FLOW AROUND SPHERES: A DIDACTIC EXPERIMENT

Carlos Roberto Ilário da Silva
UNESP – Ilha Solteira, Departamento de Engenharia Mecânica, 15385-000 – Ilha Solteira, SP, Brazil
carlos@dem.feis.unesp.br

Sérgio Said Mansur
UNESP – Ilha Solteira, Departamento de Engenharia Mecânica, 15385-000 – Ilha Solteira, SP, Brazil
mansur@dem.feis.unesp.br

Edson Del Rio Vieira
UNESP – Ilha Solteira, Departamento de Engenharia Mecânica, 15385-000 – Ilha Solteira, SP, Brazil
delrio@dem.feis.unesp.br

Abstract. *The fluids mechanics learning presents many difficulties because the complex physic phenomena inherent the movement of the fluids. In this sense, experimental activities show an opportunity to elucidate several mathematical and physical concepts. In this effort of work several didactic experiments have been proposed in order to analyze the flow field around spheres. The experiments have been carried out in a small aerodynamic tunnel (200 × 200 × 500 mm of test section) entirely built in Plexiglas and other plastic materials adequate to utilize in fluid mechanics laboratory classroom to didactical proposes. All tests have been carried out to Reynolds number (based in the sphere diameter) up to 55 000. The flow velocity profile in different positions downstream of the sphere wake has been measured in order to determine the drag coefficient by utilizing the momentum balance equation. Additionally, the pressure distribution around the sphere surface has been determined in smooth and rough spheres in different Reynolds. These experiments seem very adequate in order to introduce the undergraduate student in fluid mechanics experimental activities. Additonally, without shadow of doubt, the authors have been convinced that laboratory activities in fluid mechanics utilizing a aerodynamic tunnel offer an opportunity of a clear and direct procedure to obtain the interest of the students and wake motivations. Adequated experiments linked with a pure theory are absolutely necessary for a modern student of fluid dynamics.*

Keywords*: fluid mechanics, didactical apparatus, aerodynamics tunnels, laboratory, engineering learning.*

1. Introduction

Fluid mechanics teaching in mechanics engineering course can be considered a challenging discipline because it requires of the students a familiarity with several physical phenomena and dominium of differential and integral calculus. A prior knowledge of hydrostatics, analytical geometry, vector calculus and other related disciplines are assumed, as well as a familiarity with physical backgrounds. In others words, fluid dynamics involves a hard charge of mathematical and physical concepts.

Fluid motion governing equations show a high degree of complexity and, generally, to keep the attention of the students in a desert of dry mathematical developments shows a non-pleasing task. The complex governing continuity, momentum and energy equations for general unsteady, viscous, compressible, three-dimensional flows make a complete system of equations. Today frequently referred to in modern literature as the "complete Navier-Stokes equations". Those equations are a nonlinear partial differential coupled system and a general analytic exact solution is unknown. Only few analytical solutions have been obtained to highly specialized flow geometries – only about less than 80 cases – Schlichting and Gersten (2004) discuss some of those solutions showing a complex mathematical sense. However, fluid mechanics engineers daily confront practical viscous problems in innumerous flow geometries. The advent of computational fluid dynamics (CFD) in the last two decades revolutionized the solution of complete Navier-Stokes equations. A universe of fluid motion problems to a wide range of geometry and conditions can now be attacked by numerical approaches. This fact implies in hard modifications in a modern fluid mechanics teaching to undergraduate students, see Gad-El-Hak (1996 and 1998).

Fluid mechanics can be considered a science of many physical considerations and hypotheses. The correct understanding of the physical principles involved in the fluid motion is a considerable obstacle of difficulties to transposes. Several simplifications in the theory and an adequate use of hypotheses require a mature scientific mind. But, a typical undergraduate student rarely has that characteristic- Gad-El-Hak (1997)

Additionally, fluid mechanics teaching can be also characterized by an extended list of topics to be covered. Because of a lot of numbers of topics that should be explained, fluid dynamics students frequently lose the attention for what must be carried out. In consequence, the explanation of each topic should be carefully constructed to make sense and, frequently the teacher should be made available a "map of intentions" in order to help organize the student's thoughts. Each basic topic requires careful attention to the structure and the sequence of explanation. In order to obtain success, the fluid mechanics teacher should carefully and clearly organize the manner in which subjects are introduced to the student in the classroom.

On the other side, a modern teacher cannot neglect several historical facts – characteristics of fluid mechanics development. History involving viscous fluid motion since Galileo's days is rich in several contradictions and technical details of importance to a complete understanding of this science. Nowadays, some authors awake to the problem of including history about many thermal fluid dynamiscists and their self-philosophy of science in several textbooks, in special see Anderson Jr. (1988) and Anderson Jr. (1978). Therefore, fluid mechanics learning is characterized by a strong number of proposed exercises. The solution of an amount of exercises requires a precious sacrifice of time and a hard charge of dedication by students in order to obtain good results in the tests.

In this arid surrounding, two paradisiacal islands emerge permitting amazing moments in classroom. First of all, an appropriate utilization of flow visualization pictures permits a clear elucidation of several difficult topics. According to Truchasson (1989) and Vieira & Woiski (2001) several benefices in the fluid mechanics learning can be obtained through the use of flow visualized images. Secondly, concerning an educational standpoint, in order to obtain an effective enhancement of the several topics, proposed didactical experimental activities produce good results. During a fluid mechanics laboratory class many concepts can be easily explained and verified in locus. Fluid mechanics didactical experiments help creating an adequate environment to stimulate student's motivation and facilitate the apprenticeship – Budwig (1993).

In this effort of work, the experience of the authors utilizing several didactical experiments of the flow around a sphere employing an aerodynamic tunnel is discussed. Several technical details of the experiments are explained in order to facility their reproduction. All activities have been executed by undergraduate mechanical engineer students in a didactical laboratory in an "open access" regime

2. Open accesses activities

Nowadays, several new approaches in mechanical engineering teaching have been applied successfully in different schools around the world. New requisites for twenty-one century engineers become evident. In industry as well as in the public sector there is a need for well-qualified and versatile engineers with a broad and in depth knowledge. Today, there is a need for renaissance professionals who are able to integrate science, humanities, and management concepts. A new goal-driven engineering process is required able to budding professionals to solve any problem—technical or non-technical—as opposed to learning specific solutions to a specific set of problems – see Arora (2004).

Modern engineering professionals require several talents able to identify the real problem, solve it effectively and efficiently, generate alternatives, evaluate possible outcomes, implement solution(s), and above all provide a framework for renewal and continuous improvement – Collis (1998). In this environment, several projects integrally developed by the students have been executed in Unesp – Ilha Solteira Engineering School. Those tangible activities outside classroom permit to develop a sense of team and a direct application of the technical engineering knowledge neo-acquired.

Since the first year, the students can freely utilize the didactical laboratory infrastructure in "open access" to realize several non-curricular activities. In this sense, the use of the aerodynamic tunnel involving undergraduate students shows an excellent opportunity to raise several students' abilities. Open access involves a liberty of choice for hourly or daily use. All experiments are realized by direct teacher's orientation in extra class activity and periodic activity reports are necessary.

3. Experimental facilities

An aerodynamic tunnel is one of the most important equipment of an aerodynamics laboratory. The main objective of this equipment is to provide a regular air current in controlled conditions to experiment different kinds of models. Like airplanes, cars and ships. Besides sorts of structures, having in view the experimental measurement of drag, lift, moments, temperature and pressure distributions, in addition to other necessary information to the project, analysis, operation of different types of equipments and systems. More information about aerodynamic tunnel is available on Rae Jr. & Pope (1984) and Gorecki (1989).

The tunnel utilized in this work was entirely projected and built by the undergraduate student's team in open-accesses laboratory activities. . The tunnel is entirely built in Plexiglas plates of 10 to 12 mm thickness and other plastic materials that provide free optical access to the interior of the equipment, facilitating the understanding of its operation.

Utilizing a 3 kW centrifugal fan and a three-phase frequency controller, the facility can reach up to more than 30 m/s of free flow, velocity enough to realize a wide range of didactical experiments. The test section has 200 ×200×500 mm and an easy physical access to the model is provided by means of interchangeable windows. Several measurements of the velocity profile and turbulence levels show an effective facility able to obtain reliable results.

Figure (1) depicts a panoramic view of the blower aerodynamic tunnel showing in the first level an inclined differential manometer connected to a probe of stagnation and static pressure. The manometer of inclined liquid column and the pressure probe, in equal mode, have been made by undergraduate students in open access.

Figure 1. Aerodynamic Tunnel of the Flow Visualization Laboratory

4. Didactic experiments proposed of the flow around spheres

In order to facilitate the learning of the physics phenomena inherent in the dynamics of fluids, this work presents the results of several didactics experiments using the flow around a sphere. This open access activity also provides the involvement of students with the equipments generally used in most of the aerodynamics laboratories around the world.

The flow around a sphere has been object of several scientists' studies along the years and therefore the available literature on that subject is quite full. The problems involved in this kind of flow, according to Mittal (1999), are of great interest for engineering, because of its extensive applications in aerodynamics and hydrodynamics.

The methodology adopted in this work supplies the student the opportunity to produce a good level of knowledge using as support tools experimental methods. It's important to say that in the mechanics of fluids field there is a sort of methodologies that are able to produce results of several physics phenomenon, among them, the Computer Fluids Dynamics (CFD) has been outstanding. Although, recently Mansur & Vieira (2004) emphasized that experimental techniques still constitute an important and efficient tool in the analysis and interpretation of inherent physical phenomenon into the fluid motion.

The experiment seeks the students to obtain the velocity profile in the wake of a smooth sphere for different numbers of Reynolds (based in the sphere diameter) and by analyzing those profiles to verify the existence of an area where there is loss of momentum behind the sphere. In addition, the students will experimentally determine the pressure distribution on a smooth sphere surface and compare with the pressure distribution determined on a rough sphere surface for the same flow parameters. The practice will approach from sophisticated instrument that involve advanced concepts, like the aerodynamic tunnel, even simpler instruments, as the Pitot tube that presents great application in the industry and in the practical life of the mechanical engineer.

The smooth sphere utilized in this experiment is made of plastic material, with 0,0355m of diameter and roughness of less than 15 μm. The surface of the rough sphere was artificially controlled until a value that guaranteed enough increase of turbulence level in the boundary layer that could delay its separation.

There are several techniques and methods available to measure the velocity of a fluid. The objective of this experiment is to introduce the student to Pitot tube utilization. This is a simple, cheap, reliable and easy to build equipment. The students will have to familiarize themselves with the definitions of static and stagnation pressure. By using a positioning mechanism that allows the movement of the Pitot tube inside of the test section, they can obtain the velocity profile of the wake generated by the flow around that geometry.

It is well known that in a flow around immersed bodies one of the most important characteristics is the drag force that the body is suffering. In this sense, this work suggests the use of the balance of momentum method to determine the drag coefficient of the sphere. This method was intensely used by the National Advisory Committed for Aeronautics (NACA) to obtain the drag and the lift forces in their bi-dimensional wing shapes in the thirties.

The force [F] acting on the control volume, second Fox and MacDonald (2002), is given by Eq.1, where {v} is the velocity of the fluid, ρ is its density and {A} is the area of the section of the sphere.

$$[F]=\frac{\partial}{\partial t}\int_{VC}\{v\}\rho d\{\forall\}+\int_{SC}\{v\}\rho\{v\}\bullet d\{A\} \tag{1}$$

Equation (1) establishes that the sum of the whole forces (surface and field) acting on a control volume not submitted to acceleration is equal to the sum of the rate of variation of the momentum inside of the control volume with the liquid variation of quantity of movement through the control surface. For incompressible flow, permanent regime and not considering the field forces, the force acting on the control volume is given by Eq. (2):

$$[F]=\rho\int_{SC}\{v\}\{v\}\bullet d\{A\} \tag{2}$$

To solve Eq. (2) it would generally be accomplished by a transformation of spherical coordinates. Therefore the calculation would be extremely complex, so the calculations here accomplished propose the use of Cartesian coordinates, facilitating the acquisition of the drag force.

Comparing the velocity profile in the input and output of the control volume verifies a lack of velocity in the output, consequently a lack of momentum. This difference is due to the drag force acting on the control volume, so it's reasonable, because of the principle of mass conservation to relate the drag force with the volume of the solid of revolution, generated by the lack of velocity of the profile.

In this sense, solids of revolution have been obtained with the velocities profiles of the flow around the sphere. The curve was rotated about the y-axis resulting with the solid. Equation (3), according to Guidorizzi (2001), gives the volume (V) of a solid of revolution rotated about the y-axis.

$$V(S)=2\pi\sum_{i=a}^{b}x_iF(x_i)\Delta x \tag{3}$$

The relation between the drag force and the volume of the solid of revolution, generated by the lack of momentum, is obtained by combining Eq. (2) and Eq. (3), which results in Eq. (4)

$$F_D=2\pi\rho\left(\sum_{i=1}^{n}x_i\left(F\left(x_i\right)\right)^2\Delta x-\sum_{i=1}^{n}y_i\left(F\left(y_i\right)\right)^2\Delta y\right) \tag{4}$$

where F_D is the drag force; ρ is the viscosity of the fluid in movement; x_i is the input position of the Pitot tube inside the test section; $F(x_i)$ is the input local velocity; y_i is the output position of the Pitot tube and $F(y_i)$ is the output local velocity.

After the drag coefficient determination, the measurement of the pressure coefficient distribution around smooth and rough spheres surfaces can be started. Pressure coefficient is an important parameter of the flow around an immersed body. The pressure measure can be obtained by means of a small hole (0,5 mm internal diameter) on the sphere surface. The pressure distribution in solid surface shows sharply the boundary layer detachment point. Measurement utilizing smooth and rough spheres provides the student to visualize the aerodynamics differences between both bodies.

5. Results

Utilizing the methodology proposed in this work the student might be able to obtain similar results for the velocity profiles like the ones presented in Fig. (2) and (3). The pressure probe has been adequately positioned downstream the sphere wake in different positions (relatively to sphere diameter) showing the lack of momentum due to the drag force.

Figures (4) and (5), on the other hand, depict the pressure distribution around the sphere surface for Reynolds number up to 50 000 to smooth and rough spheres. For more information about pressure distribution around this geometry surface see Le Clair *et al.* (1970).

The experimental measures (utilizing the balance momentum method) of the drag coefficient for different Reynolds numbers are shown and compared with the results of Chow (1980) in Fig. (6).

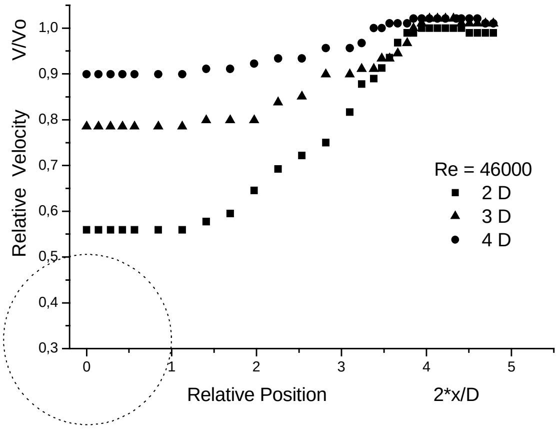

Figure 2. Velocity profile in the sphere wake for different positions of the pressure probe for Re 46 000

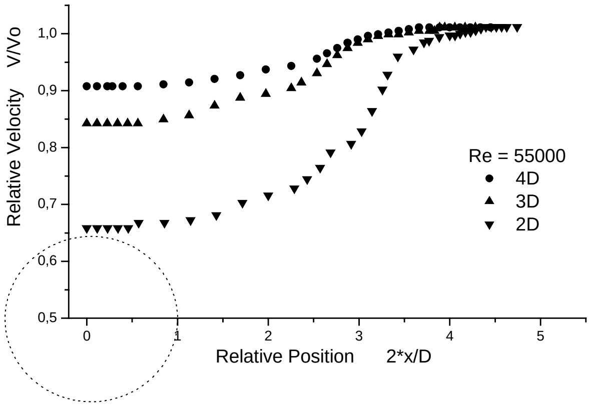

Figure 3. Velocity profile in the sphere wake for different positions of the pressure probe for Re 55 000.

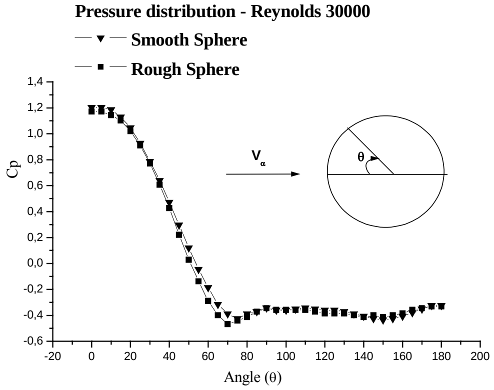

Figure 4. Pressures distributions on the smooth versus the rough spheres surfaces for Reynolds 30 000

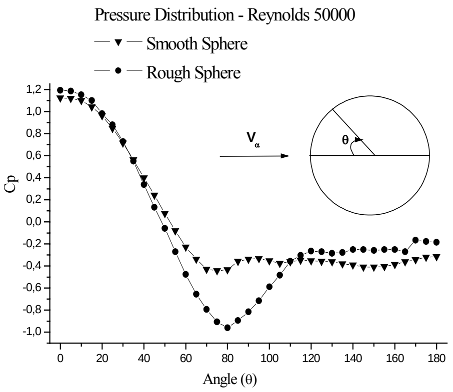

Figure 5. Pressures distributions on the smooth versus the rough spheres surfaces for Reynolds 50 000

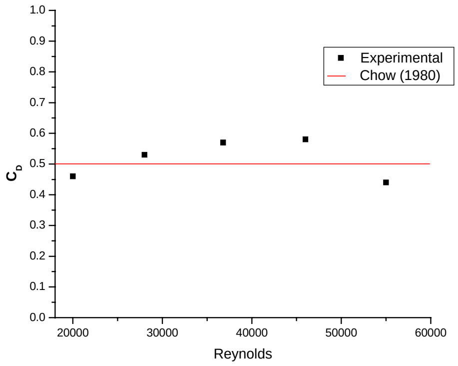

Figure 6. Drag coefficient experimentally measured for different Reynolds

5. Conclusions

A new dimension was created in the fluid mechanics learning. The traditional experimental and theoretical course now has been invaded by the ideas of computer fluid dynamics. In practical terms, CFD shows a very important instrument for modern aerodynamicists. Practically, all of the new sophisticated projects involving fluid motion were born immersed in computer analysis. The extensive utilization of "machinery" results in a new rise of discussions about fluid mechanics teaching in mechanical engineering courses. In this scenery, new educational concepts should be urgently introduced and well stable concepts need a reanalyze, showing a convenient opportunity to introduce an effective hands-on opportunity, second Collis (1998).

Fluid mechanics teaching represents a very challenging field because of the high complexity phenomena associated to the movement of the fluids. In addition, fluid mechanics connects a heavy mathematical load associated to a handful of rigorous physical concepts. In this surrounding, experimental activities provide a powerful tool enabling in order to facility this hard mission. During a fluid mechanics laboratory class, many of those concepts can be easily explained and verified with aid of several measurement techniques. Different fluid mechanics didactical experiments can be a useful help creating an adequate environment to stimulate student's motivation and facilitate the apprenticeship. Experimental activities also represent an optimal opportunity for practical demonstration of several applications of complexes different theoretical concepts – Budwig *et al.* (1993).

Laboratory classes can be transformed in a powerful source of motivation in an undergraduate engineering course if an adequate approach has been applied. Experimental activities can be viewed as an oasis in a desert of arduous mathematical effort. Frequently, many students have been attracted to aerodynamics studies because the sportive or aviation applications. Of course, car races like Formula One or airplane design can be an effective motivation driver for several students. In this sense, increases of experimental activities utilizing the recent theory acquired in classroom have been highly desirable.

An aerodynamic tunnel is an apparatus frequently found in several facilities able to experiment analysis of several aerodynamics problems, especially ones involving the airplane project. Many examples of fluid mechanics classroom experiments are available in the technical literature reporting the use of aerodynamic tunnels, most of them deploying small facilities specially built for educational purposes. A small velocity incompressible subsonic open circuit aerodynamic tunnel is a relatively inexpensive installation being capable of supplying a broad variety of several different educational experiments.

The experiments proposed in this work give the students the opportunity to use several equipments that are commonly used in a fluid laboratory. In addition, the students could apply experimentally several mathematical and physics concepts in the dynamics of fluids. In special, the momentum integrating utilizing the solid of revolution is a good example of elegant mathematical solution to an intricate problem.

Comparing the pressure distribution on the surface of the smooth and the rough spheres we can notice that for a Reynolds number up to about 30 000 doesn't show any significant difference between the separation of the boundary layer for bough spheres. However, for greater Reynolds number – about 50 000 – we can clearly see that for the rough sphere there is a retardation in the separation angle of the boundary layer that implicates in a sensible loss of drag force. This phenomenon at first sight can be very strange, but the rough generates a relative turbulence level inside the boundary layer and consequently increases the kinetics energy of the flow close to the surface, retarding the boundary layer separation. A good application of that phenomenon is the golf ball, which is covered with dimples.

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