FLOW AROUND SPHERES: A DIDACTIC EXPERIMENT

Marcelo Ferreira Pelegrini[1] and Edson Del Rio Vieira[2]

Abstract — *A steady incompressible isothermal flow past a rigid smooth sphere in an infinitum medium is experimentally investigated for Reynolds number up to 1000 in a fluid mechanics laboratory class. All tests have been carried out in hydrodynamic medium utilizing a water tunnel with 146×146×500 mm of test section, operating by gravitational effect in continuous or blow-down modes, and in a water tank with Plexiglas walls in order to visualize a sphere in free fall in a rest medium. Flow visualization by direct liquid dye injection and hot-film anemometry has been utilized in order to determine, qualitatively and quantitatively, the flow structure and turbulence characteristics in the wake. This proposed experimental activities represent good work opportunities on the teaching process, illustrating several different phenomena relative to the fluid mechanics theoretically discussed in the classroom. The complex measurement made using hot-film anemometry, and the flow visualization images generated, captured and processed directly by student's action in the hydrodynamic tunnel and in the water tank have awaked great motivation in undergraduate students of fluid mechanics.*

Index Terms — *Flow visualization, Fluid mechanics learning, Hidrodynamic tunnel, Hot-film anemometry.*

INTRODUCTION

The fluid mechanics study, without shadows of doubts, is a complex human activity, with a hard mathematical load and several intricate physical concepts. Traditionally, fluid mechanics laboratory teaching develops several challenges. The choice of adequate experiments to be offered to the students that implicate in better didactic results shows to be an arduous task. Elementary experiments should be offered allied additionally with others more complexes and showing a more elaborated thinking. Nowadays, several new flow didactical experiments, with different degree of difficulty, have been proposed, in technical literature, to be incorporated at fluid mechanics discipline of a undergraduate mechanical engineering course.

The problem represented by a rigid smooth sphere moving into a viscous incompressible fluid far of interference of the walls is a very old engineering problem, utilizing a relatively simple geometry that represents a high degree of complexity. Generally, the understanding of this problem by students is an arduous task and a challenge to the teachers.

Wakes behind a sphere are encountered so frequently in engineering applications implicating in large amounts of research that have been conducted and massive amounts of numerical and experimental data have been accumulated. The studies of the sphere wake that have been done show that the vortex topology and shedding process is significantly different from that found in the well know flow around a circular cylinder. Of course, the wake formed downstream a sphere shows high complexness of the vortex dynamics. This very complex flow exhibits several instabilities with complicated kinematics and vortical interactions and complex flow structures with fully three-dimensional unsteady flow fields in spite of the symmetry of the body.

The experience of the authors in offer the experimental class of a moving sphere in a viscous "infinite" medium to undergraduate students of a mechanical engineering course is reported in this work.

FLOW REGIMES AROUND A SPHERE

The problem of a sphere in movement on a viscous fluid wake up the attention since the Middle Ages due to interest in the cannon balls ballistic problems. The authors recommend the reading of the refs. [1,2] about the problem of the free fall of solid bodies to provide a historic understanding of this problem, including the happens of Galileu Galilei and the Pisa Tower.

The Reynolds number, $Re = \rho \, V \, D / \mu$, – based in the no perturbed upstream velocity (V), the sphere diameter (D) and the cinematic viscosity (ν), represented by ratio between the dynamic viscosity and the density (μ / ρ) – can be used as a primary parameter to classify the flow around a sphere. The flow regimes for a single sphere in a infinitum medium, can be described, in accord to ref. [3] as follows:

For Re < 5, in very small Reynolds numbers, a creeping motion is observed and in this region the flow is governed by viscous forces and no detachment appreciable is observed. These forces are proportional to the product of the viscosity, velocity and diameter of the sphere. In this situation, the Navies-Stokes differential equations can be integrated by neglecting the inertial forces. Stokes, in 1845 was the first in solved they for the case of the sphere,

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considering the complete boundary condition of no tangential velocity of the fluid along the sphere surface.

For 5 < Re < 130, the wake forms a steady recirculating eddy of axisymmetric ring shape. In this flow regime occurs a flow detachment and the detachment angle (θ) can be accuracy measured in function of Reynolds number.

For 130 < Re < 300, a wave-like laminar wake of very long period forms behind the sphere.

For 300 < Re < 420, a hairpin vortex begins to shed and a spectral peak shows up in the unsteady velocity spectrum.

For 420 < Re < 480, the shedding of the hairpin vortices becomes irregular. This is the early transition regime.

For 480 < Re < 650, the shedding mode is a continuous state of randomness, or irregularity.

For 650 < Re < 800, The shedding pattern differs from that of lower Reynolds numbers due to pulsation of the vortex sheet. Multiple frequencies can be observed and the shed vortices begin to show signs of turbulence.

For 800 < Re < 3 000, some of the vortex tubes formed by the vortex sheet separating from the sphere surface enter into the vortex formation region, while others are shed in small vortex loops. The large-scale vortices move away from the sphere rotating at random about an axis parallel to the flow through the center of the sphere. The wake becomes turbulent at Reynolds near 2000.

For 3 000 < Re < 6 000, This is other transition region where the measured low-mode vortex shedding frequency decrease rapidly with the increasing Reynolds number. The power spectrum of the fluctuating wake velocity shows one characteristic peak plus considerable broadband energy on both sides of this peak. The vortex sheet is changing from laminar to turbulent in this regime.

For 6 000 < Re < 370 000, the separated vortex sheet is now completely turbulent. The vortices shed from the formation region become stabilized because the separated shear layer is no longer laminar, but turbulent. This stabilization causes the velocity fluctuation spectrum to lose some of the broadband nature observed in the previous region. The Strouhal frequency of regular shedding increases with Reynolds number and then approaches the constant value of 0.19 at Reynolds near 20 000.

EXPERIMENTAL APPARATUS AND METHODS

In this effort of work, two different apparatus have been proposed both operating in tap water medium. The first, a water tank all made of Plexiglas of 0.127x0.127 m in cross-section and 1 m in height was used, depicted in Fig. (1).

A small plastic sphere is painted with an adequate color dye and launched from rest in the water surface. The sphere falls freely in the quiet water medium. In few centimeters run, after the sphere launch, the terminal velocity is rapidly observed. The terminal velocity is determined measuring, with help a hand chronometer, the time necessary to the sphere to move between two black adhesive tape, positioned externally on the Plexiglas wall, separated by a vertical known length (*L*), showed in the fig. (1). The relative water movement slowly dissolves the fresh dye permitting the wake visualization.
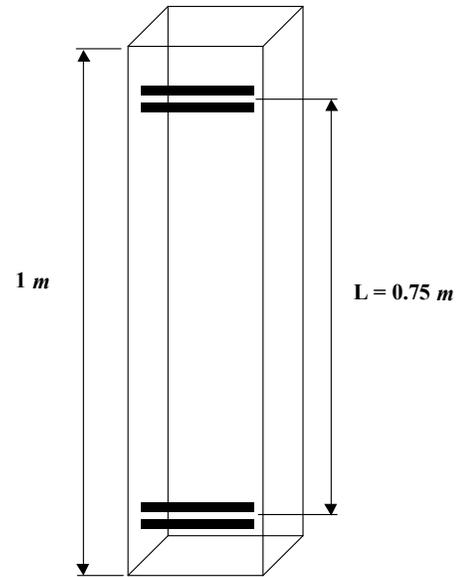
FIGURE. 1
WATER TANK FOR ESFERE WAKE VISUALIZATION.

In order to keep the water still careful attention was paid. Small variation in external air temperature causes water movement due to buoyancy effects provoked by temperature gradient between the tank wall and internal water.

In this device, plastic spheres with approximately 6 mm of diameter were utilized. These plastic spheres are the same utilized in toy guns and they are very cheap and available in toy store in large quantities. Necessarily, each sphere needs to be carefully separated in order avoid the use of egg-shape spheres in the experiment. This separation process can be easily performed with help of an inclined plane. Each individual sphere need to be carefully measured due to a large variation observed in the diameters and in the mass from sphere to sphere. Plastic spheres have internal small air bubbles. This micro-bubbles represent a large variation in the density implicating also in a need to be separation as function of they density.

In order to promote the density classification of the spheres, first of all, take a glass beaker, with one liter of clear tap water, at room temperature. Put a lot of spheres into the beaker. The spheres with density less than water, due to buoyancy force will float. This light spheres can not be utilized, but a large number of spheres remain on the bottom of the beaker. In this moment, you dissolve approximately 25 g of a salt (sodium carbonate, for example) in the water and wait a minute. Some spheres

should float on the water surface. These spheres have a density very close with the tap clear water density, and they will produce the better results in the proposed experiment, because the free fall velocity will be very small, producing moderate Reynolds number – up to 700 –, adequate to photographic capture using ISO 400 chemical films.

In order to promote the wake visualization the spheres are painted with a PVA dye. The spheres are launched with wet dye paint. The sphere movement in water provokes the wet dye dissolution permitting the wake flow visualization. An adequate illumination using cold lamps is required for image capture in order to minimize the buoyancy effects due to thermal gradients. This flow visualization process is the same utilized initially in the ref. [4].

The second apparatus utilized to the study of flow around a sphere is a vertical pilot hydrodynamic tunnel device. This equipment, made for research purposes, has been intensely utilized with success for didactical applications, see ref. [5,6,7]. Hydrodynamics tunnels are important tools for didactical purposes using flow visualization techniques. A sketch of this experimental apparatus is depicted in fig. (2).

CP Spherical test body
CT Contraction
DI Injector
MV Flow meter
RI Lower reservoir
RS Upper reservoir
SA Pump
ST Test section
TC honeycombs & screens
V# Valves
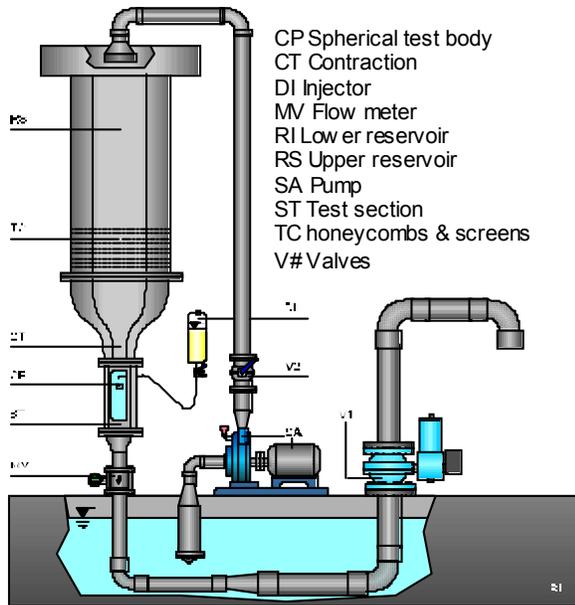
FIGURE. 2
LOW TURBULENCE VERTICAL HYDRODYNAMIC PILOT TUNNEL.

A detailed description of the tunnel operation can be obtained in ref. [8]. A plastic smooth sphere with 35.5 mm of diameter, the same utilized in roll on deodorants, is adequately fixed in the tunnel test section. A long hypodermic needle with 0.7 mm OD permits the liquid dye injection in order to allow the flow visualization. Utilizing this technique the detachment angle (θ) is measured from a processing of the visualized images. These images have been captured utilizing a Sony CD digital camera with only

1200x1600 pixel. A digital constant temperature anemometer using 55R11 Dantec probe was utilized to measure the turbulence intensity level in the wake. Details of the anemometer device are found in Ref. [8].

RESULTS

Initially, we will show the result regarded to the water tank. The wake-visualized images showed in Fig. (3), illustrate two different Reynolds regimes.

Re = 440   Re = 532
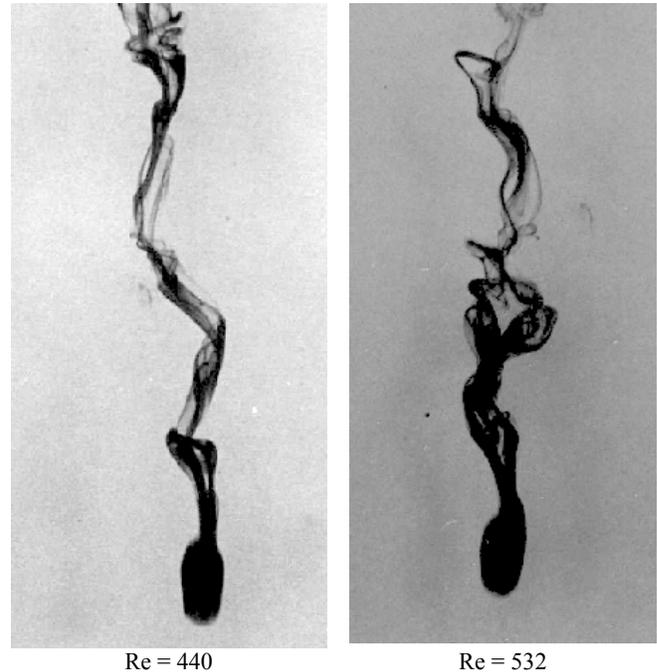
FIGURE. 3
SPHERE WAKE IMAGES CAPTURED FROM THE WATER TANK.

A terminal velocity (Vt) behavior as function of the Reynolds (Re) is depicted in the Fig. (4)
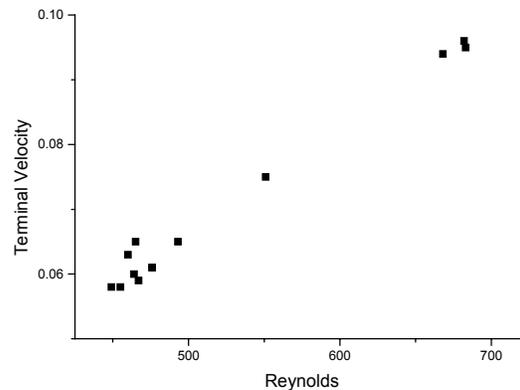
FIGURE. 4
TERMINAL VELOCITY (Vt) FOR A SPHERE.

The sphere drag coefficient (C_D) – expressed in terms of the ratio between the drag force and the kinetic energy ($0.5 \, \rho V^2 A$) – can be also obtained in the same experiment using the water tank. Illustrative results of the drag coefficient is depicted in Fig. (5)
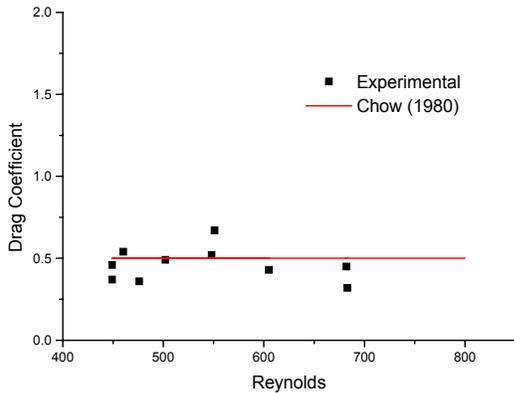
FIGURE. 5

DRAG COEFICIENT (C_D) OF A SPHERE AS FUNCION OF REYNOLDS.

In order to obtain the results relative to the hydrodynamic tunnel can be attacked firstly by the hot-film probe calibration problem. Several methods have been described in technical literature for probe calibration utilizing several different techniques. For example, ref. [9] shows a complete laboratory class utilizing a free jet in order to introduce hot-wire anemometry in a fluid mechanics course. Unfortunately, an expensive apparatus to generate a controlled low turbulence jet is required. The use of hydrodynamic tunnel in order to initiate hot-wire anemometry in undergraduate course is appropriately utilized in ref. [6]. Utilizing a hydrodynamic tunnel good calibration results can be found easily if several delicate procedures have rightly executed.

All hot-film measurements have been carried out utilizing the hydrodynamic tunnel. The hot-film probe has been positioned downstream the sphere (at Y = 5 D) and transversally moved (X direction) in order to obtain the relative turbulence level, depicted in fig.(6).
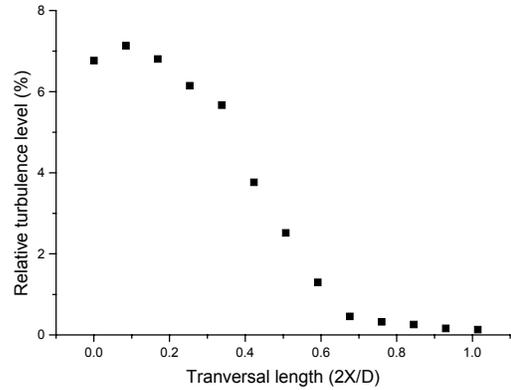
FIGURE. 6

TURBULENCE RELATIVE LEVEL IN THE SPHERE WAKE.

In the hydrodynamic tunnel visualized images in close view can be obtained. An example of these images can be observed in Fig.(7).

Re = 352   Re = 557
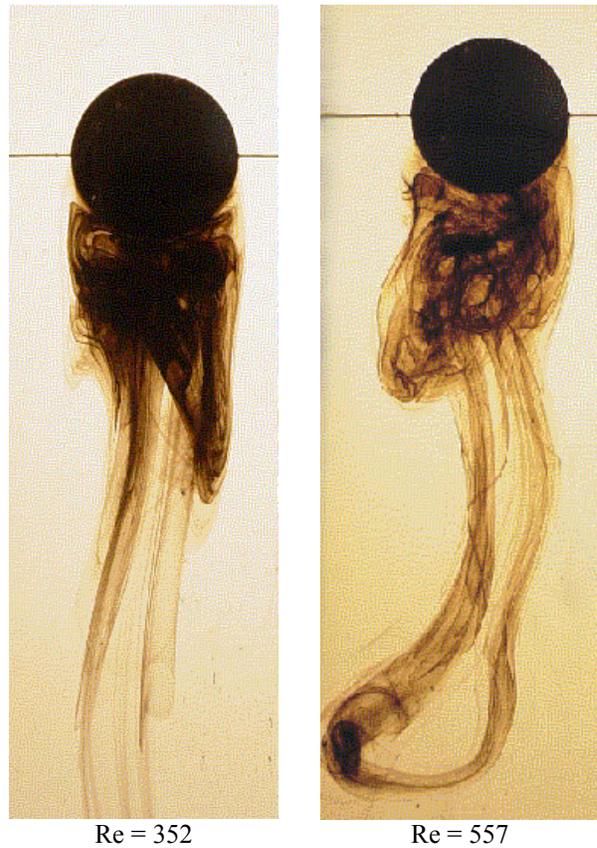
FIGURE. 7

SPHERE WAKE VISUALIZED IMAGES IN CLOSE VIEW.

A low level digital image processing of the wake images permits to obtain the boundary layer detachment angle (θ) depicted in Fig.(8).
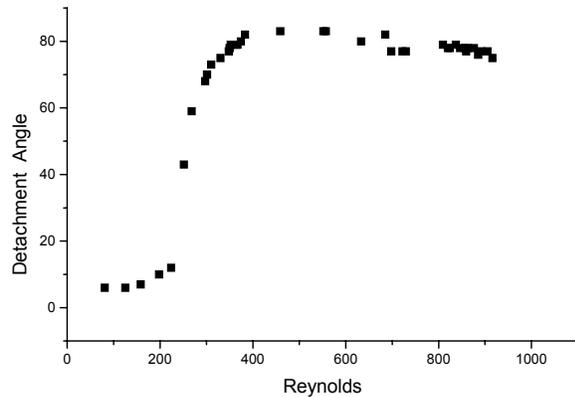
FIGURE. 8

DETACHMENT ANGLE (θ) OF A SPHERE AS FUNCION OF REYNOLDS.

CONCLUSIONS

In this paper a wake configurations observed behind a sphere falling in quiet water at terminal velocity has been proposed to an experimental class in a fluid mechanics undergraduate course. Two proposed devices – The hydrodynamic tunnel and the water Plexiglas tank – allow a careful observation of various wake-shapes images and quantitative measurements with their corresponding Reynolds number.

Experiments realized in water medium has certain advantages as a fluid medium for incompressible turbulence studies compared with air. Lower velocities may be utilized with the same Reynolds number since the kinematic viscosity (ν) of water is only one-sixteen that the air implicating in the use of lower frequency velocity sensors.

A water tank is a very cheap apparatus easy to make and to operate, permitting to obtain relative good results. Several aerodynamic concepts are possible to corroborate in this device.

Those experiments have been developed in a fluid mechanics laboratory class for, in average, six students each time. The less number of students permits a very close accomplishment, eliminating several students' doubts. A more high number of students can be an additional difficulty to the instructor, mainly in the hydrodynamic tunnel operation.

Massively separated flows as observed in a sphere wake or in many other bluff-bodies, found in several engineering applications, has been shown to be an ideal mechanism to introduce good laboratory procedures as well as procedures that have wide use in technological industries and research laboratories.

The different measurements done by student's action in the hydrodynamic tunnel and in the water tank have awaked great motivation in undergraduate students of fluid mechanics.

Other attractive point of this laboratory class is related to the use of sophisticated pieces of instrumentation. In fact, the use of "real instrumentation" like digital processing, constant temperature anemometer and the hydrodynamic tunnel in order to obtain fluid flow velocity, turbulence and other important parameters in a laboratory class, in opposition to demonstration-only experiments, highly increases the student's motivation to grasp a difficult and complex subject. In this way, the use of HWA as a teaching tool has proven to be very important to attain the goals set by the fluid mechanics instructors in engineering undergraduate studies.

ACKNOWLEDGMENT

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