23rdABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

CHARACTERIZATION AND VALIDATION OF A VERTICAL WATER TUNNEL FOR STUDIES IN LOW REYNOLDS NUMBERS

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Abstract. *The present work describes the assembling process and characterization of the flow in a bench designed by the Fluid Dynamics Metrology Division from the Brazilian National Institute of Metrology – Inmetro –, to study the flow around submerged bodies. The apparatus is a vertical water tunnel in which a steady flow in low Reynolds number (Re) up to 5540 can be run. The operating limits of the system were identified and the flow characterization was performed without a model inserted in the test section. The velocity field was acquired using the optical technique Particle Image Velocimetry (PIV) and it was found that at the test section entrance the velocity profile is uniform as expected. After that, in order to validate the apparatus applicability, the flow around a small sphere was analyzed and the results were compared with available data in the literature. This work discusses metrological aspects which must be considered when using the bench in order to ensure reliability of the results.*

Keywords: *vertical water tunnel, PIV, low Reynolds number, flow around sphere*

1. INTRODUCTION

Nowadays, with the advancement and diffusion of new technologies, optical measurement techniques and fluid flow visualization have been widely used, mainly by scientific communities as important support tools in studies where fluid flow is involved. Fluid flow is present in a large variety of everyday situations; a deep knowledge of the flow behavior can strongly impact on decisions concerning themes such as environment, nature, economy, among others.

The reliability of the measurement results, when characterizing a fluid flow, depends on the methodologies and measurement methods employed, since they are related to the complexity of the flow to be investigated. The goal of the present study is to characterize the fluid flow in a recently assembled vertical water tunnel at the National Metrology Institute from Brazil (Inmetro). After identifying the limits of applicability of this bench, an investigation of the flow around a smooth sphere allowed a qualitative validation. One reference study that exemplifies the importance of knowledge of the fluid flow behavior is Farias, *et al*., (2014), which shows the characterization of a wind tunnel in order to define how the velocity profile develops along the tunnel.

There are many scientific studies dealing with the phenomena which occur around submerged bodies, for providing aerodynamics or hydrodynamics performance improvements. For example, Przadka, *et al*., (2008) used the PIV system to investigate the behavior of the wake area of a sphere at Reynolds numbers between 250 and 310, using titanium dioxide as tracer particles. The recirculation effects in the wake were analyzed and the results showed that the nucleus of the recirculation region is elliptically shaped, with a strong interaction with vortices in the region of symmetry. Wu & Faeth (1993) also made a deep analysis on the wake in the downstream of a sphere, in which it was observed different behavior on the form of wake for different Reynolds numbers.

2. THE VERTICAL WATER TUNNEL

2.1 Assembly

The vertical water tunnel was built to allow hydrodynamic analysis around submerged bodies. The main pre-established metrological requirements, which were the basis for parameters and design definition, were: flow stability, ease of operation handling and repeatability of the measurement results. The starting point for this work was the assembly of a steel structure, with dimensions of 1.36 m length, 1.22 m width and 2.30 m height, to the support the sections that compose the water tunnel. This structure has also vibration damping feet to avoid vibration transfer from the neighborhood to the bench and its instrumentation.

The overflow section, equipped with a honeycomb made of alveolar polycarbonate sheet (60 cm x 60 cm) and three stainless steel screens, was constructed in polypropylene. Downstream the conditioner region there is the first contraction section, made of fiberglass, with areas ratio of 9. The next section is the visualization window, built in colorless polycarbonate with polished internal joints to minimize roughness, with a square section of 20 cm in side. At the bottom region there is another contraction, followed by a honeycomb made of small plastic straws and stainless steel screen. Figure 1 depicts schematically the water tunnel assembly.

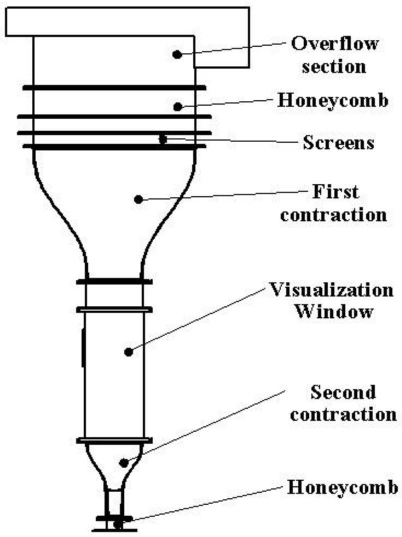

Figure 1.Vertical water tunnel sections

In order to reach the necessary of flow rate range, two screw pumps were connected to the bench, through a PVC rigid pipe. The tubing circuit has three different diameters (20 mm, 32 mm and 60 mm). The rotation frequency of both pumps (models NM015 -- 120 to 500 L/h -- and NM031 -- 1000 to 4000 L/h --Nemo, Netzsch®) are controlled by two frequency inverters (Weg®, model 08 CFW). The outlet of both pumps was divided in two sections: the first one has a bypass, which returns the fluid to a chamber (see Figure 2) and the second one conducts the fluid to an electromagnetic flow meter (Conaut®) before returning to the tunnel entrance.

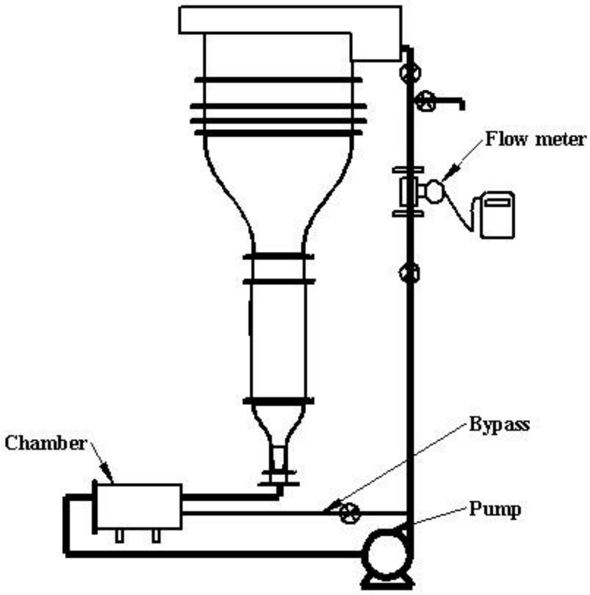

Figure 2. Operating scheme of the vertical water tunnel

2.2 Operation

The apparatus in question was designed to carry out experiments with water and to work at low Reynolds number (up to 5540). In the measuring section (visualization window), there is a little hole at one side, with sealing device, that allows to introduce rigid bodies to be studied.

The apparatus works in a closed circuit containing the two screw pumps aforementioned. The flow direction occurs from the top to bottom, and the PVC piping starts at the bottom of the water tunnel by a long curve, directing the flow to the chamber, which has the function of reducing the turbulence. After the chamber, the water continues to flow to the suction of the pumps, which have their working pressure monitored by an analogical manometer. In case of overload of the pumps, the bypass system may be kept open to relieve the pressure on pump, redirecting the flow to the chamber. A simplified schematic of the hydraulic circuit of the tunnel is shown in Fig. 2.

In order to evaluate the mean velocity inside the visualization window and Reynolds number limits, when the vertical water tunnel is operated at the lowest and the highest flow rates (120 L/h and 4000 L/h, respectively), the following formula is used:

$$V = \frac{Q}{A} \tag{1}$$

Where V is the average evaluated velocity, Q is the flow rate measured in the flow meter and A is the visualization window cross section area. The Reynolds number could also be calculated, by the formula:

$$Re = \frac{\rho V D}{\mu} \tag{2}$$

Where Re is the Reynolds number, V is the average velocity, ρ is the water density, μ is the water dynamic viscosity and D is the section diameter. Since the visualization window section is square, it is necessary to use the hydraulic diameter for D (for a square duct, the hydraulic diameter is the value of one side). The results are shown in Tab. 1.

Table 1.Variation limits of velocity and Reynolds Number according to the flow rates

Flow rate (L/h)	Mean velocity (m/s)	Reynolds number
120	0.0008	166
4000	0.0278	5539

3. CHARACTERIZATION

Initially, the tunnel was tested for leaks and influence of constructive conditions of bolted joints before it was ready to operate.

The vertical water tunnel was assembled for studies around submerged bodies. Therefore, the flow behavior and velocity profile inside the transparent window must be evaluated, before inserting any bodies in the visualization window. So, to characterize the visualization window, an optical technique (PIV) was applied and some flow rates were chosen to carry out the experiments.

3.1 Particle Image Velocimetry

The Particle Image Velocimetry (PIV) is an optical measurement technique to identify the flow velocity field. This technique consists of two planes of synchronized pulsing lasers which focus on the region of interest. The flow must contain light reflecting tracer particles, with average size ranging from 20 to 50 microns, with density close to the fluid in which they are inserted (so it can be assumed that they acquire the same speed of the fluid and, therefore, follow the flow). During the laser pulse time interval, the light reflected by the tracer particles is captured by high-resolution cameras. A series of high frequency consecutive images is acquired by CCD – Charged Couplings Devices - cameras that are capable of capturing more than 30 frames per second (Raffel, *et al.*, 2007). Through the comparison between the probable positions of tracer particles on each image, advanced mathematical tools, such as cross correlation, evaluates the displacement between two consecutive images. By knowing the time interval between these images, the magnitude and direction of the velocity vector of a group of particles can be estimated, allowing one to map the flow velocity field. The use of particle image velocimetry has some advantages compared to other fluid flow measurement techniques. It is considered a non-intrusive technique, although tracer particles are added to the flow, interference in the flow can be negligible and this technique allows to obtain the velocity profile in a whole region.

3.2 Experimental Setup

The PIV system used in the experiments was the Dantec Dynamics SA, which includes a laser "Laser 2x200 DualPower 200 -15 mJ, 15 Hz, 532 nm" type Nd-YAG (neodymium-doped yttrium aluminum garnet; Nd: $Y_3Al_5O_{12}$), and a camera "FlowSense 4M Mk2". The 2D PIV system (which uses only one camera) was chosen to characterize the vertical water tunnel. A steel support was assembled for holding the camera, which was aligned to the visualization window. The laser was placed so that the light sheet stay positioned perpendicularly to the camera view, as shown in the Fig. 3.

As the laser sheet of the system PIV does not have enough thickness to illuminate all the volume of the visualization window at once, the visualization window was divided into different positions to characterize the flow at different depths. As can be seen in the Fig. 3(a), the window was divided in two regions, A and B. For region A, the laser sheet was positioned in seven different positions, spaced by 2.5 cm from each other, wherein the center of the window is at 10 cm. For region B, only three plane positions were analyzed: 10 cm, 2.5 cm and 17.5 cm, respectively. Figure 3(b) illustrates the window division and the Fig. 4 shows the PIV system installed and aligned in the bench.

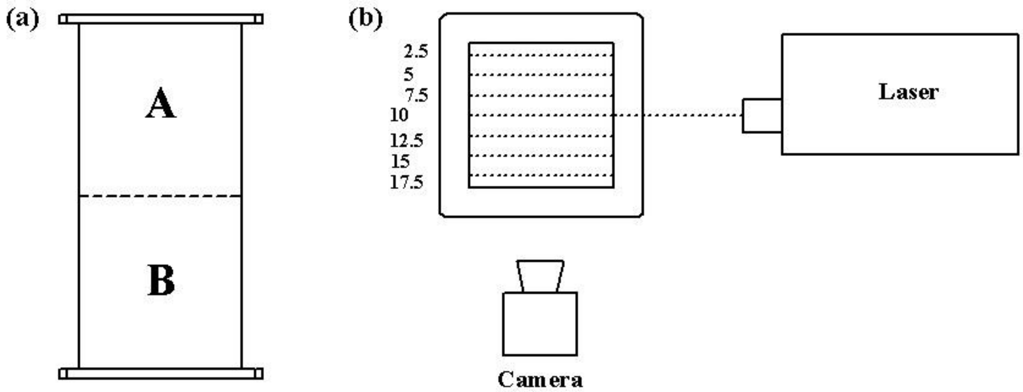

Figure 3. (a) Frontal view of visualization window divided on regions A and B. (b) Top view of visualization window and different position of laser sheets (dimensions in cm)

Figure 4. Vertical water tunnel with PIV system aligned

For all experiments it was chosen three different flow rates to evaluate how the flow would develop inside the tunnel. To estimate the mean velocity and the Reynolds number in the visualization window for characterization, Eq. (1) and Eq. (2) were applied and results are shown in Tab. 2.

Table 2. Selected flow rates for the characterization, with velocity and Reynolds number calculated according to the theory

Flow rate (L/h)	Mean velocity (m/s)	Reynolds number
500	0.0035	694
800	0.0056	1111
1100	0.0076	1528

The laser sheet was positioned at each position by using a motorized traverse. To calibrate the 2D PIV system, a ruler was inserted in the visualization window and the camera captured one single image, allowing the software to compare this image with the real scale. After the alignment and the calibration of the system, particles of Rhodamine B with size between 20 and 50 micrometers from an aqueous suspension of concentration 100 g / 400 mL, were used to seed the fluid.

3.3 Validation

After the characterization was performed, an experiment was conducted using a sphere. This experiment was conducted to determine if the water flow behavior inside the visualization window is applicable to studies of flow around submerged bodies.

The model used was a small transparent smooth hollow sphere (diameter of 2.88 cm), made of high density polyethylene. A thin rod was employed to support the sphere on the visualization window. Both sphere and thin rod were painted in black to avoid the laser light reflection to damage the camera. The assembly described above can be seen in Fig. 5 below.

Figure 5. Sphere used to validate the vertical water tunnel

Eq. (2) was applied to estimate the Reynolds number; however, since the study was carried out with a sphere, it is necessary to use the parameter D on the equation as the diameter of the sphere instead of the transversal section area. The results are shown in the Tab. 3.

Table 3. Calculated Reynolds number with the sphere inside the visualization window

Flow rate (L/h)	Reynolds number for sphere
500	100
800	160
1100	220

4. RESULTS AND DISCUSSSION

Figure 6 show the velocity vector field inside the visualization window, resulting from an average of 2000 images. The presented results were acquired at the positions of 2.5, 7.5 and 15 cm at the flow rates of 500, 800 and 1100 L/h, respectively. The results obtained for other positions are very similar to the ones presented here.

The vertical scale represents the height of visualization window and the horizontal represents the width. The center of the window is approximately at x = 120 mm and y = 100 mm. The positive vertical axis is pointing up.

For the flow rate of 500 L/h in all positions it can be observed that the velocity profile matches the profile of a laminar flow, as expected from the literature. In other words, the result approaches to a parabolic profile. It occurs because the velocity is near zero at points close to the wall and increases when it get closer to the plane center.

As expected, the flow profile in the position of 2.5 cm is influenced by the walls, showing that higher velocity is concentrated in the middle of the window. Another interesting observation is about the position of 7.5 cm and flow rate of 800 L/h, where it can be seen a little curvature in the left side, which may occur by the non-uniform overflow region in the top of the vertical water tunnel. It could also be noted that there is a wide region of high velocity in the position of 7.5 cm on the flow rate of 1100 L/h, caused by the approach of this position with to the center of visualization window.

500 L/h	800 L/h	1100 L/h

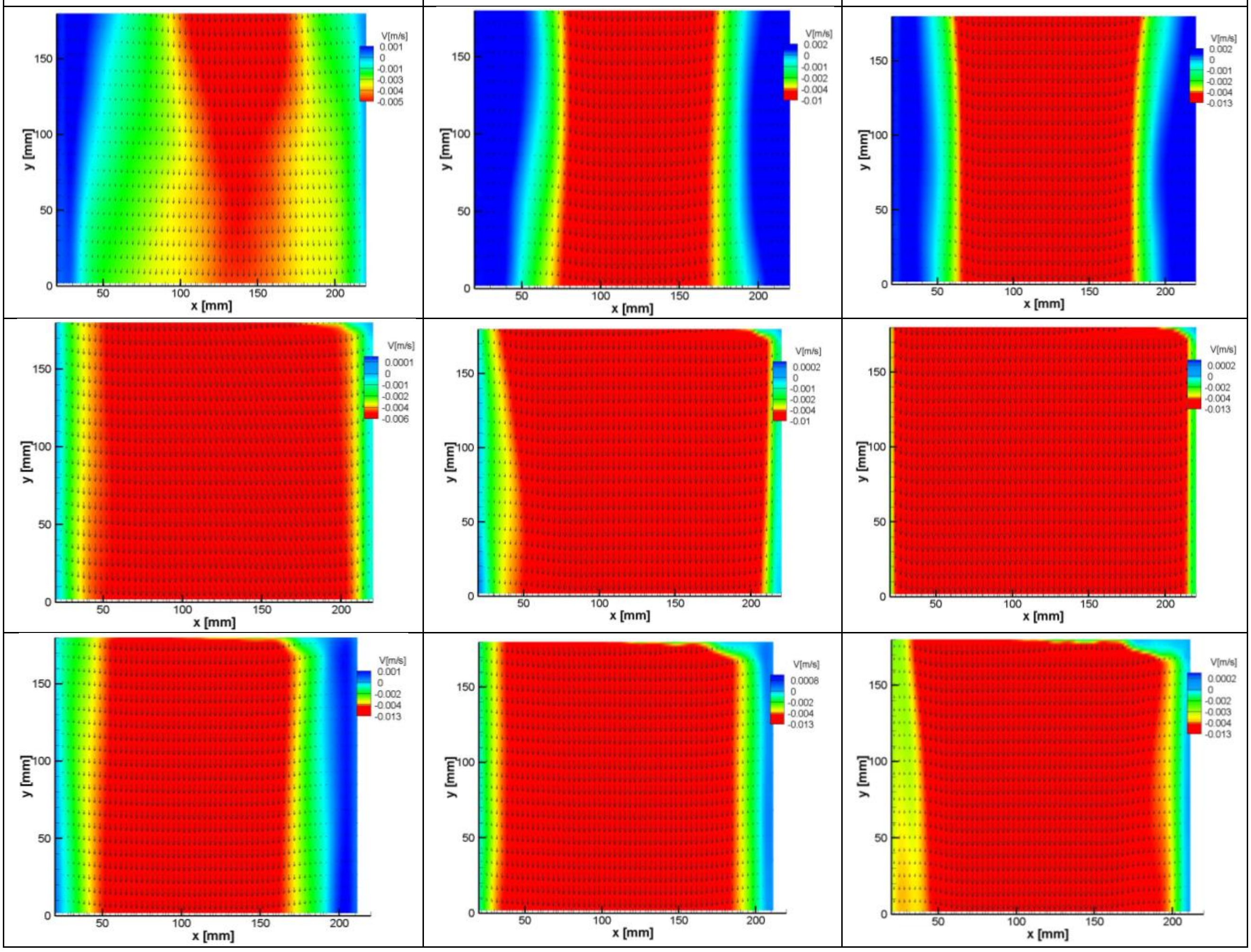

Figure 6. Velocity vector field in the visualization window for different flow rates in region A. The first, second and third rows represents the positions of 2.5 cm, 7.5 cm and 15 cm, respectively.

The result of the validation using the sphere is presented (Fig. 7) for the position of 7.5 cm in the visualization window and 1100 L/h of flow rate. The region between y = 150 and 170 mm, on the left side of the sphere, should not be taken in account since it is a shadow region. It can be noticed that the velocity field is uniform in the upstream of the sphere (white region, with absence of vectors). When approaching the upper body, the flow is split due to the impenetrability condition. The fluid has an abrupt reduction of speed and starts to contour the sphere.

It is supposed that the blue region (speed about 0.0002 m/s) near the sphere are in the boundary layer region just for presenting resulting vectors from low magnitude. It can be seen in Fig. 7, the downstream region of recirculation flow. This is the beginning of the wake formation, in which two large vortices are formed with a central symmetry line ($x \approx 116$ mm) where the velocity vectors have opposite direction to the main flow. This model resembles the cores of vortices shown in the work of Przadka, *et al*., (2008).

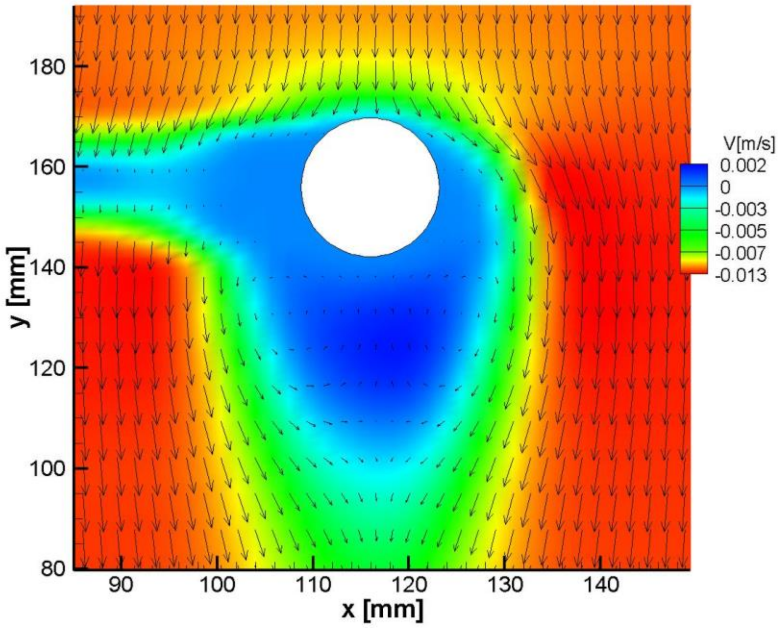

Figure 7. Velocity vector field around the sphere

5. CONCLUSIONS

The present work contributed to the development of a facility which was designed to investigate the flow behavior around bluff bodies for supporting the researches on fluid dynamics at Inmetro. Metrological requirements were applied in all steps of the experimental work, from the assembling stage to the validation of the bench.

The use of PIV allowed to characterize the velocity vector field inside the visualization window and around the sphere, resulting in satisfactory results when compared to the literature.

The uncertainties analyses related to the flow field mapping are not presented in this work due to its complexity. It is being deeply investigated, as the uncertainty analysis for fluid flow imaging is a research line which is being developed in the Fluid Dynamics Metrology Division (Dinam/Inmetro). Nevertheless, during the experiments, all possible errors sources, including errors related to the imaging acquisition system, were identified and minimized.

This work allowed the Fluid Dynamics Metrology Division to have available a facility for supporting the researches related to the Scientific Metrology activities in fluid dynamics area.

6. ACKNOWLEDGEMENTS

The authors are grateful to CNPq, FAPERJ, FINEP, PETROBRAS and INMETRO for their support and sponsorship which have become possible the development of this research.

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