Multi-Exposure PIV Measurements of Velocity Fields in Sprays.

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Abstract. This paper presents an approach to the use of the PIV method in the diagnosis of sprays generated by an effervescent atomiser. Due to the different density of the liquid phase depending on the distance from the nozzle, problems arise with the correct exposure of images for PIV analysis. The aim of the authors of this paper is to outline the possibility of solving this problem by composing a velocity field from partial measurements. To meet the objectives of the paper, in-house PIV equipment (hardware and software) was used rather than a commercial setup. This allowed for easier handling of the measured data and more sophisticated post-processing than offered by commercial products. It is clear from the results presented that, despite the fundamental differences in the optical properties of the spray particles, it is possible to obtain a velocity field from the discharge zone to the spray region with fine droplets. Moreover, it is possible to combine velocity measurements in the spray cone with measurements in the surrounding environment.

Research background: Spray is an environment with an abundance of tracers for PIV analysis (droplets), but their density, size and shape vary dramatically with distance from the nozzle. The use of PIV can therefore be challenging due to the demands of this method for correct image exposure.

Purpose of the article: Introduction of the application of the PIV method for environments with variable density and size of tracer particles

Methods: PIV, image processing.

Findings & Value added: By taking an appropriate approach to acquiring the source PIV images, it is possible to obtain information about the velocities throughout the spray cone as well as in the surrounding environment. The application of the proposed method requires a sufficiently large source data set (images) and sophisticated postprocessing. However, as a result, it is possible to obtain an overall view of the velocity field in the spray cone starting from the area behind the nozzle to the fine droplet region.

Keywords: effervescent atomizer, liquid breakup, spray, particle image velocimetry, image acquisition.

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1 Introduction

Optical methods for measuring velocities in liquids are very popular nowadays and their importance is increasing with the decreasing investment costs of their implementation. The 1-D measurement methods, such as laser doppler anemometry (LDA) or phase doppler anemometry (PDA), play an indispensable role in spray diagnostics. These methods are the only ones that allow non-invasive measurements in the dense spray region with high temporal resolution. These methods allow information to be obtained about the processes involved in the atomisation of liquids, whether they are fuels [1, 2, 3, 4] or other substances [5, 6]. The disadvantage of 1-D methods is, in turn, the inability to obtain spatial resolution without a time-consuming traversing of the measured volume across the region of interest. For spatially resolved measurements, the Particle Image Velocimetry (PIV) method is appropriate. This works on the principle of recording the image of particles passing through the light plane at two subsequent time instants. This method is very popular in basic research in fluid mechanics [7, 8] or in applied research in the development of water and wind turbines [9], HVAC systems [10, 11] as well as aerodynamics [12]. Spray, as a medium consisting of a liquid phase dispersed in a gaseous environment, is a natural candidate for PIV diagnostics. It has been used to verify the function of new types of atomiser [13], or to monitor and describe the liquid breakup for different types of atomisers [14, 15]. This method can be used to track the motion of liquid particles in sprays [16] as well as velocity fields in the surrounding gas [18].

This study will focus on the application of the PIV method in measuring the velocity field in a spray generated by an effervescent atomizer. This atomizer generates a two-phase mixture in an internal mixing chamber. The gas in the mixture, upon entering the free space, expands and breaks down the liquid into fibres (ligaments), which are further broken down. The reflective surface area of these structures is large compared to the small droplets in the final spray. This causes problems in the application of PIV if there is a need to measure the velocity field both in the region of the primary breakup and at greater distances from the nozzle.

In this study, the authors outline possible solutions to this problem by reconstructing the velocity field from partial measurements at different image exposures.

2 Experiment

The test rig is depicted in Fig. 1. The tap water was used as the working fluid, the flow rate of which was regulated by a needle valve. Due to the very low water flows, the flow rate measurements were done by weighing the flowing amount of liquid in the collection tank over a defined time. Pressurized air, used as atomization gas, was prepared by a compressor. The air pressure value in the mixing chamber was kept constant by a pressure reducing valve. The air flow rate was measured using a laminar flow meter (OMEGA, FLR1600).

The spray was generated by an effervescent atomizer, the characteristics of which are depicted in Fig. 2. The operating modes of the atomizer were defined by the overpressure in the mixing chamber and the GLR parameter, defining the gas-liquid mass flow rate ratio. The overpressure in the mixing chamber was 100 kPa for all experiments presented. The PIV method was implemented in a double-pulse/double-exposure configuration. The apparatus, depicted in Fig. 3, was assembled at our facility; no commercial PIV system was used. Illumination was provided by a dual pulse laser (Quantel Evergreen) with a maximum flash energy of 70 mJ. The laser was fitted with a cylindrical and convex lens to achieve optimal laser plane parameters at a distance of 50 cm from the laser head. The flash rate was 15 Hz. The particle image was captured with a high-speed PIV camera (IDT, Y3) equipped with a 50 mm Nikon lens and a 532 nm bandpass filter. The field of view was adjusted with
a 5 mm spacer ring to a dimension of 110 x 110 mm. The synchronisation of individual components was provided by an 8-channel timing hub (IDT) via TTL signals.

Fig. 1. Schematic drawing of the test rig.

Fig. 2. Measured characteristics of the tested atomizer working with internal overpressure pressure 100 kPa.

The basic prerequisite for PIV is the presence of tracer particles in the fluid stream. Therefore, the spray appears to be a natural fit for the application of this method. However, practical experience suggests that measuring velocities in spray using PIV is a rather challenging task. The difficulty in using PIV in spray diagnostics stems from the fact that the area under investigation (spray cone) is inhomogeneous in terms of particle size and shape. Several regions can be identified in the spray generated by the effervescent atomizer (Fig. 4). In close proximity to the exit orifice, a rapid expansion of the atomized gas occurs, which is accompanied by an initial breakup of the liquid. In this region, the liquid concentration is very high due to the small diameter of the spray cone, comparable to the exit orifice. In this region the spray is very dense. As the spray cone expands, deformation of the liquid occurs due to inertial forces on the ligaments, the filaments, which further break up into large droplets ([1]). The processes described above are called primary breakup. The products of the primary breakup-the large droplets-are further deformed and undergo secondary breakup into smaller, usually spherical, droplets. After the secondary breakup of the liquid is complete, the diameter of the spray cone is much wider than in the area downstream of the exit orifice and hence the liquid concentration is also lower.
As can be seen in Fig. 4A, the regions of spray formation described above correspond to the presence of liquid formed into structures of different shapes and densities. In the region of primary breakup, the liquid concentration is large, causing strong light reflexion and overexposure of the PIV images. The expansion of the spray cone and the gradual disintegration of the liquid into ligaments and large droplets cause the particle concentration to decrease. Therefore, in the secondary breakup region, the exposure of the image is suitable for PIV analysis. Further breakup of the large droplets into fine spray causes a gradual decrease in liquid concentration and also a decrease in the reflecting area of the individual droplets. Therefore, the fine spray region is relatively poorly exposed in the images and the low density of particles recorded may make PIV analysis impossible.
3 Results

For the above reasons, it is virtually impossible to record images suitable for PIV analysis of the velocity field in the spray from the exit orifice to the fine spray region. However, it is possible to record particle images for individual spray zones. This can be achieved by adjusting the exposure of the images (Fig. 5). To evaluate the velocity field in the primary breakup region, it is necessary to decrease the illumination intensity or increase the aperture number of the camera lens to achieve an optimal exposure in the dense spray region (Fig. 5a). On the contrary, high light intensity or low lens aperture numbers are required to obtain images of particles in the peripheral parts of the spray cone or even in the wider surroundings (Fig. 5d).

![Fig. 5](image_url)

Fig. 5. Spray image obtained with different laser intensity settings (effervescent atomizer, $\Delta p = 100$ kPa, $Q_{m,w} = 2.85\text{kg/h}$).

![Fig. 6](image_url)

Fig. 6. Mean velocity vectors obtained with different laser intensity settings (effervescent atomizer, $\Delta p = 100$ kPa, $Q_{m,w} = 2.82\text{kg/h}$).
The result of the time-averaged velocity field calculation for one working mode of the atomizer for each exposure setting is shown in Fig. 6. For the lowest laser intensity (Fig. 6a), all calculated vectors are concentrated near the central part of the spray, corresponding to the region with the spray cone clearly visible in Fig. 6a. From these images, in which the central, densest parts of the spray are overexposed, vectors in regions farther from the axis but not outside the spray cone are obtained (Figs. 6b, c). With sufficient illumination intensity, the entire spray cone region, except for its peripheral parts, is overexposed (Fig. 6d). However, the small droplets in the wider surroundings are sufficiently illuminated, so it is possible to calculate velocity vectors over the entire field of view of the camera. Due to the low velocities in this region compared to the velocities of the droplets in the spray cone, it is necessary to extend the time delay of the second laser flash so that the particle displacement between the two exposures is sufficient for PIV analysis. Thus, by varying the exposure and time delay of the laser flashes, partial velocity maps can be obtained for each region of the camera field of view.

The gaps in the obtained velocity field can also be seen by displaying the velocity profiles at distances of 40 mm and 60 mm behind the nozzle in Fig. 6 a,b. These distances were intentionally chosen for illustration because the velocity vectors at all image exposures presented in Fig. 5 are available here. Comparing the velocity profiles at exposures a) to c) close to the spray axis, it can be seen that the measured velocities differ. Closer to the nozzle (Fig. 7a) these differences are more noticeable. The velocity profiles at exposure a) are considerably distorted, indicating poor particle image quality in this region. This is because these locations were underexposed at low illumination intensities with a low density of visible particles. For exposure (b), the velocity profile obtained is the best quality of those presented. Further increasing the illumination intensity (exposure of figure (d)) disturbs the smoothness of the measured velocity profile due to the loss of pattern due to overexposure of the image. In Fig. 7b, the velocity profiles are depicted at a distance of 60 mm from the nozzle. At the lowest laser intensity (exposure (a)), the measured velocity profile is of poor quality at this distance, similar to the previous case. At moderate illumination (exposures (b) and (c)), the results overlap. This indicates a good quality particle image recording at a radial distance of up to 10 mm from the center of the spray cone for both exposure regimes.

![Velocity profiles](image)

**Fig. 7.** Mean velocity vectors obtained with different laser intensity settings (effervescent atomizer, $\Delta p = 100$ kPa, $Q_{m,w} = 2.82$ kg/h).
By merging the partial velocity fields obtained at different exposure settings, it is possible to evaluate the velocity field over the entire field of view of the camera. The resulting vector field obtained by averaging the partial results presented in Fig. 8 is shown in Fig. a). As can be seen, the velocity field is complete from the nozzle discharge region to the regions outside the spray cone. It can be concluded that merging the vector fields by averaging them removed the influence of random errors. An exception is the region just downstream of the nozzle exit (Fig. 7a, x = 0 mm, y = 10 to 20 mm) where velocity vectors can be observed for which there is reasonable doubt as to their correctness. When the radial velocity profiles are analysed (Fig. 7b), disturbances to the smooth pattern are also evident.

The aforementioned deficiencies in the quality of the resulting velocity field arise from the poor quality of the partial data used in the averaging. Unfortunately, the presented particle image acquisition technique based on several exposure settings naturally generates regions in the images where the quality of the recorded particle image is low. This is due to the fact that the illumination intensity is adjusted with respect to the image quality only in a certain region, as demonstrated in Fig. 5. Obviously, velocity vectors obtained from regions of the image with poor exposure quality are undesirable and need to be eliminated. For this purpose, a wide range of tools are used in PIV analyses. These tools can be divided into pre-processing and post-processing tools. Pre-processing is actually image adjustment (intensity, contrast, exposure) before the actual PIV analysis. From the experience of the authors of the article, it is preferable to pay more attention to the setup of the PIV apparatus and obtain the best quality images possible. Any manipulation of the source images carries the risk of losing information or, worse, generating artificial signals.

![Figure 8](image.png) 

**Fig. 8.** Velocity field obtained by averaging of the partial data (exposions a, b, c, d) (effervescent atomizer, Δp = 100 kPa, Q_m,w = 2.82kg/h).

Post-processing can be image-based or vector-based. When analysing velocity fields in sprays, setting up rules for identifying and discarding faulty vectors is crucial, since a large number of such vectors are generated during spray diagnostics (Fig. 9a). The vectors in this figure were obtained from the image of Fig. 5.b. The strategy in the presented velocity field measurement technique is to eliminate as many vectors as possible in the partial data. The post-processing of the data in this study is performed using four filters. No reverse flow can be expected in the central parts of the spray cone. Therefore, all vectors that have negative axial velocity can be filtered out in the first post-processing step (Fig. 9b). This operation cannot be applied for the regions in the peripheral parts of the spray, since interaction with the surroundings and the formation of vortices may occur here. A more versatile tool for
vector discarding is the local median filter. This filter compares each velocity vector with the median of the vectors in its vicinity. If the analysed vector is too different, it is discarded. This filtering obviously works best in areas of high vector density. As can be seen in Fig. 9c (for y>50 mm), outside the spray centre this filter does not work optimally. To remove vectors that are incorrect, but pass the previous filtering, image-based filtering is used. In the first instance, the fault data are extracted from regions of the source images, which are too bright (not necessarily overexposed) or too dark. Here, there is a loss of drawing in the image leading to a correlation failure. The result of applying this filtering is shown in Fig. 9d. Another image defect that can lead to incorrect results is the low contrast in the analysed part of the image. By appropriately selecting the threshold of the allowed contrast, additional erroneous vectors are filtered out (Fig. 9e). The effect of applying all filters is presented in Fig. 9f. Compared to the original state (Fig. 9a), the number of vectors after filtering is considerably smaller. However, the resulting velocity field contains significantly fewer bad vectors. The smaller vector density can be compensated by a larger source data set, i.e., a larger number of frames for analysis, when creating the averaged velocity field.

In Fig. 10, the result of the evaluation of the averaged velocity fields from each of the four exposure modes is shown. Compared to the identically processed data in Fig. 8a, it can be seen that the resulting vector map is of significantly higher quality when using higher quality (filtered) partial velocity fields. The number of missing or bad vectors is minimal throughout the field of view. Similar results could not be obtained without using averaging of the partial results obtained at different exposure settings.

**Fig. 9.** Velocity field obtained by averaging of the partial data (expositions a, b, c, d) (effervescent atomizer, Δp = 100 kPa, Q_{m,w} = 2.82 kg/h).
Fig. 10. Velocity field obtained by averaging of the filtered partial data (expositions a, b, c, d) (effervescent atomizer, Δp = 100 kPa).

4 Conclusion

This paper presents one possible approach to the use of the PIV method in spray diagnostics. It shows that achieving the correct exposure of droplet images is challenging. In the case where the velocity field also needs to be measured in the surrounding environment of the spray cone at the same time, this is an impossible task. In this paper, the authors present an approach to solve this problem by obtaining particle images at several exposure settings. This achieves obtaining a good quality image in the target part of the spray. If necessary, the time delay of the laser flashes can also be varied, thus increasing the range of measured velocities. This approach has the disadvantage of producing a large number of invalid vectors in areas of the image that are over- or underexposed. However, by applying appropriate filters to the sub-velocity fields, this disadvantage can be effectively removed and, as a consequence, a high-quality velocity field can be obtained from the primary liquid breakup region to the more distant surroundings of the spray cone.

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References


