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OPTIMIZATION OF PIV PROCESSING IN THE INVESTIGATION OF AN ISOTHERMAL ETHANOL SPRAY CHAMBER

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Abstract. *Due to the need to produce more sustainable internal combustion engines with higher energy conversion efficiencies, lower fuel consumption and low levels of pollutants emissions, ethanol is a good alternative for engines equipped with direct injection system. In the process of formation of the ethanol spray the dynamics of air-spray interaction is fundamental for establishing more robust and realistic models. One way to investigate the development of this two-phase flow is by applying the Particle Image Velocimetry (PIV) technique. This work suggests some good practices in order to improve the PIV processing so that the flow investigation generates more reliable results. Such proposals aim to identify and treat the dominant noisy sources of PIV images in the investigation of the gas phase flow in an isothermal ethanol spray chamber (IESC). The sprays were formed by a typical injector of internal combustion engines equipped with direct injection system. Improvements were done in the steps of preprocessing, processing and post processing. The maximization of the signal to noise ratio and spatial coherence of the fields were used as objective function in the optimization. In addition to the presence of the spray in the field of view, high velocity gradients associated with low tracer concentration are the limiting factors in the representation of gas phase flow. In this case, the large size and high overlap of the interrogation window are suggested to obtain adequate results without losing spatial resolution in air-spray interaction.*

Keywords: *PIV Optimization, air-spray interaction, ethanol.*

1. INTRODUCTION

Ethanol is an important fuel in the Brazilian energetic matrix, as the choice made by flex-fuel engines stabilized the old downward trend in the production of alcohol engines. Nowadays, with the policy of regulation of prices of petroleum products that causes adjustments in the gasoline with high frequency, the use of the ethanol returned to be an alternative.

While seeking sustainable solutions for the movement of vehicles that use fossil fuels, Brazil has an excellent opportunity in the establishment of hybrid electric / ethanol fleets, an opportunity that just few countries have. Thus, it is essential to evolve in the efficient use of this fuel. Hence, the study of the formation and the evolution in time and space of fuel sprays is of great importance for new injection strategies aimed for internal combustion engines equipped with direct injection systems, which promise interesting advantages when operated with ethanol (Baumgarten, 2006; Soid and Zainal, 2011). However, knowledge about the process of air-fuel mixture formation in this type of engine is still limited, which makes it necessary to further study the two-phase gas-spray interaction process for the cases where the flow develops in a high-pressure environment.

One way to characterize the interaction between gas and fuel spray is by using the experimental Particle Image Velocimetry (PIV) technique. However, the application of the PIV for the analysis of the two-phase gas-spray flow presents some aspects that may deny the representativeness of the result regarding to reality, such as the inadequate concentration of particle images and the high image noise, from the strong scattering of light generated when spray is developing. In addition, it is important to note that the experimental procedure should be planned to ensure that the nullity or minimal tracer particles have their motion developed out of the light plane and that the motion gradients in an image sequence are as small as possible. The gathering of these topics converges to the search for the optimization of the Effective Number of Particles, N, defined by Eq. (1), where N_I is the amount of particles sheltered by the interrogation window, F_I e F_O are the factors linked to the correlation losses due to movements inside and outside the light plane, respectively,F_Δ refers to the factor that concerns to the influence of particle population motion gradients and F_σ is the term referring to the loss of correlation due to the presence of image noise (Scharnowski and Kähler, 2016; Scharnowski et al., 2019)

$$N = N_I \cdot F_I \cdot F_O \cdot F_\Delta \cdot F_\sigma \qquad (1)$$

This paper presents a methodology for optimizing the post-acquisition phase of PIV images in order to produce more reliable velocity fields. The optimization was designed to treat all noise sources present in PIV images recorded in an isothermal ethanol spray chamber to investigate the gas phase flow using the signal to noise ratio maximization as objective function. For this purpose, to optimize the effective number of particles, improvements based on good PIV practices are made in the preprocessing, processing and post processing steps.

2. METHODOLOGY

2.1 Experimental Apparatus

To study the interaction between the surrounding gas and the ethanol spray, the injection events were performed inside a continuous flow chamber, which was specifically designed for the experiments aimed at studying the gas-spray interaction. Named as Isothermal Ethanol Spray Chamber (IESC), the apparatus is divided into two sections: preparation of the ambient air with the tracer and a translucent section in order to be possible visualize the flow to apply the PIV technique. Figure 1 shows a sectional view of IESC.

The first section of the IESC consists of a vertically arranged 100 mm diameter and 500 mm long cylinder that receives air at the top and disperses the tracers at the centerline at a distance such that the mixture between air and particles be homogeneous. At the end of this section, two radially perforated plates with equally spaced 4.0 mm holes are arranged to limit turbulence levels to an integral scale length similar to that found inside internal combustion engine cylinders. At the center of the perforated plate GDI Delphi multi-hole automotive injector is allocated to promote pressurized ethanol injection events. The second main section of the IESC is made up of four quartz windows with dimensions 85 x 136 mm and equal thickness and 3.14 mm, which form an optical access chamber with square cross section that allows the visualization of the interaction between the fluids. The frames that fix these windows have received specific chemical treatment to reduce possible reflective effects.

To discriminate between the phases, present in the two-phase flow, Rhodamine B fluorescent particles dissolved in Propylene Carbonate were used to trace the gas phase structures. Previous experiments with PDI showed that the tracers used had Sauter mean diameter of 3.0 μm. The liquid phase was studied by recording the elastic scattering of the dispersed ethanol droplets. To illuminate the flow, a double-cavity Nd: YLF laser beam was used, capable of emitting light with a wavelength of 527 nm and an energy of 15 J per pulse with light sheets of 50 mm high and 1 mm of thickness. To record the flow phases, two Phanton v3.11 cameras manufactured by Vision Research Inc. and equipped with 1280 x 800 pixel CMOS sensors with 12 bits resolution were used. Both were positioned orthogonally to the light beam. One was responsible for receiving light scattering from the droplets, while the other simultaneously recorded the fluorescence of the tracers. To record Mie-scattering images a bandpass filter was used. The recording of air tracer particles was done with a set of optical filters containing longpass, absorption and dichroic filters. Neutral density filters were coupled to both cameras to attenuate high light signals and preserve the sensors. To manage injection events and synchronize them with cameras, a comprehensive control system has been developed. Figure 2 illustrates the experimental arrangement used to obtain the two-dimensional vector fields of the gas and liquid phases independently.

Ethanol was injected at 100 bar with an average flow rate of 0.066 kg/s. All parameters defining the adopted configurations were independently controlled and the full scale length of the turbulent flow was in all cases equal to 3.5 mm. The acquisition rate of the images was 8000 Hz and the time between the imposed pulses was 20 μs, sufficient to guarantee the stabilization of the environment after a given injection event. All images were recorded considering a pixel matrix reduced to 360 x 512 pixels, responsible for images with a field of view of 20.4 x 29 mm². The spatial resolution of the imaging system was 59 $\mu m/pixel$. The adopted field of view consists of the region to the left of the spray symmetry axis, contained in the light plane and below the injector tip, as shown in Figure 2.

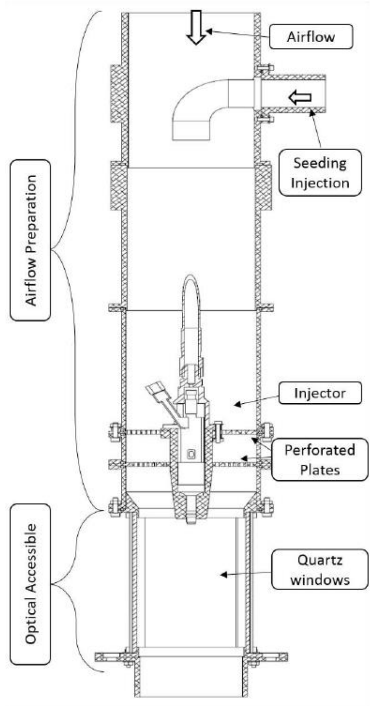

Figure 1. IESC main sections and components. Adapted from Berti (2018).

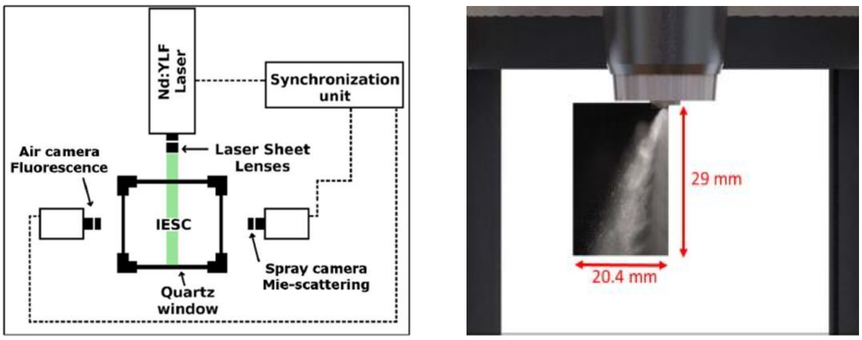

Figure 2. Illustration of the experimental arrangement used (left) and representation of the field of view considered in the experiments performed at IESC (right). Adapted from Berti (2018).

2.2 PIV Optimization

In order to maximize the Effective Number of Particles, N, from the variables controllable by simple procedures with low computational cost, the suggested PIV methodology consist on the application of best practices in all stages that follow the recording of primary images. For the preprocessing step, a primary image treatment strategy was proposed in order to better characterize the particle images from the complete elimination of noise present in the recordings. To do so a 3 x 3 pixels standard deviation spatial filter was used to remove background noise and exclude particles that were outside the range recommended by Raffel et al. (2007). After that, the Gaussian filter considering $\sigma = 0.1$ counts were applied to improve the particle image shape. Subtraction Sliding Minimum (50 x 50 pixels) and Intensity Capping strategies (as described by Shavit et al. [2007]) were used, in this order, to ensure the good contrast of particle images and the absence of bright spots in the processed images. Finally, the standard deviation filter was again used, however with $\sigma = 0.1$. At this point the preprocessing method was evaluated from different windowing and cross-correlation approaches: the Standard Cross Correlation (SCC) and the Robust Phase Correlation (RPC, as described by Eckstein and Vlachos [2009]). To apply them, the multigrid strategy was used, and the size of the interrogation window was gradually decreased. Three initial values were evaluated: 48, 36 and 24 pixels. For all proposed configurations, the window overlapping chosen was 0.25 (25 %).

In post-processing, it was used Median Absolute Deviation (MAD) in a 3x3 neighborhood of interrogation window to identify outliers. In this case, outliers are considered to be velocity values in the interrogation window greater than 3 times the MAD scale. This choice is based on the observations of Miller (1991). Outliers identified by the MAD approach were excluded and a shape-preserving piecewise cubic spline interpolation was carried out, as suggested by Fritsche and Carlson (1980). In the last post-processing step, an SNR filter was applied to remove the remaining outliers. In this filter, all results present in an interrogation window with an SNR less than 1.3 are excluded and an interpolation is applied. The postprocessing procedure was carefully done so that the final field was not misconfigured and useful information was lost.

The best results obtained by applying these steps were used to study the shear layer developed during the penetration of the ethanol spray in the surrounding environment. The analysis method proposed here was inspired by the methodologies used by Zhang et at. (2014) and by Jedelsky et al. (2018) to investigate air-spray interaction. In the processing the PRANA software was used. More details about the PRANA software are described by Eckstein and Vlachos (2009). The special coherence of the fields was analyzed by the Eq. (2) using a $k = 3x3$ kernel. This equation analyzes the coherence of the target interrogation window, $IW\{0\}$, in relation to the neighborhood $IW\{i\}$. All the approaches used and proposed in this work were developed in Matlab with the collaboration of the PIV_br group (www.piv.eng.br).

$$\text{Incoherence} = \frac{\sum_1^k |IW\{i\} - IW\{0\}|}{\sum_1^k |IW\{i\}|} \tag{2}$$

3. RESULTS

The effect of the preprocessing and correlation approach on gas phase flow parameters without spray injection for an interrogation window of 48px.0.25over = 36 px is shown in Figure 3. In this case, the effect of loss of correlation by image noise, F_σ, was not dominant. Despite the low SNR for the raw image/SCC (Figure 3[d]), the time-averaged velocity modulus distribution showed no significant difference between the different preprocessing/processing approaches (Figures 3[a-c]). However, the effect of the noisy sources becomes more evident by analyzing velocity fluctuation. In Figures 3(g-i), the high incoherence values of the RMS velocity fluctuation near the edge of the injector support can be explained by the combination of $F_I \cdot F_O \cdot F_\Delta \cdot F_\sigma$. In this case, the variation of NI was not observed. In this region, the effect of these noisy sources can be observed in the considerable decay of SNR values for all cases. The performance of the RPC approach was like the field processed with the preprocessed images. In addition, processing time has decreased considerably for this approach.

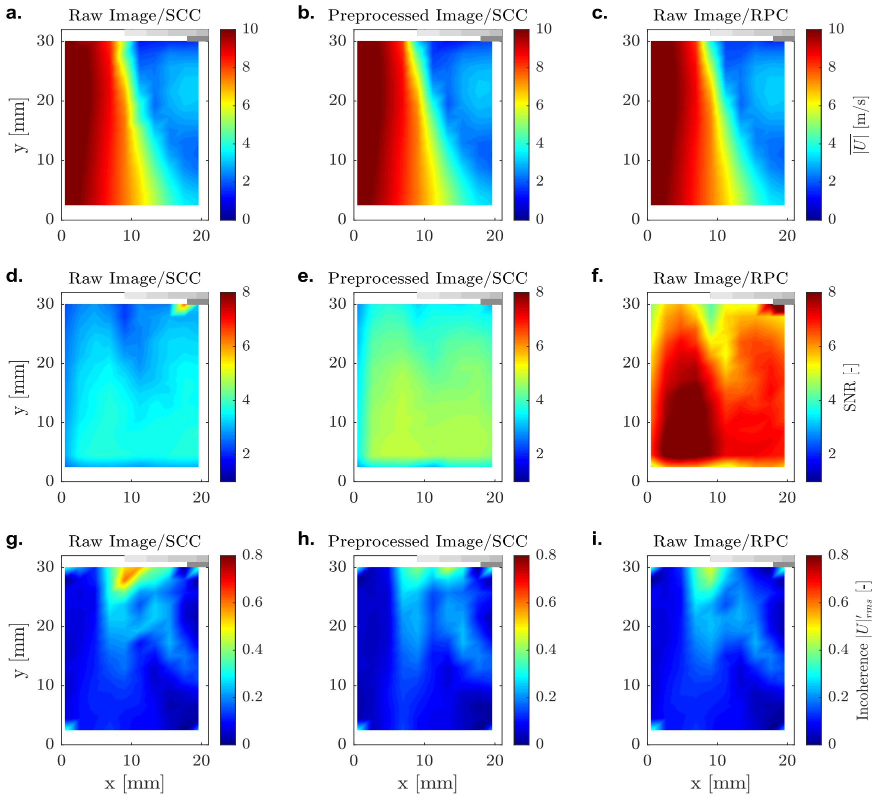

Figure 3. Effect of the PIV preprocessing and processing on gas phase flow parameters without spray injection for different approaches and with 48px.0.25over=36 px for final interrogation window: time-averaged velocity modulus (a to c), time-averaged signal to noise ratio (d to f) and incoherence of the RMS velocity fluctuation (g to i).

The effect of the noisy sources identified in Figure 3 became larger with increasing spatial resolution. An average particle density of 0.025 ppp (particle per pixel) was observed in the images. As expected, NI decreased and the combined effect of $F_I \cdot F_O \cdot F_\Delta \cdot F_\sigma$. deteriorated the field in some regions as the interrogation window size decreased. In case of this work, the increase of tracer concentration in the experiment and, consequently, of NI is unfeasible since the flow characteristics in the IESC could be changed considerably. Based on the same initial interrogation window size as shown in Figure 3, the increased window overlapping was analyzed for the SCC and RPC approach.

Figures 4 and 5 show the effect of the 0.5 and 0.66 overlapping on an interrogation window of 48 px compared to the 32px.0.25 over and 24px.0.25 over equivalents in the SCC approach, respectively, in flow with spray injection. Advantageously, the highest SNRs were observed for the initial interrogation window of 48px. However, the application of large sizes combined with the high overlapping of the interrogation windows may not register the high velocity gradients present in the flow and a parametric study becomes necessary. The SNR filter effect on post-processing is observed in the absence of velocity (white color) in the region where the spray is present. However, information loss is observed in some regions distant from the spray for 32px.0.25over and 24px.0.25over. Analyzing the SNR distribution in Figure 5, the spray shape is visibly observed for the initial interrogation window of 48px. This relationship between spray presence and low SNR values increases the performance of the SNR filter applied in post processing and facilitates the investigation of air-spray interaction. This behavior was not observed for the Raw Image/RPC case (Figures 6 and 7).

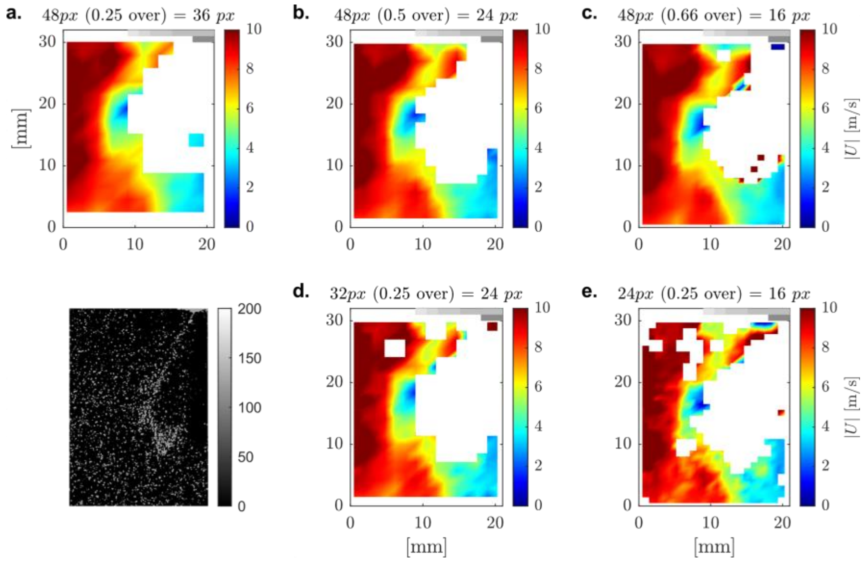

Figure 4. Windowing approach effect for preprocessed image/SCC case on velocity modulus of the gas phase with spray injection at t = 0.4 ms.

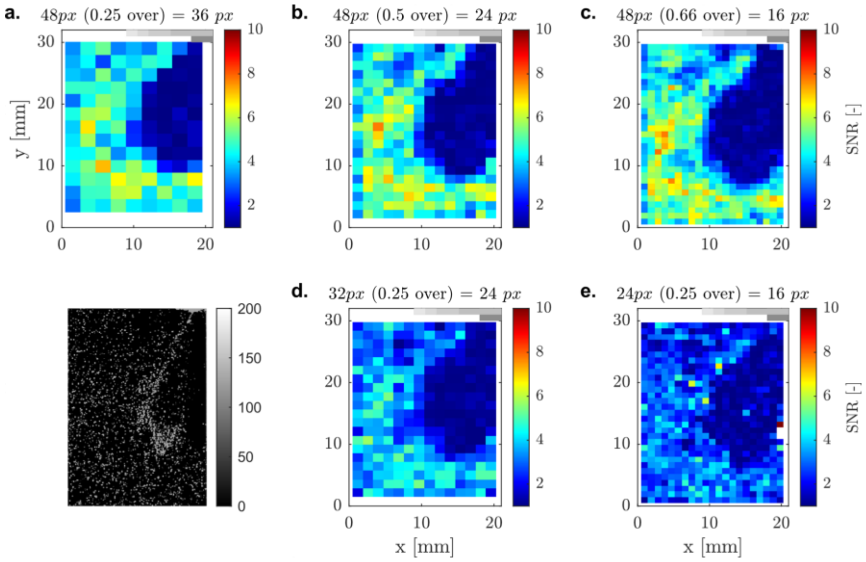

Figure 5. Windowing approach effect for preprocessed image/SCC case on signal to noise ratio of the gas phase with spray injection at t = 0.4 ms.

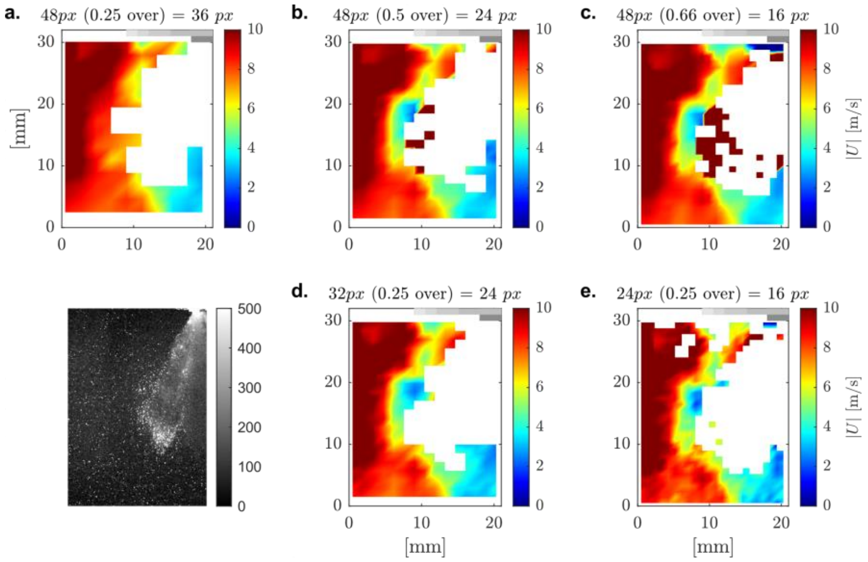

Figure 6. Windowing approach effect for raw image/RPC case on velocity modulus of the gas phase with spray injection at t = 0.4 ms.

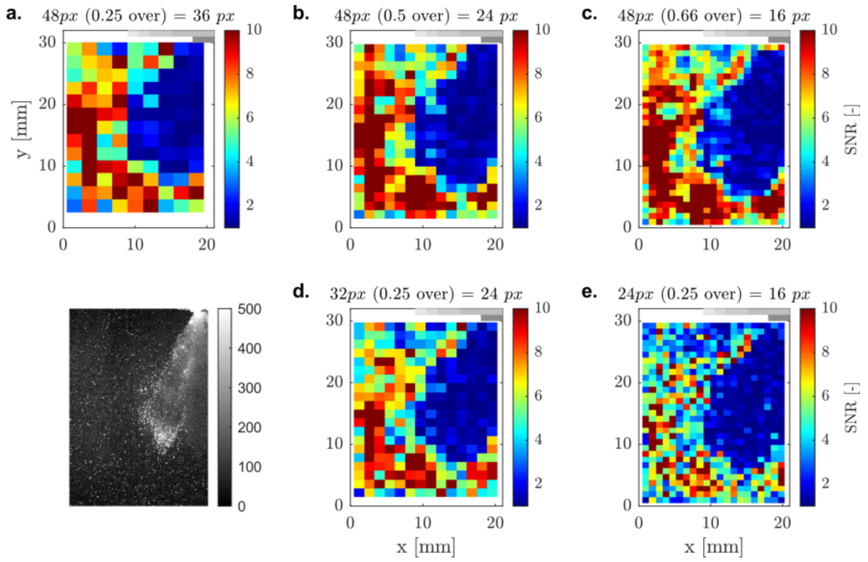

Figure 7. Windowing approach effect for raw image/RPC case on signal to noise ratio of the gas phase with spray injection at t = 0.4 ms.

The SCC approach has showed better performance in the application of the SNR filter for cases with an interrogation window of 48px and overlap of 0.5 and 0.66 (Figures 6b and 6c). In this case, noise filtering in the correlation plane by the RPC approach, which uses the effective diameter of the particle image, does not eliminate the spray effect. In Figure 7c, the velocity of the gas phase is confused with the spray droplets. This behavior was not observed in the preprocessed image/SCC case mainly due to the intensity capping filter. This preprocessing filter prevents the spray droplet (with high light scattering) becomes dominant in the displacement of the correlation peak relative to the particles' population associated with the tracer (with less light scattering). On the other hand, the RPC has presented better results for the 32px and 24px interrogation window with 0.25 overlap. The average diameter of the particle image associated with the tracer and the spray drops was 4 px and 9 px, respectively. A range of 2.8 to 4 px of effective diameter was used in the filtering of the RPC, but there were no significant differences in the SNR distribution and velocity. Based on this, SCC or RPC applied in a multigrid approach with large and small window overlays, respectively, is indicated to investigate the gas velocity without the dominant effect of the spray drops.

With the experimental limitations associated mainly with the choice and concentration of the tracer, optimization in PIV processing becomes the most viable alternative for obtaining measurements with quality and greater spatial resolution. In this case, the optimization must be carried out in each processing step, analyzing the effects coupled in the subsequent steps. The removal of the spray effect is not guaranteed only with the use of rhodamine and optical filter in

PIV recording. In addition, improvements in pre-processing, processing and post-processing must be applied. The use of the Particle Tracking Velocimetry (PTV) approach may be the best option to increase the spatial resolution in the investigation of the camera under these conditions, as stated by Cardweel et al. (2011) and Brady et al. (2009). The best PIV strategies used in Figures 6 and 7 can be used as an initial estimator for PTV correspondence, similar to the PIV-PTV hybrid. This can considerably decrease the lack of PTV matches caused mainly by the high tracer concentration for this approach.

4. CONCLUSIONS

In the present work an optimized PIV processing was proposed to investigate the air-spray interaction of an isothermal ethanol spray chamber. Particularly in the case with low tracer concentration and, consequently, low particle image density (N_{ppp}) a windowing strategy is a good choice to maintain field quality. A relatively large initial interrogation window with high overlapping has been shown to be most suitable for high spatial resolution measurement. At spray injection, the filtering image noise in the correlation plane by the Robust Phase Correlation approach does not eliminate the spray effect. However, the spray effect is decreased considerably with the application of capping intensity filter in preprocessing. In addition, the air-spray interface is appropriately obtained by using the post processing SNR filter for preprocessed images/SCC case.

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