STUDY AND CALIBRATION OF VORTEX FLOW METER

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Abstract. *The present work adopts two techniques, signal acquisition from sensors and particles images velocimetry (PIV), to calculate the size and the position of the vortex generated by the presence of an obstacle in a flow. The object used to generate the shedding flow is a flat plate put to several angles regarding the axis of the field of stream. Termistors that are bond to the plate and sensible to the variation of velocity of the fluid by the generation of vortex are used as sensors. Signals acquisitions are carried out using these sensors. This methodology is valid to determinate the vortex frequency and the flow velocity using the Strouhal number. The flow is lightened by a laser plan and visualized through acrylic pipes, before and after the plate. The images are captured by a video camera and stored on microcomputer. Successive images provide the determination of the velocity field of the particles and the tracing of their paths. The velocity field is obtained by the method of high density of traced solid particles, distributed in the flow, through the calculation of the crossed correlation function of the corresponding functions to two images obtained from different instants. The vortex frequency f is drawn as a function of the outflow Q measured using a variable area calibrated flow meter.*

Keywords: *shedding flow; vortex; flow measurement; flat plate; particles images velocimetry (PIV).*

1.Introduction

According to Bentley, 1983, the vortex occur when the stream of a fluid in a tubing finds a determined obstacle in its line of stream, as sample to Fig. (1). This kind of stream produces, in the majority of the times, displacement from the boundary-layer, existing changes of high velocity, becoming the fluid inside the layer extremely. After a determined length where the fluid is unstable, the vortex arise. Under determined conditions these vortex are emitted alternately of both the sides of the body, giving rise to wake whirlwind. The frequency of emission of the vortex (*f*) relates itself with the medium velocity in the section cross of the stream (V) and with the dimension characteristic of the solid body (*b*), where *b* is the projection from the width of the obstacle according Figs. (1) and (2), through of the number of Strouhal (Sr.), defined by the Eq. (1):

$$S_r = \frac{f \cdot b}{V} \tag{1}$$

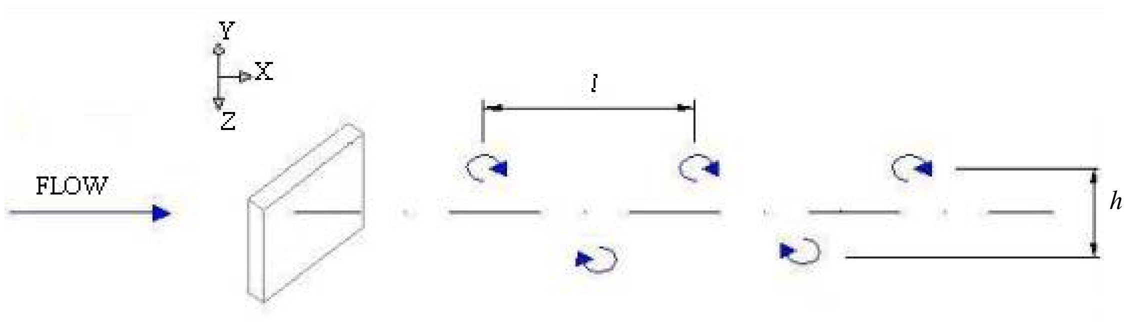


Figure 1. Wake whirlwind after they go by the flat plate to 45° with the plan yz.

Once known the number of Strouhal characteristic of the drainage around a given geometry and being quantified the number of whirls emitted by unit of time, the medium velocity of the free flow can be obtained. The studies of the vortex reveal that they are formed on both sides of the obstacle, alternately. According to the theory of Karman, mentioned by White, Rodely and McMurtrie, 1974, an arrangement of two lines of vortex is unstable, unless they are positioned according Fig. (1), and h/l given by the Eq. (2):

$$\mathrm{senh}\left(\frac{h*\pi}{l}\right)=1 \qquad \frac{h}{l}=0{,}28 \tag{2}$$

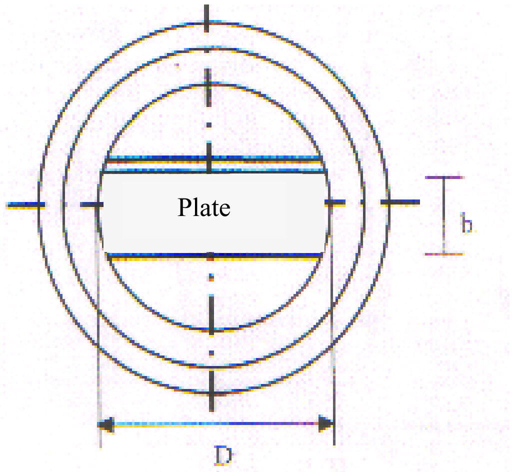


Figure 2. Flat plate inside the tubing with an angle of 45°.

Measurements of vortex are characterized by sinusoidal variations of velocity in the roundness of the obstacle and they enter in contrast with the velocities that characterize normal turbulence. They were developed, then, four systems of discovery of vortex. They are described below:

1°) Diaphragm of capacity: The sides of the obstacle possess flexible diaphragms and the small spaces between the diaphragms and main body is full with oil, forming a sensor of capacity differential, capturing the flotation of the sinusoidal pressure;

2°) Thermal sensor: A constant temperature of the anemometer of hot wire can be used for development and pedagogic work, but if it turns inadequate for industrial applications. Commercial flow measurements have a film united fine termistor added to the own obstacle;

c) Strain gauges: Discoveries of pressure flotations are measured through the tension variation on diaphragms;

d) Ultrasound scan: A connection of ultrasound scan transmission is positioned downstream to the obstacle. The vortex act on the ultrasound scan beam to be modulated in width and phase.

The first experimental observation of the phenomenon was made by Strouhal. He showed that the frequency of a wire vibrating to the wind is related to the velocity and wire diameter. Although many studies were executed with vortex, very little progress was made in the application of this beginning to measure the flow. The possibilities for flow measurement that uses vortex were pointed for Roshko,1954, and an attempt was informed to proceed, to use this beginning, by Shiba,1960, measure of the speed of a ship.

Investigation in flow measure in circular tubes using regular vortex, it was done independently by Tsuchiya and other. Recently, Tsuchiya installed a sensor of pressure forward a circular cylinder for to observe the phenomenon. In 1966, Yamasaki and Kurita they began to research the measurement of vortex that uses a detector of stick type vibrating and then later developed a detector of hot wire that it was built in the stick. This subsequent model uses techniques of control of the boundary- layer to define the separation point close to the detector. Since 1969, when the first practical model was built and installed in a plant of an petroleum industry close to Tokyo, three other systems were installed. These field attempts demonstrated the trust of this new technique [Yamasaki, 1974].

Some responsible researchers for the development of that type of flow meter were Goldstein, 1965, that researched the formation of vortex provoked in a fluid using a flat plate, Schilichting, 1968, that it accomplished the experiment using a cylinder as obstacle besides other studious like Achenbach and Heinecke (1981) and De Carlo (1984).

This work has for objectives to study the formation of the vortex and the visualization as well as the calibration of vortex flow meters. Appears then, in this work proposal a fifth system of measurement of vortex, that uses a thermal sensor which works as a strain-gage, that obtains the temperature variation, pressure and velocity, that are directly related, in function of a certain time, with the objective of determining the frequency of vortex.

2. Measurement factor (sensibility) f/Q

Assuming that the fluid is incompressible, the mass conservation equation is defined by Eq. (3):

$$Q = A \cdot V = A_1 \cdot V_1 \tag{3}$$

where:
Q = flow of fluid (m^3/s)
A, A_1 = traverse area to the flow, before and in the position of the obstacle, respectively, (m^2)
V, V_1 = velocity of the fluid before and after the obstacle respectively (m/s)

The frequency f, as Eq. (1), is described by Eq. (4):

$$f = S_r\left(\frac{V_1}{b}\right) \tag{4}$$

Assuming that the fluid will occupy the whole section A of the tube:

$$A = \frac{\pi \cdot D^2}{4} \tag{5}$$

Then, as shown in Eq. (6):

$$A_0 = D(b_1 + b_2)\,\text{sen}\,\theta \tag{6}$$

where:
b_1 = projection of the thickness of the plate perpendicular to the flow (m)
b_2 = projection of the width of the plate perpendicular to the flow (m)
A_o = total area of the plate perpendicular to the flow (projection) (m^2)
θ = angle of inclination of the plate (used 45^o in the experiment)
b = it adds of the projections b_1 and b_2 (m)
D = diameter of the tube (m)

The area A_1 where the fluid really drains is shown in Eq. (7):

$$A_1 = \frac{\pi \cdot D^2}{4} - D \cdot b \cdot \text{sen}\,\theta \tag{7}$$

Like this, in agreement with Eq. (4), the measurement factor f/Q is given by Eq. (8):

$$f/Q = \frac{S_r \cdot V}{Q \cdot b} \tag{8}$$

Then, the theoretical equation for the measurement factor f/Q is shown in Eq. (9):

$$f/Q = \frac{S_r \cdot V_1}{A_1 \cdot V_1 \cdot b} \tag{9}$$

Substituting Eq. (7) in Eq. (9) and simplifying, the theoretical equation of the sensibility factor, valid for a plane plate to 45^o, is given by Eq. (10):

$$f/Q = \frac{4 \cdot S_r}{\left[\dfrac{\pi \cdot D^3 \cdot b}{D}\left(1 - \dfrac{4 \cdot \sqrt{2} \cdot b}{2 \cdot \pi \cdot D}\right)\right]} \tag{10}$$

where: $\sqrt{2}/2$ = sin 45^o

For other obstacles, the generic expression of the sensibility factor, is shown in Eq. (11):

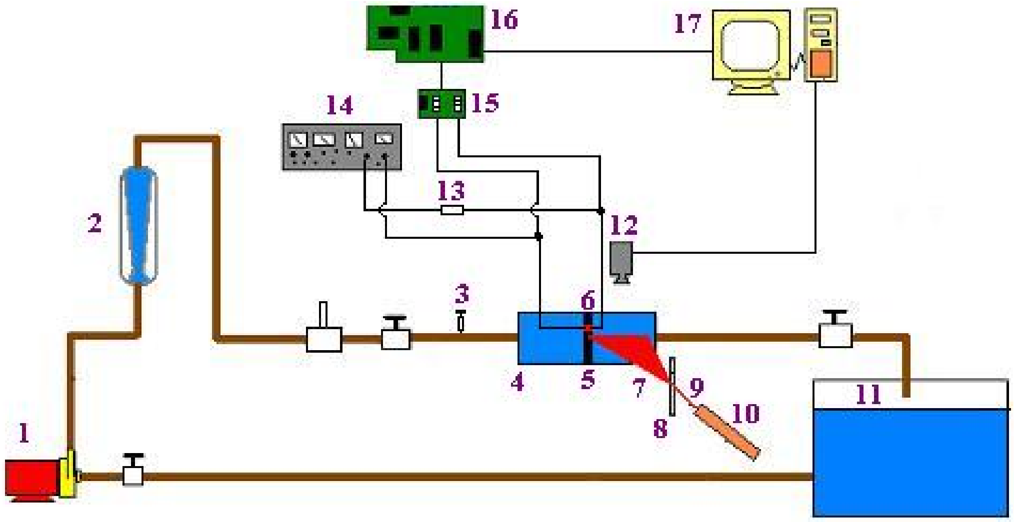
$$f/Q = \frac{4 \cdot S_r}{\left[\dfrac{\pi \cdot D^3 b}{D}\left(1 - \dfrac{4 \cdot k \cdot b}{\pi \cdot D}\right)\right]} \tag{11}$$

being:
k = 1.1 for cylindrical obstacle;
k=1.5 for obstacle with section of equilateral triangle.

3. Experiment for the study of vortex flow meter

3.1 Tests Bench

For measurement of the flotations of velocity during the formation of the vortex a bench of tests was built according to assembly outline in Fig. (3).



LEGEND
1. Pump
2. Rotameter
3. Particles injector
4. Acrylic tube
5. Flat plate
6. Termistor
7. Laser plane
8. Acrylic lens
9. Laser beam
10. Laser source
11. Water tank
12. Digital camera
13. Resistor
14. Tension source
15. Conection plate
16. Signal acquisition plate
17. Microcomputer

Figure 3. Tests Bench for study of vortex flow meter.

3.2. Vortex measurement by signals acquisition

The flat plate, which serves as obstacle for the formation of the vortex, it is positioned between the tubes of acrylic to an angle of 45°. A PTC termistor is fastened soon behind the plate, due this to be the area where they are formed the vortex. The termistors PTC are thermal sensor of variation of positive tension and NTC are sensor thermal of variation of negative tension.

The termistor is a resistor semiconductor sensitive to the temperature. Her resistance value increases quickly when a certain temperature is passed. This termistor has as function to capture the temperature variation in this point, being this signal transmitted to a computer for the due analysis. This termistor was used because the temperature varies due to the pressure variation and consequently of velocity. It was measured then, tension (ddp) associated to the change of velocity for the formation of the vortex.

Starting from the knowledge of the signals acquired in this sensor, it is possible to calculate the velocity of the fluid and, consequently, the flow in the piping.

The connection of the termistor to signal acquisition plate in the computer is shown in Figs. (4) and (5).

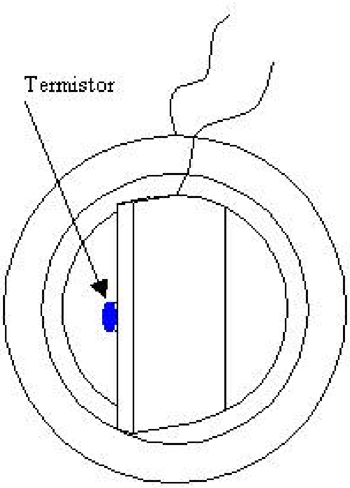


Figure 4. Sight of the plate with sensor

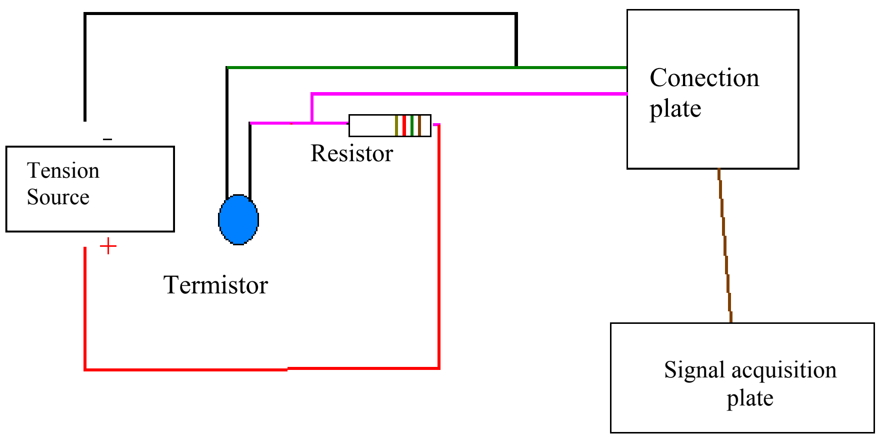


Figure 5. Scheme of sensor connection.

The signal acquisition plate possesses 8 channels, resolution of 12 bits, maximum input voltage of 35 Volts, input impedance of 10 MΩ, uncertainty of ± 0.01% LSD of reading, work range of ± 5 Volts, acquisition frequency of 100 Hz dependent of the computer and conversion rate of analogical for digital of 25 μs (Advantech, 1993).

3.3. Calibration curve of the vortex flow meter

The procedure for the plan of the curve for water is the following:

1^o) Notice an opening of the valve of sphere of the tests bench (Fig. 3)
2^o) It is read the value of the flow of the water (Q), in m^3/h, in a flow meter type calibrated rotameter;
3^o) It is acquired the signal of the sensor, ddp(V), in the microcomputer;
4^o) The frequency (*f*) of the signal of the sensor is made by the period (*T*), of the generated signal;
5^o) It is calculated the calibration factor f/Q;
6^o) Repeat the items 1 to 5 (several times);
7^o) The calibration curve f /Q x Q is drawn.

The calibration factor f /Q allows to know the Strouhal number, Sr, in agreement with Eqs. (10) or (11), for the obstacle used as former of vortex.

The Strouhal number, Sr, is constant for a great range of flows, and the frequency of the vortex, *f*, is obtained by signals processing. The flow of the fluid is known in the stream with the use of Eqs. (10) or (11), being compared with the flow of the calibrated rotameter.

4. Images acquisition for vortex visualization

For the acquisition of the vortex images the bench of Fig. (3) was used, with the components showed in the scheme of Fig. (6).

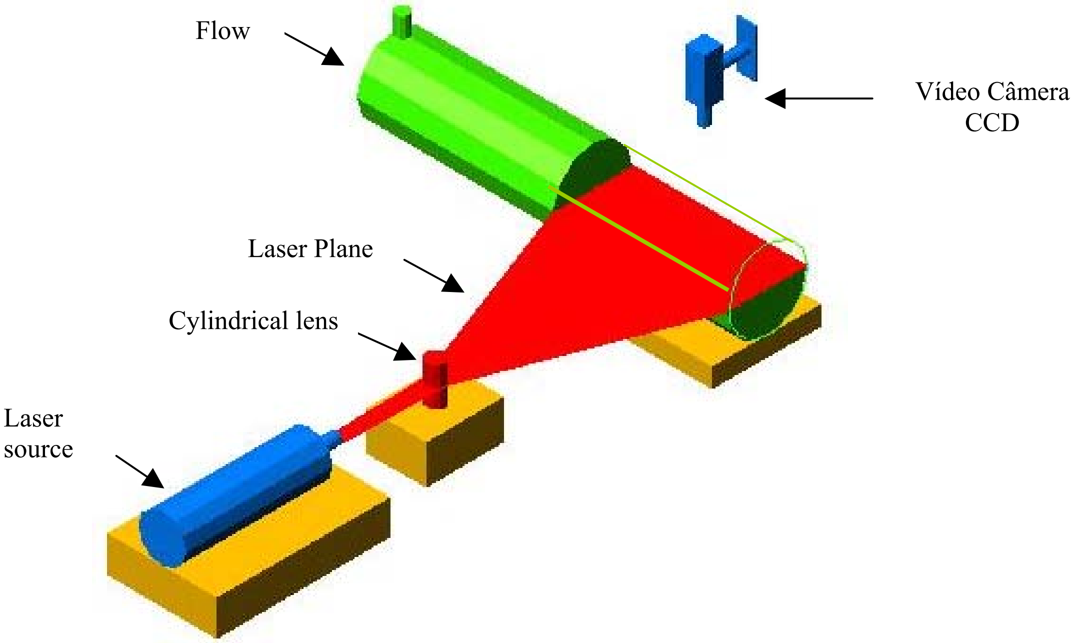


Figure 6. Three-dimensional scheme of the vortex visualization

A beam produced by the laser source is transformed in a plan of small thickness after passing for the cylindrical lens. The fluid in movement is illuminated by the laser plan incident in the diameter of the tubes of acrylic, illuminating the tracer particles. The video camera CCD, is positioned perpendicular to the stream, registering the movement of the particles, which follow the movement of the fluid. The visualized images are captured and stored in the microcomputer. Successive images provide the determination of the velocities fields of particles due to the vortex and the plan of their paths.

For determination of the wake vortex inside of the piping a digital video camera monochrome was used. It acquires 30 images/ second having equipped with opening lens F = 4 mm and resolution of 768 x 494 pixels. That visualization is possible due to the presence of two transparent tubes (of acrylic), one before the flat plate and other later. The stream in study is of water in the liquid phase and the tracer particles are metallic paint powder. Was used the method particles images velocimetry (PIV). The field of velocities is obtained by the method of high density of tracer particles distributed in the stream being calculated the function crossed correlation of the functions corresponding to two images obtained in different instants (Almeida, 1997).

5. Results

5.1. Calibration curve of the vortex flow meter

The results obtained by this experiment are limited for the flow of the used pump, whose maximum flow was of 5,5 m3/h, when the valves of it represses were totally open.

The result of the calibration of the vortex flow meter was made in according to the procedures of the section (3.3) and they can be expressed through the Table (1) and the graph of Fig. (7). The calibration curve is given by Eq. (12).

Table 1. Values regarding the period, frequency, flow and calibration factor

Values of f /Q x Q						
Q (m^3/h)	1.85±0.10	2.10±0.10	2.90±0.10	3.40±0.10	4.60±0.10	5.50±0.10
T(s)	33.75±1.95	31.50±2.02	28.75±1.14	34.30±2.05	36.00±0.72	35.71±0.96
f (Hz)	0.03000± 0.001861	0.03410± 0.003968	0.03628± 0.00291	0.03175± 0.003347	0.02798± 0.000781	0.02862± 0.001857
f/Q (pulses/m^3)	58.37 ± 4.79	54.43±4.08	43.17±3.70	31.14±3.04	21.74±2.78	18.74 ± 1.25

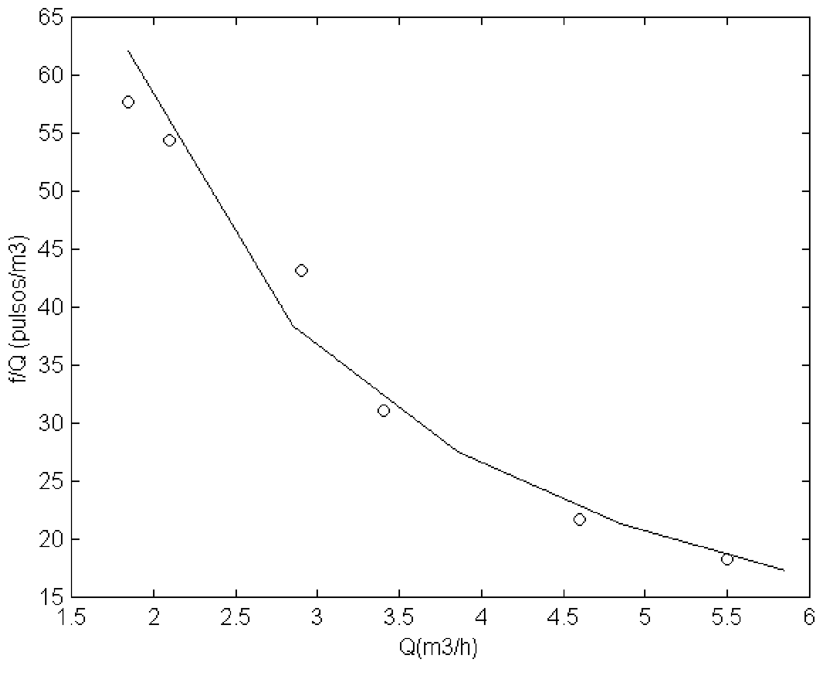


Figure 7. Calibration Curve of the vortex flow meter: factor of calibration f/Q (pulses/m3) x flow Q (m3/h)

$$\frac{f}{Q} = 112{,}63 \cdot Q^{-1{,}1071} \tag{12}$$

5.2. Vortex visualization and particles images velocimetry

The acquisition and processing of the images was made in agreement with the section 4; the Figs. (8) and (9) show the images with vortex acquired with the flow of 5.0 m^3/h, in an interval of 0.166 s. The Figure (10) shows the crossed correlation of the images from the Figs. (8) and (9).

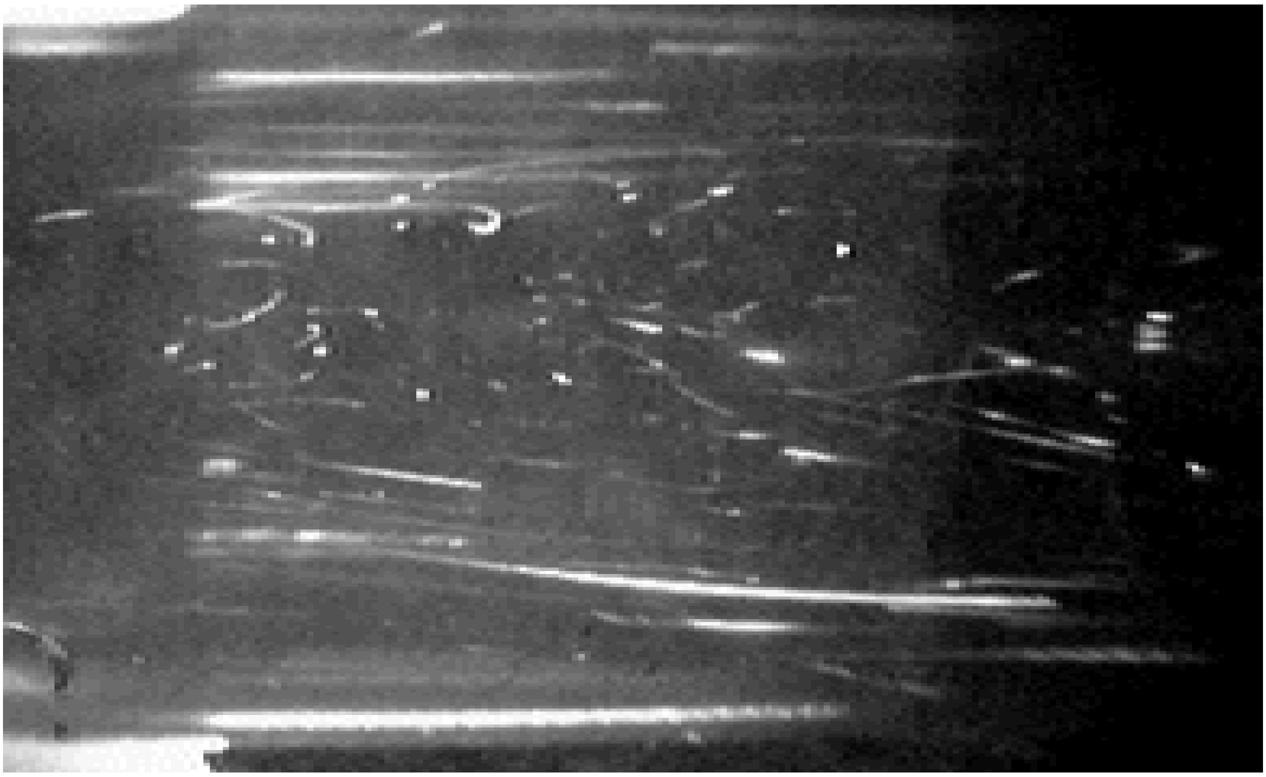


Figure 8. Acquired image with flow of 5.0 m^3/h (t=0.000s)

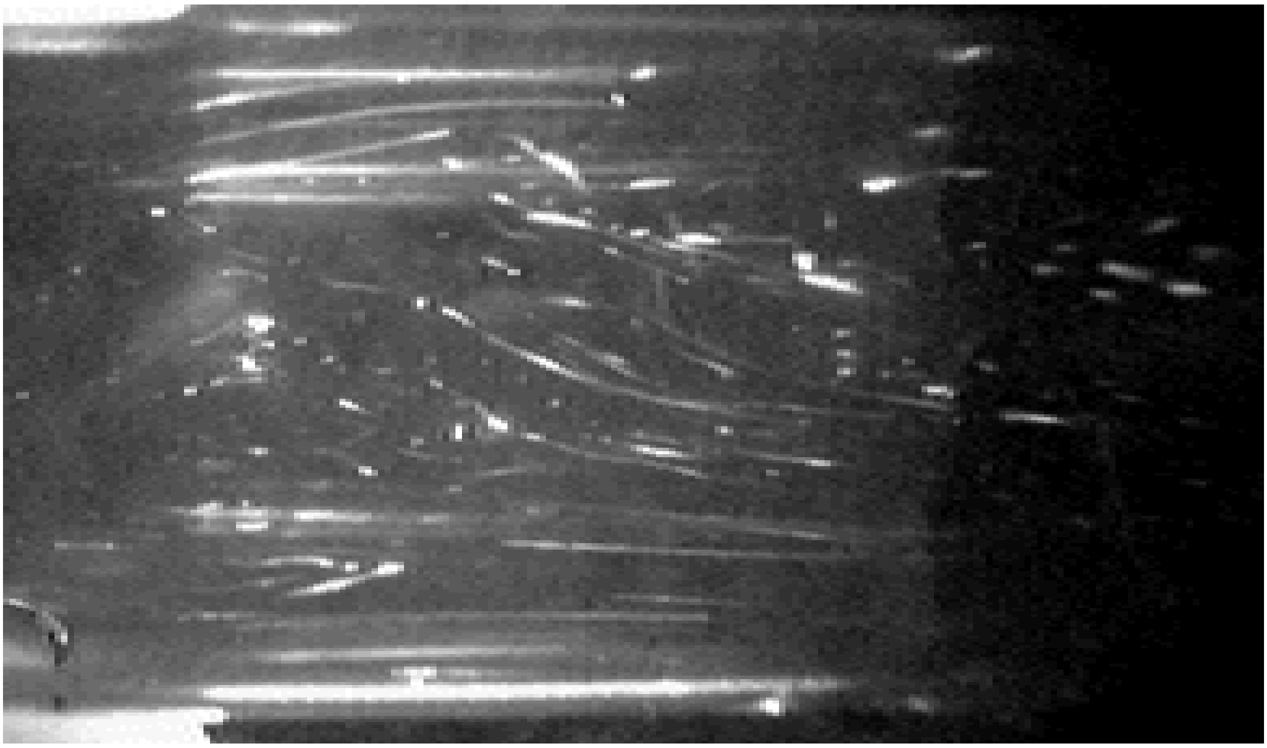


Figure 9. Image of vortex for flow of 5.0 m^3/h (t=0.166s).

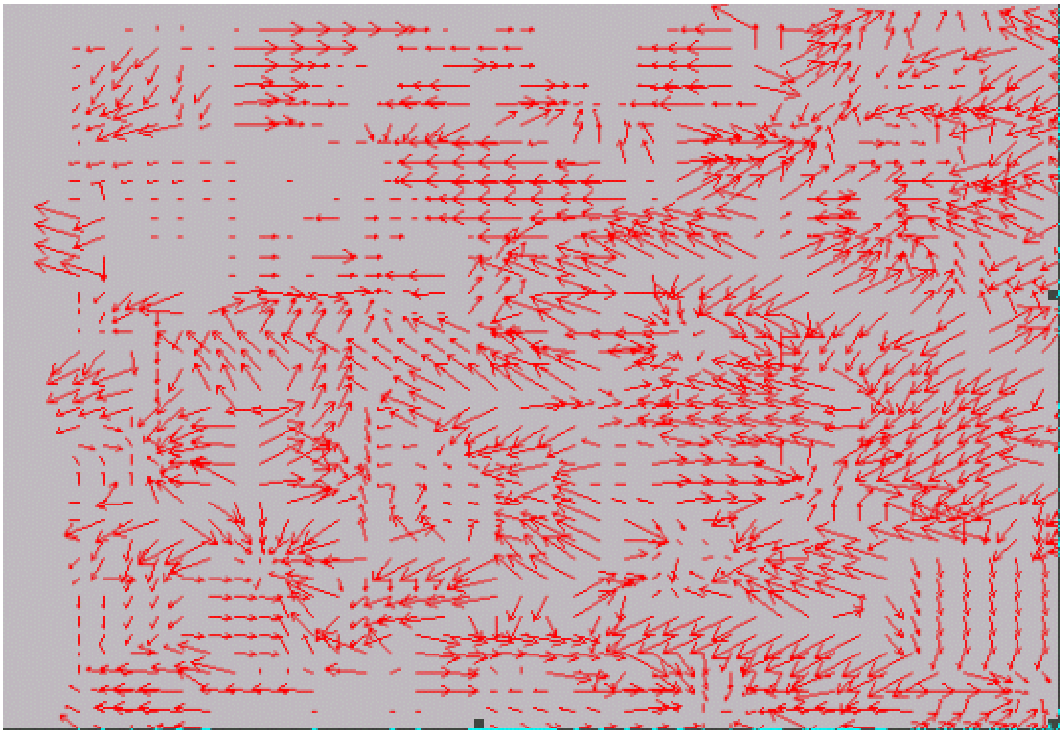


Figure 10. Crossed correlation of the images from the Figs. (8) and (9).

For obtaining of the velocities vectors were used the following parameters in the PIV program (Almeida, 1997): 50 vectors in the horizontal direction; 50 vectors in the vertical direction; base region of 20 pixels x 20 pixels; search region of 40 pixels x 40 pixels; Δt of 0.1666 s; calibration factor of 2.5 mm/ pixel; minimum correlation coefficient of 0.9 and vectors scale of 0.5.

For the determination of the flow through the particle velocity the following analysis is had:

1^{o}) Being considered the velocity composed of two components (two-dimensional stream), the resulting velocity obtained by the method of the crossed correlation is of 0.000212 m/s, corresponding to a flow of 2.16 m^3/h.

2^{o}) Considering the third component of the velocity, the resulting obtained by the method of the crossed correlation is of 0.000260 m/s, corresponding to a flow of 2.64 m^3/h.

6. Results analysis

Through the termistor installed behind the flat plate was obtained tension variations sufficiently large to accomplish the analysis of these signals, where the main objective of these results was to obtain the period of each cycle.

The largest doubt that appeared in the beginning of this work was to know if the termistor would have enough sensibility for accomplishment of the studies of vortex. It is proven that the termistor assisted the expectations, that it was of registering any existent disturbance behind the obstacle.

The maximum tensions were between 2.10 and 2.15 V and the minimum tensions were between 1.98 and 2.02 V, analyzing for each flow. As the increase of the flow, increases the tension sensibly in relation to the tension of the previous flow, that means that can relate the flow directly with the tension registered by the termistor.

Through the data presented can confirm the presence of a vortex wake in all the analyzed flows, with the obstacle whose form is of a plane plate with her respective thickness, and with the proposed angle in that the study (45^{o}).

Through the films we proved, as it was waited, that the vortex are formed starting from the obstacle positioned perpendicular to the stream, and they are distributed as acted in the Figs. (8) and (9). Through the method of crossed correlation it can also be observed, different velocities of the particle, due to the vortex, according to Fig. (10).

The resultants of the vectors speed indicate the different directions, senses and modules, that characterize the different velocities and the path of the particles. This means that the vortex are formed by boundary-layers of velocities; in other words, the velocity increases as the particle approaches the center of the vortex. It can also be observed certain convergences of vectors for certain points, characterizing a third plan of existence of vortex, for what was not waited in the beginning of this work.

The uncertainty of the experiment was calculated according BIPM, 1997. The uncertainty from the stream flow (Q) is of the kind B, being from ±1% of the bottom of scale (±1% of 10 m^3/h) (OMEL, 2002). The evaluations of the uncertainty of the variables period (T) and frequency of the vortex (f) they were calculated by the approach kind A and are based in statistical approaches, from distributions around a medium one. The uncertainty considered in the method of particles images velocimetry were related at the factor of scale (6.70%); coordinated spatial (12.03%); and quantity from the image (6.66%), resulting for the components from the velocity a maxim uncertainty of 14.86%.

7. Conclusions

The methodology adopted for the accomplishment of the experiments of the study and calibration of the vortex flow meter is valid for the determination of the frequency in that happen the vortex, with which can be arrived to the calibration factor. Through the calibration curve it is obtained the flow of a liquid in a certain piping. This flow meter can be used for liquids, gases and steams, being recommended the study of this flow meter for gases and steams, as well as it was done in this work for water.

The main reason for which is studied this type of flow meter, is not the form or direction of the vortex, but, the frequency with that they appear to go by a certain obstacle. Then a device was created to register that frequency of appearance of the vortex, that is the tension variation (ddp) in a certain time.

The experiment was shown of easy use, however it is necessary great demand of appropriate equipments, as microcomputers of great processing speeds, plate of image acquisition, software, camera of digital video, tubes of acrylic to make possible the visualization of the vortex to the they pass the flat plate, an illumination control through laser and a flow meter type calibrated rotameter.

Although, in this experiment, the need of the use of so many sophisticated and expensive equipments it is fundamental, in practice this flow meter becomes very simple and " cheap ", needing an obstacle basically and a termistor adapted on it, a microcomputer of great processing speeds and a software. It can also have the flow control in many other points simultaneously; it is enough to add a sensor and an obstacle for each point that one wants to control the flow.

The method of Particles Images Velocimetry (PIV) allows the vortex visualization, demonstrating the theoretical beginning of its creation when a fluid is obstructed by an object, in the case the flat plate.

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