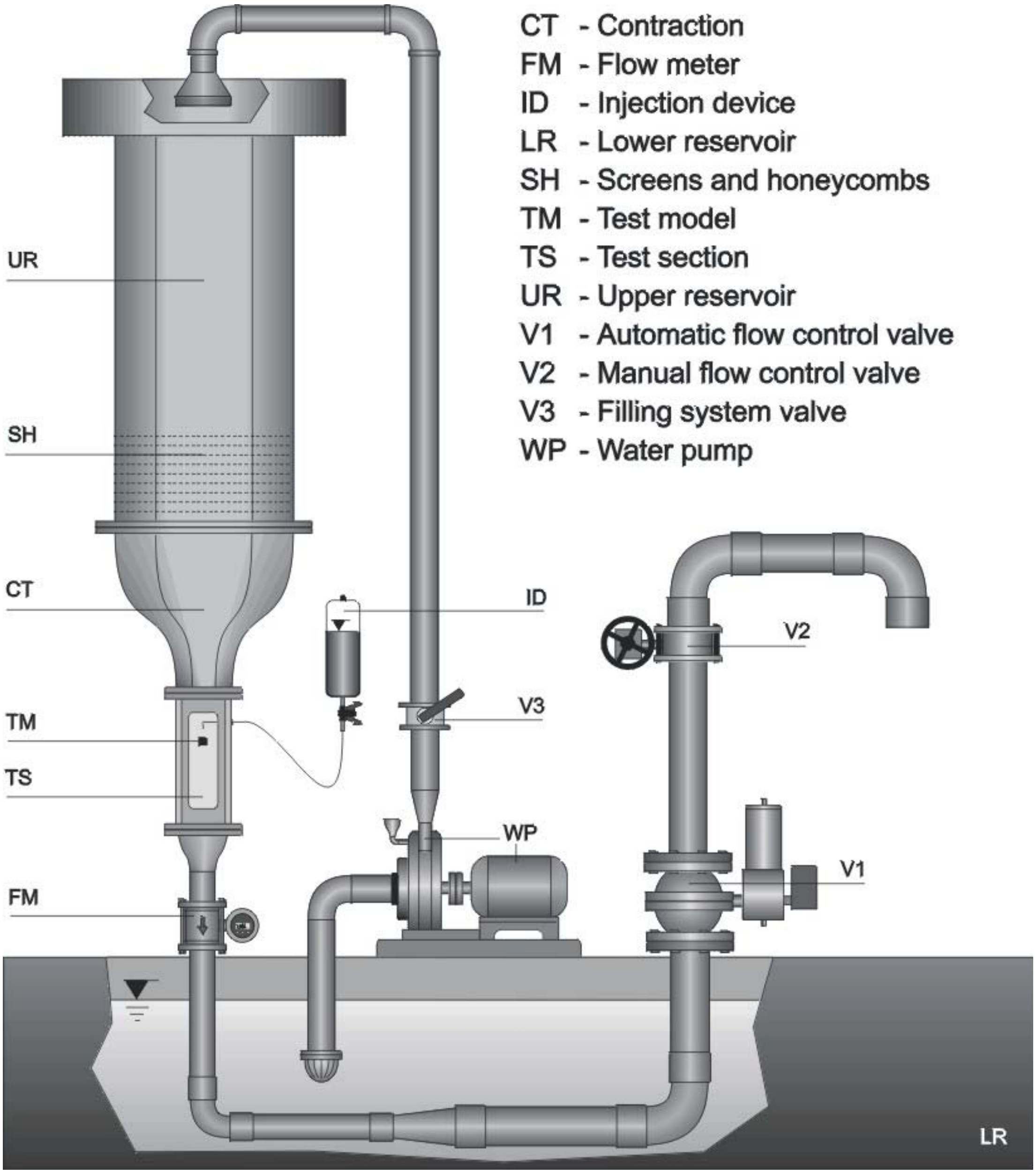


Figure 1. Vertical low turbulence hydrodynamic tunnel

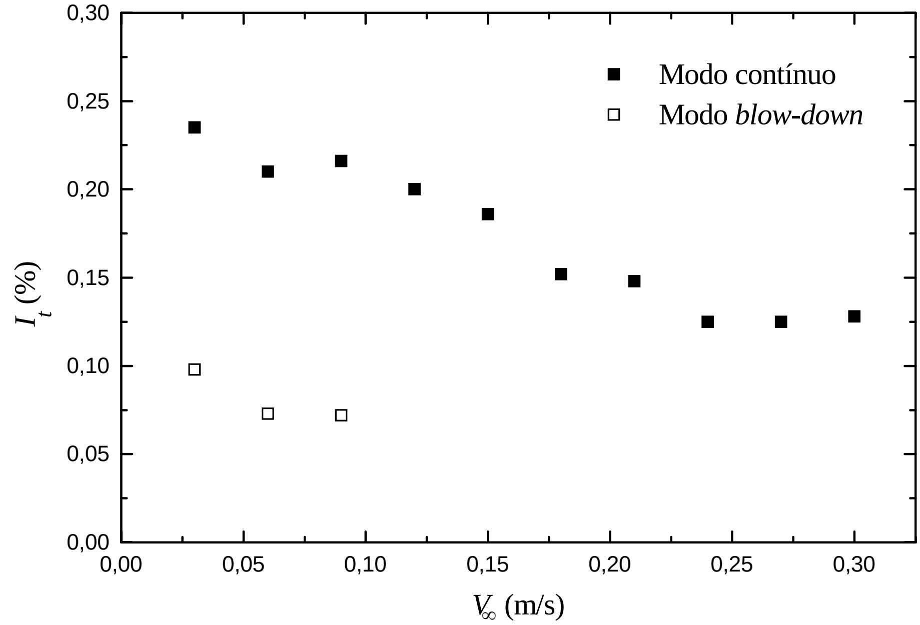
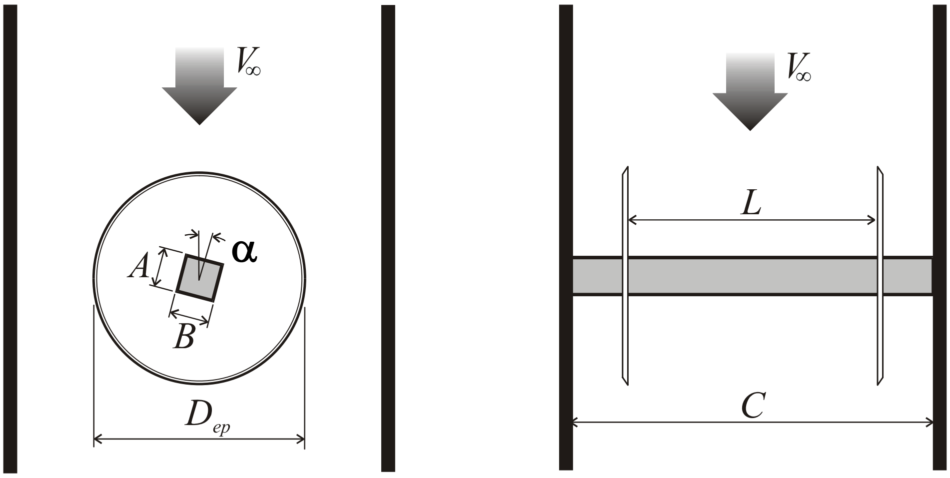


Figure 2. Relative turbulence level (in percents) of the free stream

2.2. Test model

A square cylinder model (B = C) with characteristic length (B) equal to 3 mm was used during the course of the investigation, subjected to variations in the attack angle (α). The Figure 3 shows the configuration employed in this work for to change the attack angle over the range 0 to 45 degrees. The length (C) is equal to 146 mm and end plates (with D_{ep} diameter) have been utilized in order to minimize the boundary layer effects of the test section wall. The length (L) was adjusted in order to produce always an aspect ratio (L/B) = 40.



(a) Front view

(b) Lateral view

Figure 3. Square cylinder test model positioned in the hydrodynamic tunnel

2.3. Flow visualization

In order to understand the nature of vortex-shedding process and to collect quantitative data of it, liquid dye injection flow visualization technique have been employed, due to its simplicity and efficiency. The dye injection device consists on a pressurized reservoir containing a strong aqueous solution of black PVA dye, connected to the test model perforated end through a flexible tube, regulated by a needle valve.

Photographs from the flow have been taken with a *Nikon F4s* camera mounted on a rigid tripod in front of the test section by looking through its transparent front wall towards a translucent sheet attached to the opposite wall. In order to improve the image quality, a proper illumination has been supplied by a set of *G.E. Photo-Flood* lights placed behind the test section, so that a suitable combination of diaphragm aperture and shutter speed could be selected, hence furnishing sharp pictures of the vortex street. The pictures have been taken at several Reynolds number with a *Nikkor 60mm f/1:2.8 AF* macro lens at 1/30s and f/1:16 on *Kodak Tmax ISO 400* black and white chemical film.

2.4. Hot film anemometry

To determine the fundamental vortex shedding frequency in the wake was used a hot-film anemometer DANTEC, StreamLine 90N10, equipped with one probe 55R11. The element sensor was placed in the wake at position with $x/B = -0{,}75$ and $y/B = -6$ measured of the center plane base, as showed in the Figure 4. The uncertainty attributed to frequency measurements is less than 5 %. Later on, the fundamental vortex shedding frequencies were obtained processing the hot-film traces by means of a FFT software on a PC.

All measurements have been carried out for attack angle changing progressively from 0^o to 45^o. The temporal signal of the wake velocity was captured in an acquisition rate of 100 Hz in 5 independent blocks of 4096 point each.

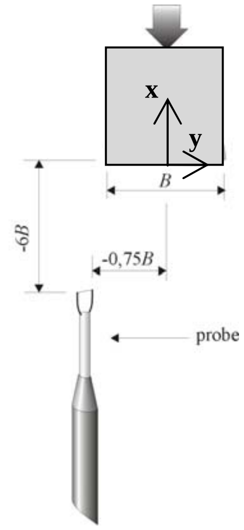


Figure 4. Hot-film probe positioned in the square cylinder's wake

3. RESULTS

Unfortunately, the technical literature shows a very small quantity of experimental results concerning to measure of the Strouhal number of square cylinders when compared with circular cylinders. Additionally, the mostly results to square cylinders are dedicated to Reynolds number significantly more elevated compared with the Reynolds obtained of this present work ($Re < 1\,000$). Meanwhile, when in comparison with the data obtained by Norberg, (1993), the experimental results of the present effort of work show a very good agreement, as depicted in the Fig. 5.

In the Figure 6, are showed Stouhal number behavior in function of the attack angle for Reynolds number equals to 100, 250, 500 and 800. In order to present all results obtained, the Fig. 7 shows the Strouhal behavior in function of the attack angle (α) for a Reynolds number range of 100 to 1 000. Fig. 7 shows a same qualitative behavior of the Strouhal with a maximum value between 10 to 15 degrees. Sharp gradients of Strouhal number in function of attack angle is observed for more elevated Reynolds number. Additionally, is clearly visible the hard influence of Reynolds number upon the Strouhal number.

Fig. 8 shows the attack angle (α) where occurs the maximum value of Strouhal in function of the Reynolds number.

The Strouhal number behavior versus attack angle can be explained in terms of detachment and reattachment of the shear boundary layer on the lateral surfaces of the square cylinder. The mechanism of detachment and reattachment of the shear boundary layer can be observed by means of flow visualization, and in Fig. 9 is showed the pictures obtained of the visualized flow around square cylinders in several attack angles for Reynolds number equal to 500. For a null attack angle, the detachment of the both shear boundary layers (left and right side in the square cylinder) occur in the leading edges, forming the von Kármán vortex street. In this situation, where the detachment occurs in both shear layers in the leading edges, can be observed a relative low level of interaction between the right and left shear boundaries downstream the cylinder inner the wake. For attack angle more than zero degree the left shear boundary detachment occurs in the trailing edge of the square cylinder, changing the flow mechanism in the wake.

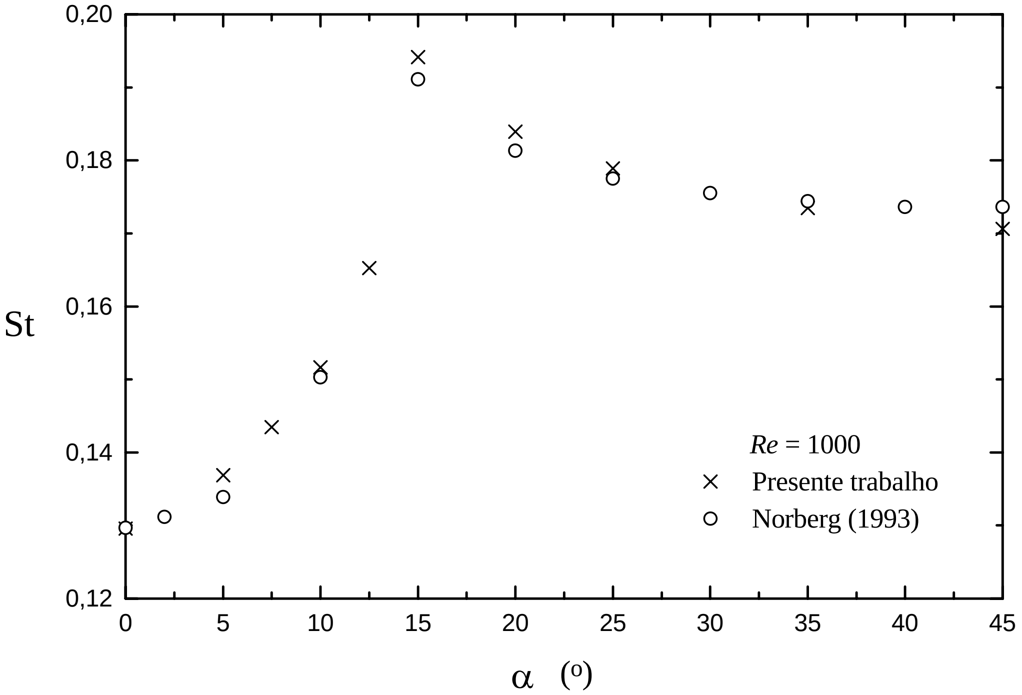
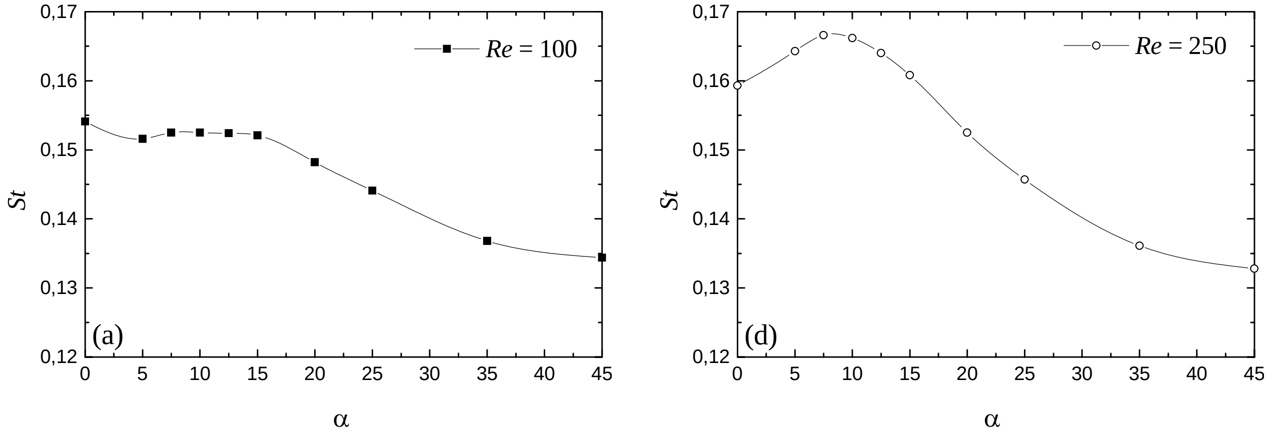
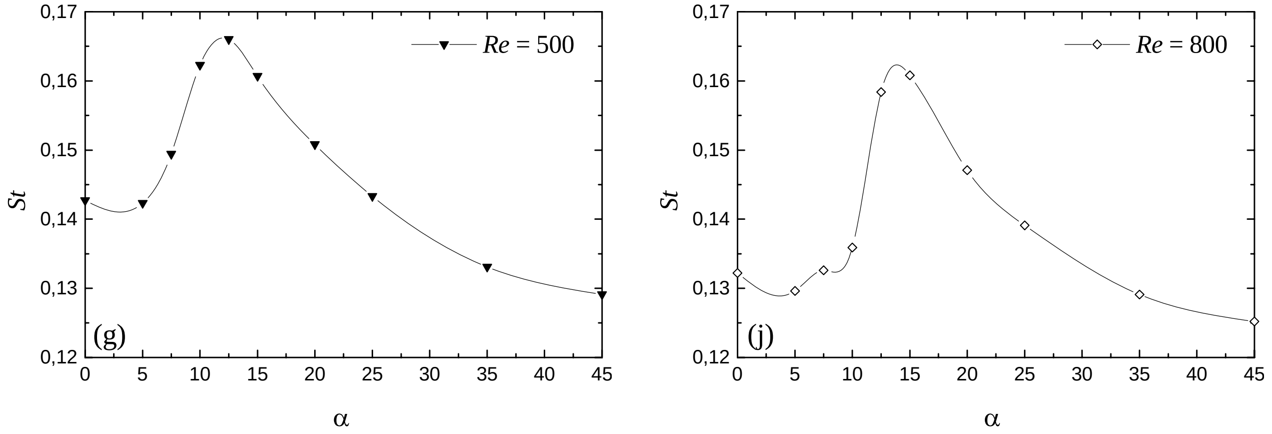


Figure 5. Strouhal number (St) in function of attack angle (α) for a square cylinder in Re = 1 000



(a) Re = 100

(b) Re = 250



(c) Re = 500

(d) Re = 800

Figure 6. Strouhal number (St) in function of Attack angle (α) for several Reynolds numbers

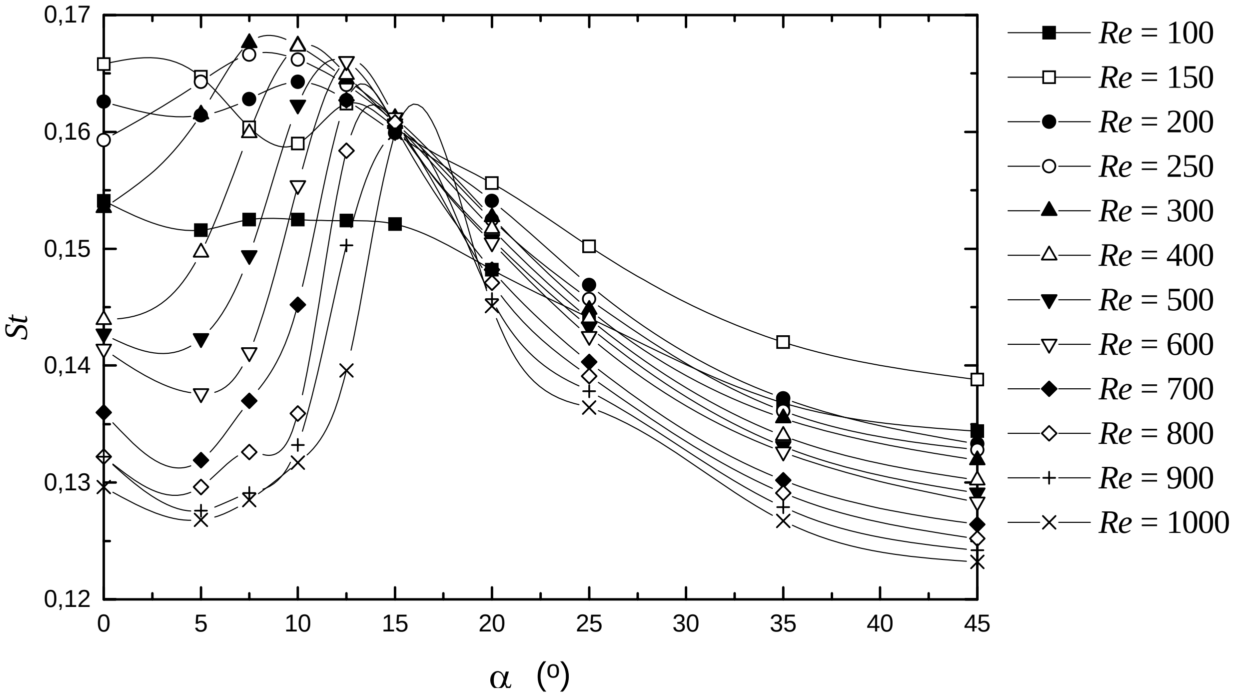


Figure 7. Strouhal number (St) in function of Attack angle (α) for several Reynolds numbers

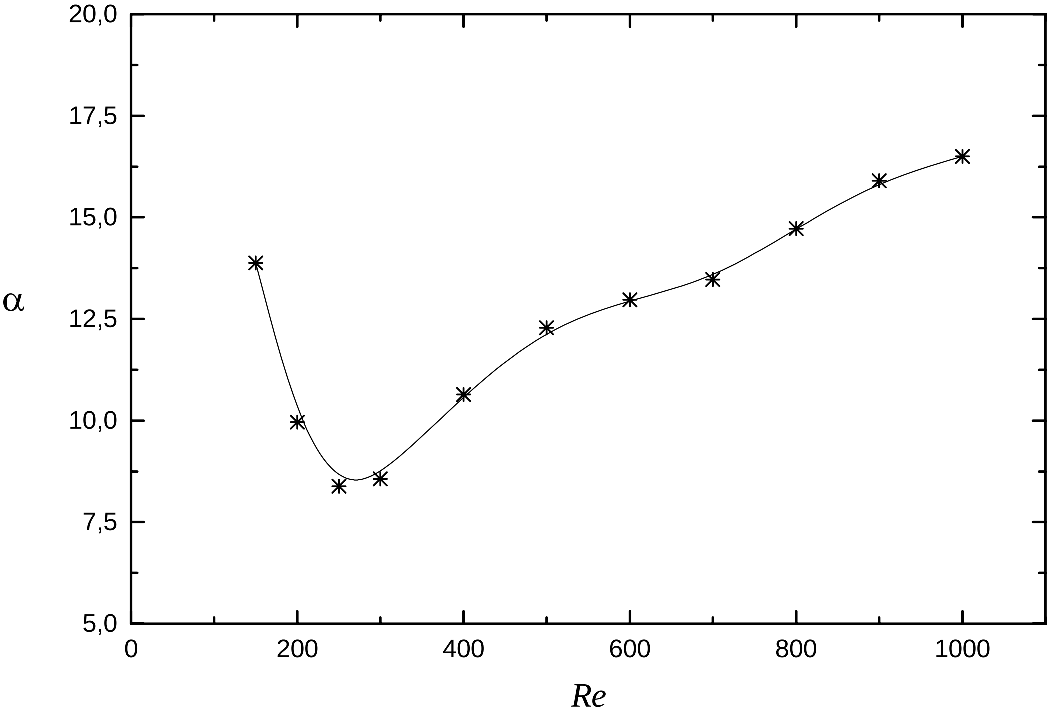


Figure 8. Attack angle (α) where occurs the maximum value of Strouhal in function of the Reynolds number

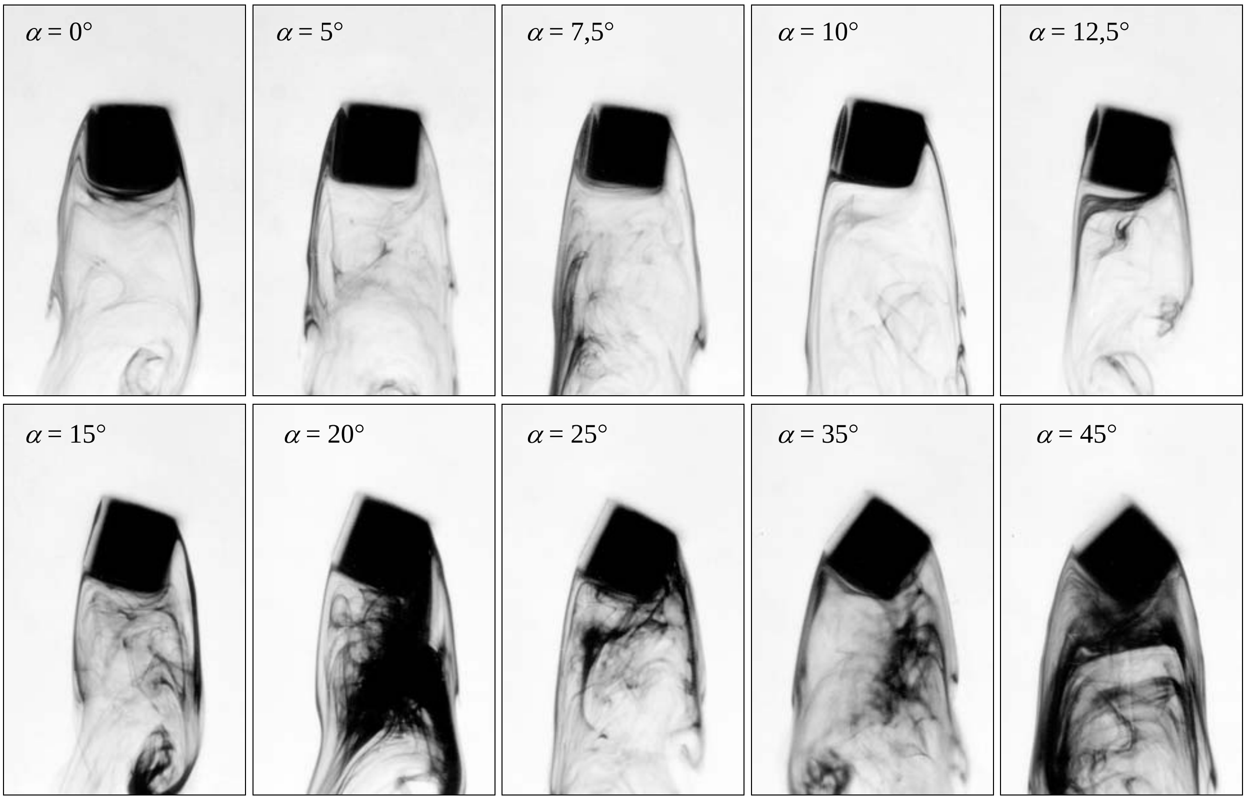


Figure 9. Flow visualized images of the wake formation in a square cylinder for Re = 500

For the attack angle equal to 12.5 degree the width of the wake shows minimum value. The relatively smaller vortex wake width allows for a higher iteration between the two shear layers, and this situation, apparently, yields a greater vortex shedding frequency. Several authors relate a relation between the wake width and the Strouhal number; including Ferreira & Vieira, (2002) and Gonçalves & Vieira, (2000).

4. CONCLUSIONS

In the past, flow visualization has demonstrated a strong influence in fluid mechanics development, on an historical and scientific basis. Today, in an engineering context, the use of images is widely spread in a large variety of applications. More specifically, qualitative flow visualization techniques associated to quantitative measurements contributing in a decisive way to the solution of practical engineering problems. In this present work, the use of flow visualization associated with hot film anemometry, with each technique strongly reinforcing complementing each other, was utilized with success.

A study of the flow around square cylinder with the attack angle from 0 to 45 degrees has been carried out in the present work. The results obtained show a bit more elevated values of the non dimensional vortex shedding frequency when compared with other works (including the self works previously realized). In face of this fact a detailed study of the influence of turbulence level of the free stream, and others possible factors, need be realized.

5. ACKNOWLEDGEMENTS

The experiments have been developed, in part, with financial support provided by FAPESP. The authors thank also the support of FUNDUNESP. The authors express too their sincere thanks to Dr. E R Woiski for his assistance in the reading the manuscripts.

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