PIV INVESTIGATION OF A PRESSURE-SWIRL ATOMIZER SPRAY

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Pressure-swirl atomizers are widely used in various combustion applications including aircraft jet engines. Spray characteristics, such as drop-size and velocity distribution have a principal influence on the combustion process. A number of studies have dealt with single-point laser diagnostic techniques, such as Phase-Doppler Anemometry, for spray measurements. An alternative approach is the use of a whole-field method – Particle Image Velocimetry (PIV). This contribution deals with investigation of spray characteristics of a spill-return pressure-swirl atomizer for a small-sized jet engine by means of PIV. The nozzle was operated on a cold test bench at atmospheric pressure and room temperature. Measurements were carried out in an axial section of the spray cone with various single-camera and stereoscopic PIV configurations. Results of our measurements provide a quantitative visualization of the spray flow fields in regimes based on the engine operating conditions. Comparison of velocity profiles obtained from the individual PIV configurations is presented and discussed. The pressure-swirl spray is recognised as an optically harsh environment for PIV due to large particle size range, high diameter-velocity correlations, strong velocity gradients and large velocity differences within an image, large variations in 'seeding' concentration and out-of-plane particle movement. The PIV results comprise new findings to the complex 3D character of velocity field in the pressure-swirl sprays.

Keywords: *Particle Image Velocimetry, PIV, stereoscopic PIV, atomization, spray, flow field*

1. Introduction

Aircraft gas turbine engines have been the subject of strict environmental policy defined by ACARE, pledging the engine manufacturers to significant reduction of fuel consumption, exhaust gas emissions and noise levels in the next decades [1]. Characteristics of the injected fuel, such as spray dispersion angle, drop-size distribution, velocity distribution and evaporation have a significant influence on the combustor performance. Poor atomization is associated with unburned hydrocarbons that emerge from the combustion chamber, and NO_x and CO emissions in the exhaust. Improvement in atomization quality (i.e. decrease of mean drop diameter) inhibits soot formation and contributes to overall combustion efficiency [2].

Many fuel injectors in general use today are pressure atomizers. As their name suggests, they rely on conversion of pressure energy of the bulk liquid into kinetic energy of dispersed droplets. In a pressure-swirl atomizer (simplex nozzle), liquid is fed through tangential ports into a swirl chamber mounted upstream the discharge orifice. A thin conical liquid sheet is

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formed at the discharge orifice which spreads under a certain angle due to centrifugal forces. Disturbances propagating on the surface of this sheet cause its disruption into ligaments and finally into droplets in the form of a hollow cone spray [2].

A drawback of the simplex nozzles is the poor atomization quality for low pressure differentials. This disadvantage can be overcome by pressure-swirl atomizers with a spill-return flow regulation. This atomizer has a passage in the rear wall of the swirl chamber which is used for return of the excessive fuel back to the fuel tank. When the spill is closed, the atomizer operates as a standard simplex nozzle. Usually a high liquid flow rate is maintained in the feed line; the amount of the discharged liquid is controlled by a valve located in the spill line. The liquid sheet thickness and the size of droplets that emerge after its breakup decrease with increasing the inlet flow rate and do not depend on the flow rate of the discharged liquid. Thus, spill-return atomizers have better atomization quality than simplex nozzles for low discharge flow rates, when the major fraction of the inlet flow rate is diverted to the spill return [3]. Disadvantage of this design is the cone angle variation with changing the spill-return flow rate which can have a negative influence on combustion efficiency.

An early implementation of the fuel system with spill control for gas turbine engines was described by Carey [4]. He showed that a satisfactory atomization can be achieved with as low discharge flow rate as 1 % of the inlet flow rate. Kapitaniak [5] studied the influence of the internal nozzle geometry of spill-return atomizers on their performance and suggested optimal design parameters for certain ranges of flow rates. Rizk and Lefebvre [6, 7] studied spray characteristics and drop-size distribution of spill-return nozzles with aviation kerosene as the test liquid. Their findings show that increase of the spill-return fraction slightly reduces the SMD and the spread of drop sizes. Löffler-Mang and Leuckel [8] studied the flow field inside of an enlarged model of a spill-return atomizer for different spill-to-feed ratios.

Several light scattering techniques have been developed for point and planar measurements of droplet velocity and size. Phase-Doppler Anemometry (PDA) is a well-established technique allowing simultaneous measurement of particle velocity and size. Information about the droplet velocity can be also obtained by imaging and image processing techniques, such as Particle Image Velocimetry (PIV). PIV is a method used in experimental fluid mechanics to determine instantaneous velocity vector fields by measuring the displacements of fine particles dispersed in the flow. Application of PIV in a spray field is less common and it is rather a challenging task. In the measurement of a spray velocity field using the PIV technique, droplets play the role of seeding particles. Droplet characteristics of velocity and size depend on the atomizer design and the spatial location within the spray field. This results in different levels of accuracy of the PIV processing in various regions of the spray. The most significant problems with PIV measurement of droplet velocities are due to the dense nature of sprays, the wide spectrum of droplet diameters and high velocity gradients. PIV ideally requires clearly resolved images of homogeneous seeding particles (droplets) in the flow [9]. In a fuel spray, droplets overlap to some extent, creating speckles in the image plane. For the description of dynamics of droplets of various diameters, Ikeda et al. [10] proposed a multi-intensity-layer technique (MI-PIV) which distributes droplets into different size classes based on the principle that the light scattered from small particles is proportional to their diameters. Palero and Ikeda [11] combined this technique with stereoscopic PIV measurements (SPIV) for reconstruction of three velocity components of spray droplets. Feasibility of this technique for flashing jets was assessed by Yildiz [12]. In his measurements, MI-PIV did not improve the signal-to-noise ratio compared to standard PIV.

PIV has been used for characterization of sprays for gasoline direct injection (GDI) engines. Spray structure of GDI sprays has been investigated using single camera PIV [13, 14]. Due to the high spray density, Wu [14] was able to apply standard PIV interrogation only in a distant region from the nozzle orifice. Recent research has focused on interaction of GDI spray droplets nozzle with ambient air using fluorescent seeding particles to trace the gas phase [15–17]. Zama et al. [18] proposed a technique for 3D particle tracking and determination of particle size from combination of SPIV captures and interferometric laser imaging. This method was found accurate in the area of low spray density. In pressure-swirl sprays, Campbell et al. [19] applied two-colour PIV to analyse droplet velocity field produced by a large-scale nozzle. They obtained an average droplet velocity in the distant region from the nozzle tip.

This study deals with the investigation of spray characteristics of a miniature spill-return pressure-swirl atomizer for a small-sized jet engine designed for an experimental aircraft and gliders. It plays an important step in the engine development process. Single-camera PIV and stereoscopic PIV measurements were carried out in various configurations. Our interest is focused upon the analysis of differences in results obtained with various configurations of the measurement system and processing settings. This study will lead to further optimization of the PIV system for future measurements of spray flow fields.

2. Experimental Methods

2.1. Nozzle

The internal geometry of the tested nozzle is presented in Fig. 1 (discharge orifice $d_o =$ $= 0.36$ mm, spill return orifice $D_{spill} = 1$ mm, swirl chamber diameter $D_s = 3$ mm). Jet-A1 kerosene fuel is fed into the swirl chamber through two tangential ports with square cross section.

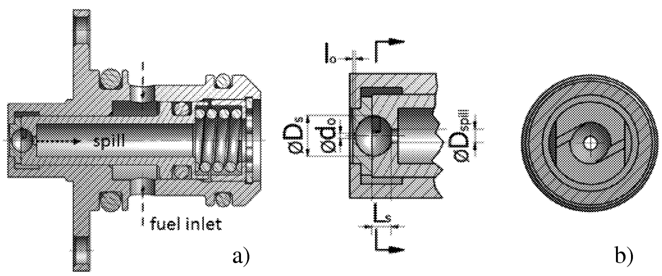

Fig.1: a) section view of the tested nozzle; b) swirl chamber detail

2.2. Test Rig

The test rig for studying spray characteristics comprised a cylindrical collection vessel (approx. 80 cm long and 50 cm in diameter) mounted on a stand with its axis in the vertical position. The atomizer was located centrally approx. 20 cm above the vessel. The nozzle discharge orifice was oriented vertically downwards. The atomized kerosene gravitated to the bottom of the vessel, from where it was returned to the fuel tank (Fig. 2). The atomizer was tested for various inlet pressures (150 kPa – 1 MPa) and spill line pressures based on the typical engine operating regimes. In this paper, two regimes are presented: 200 kPa inlet pressure with 50 kPa spill line pressure (called 'regime 1' hereafter) and 1 MPa inlet pressure with 400 kPa spill line pressure (called 'regime 2' hereafter).

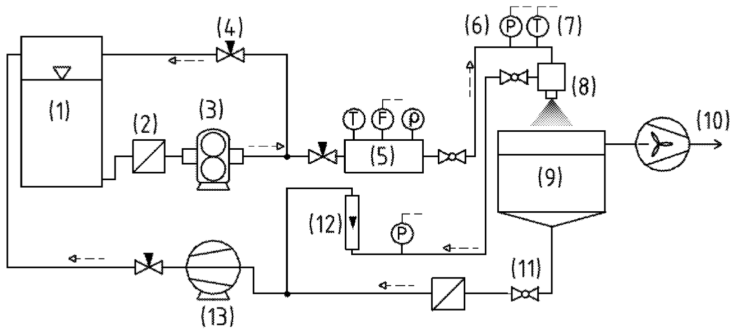

Fig.2: Test rig: (1) fuel tank, (2) filter, (3) gear pump, (4) needle valve, (5) mass flow meter, (6) pressure sensor, (7) temperature sensor, (8) atomizer in a holder, (9) collecting vessel, (10) axial fan and mist extraction, (11) ball valve, (12) rotameter, (13) fuel pump

2.3. Data Acquisition

A light sheet generated by an Nd:YAG double-pulse laser (New Wave Gemini – 15 Hz) illuminated an axial cross section of the spray. Thanks to good light scattering characteristics of kerosene droplets, relatively low laser energy was needed for the experiments (approx. 15 mJ per pulse). Particle images were captured by 12-bit TSI PIVCAM 13-8 cameras with 1.3 Mpx resolution and 3.6 Hz image acquisition frequency. Single-camera measurements were carried out first with a 60 mm macro lens; the latter measurement incorporated a 28 mm lens for a larger field of view and shorter particle image displacements. The camera was oriented perpendicular to the plane of the light sheet (Fig. 3). Both SPIV configurations were symmetrical with the stereoscopic half angle θ set to 40°, which should provide a sufficient accuracy for the measurement of the out-of-plane velocity component [9]. The 28 mm lens was used also for SPIV 1 and 60 mm lens in case of SPIV 2. Each of the tested regimes required different time delay Δt between laser pulses in order to minimize the out-of-plane displacement of particle images between the paired captures, as well as the in-plane loss of correlation due to large particle displacement at higher droplet velocities (Tab. 1). This optimization of Δt for each PIV configuration led to different time delay in each of these configurations due to their unlike field of view as well.

Configuration	Field of view (mm^2)	No. of image pairs	Δt regime 1 (μs)	Δt regime 2 (μs)
Mono 60 mm	77 × 62	500	40	15
Mono 28 mm	162 × 130	500	30	20
SPIV 1 60 mm	200 × 125 (dewarped)	1500	50	20
SPIV 2 28 mm	107 × 60 (dewarped)	500	30	15

Tab.1: Acquisition setup

3. Data Processing

TSI Insight 3G 10.0 was used for image acquisition, pre-processing and processing. The relationship between pixels and physical space was obtained using a dual plane/dual sided calibration target. For stereoscopic measurements, auto-mapping procedure was used for correction of the misalignment between the position of the light sheet and the calibration target [20]. A typical correction of the target translation was ±0.5 mm. Image pairs with subtracted background were interrogated using a recursive, two-pass multi-grid cross-correlation algorithm. The starting window size was 64×64 px, followed by one refinement at 32×32 px. A window offset in the range of 3–6 px in the mean flow direction (z-axis) was set between successive passes to increase number of valid vectors by improving the signal-to-noise ratio and decreasing the in-plane correlation loss. Window overlap was set to 50 % and 75 % in the first and second pass, respectively. A deformation grid algorithm was applied on mono PIV captures for comparison with the rectangular grid algorithm. This processor is a refined version of the multi-pass processor where the input image is 'deformed' to remove effects of flow rotation and gradients within the interrogation region. This technique is usually performed in 4–5 iterations [21]. Resulting velocity vector fields were validated using median filters and global validation was set to remove invalid vectors which were not in the preset velocity range. In average 3 % of invalid vectors were interpolated.

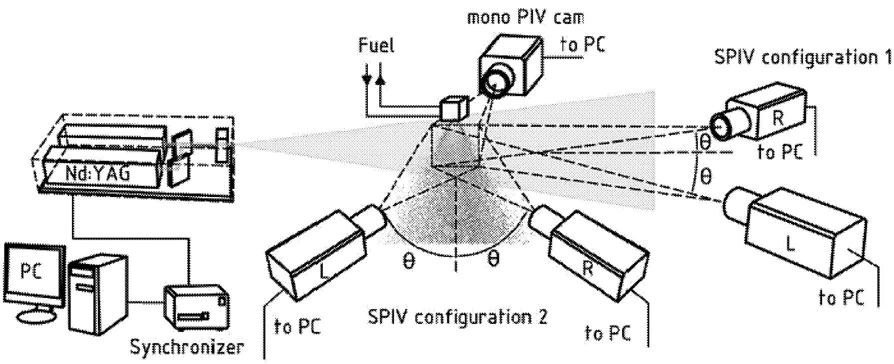

Fig.3: Configurations of the PIV system

4. Results and Discussion

The miniature spill-return pressure-swirl atomizer uses swirl effect to form the liquid into a thin conical sheet prior to discharge. Original pressure energy of the liquid is turned into kinetic energy with helical character of internal flow. The tangential velocity component leads to the sheet formation and its widening downstream. The bulk discharged liquid moves in the direction of the sheet envelope with its origin in the discharge orifice. However some fraction of the original tangential component is conserved (see Fig. 7 below) and results in out-of-plane particle movement when the axially positioned laser sheet used. The conical sheet deforms during the flow and reduces its thickness. Shear forces lead to a disintegration of the sheet while surface tension tends to warp the liquid volumes into droplets. These droplets interact with ambient air, decelerate, undergo a high-shear turbulent motion and form clusters. The near-nozzle spray contains rests of the original sheet, ligaments and large droplets. The size distribution of droplets in individual positions of the developed spray roughly corresponds to the log-normal distribution [3] with very small (micron sized) as well as large (typically 100 micron in diameter) droplets. Sauter mean diameter varies strongly with the radial position in the spray. Our measurements by means of PDA (not documented here, see also our former paper [22]) show that Sauter mean diameter spans from 60 to 120 μm for regime 1 and from 20 to 100 μm for regime 2, the smaller values are found in the spray centre and the larger at the spray border. Large droplets with large momentum keep almost their original velocity while small droplets tend to decelerate while flowing through the ambient atmosphere. These small droplets, following the air, move also transversally (in radial direction) into the spray centreline where their population dominates. Turbulent, shear-driven flow in the spray core leads to the droplet agglomeration known as clustering. The difference between velocity of large and small particles (pressure sprays exhibit strong diameter-velocity correlation) within an interrogation area leads to their different displacement for an image pair. For more information regarding spray characteristics see our former paper [22].

As described, the atomization process is responsible for a very specific flow field with natural seeding which is far away from an ideal PIV seeding. Main features important for the PIV setup are as follows: large particle size range, high diameter-velocity correlation, strong velocity gradients and large velocity differences within image, large variations in 'seeding' concentration and out-of-plane particle movement. The above given description implies that sprays in general represent an optically harsh environment for PIV.

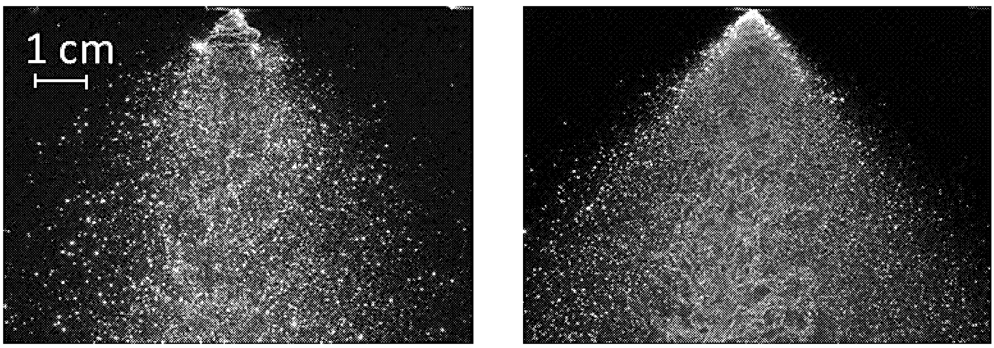

Fig.4: Instantaneous PIV captures; left : regime 1, right : regime 2

The flow field in the spray was at first measured using single-camera PIV. 1500 instantaneous velocity fields were processed using 2-pass algorithm (window size 64×64 and 32×32 pixels, respectively). The average field of velocity magnitude was calculated from image pairs (such as the images shown in Fig. 4). The flow fields, depicted in Fig. 6 for both the regimes, show the velocity is highly spatially variable with its maximum near the discharge orifice and the main stream following the spray border. The main-stream droplets decelerate to one half of their original velocity after ∼15 mm. Velocity in distances larger than about 40 mm is already only a small fraction of the original velocity. Significant differences can be seen between the two investigated regimes. Droplet velocity distribution in the spray is highly dependent on the injection pressure differential. A core with higher-than-surrounding velocity is formed in axial distance of 15 mm at regime 1. In this case the spray shows smaller and 'warping' cone. Regime 2 is characterized with the formation of a hollow cone which is later filled with small droplets. The core velocity is markedly lower than the main-stream velocity however also in this case a central area with an increased velocity is formed. The main-stream jet propagates with roughly parabolic velocity profile, its velocity is decelerated from both sides due to the surrounding still air.

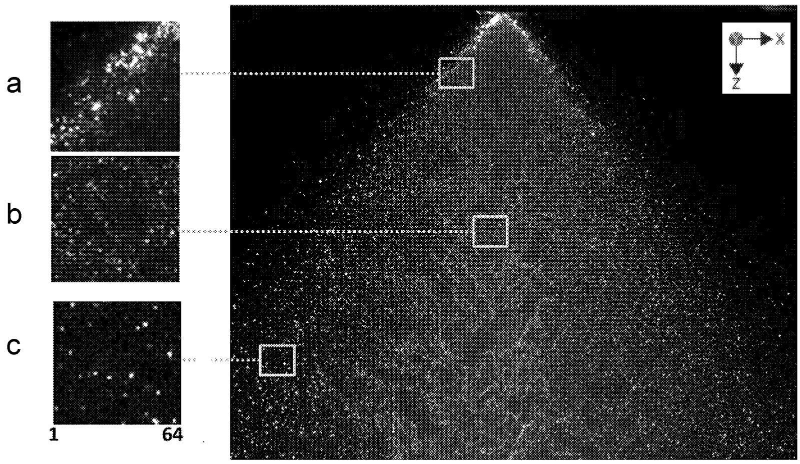

Fig.5: Instantaneous PIV capture with different seeding situations: a) large droplets and ligaments, b) fine particles, good concentration (optimum seeding), c) low particle concentration

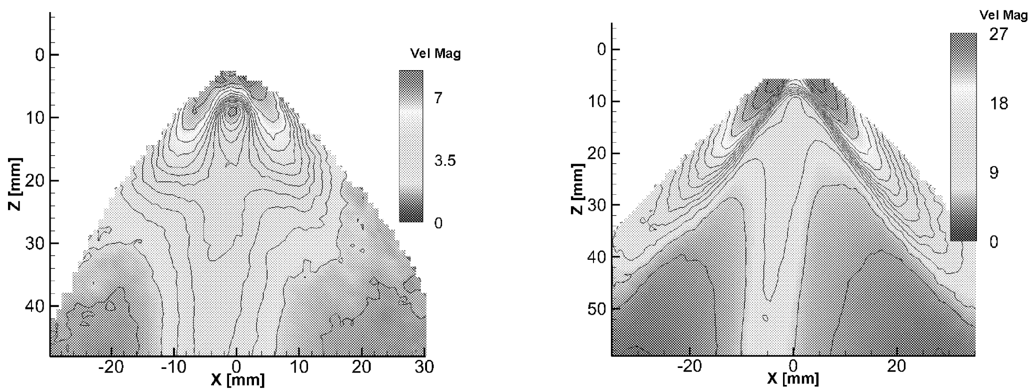

Fig. 6: Average field of velocity magnitude from single-camera PIV; left: regime 1, right: regime 2

A deeper analysis of the PIV results show that in some areas the measurement was inaccurate mainly due to low seeding density (Fig. 5c), large speckles (Fig. 5a) and droplet clusters (Fig. 5 centreline downward area). In principle, PIV measures the displacement of all objects in the flow, either ligaments or droplets. However, quality of PIV relies very much on the size, concentration and spatial distribution of seeding particles. Excessive velocity gradients contribute to in-plane and out-of-plane loss of correlation. This phenomenon is most significant at the spray periphery. This area is formed by ligaments and large droplets with high kinetic energy. The best seeding quality was achieved in the spray core (Fig. 5b) at higher pressures. This area is formed by a fraction of the smallest droplets with low velocity.

Single-camera PIV is unable to resolve the tangential velocity component due to perspective error and this component is lost. SPIV eliminates this problem and one can expect higher mean velocity obtained from SPIV. The tangential velocity component is highly spatially dependent and its typical values reach units of m/s as shown in Fig. 7 for regime 2.

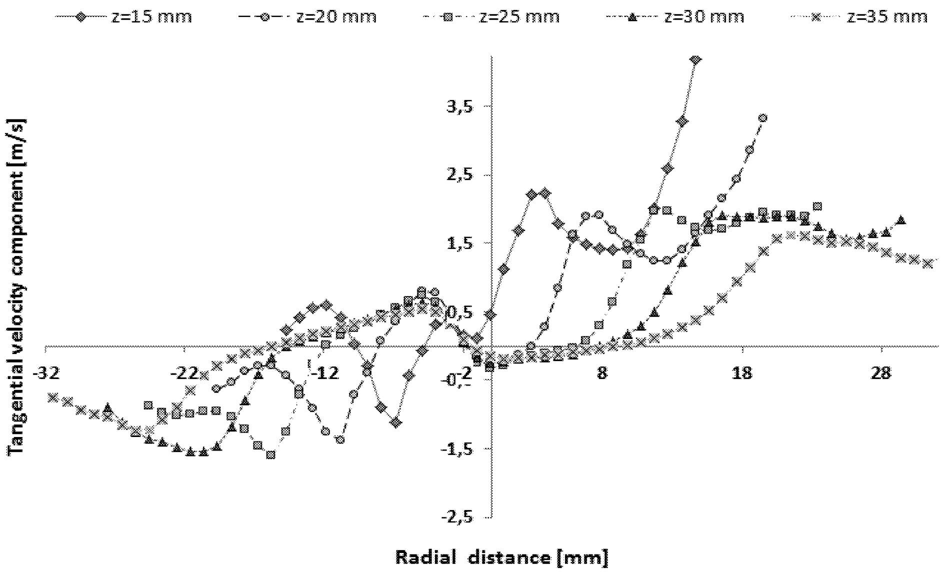

Fig. 7: Tangential velocity component at varying z positions; regime 2

Comparison of the velocity profiles at various z-values downstream from the nozzle has revealed that data measured with SPIV 1 are shifted towards higher values (Fig. 8). Tangential velocity reaches maxima close to the nozzle orifice at the highest pressure setting (up to 4 m/s). With increasing downstream distance, influence of the tangential component decreases (Fig. 7 and 9). In contradiction to SPIV 1, configuration SPIV 2 in average gave lower velocity values than the other three settings. This might have been either due to a calibration misalignment or acquisition settings (Δt, field of view). A relatively high residual error of this setting resulted in rejection of significant portion of reconstructed 3C vectors in area close to the nozzle orifice. Anyway, this configuration is potentially interesting since both cameras are aligned in the forward scattering mode (lens apertures can be set identically) and it will be exploited in future experiments. High number of valid vectors in the single- camera measurements was achieved with the larger field of view (28 mm lens). This is primarily due to smaller effective particle image diameters and shorter pulse separation times set for this configuration. Note that the results presented in Fig. 8 and Fig. 9 were acquired during several independent experiments with limited precision and repeatability of the geometrical setup (configuration of the atomizer and the laser sheet position) as well as other factors that affect the flow field. These effects contribute to the velocity differences found between individual configurations. The two different (60 and 28 mm) lenses were used to make acquisitions with different field of view and particle image displacements. However the time delays Δt for these two lens settings were set independently. Measurement uncertainties of individual configurations depend on the image resolution and on the displacement as well which must be taken into account when comparing the data.

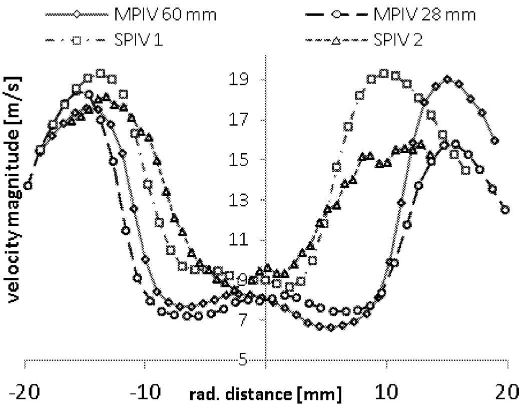

Fig.8: Velocity magnitude at $z = 20 \pm 1$ mm; regime 2

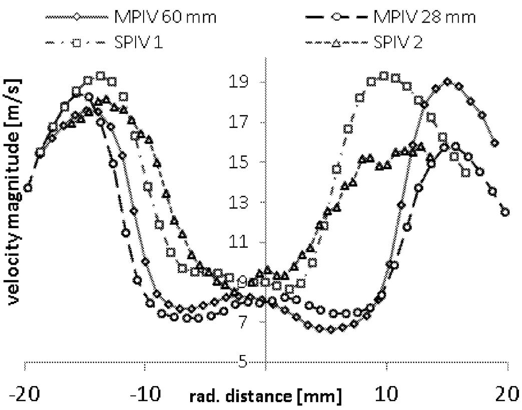

Fig.9: Velocity magnitude at $z = 40 \pm 1$ mm; regime 2

As pointed out above the effectiveness of PIV processing depends significantly on several seeding and flow related factors. Amongst them seeding density, mean particle size, size range, out-of-plane particle movement and velocity gradients were found to be very important. Inappropriate processing algorithm can lead to wrong results. Deformation grid and rectangular grid were applied to mono PIV measurements with 60 mm lens in our case of flow with large velocity gradients. Comparison of the velocity profiles obtained with both the grids is shown in Fig. 10. Deformation processing allows for larger velocity displacements within the interrogation spot. As shown in Fig. 6 and Fig. 8 it applies to the 'main stream' areas with high flow rates and large droplets that are the most important for combustion processes. Both the processing ways gave almost identical results in terms of velocity magnitude, however, vector count in the problematic areas was markedly improved (typically doubled) in the case of deformation grid.

5. Conclusions

This study focused on the application of PIV to pressure-swirl sprays. The flow field in pressure-swirl sprays was described based on our experience and on acquired PIV images as very specific; large velocity gradients, dense near nozzle spray, seeding density and particle size highly variable within image, presence of out-of-plane particle movement make it a chal-

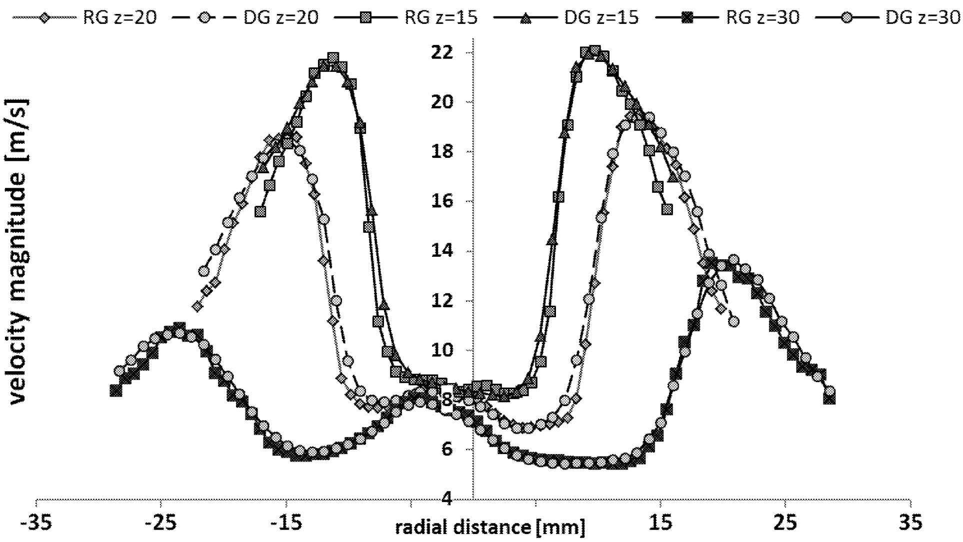

Fig.10: Comparison of deformation grid (DG) and rectangular grid (RG) for different z-values

lenge for appropriate application of PIV, its setup and choice of processing methods. Beside a compromise setup for the wide range of individual factors within the image a particular solution would be to focus on smaller areas of interest with individually optimized setup.

The investigation of spray characteristics was performed by means of single-camera and stereoscopic PIV. Results of our measurements provide an insight into the spray flow fields. Velocity distributions obtained from single-camera measurements are in good agreement. Results of stereoscopic measurements are contradictory. SPIV configuration 1 confirmed our expectations; however, a disagreement was found in the results obtained with SPIV 2, where velocity profiles in all tested regimes exhibited lower values than in other three PIV configurations. Differences found in results amongst the different PIV configurations suggest for a need to carefully choose the appropriate PIV arrangement and data processing. An emphasis must be given to the repeatability of the PIV calibration, conformity in the geometrical configuration and other factors of the experiment as well. A number of aspects affect the PIV setup and only some of them were addressed in the paper, however the authors believe the findings presented here contribute to our knowledge for PIV application in sprays and give the base for this ongoing research. Future investigations will focus on the refinement of PIV for spray applications, advanced post-processing techniques and finally to deep investigation of the pressure-swirl spray.

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References

[1] Quentin F.: ACARE: The European Technology Platform for Aeronautics, December 2007, Available online: ftp://ftp.cordis.europa.eu/pub/etp/docs/acare_en.pdf

[2] Lefebvre A.H., Ballal D.R.: Gas Turbine Combustion. CRC Press, 3rd edition, 2010, 560 p., ISBN 978-1-4200-8605-8

[3] Lefebvre A.H.: Atomization and Sprays, Hemisphere Publishing, 1989, 434 p., ISBN 978-0891166030

[4] Carey F.H.: The Development of the Spill Flow Burner and Its Control System for Gas Turbine Engines, Journal of the Royal Aeronautical Society, November 1954, 58

[5] Kapitaniak A.: The Influence of Chosen Construction Parameters on the Performance of Spill-Control Pressure-Jet Atomizers, Journal of the Institute of Fuel, January 1967

[6] Rizk N.K., Lefebvre A.H.: Drop-Size Distribution Characteristics of Spill-Return Atomizers. Journal of Propulsion and Power. 1985, 1, 1. p. 16–22

[7] Rizk N.K., Lefebvre A.H.: Spray Characteristics of Spill-Return Atomizers. Journal of Propulsion and Power, 1985, 1, 3, p. 200–204

[8] Loeffler-Mang M., Leuckel W.: Atomization with spill-controlled swirl pressure-jet nozzles, NIST Special Publication, p. 431–440, 1991

[9] Adrian R., Westerweel J.: Particle image velocimetry, Cambridge : Cambridge University Press, 1st edition, 2011, 558 p., ISBN 978-0-521-44008-0

[10] Ikeda Y. et al.: Multi-intensity-layer particle-image Velocimetry for spray measurement, Measurement Science and Technology, Vol. 11, 2000

[11] Palero V. R., Ikeda Y.: Droplet-size-classified stereoscopic PIV for spray characterization, Measurement Science and Technology, Vol. 13, 2002

[12] Yildiz D. et al.: Feasibility Exploration of Laser-based Techniques for Characterization of a Flashing Jet, Particle & Particle Systems Characterization, Vol. 21, 2004, p. 390–402

[13] Cao Z.M. et al.: PIV measurement of internal structure of diesel fuel spray, Experiments in Fluids, Vol. 29, number 7, 2000, p. 211–219, ISSN 0723-4864

[14] Wu Z. et al.: An experimental study on the spray structure of oxygenated fuel using laser-based visualization and particle image Velocimetry, Fuel, Vol. 85, 2006, p. 1458–1464.

[15] Rottenkolber G. et al.: Spray analysis of a gasoline direct injector by means of two-phase PIV, Experiments in Fluids, Vol. 32, Number 6, 2005, p. 710–721, ISSN 0723-4864

[16] Towers D.P.: A colour PIV system employing fluorescent particles for two-phase flow measurements. Measurement Science and Technology, Vol. 10, 1999, p. 824–830

[17] Changuan W. et al.: Experimental research on the characteristics of dense spray of diesel engine, International Conference on Computer Distributed control and Intelligent Environmental Monitoring, 2011

[18] Zama Y. et al.: Simultaneous measurement method of size and 3D velocity components of droplets in a spray field illuminated with a thin laser-light sheet, Measurement Science and Technology, vol. 16, 2005, p. 1977–1986

[19] Campbell I.G. et al.: Pressure Atomizer Spray Field Velocity Analysis using Two-Color PIV, 12th Annual Conference on Liquid Atomization and Spray Systems, 1999

[20] Wieneke B.: Stereo-PIV using self-calibration on particle images, Experiments in Fluids, Vol. 39, 2005, p. 267–280

[21] Scarano F.: Iterative image deformation methods in PIV, Measurement Science and Technology, Vol. 13, 2002

[22] Durdina L., Jedelsky J., Jicha M.: Spray structure of a pressure-swirl atomizer for combustion applications, EPJ Web of Conferences, 25, 01010, 2012, Available online : http://dx.doi.org/10.1051/epjconf/20122501010

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