EPJ Web of Conferences **25**, 01010 (2012)
DOI: 10.1051/epjconf/20122501010

SPRAY STRUCTURE OF A PRESSURE-SWIRL ATOMIZER FOR COMBUSTION APPLICATIONS

Lukas DURDINA, Jan JEDELSKY, Miroslav JICHA•

Abstract: *In the present work, global as well as spatially resolved parameters of a spray produced by a pressure-swirl atomizer are obtained. Small pressure-swirl atomizer for aircraft combustion chambers was run on a newly designed test bench with Jet A-1 kerosene type aviation fuel. The atomizer was tested in four regimes based on typical operation conditions of the engine. Spray characteristics were studied using two optical measurement systems, Particle Image velocimetry (PIV) and Phase-Doppler Particle Analyzer (P/DPA). The results obtained with P/DPA include information about Sauter Mean Diameter of droplets and spray velocity profiles in one plane perpendicular to the spray axis. Velocity magnitudes of droplets in an axial section of the spray were obtained using PIV. The experimental outputs also show a good confirmation of velocity profiles obtained with both instruments in the test plane. These data together will elucidate impact of the spray quality on the whole combustion process, its efficiency and exhaust gas emissions.*

1. INTRODUCTION

Pressure-swirl atomizers as relatively old type of atomizing devices are nowadays often being replaced in many applications by twin-fluid atomizers. But they are still very common parts of present combustion systems mainly for low power demands. Their popularity is based on simple design and operation without additional expensive devices that could lead to unwanted increase of weight in mobile applications and also to reduction of reliability, which are important factors not only in aircraft industry. Research works focused on improvement of atomization characteristics of the pressure-swirl atomizers are persistent despite long-lasting history of their development and utilization in many industrial sectors. Today research effort stems from changes in the legislative, reflects more frequent usage of less refined fuels and answers requirements for more efficient combustion devices.

In general, a swirl-flow of the liquid in a pressure-swirl atomizer is induced by feeding the liquid into a swirl chamber through one or several tangential ports, that give it high angular velocity, thereby creating an air-cored vortex. In this manner, the air-core blocks a part of the nozzle outlet orifice. Under both axial and radial forces emerges the fuel through this orifice in the form of a hollow conical sheet. As the sheet expands, its thickness decreases and it soon becomes unstable and disintegrates into ligaments and then drops in the form of a well-defined hollow-cone spray. Disintegration of the sheet depends mainly on the liquid discharge velocity and thus on the liquid injection pressure. Description of the spray development with increasing injection pressure is presented, for

• Bc. Lukas Durdina, Jan Jedelsky, PhD., Prof. Miroslav Jicha, CSc., Department of Thermodynamics and Environmental Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69, Brno, email: lukas.durdina@gmail.com

example in [1]. For low-viscosity fuels, the lowest injection pressure for achieving atomization using pressure-swirl atomizer is about 0.1 MPa.
Evaluation of the atomization performance is based on the knowledge of spray parameters such as spray velocity, spray area, droplet size, distance and uniformity. The spray velocity depends on the driving pressure, volume flow rate and the nozzle geometry. The axial and radial velocity components also affect the spray cone angle and the spray range. The most fundamental index for atomization performance evaluation is the droplet size. Smaller droplet size positively influences the effect of heat and mass transfer and accelerates the chemical reactions.
Lefebvre [1] describes various methods employed in spray characteristics measurement based on mechanical and electrical principles, which were used before the deployment of digital processing. In the recent decades, considerable advances have been made in the development of laser diagnostic and imaging techniques for measuring particle size and velocity in sprays such as Phase-Doppler Particle Analyzer (P/DPA), Planar Laser Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV). Every technique has its own advantages and drawbacks, depending on the application, therefore verification of the results obtained with one method by another one is desirable, which is also aim of this work.
Several teams deal with pressure-swirl atomizer research by optical methods. Recent experimental work is focused on optimization of the spray characteristics. The aim of Chu et al. [2] was to support a theoretical model of a pressure-swirl atomizer with experiments performed by optical methods. Musemic and Walzel provided an estimation of drop size in the region of sheet formation [3]. Muliadi and Sojka [4] compared patternation information of a pressure-swirl atomizer derived P/DPA measurements with values measured using PLIF.
A pressure-swirl atomizer with new design of its internal mixing chamber is intended to replace the original atomizer within an update process of a combustion chamber of an aircraft engine. Micro- and macroscopic spray characteristics are to be gained as an important step during the engine innovation process. Combustion chamber adaptation and consequent numerical simulations will be based on these data.
Spray structure of the new atomizer for several typical operational pressures is described within the text. Arbitrary results of two optical diagnostic systems, PIV and P/DPA, are presented and analyzed.

2. EXPERIMENTAL APPARATUS

The experimental equipment includes pressure-swirl atomizer, cold test bench with fluid supply system and mist extraction, Phase/Doppler Particle Analyzer and Particle Image Velocimetry. Description of our Dantec 1D P/DPA used for drop size and velocity measurements can be found in [5].

Atomizer description and operation

Single fluid pressure-swirl atomizer (Fig. 1) atomizes kerosene into a still ambient air. The newly designed atomizer is placed into a segment of kerosene feeding line, it is continuously operated and studied in the vertical downward position of the main axis (Fig. 2). The atomized fuel type is Jet A-1 aviation turbine fuel (kerosene type) with dynamic viscosity 2 mPa.s, density 810 kg/m^3 and surface tension 26 mN/m at room temperature [6]. Liquid inlet temperatures, gauge pressure and volumetric flow rate were measured. The temperature was kept at 22 ± 2 °C during the experiments.

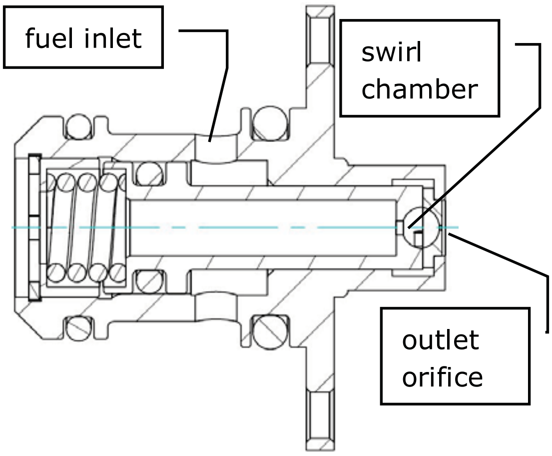

Figure 1: Section view of an aircraft-type pressure-swirl atomizer (Courtesy PBS Velka Bites).

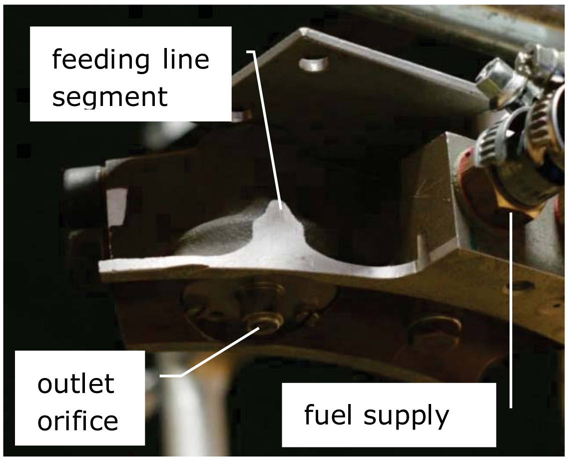

Figure 2: Photograph of the atomizer on cold test bench.

Description of the test bench and the fuel supply system

Fuel supply circuit is mounted into a mobile frame with the footprint of 600x600 mm, assembled from industrial aluminium profiles (Fig. 4). This solution offers easy transportability and enables quick alteration by fitting the elements to the frame according to our needs. The circuit consists of a stainless-steel fuel tank from which fuel is pumped by a gear pump (LUN 6223.01-8) through the fuel filter to the nozzle. Regulator elements, flow meter, pressure sensor and fuel temperature sensor are included in the circuit, linked with copper pipes and Swagelok fittings. The nozzle is mounted in a traverse holder upright with the outlet orifice directing downwards. Fuel is sprayed into the collecting vessel and returned by a solid state fuel pump back into the fuel tank. In the upper part of the collecting vessel, air extraction is ensured in order to remove the fuel vapours and aerosol from the test site (Fig. 3).

Operational regimes

The nozzle was tested in four regimes with following gauge pressure values: 150 kPa, 340 kPa, 690 kPa, 1 MPa. These values are based on typical operational conditions of the engine, from start and idle to maximum power regime. Required gauge pressure values were reached by regulating the pump speed.

3. Data Acquisition and Processing

Particle Image Velocimetry (PIV) equipment and setup

Particle Image Velocimetry (PIV) serves for planar droplet velocity measurement. A laser light sheet of approximately 1 mm thickness was produced by a dual-head pulsed Nd:YAG laser (NewWave Research Gemini, 50 mJ per pulse, max. repetition rate 15 Hz) conditioned through a cylindrical lens. The light sheet illuminated the spray in the spray axis. The image capture system consisted of TSI PIVCAM 13-8 CCD camera (1.3 Mpx) fitted with Nikon 14 mm extension tube PK-12 and Nikon 60mm f/2.8D AF Micro-Nikkor lens.

Camera axis was aligned in perpendicular view with respect to the light sheet (Fig. 5). Camera was placed approximately in 1 meter distance from the nozzle orifice, providing field of view of about 132.5x106 mm and spatial resolution of the raw frames of 0.103 mm/px.

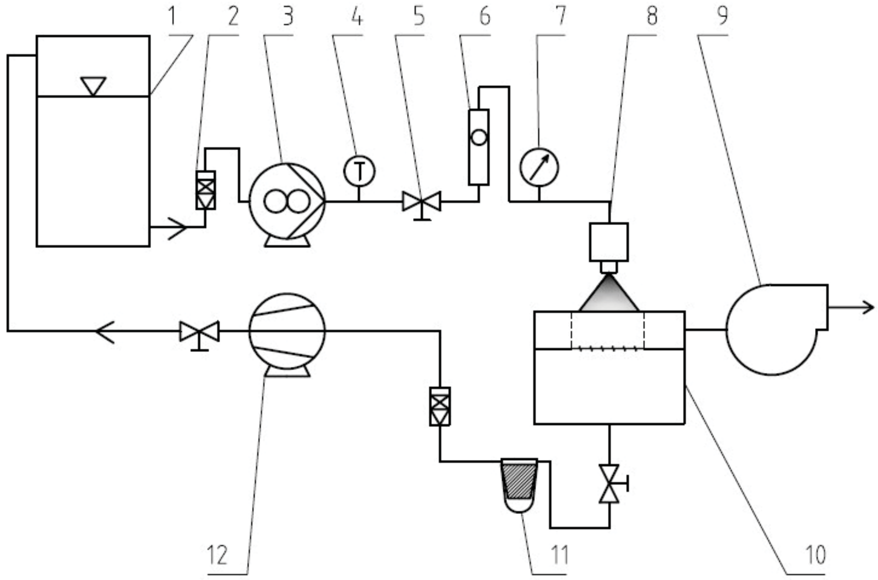

Figure 3: Schematics of the fuel supply circuit. 1, fuel tank; 2, fine fuel filter; 3, gear pump; 4, temperature sensor; 5, control valve; 6, rotameter; 7, pressure gauge; 8, atomizer; 9, mist extraction; 10, fuel collecting vessel; 11, coarse fuel filter (strainer); 12, solid state fuel pump.

The timing of the PIV system was controlled by a TSI LaserPulse Model 610034 timing synchronizer in concert with the acquisition computer (Pentium 4 3,2 GHz HT, 3 GB RAM, Windows XP SP3), with the PIV images acquired with the TSI Insight 3G 9.1.0 software package.

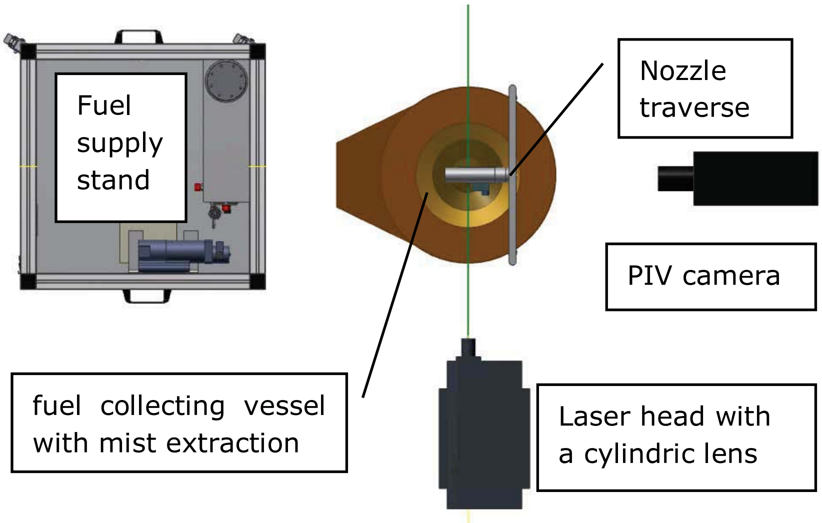

Figure 4: PIV experiment setup.

PIV processing setup
For the experiment detailed herein, 250 paired images yielding two-dimensional velocity fields (u, v) along the plane crossing the spray axis (x, z) were captured for each experimental run using straddle mode with 3.66 Hz laser pulse frequency. Required time delay Δt between laser pulses for satisfactory image processing of the whole field of view was set to 20 μs.
Pre-processing involved background subtraction for each image sequence. Each frame was normalized using the minimum and maximum intensity before the correlation analysis. For the image processing, ensemble PIV algorithm was selected. The PIV image pairs were interrogated using a recursive cross-correlation. For highest accuracy, deformation grid was selected. This method processes the image in multiple passes and performs image deformation, where the two frames are shifted in opposite directions and the total amount of shift should equal to the local velocity. The starting and final spot dimensions were selected to 64x64 px and 32x32 px respectively. As correlation engine, FFT Correlator was selected, followed by Gaussian peak engine for the peak location in the correlation map. The resulting instantaneous velocity fields were then validated using mean and median filters followed by Rohaly-Hart analysis [7] in one pass to replace invalid vectors, whereas the PIV processor adds the correlation maps from neighbor spots on top of the correlation map from current spot to get a good correlation peak in the summed correlation map.

4. RESULTS AND DISCUSSION

Spray morphology, influence of the liquid injection pressure
In the figure 5, axial sections of the spray illuminated with a laser sheet are presented. At the lowest gauge pressure, 150 kPa, fuel emerges from the nozzle orifice in the form of a conical liquid sheet, but is contracted by surface tension forces into a closed bubble. Presented pictures (Fig. 5a, b, c, d) are axial sections of the spray According to the established nomenclature [1, 8], this stage is described as the onion stage (Fig. 5a). During the film propagation, Kelvin-Helmholtz type of instability together with turbulent deformations leads to the primary break-up of the liquid sheet. Spray is very narrow, which is given by the nozzle design and also by the collapse of the liquid sheet in a close distance from the outlet orifice. Mass flow is then concentrated in the proximity of the nozzle axis. No inhomogeneities in liquid concentration are visible. In vertical position of the nozzle axis at this pressure, low velocity magnitude and influence of gravity may lead to asymmetrical spray formation.

With increasing gauge pressure, liquid sheet bubble opens into a hollow tulip shape terminating in a ragged edge, where the liquid disintegrates into drops. Spray cone angle increases as well. (Fig. 5b) Increasing kinetic energy and higher pressure differences between the emerging fluid and ambient air (Fig. 5c, d) lead to straightening of the liquid sheet and diminishing its thickness. The liquid sheet disintegrates into ligaments and drops in very short distance from the nozzle orifice in the form of well-defined hollow-cone spray. At this stage, spray cone angle is defined by the inner geometry of the nozzle. Formed drops have higher initial velocity magnitude and thus the range. This behaviour complies with other pressure-swirl atomizers [1, 8]. In the figures 5b, c, d is evident, that the spray core is formed mainly by smaller drops, and in the radial distance drop size increases.

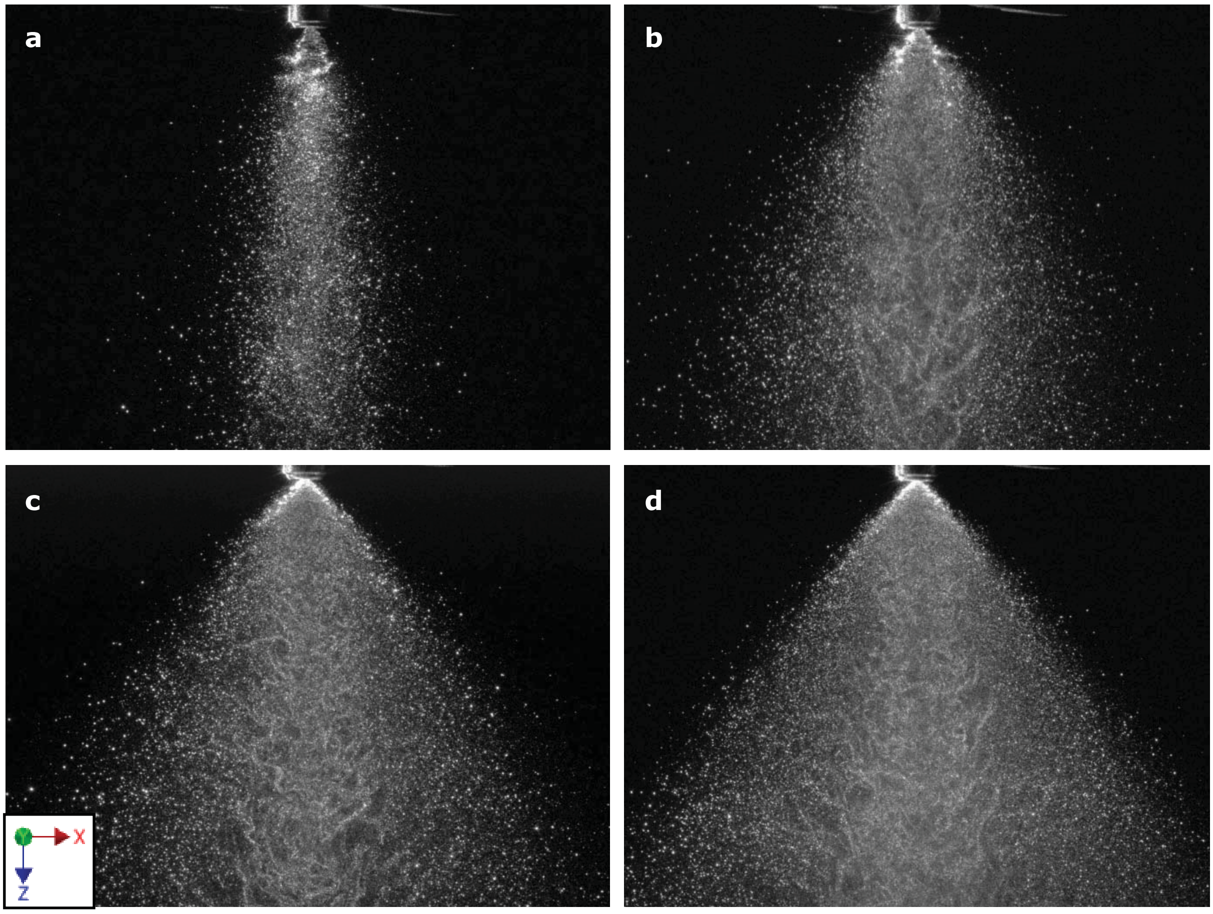

Figure 5: PIV photographs of the spray for different gauge pressures: a, 150 kPa; b, 340 kPa; c, 690 kPa; d, 1 MPa.

In the spray core, more or less distinctive droplet clusters are present, which is the result of the interaction between spray and ambient air.

Description of P/DPA results

P/DPA measurement was performed in the (x,y) plane perpendicular to the nozzle axis in 25 mm distance from the outlet orifice.

Sauter mean diameter of droplets D_{32} (Figure 6) changes significantly with increasing gauge pressure and radial distance. For low pressure, particles with the greatest diameter are concentrated close to the spray axis (area of the greatest mass flux). With increasing gauge pressure, mean drop diameter drops significantly and the difference between minimal and maximal D_{32} increases. For higher pressures, Sauter mean diameter values in the axis and on the periphery of the spray vary more than threefold. At 150 kPa gauge pressure, droplet size asymmetry is evident, which may be caused by the aforementioned collapse of the liquid sheet envelope at lower gauge pressures. We assume that this phenomenon is spatially unstable. For low gauge pressures, droplets reach the highest velocity magnitude in the spray axis. With increasing gauge pressure and thus changing spray characteristics, local velocity maxima are formed in the areas of highest mass flux values, i.e. areas of the main flow of droplets generated by the break-up of the liquid sheet. For high gauge pressures, these maxima become dominant (Fig. 8).

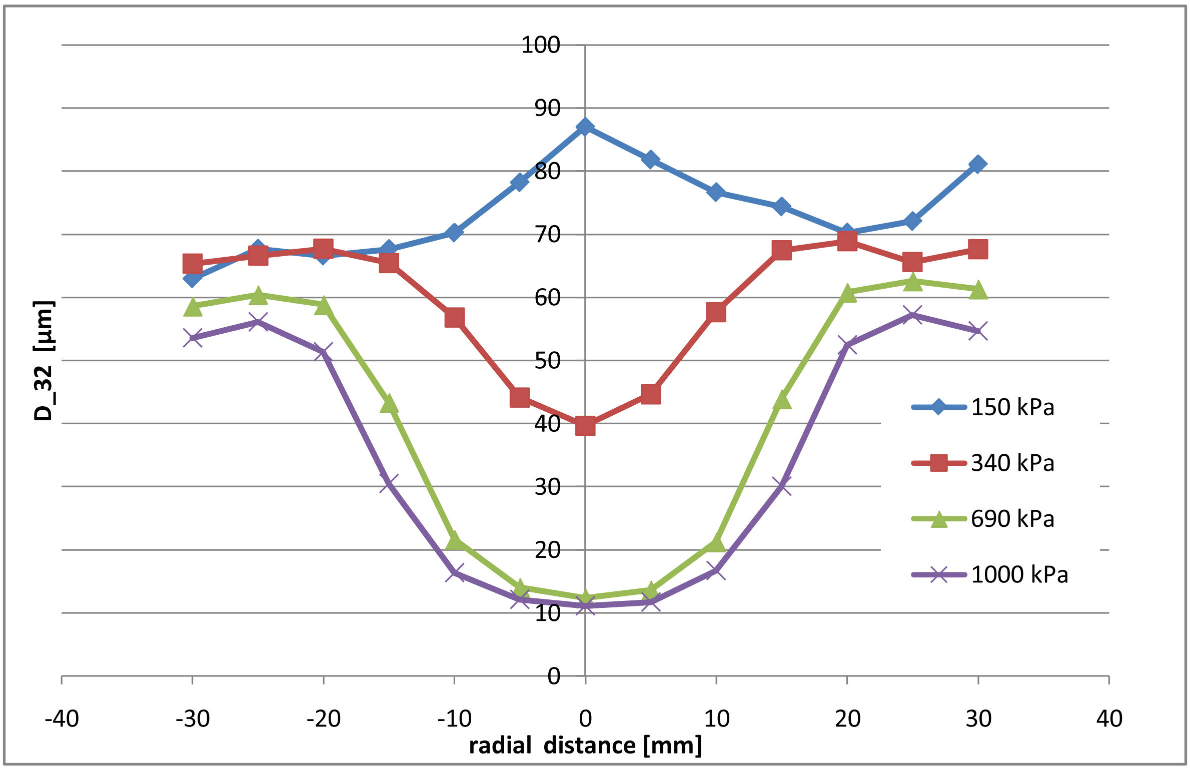

Figure 6: Sauter mean diameter of droplets, z=25 mm.

Description of PIV results

Processing of the resultant vector files generated with Insight 3G software package, calculation of variables and graphical output were done with the Tecplot 360 2010 software. Velocity magnitudes below 0.1 m/s were cut off from the graphs.

Processed PIV images provide visualization of the droplet velocity magnitude in the whole field of view and complement the P/DPA measurement. For the lowest gauge pressure, fluid mass is concentrated around the spray axis (Fig. 7a) and the highest velocity magnitude is reached in the distance interval z=15..25 mm on the spray axis. This is the area exactly under the break-up spot of the liquid sheet bubble. With increasing gauge pressure, local velocity maxima in the interconical region at the spray periphery are dominant. Droplet dynamics leads to deformation of the velocity profile with increasing axial distance. Influence of the ambient air leads to significant deceleration of drops with increasing distance from the nozzle orifice. As the figure 7 shows, velocity profile and thus liquid mass in the spray cone is unevenly distributed. For gauge pressures 340 kPa and higher, we can describe the spray shape as a hollow cone. Although the spray core is formed by large number of small drops, due to their small volume is the mass flux in this area only a fraction of the whole mass flux perpendicular to the spray axis. With increasing gauge pressure, cone angle increases first significantly (Fig. 7a, b) and then only moderately (Fig. 7c, d), what is evident from the spray photographs as well.

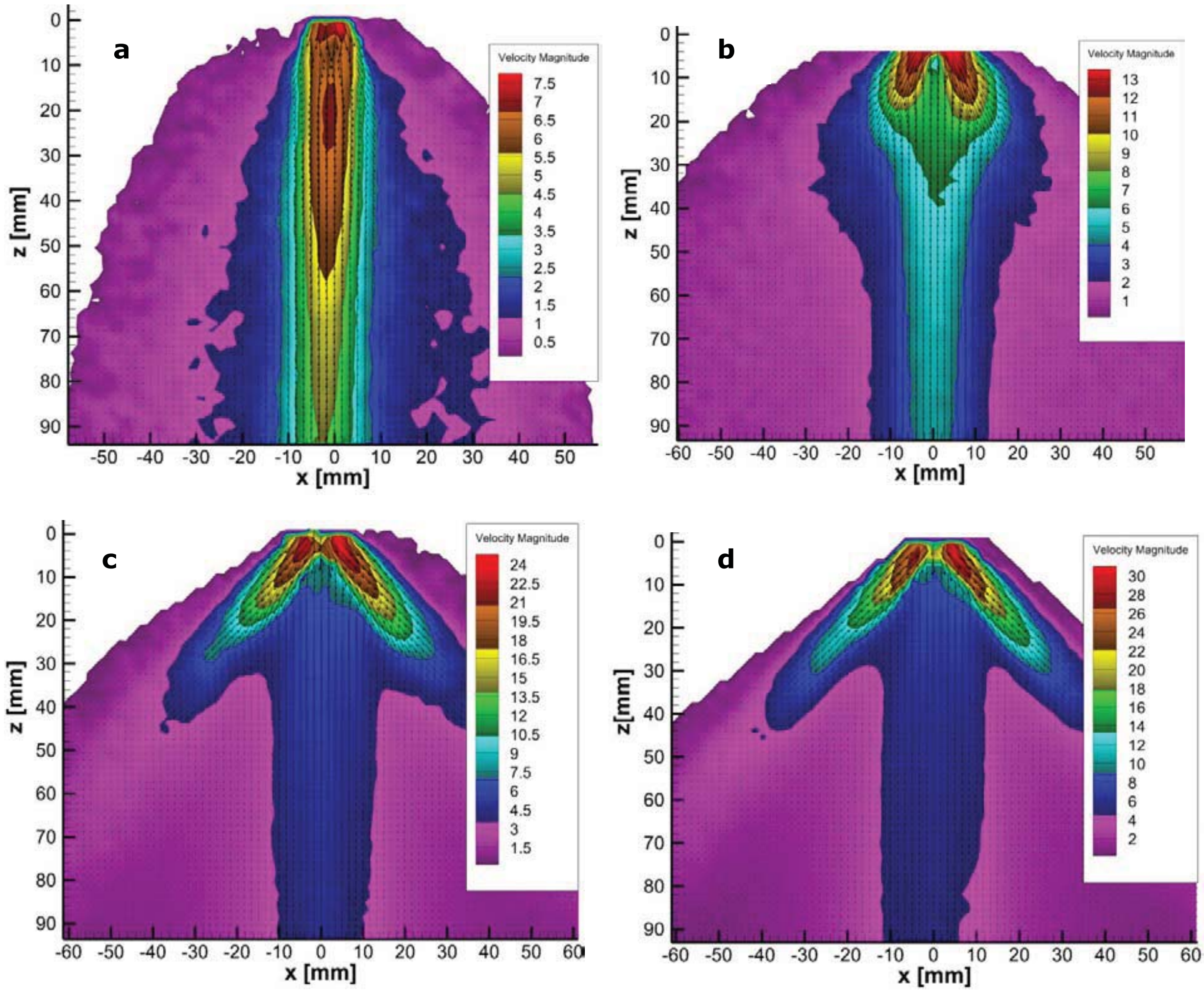

Figure 7: Spray velocity fields: a, 150 kPa; b, 340 kPa; c, 690 kPa; d, 1 MPa.

Comparison of P/DPA and PIV data

Matching of P/DPA and PIV measurements was examined. Velocity data were extracted from the PIV vector files generated with Insight 3G for the coordinates z=25 mm, x= (-30..30) mm and compared with the P/DPA data. Figures 8 and 9 are showing the P/DPA and PIV data, respectively. One can see, that in this distance from the nozzle orifice, both methods indicate similar values. Differences in the results may be caused by different principles, on which these methods are based. Choice of processing setup for PIV and different conditions of the ambient may have significant influence as well.

Due to higher number of points in case of PIV measurement, smooth average velocity profiles are obtained. However, velocity profiles obtained with P/DPA are more symmetrical at higher pressures.

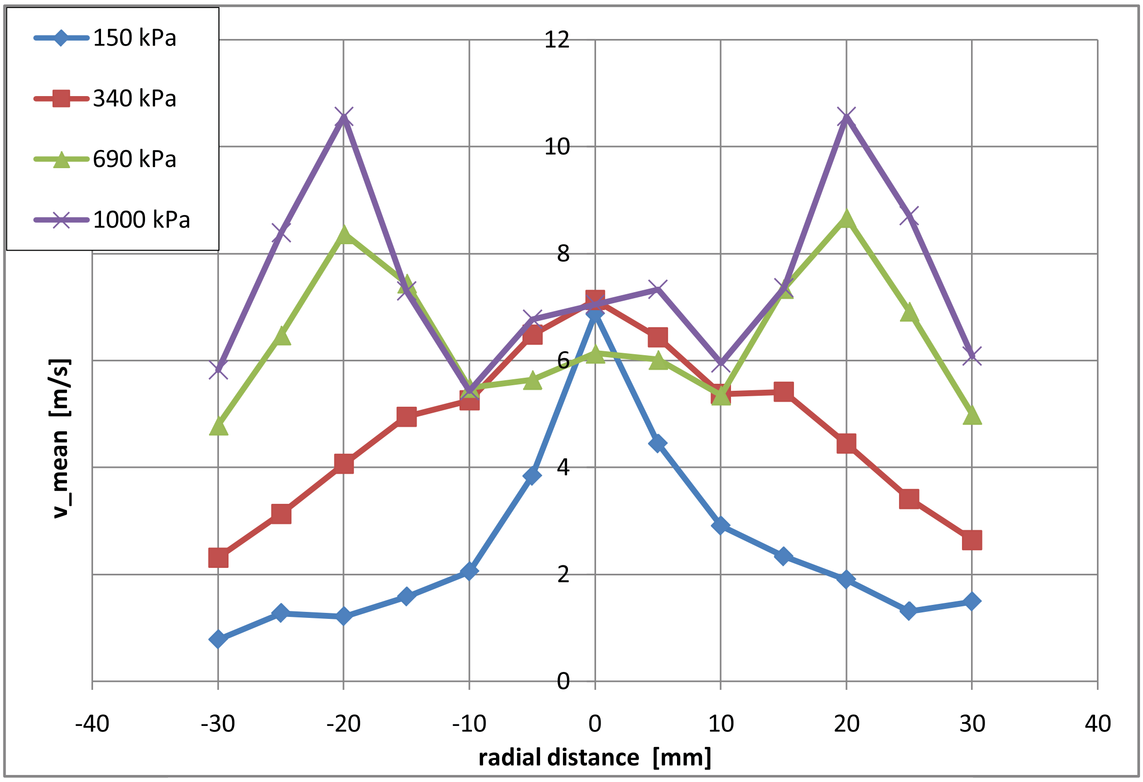

Figure 8: Mean velocity of droplets, P/DPA, z=25 mm.

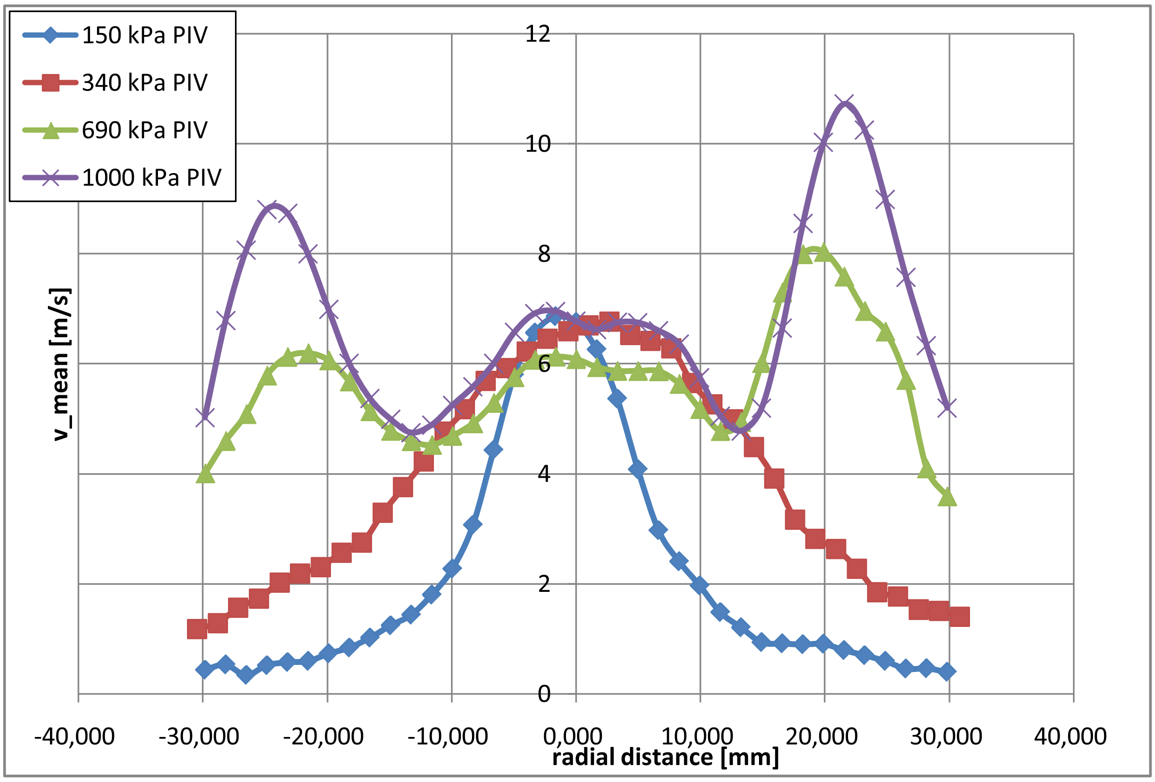

Figure 9: Mean velocity of droplets, PIV, z=25 mm.

5. CONCLUSIONS

In the present work, characteristics of spray generated with a newly designed pressure-swirl atomizer for a jet-engine combustion chamber are obtained using two optical diagnostic methods – Particle Image Velocimetry and Phase/Doppler Particle Analyzer.
Significant changes of spray characteristics for lower gauge pressures (150 kPa, 340 kPa) and less significant for higher gauge pressures (690 kPa, 1 MPa) were observed. Liquid mass is concentrated around the spray axis for lower gauge pressures. For higher gauge pressures, local velocity and mass flow maxima in the interconical region at the spray periphery are dominant, forming a hollow-cone spray.
Certain agreement of droplet velocity profiles obtained from both instruments for 25 mm distance from the outlet orifice is evident from the presented graphs.
Detailed PIV measurements will be performed in the next phase of our research. Spray images will be captured in various areas of the spray in closer distance from the nozzle with different processing settings according to the droplet velocity in each area. Stereoscopic PIV measurement will be performed as well.
PC-based data gathering system of pressure, flow rate and temperature values and fuel pre-heating/cooling device will be added to the presented test bench in a short time.

6. ACKNOWLEDGEMENTS

Authors greatly acknowledge financial support from project No. 101/11/1264 funded by the Czech Science Foundation and from Operational Programme "Research and Development for Innovations" – "NETME Centre – New Technologies for Mechanical Engineering" Reg. No. CZ.1.05/2.1.00/01.0002.

7. REFERENCES

[1] Lefebvre A.H.: Atomization and Sprays, Hemisphere Publishing, 1989, 421 p.

[2] Chu C., Chou S., Lin H. and Liann Y.: An Experimental Investigation of Swirl Atomizer Sprays, Heat and Mass Transfer (2008) 45:11-22, DOI:10.1007/s00231-008-0389-1

[3] Musemic E., Walzel P.: Estimation of Drop Sizes Using Pressure Swirl Atomizers, ILASS-Europe 2011, 24th European Conference on Liquid Atomization and Sprays Systems.

[4] Muliadi A.R., Sojka P.E., Sivathanu, Y. R., and Lim, J.: A Comparison of Phase Doppler Analyzer (Dual-PDA) and Optical Patternator Data for Twin-Fluid and Pressure-Swirl Atomizer Sprays, Journal of Fluids Engineering, Transactions of the ASME, 132,no.6: 0614021-06140210. Database on-line. Available from Scopus.

[5] Jedelsky J., Jicha M., Slama J. and Otahal J.: Development of Effervescent Atomizer for Industrial Burners, Energy & Fuels 2009, 23, American Chemical Society, SN - 0887-0624, p 6121–6130 : DOI:10.1021/ef900670g, available via the intenet at http://dx.doi.org/10.1021/ef900670g. Accessed January 2010.

[6] Environment Canada, Emergencies Science and Technology Division. *Jet A / Jet A-1.* Cit. 15. September 2011. [Online]: Oil Properties Database: http://www.etc-cte.ec.gc.ca/databases/Oilproperties/pdf/WEB_Jet_A-Jet_A-1.pdf

[7] Rohaly, J., F. Frigerio, and D. P. Hart.: Reverse hierarchical PIV processing. Measurement Science and Technology (2002) 13, no. 7: 984-996. Database on-line. Available from Scopus.
Bayvel L., Orzechowski Z.: Liquid Atomization, Taylor&Francis, 1993, 462p.