Experimental evaluation of a facility for jet induced flow analysis

M H Farias, A M Santos and Y B Zanirath
Fluid Dynamics Metrology Division, Scientific and Industrial Metrology, National Institute of Metrology, Quality and Technology (Inmetro), Rio de Janeiro, Brazil
E-mail: mhfarias@inmetro.gov.br

Abstract. In this work, the performance of a bench, which was designed for investigating the hydrodynamics of jets and plumes in quiescent environment is evaluated. This bench is mainly composed by a water tank with a nozzle placed at the center of its bottom. Through the nozzle, fluid is injected vertically upward into the tank. The tank, with square cross section, has a device attached to its upper edge for containing overflow. For fluid flow measurement and visualization, the optical technique Stereo Particle Image Velocimetry (SPIV) was employed and the influence parameters for the resulting flow pattern inside the tank were analyzed. The investigations showed that, in order to avoid tank wall effects to the axisymmetric jet profile, the minimum and maximum flow rate of injected liquid allowed in the stagnant environment were 0.05 L/min and 0.20 L/min, respectively. All the measurements were accomplished under the maximum water column in the tank.

1. Introduction
Jet induced flow is frequently used in industrial or technological processes and it is present in natural events. This kind of flow is highly complex[1]. Although several studies have been done for getting a best understanding on this flow behavior, more still need to be done. Improvements and advances in important areas, such as irrigation, oil and gas industry, environmental (flow in rivers, atmosphere, lake and oceans, as well as pollutant dispersion processes in these environments etc.), among others, can depend strongly on the knowledge of the hydrodynamics phenomena which occurs in jet or plume induced flow. In pursuing reliability of the measurements when detailed investigations of flows induced by jets or plumes are performed, metrological demands arise. Difficulties due to technologies capability limitations in addition to the physical phenomena complexity characteristics of the flow make the work a challenging task. In the literature, issues related to jets and plumes flows [2,3] clearly show that exists a not deeply explored field, this one concerned to improvement of measurement procedures of such complex flows, which claims to metrologist attention. So, the aim of the present work is to identify, considering rigorous metrology requirements, the applicability limits of a facility for studies of mixing process of liquids injected in quiescent liquid. The bench is a tank containing accessory for liquid overflowing storage. As the procedure of evaluating such facility requires investigations of the mixing flow inside the tank, the analysis also includes the velocity field behavior characterization for a turbulent induced flow. The experimental apparatus and accessories were designed and constructed by the Brazilian National Metrology Institute -
Inmetro researchers, whom intend to contribute for knowledge enhancement in the complex flow dynamics area.

2. Experimental apparatus and setup

2.1. The apparatus assembly

The experimental apparatus was built to analyze the dynamics of liquid mixing process driven by fluid injection in stagnant environment. In this kind of bench, an important metrological requirement which has to be fulfilled is the absence of disturbances generated by sources which are not due to the own fluid injection process. In this direction, during the design, assembling and commissioning of the bench, all scaling and configurations definitions were oriented by the criteria of minimization of undesirable influences on the flow.

The first step of the assembling task was the connection of an acrylic tank to the hydraulic circuitry, as shown in Figure 1. Externally and close to the upper edge of this tank, a device for liquid overflow catching was attached. When liquid jet is inserted into the stagnant liquid, the overflow can occur deliberately if the experiment starts under the maximum liquid column of the tank or if the purpose of the experiment is to observe the free surface in upward movement.

![Figure 1. Tank with a device for containing overflow](image)

The tank has square section of 0.5 m x 0.5 m and 0.7 m in height, with rounded edges in the top. The rounded edges were introduced with the aim of benefiting the homogeneity of fluid distribution when the liquid overflows. With the tank buttressed, the bench mounting was developed as illustrated in Figure 2. The facility after assembled is shown in Figure 3.

The reservoir was made of polypropylene and its dimensions are 0.5 m x 0.5 m x 0.4 m (L x W x H). Through a PVC pipe of inner diameter 1 inch, the suction end of a progressive cavity pump (model HD15, Weatherford\textsuperscript{TM}, Geremia) was connected to the reservoir bottom, and in the pump discharge end was installed a valve(bypass) in order to control the liquid return quantity to the reservoir and also into the tank. The work fluid was filtered water, and the flow rate was monitored by an electromagnetic flowmeter (Conault\textsuperscript{TM}). The flowmeter was calibrated in totalized volume quantity, and also in instantaneous volumetric flow rate. The nozzle injector, with capillary length to diameter ratio of 10 (length = 10 mm and inner diameter = 1 mm), was made in 304 stainless steel. All the pipeline have inner diameter of 0.5 inch.
2.2. Velocity measurements by particle image velocimetry

In the Particle Image Velocimetry-PIV method, the instantaneous fields of the velocity vector are determined through the displacement of fine particles which move following the fluid motion \cite{5,6}. The PIV technique consists of two pulsed light sources (sheet of light) which illuminate tracer particles in the flow field, and then high speed cameras, CCD or CMOS, acquire sequential images of the scattered light from the particles. By using mathematical tools as cross-correlation or auto-correlation, the displacement field is determined as an average displacement of particles within small regions (called interrogation areas) of the image plane captured during a known time interval between the acquisition of two images \cite{7}. It is possible to determine the velocity vector on 2 or 3 components. In most of literature reference, the PIV technique is considered non-intrusive, but according to metrology concepts, in fact it is intrusive, since the technique demands insertion of particles in the flow.
In this work, the system employed was 3D (StereoPIV) from LaVision\textsuperscript{TM}. The system is a double cavity Nd:YAG laser, with power of 120 mJ/pulse at 532 nm, in which two laser sheet pulse synchronized with two high speed cameras aperture. The trigger signal for both Nd:YAG laser is given by the LaVision\textsuperscript{TM} programmable timing unit (PTU), manually or by computer control. The integrated cameras of the system (LaVision\textsuperscript{TM}, Imager Pro X 2M, 1648 x 1214 pixel resolution, from 30 frames/s up to 135 frames/s) are based on a charge-coupled device (CCD) sensor with high resolution and high sensitivity. In the experiments, glass filter high pass (cut-off at 540 nm) were installed in each camera, and both cameras captured images in double frame, with inter frame time of 5500 $\mu$s. As tracer, particles in sizes between 20 $\mu$m and 50 $\mu$m of Rhodamine B (PMMA-Rhodamine B aqueous suspension 100 g/400mL) were used. 

The system is operated by DaVis\textsuperscript{TM} 7.2 software, and the particles shift is calculated in the post-processing for determining the velocity vectors and associated turbulence characteristics of the flow field.

2.3. Experimental procedure and data processing

Before using the PIV system for measurement of the resulting flow field characteristics inside the tank, it was necessary to determine the minimum and maximum water flow rate on which the pump of the bench could be operated. Among the acceptance criteria for flow rate operation limits, two were detached: a) the need of stability maintenance for the flow rate along the time and b) stability of the pressure level at the pump exit during the running experiments. For the minimum water flow rate identification, by considering that one critical condition for the pump operation is the minimum value of the motor pump speed on which none fail or stop due to motor temperature increasing could occur, tests towards accomplishing this requirement were performed. In this case, as the worst situation was set up when the bypass was totally closed (see the bypass in Figure 4), the limits were experimentally searched out under this condition.

![Figure 4. Detail of the bypass](image)

Although the minimum water flow rate had been pursued in accordance to the aforementioned conditions, after to find this value it was important to verify if in such minimum flow rate the PIV system could detect movement of the tracer particles in the induced flow inside the tank. Thus, to make sure the minimum flow rate achieved in the previous step was enough, a comparison between two subsequent images of the flow captured by the PIV cameras was conducted. If the frequency of image acquisition is coherent for getting details of the flow behavior, the reliability of the resulting flow mapped by PIV increases. However, this right frequency is empirically achieved, since it also will depends on the own flow behavior. As the resulting flow mapping quality is affected by the capacity of combining the best image acquisition frequency with planned scale for the flow details detection, in metrological sense it means that the performance of the PIV also plays an important role on the bench applicability limits, if PIV is chosen to be used in
the flow investigations. As in the present article the authors not intend to deep on PIV system settings, the readers can get more details about this subject in the literature.

Another point to consider in the bench performance analysis is the influence of tank wall effects to the jet entrainment rate. Consequently, nevertheless liquid overflows the tank, the flow rate at the nozzle always affects the magnitude of the recirculating zone within the tank. Then, considering all these aspects, after some tests the flow rate levels selected to the bench evaluation were 0.05 L/min and 0.20 L/min. The experiments were performed under the maximum water column (0.70 m), and the rhodamine concentration in the tank and reservoir were equal. Previous experiments carried out in the laboratory were used as base for determining the tracer particles concentration in these experiments.

With the PIV system, a synchronization circuit between the pulsed laser and imaging system allowed the digitalization and storage of double frame images, totaling 1190 images (7 sets containing 190 images each one) with a time separation of 5500 µs between frames. After capturing the 1190 images for each flow rate, the post-processing was initiated. So, the camera images were divided into rectangular sections (interrogation regions) in two steps: firstly, into interrogation area equal 64 x 64 pixels and, second, into 32 x 32 pixels. The condition for determining the interrogation area size is that it must be sufficiently small so that the velocity gradients across it can be neglected, but large enough to ensure that there is sufficient seeding particle pair to contribute to the statistical analysis of the fluid movement. In these experiments, the flow visualized region was in a vertical plane placed just above the nozzle exit, 120 mm large and 120 mm in height. The symmetry axis of this plane coincided with the nozzle axis. In this way, it was possible to evaluate the behavior of the liquid jet, and also, to compare such results with the similar case of axisymmetric air bubble plume on which the authors have been studying [7].

Finally, the main variables useful to evaluate the resulting flow field were explored using the free software SciDAVis™ (Scientific Data Analysis and Visualization) supported by Excel spreadsheets from Microsoft™.

3. Results and discussion
The obtained results of the axisymmetric jet flow field in the minimum and maximum flow rate are presented in Figures 5 to 8. In Figures 5 and 6, X-axis shows the parallel plane to the tank bottom and Y-axis indicates the vertical position along the tank height.

The vertical velocity distributions, as shown in Figures 5 and 6, along a horizontal section of the tank show a Gaussian profile, and are in accordance to results referred to in the literature [1].
Figure 5. Velocity profiles \( V_x \) (top) and \( V_y \) (bottom) at several horizontal cross section positions for the minimum flow rate.

Figure 6. Velocity profiles \( V_x \) (top) and \( V_y \) (bottom) at several horizontal cross section positions for the maximum flow rate.
Since the injector is an axisymmetric nozzle, it is expected a coincidence of the symmetry lines of each jet vertical velocity profile on different distances of a horizontal section to the injector. Nevertheless, the peak values of $V_y$ does not coincide with the injector centerline when the flow rate is minimum. Furthermore, on the flow rate equal to 0.05 L/min, near the injection point the maximum velocity $V_y$ increases slightly, but it decreases as the position up to the injector increases. For maximum flow rate (0.2 L/min), the peak velocity ($V_y$) increases gradually until to reach a plateau near 0.2 m/s, how is shown in Figure 7.

![Figure 7](Image)

**Figure 7.** Velocity peaks at several horizontal cross section positions

Analyzing the Figure 8, it is noted that in case of low flow rate the core of high velocities is situated near the injection point and it occupies a small volume of the axisymmetric jet. Otherwise, for high flow rate this core is larger than for low flow rate and it is set far from the injection point. It occurs due to the momentum transfer rate be more significant at high flow rate. More experimental observations shall be made, including in those planes placed above that one observed during the present work realization.

![Figure 8](Image)

**Figure 8.** Velocities field for the minimum flow rate (left) and the maximum flow rate (right); colors range: near 0 m/s - dark blue, 0.2 m/s - red; graphs generated by DaVis™7.2 and adapted by the authors
4. Conclusion
In this work an evaluation process of a facility which was designed to be used for jet induced flow investigation is shown. Metrological requirements and concepts guided all steps of the experimental work, from the mounting facility up to the limits of the bench use determination. A StereoPIV system was employed to identify the resulting flow behavior of the axisymmetric jet in the stagnant environment. The results indicated that with a nozzle of inner diameter 1mm the best range of flow rate for working in the bench with the bypass totally closed goes from 0.05 to 0.2 L/min. This is the total flow rate which pass through the nozzle. It is important to mention that this range can be different if the nozzle diameter or the number of nozzles change, since it can modify the pressure conditions inside the pipeline. Depending on the situation the bypass aperture can be demanded. Future works in this bench will include experiments using different configurations of the nozzles.

As additional result of this work, an experimental procedure for PIV use at the Fluid Dynamics Metrology Division (Dinam/Inmetro) was improved, thus contributing in sense of metrological approach considerably. It was extremely important for the Dinam/Inmetro researchers knowledge, since the uncertainty analysis for imaging of fluid flow is a research line which is being introduced as essential for the activities in the Division. In this work, the uncertainties analyses related to the flow field mapping are not presented, since the issue is complex and it is being investigated. However, during the work, in several steps of using the imaging acquisition system, errors were quantified and minimized.

The experiments here described had the purpose of confirming the applicability of the bench for studies on the hydrodynamics of mixing process induced by injection of liquid in liquid. In the environmental research area, this theme is fundamental for understanding pollutant dispersion mechanisms.

The bench was approved to be used according to the expected, and from now it will be a facility for supporting the researches on fluid dynamics investigations at Inmetro.

Acknowledgments
The authors are grateful to CNPq, FAPERJ, FINEP, PETROBRAS, PFRH-PETROBRAS and INMETRO for their support and sponsorship which have become possible the development of this research.

References
[1] Lee W H and Chu V H 2003 Turbulent jets and plumes - a Lagrangian approach (Norwell: Kluver Academic Publishers)
[2] Carazzo G, Kaminski E and Tait S 2006 J. Fluid. Mec. 547 137
[3] Simiano M and Lakehal D 2012 Int. J. Mult. Flow. 47 141
[4] Adrian R J and Westerweel J 2011 Particle image velocimetry. 4th Ed. (New York: Cambridge University Press)
[5] Goldstein R J 1996 Fluid mechanics measurement. 2nd Ed. (Washington: Taylor and Francis)
[6] Borg A, Bolinder J and Fuchs L 2001 Exp. Fluids. 31 140
[7] Farias M H and Santos A M 2014 Abst. book - 8th Int. Conf. Adv. Comp. Eng. Exp. art. 242