AN IMAGE PROCESSING APPROACH FOR DETERMINING THE SPRAY CONE ANGLE OF A PRESSURE SWIRL INJECTOR EQUIPPED IN A GAS-TURBINE ENGINE

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Abstract

This paper adopts the directionality tool provided by the ImageJ package to determine the spray cone angle of a gas-turbine engine's injector. An imaging experiment system has been developed in this study to image a spray of a practical gas-turbine injector under injection pressure conditions varying from 2 to 6 bars. The results show that the reliability of the measurement is achieved when analyzing at least 500 images. Preferably, using 1500 images shows the uncertainty of less than 0.5% (approximately corresponding with 0.2° of the angle). The average spray cone angle varies between 100° and 128.15° when the injection pressure increases from 2 to 6 bars. An accurate determination of the spray cone angle helps to improve the quality of research on micro and macro spray characteristics including the droplet concentration and distribution. The results could also be utilized to develop a diagnostic technique for gas-turbine injectors.

Keywords: *Spray cone angle; directionality tool; ImageJ; gas turbine engine; swirl injector.*

1. Introduction

Gas-turbine engines are typically equipped with pressure swirl injectors. The injectors supply fuel into the combustion chamber under the condition of high-speed airflow output from the compressor. Among the parameters that could be adopted to evaluate the fuel injection quality, spray cone angle is one of the most critically important parameters affecting the fuel particle/droplet density, size and distribution. As such, cone angle directly affects engine efficiency, flame zone, and heat distribution in the combustion chamber. An unreasonable spray cone angle may lead to unexpected fuel-air ratio zones and this results in unstable flame and poor combustion quality, high emission concentrations and short engine lifetime [1]. Spray cone angle is also one of the best diagnosing parameters. For more in-depth studies [2, 3], spray cone angle

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measurement is also a basic requirement to compute size and distribution of droplets generated due to fuel atomization.

In experimental studies, spray cone angle is often captured using cameras along with image processing software [4, 5]. One of the difficulties is that the spray angle is naturally not a constant value through time. It fluctuates with time and this is due to the randomness of the atomization process. This requires processing a large enough number of images to ensure the reliability of the average spray angle. Nevertheless, this method normally requires processing on the binary image. Besides, the unreasonable binary threshold choice will significantly affect the accuracy [9]. Therefore, this paper chooses specialized image analysis software known as ImageJ [10] to improve the uncertainty of image processing. ImageJ has been used widely in the studies of the fuel injection process in general [11-13] and the determination of the spray cone angle in particular [14-16]. However, these reports only use the manual tool of angle measurement on the software. Although ImageJ is a well-known image processor, the novelty of this work is adopting ImageJ's directionality tool for the spray cone angle measurement. Alternative approaches to determine the spray cone angle are also available and particle imaging velocimetry - PIV technique is among them as reported in [17]. These methods often supply fairly good results, however, are very expensive.

The method provided in this study allows automatically processing the cone angle from a large number of images without choosing the binary threshold. Besides, a laboratory system is developed to record spray images for a gas-turbine engine injector under varying operating conditions. The paper consists of 3 main sections: theoretical background and experimental model are presented in Section 2; Section 3 describes the image processing method, and Section 4 provides some results as well as analysis of the spray angle.

2. Theoretical background and experimental system

2.1. Theoretical background

2.1.1. Geometry characteristics of spray cone angle in gas turbines engine

Gas-turbine engine injectors are typically pressure-swirl airblast atomizers. This injector type normally creates wide spray angles, around 110° [18]. This aims to increase the fuel spray dispersion in the combustion chamber to increase combustion efficiency alongside increasing the flame stability [19, 20]. A wide spray cone angle is also synonymous with a short flame length, and this is an important feature of the gas turbine engine to reduce the turbine blades' temperature. Basically, the fuel spray of gas turbine engines is a hollow cone shape that is symmetrical around the vertical axis of the injector as schematically shown in Fig. 1.

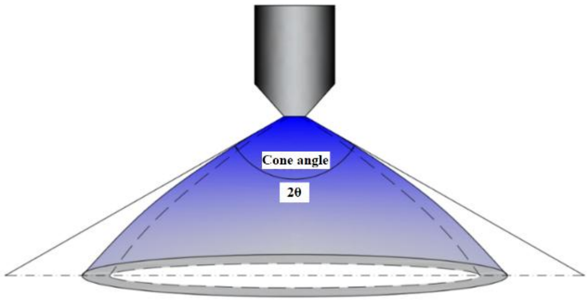


Fig. 1. Spray cone angle of the gas turbine engine

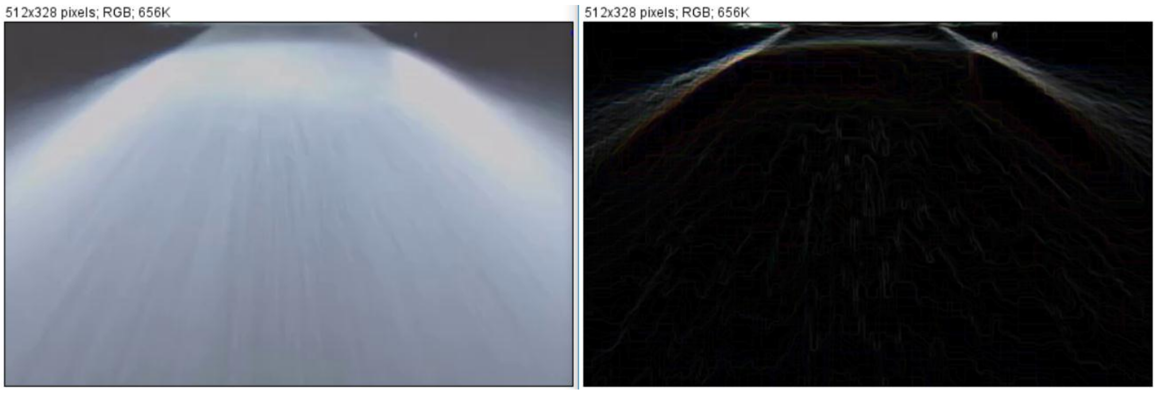
The basic spray structure is shown in Fig. 1 consists of 2 main zones: upstream and downstream. The upstream zone (near the injector orifice) has a dense spray, at which the average boundary approximates a straight line. At the downstream zone (far from the injector orifice), because of the spray dispersion and fuel evaporation into the surrounding air, the fuel droplet density is lower, especially near the edge. At this zone, the boundary will be curved, looks like a mushroom shape, and more challenging to define. Therefore, the cone angle is defined as the angle between two straight lines that tangent with the spray boundary created by the upstream zone. In the case of the airblast flow neglected, according to the [21], the mean spray cone angle for the pressure-swirl atomizer is estimated as the following expression:

$$2\theta_m = 6K^{-0.15}\left(\frac{\Delta P_L d_0^2 \rho_L}{\mu_L^2}\right)^{0.11} \tag{1}$$

where θ_m is the mean spray cone half-angle (degrees), K is the geometry coefficient [22], ΔP_L is the injection pressure (Pa), d_0 is the discharge orifice diameter (m), ρ_L is the liquid density (kg/m^3), μ_L is the liquid viscosity (kg/m·s).

2.1.2. Image processing algorithm

Using the edge detection algorithm is an effective method for determining the spray cone angle from the captured images. The idea of this method is to define all edges at the spray boundary region of each image then an average angle of all images will be output. The angle of each edge is measured relative to a given frame. Statistics of the borderlines with the same angle allow determining the direction of the injected fuel movement. Here, the edge in image processing is a set of edge points. And, the edge points are points at which the image brightness sharply changes. Therefore, it is necessary to create a sudden change in the image brightness in the considered area to accentuate the edge to improve the image processing uncertainty. For fuel spray cases, usually use the backlight method or capture images against a black background under the inclined light source. Fig. 2 shows an example of the edge detection analysis for the fuel spray. The original image is captured by an HD camera against a black background under the inclined light source.



(a) *(b)*

Fig. 2. The edge detection for the spray image

(a) Original image; (b) Edges image

This paper utilized the Sobel 5x5 method [22] to detect the edge. This is one of the most popular edge detection methods in image processing. The advantage of this method is good edge detection and is less affected by noise. The Sobel 5x5 algorithm uses an orthogonal matrix pair to calculate the vertical (H_1) and horizontal (H_2) brightness gradients, as shown below:

$$H_1 = \begin{bmatrix} 1 & 2 & 0 & -2 & -1 \\ 4 & 8 & 0 & -8 & -4 \\ 6 & 12 & 0 & -12 & -6 \\ 4 & 8 & 0 & -8 & -4 \\ 1 & 2 & 0 & -2 & -1 \end{bmatrix} \text{ and } H_2 = \begin{bmatrix} 1 & 4 & 6 & 4 & 1 \\ 2 & 8 & 12 & 8 & 2 \\ 0 & 0 & 0 & 0 & 0 \\ -2 & -8 & -12 & -8 & -2 \\ -1 & -4 & -6 & -4 & -1 \end{bmatrix} \quad (2)$$

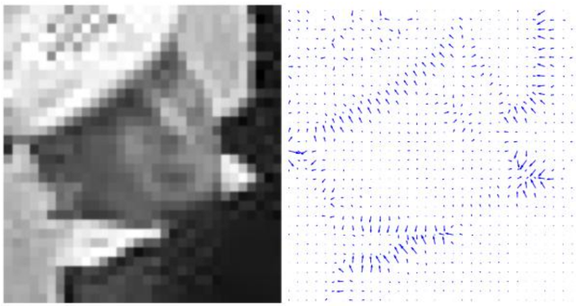
Then the brightness gradient at each pixel in the image is calculated as follows:

$$G_x = H_1 * Z \,;\; G_y = H_2 * Z \quad (3)$$

$$G = \sqrt{G_x^2 + G_y^2} \tag{4}$$

$$\tan\alpha = {G_y}/{G_x} \tag{5}$$

in which, G_x and G_y are vertical and horizontal brightness gradients at the considered pixel, respectively. Besides, Z is a 5x5-pixel matrix extracted from the original image with the examined point in the matrix center. The "*" here represents the convolutional product of the two matrices. The brightness gradient at the estimated point is a vector that has magnitude G calculated by Equation (4), and direction is defined using Equation (5). Finally, an image of the gradient vectors is created (Fig. 3b) after applying the above computations for all pixels. Next, for each pixel, the angle α is rounded to the nearest multiple of 45°. According to the direction of the rounded angle vector, if the brightness gradient of the front and behind pixels is smaller than the gradient at the considered point, this point is an edge point.



(a) *(b)*

Fig. 3. Determining the brightness gradients [22]
(a) Original image; (b) Image of the gradient vectors

2.2. Experimental model for determining the spray cone angle

Fig. 4 shows the experimental system developed in this study to quantify the fuel spray cone angle of a gas turbine engine. The pneumatic source is responsible for increasing the pressure of the fuel tank up to 7 bar. This pressure value is adjusted and stabilized by the pneumatic regulator. The system is protected using a safety valve set at 8 bar. The pressure values of the gas supply and the fuel tank are displayed on the gas manometers. Fuel at 7 bar of pressure condition from the fuel tank passes through the fuel filter, lock, reducing valve, and flows to the injector. The fuel pressure is preset and stable according to each test mode using the pressure regulator. Then, fuel passes through the injector orifice and into the air. The fuel pressure value is displayed on the fuel manometer. The spray image is captured by a HD camera along with a black background under the inclined light source. The spray images were captured utilizing an HD camera on a black background under the inclined light source. The spray images are recorded after few minutes from the injection start when the injection process reaches stability. It should be noted that the air-blast injector is different from the ones utilized in internal combustion engines. The air-blast counterparts are continuously operating, and as such, the phenomenon of starting injection is not quite important in atomization studies for air-blast injectors. All obtained images are saved as a video file with a speed of 30 frames per second and a time length of 60 seconds, corresponding to 1800 photos for each measurement.

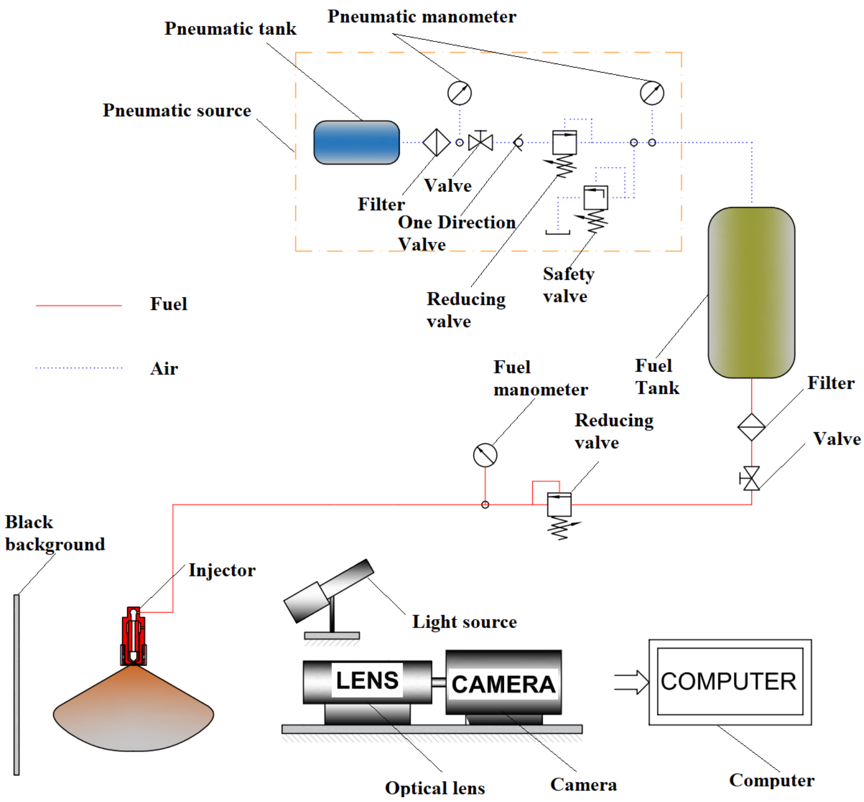


Fig. 4. Experimental model for determining the spray cone angle.

According to [24], the cone angle depends on many factors such as the injector geometry, the fuel pressure difference inner the injector and the environment, the relative velocity between the fuel jet and the air, or the fuel properties. In which the injector geometry, relative velocity, and injection pressure are more influencing factors than others. However, to develop the method of determining the cone angle, the experimental system is just limited to a simple case that simulates the fuel injection process in the low-pressure range (2-6 bar), whereas the gas flows in the combustion chamber is ignored. In this case, equation (1) is reasonable to calculate the spray cone angle. Moreover, the experiment is implemented at the atmospheric pressure and 30^{o}C ambient temperature. In addition, fuel here is replaced by pure water. Of course, using water could be able to increase the spray cone angle. From equation (1), the spray cone angle of water could be 6.3% greater than that of TS-1 fuel due to the difference in density and viscosity of those fuels. However, using the real fuel will lead to a more complex experimental system, and as such, the method adopted in this work is also commonly used in literature. Water is also used for calibrating /diagnosing gas-turbine injectors. Nevertheless, this paper focuses on developing a measuring technique for cone angle and the issue mentioned above is beyond the scope of this work.

In this paper, the spray images are recorded in a pressure range from 2-6 bars and samples of spray images captured under these conditions are provided in Fig. 5. The preliminary images show that the spray cone angle increases with increasing injection pressure. In particular, the cone angle at a pressure from 3-6 bar is quite stable, while the one at 2 bar is not clear, and sometimes the local drip phenomenon appears. These images will be processed on the software to determine the cone angle.

2 bar	3 bar	4 bar	5 bar	6 bar
				

Fig. 5. Spray images at different pressures.

3. Software, tools, and image processing methods

As mentioned above, image processing is an effective method for studying fuel spray. In this paper, ImageJ image processing software [10] is utilized to determine the spray cone angle. It is a powerful image processing software with open source. Besides, it also allows users to both exploit and develop tools or build custom processing programs. Thus, this software is usually utilized in processing experimental data of many studies with thousands of plug-ins and macros. These include applications that are important to study the spray such as particle analysis, accurate measurement, etc. Moreover, this software also allows processing in various file formats of multiple images or movies.

The method adopted in this paper uses the Directionality tool available in the software. Basically, this tool calculates the probability of the most appearing angle in the processed image. The algorithm applied here is the edge detection algorithm by the Sobel 5x5 method, as mentioned in Section 2.1.2. The edges will be defined at locations where the brightness changes suddenly, their angles are measured relative to the horizontal direction of the image. In which the positive angle is conventionally counter-clockwise. The amount of edges with the same angle is evaluated and displayed in a distribution graph (Fig. 6) that can be export as a data file. For the problems in measuring the spray cone angle, the most likely occurrence angle will be in the spray boundary area, so this method is suitable.

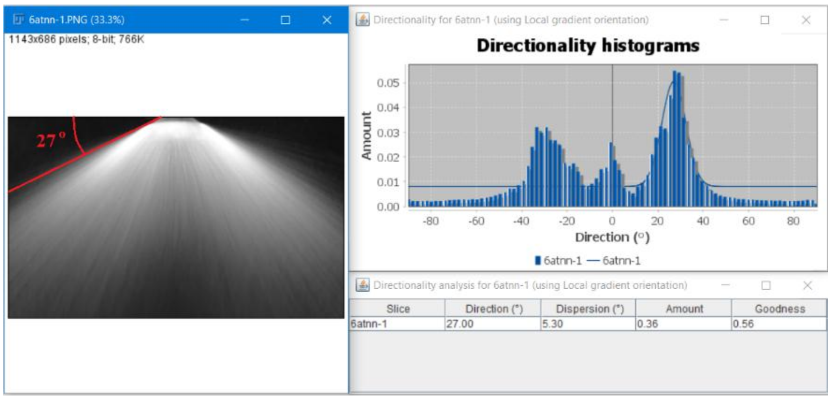


Fig. 6. Analytical results for the whole spray image at 6 bar.

Fig. 6 shows an example of a procedure of image processing. First, the image is converted to grayscale for processing. The Directionality tool results that the angle appears at most 27° relatively to the horizontal of the image. The column "Amount" shows the appearance probability that the edges with the same angle of 27° as 36%. The "Goodness" column evaluates the quality of the directional analysis. This value ranges from 0-1, in which the closer to 1 the analytical quality is possible. Essentially, images with a pronounced luminance contrast make it easier to analyze the direction and improve analysis quality. On the other hand, analyzing the whole frame is more complicated and leads to poor analytical quality. That is the reason in Fig. 6 the "Goodness" is only 0.56. For the spray angle measurement problem, the analysis quality will be improved when analyzing only the spray boundary area near the injector orifice. Besides, when measuring the spray angle, this software shows only the spray angle value that is the most occurrence. As shown in Fig. 6, when analyzing the whole image, although there are two peaks appeared on the Histogram, the displayed result shows only the value of the angle most appearing. Therefore, when measuring the spray angle, it is necessary to process each left and right halves of the image, then combine the result of two parts to find the spray angle. Fig. 7 shows that, as processing only the spray left half, the image analysis quality is significantly increased (Goodness is up to 0.91). Besides, the measured result is diminished from 27° to 26.87°.

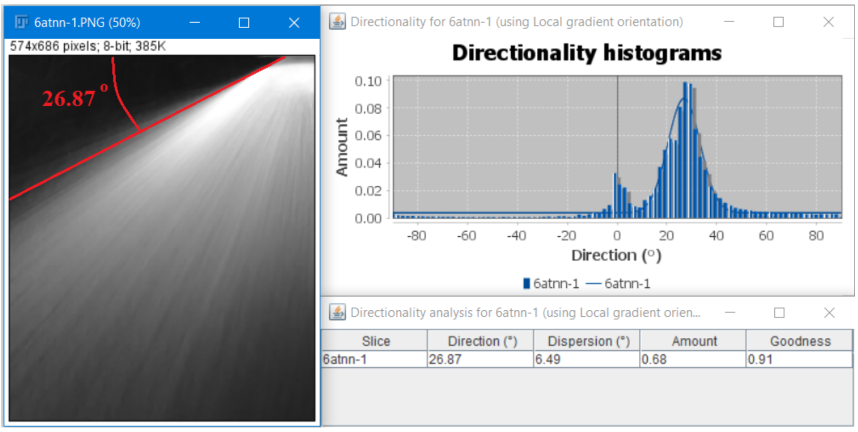


Fig. 7. Analytical results for the left half of the spray image at 6 bar.

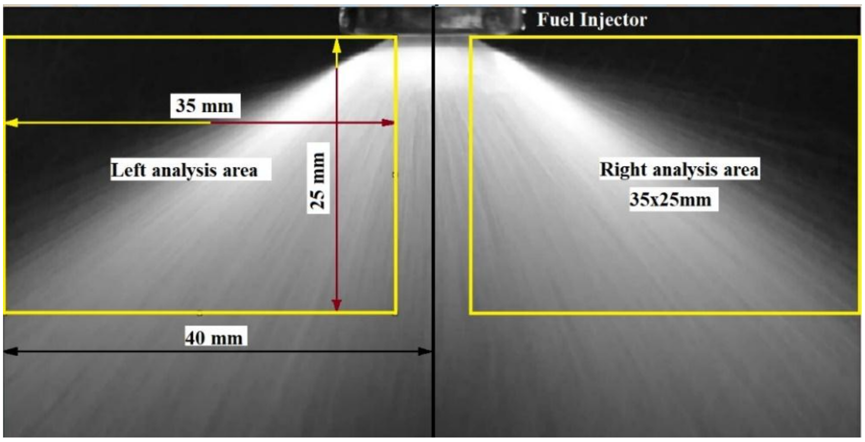


Fig. 8. Choosing the analysis areas.

However, analyzing half image is still not the optimal solution because the area of interest is only located at the spray boundary. As mentioned above, the spray boundary near the injector orifice is easier detected because of the dense spray. So, choosing the analysis area near the injector orifice could help improve processing quality. Observing the images obtained from the pressure range 2-6 bar allows determine the analysis areas, as shown in Fig. 8. The analysis area consists of 2 parts, those corresponding to the left and right sides of the spray, both measure 35 x 25 mm. In there, 25 mm is the distance far from the injector orifice. And 35 mm is the distance from the edge of the discharge orifice to the left and right, respectively. These are basically areas that contain the entire quasi straight-line part of the spray boundary. The processing result for the left analysis area is shown in Fig. 9. It can be seen in this figure, the analyzing quality is improved (Goodness raised to 0.96), and the measured angle decreases from 26.87° to 26.84°.

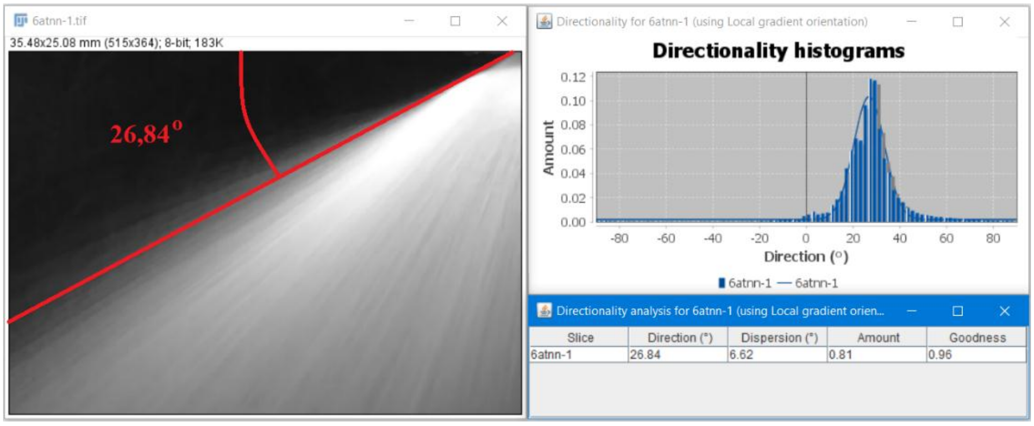


Fig. 9. Analytical results for the left analysis area at 6 bar.

Image files obtained from the experiments, in video form (1 minute in length, 30 frames per second), were imported into the software in the form of 1800 photos. After converting to gray images and defining the analysis area (left or right half), the direction analysis tool will automatically analyze all imported pictures. The results obtained for all images are shown in a table as shown in Fig. 10. Similar to the results of analyzing a single image, the local analysis results of 1800 images remain good analytical quality (minimum 0.96). Moreover, it can be seen that, at the same injection pressure, the measured angle is not a fixed value. For example, as shown in Fig. 10, at 6 bar pressure, the spray left angle can vibrate up to 2.46°. The analyzed results can be saved as an excel file for later calculations.

Directionality analysis for E:\NghiencuuSinh\Atomization\Spray_Angle\28-8-20...

Slice	Direction (°)	Dispersion (°)	Amount	Goodness
Slice_1699	25.28	8.64	0.82	0.98
Slice_1700	24.92	10.12	0.86	0.97
Slice_1701	25.85	7.73	0.80	0.97
Slice_1702	26.18	9.77	0.84	0.99
Slice_1703	26.38	7.91	0.83	0.97
Slice_1704	27.38	6.93	0.77	0.97
Slice_1705	25.98	8.90	0.83	0.97
Slice_1706	27.08	8.13	0.82	0.96

Fig. 10. Analytical results of 1800 images for the spray left analysis area at 6 bar.

4. Results and Discussion

As mentioned above, since the cone angle value is varying with time due to the randomness of the atomization process, an approach to measure the average spray cone angle is presented in this work. Fig. 11 shows the variation of the average spray cone angle depending on the number of analyzed images at different pressures. Spray angle vibration amplitude can reach a maximum of 3.4° at the injection pressure of 5 bar. This graph shows that the spray angle value trend is more stable as the number of analyzed images is large enough. Therefore, the next problem is to determine the necessary number of images to guarantee the reliability of the results.

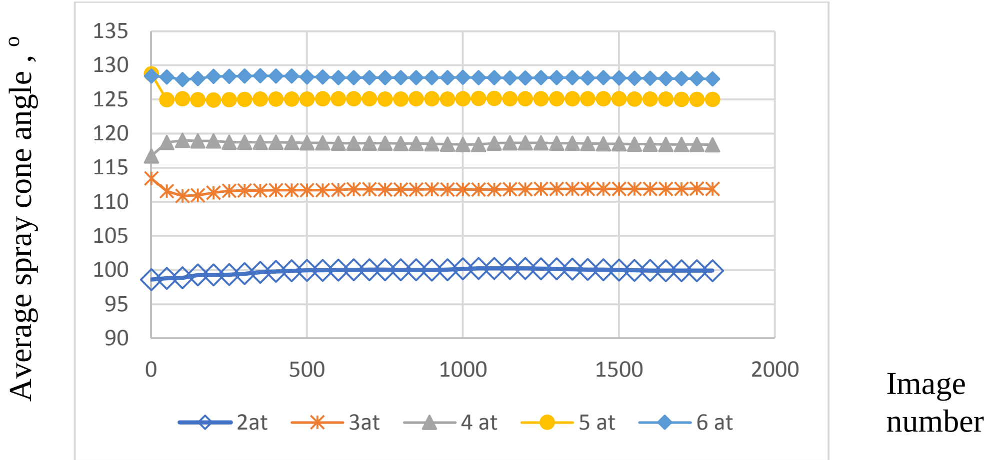


Fig. 11. The dependence of the average spray cone angle on the image number at various pressure.

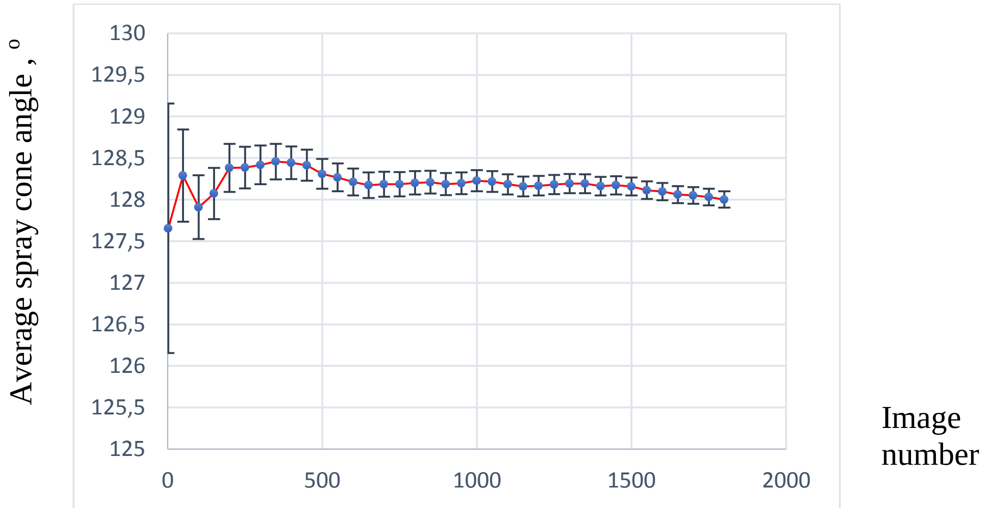


Fig. 12. The dependence of the average spray cone angle on the image number at 6 bar.

A standard error graph constructed for different pressures, as shown in Fig. 12, is a graph of the spray angle depending on the number of analyzed images at 6 bar. This graph shows that, at 6 bar, when analyzing 250 images, the error is ±0.25°, 500 images are ±0.18°, this value in 1000 images is ±0.13°, and from 1500-1800 images is ±0.1°. Obviously, the reliability increases as growing the number of analyzed images, but with a sufficient number of images, this does not significantly change. As shown in Fig. 12

(at 6 bar), the cone angle value achieved satisfactory reliability when analyzing 1500 images (128.16±0.1°).

Table 1. The standard error evaluation of the average spray angle depending on the image number at different injection pressures.

Pressure	Spray cone angle				
	50 images	**500 images**	**1000 images**	**1500 images**	**1800 images**
2 bar	98.8±0.73°	100±0.22°	100±0.2°	100±0.2°	100±0.19°
3 bar	111.5±0.6°	111.7±0.17°	111.7±0.11°	111.8±0.09°	111.9±0.085°
4 bar	118.7±0.44°	118.6±0.15°	118.42±0.11°	118.5±0.1°	118.4±0.1°
5 bar	125±0.48°	125±0.15°	125±0.12°	125±0.09°	125±0.085°
6 bar	128.3±0,6°	128.3±0.18°	128.2±0.13°	128.15±0.1°	128±0.1°

Table 1 shows the standard error evaluation of the average spray angle depending on the number of processed images at different injection pressures. Essentially, analyzing 500 images will give good enough results. To increase the reliability to ±0.1°, in this paper, we adopted results from 1500 images.

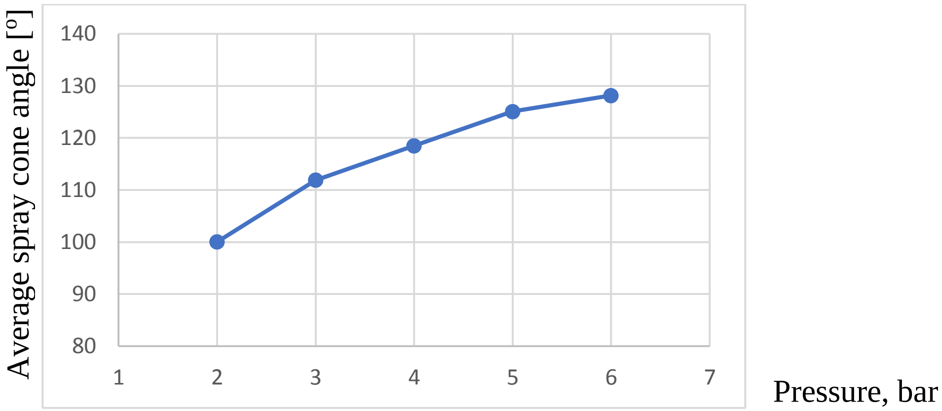


Fig. 13. The variation of the average spray cone angle depends on the injection pressure when analyzing 1500 images.

The variation of the cone angle depending on the spray pressure when processing 1500 images is shown in Fig. 13. This graph reveals that the cone angle increases from 100° to 128.15° when the injection pressure increases from 2 up to 6 bar. However, the slope of the graph diminishes when increasing pressure. It can be predicted that the cone angle only rises to a certain value. This thing is suitable due to the spray angle is limited by the injector structure.

5. Conclusion

The paper has developed an experimental system along with adopting the ImageJ package to quantify the fuel spray cone angle of a gas turbine engine injector. The image processing method has many advantages in automatically analyzing multiple images without the need to binarize them. The experiment system allows testing real gas turbine injectors under varying operating pressure conditions. The experiment here uses water as a fluid for the cone angle measurement. This is to avoid the complexities of using practical fuels and not affect the aim of this work which is to develop a measuring technique. The results show that the average spray cone angle increases (from 100° to 128.15°) when increasing injection pressure in the low-pressure range (e.g. from 2 to 6 bar in this study). These results of cone angle measured here could be about 6.3% greater than that of TS-1 and this is attributable to the difference in water and TS-1 properties. Measurement results reached acceptable accuracy when analyzing at least 500 images. For studies requiring higher uncertainty, it requires analyzing 1500 images or more.

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MỘT PHƯƠNG PHÁP XỬ LÝ ẢNH ĐO GÓC CÔN CỦA CHÙM TIA PHUN CỦA VÒI PHUN DẠNG XOÁY ÁP LỰC TRANG BỊ TRÊN ĐỘNG CƠ TUA-BIN KHÍ

Tóm tắt: *Bài báo sử dụng công cụ định hướng trong phần mềm ImageJ để xác định góc côn của tia phun của một vòi phun tua-bin khí. Một hệ thống thí nghiệm đã được xây dựng để thu được hình ảnh chùm tia phun của một vòi phun động cơ tua-bin khí thực trong điều kiện áp suất phun thay đổi từ 2-6 bar. Các kết quả cho thấy độ tin cậy của phép đo đạt được khi phân tích ít nhất 500 ảnh. Việc phân tích trên 1500 ảnh cho kết quả tốt hơn với độ lệch nhỏ hơn 0,5% (tương ứng với góc 0,2°). Góc côn trung bình của chùm tia phun tăng (từ 100° đến 128,15°) theo chiều tăng của áp suất phun ở dải áp suất thấp (từ 2 đến 6 bar). Việc xác định được góc côn của tia phun giúp nâng cao chất lượng cho các nghiên cứu về mật độ hạt, phân bố hạt sau quá trình phân rã tia phun. Kết quả nghiên cứu cũng có thể được áp dụng để xây dựng và phát triển công nghệ chẩn đoán tình trạng kỹ thuật của vòi phun động cơ tua-bin khí.*

Từ khóa: Góc côn của chùm tia phun; phân tích hướng; ImageJ; động cơ tua-bin khí; vòi phun xoáy áp lực.

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