Experimental study on jet flow characteristics of fire water monitor

Xiumei Liu1, Jingjing Wang1,2, Wei Li1

1School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou 221000, People’s Republic of China
2State Key Laboratory of Fluid Power and Mechatronic Systems, Zhe Jiang University, Hangzhou 310027, People’s Republic of China

Abstract: Fire water monitor is an important part of a sprinkler system. In this study, the jet flow characteristics of the external jet of the fire water monitor are studied. The water jet system is used to launch the water jet experiment under six pressures. A high-speed camera is used to obtain the water jet images. The feature extraction of water jet is obtained based on image processing technology, and it is used to study the jet diffusion angle and bundling of the fire water monitor under different pressures. The results of this study show that the jet pressure is an important parameter, which has a great influence on the cluster and surface characteristics of the jet. The fire water monitor has a limited range of pressure. When the pressure is constant, the jet distance determines the size of the air acting on water column, so the cluster and surface characteristics of the water column have changed obviously with the jet distance.

1 Introduction

With the increase in large-scale, high-rise, and intensive construction of urban buildings, higher requirements are placed on fire safety. At present, urban fires are mainly based on a sprinkler system. Fire water monitor is the execution component of the sprinkler system. It is the final component that converts the pressure potential energy of water into dynamic potential energy and is the key hydraulic component that determines the jet characteristics [1]. The jet characteristics of fire water monitor directly affect the fire extinguishing efficiency. Therefore, it has important engineering practical significance to study the jet characteristics of fire water monitor.

The DC fire water monitor has the advantages of large flow, long range, good bundling, and easy processing, so it is widely used in various fire extinguishing systems. The jet of fire water monitor is a typical water jet phenomenon. According to the classification standard of water jet, the jet of fire water monitor is a kind of low pressure, non-submerged, and free water jet. The anatomy of this kind of water jets is shown in Fig. 1. Such jet can mainly based on the diffusion condition and the surface profile characteristics.

The water jet in air of fire water monitor is a complex process. At present, relevant research works have studied the jet characteristics of water jet and fire water monitor. The CFD simulation method is widely used for the study of water jet [3–5]. Hu et al. [6–8] studied the internal flow characteristics of the fire water monitor based on the numerical calculation and experimental method. The optimal structural parameters of the fire water monitor were obtained. Miyashita et al. [9, 10] simulated the fire water jet based on the moving particle semi-implicit (MPS) method and the 3D simulation model. They verified the relationship between the jet particle fraction and flow rate as well as the jet trajectory and flow rate. Xiang et al. [11] found that the straighteners can improve the flow pattern evidently. Moreover, the surface area of straightener exhibits a more significant rectifying effect than the volume does. There is a suitable length for a straightener. Yuan et al. [12] simulated the internal flow of the fire water monitor based on Fluent software numerically. They found that the placement of the deflector can eliminate the core area of the turbulent flow in the pipe, improve the flow, reduce the turbulent energy of the exit, and increase the range of the fire monitor. The above-mentioned research works are mainly focused on the study of structural parameters and jet trajectory of the fire water monitor, but lack in in-depth analysis of the structural characteristics of the jet flow fields. It is still very challenging to evaluate the flow field characteristics of the fire water monitor and accurately divide the flow field structure of jets.

This paper mainly develops the jet experiment in the natural environment of the DC fire water monitor. The near-flow field images of the water jet under different pressure conditions are obtained by a high-speed camera. The captured images are mainly based on the diffusion condition and the surface profile characteristics.

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Fig. 1 Water jet structure based on theory [2]
processed. The structural characteristics of the jet flow field are quantitatively analysed, and the influence of pressure on jet divergence angle, bundling and surface profile characteristics is analysed. A new method to study the structure of water jet flow field of the fire water monitor is proposed.

2 Methodology

2.1 Experimental setup

The principle of the fire water jet experimental system is shown in Fig. 2. There are two main parts. The first part is the jet system including a water tank, a centrifugal pump, a pressure transmitter, a flow transmitter, a fire water monitor and various control valves. The second part is the image acquisition system including a high-speed camera, a computer and related processing software. In order to facilitate image processing, a black curtain is used as the image background. Fig. 3 shows the physical diagram of the jet system.

The jet system of the fire water monitor is powered by a centrifugal pump, which feeds the water in the water tank into the pipeline. Water is fired into air through the fire water monitor to form a water jet. The frequency of the centrifugal pump is controlled by a frequency converter to control the pressure and flow of the jet. The pipeline, components and interfaces between the centrifugal pump and the fire water monitor in the jet system are DN80. The size of other devices is DN100.

The high-speed digital camera used in the experiment is the US-made Phantom VEOS-710L. The high-speed camera has a maximum shooting frequency of 68,000 frames per second, and the camera's maximum global image size is 1280 × 800 pixels. The shooting speed of the high-speed camera used in the experiment was 1000 frames per second. The size of the obtained global images was 1280 × 720 pixels. The experimental resolution was 1.70 mm/pixel. The exposure time of 1000 μs can effectively reduce the dynamic blur of the image.

Fig. 4 shows the structure of the fire water monitor head used in the experiment. The monitor head is mounted on the monitor body with a threaded interface. The inlet diameter (D) is 64 mm, the outlet diameter (d) is 34 mm, the length (L) is 420 mm and the length of the rectifier section (l) is 34 mm. The contraction angle (θ) is 5°. The spray angle of the fire water monitor of this experiment is set to 0°, that is, horizontal spray. The experimental injection pressures were 0.355, 0.480, 0.634, 0.717, 0.789 and 0.996 MPa, respectively. Due to the large space required for the experiment, the experimental site is an outdoor experimental site under natural conditions.

2.2 Image processing

The jet images are shot when the jets are stable. The better shooting results are selected for processing. The collected global images are cropped, so that the images of the jet region are extracted. The size of the cropped images is 1260 × 250 pixels. Fig. 5 shows the images of the fire water jets under the six kinds of pressures collected by the experiment. It can be seen from the figure that the variation of the flow field structure along the jet direction under different pressures has a certain similarity. When the water stream is ejected, the water column is relatively smooth near the exit and the surface has only weak fluctuations. As the jet distance increases, the surface of the jet appears to fluctuate greatly, with large water droplets falling off the jet stream. With the increase of pressure, the flow field structure also has different points. The diameter of the water bundle increases. The shedding phenomenon of larger water droplets on the jet surface is intensified, and the jet atomisation phenomenon is intensified.

In order to accurately extract the structural characteristics of the jet flow field, the jet images of the fire water monitor are processed according to the flow shown in Fig. 6. The images are denoised,
needs to be sharpened. The image sharpening in this paper is a good inhibitory effect on salt and pepper noise. Therefore, comparing the results, the median filtering is used to denoise the jet image. Mean filtering, median filtering and the water jet image, and the second step is performing partial sharpening according to the sharpened result to obtain a well-defined image of water jet.

Binarisation is the most basic image segmentation method in image processing. By means of threshold transform, the grey-level image is transformed into a two value images with two colours of black and white. The target part is separated from the complex image background to help the detection and extraction of the jet contour. Image segmentation method used in this paper is common. We add the pixel values of each point of the jet image and then divide the total number of pixels to obtain an intermediate value. The intermediate value is used as the threshold to binarise. The image contour after binarisation still has some burr impurities. In this paper, the open operation of morphological filtering is used to further process the binary image, that is, the image is first corroded and then expanded [14]. The corrosion operation removes the fine impurities at the edge of the jet profile. When the expansion operation is performed, the remaining jet shape returns to its original size, so that the main profile of the jet stream is obtained. Fig. 7 shows the results of image segmentation at the pressure of 0.355 MPa.

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2.2.2 Edge detection and feature extraction: In order to extract the structural characteristics of the water monitor jet, the external water jet is mainly analysed in this paper. The Canny operator is a newer edge detection operator, which is widely used in image contour extraction with good edge detection ability [15]. In this paper, the edge of the jet is detected by the Canny operator. The pixel coordinates of the jet profile are extracted, and curves are fitted to characterise the macroscopic characteristics of the water column. Fig. 8 shows the extraction result of the jet outline at the pressure of 0.355 MPa.

3 Results and discussion

3.1 Analysis of jet cluster

In order to better express the macroscopic characteristics of the jet, the contour of the fitted jet is analysed. As shown in Fig. 9, the initial position diameter of the jet is recorded as \( D_0 \), the distance from the nozzle exit to any point of the jet is recorded as \( L_x \) and the diameter of the fitted column at this point is recorded as \( D_x \). \( D_0 \) and \( L_x/d \) are used to indicate the variation of the diameter of the jet with the jet distance.

Fig. 10 shows the variation of the water column diameter with the jet flow distance and under different pressures. When the jet flow distance is constant, due to the effect of air resistance, the expansion of the water jet is mainly analysed in this paper. The Canny operator is a newer edge detection operator, which is widely used in image contour extraction with good edge detection ability [15]. In this paper, the edge of the jet is detected by the Canny operator. The pixel coordinates of the jet profile are extracted, and curves are fitted to characterise the macroscopic characteristics of the water column. Fig. 8 shows the extraction result of the jet outline at the pressure of 0.355 MPa.
In order to better evaluate the structural characteristics of the jet, the jet diffusion angle ($\alpha$) is used as an evaluation index of the jet characteristics [16]. Its calculation formula is as follows:

$$\alpha = 2\arctan\left(\frac{D_y/2}{L_x}\right)$$

(1)

Fig. 11 shows the variation of the jet diffusion angle with the jet distance under different pressures. All the curves show that the jet diffusion angle decreases rapidly with the increase of the jet distance within the distance of approximately 10($L_x/d$). This phenomenon indicates that the rate of change of the diameter within the distance is much smaller than the corresponding rate of change of the jet distance, that is, the change of the water column diameter is small and the jet bundle is fine. When the jet distance continues to increase, the jet diffusion angle decreases slowly. The reason is that as the jet distance increases, the jet intake air volume increases gradually, leading to the growth in quantity in droplet separation and decrease in the diameter of the jet column.

Fig. 12 shows the variation of the diffusion angle with pressure at different distances. When $L_x/d$ is 10, 20, 30, 40 and 50, the jet diffusion angle increases with the increase of pressure, and the increased amplitude decreases first and then increases. This phenomenon indicates that within a certain pressure range, the increase of jet pressure has a little effect on the jet bundling property. When this range is exceeded, the increase of pressure will decrease the clustering property rapidly. Therefore, the jet pressure of the fire monitor should be controlled within a certain range. Excessive pressure will have a negative impact on jet characteristics. When $L_x/d$ is 60, the jet diffusion angle increases first and then decreases. This indicates that when the jet distance is far away, the larger pressure is not conducive to maintaining the cluster state of the jet.

### 3.2 Analysis of surface characteristics of jets

Due to the effect of ambient air, the surface morphology will fluctuate when the water flows out of the fire water monitor. The fluctuation can reflect the jet characteristics to some extent. Taking into account the influence of environmental factors, the upper contour of the jets is selected as the research object. In order to study the surface characteristics of the fire water jet, the wave characteristics of the jet surface are characterised by the square of the difference between the actual contour and the fitted contour. So, $(y - y_f)^2$ is used to indicate the fluctuation of the jet surface, where $y$ is the true contour value and $y_f$ is the fitted contour value.

The distribution of surface wave characteristics of the jet is shown in Fig. 13. When the water flow is ejected from the fire water monitor, ripples appear on the surface of the water jet column within a certain distance. The surface of the jet begins to show slight fluctuation due to the action of air. In the initial jet distance, the amplitude of the fluctuation increases slowly with the jet distance. As the jet distance continues to grow, the amplitude reaches a certain level, the surface of the jet begins to crack and a small amount of air is sucked in. At this time, the surface of the jet breaks into a large mass of water and the jet stream begins to split. When more air is doped into the jet, large shedding masses begin to appear and the surface of the jet begins to fluctuate drastically.

Moreover, as the pressure increases, the length of slight fluctuation decreases gradually and the rate of decrease descends. This phenomenon indicates that the jet pressure will affect the atomisation characteristics of the jet flow field and further affect the range of the water monitor. Excessively high pressure is not conducive to maintaining the stability of the jet flow; on the contrary, it will bring many unfavourable factors to the use of the fire water monitor.
structure of jet flow of the fire water monitor is proposed. We draw the following conclusions:

i. With reference to pressure, the diameter of the water column increases first and then decreases, and the jet diffusion angle decreases rapidly and then decreases slowly with the growth of jet distance. With reference to the jet distance, as the pressure increases, the diameter of the water column and the jet diffusion angle increase. There is a certain range of pressure for the fire water monitor.

ii. When the pressure is constant, as the distance increases, the interaction between the jet column and the environmental medium exacerbates, and hence, the surface irregularity intensifies. Within a certain range, as the pressure increases, the length of slight fluctuation decreases gradually and the rate of decrease descends.

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6 References
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