FLOW PAST A SPHERE AT MODERATE REYNOLDS NUMBERS

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Abstract. A steady incompressible isothermal flow past a rigid smooth sphere in a infinitum medium is experimentally investigated for Reynolds up to 3000 in this effort of work. All test have been carried out in a vertical low-turbulence hydrodynamic tunnel with $146 \times 146 \times 500$ mm of test section, operating by gravitational effect in continuous mode, utilizing a smooth plastic sphere with 35.5 mm of diameter (blockage ratio less than 5.4 %). Flow visualization by direct liquid dye injection and hot-film anemometry have been utilized in order to determine, qualitatively and quantitatively, the flow structure and turbulence characteristics in the wake. Velocity profile, turbulence level, recirculation bubble length and the detachment angle behavior in function of Reynolds number have been determined. Results for Reynolds number up to 3000 have been compared with data obtained by experimental and numeric techniques showing good agreement.

Keywords. *Sphere, Strouhal, Flow visualization, Wake, Hot-film anemometry*

1. Introduction

The wakes of spheres have received a great deal of attention, since the theoretical solution proposed by Stokes in 1851 relative for the creeping flow around a sphere. Nowadays, many researchers are carrying out exhaustive studies relative to incompressible isothermal viscous flow around spheres without rotating movement in an infinite medium, mainly through by experimental efforts. Wakes behind a sphere are encountered so frequently in engineering applications implicating that a large amount of research have been conducted and massive amounts of data have been accumulated. Extensive steady wake flow studies for axisymmetric numerical solution for a sphere have been reported by several authors. For example, Tomboulides & Orszag, (2000) produced numerical results for the toroidal recirculating wake length (L) and boundary layer separation angle (θ). Obviously, these results should be carefully handled because of the steady flow character admitted in the solution. It is well known, according to different works, the existence of a transition to unsteady wake occurring in Reynolds about from 130 to 210.

More recent experiments and numerical simulations have also added to our knowledge on the various complex configurations that the sphere wake undergoes as the Reynolds number is increased. Based on these studies it is known that vortex shedding in the sphere wake occurs for Reynolds numbers greater than about 300. As the Reynolds number is increased beyond this value the vortex shedding process goes through a series of stages whit increasing complexity.

Second Johnson & Patel (1999), is particularly interesting that within a small range of the onset of shedding, corresponding to a single frequency range, the visualized hairpin vortices are all shed with the same orientation. There is a definite difference between this three dimensional structure and the alternately shed vortices behind a two dimensional body. Experimental visualizations have provided some insight into the geometry of the process but finer details and the actual dynamics remain unclear. Mittal (1999) shows that the only feature of the wake in this regime is that it seems to exhibit symmetry about a plane passing trough the wake centerline.

Unfortunately, the research results about the vortex shedding from a sphere differ from report to report. Second Sakamoto & Haniu (1990) those discrepancies must be pointed out due to the fact that vortex formation mechanism has not been properly clarified.

The measurement velocity profile in a wake produced by a non spin smooth sphere for Reynolds number (Re) up to 3000 has been carried out in this work by processing the output velocity signal obtained by means of hot-film anemometry. Additionally, still photographic images have been captured for several different wake flow structures and measurements of the boundary layer detachment angle (θ) and the bubble length (L) have been also determined from the digital analysis of the pictures.

2. Fluid flow regimes configurations of a sphere

The wake structure behind a long circular cylinder is much studied, see Gersten, (1983) and Coutanceau & Defaye, (1991), two excellent reviews of the flow around circular cylinders with high aspect ratio. A great deal of attention also has been devoted to the problem of the low aspect ratio cylinders with free ends conditions – i.e., without end plates or other manipulation device to provide parallel vortex emission. The sphere appears as the limiting case of the geometry of cylinders with two free hemispherical ends. Unfortunately, according to Mittal & Najjar (1999), the studies of the sphere wake that have been done up to date have shown that the vortex topology and shedding process are significantly different from that found in the circular cylinders. In the last years, an extensive experimental and numerical research have been conducted in this field producing a vast amount of accumulated data.

The Reynolds number, $Re = r \; V D / m$, – based in the undisturbed upstream velocity (V), the sphere diameter (D) and the cinematic viscosity (n) – can be used as a primary parameter to classify the flow around a sphere. The flow regimes for a single sphere in an infinitum medium can be described, in accord to Lauchle & Jones, (1998), 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 appreciable detachment is observed. These forces are proportional to the product of the viscosity, velocity and diameter of the sphere. In this situation, the Navier-Stokes differential equations can be integrated by neglecting the inertial forces. Stokes, in 1845 was the first in solving then for the case of the sphere, considering the complete boundary condition of no tangential velocity of the fluid along the sphere surface.

For 5– 20 < Re < 130, the wake forms a steady recirculating eddy of axisymmetric ring shape.

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. Multiples 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, there is another transition region where the measured low-mode shedding Strouhal numbers 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 6000 < 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.

Those Reynolds number values, described by Lauchle & Jones (1998), exemplifying the different wake configurations, show a little disagreement compared with others authors, for the same flow structures. For example, Nakamura (1976), found an attached boundary layer for Reynolds down 7.3, and for Reynolds between 7.3 and 190, the wake shows a steady toroidal recirculating eddy and only to Reynolds upper to 190 the wake shows an unsteady deformed asymmetric configuration. Taneda (1956) observed non detachment in the sphere for approximately Re < 20~25. After this Reynolds, a closed steady recirculating forms. The wake unsteadiness is observed by Taneda only for Re > 130. More recently, Tomboulides & Orszag (2000), related experimental investigation developed by several researchers who find the flow to be steady and axisymmetric up to Reynolds approximately 210. Utilizing linear stability analysis, Kim and Pearlstein, (1990), suggested that this transition from a steady two-dimension to an unsteady periodic tri-dimensional wake should appear at Reynolds of about 175. Using the same linear stability analysis formulation, Natarajan & Acrivos, (1993) found that the first transition to unsteady only occurs at Reynolds equal to 210. Mittal (1999) and Mittal *et al*. (2001) found a nonaxisymmetric steady state (or double-thread wake) which occurs at 210 < Re < 270, the wake becomes unsteady afterwards.

Experimentally, Sakamoto & Haniu (1990), in according to Lauchle & Jones (1998), observed that the hairpin-shaped vortices begin to be periodically shed when the Reynolds number reaches about 300, but they reported others authors who specified the begin of the hairpin vortex shedding occurring only to Reynolds between 350-400. Finalizing, Wu & Faeth, (1993) found a recirculating zone stable and symmetric for Re = 200, stable and unsymmetric for 200 < Re < 280, and unstable with vortex shedding present for Re = 280.

3. Experimental apparatus and procedure

Several devices and instrumentations can be utilized for wake sphere studies. A horizontal tow channel using a digitally controlled stepping motor driving an underwater sphere is employed by Lauchle & Jones (1998) and by Masliyah (1972) using spherical models, rigidly fixed in the carriage, immersed in polyethylene glycol. Wu & Faeth (1993) utilize a vertical tow tank and the flow velocity fluctuation measurements have been carried out using laser Doppler anemometry. In both cases, horizontal and vertical tow tanks, the sphere has been moved by a carriage mechanism, generally activated by an electrical step motor. Sphere wake studies have been carried out also utilizing a vertical water tank. In this case, the water remains in rest and the sphere is launched in free fall. Generally, the free fall studies are carried out utilizing flow visualization techniques; for example, see the work of Nakamura (1976). This is a very simple device and the images captured are generally very beautiful. In this present effort of work, we have utilized a hydrodynamic tunnel linked with flow visualization techniques and hot-film anemometry. A detailed description of the experimental setup utilized is showed next.

3.1 The vertical hydrodynamic tunnel

All experiments were carried out in a low-turbulence pilot hydrodynamic tunnel with 146x146x500 mm of test section operates by gravitational effect. An extensive description of this apparatus can be found in the publications of Lindquist (2000). A sketch of this device is showed in Fig. (1).

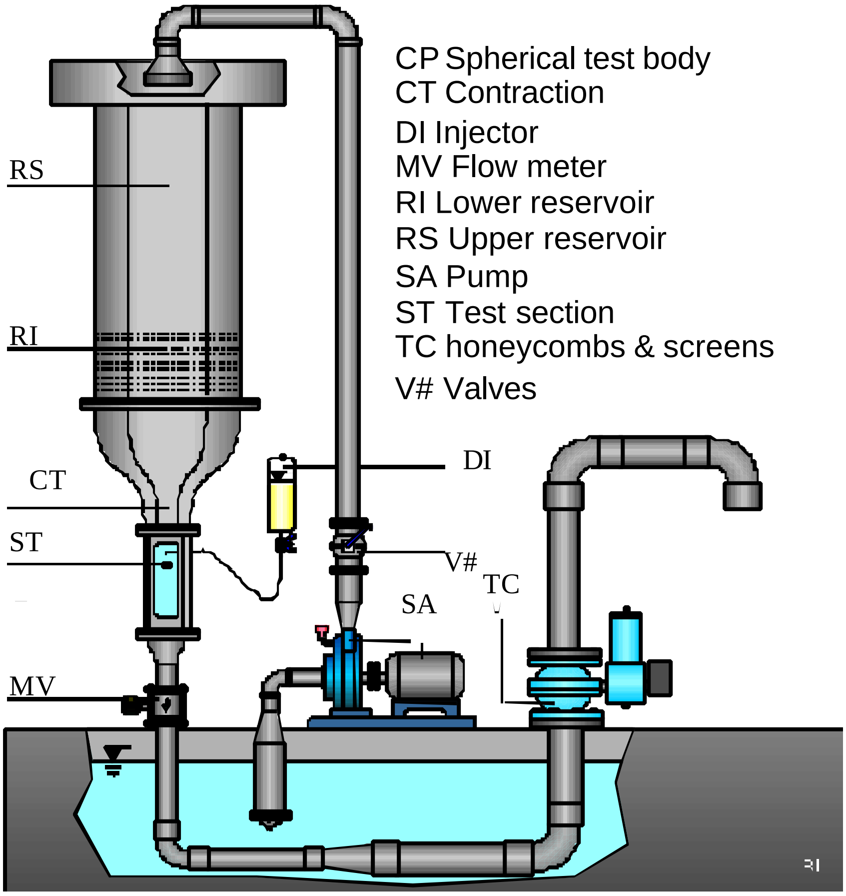


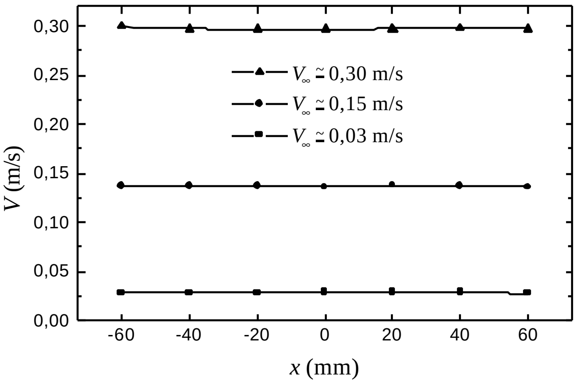
Figure 1. The low-turbulence vertical hydrodynamic tunnel.

The test sphere was a 35.5 mm of diameter smooth plastic ball (±50 µm radius tolerance, sphericity within 50 µm, and surface roughness less than 15 µm). The test section of the tunnel has 0.186 m^2 of cross section area, producing a blockage ratio of only 5.4 %. The sphere was mounted on a 125 µm of diameter stainless-steel wire which passed horizontally through its center and sealed with polyester resin. The wire was mounted in tension between two walls of the test section. The arrangement was sufficiently rigid so that sphere vibrations during the test were not detected.

3.2 Measurement of the free stream velocity

In aerodynamic tunnel Pitot tubes are frequently employed for measurements of flow velocity. In a hydrodynamic tunnel it is very difficult to measure the free stream velocity using a Pitot tube when the velocity is lower than 1 m/s. Pitot tube readings, for those small velocities in water medium, is imprecise because of the very small values of the differential pressure. Approximately a century after the advent of the hot-wire anemometry, this powerful tool remains an effective flow velocity measurement method. On other side, the current use of hot-film anemometry found several restrictions in low velocity in a hydrodynamic medium. The principal problem is caused by the thermal convection effects provoked by the temperature difference between the hot-film probe and the water medium. Many problems of calibration loss are frequent related in water medium due to impurities, dissolved salts and free-ions present in the liquid flows, notably in tap water. Impurities are undesirable substances that tend to adhere on the probe surface, principally when the flow velocity is very low, changing the calibration setup. The free-ions and dissolved salts react with the probe material provoking the metal rupture. Additionally, the hot-film anemometry system shows a high sensibility to small fluid temperature variations in low velocity, in other words, a small fluid temperature variation may to provoke a sensible variation in the output velocity signal. Of course, much attention in technical literature have been dedicated to hot-wire probe measure in air in contrast with measures performed in low velocity water medium using hot-film probes. Eguti *et al.* (2002) shows several detected difficulties in hot-film measurements realized in low velocity water medium. In this situation careful measurements should be carried out in very well controlled conditions and measurement repetitions is needed in order to obtain a reliable data set.

The free flow velocity profile and the correspondent relative turbulence level (R_t) in the test section of the hydrodynamic tunnel, measured by hot-film anemometry are showed in Fig. (2), showing a flat profile and a low relative turbulence level.



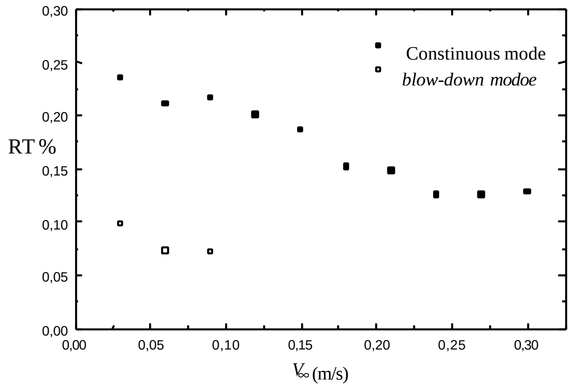


Figure 2. Free stream velocity profile and relative turbulence intensity in the test section of the tunnel.

In all tests performed out, the non-perturbed velocity upstream the test model has been obtained using a *Yokogawa* electromagnetic flowmeter assembled downstream the test section. Measuring the volumetric flow rate and knowing the cross-section area at the test section is possible to obtain the free velocity. An estimation of the errors associated to thefree stream velocity showed to be less than about 2.0%, when compared with data obtained by hot-film anemometer.

3.3 Flow visualization

The observation of the wake configuration for the sphere has been carried out using flow visualization techniques. The flow past the sphere in the hydrodynamic tunnel was visualized using an opaque black liquid PVA dye. This liquid dye was injected into the test section using a rake of hypodermic needles with 0.7 mm of external diameter. After the liquid dye was injected for a specified time period, sufficient to color all the flow around the sphere, the injection was suddenly stopped and the rake of stainless tubes removed from the flow field in order to avoid any possible disturbance generated by it. After some seconds, the clear flow field washes the test section, except in the region delimited by the wake, because in this region the flow velocity is sensibly lower than in the external region out the wake. This procedure permits to observe the wake for a short period of time, but enough to register the image. This technique is indicated to visualization in hydrodynamic medium in very low velocity (few centimeters per second). Fluorescent cold lights generate a back lighting diffuse illumination. The still images have been captured utilizing a photographic CCD *Sony* camera equipped with a zoom macro lens with 1600×1200 pixel and 8 bit of colors (256 tons of gray) enough to obtain all technical information developed in this work.

Only low level of digital image processing has been performed out in order to obtain an image enhancement, cut of non interest image parts and small retouching. The recirculating length (L) and the detachment angle (θ) have been obtained directly by manual image quantification using calibrate images.

3.4 Measurement of wake velocity using hot-film anemometry

The flow velocities past the sphere have been obtained with a constant temperature anemometer *Dantec* - StreamLine 90N10, equipped with one probe 55R11. Before each velocity calibration in a special apparatus, the hot film probe has been adequately cleared. For this experience, the hydrodynamic tunnel was operated in continuous mode. The displacement of the probe along the traverse axis of the test section has been determined with a milimetric screw coupled to the positioner device. The transverse mechanism utilized for probe positioning was manually moved yielding an accuracy of 0.01 mm. Initial probe position has been careful obtained by optical measurements. The uncertainty of the initial probe position has been less than 0.5 mm.

Figure 3. shows a lateral window view of the test section where the hot wire probe was inserted. The points A, B, C, D show the several probe positions (Y) utilized in the tests. The relative distances of hot-film probe in relation to the sphere center were, respectively 1.75 D, 2.45 D, 3.15 D and 4.50 D.

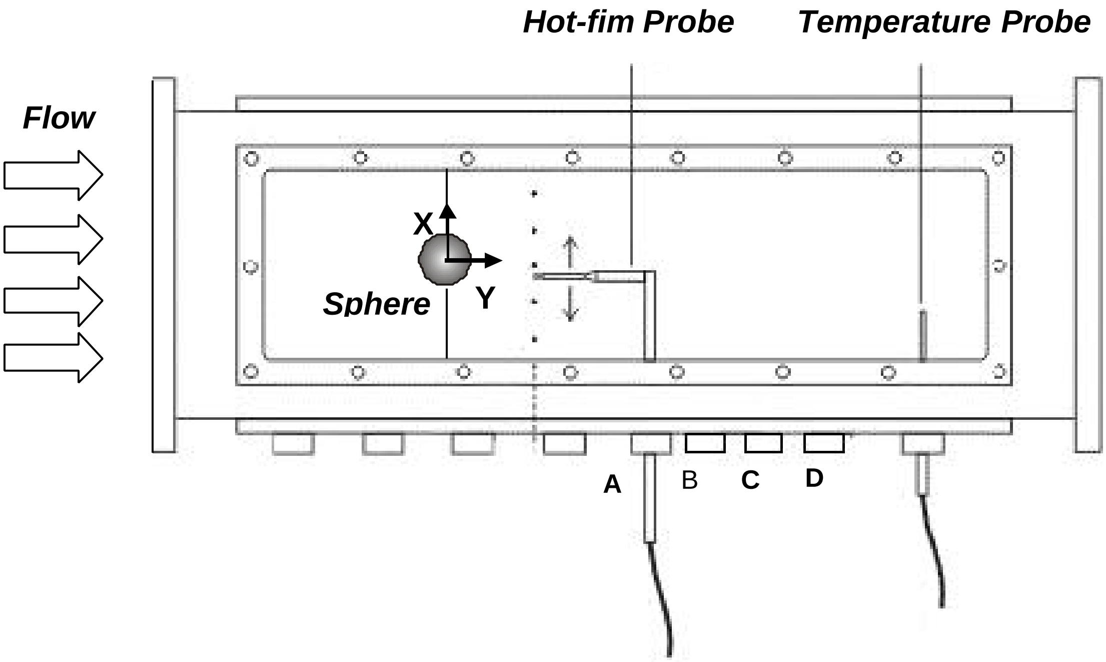


Figure 3 Experimental assemble utilized in the test section.

The sample frequency utilized has been of 100 Hz and the sampling of 4096 points, yielding to a test time of 40.96s. Each measurement has been repeated at least 3 times, and the average values has been calculated. Measurements have been carried out for Reynolds number of 1000, 2000 and 3000.

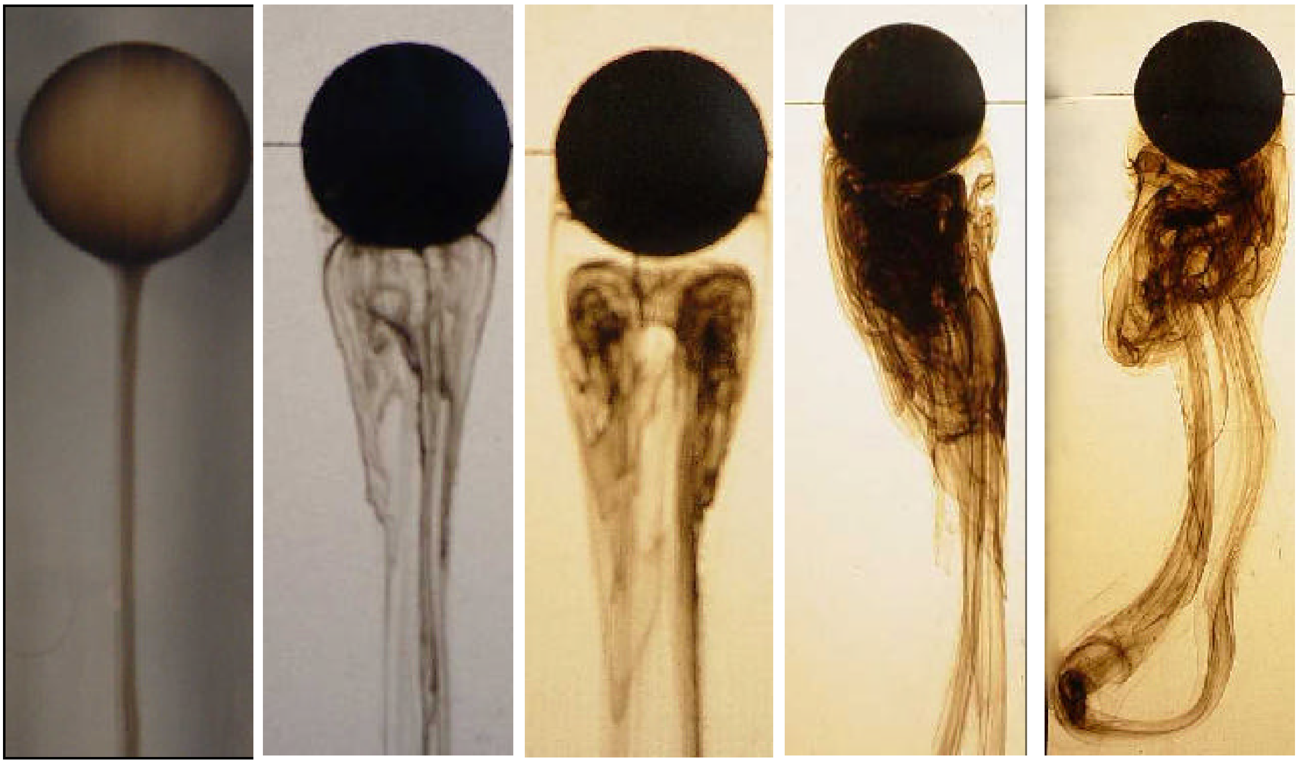
The vortex frequency observed in the sphere wake has been determined using a Fourier Fast Transformer available in *Matlab* software. Identical to results obtained by other researchers, the vortex shedding frequency shows a very high dispersion. In order to understand this behavior, an effort of work has been carried out.

4. Results and discussions

In the hydrodynamic tunnel flow visualized still images in close view have been captured revealing several flow details. A collection of those images can be observed in Fig. (4). Fig. (4 a) depicts a symmetrical flow without an appreciate boundary layer detachment for a relative low Reynolds number of 28. In this case, the wake shows a notable stability, remaining steady. In Fig(4 b), for a higher Reynolds number (Re = 251), the boundary layer detachment is notable and easily detectable. The detachment angle (θ) can be directly obtained from digital image processing utilizing an adequate calibrated image. In this flow configuration the wake is steady and relatively symmetrical.

In Fig. (4c), for a Reynolds number of 297, a recirculating bubble in a ring (or toroidal) shape has been formed. This recirculating bubble still shows a steady flow. For Reynolds still higher (Re = 367), showed in Fig. (4d), a non symmetrical unsteady wake is visualized. In this case, the vortex shedding frequency, obtained by hot-film measurements, shows a notable fluctuation, in agreement whit the technical literature. Utilizing flow visualization it is possible to determine the vortex shedding frequency only by visual efforts in very low flow velocity. In this situation, in equal mode, a vortex shedding frequency a considerable dispersion of results.

Fig. (4e) shows a characteristic sphere hairpin vortex observed in Reynolds equal to 557. The stainless steel wire used to fixe the sphere in the test section is visible. The small diameter of this wire provokes minimal flow disturbs, according to flow visualization observations.



(a) Re = 28 (b) Re = 251 (c) Re = 297 (d) Re = 367 (e) Re = 557

Figure. 4 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) and the recirculating wake length (L) depicted in Fig. (5). The captured still images have been calibrated using a normalized image. The symbol (L/D) represent the ratio between the recirculating wake length and the sphere diameter.

In Fig(5a), it is observed two regions where the detachment angle is constant. In Reynolds number about 250, the detachment angle increases, entering in the transition region.

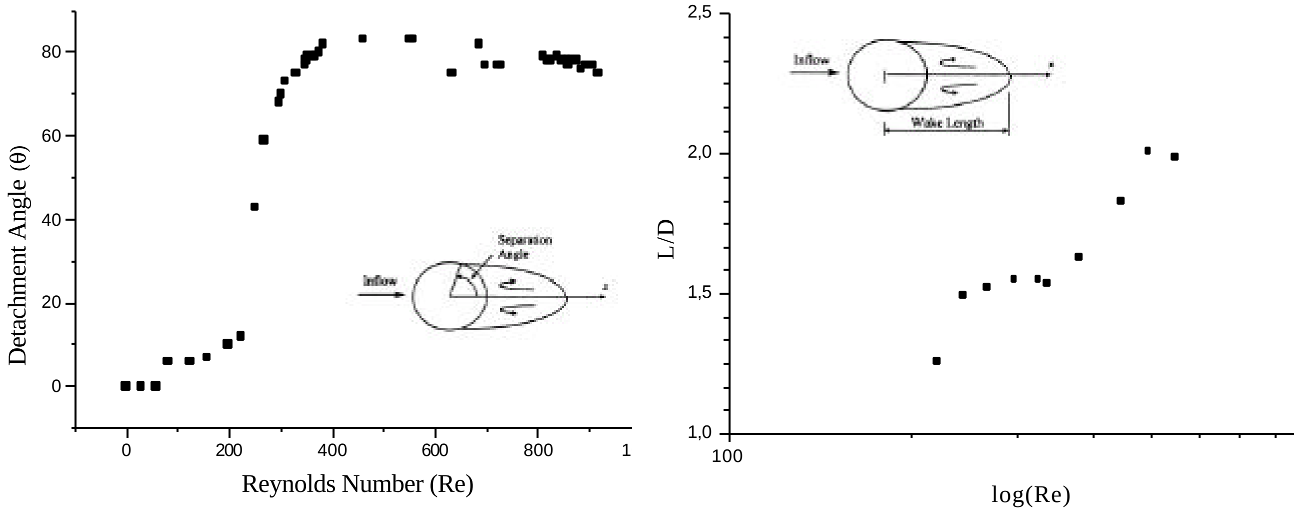


Figure 5. Detachment angle (θ) and length bubble recirculating (L) in function of Reynolds number

Figure (6) shows the velocity profiles and relative turbulence level, for Reynolds number of 1000, 2000 and 3000 for several positions behind the sphere.

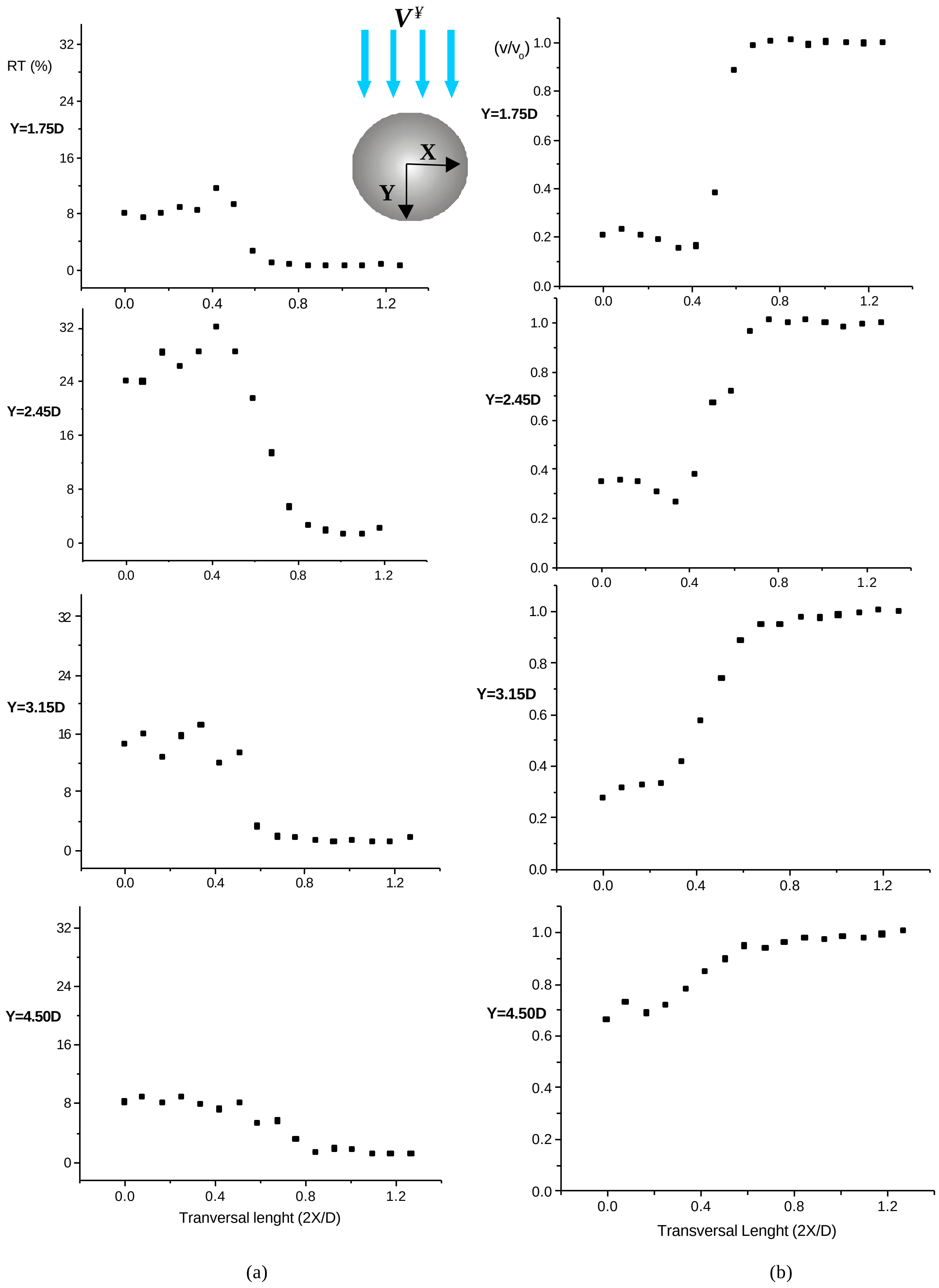
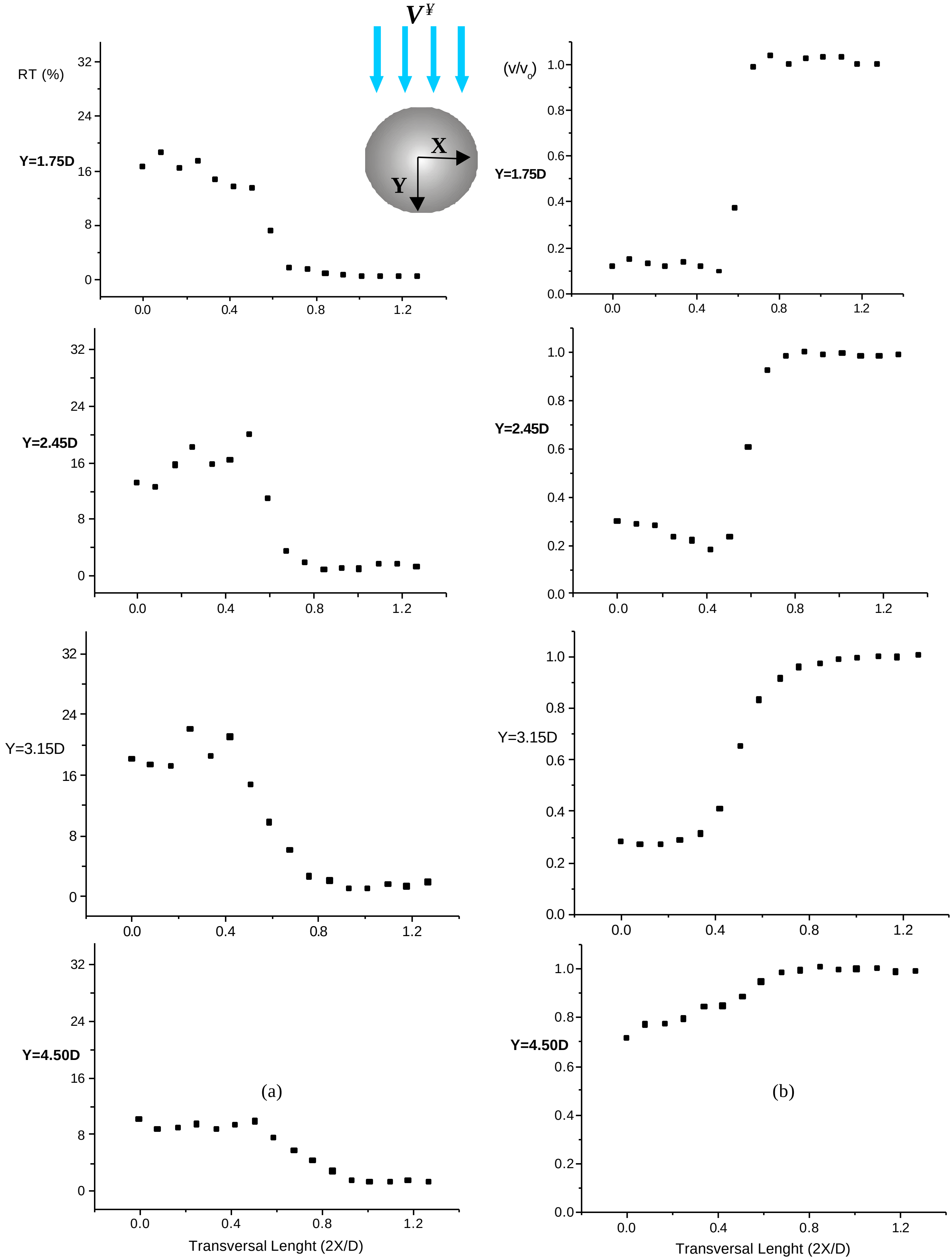
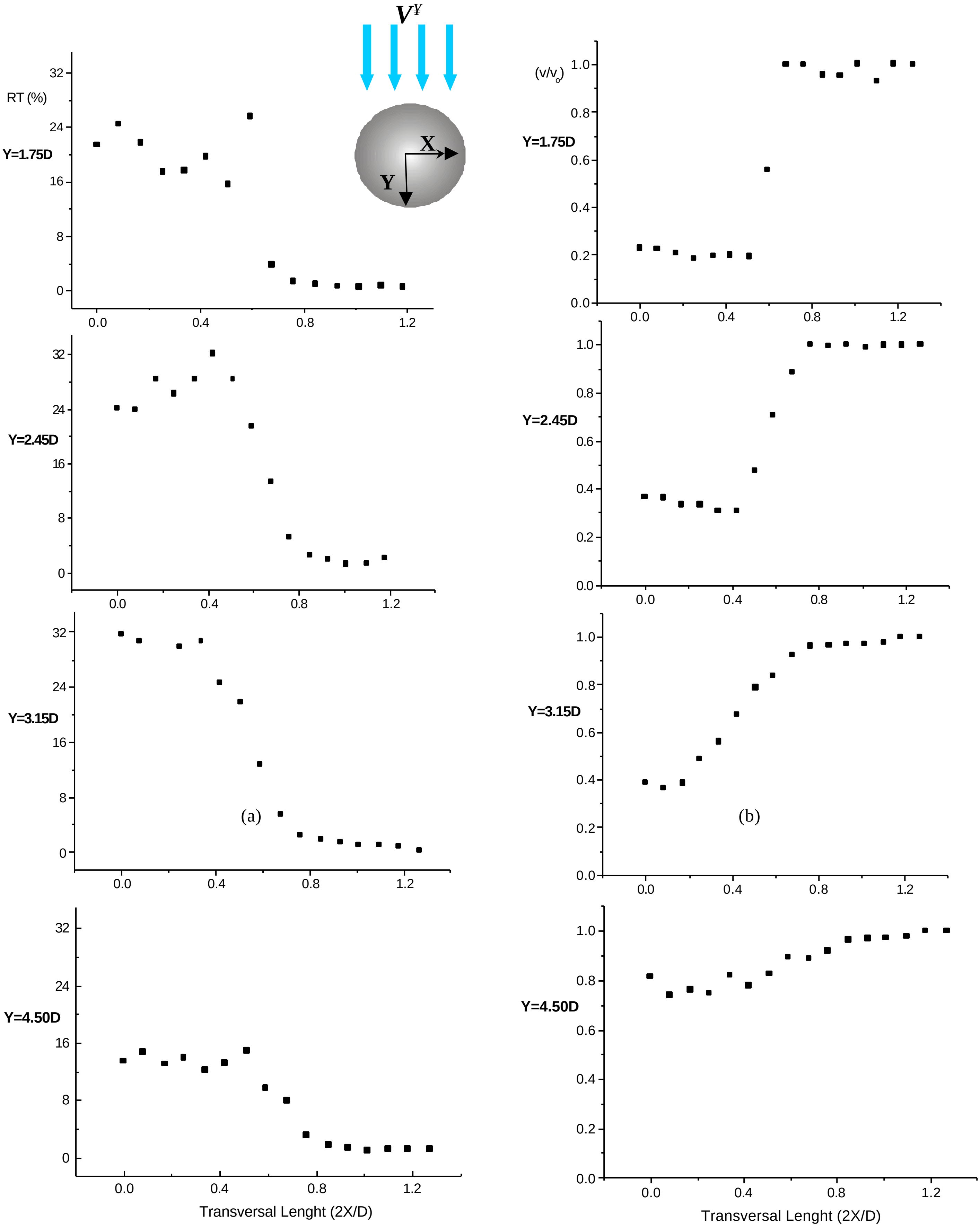


Figure 6. Relative turbulence level (a) and velocity profiles (b) as function of the transversal lenght, for Reynolds number 1000.



(a) (b)

Figure 7. Relative turbulence level (a) and velocity profiles (b) as function of the transversal lenght, for Reynolds number 2000.



(a) (b)

Figure 8. Relative turbulence level (a) and velocity profiles (b) as function of the transversal lenght, for Reynolds number 3000.

. Conclusions

The present investigation has been undertaken to provide information about the structure of the flow near spheres at intermediate Reynolds numbers. Flow visualization, performed in Reynolds up to 1000, provides qualitative and quantitative information about the flow topology. Recirculating bubble, angle of detachment and vortex shedding has been also included. Measurements of the flow profile and *rms* velocity fluctuations downstream the sphere has been performed out in the Reynolds range of $1000 - 3000$.

Hot-film anemometry is a useful tool for fluid mechanics measurements. Utilizing tap water and a 50 μm filter, several problems have been found in respect to probe calibration. A loss of calibration has been observed in all the tests. This is a delicate situation because it requires a excessive repetition of the tests.

Hydrodynamic tunnel and the apparatus for probe calibration utilize a clean reservoir with $3m^3$ of volum in order to keep the water temperature constant along of the time and to avoid problems relative to temperature fluctuations.

A high turbulent wake has been observed, with very low frequencies. The dominant frequency value obtained in the wake shows a sensible fluctuations along the time. Near the sphere, the turbulence intensity level in the wake shows high values and tends to minimize fast far the sphere.

We observe, in accord to, Fornberg, (1988) that the toroidal wake length (L) vary approximately as logarithmic for the Reynolds number (Re) greater than 75.

Finalizing, the present results are useful date to numerical simulation in order to validated new computations codes.

6. Acknowledgement

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