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LOW COST APPARATUS FOR EDUCATIONAL FLOW VISUALIZATION WITH SMOKE LASER TECHNIQUE

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Abstract. *Fluid flow visualization is a very important tool to understand the fluid mechanics. Experimental observation has always been a very interesting way in analysis of physical phenomena, because all relevant variables to the problem are present. Nowadays fast computers are more accessible and freeware computational tools are easily found on the internet, so a regular engineering student can virtually visualize any fluid flow configuration on the computer screen. This facility brings to the classroom an interactive tool that makes possible the solution and discussion of more complex problems approaching to real world problems that student will face after graduation. With all these computing facilities, experimental visualization is always impressive to student and makes solid the theoretical knowledge. This paper presents some results for flow visualization using the method of smoke and lasers in the low cost workbench that can be used in teaching, for demonstration of traditional and complex flow configurations and assisting in the learning of fluid mechanics.*

Keywords: *flow visualization, educational workbench, smoke laser technique*

1. INTRODUCTION

Experimental methods have always been undoubted ways to natural phenomena analysis. It is known that the engineering education becomes more advantageous and efficient when is possible the experimental verification of physical phenomena that are studied theoretically. Experimental workbench, as educational level or even full-scale level helps the overall understanding of the issues seen in the classroom.

Earlier times, many of the laboratories in engineering schools were built by teachers who created their own workbenches for the experimental classes, but today it is easy to find a lot of companies that develop this kind of equipment in didactic scale with high quality. Didactic workbenches to different areas such as fluid mechanics, heat transfer, combustion, strength of materials, etc, which are very easy to install and very easy to find today, however the cost of each one of these devices can exceed the available budget of some Brazilian schools today. The proposed work of low cost apparatus, providing flow visualization in various geometric configurations may represent an important step in teaching of fluid mechanics.

Today with the fast development and decreasing costs of computers with high performance, the experimental verification is sharing space with the computer simulation, which is also a studying tool with a high level of interactivity. The possibility of visualization of phenomena, either experimental or computational way, has great impact on theoretical understanding. This is the quest to accelerate and improve engineering education.

Considering three distinct ways to solve problems in engineering: theoretical analytical, experimental and computational. It is known that each one has some advantages and disadvantages, which can be seen in the diagram in Figure 1.

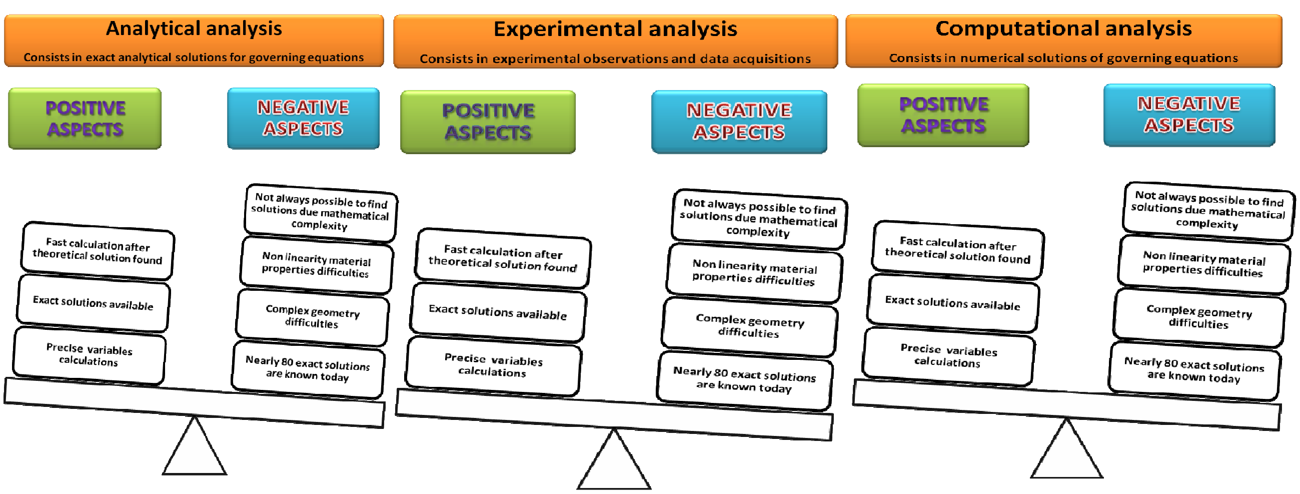

Figure 1. Advantages and disadvantages of analysis methods for fluid mechanics problems.

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Analytical methods represent the exact solutions of the physical phenomena governing equations. White (1991), comments that there are few exact solutions, about 80, for Navier-Stokes equations in the field of fluid mechanics. This is due to the complex nature of the phenomenon and therefore the governing equations, which in most cases are nonlinear. The geometric complexity also interferes with obtaining the exact solutions. More complex is the geometry, more sophisticated solution methods will be necessary.

Computational methods have emerged as a great promise to overcome all the difficulties already observed in analytical methods. However, the results are approximate and computational errors not present in the analytical methods must be considered, such as the inherent error present in numerical integral function calculations. This kind of tool can be as precise as necessary, or limited by computational effort that is directly related to the computer used. Until very recently, it would not be possible to solve problems with a very large number of variables on a personal computer. The limit imposed by the equipment would be in data storage or processing speed, however today it is possible to solve problems up to 10^6 mesh points easily without resorting to large computers.

Experimental methods were the first form of study of physical phenomena and still are a useful tool in the understanding of fluid mechanics. One of the most important benefits is the fact that in experimental observation all possible variables are present, which are important for the phenomenon or not.

Experimental visualization techniques have always been used to aid the understanding of fluid mechanics, and the main goal is to enable visual observation of the flow that not always is able to do naturally. In general these techniques are based on the introduction of a foreign element (marker) and the fluid medium and monitoring over time for an Eulerian or Lagrangian analysis. There are several methods for this purpose, but one of the restrictions for choosing the appropriate marker is that it cannot interfere with the behavior of the fluid under study.

2. FLOW VISUALIZATION TECHNIQUES FOR GASES

Gas flow visualization can be done in several ways where which each one have a specific application. The following describes some of the most traditional technique to visualize air fluid flow.

2.1 Oil film technique

The technique of the oil film over surfaces has been used to allow visualization of the flow over (very near) surfaces, especially in regions with difficult access. It is also indicated for turbulent flow because the oil film will behave as a buffer for fluctuations of velocity and pressure present and the result would be something related to the mean field these quantities. The technique consists in mixing a fluid with low surface tension, oil for example, and some sort of very fine particles, some kind of powder for example.

This oil and pigment mixture is distributed in a very thin layer or droplets spread over the surface and then the surface must be imposed on the flow field. As time passes, the mixture will be drawn by viscous forces air interaction with the surface and thus are created streamlines over the surface where it will be possible to view. Special care should be taken that the oil film or the drops do not produce lines due to the gravitational action. The lines produced should be the result of the exclusive action of the flowing air drag. This technique will not succeed if the flow is highly unstable but is well suited for determining regions of separation or reattaching flow, it will be possible to visualize lines oriented in opposite directions.

Martinuzzi and Tropea (1993) used the technique of oil film combined with the smoke dispersion for visualization on various geometric configurations. The fluid mixture proposed is composed of kerosene, hydraulic transmission oil and graphite powder.

Hunt *et al* (1978) use a zinc oxide powder with Crisco oil mixture in 10-90% proportion for flow visualization around obstacles mounted on flat surfaces. With this mixture, the flow profiles took approximately 1 hour to be achieved and the advantage over titanium oxide with light oil mixture, is that the excessive accumulation of particulate matter in regions where shear stresses are nil is avoided.

Byun and Simpson (2002) use the method of the oil film with oleic acid (20%), titanium dioxide (20%) and kerosene (60%) mixture. Some examples of using oil film technique are shown in Fig 2.

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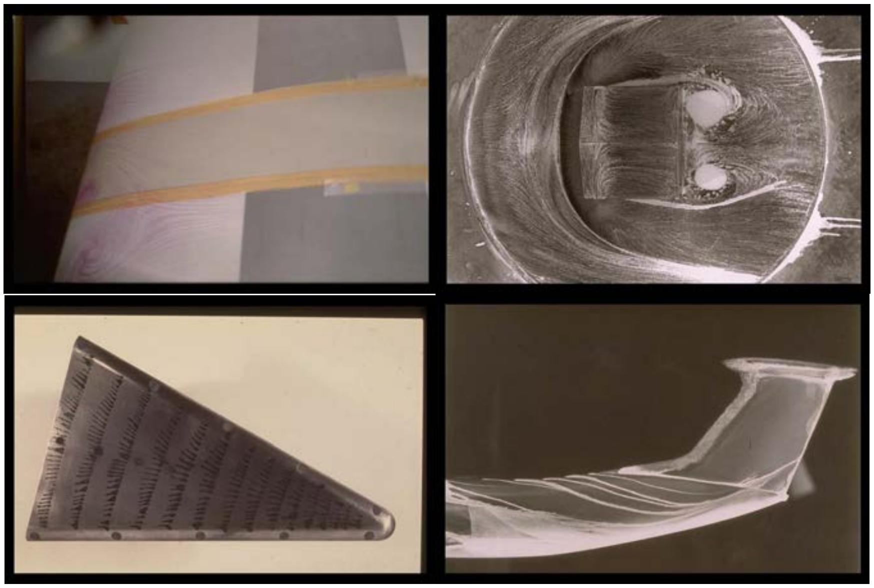

Figure 2. Examples of oil film and oil droplets on surface flow visualization techniques. Carbonaro (1994).

2.2 Hot wire smoke technique

This technique is widely used for streamlines visualization along the flow near or distant from surfaces. Smoke is produced from a thin steel wire coated with oil. The wire is connected to an electric circuit and when this is on, the wire heats turning the oil to smoke. Pulsating the electric power in the circuit, a sequence of smoke lines can be produced.

Lee and Lee (2001) in their work to visualize the boundary layer in grooved surfaces, use the technique of hot-wire smoke combined with the projection of laser light planes. Note that the problem addressed in this technique is feasible when the Reynolds number based on the wire diameter is less than 40, otherwise it would result in flow disturbances that would hamper the analysis, however they use for the Reynolds case 66,7. The assembled apparatus comprises two nickel-chromium wire of 0.1 mm diameter twisted each other and properly tensioned by a spring for compensation of thermal expansion. A light plane is formed from a cylindrical lens and directed into the test section. They used two types of fluid, SAFEX oil and paraffin. A feature of the hot wire is the generation time of smoke can last only a few seconds. Usually voltages between 25V and 35V DC are used, which should be adjusted to wind speed and desired density of smoke.

Cornaro *et al* (1999) use stainless steel wire with 0,1 mm diameter coated with mineral oil to smoke generation for flow visualization on the convex and concave surfaces. Duda *et al* (2008) use the hot wire technique for flow visualization of jet colliding in flat plate supported on cylindrical pedestal. Examples of this technique usage are shown in Fig. 3.

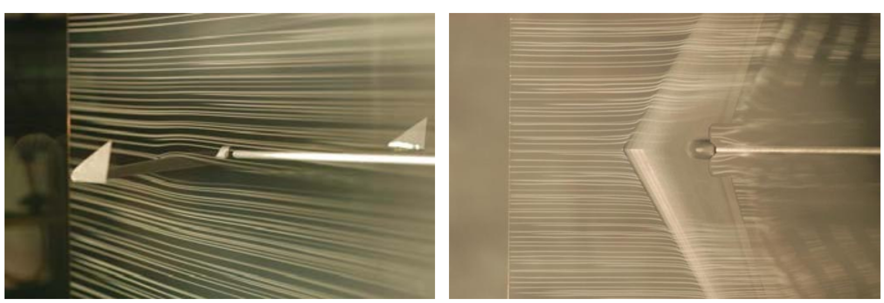

Figure 3. Examples of smoke wire visualization technique. RAFD (2013).

2.3 Suspended particles technique

Direct injection of particles may be used as a means of flow visualization. Streamlines will be provided if the particle is a good light reflector. To visualization the technique is very similar to that used in the hot wire oil where a plane light is generated by a laser beam after passing through cylindrical lens. Cui *et al* (2006) use the dispersion of smoke particulates with calcium carbonate powder with 50 μm to 350 μm for the visualization of the turbulent flow intensity in free jets. Figure 4 shows the flow visualization around a cylinder using the technique of the suspended particles.

Wright *et al* (2006) use this technique of smoke generation for flow visualization in cavities with high aspect ratios. Smoke particles act like tiny light reflectors that allow the visualization of the flow from the projection of the plane of light. Figure 4 shows an example of this technique applied to visualize the flow around a cylinder.

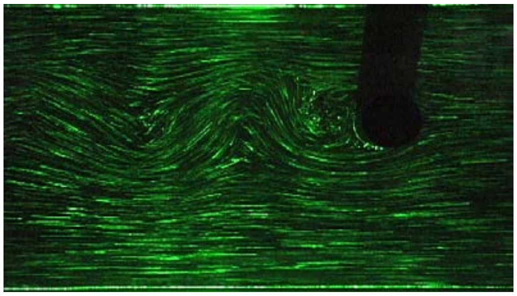

Figure 4. Example of flow visualization over cylinder with suspended particulates. FEBL (2013).

2.4 Tufts

This technique can be used for flow visualization near the surface. Probably this should be one of the cheapest techniques for visualization. It consists to place along the surface, small flexible strips. The orientation of the strips indicates the direction of the velocity. Figure 5 shows two examples of this technique applied to visualization over aerodynamics profiles.

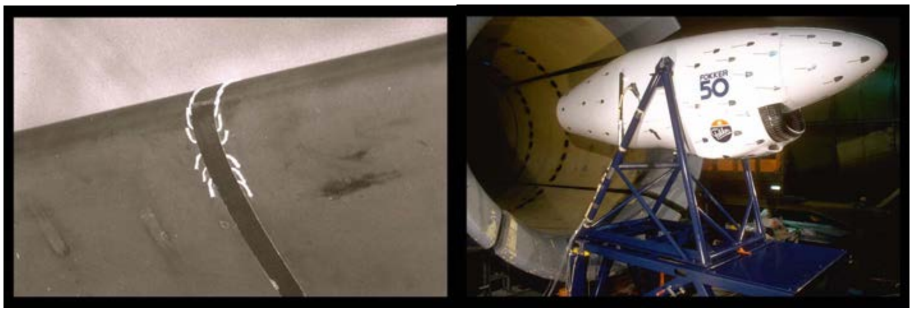

Figure 5. Examples of tufts technique for flow visualization. Carbonaro (1994).

3. EXPERIMENTAL SETUP CONFIGURATIONS

The workbench proposal will be used to visualize flow profile where the working fluid is the air and the method used is the injection of smoke. An overview of the operation steps sequence is shown in Fig. 6.

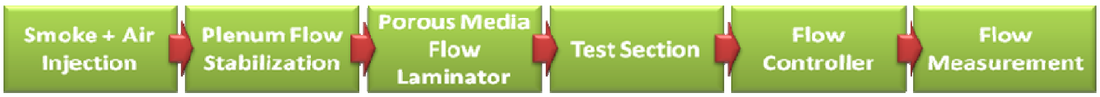

Figure 6. Sequence sections inside flow duct

All components of the bench are shown in Fig. 7. The use of one or another component in the list, and its physical arrangement will be defined by flow characteristics and geometry.

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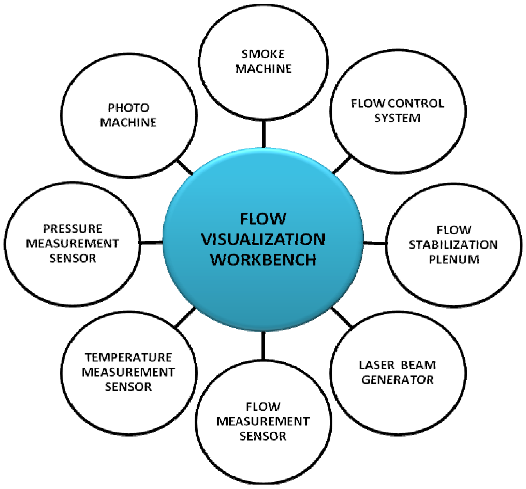

Figure 7.: Flow visualization workbench structure

Figures 8 and 9 shows two different assembling configurations. The first one is an arrangement for flow visualization inside U Duct with square cross section and the flow over confined cylinder. The second one shows the assembly for flow visualization in backward step expansion in square duct section.

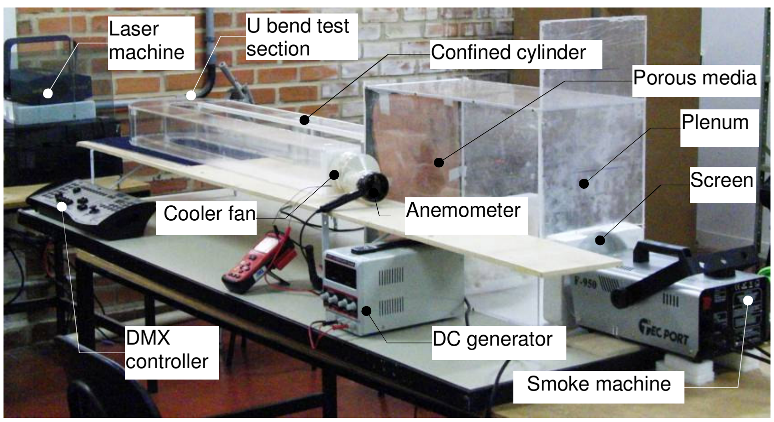

Figure 8. Workbench arrangement for flow visualization on U Duct and cylinder confined configurations

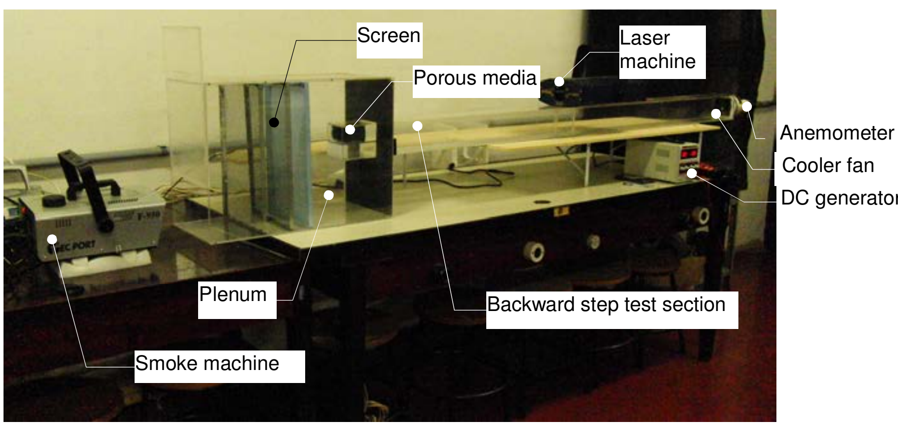

Figure 9. Workbench arrangement for backward step flow configuration

As stated, the workbench is composed by several interchangeable modules. Straight sections, bends, expansions, contractions, etc., which allows the adaptation to various configurations, as shown in Fig. 8 and 9. It is important that all sections are made of transparent material, which in this case was used transparent crystal polystyrene, 4 mm thick plate, so that it is possible to visualize the flow across the walls and not only in the test section.

The smoke generator machine used was a PORT-TEC brand, model F-950, commonly used in commemorative events, parties, concerts, etc., manually operated via remote control. The smoke is stored in a 300x300x150 mm plenum

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inside divided by three nylon screens located at the beginning of the circuit. The plenum is necessary to calm down the smoke jet generated by the smoke machine and prepare the fluid to enter the duct section.

The laser machine used was a Optilux brand, model OP-3022 Laser Aerial Device, also very common to use in commemorative events. Working together with a DMX Table, EXELL brand, model DMX-512 Controller Operator II, it is possible to program the laser beam allowing the display of multiple plans simultaneously, but for the present study was used only one light plane that was generated statically with a plane-concave lens positioned in front of the light beam. A camera with high resolution CASIO brand, model EXILIM EX-F1, was also used to capture the images.

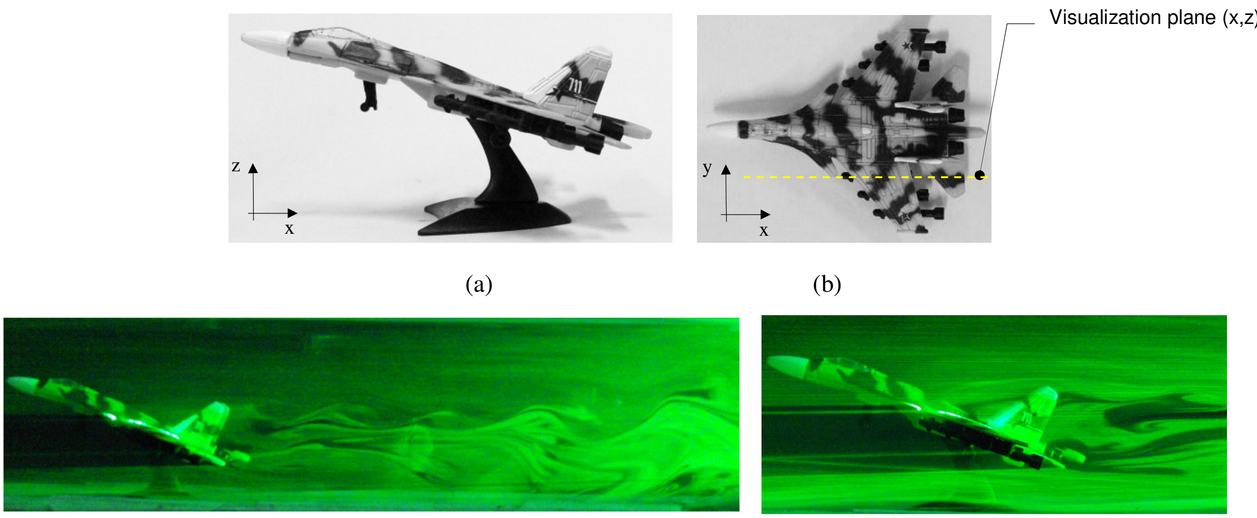
The flow was measured by an anemometer Instrutherm brand, model TAD-500 assembled on the output section of the circuit, with an exhaust fan (cooler) 12V DC, whose rotation was controlled by a DC generator Instrutherm brand, model Power Supply FA-3005. Table 1 presents a list of updated costs for the components of the workbench.

Table 1. Flow visualization workbench accessories costs – values actualized may-2013

Item	Description	Individual cost
01	Polystyrene transparent crystal plate 4 mm	R$/m^2 98,00
02	Smoke machine	R$ 390,00
03	Laser beam machine	R$ 420,00
04	DC generator	R$ 700,00
05	Cooler	R$ 80,00
06	Anemometer	R$ 450,00
07	DMX controller	R$ 250,00
08	Oddments	R$ 200,00
09	Support table	R$ 200,00
10	Nylon screen - 1 mm mesh	R$/m^2 30,00
	TOTAL (considering 3m^2 poliestirene e 1m^2 nylon screen)	**R$ 2818,00**

4. RESULTS

Initial tests have been conducted to evaluate the method. In two of them, the flow on scale model aircraft brand Maisto model SU-37 Super Flanker, Fig. 10 and vehicle brand Maisto, car model Porsche 911 Turbo, were merely illustrative, Fig. 11, without any flow control, only for vortex visualization, and in three other tests, the flow inside square section U duct, Fig. 12, the flow in confined cylinder with blockage aspect 0,1<β<0,9, Fig. 13 and backward step flow, Fig. 14, were performed under controlled parameters.



(a) (b)

(c) (d)

Figure 10. Scale model aircraft. (a) image of side profile, (b) top image, (c), (d) vortex visualization.

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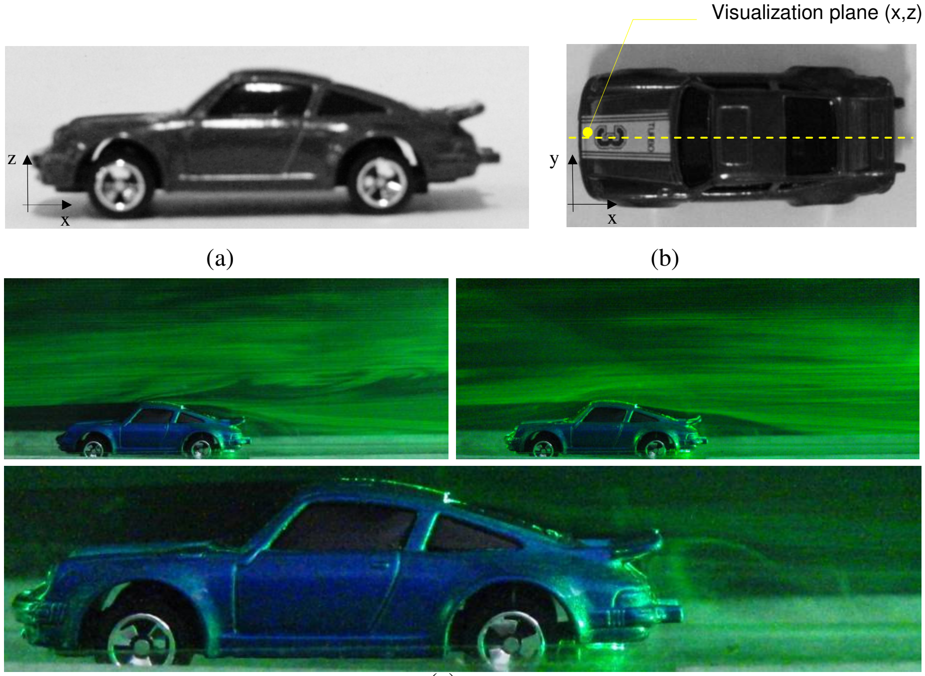

Figure 11. Scale model car. (a) image of side profile, (b) top image, (c) vortex visualization.

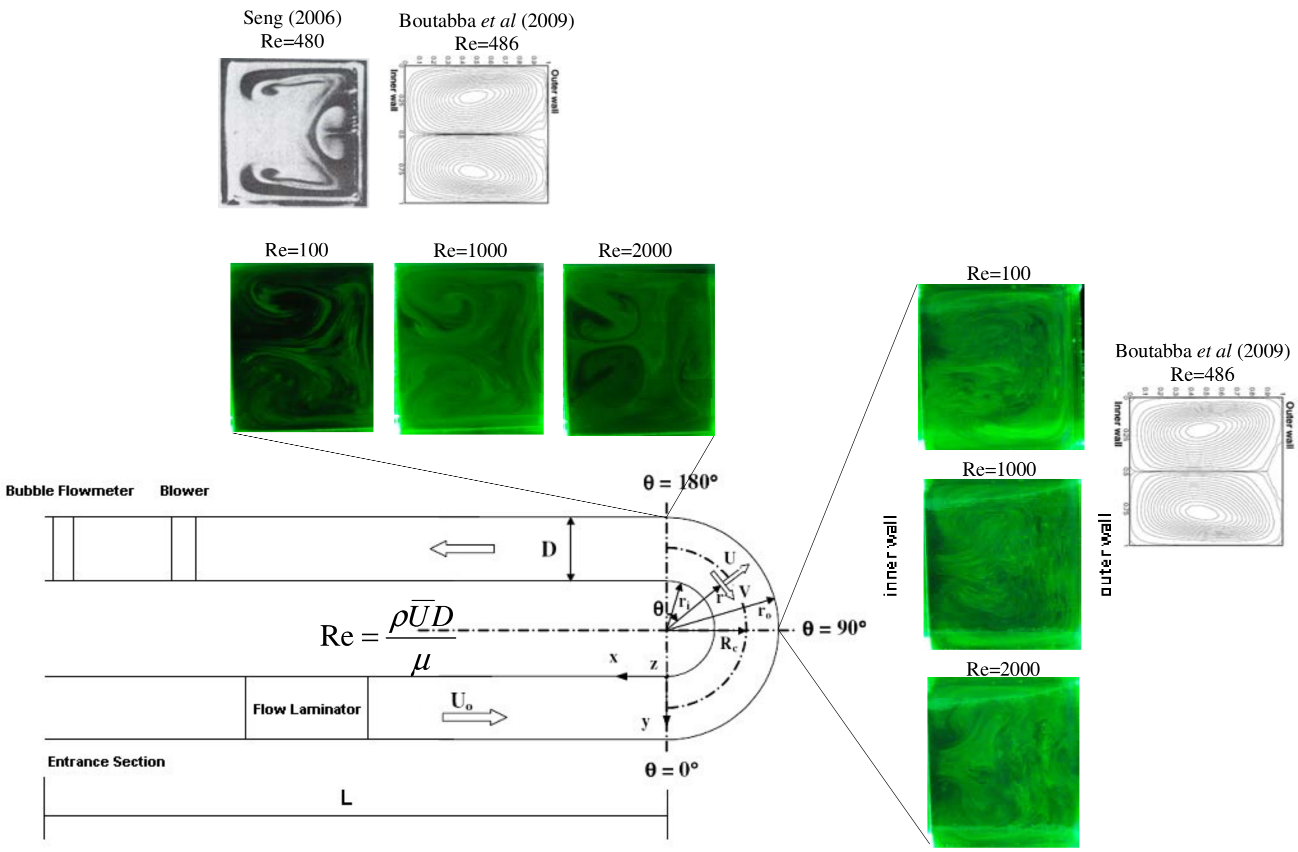

Figure 12. U duct flow visualization over cross section planes at 90^o and 180^o.

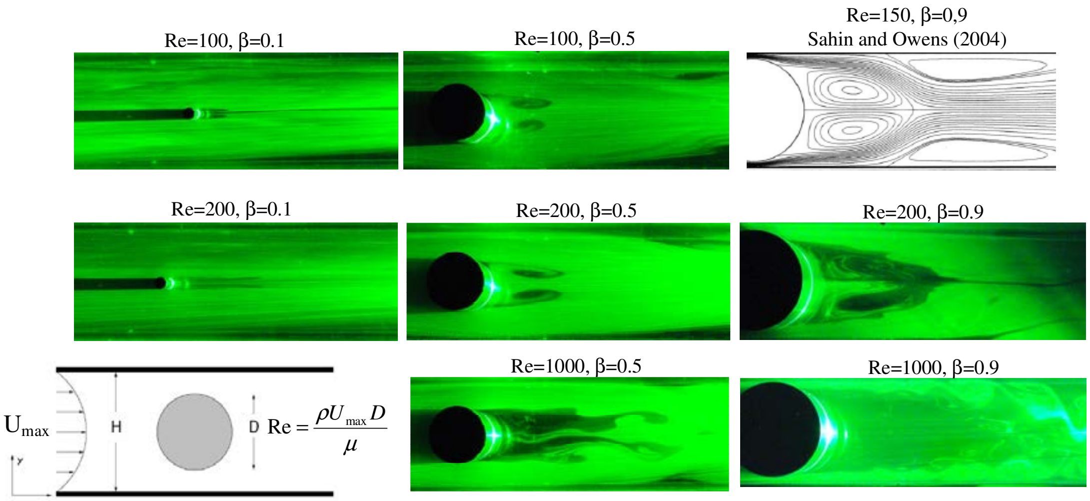

Figure 13. Flow visualization over confined cylinder at various aspect ratios and Reynolds number.

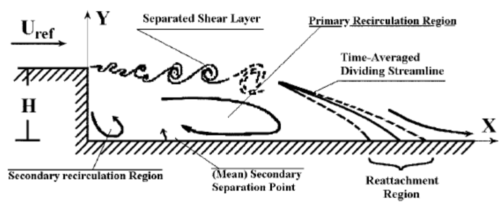

Figure 14. Sketch of the expected topology of a backward-facing step flow- extracted from Spazzini *et al* (2001)

Spazzini *et al* (2001) comment that flows with detachment and reattachment points are unstable and represent an important aspect in the technological design of industrial equipment. They identify some distinct regions in the flow in abrupt expansion, Fig. 14: primary recirculation located immediately after the step in the lower section of the channel, secondary recirculation located in the lower left corner between the vertical wall of the step and the bottom wall of the channel layer flow separation, characterized by the speed difference between the border and the primary recirculation upper main flow velocity. In this region that features structures arise from Kelvin-Helmholtz instability. In the experiment, these structures are visible already in Reynolds equal to 1000 The region characterized by reattachment point shows to be an unstable region, and did not show a specific point to cases of Reynolds> 500.

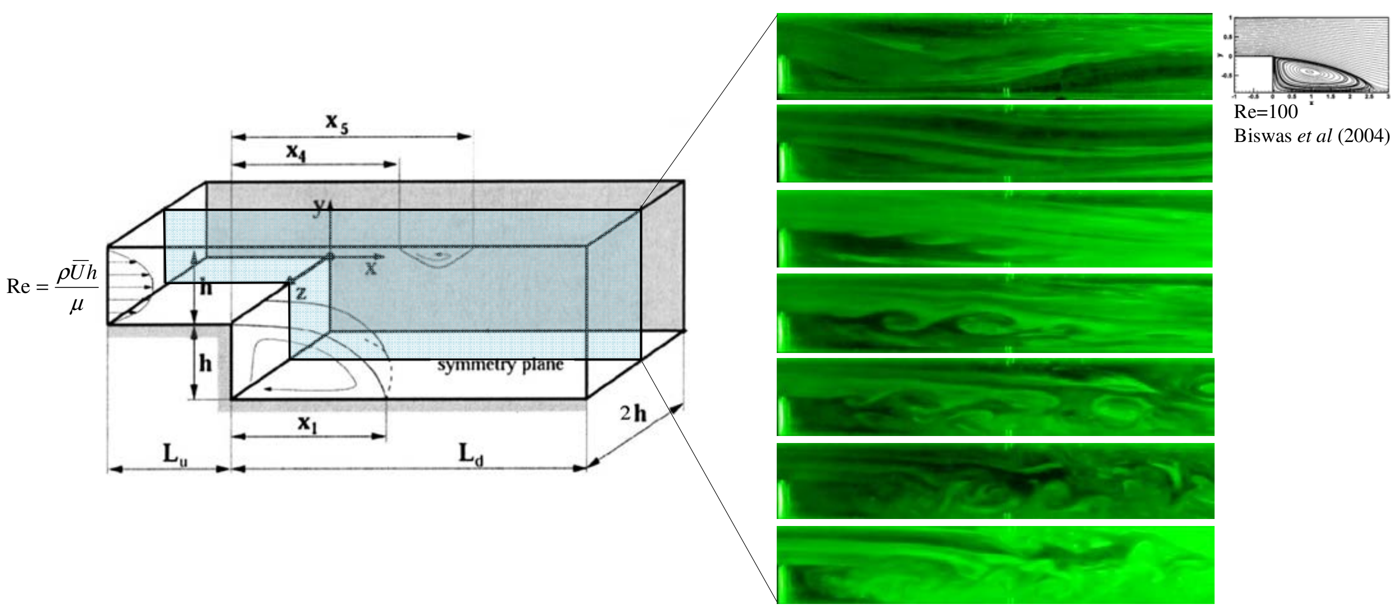

Figure 14. Flow visualization over backward step for various Reynolds number: Re=100, 500, 1000, 1500, 2000, 2500, 3000

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5. CONCLUSION

The laser and smoke visualization technique applied to the workbench proposed, proved to be quite interesting putting didactic purposes for two reasons: first, it is possible to visualize the flow profile in various geometric configurations just changing some of the modules from the workbench and second because the construction cost is very low compared to some commercial equipment. For cases when the Reynolds number of the problem is very low, this technique requires special attention to the amount of smoke added to the flow, because as the smoke is generated with a temperature above from the room temperature, natural convection effects can happens and interfere with the main flow and generate secondary flows which are not present originally. One way to minimize this phenomenon is use some kind of thermal cover protection over the duct section.

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