REBUILDING AND TESTING A VERTICAL HYDRODYNAMIC TUNNEL

Rodrigo Augusto Bassan, bassan@dem.feis.unesp.
Sérgio Said Mansur, mansur@dem.feis.unesp.br
Edson Del Rio Vieira, delrio@dem.feis.unesp.br

Unesp- Ilha Solteira – Faculdade de Engenharia de Ilha Solteira Av. Brasil Centro, 56 15385 000 Ilha Solteira, SP - Brazil

Abstract. *Hydrodynamic tunnels are widely employed in several fluid dynamics laboratories around the world to simulate flow around immersed bodies at moderate Reynolds numbers and low free-stream turbulence levels. In 1994 a vertical hydrodynamic tunnel with 146 × 146 mm of test section has been built in the workshops of the Mechanical Engineering Department of UNESP at Ilha Solteira and installed in the Flow Visualization Laboratory providing effective support to experimental studies concerning with flow past bluff bodies. That facility has run up to 2003, when it has been seriously damaged by a large fire destroying much of the laboratory. In the subsequent years a hard restoration effort has been made to put back the system into operation. During the execution of that work, several modifications have been introduced in the original plant design to improve the run time in blow down operation mode and to further reduce the turbulence level in continuous mode operation. After reconstruction, flow visualization and local velocity measurements have been carried out to check the hydraulic performance afforded by the new system. In this paper the main steps of the repair and test process are reported and discussed. In order to illustrate the potential of this facility as a tool for fluid flow research, qualitave and quantitative results concerning with the flow over a flat plate equiped with square protuberance are presented.*

Keywords*: Vertical hydrodynamic tunnel, Flow visualization, Hot film anemometry, Turbulence.*

1. INTRODUCTION

In applied fluid dynamics – and particularly in aerodynamics – the optimized design of machinery and equipment depends on the knowledge acquired on the flow features in its different components. In such flows, complicated mechanisms are almost always present whose complete nature cannot be revealed exclusively by means of punctual measurements, as it is usually performed with the help of hot-wire or laser Doppler anemometry. On the other hand, flow visualization represents an efficient tool for qualitative analysis of fluid motion, providing topological issues about flow fields. In other words, while local measurements in general supply only quantitative information – or hard data – flow visualization walks in the opposite way, contributing to physical interpretation of results. Indeed, both techniques can be considered complementary to each other and their simultaneous use can strongly contribute to the study of complex flows. An interesting example of that association is presented in the work of Freymuth *et al*. (1983), where flow visualization and hot-wire anemometry have been allied to study the accelerating flow around an airfoil.

Although a hydrodynamic tunnel uses water instead of air as working fluid, the design of such an apparatus is conceptually very close with a low speed wind tunnel. Nevertheless, the former is more favorable to implementation of flow visualization techniques than the latter. In an aqueous medium, pathlines, streamlines, streaklines, or timelines can easily became visible by using solid particles, liquid dye filaments, or gaseous bubbles suspended in the water. A suitable lighting generates good images with striking results. Many reviews in flow visualization in water have been presented by Clayton & Massey (1967), Werlé (1973), Freymuth (1993) and Vieira & Mansur (2004). Besides, hydrodynamic tunnels allow the testing of high Reynolds numbers without compressibility effects. For these reasons, hydrodynamic tunnels have been widely utilized in several fluid dynamics laboratories around the world. Erickson (1981) compiles around 200 different plants which systematically employ hydrodynamic tunnels in fluid dynamics and turbulence research. According to Robertson (1954), a dozen large water tunnels with closed circuit and closed horizontal working section was operating in USA in 1954. Many of these facilities were built to cavitation studies or flow around hydrofoils and airfoils. Consequently, flow visualization techniques were extensively utilized. Some of those facilities gained notoriety due to their incontestable contribution to the fluid mechanics sciences progress.

Closed circuit hydrodynamic tunnels, like the well known high speed hydrodynamic tunnel of CALTEC, in Pasadena, have been exhaustively used to solve aeronautical problems, even using water as working fluid. This tunnel has a closed test section of 457 × 483 mm and operates since 1941 powered by an electrical motor of 263 kW. To keep dynamic similarity, it often must operate at speeds close to 30 m/s. A second important closed circuit water tunnel, with free surface test section of 508 × 508 mm, was also installed in CALTEC and has begun its operation in 1947. Detailed information about these devices are available in the work of Ward (1976).

The NAE water tunnel facility belonging to National Research Council of Canada, in Montreal, was designed and built in Göttingen, in 1939, by the Aerodynamische Versuchanstalt and it has rendered great service to the German aircraft industry during World War II. After the war, this facility was dismantled and assembled permanently in the Low Speed Aerodynamic Laboratory, in Canada. Since then, several modernizations programs have took place to improve the performance of this tunnel and extend its operating envelope. With a working section of 305 × 330 mm and with a free stream velocity up to 1.5 m/s, this equipment is extensively employed for flow visualization purposes. According to Dobrodzicki (1982), bluff bodies and vehicles of different shapes and sizes have been experimentally studied in that installation. It is interesting to comment that exact copies of such a facility have been reproduced by other laboratories in different countries.

In many situations, tests must be conducted with large models and very low Reynolds numbers in order to identify fine details of the flow. In these cases, low speeds are required, which causes numerous problems associated to flow instabilities. The use of vertical hydrodynamic tunnels operating in blow-down mode is particularly suitable to this purpose. Indeed, blow-down operation mode in general produces a flow with flat velocity profiles, thin boundary layers, and low residual turbulence levels, as discussed by Vogt *et al*. (1983). It is important to emphasize that tests at higher Reynolds number may also be conducted in hydrodynamic tunnels since the kinematic viscosity of water (viscosity to density ratio) is about 1/10 of that of the air at the same temperature. Hence, the Reynolds number obtained is 10 times greater in water than in air to the same scale and speed. However, this value will still be lower than that achievable in large wind tunnels. Obviously, this limitation must be considered in the interpretation of experimental results.

Several laboratories employ vertical water tunnels. For example, the Masserschmitt-Bölkow-Blohm GMBH facility, in Munich, has a test section of 300 × 300 mm and allow a maximum velocity of 1.4 m/s in blown down operation and 0.75 m/s in continuum operation mode, Stied (1981). The ONERA laboratories, in France, utilize water tunnels in aeronautical applications since the fifties years. Three open circuit hydrodynamic tunnels with closed vertical test sections have been utilized in several tests utilizing a variety of models. Images of vortex flow on delta wings captured by Henry Werlé have been divulged in several publications, Mueller (1983). Many other Werlé's publications show the advantages of vertical water tunnel for flow visualization applications. Like the Göttingen's tunnel, the design of ONERA's vertical tunnels have been copied by many laboratories, with some modifications and adaptations. The water tunnel of USAF/WAL, with a test section of 146 × 146 × 457 mm, has been built as a pilot facility in order to develop components for a much large tunnel, and represents a good example of this.

In 1993, a vertical water tunnel operating by gravitation action was built in the workshops of the Mechanical Engineering Department of UNESP at Ilha Solteira and installed in the Flow Visualization Laboratory providing effective support to experimental studies concerning with flow past bluff bodies.. The initial design was based on the USAF/WAL pilot tunnel. Rapidly, this installation shows its large potential for research of flow around bluff bodies in relatively low Reynolds number. Several experiments have been performed since then, showing the wake of square and rectangular cylinder bodies with Reynolds number up to 1000 – Lindquist (2000), Gonçalves (2001). During many years beautiful visualized images have been obtained in experimental class with very motivated students using liquid dye injection. The works of Pelegrini & Vieira (2003), Woiski & Vieira (2001) and Lindquist *et al*. (1999) report the use of this hydrodynamic vertical tunnel to produce fluid dynamics experiments in undergraduate activities.

Unfortunately, in 2003, a large fire caused many losses on the Flow Visualization Laboratory and the total destruction of the vertical hydrodynamic tunnel. The built of a new hydrodynamic tunnel with several modifications and adaptations took place. Modifications in the original plant have been executed in order to improve the hydraulic performance of this apparatus and extend its operational envelope. In this present work a detailed description of the new vertical hydrodynamic tunnel is carried out and qualitative and quantitative results concerning with the flow over a flat plate equipped with square protuberance are presented, in order to illustrate the potential of this facility as a tool for fluid flow research.

2. EXPERIMENTAL APPARATUS

2.1. The original pilot hydrodynamic tunnel

In 1993 was start up on Flow Visualization Laboratory a first vertical low turbulence pilot hydrodynamic tunnel with 146 × 146 × 500 mm square cross test section. This tunnel design was made integrally based in the facility of the US Air Force Wright Aeronautical Laboratory facility, described in Erickson (1981) and also Mueller (1983). Initially, the tunnel, with only 3.2 m of height, operated with a free stream velocity range of 30 to 300 mm/s with a turbulence intensity level less than 1 % in blown-down mode. This device shows several structural vibration modes. In a vertical hydrodynamic tunnel design, structure should be careful calculated in order to minimize all problems due to vibration. The turbulence measurement includes undesired structural vibrations effects. The probe support vibration, due to vortex shedding phenomena, also provokes serious interference in turbulence measurement. Of course, in a hot wire/film anemometer, probe vibration mistakes the velocity fluctuation signal. An arduous work has been necessary to isolate undesirable vibration effects in turbulence measuring. The free flow velocity has been determined utilizing a 3" Yokogawa electromagnetic flowmeter ADMAG AE208MG. The uncertainty in the free flow velocity determination is less ±3%, in the small velocity - more adverse case -, producing a maximum uncertain less than 5% for Reynolds number. Initially, the still image capture has been carried out utilizing a Pentax K 1 000 35 mm camera and Kodak Tmax black & white chemical roll film. Video images capture also has been realized using an old analogical SuperVHS system (with 400 lines of resolution) and a Commodore 64 computer utilizing a Motorolla 68000 chip for digital processing. First results in flow visualization digital image processing (determination of the vortex length in a von Kármán vortex street produced by a circular cylinder) have been published by Vieira *et al.* (1996). For further information on the water tunnel preliminary characteristics, reference may be made to Mansur *et al*. (1996). Since this time, several modifications have been carried out extending its operational envelope up to 1.5 m/s with a relative turbulence level less than 1.1 %. Obviously, the more impacting improving is relative to digital image capture with high resolution digital still cameras and the employ of full HD video cameras.

2.2. The new hydrodynamic tunnel

The new tunnel presents also a 146 × 146 × 500 mm test section with octagonal cross section but with more than 6 m of height, representing a sensible increase of the total water mass stocked internal the tunnel. The increase of the water mass internal the tunnel permitted to extend the blow-down run time of operation several times. Obviously, the increase in the tunnel size forced a new design of all tunnel components. In a water tunnel all walls and parts need to be not flexible and enough rigid in order to no provoke flow oscillations. Fig. 1 depicts a sketch of the new vertical hydrodynamic tunnel showing the principal parts. An external subterraneous water tank (LR) with a capacity of 9.8 m^3, careful protected against dust and possible contaminants, provides the water for the experiments. In the old tunnel the lower reservoir was installed internal the laboratory, and frequently occurred the water contamination forcing frequent experiment interruption. The construction of an external sealed tank with large dimensions shows a good solution in order to remain clear the water along the experiments avoid frequent water changes. A membrane filter and a small pump (both no showed in Fig. 1) remove up to 10µm particles of the water. The water pump (PP) is a KSB pump model Megachem 32-200 type of 5,5 KW of power all constructed in stainless steel to fit out in a level below of the reservoir level. In the old facility, the water pump was positioned above reservoir level and frequently the restart of the pump was difficult because the air bubble formation inside the pump. Air ingestion occurs when the reservoir presents limited dimensions because the vortex formation in the tube entrance if the flow rate is high or due to fall in the check valve. The pump installation bellow the reservoir level eliminates the check valve. The pump is installed in a subterraneous power-house, external the laboratory room, careful to fit up on vibration isolated supports in order to minimize the vibration transmission to the tunnel. A 75 mm nominal diameter PVC tube with 5 mm of wall thickness positioned in the exhaust of the pump discharge the flow to the upper of the tunnel. All valves are made in stainless steel except to valve #3. All valves showed in Fig. 1 are of manual operating. An automatic sphere valve pneumatically powered and electrically driver, no showed in Fig. 1, should be mounted in order to remote control the flow. Use of sphere valve also permits to control the flow rate adequately. Unfortunately, sphere and butterfly valves utilized in chemical industry applications are expensive because the rigid security norms. The valve #2, is a butterfly valve installed in order to manually control the flow inlet the tunnel. This valve type mounted after the pump in a high pressure line and operated only by one quarter of lap need be slowly moved in order to avoid the sudden flow interruption causing undesirable hydraulic ham effect.

The tunnel stagnation section (the upper part of the tunnel) is composed by an upper reservoir (UR), an upper contraction (UC), screens (S), honeycombs (SH) and a discharge diffuser. Discharge diffuser, contraction and screens are needed in order to introduce the flow field with a minimal turbulence in stagnation section. The work of Vogt (1983) discusses the problem due to residual turbulence internal the stagnation section in vertical hydrodynamic tunnel. The honeycombs with hexagonal cells of 6 mm and 280 mm of thickness are made of fine sheet of alloy 3003 aluminium. The discharge diffuser shows 614 small holes of 3 mm of diameter proportionally distributed order to delivery uniformly the flow inside the stagnation section producing a minimal perturbation, principally in continuous mode operation.

The maximum water level internal the upper reservoir in controlled by an exhaust PVC pipe of 100 mm nominal diameter. The contraction (LC) has a short length and a contraction ratio of 1:16. The test section (TS) was made of aeronautical aluminium 4050 with windows of optical Plexiglas with 10 mm of thickness. The average velocity at the test section has been determined from the water flow rate measured by an electromagnetic flowmeter (FM). This practice of determination of the average velocity in the test section measuring the downstream bulk flow rate is recommended by several authors, and currently used in many water tunnel facilities. The non-perturbed velocity, upstream the test model has been obtained, in this work, using an AXF100G model *Yokogawa* electromagnetic flow meter mounted downstream the test section. An assessment of the uncertain associated to free stream velocity shown less than 4%, when compared with data obtained by hot film anemometer (*Dantec CTA Streamline*).

The tunnel structural support was entirely constructed of NPS 6 Schedule 40 steel pipes with 150 mm of nominal diameter and 7 mm of wall thickness for a rigid structure with minimal vibrations. Seamless Schedule pipes provide a high quality tube for structural application. The tunnel structure need be to place careful in an adequate foundation bases in order to isolate external vibration conducted by the ground. Fig. 2(a) shows a view image of the tunnel showing the support structure, foundations and several instrumentations and, in fig. 2(b) a detail view of the test section.

The tunnel structural support was entirely constructed of NPS 6 Schedule 40 steel pipes with 150 mm of nominal diameter and 7 mm of wall thickness for a rigid structure with minimal vibrations. Seamless Schedule pipes provide a high quality tube for structural application. The tunnel structure need be to place careful in an adequate foundation

bases in order to isolate external vibration conducted by the ground. Fig. 2(a) shows a view image of the tunnel showing the support structure, foundations and several instrumentations and, in fig. 2(b) a detail view of the test section.

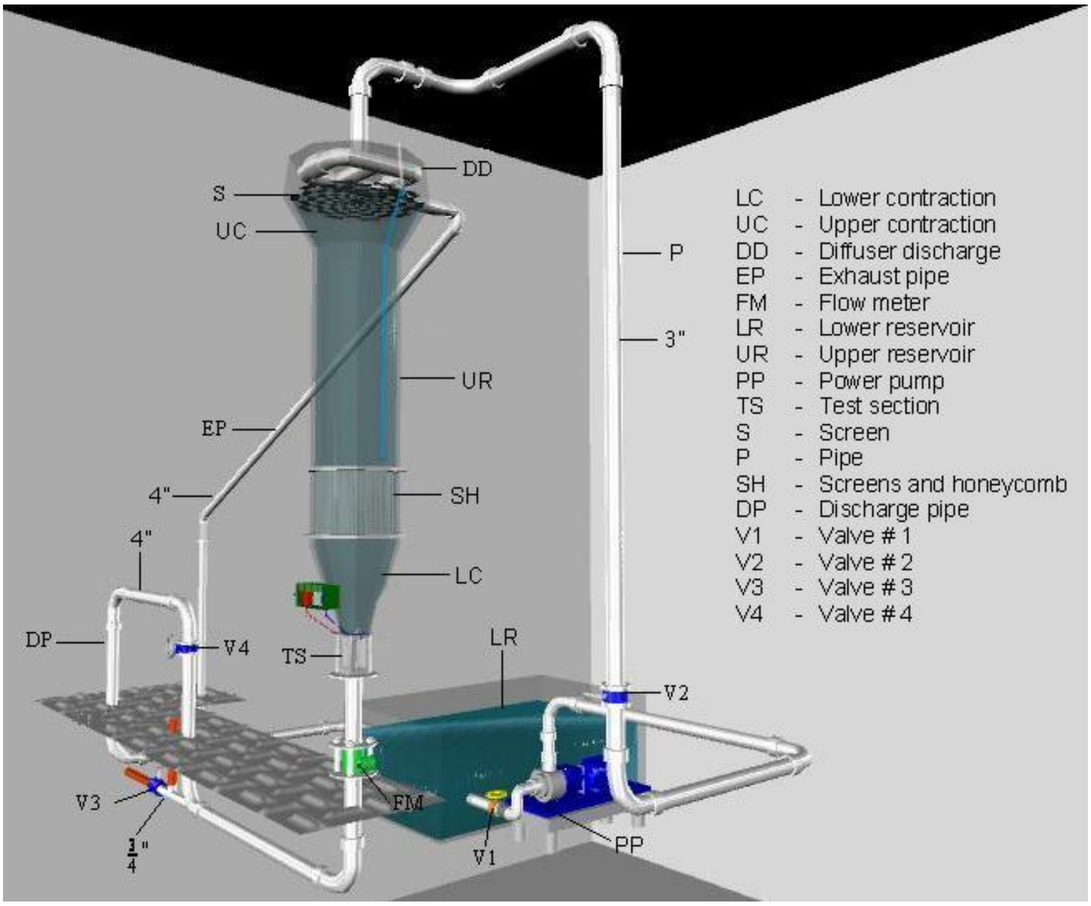
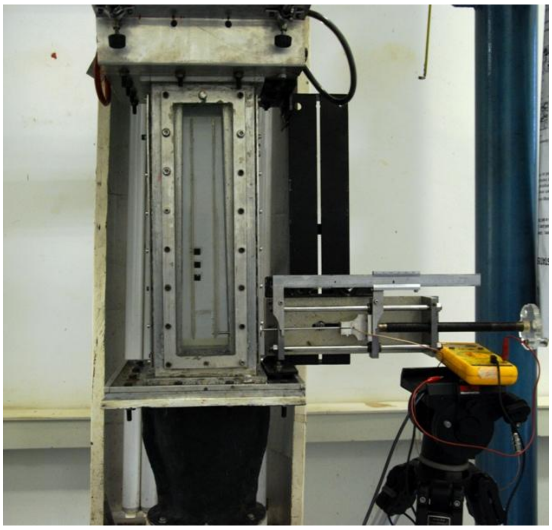


Figure 1. The new vertical hydrodynamic tunnel of the Flow Visualization Laboratory

(a) Panoramic view



(b) Test section

Figure 2. The vertical hydrodynamic tunnel

All parts of tunnel have been made of low water absorption composite material (polyester isophthalic resins and glass fiber) with 8 mm of thickness strengthened with a steel gage in order to provide very strong walls. In a hydrodynamic tunnel, all walls need be sufficiently rigid because small wall oscillations can provoke boundary layer detachment and high level of turbulence. Direct water contact with metallic walls provokes the ions formation generating several chemical reactions in many parts of the tunnel and irreversible damages on expensive hot film probes. In order to minimize the chemical reactions, all the tubes and connections have been made of thermoplastic PVC (Polyvinyl chloride). In order to avoid undesirable vibrations and deformations of the tubes and to support severe operation modes, all tubes present a minimal of 3 mm of wall thickness. All valves and the pump are of stainless steel due to use of carbon steel in water contact generates severe oxidation and water contamination.

The employ of hot film anemometry need to an adequate electrical ground reference. Due to use of electric non conductor plastic composite material in many tunnel parts of the tunnel an adequate electrical ground should be careful made.

A system to remove gaseous dissolved in the work water by suction is positioned in the discharge tube (DP) after the valve of flow control (valve V#4) avoid small bubble formation in the exhaust pipe. Air bubbles in exhaust pipe need be drained because produce undesirable flow rate oscillations.

Boundary layer thickness effect on velocity profile is controlled by divergent walls in the test section showing an adequate solution. Low velocity aerodynamic tunnel also utilizes currently divergent walls in test section in order to remain constant the velocity profile.

In the old facility, the flow image has been illuminated by eight (150 W) *G.E. Photo Flood* tungsten lamps placed in line with the camera and shielded by white velvet-like translucent paper to provide a uniformly diffuse bright background against which the dye patterns were photographed. *Photo Flood* is a low-cost lamp, and supplies white light with relative high color temperature. Unfortunately, *Photo Flood* is an incandescent lamp that emits a high heat flux, requiring an efficient air-cooling system in order to avoid convection in the experiment. New cold illumination by means of fluorescent lamps with high color temperature but minimal heat emission has been adapted in the new tunnel permitting sharp and well defined images. The use of Rosco color illuminating filter Cinegel#3308 converts daylight fluorescent lamps to 5 500 K and a diffuser Cinegel#3007, a slight filter with less density softens edge and provides a good illumination for still and video image capture.

The average velocity at the test section has been determined from the water flow rate measured by an electromagnetic flowmeter. This practice of determination of the average velocity in the test section measuring the downstream bulk flow rate is recommended by several authors, and currently used in many water tunnel facilities. The non-perturbed velocity, upstream the test model has been obtained, in this work, using a *Yokogawa* electromagnetic flowmeter AXF100G model mounted downstream the test section (FM). The free flow velocity has been determined by measuring the mass flow during the experiments; the uncertainty in the free flow velocity determination is estimated in ±5%.

The water tunnel is operated by gravitational action, and can be used in continuous or blow-down mode. Blow-down mode have been used in this work, due to its lower turbulence level, although in this mode, the free stream mean velocity decreases noticeably with the water level inside the upper reservoir. To account for that, it has been estimated that, for a period up to 15 seconds, the effects of decreasing free stream mean velocity are overshadowed by turbulence.

3. RESULTS

After the tunnel start up begins the hard task of verify the entire flow field in the test section. Is a very lengthy and arduous process to verify the flow homogeneity in the test section and many changes in the facility need be executed in order to obtain the desirable flow.

Results can be divided in qualitative results and quantitative results. Qualitative results are concerning to the capture of flow visualized images of the flow around squares protuberances positioned in tunnel walls in Reynolds numbers up to 1 000. Quantitative test have been made with the help of a hot film anemometer.

3.1. Qualitative results: First image capture of the flow over square cylinders positioned on the walls

First test operating in very low velocity permits to achieve free stream velocity lower than 0.5 mm/s. In this extreme situation, the tunnel Reynolds number (based in a characteristic length of the test section of 0.146 m) is very lower than 10^2. In this high viscous regime due to a very low velocity, a very small velocity oscillation can provokes serious flow perturbations. Operation of the tunnel in very low velocity is a good way to identify several problems relative to flow perturbations. Is important to emphasize, in this flow regime with very small velocity, very small perturbations predispose to amplify producing very large perturbations. Tunnel operation in very small velocities is an optimal condition for testing the flow stability in the test section. In the Fig. 3 is showed an image of the flow over three square cylinders orthogonally positioned in the tunnel wall. The cylinders have 10 mm of side and positioned with 10 mm of space between they and the flow direction is from left to right. The flow regime is very viscous and two layer of dye have been injected in order to visualize the flow. The first dye layer (red color) is first injected and after a few seconds a second layer (black color) has been injected in order to put over the first. The flow characteristic of this regime shows a viscous forces dominating over the inertial forces and a stable flow is observed showing an adequate test facility.

Figure 3. Low velocity test in Re ≅ 5 shows a stable flow in very low velocity.

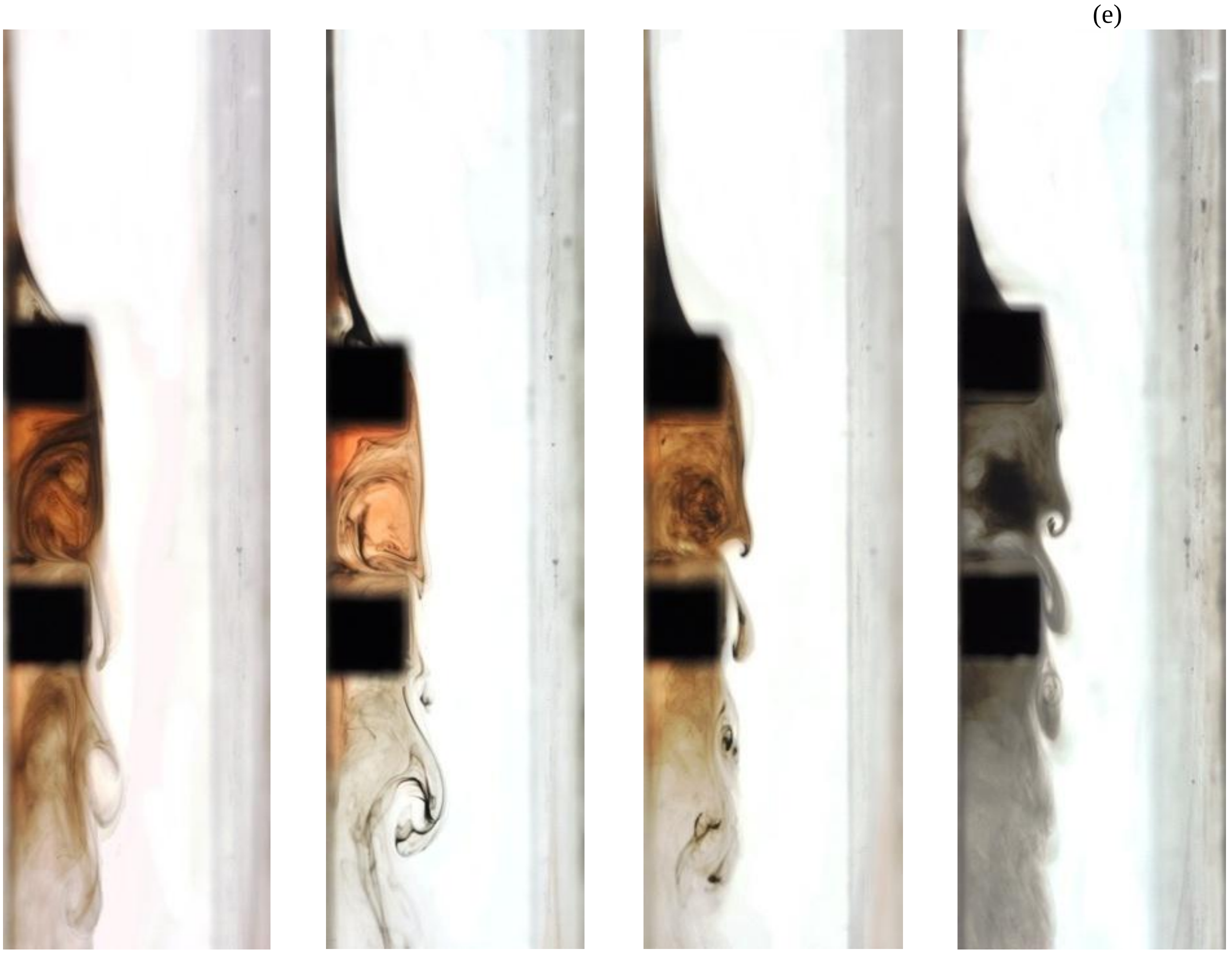
The flow visualization technique applied in the present work is the direct injection of opaque liquid dye in non-perturbed flow by means a rake of long hypodermic needles of 0.7 mm O.D.. The dye utilized is a solution of black PVA pigments, water and ethyl alcohol. Ethyl alcohol is only to correct the solution density very close to water. If occurs density difference between the dye solution and water, in very low Reynolds number, undesirable effects of convection is visible. Strong amount of this colored dye has been injected directly in the non perturbed stream, sufficient to color the entire flow field. Subtly, the injection dye is stopped, and the clean water flow wash the entire flow field, except in the cylinder wake, because in this region the flow speed is significantly small than other regions. This procedure permits to see, for seconds, the re-circulating bubble and the wake downstream the cylinder. Fig. 4 shows several flow visualized image for two square cylinders orthogonally positioned in the tunnel wall. The cylinders have 10 mm of side and spaced in 20 mm. The flow field is descendent and Reynolds number is based in the side of the cylinder.

All experiments have been performed out using test model made from aeronautical polished aluminum of D = 10 mm. In this situation, the blockage ratio is less than 5 % and aspect ratio (length to characteristic dimension (*D*) ratio) more than 24.

Still images are also captured using a 12.3 megapixel *Nikon* D 90 DSLR single lens reflex camera equipped with a special *Nikkor* medical macro lens with 120 mm and f/1:4. The pictures have been obtained in f/1:11 and 1/250 s for ISO 100. The very expensive medical Nikkor macro lens was designed for application in full frame (24 ×36 mm) chemical 35 mm roll film cameras generating very good macro photography ideal to image capture in medical surgery. With the advent of the DSLR, this lens type comes to obsolesces. Use of the very good medical lens in a Nikon DX format camera was possible only by a special connection adapted ring permitting very good macro images with a minimal distortion. A preliminary estimation of the errors due to optical distortion and image capture process has been made shooting a 10 division per millimeter ruler printed in a rigid high contrast negative film inserted in the test section. This captured image has been analyzed and the distortion has been evaluated in no more than 2 %. Nikon D90 has a CMOS image sensor of 23.6×15.8 mm producing, in relation the full frame, a scale factor of 1.5 in focal length (120 to 180 mm). Nikon D 90 camera has a high precision curtain shutter tested to over 100,000 cycles assuring a good shutter life. Commonly, DSLR cameras operate a shutter to near only 30,000 shootings implicating in a very short useful live when applied in laboratory where hundreds of images are captured in a single test.

The images obtained allow to identify several structures of the flow, as Kelvin-Helmoltz instabilities and recirculating zones. Figure 4(a), obtained for Reynolds number equals to 8 is representative of a very viscous flow.

(a) Re ≅ 8 (b) Re ≅ 50 (c) Re ≅ 100 (d) Re ≅ 270
(e)



(f) Re ≅ 330 (g) Re ≅ 420 (h) Re ≅ 740 (i) Re ≅ 900

Figure 4. Flow visualized images obtained in new vertical hydrodynamic tunnel.

3.2. Quantitative results: Hot film anemometry

In all experiments was utilized the 55R11 fiber-film probe made by *Dantec Measurement Technology*, with 70 µm diameter quartz fiber coated with 2 µm nickel film and with an overall length of 3 mm. This is a straight general-purpose type sensor which permits a wide measurement range in water medium. For very small velocities (up to 0.10 m/s) several special cares could be observed in order to reduce the convection effect around the probe. A *Dantec StreamLine* 90C10 frame with 3 CTA modules 90C10 permits simultaneously measurements in 3 channels. An A/D board NI-DAQmx 8.7.1 (16 bits), made by *National Instrument,* has been utilized in order to record the output voltage signal. The Fig. 5 shows a stating impulsive measurement made in the tunnel without test model. The probe is positioned in the same place of the test model and the flow velocity is zero. Suddenly, the valve#4 of the flow control of the tunnel is quickly opened begins a accelerated flow producing several flow instabilities due to the rapid increased of the momentum and only after 10 seconds the instabilities is dampened generating a stable flow. This type of test shows a very stable device. Obviously, in a normal test, the opening of the control valve should be realized slowly.

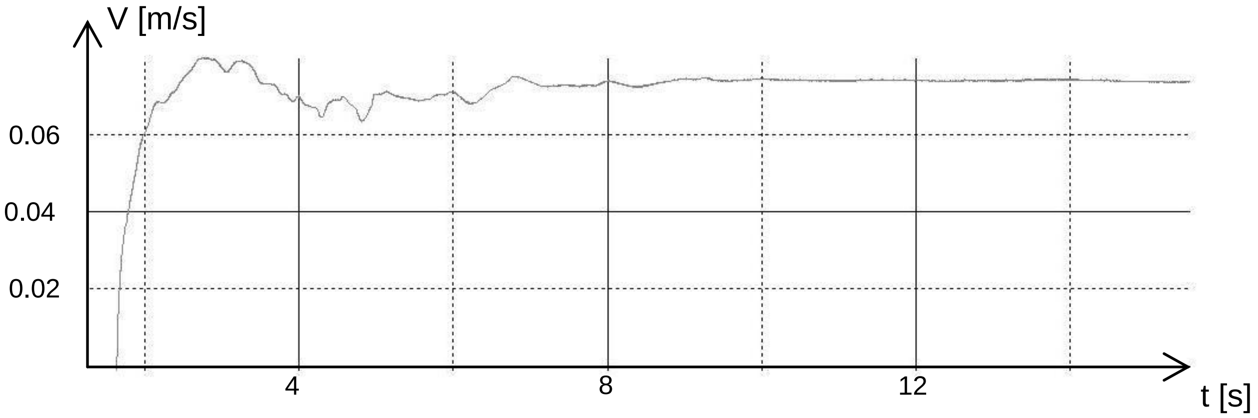


Figure 5. Starting accelerated flow in the test section.

The velocity profile in the test section is showed in the Fig. 6 with the tunnel operating in continuous mode and in a relative high velocity showing a flat profile.

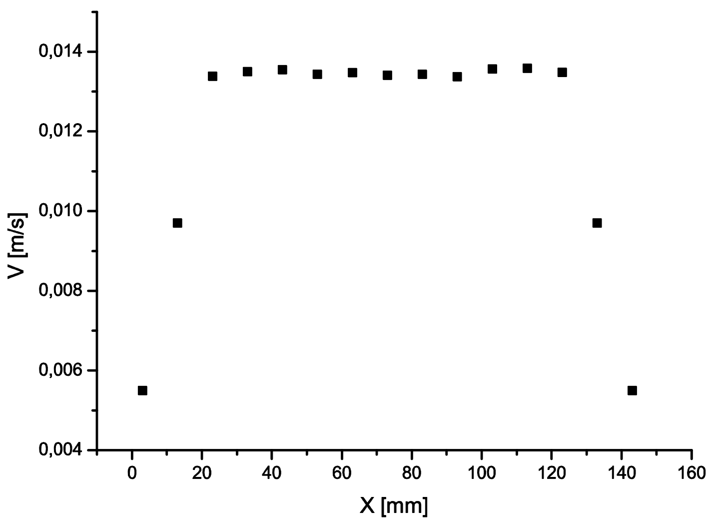


Figure 6. Velocity profile in the test section.

Figure 7 shows a velocity decline in function of the time for a run of 36 minutes in blow down operation mode.

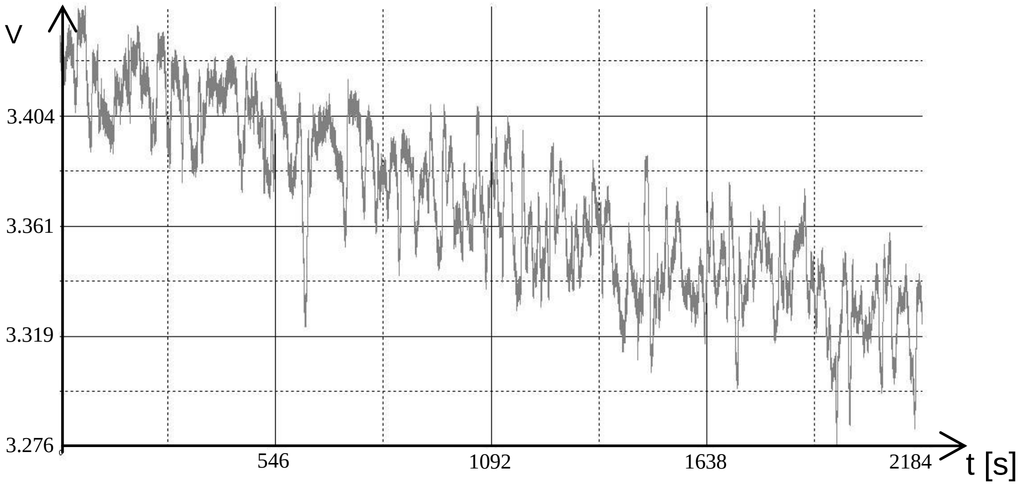


Figure 7. Velocity decline in the test section for a long time run.

Figure 8 shows a typical result of a turbulence level obtained in the test section for a short time of 10 seconds.

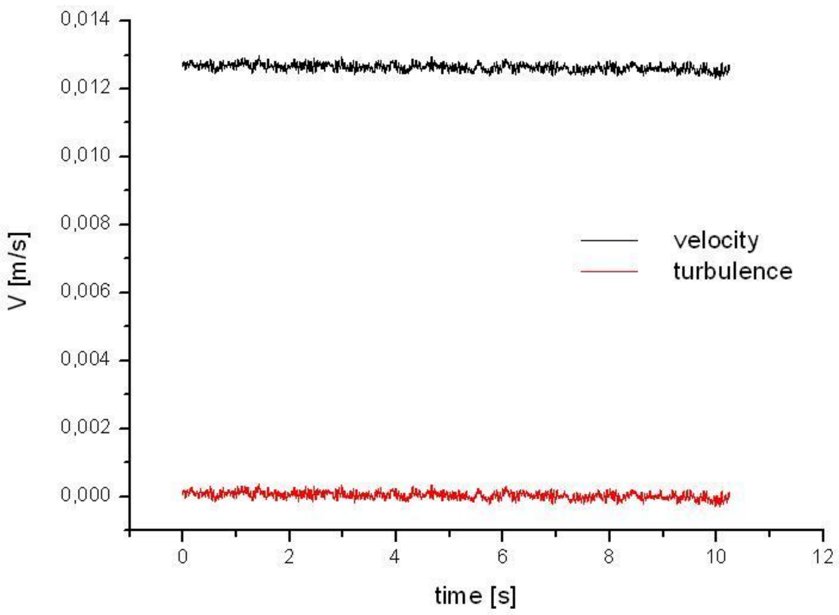


Figure 6. Velocity profile in the test section.

4. CONCLUSIONS

Experimental flow visualization plays a key role in our understanding of complex flow phenomena. That important experimental tool has been utilized in this working effort to obtain the first results of the study of flow internal channels with square protuberances in the walls.

The small dimensions of the present water tunnel test section lead to a limited test model aspect ratio when compared with other aerodynamic tunnel experiments as described in the literature, and this fact alone can exert a certain influence on results. In fact, Williamson (1996) has stated that the Strouhal scattering has been related to three dimensional effects in the developing wake, which would distort measurement results. According to him, those effects could be imputed to cylinder extremities. Hence it would be possible to reduce scattering with the help of some endplates conveniently located at each side of cylinder. Due to their importance for future work, the investigation of the effects of endplates on the wake behavior is under planning.

Unfortunately, the testes have been restricted to Reynolds numbers up to 1 000, because the limitations in flow visualization technique by means of liquid dye injection.

3. 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. Thanks also to Prof. Emanuel Woiski for proofreading the manuscripts and opportune collaborations in several opportunities.

4. REFERENCES

Clayton, B.R. and Massey, B.S., 1967, "Flow Visualization in Water: A review of Techniques", Journal of Scientific Instrumentation, Vol.44, pp.2-11.

Dobrodzicki, G.A., 1982, "Flow Visualization Water Tunnel – Its Construction and Capabilities", National Aeronautical Establishment – Aeronautical Report LR – 610 – NRC No. 20235, 49 p.

Erickson, G.E., 1981, "Vortex Flow Correlation", Air Force Wright Aeronautical Laboratory Report AFWAL – TR-3143, 354 p. (avaliable in micro film).

Freymuth, P., 1993, "Flow Visualization in Fluid Mechanics", Review Scientific Intruments, Vol. 64, pp.1-18.

Freymuth, P., Bank, W. and Palmer, M., 1983, "Flow Visualization and Hot-Wire Anemometry", TSI Quartely, Vol.9, No. 4, Oct.-Dec., pp.11-14.

Vogt, G.L., 1983, "Water Tunnel Construction for Continuous Mode Flow Visualization", AIAA-83-0657, 10 p.

Gonçalves, H. C., 2001, Experimental Determination of Bluff Bodies Vortex Shedding Frequency (in Portugueese), Dissertação de mestrado, UNESP-Ilha Solteira, 201 p.

Lindquist, C.; Mansur, S.S ; Vieira, E.D.R., 1999, "Flow Visualization of the von Kármán Vortex Street: a Tool for Fluid Mechanics Learning", proceedings of the ICECE 99 - International Conference on Engineering and Computer Education, Rio de Janeiro.

Linquist, C., 2000, Estudo Experimental do Escoamento ao Redor de Cilindros de Base Quadrada e Retangular, Dissertação de mestrado, UNESP-Ilha Solteira, 174 p.

Mansur, S.S., Vieira, E.D.R., Saito, M. and Esperança, G.A.S., 1996, "Visualização Experimental do Escoamento ao Redor de Cilindros de Base Quadrada Posicionados Transversalmente ao Fluxo Livre", Proceedings of the VI ENCIT/LATCYN, vol.2, Florianópolis, SC, Brazil, pp.1103-1108.

Mueller, T.J., 1983, "Flow Visualization by Direct injection", *in*: Fluid Mechanics Measurements, Goldstein, R.J. (ed.), cap. 7, pp.307-375.

Pelegrini, M. F. ; Vieira, E. D. R., 2003, "Flow Around Spheres: A Didactic Experiment", Proceedings of the: ICECE 2003 - International Conference on Engineering and Computer Education.

Robertson, J.M., 1954, "The Water Tunnel: Tool in Aerodynamic Research", Aero Digest, November, pp.34-38.

Stieb, R., 1981, "Descripton of the MBB-Water Tunnel", MMB Publication MMB/FE123/S/R/1526, 12 p.

Ward, T., 1976, "The Hydrodynamics Laboratory at the California Institute of Technology – 1976", Journal of Fluids Engineering, Vol. 98, No. 4, pp. 740-748. Also avaliable in ASME Publication 77-FE-12, 1976.

Vieira, E. D. R.; Mansur, S. S. and Zaparoli, E. L., 1996, "Visualização de Escoamentos em Meio Hidrodinâmico: Geração, Captação e Processamento Através de Sistema de Baixo Custo", proceedings of the CEM NNE/96 IV Congresso Brasileiro de Engenharia mecânica Norte Nordeste, vol. 1, pp. 839-844.

Vieira, E.D.R and Mansur, S.S., 2004, "Visualização Experimental de Escoamentos, *Turbulência* , Coleção Cadernos de Turbulência**,** vol.4, Möller, S.V., Silvestrini, J.H. (eds.), pp.33-71, Associação Brasileira de Engenharia e Ciências Mecânicas - ABCM, Porto Alegre, 2004. ISBN 85-85769-19-X.

Werlé, H., 1973, "Hydrodynamic Flow Visualization", Annual Review of Fluid Mechanics, Vol.5, pp.361-382.

Williamson, C.H.K., 1996, "Three-dimensional Vortex Dynamics in Bluff Body Wakes", Experimental Thermal and Fluid Science, vol.12, pp.150-168.

Woiski, E.R. ; Vieira, E.D.R., 2003, "Use of Flow Visualization in a Vertical Water Tunnel in Engineering Teaching", proceedings of the Cobem 2001 – 16th Brazilian Congress of Mechanical Engineering, 2001, Uberlândia, MG.

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.