The Investigation of the Industrial Spray Systems Using Interferometry Particle Imaging Method

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Abstract The spray analysis, the knowledge of stray distribution, geometry and structures is a fundamental for many industrial applications. Here we present the optical method for non-contact spray investigation based on the principle of light interference. The advantages of this method are demonstrated on three examples from industrial application, each examining the two phase flow systems in various scales of particle diameters and impacting velocities. Demonstrated here are results analyzing EHDA atomizer, pneumatic nozzle and disintegration of the liquid behind the blade profile.

Keywords: atomization, Interferometry particle imaging method, optical measurement, Particle image velocimetry, spray analysis


1. Introduction

The atomization of liquids found its place in many industrial applications such as dye landing, lubrication, coating, injection, moisturizing, humidification, cooling, gas conditioning, and dust control.

Each application has its own specifications on working liquid, accurate flow rate, constant pressure and spray pattern. These conditions impose appropriate requirements on the spraying nozzle. Before the spray nozzle can be used in particular industrial application, as a part of complex system, it needs to be analysed and tested for its spray characteristics.

The inner construction of spraying nozzle has significant influence on the spray geometry. Here we used the vane less full cone nozzle. This geometry leads to narrow spray angle and fine droplet distribution. In this configuration the liquid enters the inner chamber and it is forced through an offset orifice into a swirl chamber. As the liquid leaves the orifice, the droplets follow a trajectory influenced by the orifice shape. The droplet size and spray distribution are predictable and not dependant on the laminar flow. [1,2]

The atomization is very complex system that includes various steps from primary breakup to secondary one via Kelvin-Helmholtz or Rayleigh-Taylor mechanisms. The degree of droplets atomization depends on their Weber number. This approach is common and general assumption of droplet breakup in every model. The breakup of liquid jets is a subject of fundamental importance in the optimization and industrial spray processes control. It can be said that the experimental study is of the same value as the theoretical and numerical simulation. Therefore experimental study is necessary to verify and improve the theoretical model and to determine boundary and initial conditions. [3]

In recent years many measuring and reporting methods that evaluate a nozzle capacity, spraying pressure, spray angle, and drop size distribution have been developed. Basically, we differentiate two types of measurements: spatial and flux technique. The spatial technique gives information of droplets in a sampled volume. This type of measurement is sensitive to the number of density in each class size and the number of particles per unit volume. The flux technique analyses individual droplets that pass through the cross-section of a sampling region. These types of measurements are usually based on optical principles that are capable of sensing individual droplets. The most of the optical measurement methods enables to analyse the droplet size distribution, velocity profile, as well as other spray characteristics.

Here we applied the IPI method on three industrial problems. At first we investigated the pneumatic water nozzle. In this issue we were expecting hundreds of micron in size of droplets moving with high velocity.

In second case we studied nozzle that is working on the electro hydrodynamic principal and the droplet produced with this nozzle fulfil the micrometre distribution.

In the third task we followed the development of water spray behind the blade of turbine. The droplets developed in this situation reach sub millimetre size and are very un-homogeneous.

This article describes the potential of non-invasive and nonintrusive optical based measurement technique for
characterization and analysing pressured air sprays. The Interferometry particle imaging method (IPI) enables to measure spray characteristics, droplets velocities and size distribution at once. This method belongs to the type of flux techniques and in association with Particle image velocimetry (PIV) describes the size distribution and velocity flow field.

2. Experimental Setup

2.1. Interferometry Particle Imaging Method

Here we use the Interferometry particle imaging method (IPI). This method is based on the interference of the reflection and refraction of glare points. The technique utilizes the interferometry pattern created from a particle illuminated by a laser sheet. The particles must be transparent, homogeneous and spherical. All these procedural conditions are fulfilled by sprays.

The Interferometry Particle imaging technique is based on the interference of the reflection and refraction glare points. Any phenomena that might affect one of the glare points will make the size measurement impossible. Thus, the particles must be transparent, homogeneous and spherical. Liquid droplet, air bubbles, glass balls are good candidates for the IPI technique. Good image quality (contrast) will be obtained for a relative refractive index, m, defined as the particle refractive index divided by the medium refractive index between below 0.8 or above 1.2. As long as the ratio of refractive indices steers clear of unity, there is the possibility of good measurements.

To ensure sufficient contrast of the interference pattern, the intensity of the two glare points must be comparable. This condition determines the position of the camera and depends on the relative refractive index, polarisation and wavelength of the laser sheet. For perpendicular polarisation, the camera should be located around \( \phi = 68 \) deg, and for the parallel polarisation it should be located at \( \phi = 90 \) deg.

\[
\text{For droplets where the relative refractive index (m > 1), liquid droplets, glare particles:} \quad \kappa = \frac{\arcsin \left( \frac{d_a}{2z} \right)}{\lambda} \left( \frac{\sin \left( \frac{\phi}{2} \right)}{m^2 + 1 - 2m \cos \left( \frac{\phi}{2} \right)} \right) \quad (2)
\]

\[
\text{For (m < 1 ), bubbles, glass spheres:} \quad \kappa = \frac{\arcsin \left( \frac{d_a}{2z} \right)}{\lambda} \left( \frac{\cos \left( \frac{\phi}{2} \right)}{m^2 + 1 - 2m \cos \left( \frac{\phi}{2} \right)} \right) \quad (3)
\]

Where: \( d_p \) particle diameter, \( \kappa \) geometric factor, \( N_{fr} \) number of fringes, \( z \) distance from light sheet to camera lens, \( d_a \) aperture diameter, \( m \) relative index of refraction, \( \phi \) observation angle.

The minimum particle size is calculated from size that represents one fringe:

\[
d_{\text{min}} = \frac{\sqrt{\kappa}}{\lambda} \quad (4)
\]

The maximum size is determined from Nyquist criteria in meaning that at least two pixels define the fringe:

\[
d_{\text{min}} = \frac{n_x}{2\kappa \Delta x} \left[ 1 - z_r \left( \frac{1}{f} - \frac{1}{z_1} \right) \right] \quad (5)
\]

Where: \( n_x \) the number of pixels in the x-direction, \( \Delta x \) dimension of the CCD array in the x-direction.

The IPI measurement system consists of NewWave Gemini Nd:YAG pulsed laser of energy in each pulse 120mJ. The duration of one pulse was 10ns. The light sheet used in these studies was 3mm thick. The image records were captured by two HiSense Neo, the sCMOS cameras of the spatial resolution (2560×2160) px with pixel size 6.5 µm. This new camera is unique in its ability to simultaneously offer ultra-low noise (1.4 e-), extremely fast frame rates (50 Hz in global shutter mode), wide dynamic range (>20,000), high resolution (5.5 MP) and a large field of view. This unique equipment allows obtaining high quality image and high contrast that enables the mathematical analysis.

The cameras were aligned to observe the same area in the same optical axis, for this arrangement we used special
IPI lens fitting adapter. Each camera was fitted with the lens of focal length 60mm; the one for focused image and one for defocused. The cameras setting was placed under angle $\phi = 90^\circ$ in the distance 670mm of the camera lens to the laser sheet. The aperture diameter was 15mm. The datasets of double images was recorded by IPI system of focused and defocused images were taken. The focused images were cross correlated and validated using the set of validation methods. Defocused images were analysed by Interferometry calculating algorithm. The validation of defocused images is dependent on the saturation density of particles, distance between particles and level of background noise. The optical setup enables to measure particles in the range from 20 up to 280 micrometres. The Figure 1 shows the IPI measurement configuration, synchronization between cameras and laser that is provided by the synchronization hub unit. Here it is also seen the angle $\phi$ between camera alignment and laser sheet that is dependent on the drop reflection index.

2.2. Atomization Setup

2.2.1. The pneumatic nozzle

The analysed pneumatic nozzle system that we used here enables huge range of modification for the purpose of exact industrial application. The nozzle attributes can be influenced by the nozzle diameter, shape, design, pressure adjustment, working liquid characteristics or the inner chamber construction and the external add-ons. The basic adjustment has potential for application, where the droplets of relatively small size are required and the drop impact velocity is small.

Here we use the full cone spray nozzle. This kind of nozzle produces full cone sprays round pattern that is completely filled with spray drops. The spray is formed by the vane less chamber, which imparts the liquid to the orifice due the controlled turbulence. The turbulence is induced by inner structures and proportions of the chamber. The inner geometry of mixing chamber is shown in Figure 2. The spray pattern is taken in the working distance of the atomization process. The working distance depends on the applied pressure or liquid feed rate. In this study we used the external mix, so the liquid is aspirated due the gravity force or the ejector effect to the nozzle. According to Figure 2 the spatial distribution of spray pattern is homogeneous and well sharped.

![Figure 2. Simplified sketch of the spraying nozzle and the full cone spray pattern](image)

The full cone spray nozzle consists of 1/8J stainless steel nozzle body and round spray air cap for external mix to produce full cone found spray pattern. This type of nozzle works with maximum air pressure 4bar, feed rate 0.68l/hour and maximum spray distance 1.8m.

The spray nozzle was joined into the system as an external mix configuration. The external mix system supplied the liquid into the nozzle by liquid siphon. This setup is designed to draw the liquid from a container through the feed line into the air flow, where it is atomized. The second exit of the nozzle was fed by compressed air. The pressure of the incoming air was measured by digital barometer Almemo and controlled by the reduction valve.

![Figure 3. The investigated areas A, B, C of the spray plume](image)

2.2.2. The EHDA Nozzle

The second kind of nozzle that is mostly used for colouring bodies in car industry is based on uniform electrostatic field.

Electrohydrodynamic atomization (EHDA) is the disruption of a liquid surface by electrical forces resulting in the formation of charged droplets. The physics of electrostatic spraying was first systematically examined by Lord Rayleigh in the late 1800’s. He also calculated the critical amount of charge that is necessary to destabilize a spherical droplet and observed the resulting instability that leads to the liquid jets production. These jets break up forming small stable charged droplets. Further motion of these droplets and their velocity is influenced by the electrostatic field. According to the applied high voltage, electrode distance and of course the chemical and physical properties of used solution, the droplets of micrometer or nanometer diameter can be produced.

The basic principle of the electrostatic spray technique can be briefly described as a linear pumping system with variable feed rate that is used to eject a liquid solution from a reservoir and fill the capillary. The electrical system consists of two electrodes axially placed in a certain distance, the gap. When a high voltage is applied on one of the electrodes, mostly the nozzle and the electrostatic force acting on the ejected droplet overcomes the surface tension of the solution and a straight jet erupts from the apex of the Taylor cone at the nozzle and travels toward an electrically oppositely charged electrode, generally named as a collector. The collecting mechanism at the target electrode can be explained using a dielectrophoresis force. The force directs the sprayed droplets toward the highest voltage gradient and is closely dependent on the droplet diameter, conductivity and applied field.

The attracting force acting on a droplet in a non-uniform electric field, $V E \neq 0$ is given by, $F_d = (\mu V) E$ where $\mu$ is a dipole moment. This dipole moment can be written as $\mu = (V \epsilon_0 \beta E)$ where $\beta$ are a function of the dielectric constant and the electrical conductivity of the sprayed droplet, and $\epsilon_0$ is a permittivity of vacuum.

The prediction of optimal feed rate for particular solution can be calculated from the quotation (6) [4] A critical voltage for needle spraying apparatus that is needed to disintegrate the droplets can be calculated.
correspondingly with Rayleigh theory about a disintegration of liquid bodies and is set along the equitation (7). Finally we can set the optimal feed rate, that corresponds directly with critical charge, desired droplet size and vaporization rate of the sprayed solution, counting with the humidity of ambient space and minimum sphere segments height needed for good start of electrostatic spraying.[5,6,7]

\[
f = \frac{\gamma \epsilon \rho}{2K}
\]

\[
y^2 = 4\ln\left(\frac{2h}{R}\right)(1,30\pi R\gamma)(0.09)
\]

where \( f \) is the optimal feed rate of solution, \( d \) is the prediction of droplet diameter, \( q \) is the suitable voltage that should be applied, \( \gamma \) is liquid–gas surface pension and \( \rho \) the density of the solution, \( \epsilon \) is the permittivity of the solution, \( h \) is the distance from the needle tip to the collector in centimeters, \( R \) is the needle outer radius.

### 2.2.3. The Liquid Flow behind the Blade Profile

The third application of the IPI method was the visualization of the liquid flow behind the blade profile. This situation is common in power industry and the effect of water condensation on the blades of turbine is causing a lot of damages on the equipment itself and the others in the row. The measurements for flow profile in the wind tunnel were implemented. Here we used this non-invasive technique for the size distribution of aerosols that was monitored withheld from the profile at three basic flows (0.1 l/min, 1l/min, and 5l/min). The air velocity in the wind tunnel was maintained at all times at 30 m/s.

Method IPI evaluated the droplet size sprays using interference structures drop illuminated laser cut. In principle it is possible to measure only single drops falling apart and not departing jets of water. These non-segregated streams primarily occurred when water 5l/min and could not be evaluated. A method IPI was also recorded in this mode each breakaway drops at a greater distance from the profile.

Here we were tested different distances of the camera from the laser cut (190mm, 700 mm and 1080 mm). Distance from lens to laser cut is affected by the size of the scan area, the spatial resolution of the current field and the range and quality of measurement of droplet size. At baseline measurement the optimum arrangement in terms of the given parameters was selected for placement of the camera lens to a distance of 1080 mm from the laser cut.

Depending on the velocity of the fluid flow on the surface profile is also changing the character and appearance of the spray.

![Figure 4. The spray of water just behind the wing profile](image)

Just beyond the edge of the profile were tracked the individual droplets. We could be very accurate in this mode as well as in determining the dynamic properties of the spray. Using the basic PIV method we measured the velocity of the droplets at each location for the profile.

### 3. Results and Discussion

#### 3.1. The Results of the Pneumatic Nozzle

The effect on the spray geometry has several liquid properties: viscosity, surface tension and density. The surface tension and viscosity represent the forces acting at the interface between two fluids (water, air). During the atomization the breakup of continuous liquid body into many small one increase the surface area over the whole liquid, thus the potential energy increases. The potential energy of the system is supplied by shear force acting on the liquid flow. The liquid flow is expressed as a pressure driven liquid flow through an orifice.

In this section is presented a visualization of spray geometry investigated in three areas. The first area was close to the nozzle exit, the second in the distance 0.7m far from the nozzle exit and the third one in 1.7m. In all investigated areas the spray was analysed on the drop size distribution. The applied air pressure was chosen according to the optimal nozzle range.

![Figure 5. The velocity profiles in the distance 0.1m from the nozzle exit](image)
The average size of the liquid aerosol was in order of submillimeters.

With increasing pressure there were only very small changes in the spray angle. That is achieved by the optimal shape of nozzle’s orifice. As it is seen on visualizations in Figure 5, the divergence of main droplet stream is in the limit of 17 degrees. If the stream starts to shift its parameters it is the sign of the nozzle damage or malfunction.

With higher pressure the instabilities in the stream occur. The instabilities are caused by local vorticities in the flow. The PIV method was used to determine the flow field of the carrying air and recognize the turbulences. The air flow field has the typical shape of submerged jet. About 30mm above the nozzle exit the stream of the liquid disrupt into the filaments. Upper from this area continues the secondary part of liquid bodies’ disintegration into the larger and smaller droplets. Larger bodies are carried close to the central line of the main air stream, where the velocities are higher and the local depression effects.

Figure 5 shows the calculated scalar maps of droplets motion velocity for applied pressure 1.3, 2.7 and 3.5 bar. It is significant velocity rise. The maximum velocity of the spray was 75m/s under pressure 3.5bar. In industrial process the common pressure is set on 2.5bar. The velocity of droplets in this regime and area reach the value of 30m/s.

The results of the droplet diameter just above the nozzle orifice are influenced by the measurement error. The droplets in this region are joined into one massive bulk of liquid and the motion of this jet cannot be recorded and analysed with PIV procedures. In the distance 15mm above the nozzle exit the jet disrupts and separated liquid blobs are measurable. These initial blobs have 1mm in diameter. According to this diameter, the dynamics of the blob is considerable and the velocity doesn’t correspond to the velocity of air flow.

The final size distribution is dependent not only on the applied pressure but also on applied voltage. This dependence is shown on Figure 7. The resulting impact velocity is not significantly influenced, but using optimal high DC voltage can be reduced the droplet diameter. The histogram is uncovering the effect of primary and secondary atomization. The secondary atomization is caused due the surface charge on the droplets and effective optimization can lead to micro scale diameters.

3.2. The Results of the EHDA Nozzle

The EHDA nozzle was connected to the positive high voltage power supply (FX50P06, Glassman High Voltage) with an applied the voltage from 10 kV to 20kV. A grounded steel collector was placed at 250 mm from the nozzle orifice. The nozzle was continuously fed with 20ml/min with linear pump and pressure of 1.3bar. Here we were focused on the resulting impact velocity that strongly corresponds to the droplet diameter. For this purpose the histogram of spray distribution was analysed in the distance 250mm from the nozzle orifice close to the surface of the grounded electrode [8].

The recorded flow field was evaluated and compared on velocity profiles in 0.1m and 1.7m distance from the nozzle exit. These distances conform to the selected investigated areas A and C Figure 5. The highest velocities can be measured close to the nozzle in core of the central stream. During the atomization process the droplets lose their kinetic energy on disintegration, friction force and the part of the energy converts to potential energy according to Navier-Stokes equation.

3.3. The Results of the Liquid Flow behind the Blade Profile

For the profile in the regime forms part of the water stream that couldn’t be pulled by air apart into individual droplets. PIV measurement in this area can be considered correct. The nature of these non-disruptive ligaments close to the blade surface could be monitored by other visualization techniques.

At maximum liquid flow speed - 5l/min, reached the compact flow before spreading to spray a few inches. The stream changed its geometry depending on the air speed from the blade profile and finally shaped into the form expected Karman vortex trail.

As the first stage there was measured the flow fields of the droplet spray. These results demonstrate the dynamics of particles and illustrate the extent to spray that follows the movement of the air stream. Beyond the basic vector maps were plotted stream profiles in the different sections of the monitored area.

Compactness of the stream flow 5l/min is obvious from visualization. The graph in Figure 8 compares the stream which is less accelerated with the ambient air with the individual drops in previous regimes. The comparison of histograms (see Figure 9) shows the changes in the
droplet size diameter and distribution that is non-affected by the liquid flow. From the Kelvin-Helmholz theory of disintegration the liquid into the spray results that the spray is mostly influenced by the surrounding air flow of higher velocity. This condition is also relevant in this case.

Figure 8. The vector map of the spray of droplet motion in the 0.1l/min, 1l/min and 5l/min liquid flow in the wind tunnel of constant air flow speed 30m/sec

Figure 9. The histogram of droplet size distribution taken for 0.1l/min and 5l/min liquid flow behind the blade profile

4. Conclusion

The purpose of this article was to show the advantages of the non-contact optical method of the spray analysis for the industrial application. The advantages of this method were demonstrated on three examples: the analysis of EHDA atomizer, pneumatic nozzle and disintegration of the liquid behind the blade profile.

Each application has its own specifications on working liquid, accurate flow rate, constant pressure and spray pattern. These conditions impose appropriate requirements on the spraying nozzle. Before the spray nozzle can be used in particular industrial application, as a part of complex system, it needs to be analysed and tested for its spray characteristics.

With the help of the IPI method the spray and the various liquid disintegration can be studied for its geometry, impact velocity and droplet size distribution in one step. As it was shown here, the method offers the measurement of wide range distributions just adapting the setup geometry.

The atomization is very complex system that includes various steps from primary breakup to secondary one via Kelvin-Helmholtz or Rayleigh-Taylor mechanisms. The degree of droplets atomization depends on their Weber number. This approach is common and general assumption of droplet breakup in every mathematical model. The breakup of liquid jets is a subject of fundamental importance in the optimization of industrial spray processes control. It can be said that the experimental study is of the same value as the theoretical and numerical simulation. Therefore the experimental study is necessary to verify and improve the theoretical model and to determine boundary and initial conditions.

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