VORTEX FLOWMETER WITH SQUARE SHEDDERS AT MODERATE REYNOLDS NUMBERS

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Abstract. *Vortex flowmeters, also known as vortex shedding flowmeters or oscillatory flowmeters, utilize prismatic bluff bodies placed inside a tube in order to produce a von Kármán vortex street. Because the vortex frequency is proportional to the flow velocity, the measure of the vortex shedding frequency permits to obtain the mean flow velocity. Measurement of frequency is easily obtained by many ways and the signal processing is relatively simple, precise and cheap. Nowadays, vortex flowmetes are realiable and precise and present costs low than orifice plates equipped with electronic pressure meter. In the present work, an experimental study of a vortex flowmeter utilizing rectangular cylinders as shedder operating in relative low Reynolds numbers (up to* 4×10^4*) was performed in a hydrodynamic mean using flow visualization and hot film anemometry.*

Keywords*: vortex flowmeter, vortex, flow visualization, hot film anemometry.*

1. INTRODUCTION

Flowmeters can be classified, in accord to design technology employed, in two large groups. The first of all is relative to very traditional technologies utilizing differential pressure (orifice plates, Venturi meters, Pitot tubes, etc), positive displacement (piston and gear pumps), turbines and many others like open channels, rotameters, etc. The second group is relative the new technologies introduced after the second half of the last century. These new types of flow meters utilize distinct physical principle in order to obtain a precise flow measurement and avoid several problems associated to flowmeters utilizing traditional technologies. For example, ultrasonic or electromagnetic flow meters operate with a very low pressure loss (practically null) in opposite to orifice plates. In this sense, electromagnetic flowmeters are introduced in the market since 1952, ultrasonic flowmeters after 1963, vortex flowmeters in 1969 and Coriolis after 1977.

The idea of building a flow meter based on the assumption of Strouhal number variation as a function of Reynolds number (*R*), in accord to several authors, was first proposed by Anatol Roshko in 1953. He studied vortex shedding from a circular cylinder and established the functional relationship between (*Sr*) and (*R*) within certain ranges of Reynolds number with sufficient accuracy to enable it to be used as a mean of measuring air speed – Ower & Pankhurrst (1977).

Today, vortex shedding flow meter or only vortex meter, has been used in steady flow in several industrial applications for over two decades and have proven themselves to be accurate and reliable. Vortex meter is a flow meter with a simple configuration, high accuracy, linearity, wide dynamic range, poor dependency of fluid viscosity and no containing moving parts submitted to deterioration, it is in fact high reliability – Wolochuk *et al*. (1996) and Yokoi & Kamemoto (1994).

Vortex meter is an excellent device for flow measurement, but the main drawback of such vortex flow meter is the very complicated design. It is related to numerous and miscellaneous factors influencing the vortex shedding. First of all, the phenomenon is influenced by the bluff body geometry, where the regularity and power of the generated vortices are strongly sensitive on the shape and dimensions, Pankanin & Krystkowicz (1995). Prismatic bluff bodies of several shape cross sections positioned in cross flow have been tested as a shedder by many manufacturers in a constant search to a stable vortex shedding curve, Doebelin, (2004). Several studies have been made in order to obtain optimized geometry of shedders and different shapes have been proposed in technical literature – Kawakita & Silvares, 1993.

In the present work, the frequency of vortex shedding of square cylinder has been experimental determined, utilizing a hot film anemometry in relative low Reynolds numbers (up to 4×10^4) in order to apply in vortex flowmeter.

2. EXPERIMENTAL APPARATUS DESCRIPTION

Since the vortex shedding frequency is strongly dependent of the turbulence level the experimental device for testing vortex shedders should be careful designed and constructed in order to ensure a controlled level of turbulence in the test section. In this sense, several turbulence manipulators have been made in the experimental device in order to supply a desirable velocity profile and a controlled turbulence level. All experiments have been carried out in an apparatus specially made to this work, depicted in the Fig. 1. An elevated tank, with 1 m^3 of volumetric capacity, supplies the tap water in ambient temperature for the experiments. The water is conducted to a 203 mm (8”) of internal diameter PVC tube by means of a device in order to remain constant the water level. A long radius curve (1.5 m) with internal vanes provides minimum flow perturbation in a quasi stagnation section and eliminates the secondary velocities in the test section. A quasi stagnation section with internal aluminum honeycombs and wire screens provides flow regularization, an adequate velocity profile and turbulence level control. A contraction made in fiberglass with accurate internal finish links the quasi stagnation section with the test section. The contraction design has been executed by solution of the Stokes–Beltrami equation for stream function, in accord to propose by Cohen & Ritchie (1962). This contraction reduces the nominal diameter to only 100 mm. The flow acceleration achieved in the contraction, basically, serves to reduce no uniformities in the mean-flow in order to produce an even velocity profile at the test-section entrance and to reduce the relative turbulence level. Aparecido & Vieira (1999) shows several practical recommendations in order to design and construction radial symmetric contractions applied to water flow in tubes utilizing the same design rules of low speed aerodynamics tunnel contractions. This contraction provides too a stable boundary layer thickness in the entrance of test section. Additionally, the presence of contraction reduces significantly the entrance length of the tube in order to create a completely developed velocity profile in the test section.

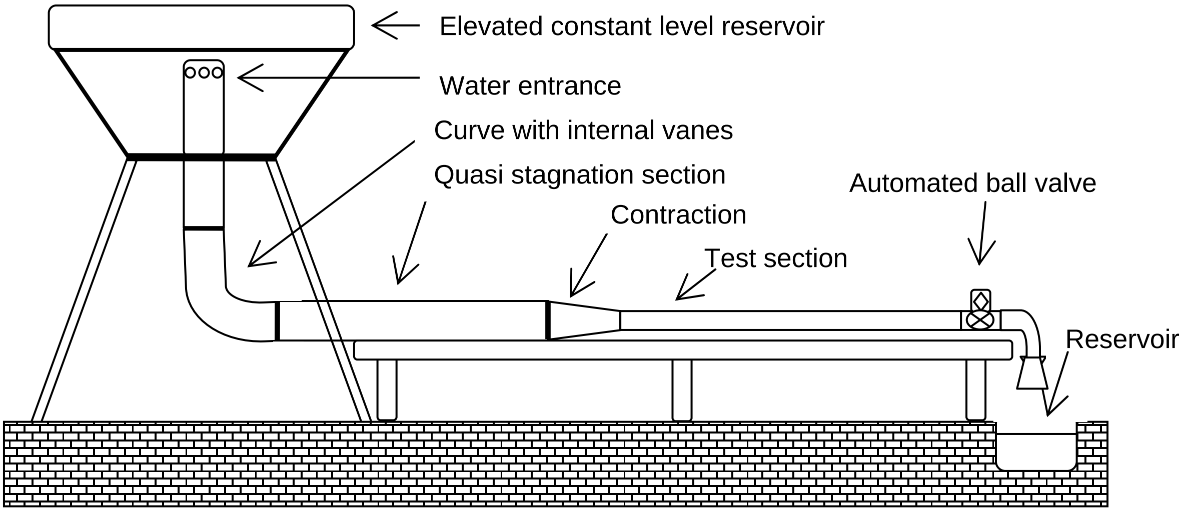


Figure 1. Schematic view of the experimental apparatus for vortex meter testing.

After the contraction section a long Plexiglas tube with 2.8 meters provides the test section. Internal of the test section is adequately positioned the bluff body square prismatic shedder, the hot film probes and the dye injection needle. After the test section an automated ball valve permits an accurate flow regulation. In the Fig. 2 is possible to visualize the velocity profile and the relative turbulent level in three different flow rates (high, medium and low velocity). The relative turbulence level (I) is calculated by RMS of the data divided by temporal mean velocity and conventionally expressed in per cents. The aerodynamic contraction, honeycombs, vanes and wire screens operate with turbulence manipulators permitting to obtain a very low relative turbulence level. Like most flow devices, a vortex flow meter requires a well developed and symmetrical flow velocity profile, free from any distortions or swirls if it is to give good accuracy and repeatability.

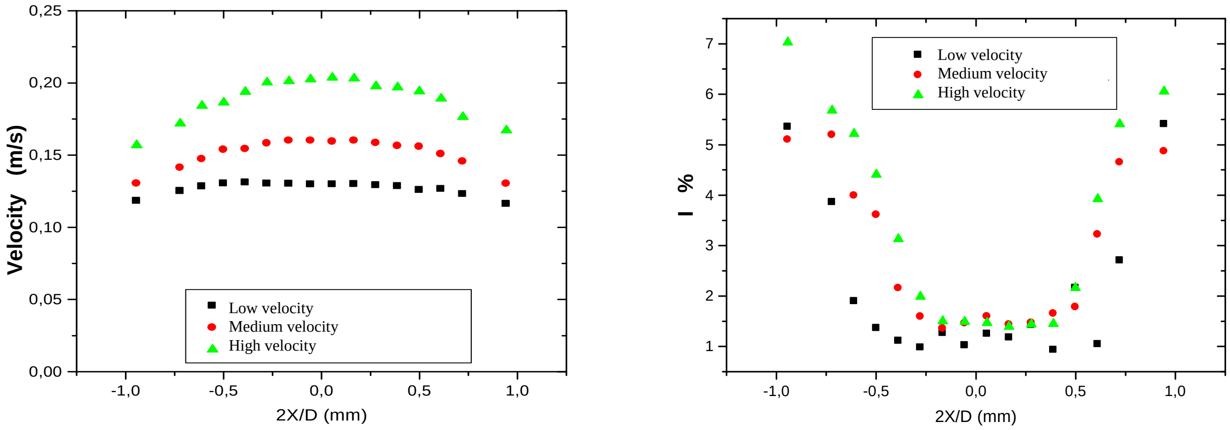


Figure 2. Velocity profile (left side) and relative turbulent level profile (right side) in the test section.

Figure 3 shows a detailed view of the test section showing the Plexiglas tube. Due to the Plexiglas tube in filled with water produces the effect same a bicylindrical lens generating considerable image distortions. In order to capture the flow visualized images avoid of distortions a sealed box has been utilized.

Since the famous Strouhal´s experiment of the eolic harp, several accurate methods for determining the vortex shedding frequency have been proposed. Vortex shedding frequency (f) determination is possible by means of direct flow visualization, as utilized by Lindquist *et al.* (1998). Of course, flow visualization provides a cheap way to determine the vortex shedding frequency. Unfortunately, flow visualization permits to determine only the fundamental frequency of the vortices. In some geometries can occurs two simultaneous vortex shedding frequency – Lindquist *et al.* (1998). Additionally, the vortex frequency obtained by visual observation of visualized images of the flow can be a tedious and boring task. Direct measure of vortex frequency can be made by many different techniques. An extended description of several means of vortex frequency determination is related in the work of Gonçalves & Vieira, (1999).

In order to determine the vortex frequency many works utilize thermal anemometers. Hot-wire/film anemometry (HWA) technique is a powerful tool in experimental research in fluid flows. Many advantages can be noted down using HWA systems in research environment. High frequency response (up to several hundred kilohertz in ideal conditions can be obtained), small-size sensors, very wide velocity measurement range (from very low velocity to compressible flows), very accurate results, and many others advantages have been verified in HWA practical books, in accord to Bruun, 1995.

Since HWA is a thermal transducer, it is a rather complicated instrument and its operation should be made with care conditions. Frequently, problems associated to probes calibration of HWA are observed in almost all works, principally utilizing tap water. Of course, hot film probes are very sensible to loss of calibration due to several contaminants presents in the water. Additionally, electrical current present in the probes provokes hydrolyze of salts dissolute in water. But, in order to determine the vortex frequency (f) the velocity probe calibration is no necessary because voltage output signal processing using Fast Fourier Transform (FFT) permits to determine the vortex frequency. Obviously, the use of FFT can be followed by several cares and precautions in order to obtain realistic physical values.

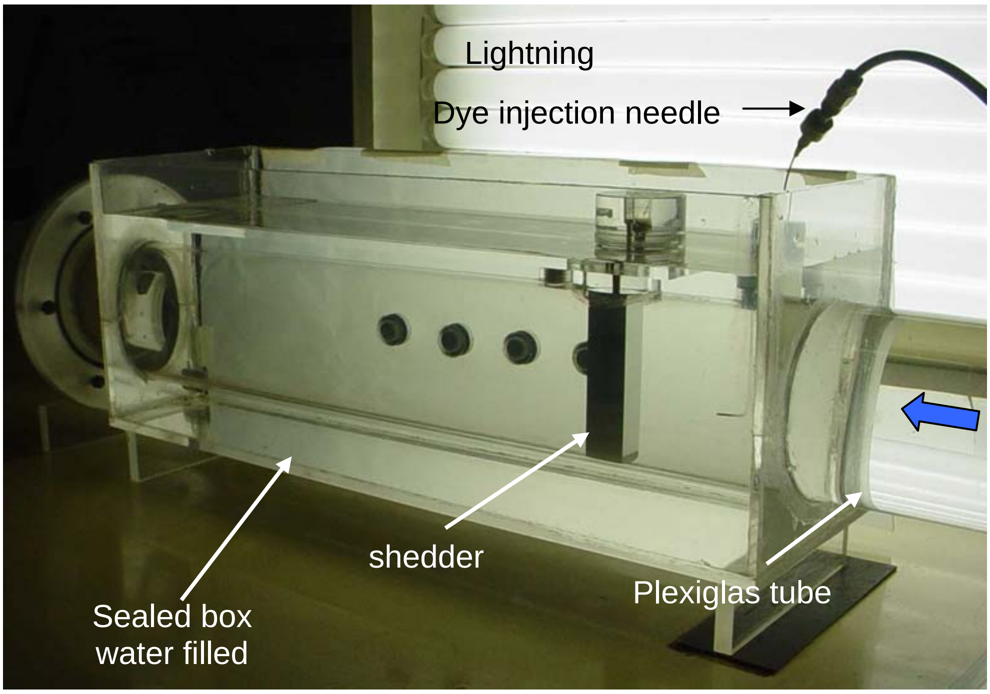


Figure 3. Detailed view of the test section, the sealed box, and the needle for dye injection.

Images of the von Kármán vortex shedding were obtained with the *dye wash* flow visualization technique. This procedure consists on adequate injection of opaque liquid dye into the non-disturbed flow upstream to the solid body by means of a needle of 0.5 mm OD. In the present work, the section test was illuminated in back-light by eight flooding cold lamps, providing a uniformly diffuse bright background against which the dye patterns have been photographed. The dye employed is strong aqueous solution of black PVA pigment and ethylic alcohol. The images generated were registered on a chemical photographic film ISO 400, employing a photographic 35 mm Nikon F4s camera equipped with a Nikkor Micro 120 mm lens.

A combination of the two techniques – flow visualization and hot-film anemometry – with each technique reinforcing the other one and complement each other strongly, is extensively discussed by Freymuth *et al* (1983) and utilized with success in this work.

Today, commercial vortex flowmeter has finding out a broad numbers of industrial applications. In many applications a loss of pressure is an important parameter of design. In order to measure the pressure loss an electronic pressure transducer Yokogawa model EJA 120 has been utilized. The relative pressure loss (RPL) is a non dimensional parameter ratio of the loss pressure due to vortex shedder divided by the loss pressure in a clear tube. In all experiments, in the present work, the Reynolds numbers has been limited up to 4 x 10^4.

3. RESULTS

Several bluff body geometries of shedders are proposed in the literature. In the present work only square cylinders have been tested. Fig. 4 shows the principal dimensions of the shedder positioned inner the test section and is possible to visualize a small gap in the bottom of the shedder. This gap produces a notable influence in the flow downstream the shedder generating a strong turbulence in the wake, as visualized in the Fig. 5, for Reynolds number equal to 6100. The von Kármán vortex street is possible to visualize in the Fig. 6. In all cases the flow direction is from right to left.

In few words, in accord to Summer *et al*. 1977, the flow around a cylinder is characterized by two basic structures. The first of all is named by horseshoe vortex formed upstream the cylinder and the second is the lee side vortices. The adverse pressure gradient caused by presence of the shedder forces the boundary layer detachment ahead of the body generating the horseshoe vortex around the cylinder. Lee vortices are caused by boundary layer rotation. In the Fig. 7 is showed two different views of the horse shoes vortex formed around the square prismatic shedder.

In order to eliminate the undesirable influence of the gap between the shedder and the bottom of the tube, a gap was eliminating utilizing an epoxy moldable resin. The vortex generate with the square shedder without the gap was showed in the Fig. 8. No appreciable difference was observed in the vortex frequency due to presence of the gap.

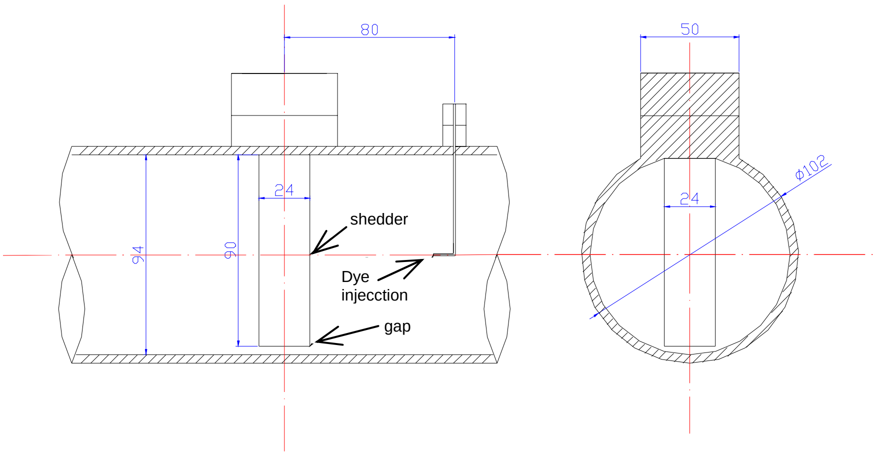


Figure 4. Detailed view of the test section, dimension in millimeters.

Figure 5. Visualization of the flow through the gap (lateral view).

Figure 6. Visualization of vortices (top view).

(a) downstrean top view.

(b) Lateral view.

Figure 7. Horseshoe vortex visualization.

Figure 8. Visualization of the von Kármán vortex street without gap.

The non dimensional vortex shedding frequency (Strouhal number) was measure by means of the hot film anemometry and the results have been depicted in the Fig. 9. For the calculus of the Strouhal and to Reynolds numbers the characteristic length is equals to the internal diameter of the tube (94 mm). The experimental results show a range of quasi constant Strouhal number (St≈0,91), between $17{,}5 \times 10^3 < Re < 36 \times 10^3$. For Reynolds number low than

5×10^3 , the results show a tendency to grow. Results obtained in the present work compared with results obtained by Kawakita, (1992) and Gonçalves, (2001) show a good agrees.

The blockage ratio can be defined by the projected area of the shedder divided by area of the transversal section of the tube. In the present work the tube utilized shows 94.0 mm of internal diameter and the shedders 24.0 mm of width, producing a blockage ratio of 0.33. In the work of Kawakita (1992) was utilized a 100.4 mm internal diameter tube with a shedder of 31.5 mm producing a blockage ratio of 0.40. Finalizing, the work of Gonçalves (2001) was utilized a 76.2 mm diameter tube with shedders of 24.6 mm of width generating a blockage ratio of 0.41. The range of uncertain was measured and showed in the Fig. 9.

In the Figure 10 is showed examples of typical anemometer signal output obtained in the wake of the square shedder and the respective spectral frequency distribution for three different Reynolds number. The Signal obtained was stored in four groups with 1024 acquisition points each. A specific software developed in Matlab software permits to obtain the fundamental vortex frequency utilizing a FFT (fast Fourier transform). The Strouhal value was computed using the mean value of the four data group availed. In order to obtain the uncertain interval, twenty data acquisition groups with 1024 acquisition point was analyzed.

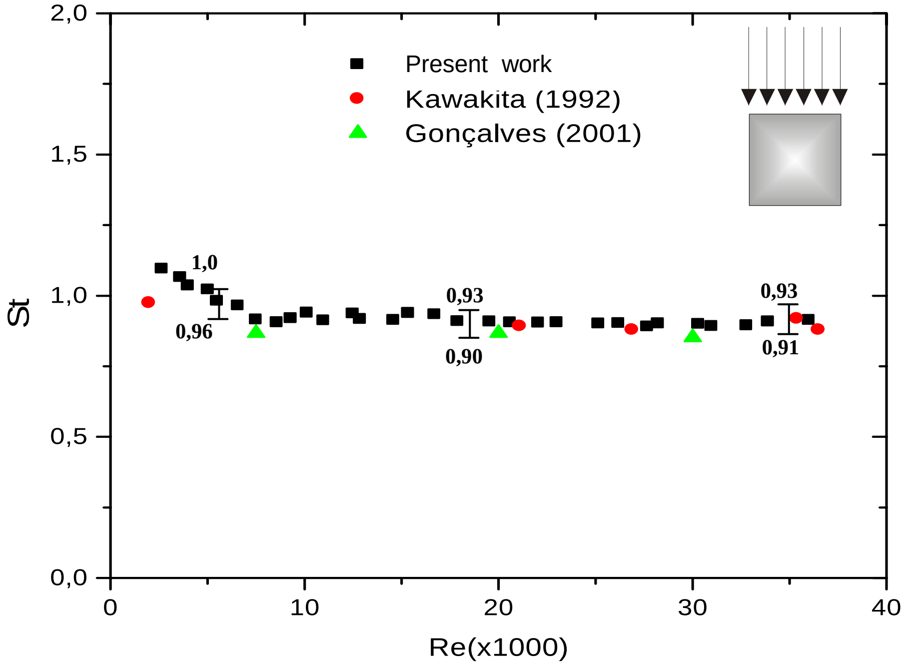
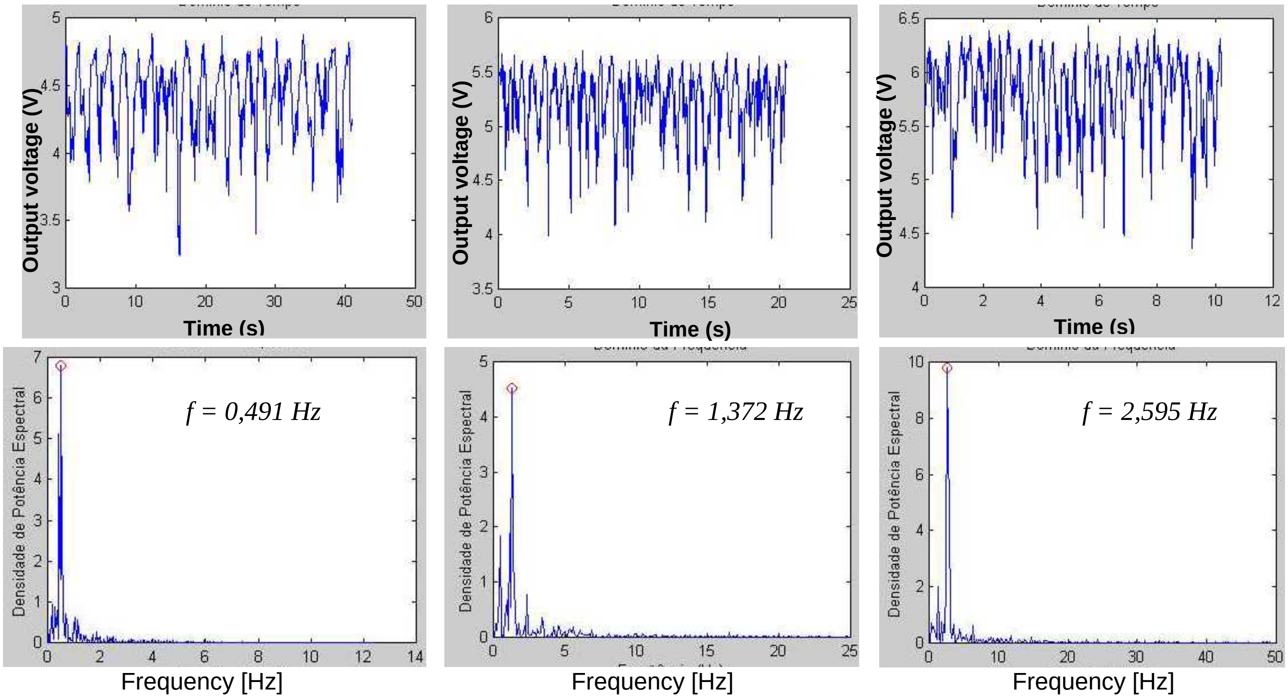


Figure 9. Strohal number versus Reynolds number of a square shedder.

An important parameter in a choice of a flowmeter type is a pressure loss generated. Of course, the presence of a bluff body generating the vortex street produces high level of pressure levels. In this present work the pressure loss was measured utilizing a piezoelectric transducer and compared with the pressure loss due to free tube.

Relative pressure losses (RPL) for three different geometry of shedders are showed in the Fig. 10. A circular cylinder with 24 mm of diameter has been positioned like a shedder and the pressure loss measured showing very low values than the square shedder with 24 mm of width. In order to compare the pressure loss of the square and cylindrical geometries a pressure loss of an available commercially geometry was measured. In order to produces stable vortex shedding frequency several laboratories tested several combinations of geometries. In Fig. 10, the composite geometry named as optimized, second Kawakita & Silvares, (1992), has been tested and a more elevated pressure loss. Several different composite geometries are proposed in order to operate as vortex shedder.



Re ≈ $5,1x10^3$ Re ≈ $1,5x10^4$ Re ≈ $3x10^4$

Figure 9. Examples of the acquisition output signal obtained in the wake of square shedder.

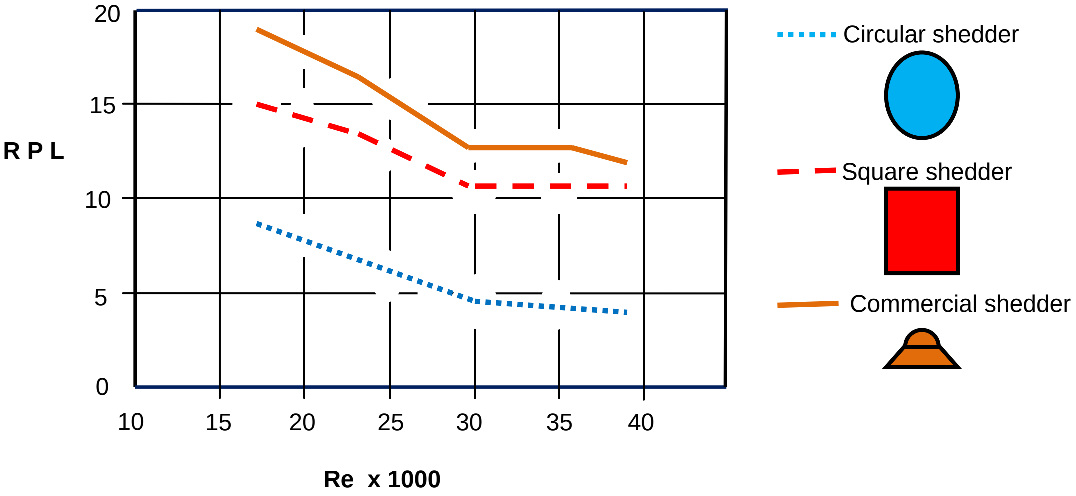


Figure 10. Relative pressure loss of 3 different shedder geometries, all with 24 mm of width.

4. CONCLUSIONS

The use of vortex flowmeters has significantly increasing during the last 30 years due theirs high applicability, reliability, and accuracy. These advantages coupled with the resources of the modern electronics, this kind of meter shows low cost-effective when compared with other devices. Due to continuum advances in vortex flowmeter several new applications rise. One of these new applications is associated to custody transfer operations. Custody transfer is a critical flowmeter application. In custody transfer operations, the custody or ownership of a fluid change hands; it passes from one entity to another. If the fluid has high value (petroleum liquids, natural gas, alcohols, etc) making an accurate and reliable measurement is extremely important. Today, flowmeter market is dominated by magnetic, ultrasonic, vortex meter and Coriolis measurement; accounted for close to half of all flowmeters revenues worldwide.

These new technologies devices continue to displace the old standards of flow measurement (differential pressure, turbine, etc) in many applications. Since 2007, gas and petroleum American associations (AGA and API) have been approved the use of vortex flowmeter in custody applications. These approvals have been significant growth factor for vortex flowmeters in the next years. Today, because the large range of vortex flowmeter applications a detailed knowledge of the effects of different shedder geometries is very important.

The vortex shedding frequency, in industrial vortex meters, for maximum flow rate, are of the order of 200 to 500 Hz. In this work, the main aim is the use of vortex meter application for small velocity flow measurement in liquids, in other words for shedding frequency about 1 Hz. Very low velocities in liquid flow producing low shedding frequencies are availed in this work.

The permanent pressure loss for three different shedder shapes (square, cylindrical and a commercial) has been evaluated in this effort of work. It is seen that the cylindrical shape shows minimum pressure loss. But, the vortex flowmeter, in accord to Gandhi *et al.* (2004), requires as body shape corners to generate stable vortex shedding frequency. The values of pressure loss for the commercial shedder are marginally higher than compared to the cylindrical shape.

4. ACKNOWLEDGEMENTS

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