Research Article

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Diagnosis of the power frequency vacuum arc shape based on 2D-PIV

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Abstract: Vacuum circuit breaker (VCB) is one of the important elements in the power grid that can control and protect the system. The diagnosis of the vacuum arc images in VCBs is helpful to the study on their breaking performance. But up to now, there are few reports on the macro-particle motion trajectories in the arc. As the macro-particles in the arc are flowing, the particle image velocimetry (PIV) can be grafted into the vacuum arc image processing. In this paper, the power frequency vacuum arc (peak is 6.9kA) was used as the treatment object, geometric characteristics of the vacuum arc shape using digital image processing technology were extracted, and the two dimensional motion trajectory and velocity distribution of the arc macro particles in different arc combustion stages were obtained based on 2D-PIV technology. Three stages were analyzed. In the rapid diffusion stage, the collision of the macro-particles is very intense in the anode region, and they spray along the anode surface. In the stable combustion stage, the velocity of the particles near the anode is small, and there is a smaller shrink. And finally in the extinction stage, their motion trajectories are in a state of rotation, near the anode and cathode are in a state of contraction.

Keywords: Vacuum arcs, Particle image velocimetry (PIV), Macro-particle, Digital image processing

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1 Introduction

Research on the basic theory of vacuum arc have great influences on the development of vacuum circuit breaker (VCB). A lot of researches in the field of vacuum arc theory have been done at home and abroad, and the work focuses on the arc plasma, arc morphology and plasma parameters [1–7], but in fact macro-particle phenomenon is existed in vacuum arc theory. Macro-particles can get gain energy and velocity increment from plasma, at the same time, macro-particles will produce ion source for plasma. Up to today, studies of the macro-particles in vacuum arc have made initial progress [8–11], but in recent years, in the field of VCB studies of the macro-particles has been reported rarely. In view that the macro-particle has an important impact on VCB's breaking performance, in-depth study of the short gap VCB macro-particles not only has a theoretical value, but also has a very important practical significance.

Particle image velocimetry (PIV) is a non-contact flow field measurement technology based on flow visualization technology, which is developed by image processing technology. PIV has been widely used in wind tunnel velocity measurement, aerodynamics, hydrodynamics, environment, bio-medicine and so on [12–18]. If PIV technology can be applied to measure the flow field of the vacuum arc, the actual speed of information flow and distribution can be gotten, and we can has an intuitive understanding of the arc macro-particles flow field, all these can provide an effective experimental basis for the establishment of control theory. Based on this concept, in this paper, according to the research status of vacuum arc, the power frequency vacuum arc with peak about 6.9kA was used as the object, geometric characteristics of the vacuum arc shape using digital image processing technology were extracted, and the two dimensional motion trajectory and velocity distribution of the particle in the vacuum arc were obtained.

2 Experimental device

The experimental principle is shown in Figure 1. The experimental system consists of five parts, LC oscillation circuit, demountable vacuum arc chamber, trigger circuit, measuring apparatus and vacuum measuring devices. L is 47.4μH, C is 214.1mF. The demountable vacuum arc chamber is composed of anode contact, cathode contact, trigger electrode, and the chamber shell. The vacuum degree of the chamber is guaranteed by a rotary pump, a magnetic valve, and a diffusion pump, its pressure can reach 10^{-3}Pa. The material of the contacts is CuCr25, the diameter is 40mm, and the separation between anode and cathode is 6mm. Before the experiment starts, the main switch S was switched off, and capacitor C was charged to predetermine value. At the start of the experiment, main switch S is closed, the vacuum gap is triggered by trigger circuit. At the same time, the LC oscillation circuit was injected into the gap, and the AC arc is generated.

2D-PIV testing system generally consists of the optical system, the image acquisition system, the tracer particles, and the image data analysis system. The CamRecord 1000C high-speed CMOS camera was chosen as the vacuum arc image acquisition equipment in the experiment. The macro-particles in the arc plasma are flowing, so they can be used as tracer particles. Here, the mentioned macro-particles are internal electronics, neutral particles, metal ions, and so on. The arc can be looked as electric neutrality, and the 2D-PIV diagnostic method can realize the velocity distribution and the motion trajectory of the flowing particles.

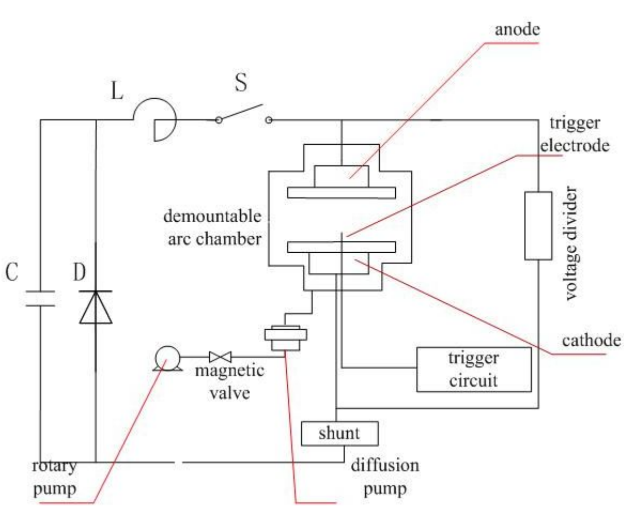


Figure 1: Schematic diagram of vacuum arc experiment device

Figure 2: The experiment device

The main idea of 2D-PIV velocity measurement is to calculate the three-dimensional space coordinates of the tracer particles, and then get the three-dimensional velocity vector of the particles according to the space displacement of the particles and the exposure interval time. The key link is to obtain the space coordinates and displacements of particles. The core of the former is to establish the mapping relationship between space coordinates and image plane coordinates. According to the parallax relation of particles on different camera image planes, the space coordinates of particles at a certain time are extracted. The difficulty of the latter is particle matching. After particle matching, the space coordinates of adjacent particles can be calculated, and the space displacement can be obtained. PIV technology is based on a simple relationship that speed is the distance of movement per unit time. The particles are put into the flow field with suitable conditions and will follow the fluid motion with a certain follower. If a moving particle (swarm) image is obtained before and after a certain time interval, the motion displacement of the particle (swarm) is calculated by cross-correlation algorithm by comparing the same query area in the two images. With the known time intervals, the velocity vectors of particles (groups) can be obtained. The parameters of 2D-PIV system produced by TSI company are shown in Table 1.

Generally, the 2D-PIV testing system consists of optical path system, image acquisition system, tracer particles reflecting the characteristics of flow field and image data analysis system. Vacuum switching arc life is short, generally only about 10 ms, so it is necessary to select high-speed camera to achieve high-resolution arc image acquisition. In the experiment, a high-speed CamRecord 1000C camera is selected. The acquisition speed of the camera can reach 1000 frames per second at 1280 *1024 resolution, and the camera has a 4G buffer. Under this condition, it can shoot 3.2 seconds continuously. The acquisition speed can reach 200 000 frames per second at a resolution of

Table 1: PIV system component parameters

Components	Model	Parameter
laser	Dual ND: YAG Laser	Power: 120mJ/pulse
CCD	PIVCAM 14-10	1376pixel×1024pixel
synchronizer	610035	programmable
lens	NIKON	Kx=0.15
software	Insight 3G	Version9.1
particles	Glycenin, ethylene glycol	Particle diameter≈ 5μm

1280 *4. Under this condition, it can shoot 4.2 seconds continuously, which can meet the needs of the experiment. In vacuum switching arc vapor, arc particles themselves are the object of study, *i.e.* tracer particles, because the particles in arc plasma are part of multiphase flow. In the optical system, the vacuum switching arc itself produces very strong brightness. This experiment studies the characteristics of the vacuum switching arc flow field, so no auxiliary light source is needed. Figure 3 is the measurement error distribution and the corresponding theoretical error distribution.

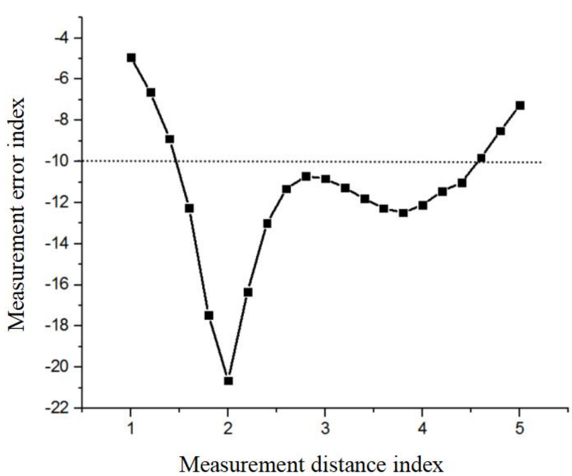


Figure 3: The influence of CCD lens on perspective error

The CCD camera uses a fixed focus lens with a fixed field angle (field coefficient). When the test distance is changed, the image size will also change. Figure 4 is the error distribution in the field of view and the comparison with the theoretical error distribution. The results show that the error distribution in the rear view field does not change with the change of test distance. In fact, as long as the lens remains unchanged, the error distribution in the field of view is the same.

3 Arc image processing based on 2D-PIV

3.1 The principle of 2D-PIV

A basic principle of 2D-PIV measurement is putting tracer particles in a uniform flow field. According to the particle velocity we can get their respective position in the flow field. A test plane is irradiated by continuous or pulsed laser beam light source. As a result, the displacement of the point particle will be found using image analysis technology, the flow field velocity vector points can result from displacement and exposure time interval, and we can calculate flow velocity vector.

Assuming at time t the particle is located on the point $(x(t),y(t))$, then a time interval Δt the particle moves to the position $(x(t+\Delta t),y(t+\Delta t))$. When Δt is very small, the movement of the particle can be considered uniform motion, we can find the velocity of that point shown in equation (1), (2):

$$v_x = \frac{dx(t)}{dt} = \frac{x(t+\Delta t)-x(t)}{\Delta t} \quad (1)$$

$$v_y = \frac{dy(t)}{dt} = \frac{y(t+\Delta t)-y(t)}{\Delta t} \quad (2)$$

Based on this principle, the conventional 2D-PIV is good at measuring velocity distribution parallel to the streamwise cross section. Theoretically, the optical path layout requires that the laser sheet light is parallel to the incoming flow, that is, the axis of the CCD camera is perpendicular to the laser sheet light. Figure 5 is the conventional 2D-PIV optical path layout.

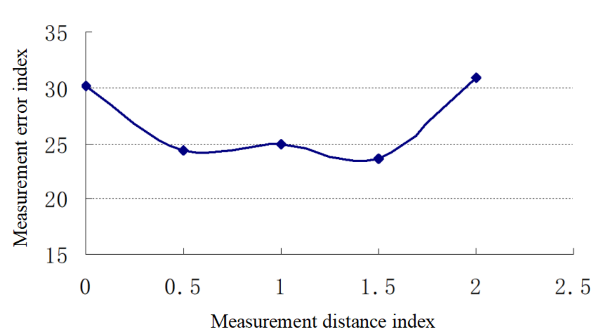


Figure 4: Influence of measurement distance on perspective error

However, it is not uncommon to use the 2D-PIV equipment to test the flow field in the cross-section perpendicular to the flow direction, such as the measurement of the flow direction vortex. Figure 6 is a typical optical path layout of 2D-PIV for wingtip vortex measurement. The measurement plane is perpendicular to the flow direction. Obvious measurement errors may occur in such optical path layout.

The basic principle of PIV technology can be expressed as follows: the tracer particles are dispersed in the flow field to follow the flow field, and then the flow field is illuminated by a laser lamp. Through two or more exposures, digital cameras are used to capture the flow field test section images of recorded illumination. Then the average displacement of particles in each inquiry area is calculated by image correlation method, and the velocity field distribution in the flow field is calculated according to the exposure time interval. When the liquid is in natural convection state, its motion speed is low. Continuous laser can be used as illumination source and scientific research CCD camera as image acquisition equipment. The experimental parameters of various factors are shown in Table 2.

Table 2: Experimental parameters of various influencing factors

Influence factors	Experimental values
Incoming flow	35.9
Measurement distance	150
Lens focus length	100

The realization of 2D-PIV is carried out in sequence according to camera calibration, flow field image acquisition, particle matching, particle motion matching and velocity field display. The purpose of camera calibration is to determine the mapping function M. The calibration methods can be divided into traditional calibration method and self-calibration method. The traditional calibration method usually uses two dimensional flat panel or three dimensional wave plate to calibrate. The former needs to collect the calibration plate images at different positions

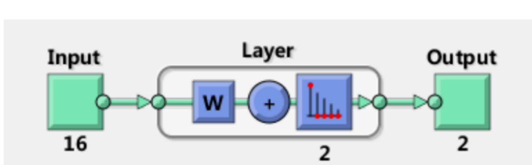


Figure 5: Schematic diagram of conventional 2D-PIV optical path layout

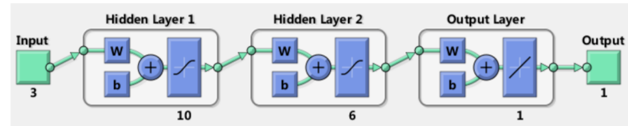


Figure 6: Schematic diagram of typical optical path layout for 2D-PIV wingtip vortex measurement

within the film thickness, while the latter can complete the calibration process at one time without moving the calibration plate. Targets on the board are usually circular, rectangular or cross regular shapes, arranged in a grid, which is convenient for sub-pixel positioning of target image center coordinates. At present, many camera calibration algorithms have been developed, such as direct linear transformation DLT, Tsai's algorithm, Zhang's algorithm and so on. The Tsai 's method is more classic, but it has been applied to PIV field in recent years. It only considers the radial axis symmetry error of the lens, and extracts the coordinates of the target center with known spatial position. First, the lens error is neglected, and the calibration equation is transformed into a set of linear equations to obtain the external parameters according to the radial constraints. Then the internal parameters are optimized according to the solution parameters to complete the camera calibration process. Table 3 is the area of the field of view for each test distance.

Table 3: Size of field of view under different test distances

Measurement distance	View field W×H (mm×mm)
300	33×35.9
400	40×30.1
500	65×41.8

3.2 Digital image processing of vacuum arc

The vacuum arc images captured by the high-speed camera are shown in Figure 7, Δt is 0.3ms, the charging voltage of the LC oscillation circuit was 120V, and the peak current was about 6.9kA.

In the diagnosis of vacuum switching arc plasma parameters and arc morphology, some conventional methods are powerless because of the particularity of vacuum switching arc. With the appearance of CCD, a breakthrough has been made in the diagnosis of arc shape and plasma characteristics of vacuum switches. But when CCD camera is used to acquire vacuum switching arc image,

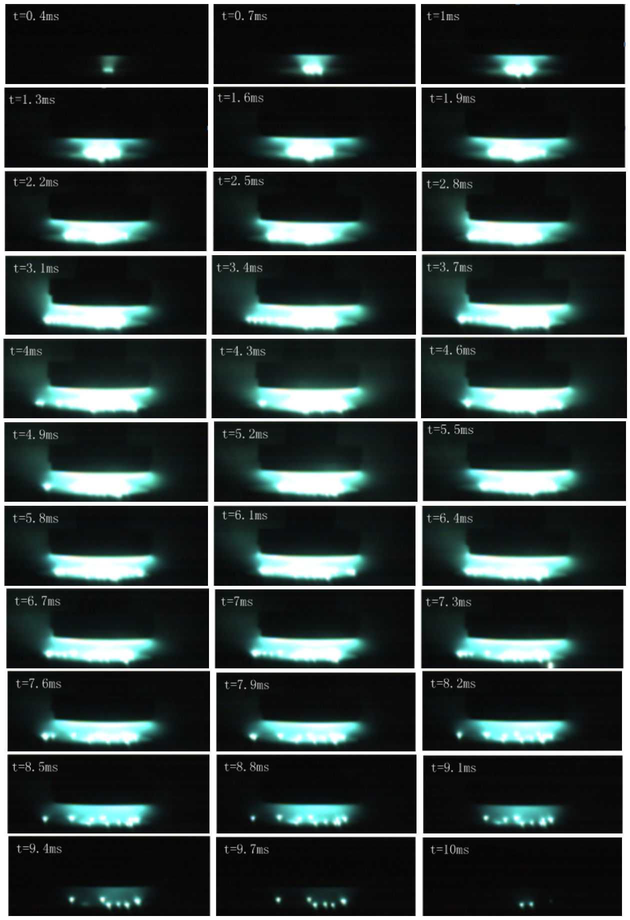


Figure 7: The vacuum arc images

semiconductor electrons, photons, quantization and other interference noises are unavoidable. And the image after A / D conversion, line transmission interference, etc., resulting in the quality of the image is not clear, difficult to see the details of the serious image will be blurred. Even the most basic outline is not clear, or the image distortion, resulting in the shape and size of the image and even color distortion. In this way, before analyzing the original image of vacuum arc, in order to ensure the image quality and highlight the image characteristics, it is necessary to improve the quality of the collected degraded image, that is, image preprocessing. The main purpose of image preprocessing is to improve the image quality, make the image clearer, improve the visual effect of the image, which is conducive to the subsequent processing of image feature extraction and internal information mining. Image preprocessing mainly includes image smoothing, image enhancement, binary processing, edge detection and feature extraction. Image two value processing can improve the processing speed and reduce the cost. Changes in arc area and arc area are shown in Figures 8 and 9.

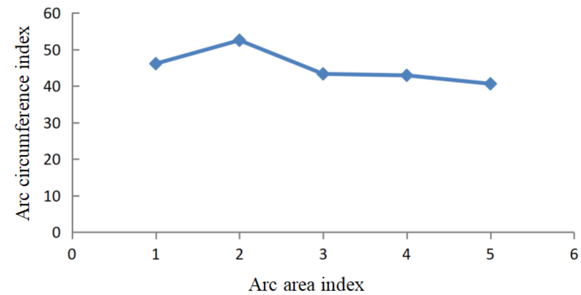


Figure 8: Arc area change curve

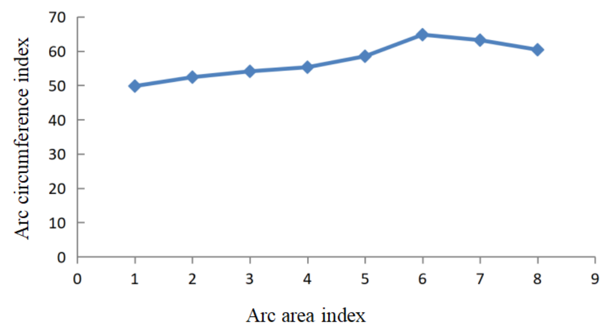
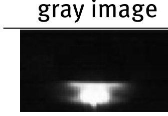
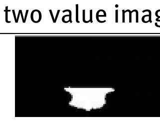
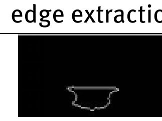


Figure 9: Arc area change velocity curve

During the acquisition process of vacuum arc information, the interference from inside and outside of the image acquisition system will be received, and it is extremely unfavorable to study the characteristics of arc, so it is necessary to preprocess the arc image. In this paper, gray level transformation and median filtering are used as the arc image preprocessing that can eliminate these interferences in general, and also can restore some important features of the arc images. After the arc image preprocessing, the methods of two value and boundary extraction based on the digital processing are used to process the images. In the two value image, each pixel only has two values, namely 0 and 1, 0 represents the background and 1 represents the arc. Therefore, the geometric features of the arc can be extracted by calculating the number of the pixel that value is 1 to calculate the perimeter and area of the arc. The digital image processing of the single arc image (t=1.3ms) is shown in Table 4, the area and perime-

Table 4: Digital image processing of vacuum arc

gray image	two value image	edge extraction
		

ter curves of the arc are shown in Figure 10. From the processing results we can see that, time sequence from 0 to 3ms, the arc shape is in a state of rapid diffusion. From 3ms to 5ms, the speed of this diffusion becomes slowed down obviously, and tends to stable combustion. When the current is near to the peak (t=5ms), the arc shape has a slight contraction, and then continue to spread, but the rate of diffusion is much lower than that of arc diffusion from 0 to 3ms. With the gradual decrease of the current, the arc shape shows a negative growth trend, until it extinguishes.

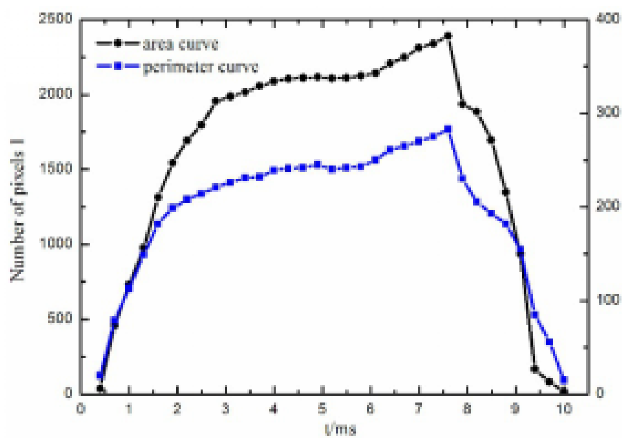


Figure 10: The area and perimeter curves of the arc

Because of the camera layout, the imaging position of particles on different cameras is different, that is, there is parallax, which is the basis of realizing the three-dimensional PIV measurement. Particle matching refers to the corresponding relationship between the same particle imaging on different cameras. Particle motion matching refers to the corresponding relationship between the same particle and the time series image of the same camera. With the complexity of the moving object, the requirement of motion matching algorithm is higher. According to the geometric collinearity principle, the space linear equation of the particle image center and the camera optical center can only be determined, but the specific position of the particle in the line cannot be pointed out. Figure 11 shows the arc area variation velocity curves for different voltages, 80V and 60V, respectively.

Images are obtained by observing the objective world in different forms and means through various observation systems, which can act directly or indirectly on the human eye to produce visual perception of the entity. Digital image processing technology refers to the use of digital computers and other related digital technology to im-

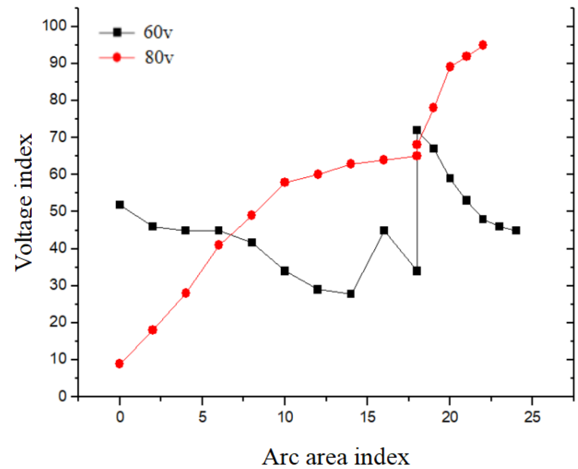


Figure 11: Curves of arc area at different voltages

pose certain operations and processing on the image to achieve a predetermined purpose. At present, the main development directions of digital image processing technology are: high resolution, high speed, high precision; three-dimensional visualization and intelligent. Two lenses with different focal lengths were used to test the effect of the field coefficient on the perspective error. The two lens parameters are shown in Table 5.

Table 5: 2 shot parameters

Focus length/mm	View field coefficient (x & y direction)	
66	0.211	0.115
110	0.058	0.081

Digital image processing technology is to convert the image into a digital matrix stored in the computer, and use a certain algorithm to process it. The main contents of image processing include digitization, image enhancement, data coding and transmission, image smoothing, edge sharpening, edge segmentation and feature extraction, image analysis, pattern recognition, artificial intelligence and computer vision. After processing, the image quality and visual effect are improved, which makes it convenient for computer to analyze and recognize the image. Digital image processing technology is a new subject with the rapid development of computer and microelectronics technology. At present, it has been widely used in remote sensing technology, medical image processing, character recognition, industrial fields, security systems and other fields. And with the continuous development of the theory,

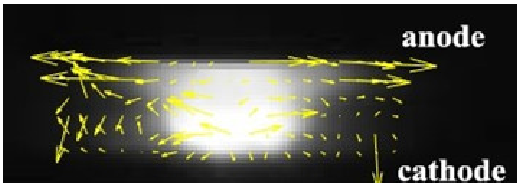


Figure 12: The 2-D PIV arc image in rapid diffusion stage

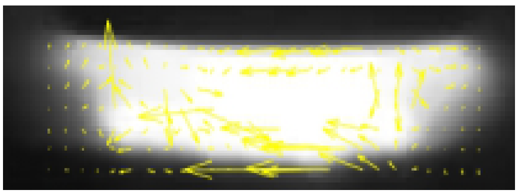


Figure 13: The 2-D PIV arc image in stable combustion stage

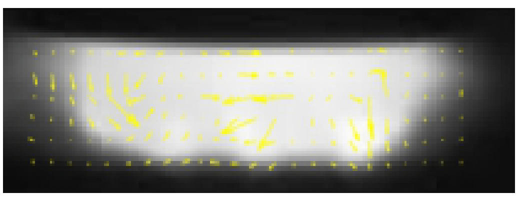


Figure 14: The 2-D PIV arc image in extinction stage

method and technology of digital image processing technology, its application scope will be wider and wider.

3.3 2-D PIV Diagnosis

In order to study the motion trajectory and velocity distribution of the macro-particles, the software MATLAB is used to realize the 2D-PIV diagnosis, the results are shown in Figure 12 to 14. In the arc 2D-PIV images, the yellow arrows represent the direction and magnitude of the macro-particles.

In the rapid diffusion stage (Figure 12), two arc images (t=1ms and t=1.3ms) are chosen as the diagnostic objects. The cathode spots are generated on the cathode surface, and a large number of electrons and metal ions are injected into the arc column and anode. At the same time, due to the thermal ionization, the neutral particles under high temperature can produce a large number of particles, these particles collide with each other in the gap, and the gas pressure increases that makes the macro-particles spraying. In the anode region, the collision of the macro-particles is very intense, and they spray along the anode surface. Near the cathode, this trend is slow. In the arc column region, the particle velocity is smaller than that of the anode region, and it can be observed that the particles spray from inside of the gap to outside of it.

In the stable combustion stage (Figure 13), two arc images (t=4.9ms and t=5.2ms) are chosen as the diagnostic objects. As current approaches the peak, number of the cathode spots is increasing. Velocity of the particles near the anode is small, and there is a smaller shrink. Condition near the cathode is similar to the anode's, and the particles spraying area is full of the anode and the cathode surface. Field emission leads to a large number of electron and metal ions spraying from the cathode spots, which maintains the stable combustion of the arc. In the arc column region, the motion trajectory of the particles is in the state of cyclotron, and the collisions among the particles are more intense.

In the extinction stage (Figure 14), two arc images (t=7.9ms and t=8.2ms) are chosen as the diagnostic objects. As the current decreases, the metal vapor is condensed on the anode surface and shield, resulting in a sharp decrease of the particles density, and the intensity of the particles collisions is greatly reduced. In the arc column region, the velocity of the particles is very slow, their motion trajectories are in a state of rotation, and the particles motion trajectories near the anode and cathode are in a state of contraction.

4 Discussion and conclusion

PIV technology has been introduced to measure the flow field of the vacuum arc by image processing in this paper. As an example the vacuum arc with power frequency(peak is 6.0kA) was taken as the treatment object, geometric characteristics of the vacuum arc shape using digital image processing technology were extracted, and the two dimensional motion trajectory and velocity distribution of the arc macro particles in different arc combustion stages were obtained based on 2D-PIV technology. Some results can be got by the diagnosis and analysis.

1. In the rapid diffusion stage, in the anode region, the collision of the macro-particles is very intense, and they spray along the anode surface. Near the cathode, this trend is slow. In the arc column region, the particle velocity is smaller than that of the anode region, and it can be observed that the particles spray from inside of the gap to outside of it.
2. In the stable combustion stage, velocity of the particles near the anode is small, and there is a smaller shrink. Condition near the cathode is similar to the anode's, and the particles spraying area is full of the anode and the cathode surface. Field emission leads to a large number of electron and metal ions spray-

ing from the cathode spots, which maintains the stable combustion of the arc. In the arc column region, the motion trajectory of the particles is in the state of cyclotron, and the collisions among the particles are more intense.

3. In the extinction stage, in the arc column region, the velocity of the particles is very slow, their motion trajectories are in a state of rotation, and the particles motion trajectories near the anode and cathode are in a state of contraction. At present, we can only get the two dimensional motion trajectory and velocity distribution of the arc particles from the macroscopic point of view. But in fact, the arc is three dimensional vertical, it is still a difficult problem to reveal the microscopic theory of arc combustion by image processing technology. In the studies of the three-dimensional flow field, the multi-pass light amplification system and more high-speed cameras are used to reveal the complex 3D structure of the flow field [19–23]. So if the 3D-PIV technology can be applied to the study of vacuum arc flow field, we may distinguish the types of these flowing particles, such as electrons, neutral particles, and metal ions, through their three dimensional motion trajectory and velocity distribution combined with the electromagnetic [24, 25]. If this diagnostic method is feasible, it will be of great significance to the study of arc micro theory. In the future work, in order to obtain the three dimensional motion and trajectory and velocity distribution of the arc particles, we will use more CMOS high-speed cameras to capture the arc shape synchronously, that will be helpful to obtain the three dimensional motion and trajectory and velocity distribution of the arc particles.

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