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## The behaviour of PIV tracers in a homogeneous environment

M. MANFRIN(\*)

*Dipartimento di Fisica Generale, Università di Torino - Torino, Italy*

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**Summary.** — The Particle Image Velocimetry (PIV), a technique which is today completely developed, relies on the measured light scattered by suitable particles suspended in the flow. The choice of the proper tracers depends on the experiment type too: in the stratified one, according to the long time required for the preparation, it is very important to be sure to have the correct seeding density at the measurement time. For this reason it is very important to know well the tracers behaviour. In fact it can depend not only on the tracers type and size but also on the interaction with the environment in which they are used. In this work a preliminary study has been developed in order to check the tracers behaviour under different water conditions and with a simplified experimental set-up.

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### 1. – Introduction

In order to investigate the (kinematic and dynamic) behaviour of complex flow fields with non-intrusive diagnostic methods, in the nineties, the Particle Image Velocimetry (PIV) had a vigorous and deep development, allowed by the drastic improvement in the computational power and in the appearance of digital cameras [1-4].

This technique, which is today completely developed, relies on the measured light scattered by suitable particles suspended in the flow in order to provide the velocity information for continuous media like liquids or gas. The illuminated field of view is captured by a camera and the resulting image is processed with various techniques: these are based on the computation of the cross-correlation of parts of two different images that have a short (according to the investigated flow) time lag between them.

The result of this procedure is a velocity field that allows a description of the flow properties; the theoretical accuracy of the computed fields is limited by the ability of the scattering particles to follow the instantaneous motion of the fluids.

So, a compromise is necessary between reducing the particle size in order to improve the flow tracking and increasing it so as to have more light scattered and consequently a better quality image [5].

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(\*) E-mail: [manfrin@to.infn.it](mailto:manfrin@to.infn.it)

For a reliable PIV, the proper flow seeding is a key point, leaving out of consideration the laser power. During the experimental set-up care should be taken in choosing the proper tracer size which can depend on the distance and dimensions of the view fields, on the camera types and so on. Moreover, in order to investigate all the acquired images with the same spatial accuracy, it is very important to have a uniform seeding in the fluid.

This feature is not too difficult to achieve when performing experiments that reproduce stationary/high speed flows (induced, for example, by a pump) that mix up the fluid. On the other hand, it becomes particularly important when examining decaying or stratified flows reproduced in cylindrical tanks. In fact in this type of facilities flows are usually generated by a sudden variation of the rotation period of the tank.

In this case, when performing an experiment, as a rule it is necessary to gain the solid body rotation before varying the angular speed in order to get the proper flow speed. According to the water depth and to the roughness of the tank wall, the time required for this operation may span from tenth of minutes to several hours.

During this period, when the turbulence in the fluid is weak, it is very important to hold the tracers in suspension and not to let them settle on the tank floor. Moreover, when performing experiments with two or more density stable stratified layers (density variation can be obtained by adding different quantities of salt to water) the solid body rotation is acquired at the cost of a longer waiting period. As a matter of fact, the necessity to keep interfaces well defined, preventing mixing, renders a very smooth acceleration of the tank necessary and the stable stratification inhibits the vertical transfers of momentum, delaying its turbulent and forced transport. So, the layer that is in contact with the floor will reach the solid body rotation by the expected time, while the upper, less dense, layer will take much more time (at least 3–4 times the time spent by the bottom layer).

Then, especially in the stratified case, the tracers should be kept in suspension for the proper amount of time, in order to shoot the frame with the correct seeding density and distribution.

## 2. – Experimental tests

In 2005, the Department of General Physics of the Turin University built a large rotating hydraulic tank (diameter of 5 m) that was created for experimental fluidodynamics studies especially involving the presence of Coriolis forces.

This tank, which can be filled up with a maximum of about 90 cm of water or any other suitable fluid, has the capability to rotate at very high angular speed: it can reach 20 rev/min.

The laboratory, in which the rotating tank is installed, is equipped with different cameras: they can mount different lenses allowing the study of fields of view ranging from  $3 \times 3 \text{ cm}^2$  to about  $1 \times 1 \text{ m}^2$ , and letting the researcher acquire images with a rate spanning from a few frames for each second to many hundreds.

The tracers that are used in the laboratory are microfine polyamide powders (Atofina Orgasol): they have a round, but not regular (fig. 1), shape and their sizes usually range from 5 to 60 microns; they have a bulk density of  $1.03 \text{ g/cm}^3$ , and an apparent<sup>(1)</sup> density ranging from 0.215 to 0.425 according to the particle sizes.

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<sup>(1)</sup> The “apparent” term refers to the density value obtained from the ratio of the weight and the volume of tracers: when particles are in a powder form, due to the air inserted between them, this value does not generally coincide with the density of the material.

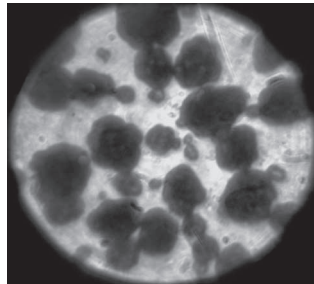


Fig. 1. – Images of 30 micron tracers obtained with an optical microscope: the shape is rounded but not spherical.

It should be taken into account that the real diameter of the tracers does not correspond to the nominal fixed value, but to an asymmetric bell-shaped distribution of sizes centered upon the nominal one: for example, a sample of 60 micron particles has 10% of them with a diameter less than 40 microns and 5% with a diameter greater than 80 microns.

Tracers, before their use, are prepared by treating them with a wetting agent (Agepon Agfa) that reduces the water surface tension and lets the particle be easily suspensible.

In order to test the behaviour of the tracers, a preliminary study has been developed in the research work described here, using a small glass tank that can be filled up with a maximum of 40 liters, a light source, a collimator lens, and an instrument (a luxmeter that measures the incoming total radiation) connected with an acquisition system: the aim is to measure the transmitted light according to the particle quantity in suspension (see fig. 2).

The choice of glass has been made in order to reduce the environment influence on the analyzed solution: in this way there is no exchange of any substances between glass and water (salty or not) but only between water and air; this possibility can be reduced by using a suitable cap.

After having added the particles to water, the light transmitted will drop to a given value that, later on, will rise to almost the original one according to the vertical drifting rate of the tracers: the final value will be not equal to that of the pure water one, because of the presence of the smallest particles (belonging to the left tail of the bell-shaped distribution) which remain in suspension indefinitely.

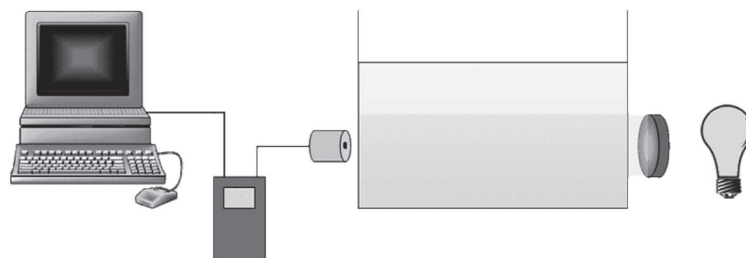


Fig. 2. – Sketch of the experimental set-up.

TABLE I. – *Time spent by the particles to reach a 50% value of the initial concentration.*

Tracers	Fresh tap water $\rho = 0.9990 \text{ g/cm}^3$	Salty water I $\rho = 1.0200 \text{ g/cm}^3$	Salty water II $\rho = 1.0300 \text{ g/cm}^3$
60 micron	52'	3 h 5'	18 h 40'
30 micron	4 h 20'	8 h 10'	$\sim 4$ days

It is important to underline that the “proper” amount of particles should be used: if the usual tank seeding is used, the experimental apparatus is not able to measure with a good accuracy the variation in the transmitted light.

In order to better clarify this feature, it should be taken into consideration that, in the tank, usually 60–80 g of particles are added to 8 cubic meters of water (operational case): the extinction rate of light in a short path (like the one of our glass tank) is consequently very small and will require a very sensitive and expensive instrument.

On the other hand, by adding a greater amount of particles (about 20 times that used in the operational case) it is possible to use a normal instrument and to perform a visual check of the tracers’ behaviour which, however, is more difficult in practice. For tests, a fixed quantity of 15 l of water with the addition of 5 g of wetted particles (corresponding to approximately 2.5 g of dry ones) were used.

A few trials, performed in order to verify the stability of the solution, showed a very slight progressive increase in its opacity, increase that became faster and greater after about 10 days (it can depend especially on the environmental temperature and on the time elapsed since the preparation of the particles with the wetting agent). So, water in the glass tank can be considered free of the influence of biological features (like bacteria and algae) for about 10 days after which it is necessary to throw out the liquid, wash the tank and make the proper solution again.

In order to be able to compare results coming from different runs (although with the same characteristics), the particle quantity still in suspension is expressed as a percentage, according to the equation

$$(1) \quad \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} \cdot 100,$$

where  $x_i$  is the current instruments reading,  $x_{\max}$  is the final maximum reading when there is no more variation in the signal and  $x_{\min}$  is the starting value as soon as the solution has been well mixed and has reached a quiet status.

The above equation, by choosing as the maximum value the stationary value reached after a long enough time and not the background value, permits the comparison of different runs performed with possibly different light conditions. Moreover, the use of this equation makes it possible to take into account the fact that the smallest particles (according to the bell-shaped size distribution) make the water less transparent than fresh water, thus affecting the luxmeter readout.

Three different cases were taken into account in this experiment: water density of 1.00 (fresh tap water), 1.02 and 1.03 g/cm<sup>3</sup>, with 2 nominal sizes of particles, 60 and 30 microns. The data in each case study has been acquired 3 times in order to assess its validity and to obtain a smooth curve resulting from the average of the 3 runs. For the same purpose a running mean was applied.

Finally, the original data measured by the luxmeter were best-fitted in order to obtain an analytical description of the tracers behaviour: table I and table II summarize the results.

TABLE II. – *Best-fitted curve of the behaviour of 30 and 60 microns particles ( $x$  is time expressed in hours).*

Density	60 micron particles	30 micron particles
Fresh tap water	$\frac{1.492x^2 - 0.053x + 0.61}{x^2 - 0.065x + 0.826}$	$\frac{1.282x^2 + 17.92x + 85.13}{x^2 + 7.92x + 119.8}$
Salty water I	$\frac{1.688x^2 + 3.78x + 9.47}{x^2 - 2.54x + 14.26}$	$\frac{0.62x^2 + 47.63x + 665.6}{x^2 + 7.06x + 862.4}$
Salty water II	$\frac{-8.6 \cdot 10^{-5}x^3 + 0.0121x^2 + 1.15x + 9.5}{9.5x + 11.96}$	$0.03902x + 0.7243$

Plots represented in fig. 3 have been drawn by applying eq. (1) to the fitted values. As a maximum time range,  $x$ -axis has been cut after about 60 hours because longer time has no practical interest. In the case of density  $1.03 \text{ g/cm}^3$ , the maximum value was reached after about 7 days.

Looking at fig. 3, the behaviour of the two tracer sizes analyzed appears clear: 60 micron tracers fall very quickly in pure water: after about 4 hours all of them are on the floor, while the 30 micron ones take more than a day.

Increasing the water density by adding industrial sea salt, the falling rate slows very much, but not uniformly: when the density is  $1.02 \text{ g/cm}^3$ , the falling time increases more for the 60 microns particles. The rate of increase is of about 4 in the fresh and heavily salted case dropping to about 2.5 in the moderate salty water.

When using a density of  $1.03 \text{ g/cm}^3$ , the falling rate slows yet further and the smaller tracers almost stop their movement showing a temporal behaviour that becomes almost linear at least for the first 5 days.

This is the confirmation that, although the nominal density is 1.03, the “real” density ranges around this value. In addition to the sizes distribution, this fact could be due to the porosity in the tracer material that can be filled in a different way by salt, air and water molecules, varying slightly their density. In this last case the fact that tracers move also toward the surface should be also remarked.

The temporal behaviour can be explained by the following considerations.

If each particle is considered spherical and homogeneous, the forces acting over it will be the gravity, the buoyancy force and the friction force (Stokes effect). So, the basic equations that describe the system are

$$F = \frac{4}{3}\pi r^3 \rho_a g, \quad F = \frac{4}{3}\pi r^3 \rho_p g, \quad F = 6\pi r \eta \bar{v},$$

where  $r$  is the particle radius,  $\rho_a$  the water density,  $\rho_p$  the particle density,  $\bar{v}$  is the mean falling speed,  $\eta$  the dynamic viscosity.

Combining these three equations, the following equilibrium expression can be written:

$$\Delta\rho \frac{4}{3}\pi r^3 g - 6\pi r \eta \bar{v} = 0$$

that can be modified as

$$(2) \quad \bar{v} = \frac{2r^2 g \Delta\rho}{9\eta}.$$

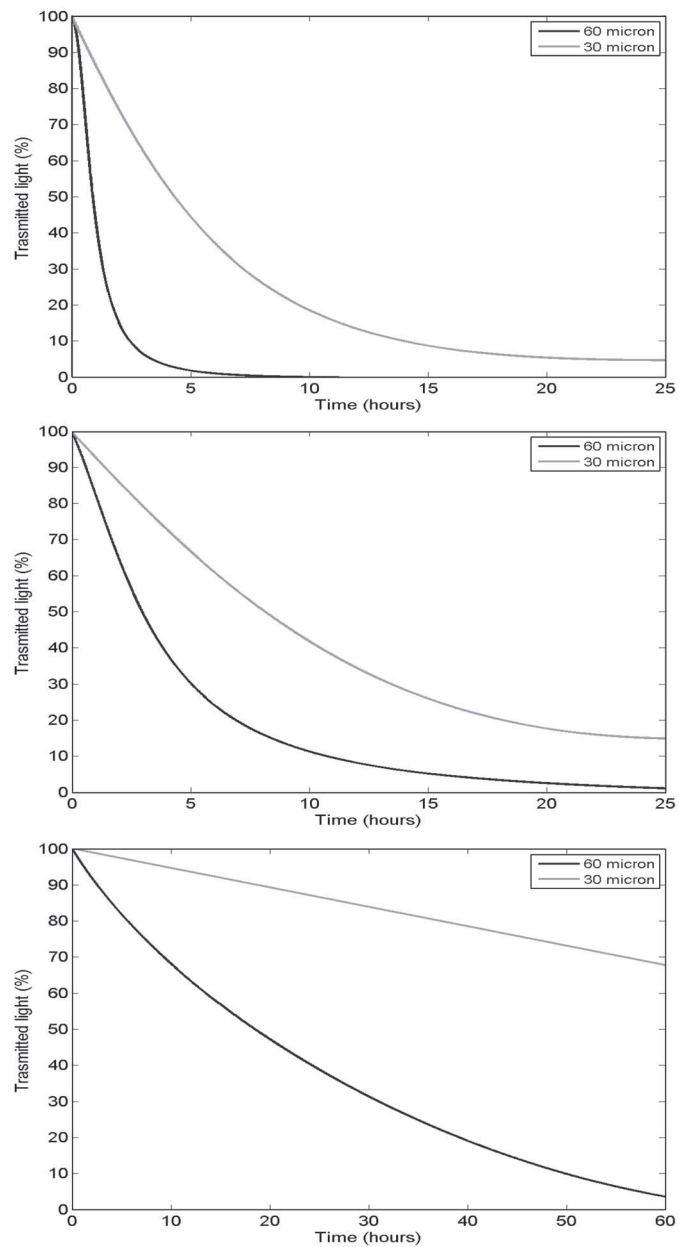


Fig. 3. – Behavior of the transmitted light as a function of time (density measured by an Anthon Paar densimeter, the associated error is  $0.0005 \text{ g/cm}^3$ ). Top: fresh tap water density  $0.9990$ ; center: salted water I, density  $1.0200$ ; bottom: salted water II, density  $1.0300$ .

TABLE III. – *Tracers falling speed: evaluated theoretically according to eq. (2) (on the left); measured (on the right).*

Density (g/cm <sup>3</sup> )	Particles size ( $\mu\text{m}$ )	Falling speed Theory (m/s)	Falling speed Experimental (m/s)
Fresh tap water	60	$6 \times 10^{-5} \pm 1 \times 10^{-5}$	$2.3 \times 10^{-5} \pm 1 \times 10^{-6}$
$\rho = 0.9990 \pm 5 \times 10^{-4}$	30	$1.5 \times 10^{-5} \pm 4 \times 10^{-6}$	$4.6 \times 10^{-6} \pm 3 \times 10^{-7}$
Salty water I	60	$2.0 \times 10^{-5} \pm 5 \times 10^{-6}$	$6.9 \times 10^{-6} \pm 4 \times 10^{-7}$
$\rho = 1.0200 \pm 5 \times 10^{-4}$	30	$5 \times 10^{-6} \pm 1 \times 10^{-6}$	$2.5 \times 10^{-6} \pm 2 \times 10^{-7}$
Salty water I	60	$0.0 \pm 1 \times 10^{-6}$	$1.08 \times 10^{-6} \pm 7 \times 10^{-8}$
$\rho = 1.0300 \pm 5 \times 10^{-4}$	30	$0.0 \pm 2 \times 10^{-7}$	$2.1 \times 10^{-7} \pm 1 \times 10^{-8}$

The last equation shows the stationary velocity that is achieved by the falling particle. A comparison of the values computed using the above expression with the experimental values can be found in table III.

The experimental values are comparable with the theoretical one, especially considering the assumption on which this calculation is based. The great difference, as previously underlined, is with the denser solution: the theoretical model fails due to the lack of homogeneity, that can be found in the tracers and alters the results in a significant way. So, in this last case the preliminary experimental tests become very important.

As a final note an important feature should be remarked: the behaviour of tracers can be affected also by substances dissolved in the water.

A few tests performed in our lab showed that unpainted aluminium is a wrong choice as base material for tanks because, especially when water is salty, it induces a strong and very fast (of the order of tenths of minutes) agglutination of the particles, causing them to fall down and making them unsuitable for any PIV acquisition.

On the other hand, paint also plays an important role: another series of tests performed over many pieces of aluminium showed that standard epoxy paints are not able to perfectly insulate the metal. After a time lag that is greater than in the “aluminium-only” case, although with a less important impact in the case of salty water, few agglutinated macro-particles appeared. The explanation lies both in the substances probably released by the paint itself and in the imperfect insulation of the metal from the salty water action.

### 3. – Conclusions

PIV is a powerful tool used to investigate flows behaviour.

When preparing an experiment that uses this technique, many features have to be evaluated: among these, the choice of the correct tracers is a key feature in order to ensure the correct seeding density at the measurements time.

In this work it has been pointed out how important it is to take into account the interaction between tracers and the surrounding environment in the PIV experiments including not only the physical aspect but also the chemical and biological ones. The researcher should be warned against unexpected behaviour of tracers and encouraged to acquire a deeper knowledge of them by performing preliminary tests when working with new tracers or new experimental set-up.

According to the author, the results obtained should be used to adjust the water density according to the desired profile in order to attain the optimal seeding density at the measurement time, considering also the possibility to add, at the beginning, more particles than those desired in order to have, at the right time, their right value.

As a final remark it should be noted that these tests were performed with the intention of finding the simplest environment. In this way there is no exchange of any substance between glass and water and a small exchange between air and water (dust falling in the water can act like "condensation" nuclei that can glue tracers together). In practice, the material of the tank (and the paint on it too) is very important in conditioning the behaviour of the tracers by releasing materials that can interact with particles, making their fall faster.

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