Measurement and analysis of abrasive particles velocities in AWSJ


Abstract

Abrasive water suspension (AWS) is a progressive cutting technology used in many industrial applications. Potential of this technology is very high due to good mobility and flexibility of the cutting process. It is mainly applied in the fields of defusing explosives, repairing and dismantling of nuclear power plants, offshore applications and special industrial structures. Although this technology works very well, further improvement of basic components and optimization of the cutting process is vital. In this experimental work, the applicability of LIF (Laser Induced Fluorescence) technique combined with PTV (Particle Tracking Velocity) was tested for the identification of velocities of abrasive particles at the output of a cutting nozzle. The combination of various pressure levels with different abrasive mass concentration was tested. The obtained results of abrasive particle velocities are presented in the paper.

1. Introduction

The abrasive water jet (AWJ) technology has been developed from the plain water jet cutting method [1]. The idea of addition of abrasive particles into the plain water jet was born in order to disintegrate harder materials such as steel, concrete, other alloys, etc. The disintegration phenomenon is based on transmission of high energy to an extremely small area. Material destruction is caused by physical processes occurring during the jet impact erosion, shearing and failure under rapidly changing localized stress fields [1][2].

Two basic systems for generation of abrasive water jets were developed over the years. The first technique called abrasive water injection water jet (AWIJ) was developed in the late 1950s and early 1960s. The main part of the AWIJ technology is composed of a high pressure water pump, high pressure (HP) pipes and cutting head. The cutting head is assembled from a water nozzle, mixing chamber and focusing tube. The water nozzle with a diameter in the of range 0.1 to 0.4 mm generates a plain water jet which moves at very high speeds depending on the input pressure level. The water jets generate vacuum pressure inside a mixing chamber which is open from one side. Abrasive particles are delivered from this side with a stream of air due to recombination of pressures. Abrasive particles, air and high speed water jet are mixed inside the chamber. Final shape and acceleration of the high speed abrasive water jet is given by the inner geometry of a focusing tube. HP pumps are commonly designed up to 400 MPa; the highest commercially available pressure levels are up to 690 MPa [3].
Second technique for generation of abrasive water jet is called abrasive water suspension jet (AWSJ) developed in 1984. This method differs from the AWIJ by the absence of air. Transformation of the high pressure suspension water into the high speed suspension water happens as the water passes through the cutting nozzle. This enables getting a suspension water jet with better coherent structure, stability and significantly higher cutting performance. Important parts of the equipment are a high pressure pump, mixing unit for the abrasive material delivery, HP hoses and cutting nozzle of 0.5 to 1.3 mm in diameter. Commonly used pressure levels of water are up to 250MPa. Three different principles of the AWSJ generation (i.e. direct pumping, indirect pumping and bypass principle) were developed. Commercial systems mostly use the bypass circuit (see Fig. 1a). HP water is delivered from the pump into the abrasive mixing unit. Water stream is divided inside the mixing unit and the water flows into a plain water line and a bypass line. The water coming through the bypass line pressurizes vessels with abrasives. The plain water line and the bypass line are connected at the output of the mixing unit. Suspension mixture is delivered by a hose directly to the cutting head. Volume rate of abrasives in the bypass line is controlled by a restriction valve. Picture of the abrasive mixture unit with the bypass circuit developed by ANT Applied New Technologies AG in Lübeck, Germany, is shown in Fig. 1b. [3].

With regard to the development of the AWSJ technology, the interest in understanding the inner relations accompanying the process of the AWSJ generation is high. The knowledge of velocities of abrasive particles inside the water jet based on CFD modelling and cutting tests provides important information about the efficiency of the technology and gives new opportunities for its further improvement.

Lots of experimental studies on determination of abrasive particle velocities in water jets were published in the late nineties of the last century. The results are summarized in publications written by the authors Geskin et al., Li et al., Isobe et al., Swanson et al. [4][6][7]. Observation techniques were significantly improved using optical techniques of Laser Doppler Anemometry (LDA) and Laser Transit Velocimetry (LTV) in years 1994 to 1997 [8][9].
The best progress in measuring velocities of abrasive particles in the water jet was achieved using the laser induced fluorescence method firstly introduced by Roth et al. (2009) [10]. This method allowed determining 2D velocity fields of each individual fluorescent coated particle inside the water jet. Balz et al. (2010) improved this technique using two cameras arranged in stereo configuration [11]. This setup was applied to obtain images in three spatial dimensions of the water jet. Zeleňák, Foldyna et al. [12] realized a complex study on abrasive velocities distribution within water in 2014. All tests were performed using an injection system with maximal pressures up to 415 MPa. In the same year, first measurement with the suspension jet was realized in the initial phase of cooperation between ANT Applied New Technologies AG and IGN of the CAS.

The aim of this experimental work was to test the applicability of the laser induced fluorescence technique combined with the particle tracking velocity for identification of velocities of abrasive particles within suspension jet at the output of the cutting nozzle. The combination of various pressure levels with different abrasive mass concentration was tested. The results of measurement of abrasive particle velocities are presented in the paper.

2. Principles of measurement using LIF combined with PIV

2.1. LIF

Laser induced fluorescence is a spectroscopic method used for amplification of a light signal of tracking particles in non-transparent liquid flows. Due to the fact that ASWJ represents a non-transparent water flow, abrasive particles had to be coated with molecules of Rhodamine B (C₂₈H₃₁CIN₂O₃). Rhodamine B has an absorption spectrum (see Fig. 2) that differs from emission spectrum of abrasive particles. If the laser emitting green light (wavelength of 532 nm) illuminates Rhodamine B, the emission maximum of Rhodamine B molecules occurs in the yellow-red wavelength of 564 nm. Thus, the monochrome emission of a laser illuminating abrasive particles is captured at a different wavelength. Using a band-pass filter with transmission range of 545 to 800 nm, any undesired green light reflection can be eliminated and only the signal of the dye is recorded. This allows detecting abrasive particles within the jet.

2.2. PIV

PIV method measures whole velocity fields by taking minimally two images shortly after each other and calculating the distance of individual particles travelled within this time. From the known time difference and the measured displacement, the particle velocity is calculated. Laser light pulses focused into a thin light sheet are used to illuminate the flow so that only particles in that plane are imaged. The time duration of pulses is typically only 6 to 10 ns long and therefore they freeze any motion. A CCD camera is utilized so that it can store the first image (frame) fast enough to be ready for the second exposure. Interframe time necessary for image transfer is shortened down to 100 ns. Particle Tracking Velocimetry (PTV) is often called low particle number density PIV. PTV algorithm tracks the trajectories of individual particles. Particle identification and determination of its position in space is a very important step in PTV. This is only possible if the number of particles per unit volume is not too high. The time interval between frames is prescribed by the pulse illumination frequency in PIV and by imaging frequency in PTV. Schematic drawing of a planar PIV system used for LIF measurement of velocities of abrasive particles is presented in Fig. 3.
3. Experimental procedure

The experimental assembly used for the visualization of abrasive particles and the measurement of their velocity in the AWSJ consisted of a high-pressure pump Hammelmann 2500/13, an abrasive mixing unit ANT AG AMU 2500-40, an AWSJ cutting head ANT, a water catching tank and a PIV system for particle velocity measurement (Fig. 4). The AWSJ cutting head was fixed in the holder and directed to the catching tank. The recording system consisted of the LaVision Imager Pro X2M CCD camera with macro lens and LIF edge filter, and Nd:YAG NL 135-15 double-pulse laser (wavelength of 532 nm, pulse width of 6 to 9 ns). The CCD camera with maximum recording rate of 15 Hz operated at double frame mode and was synchronized with the laser by means of a PTU 9 controller. The camera was positioned perpendicularly to the output of the AWJ cutting head and the laser equipped by sheet optics creating the light sheet was placed from the left side perpendicular to the position of CCD sensor (Fig. 5). The maximum output energy of the laser was 2x135 mJ for each laser pulse and the time delay between 1st and 2nd laser pulse was changed from 0.2 to 0.5 μs, depending on operating parameters of AWSJ.
The measurement was performed at the operating pressure set to 70 MPa (abrasive concentration 10%), 120 MPa (abrasive concentration 10%), 150 MPa (abrasive concentrations 7%, 10% and 13%), 200 MPa (abrasive concentration 12%), 220 MPa (abrasive concentration 5%), and 240 MPa (abrasive concentrations 8%, 10% and 24%). Nozzle with diameter of 0.55 mm was used in tests at the operating pressures of 70 and 220 MPa. Nozzle with a diameter of 0.51 mm was used in all other experiments.

3.1. Abrasive particle preparation

To obtain fluorescent abrasive particles, the natural Australian garnet with MESH size 80 (actual size of particles was within the range of 150 to 300 μm) was dispersed in the polyurethane refined acrylate lacquer with water and dissolved fluorescent dye Rhodamine B. The mixture was dried at the temperature of 80°C for a period of about 20 hours. Then, the particles coated by the “Rhodamine lacquer” were separated and sieved. The procedure was repeated twice to minimize coloring of the water when the particles were dispersed in the water for a longer time. The coating of the Rhodamine B on the surface of abrasives was visually controlled by a confocal microscope (Fig. 6). The total amount of abrasive prepared was about 10 kg.

![Figure 6. Detail of fluorescent-dye coated abrasive particles](image)
3.2. Image analysis

All pictures taken by the CCD double frame camera were analyzed separately. Each frame was analyzed using the following algorithms: firstly, the subtracted offset algorithm was used to separate the light noise from the basic source image. Consequently, the experimental images were smoothed over a neighborhood of 9 pixels. In the next step, PTV algorithm for the study of individual particles movement was applied [13][14][15]. The procedure of image post-processing is illustrated in Fig. 7. Finally, the calculation of the vector statistics was performed.

![Image Post-processing Diagram](image)

Figure 7. Procedure of image post-processing: a) source image, b) subtraction of noise from background, c) smoothing of neighbourhood exceeding 9 pixels, d) PTV – algorithm for tracking movement of individual particles

4. Results

Summary of results of the measurement of abrasive particle velocities in the AWSJ downstream of the nozzle exit in terms of the average velocity of particles under given experimental conditions is presented in Table 1 and Figures 8 and 9. More detailed information regarding particle velocities under given experimental conditions can be found in Figures 10 and 11 where the results are presented in form of histogram graphs.

The velocities were evaluated not only within the whole range of standoff distances from the nozzle exit up to 15 mm downstream the nozzle exit but also in partial ranges of standoff distances from 0 mm to 5 mm, 5 mm to 10 mm and 10 mm to 15 mm. It is quite remarkable that the average velocity of abrasive particles slightly increases at larger standoff distances at the operating pressure of 70 MPa. On the other hand, the average velocity of abrasive particles slightly decreases at pressures of 200 MPa and higher.

It is of interest to note that the abrasive particle velocities are lower than expected at the operating pressures higher than 200 MPa. The reason is not clear yet – it could be due to improper matching of the nozzle diameter with abrasive grain size or the nozzle design is not optimized for these pressure levels.

Table 1. Summary of results of measurement of abrasive particle velocities (p – operating pressure, AC – abrasive concentration, N – total number of measured particles, \(v_{avg}\) – average velocity of particles)

<table>
<thead>
<tr>
<th>p[MPa]</th>
<th>AC [%]</th>
<th>0 – 15 mm</th>
<th>Standoff distance from the nozzle exit</th>
<th>10 – 15 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 – 5 mm</td>
<td>5-10 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N)</td>
<td>(v_{avg}) [m/s]</td>
<td>(v_{avg})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(N)</td>
<td>(v_{avg}) [m/s]</td>
<td>(N)</td>
</tr>
<tr>
<td>70</td>
<td>10</td>
<td>13121</td>
<td>272.8</td>
<td>7269</td>
</tr>
<tr>
<td>120</td>
<td>10</td>
<td>5935</td>
<td>358.9</td>
<td>2124</td>
</tr>
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<td>7</td>
<td>6643</td>
<td>404.2</td>
<td>2323</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>4952</td>
<td>395.5</td>
<td>1759</td>
</tr>
<tr>
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<td>13</td>
<td>5502</td>
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<td>899</td>
</tr>
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<td>4731</td>
<td>484.8</td>
<td>2998</td>
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<td>240</td>
<td>24</td>
<td>6318</td>
<td>468.5</td>
<td>2440</td>
</tr>
</tbody>
</table>
Figure 8. Average velocity of abrasive particles as function of operating pressure.

Figure 9. Average velocity of abrasive particles as function of abrasive concentration.
Figure 10. Histograms of velocity of abrasive particles measured within the range of standoff distances from 0 to 15 mm (pressures of 70, 120, 150, 200, 220, 240 MPa with different concentrations)
5. Conclusion

In this experimental work, the applicability of the PIV system extended for the LIF measurement combined with PTV processing algorithms to analyze particle velocities downstream of the nozzle exit was tested. The results obtained in this experiment provide with important information that can be used for CFD numerical calculations of the flow in the cutting head. Based on the calculations, a new design of the cutting head can lead to further improvement of the cutting process. Significant amount of time and money can be then saved in the design process. Thus, the applied measurement technique becomes an important part of a very effective optimization process of the design of new components of the cutting head.

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References