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Study on atomization characteristics of kerosene jet in crossflow

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Abstract

The atomization and mixing process of fuel under transverse jet is one of the important contents in the research of scramjet. In this paper, the atomization characteristics and penetration of kerosene under transverse jet are studied. The influences of pore size, quantity and arrangement, momentum flux ratio and the Mach number of the transverse flow were analyzed by using different optical measuring instruments. The results show that the pressure drop of fuel injection and the transverse jet velocity are all positively correlated with atomization characteristics, while the pore size is negatively correlated with atomization characteristics. By analyzing the penetration depth under different working conditions， it can be seen that, when other factors are the same, the penetration depth increases with the increase of pore size and pressure drop. Through analysis the experimental data, the empirical formula of jet penetration about momentum flux ratio and axial distance are obtained, it's

$$\frac{h}{d} = 3.365 * q^{0.429} * \left(\frac{x}{d}\right)^{0.393}.$$

Key Words: crossflow, kerosene jet, atomization characteristics, penetration

1. Introduction

As the main product of hypersonic propulsion technology, Scramjet has excellent performance under high Mach number and has become one of the research focuses in the aerospace field. When the Mach number is between 4.5 to 8, hydrocarbon fuel (mainly kerosene) is generally used as propellants, which is mainly used for the power propulsion device of high maneuvering and small aircraft [1].

In a scramjet, the residence time of the transverse jet in the combustion chamber is very short, usually on the order of milliseconds. During this time, the liquid fuel needs to complete the atomization, mixing and combustion, which will directly affect the performance of the engine. Generally speaking, the atomization and mixing of fuel is very complex in the engine. In the whole process, with the influence of shock wave and various vortexes, there are a large number of droplets breaking down, coalescence and evaporation. The interaction between gas and liquid is complex and constantly changing, and the breakup process is highly nonlinear. The atomization and mixing effect directly determines the combustion efficiency of fuel [2]. Therefore, it is of great significance to study the atomization and mixing mechanism of fuel under transverse jet.

Based on the influence of fuel atomization and mixing on engine performance under the transverse jet, since the 1960s [3-5], many scholars have started to study the atomization characteristics and penetration of propellant under

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the transverse jet. In the early stage, the influences of different factors were mainly studied, including injection mode [3, 6], physical properties of liquid [4, 5] and shape of jet hole [5], etc., and a large number of droplet distribution data were obtained. The study of atomization characteristics under transverse jet flow mainly focuses on the droplet size and droplet velocity. Brian Derrick Miller [7] studied the atomization characteristics of subsonic crossflow using digital holographic diagnosis technology, and compared the size distribution of different gas-liquid ratio (GLR). Samir B. Tambe et al. [8] studied the influence of liquid-gas momentum ratio, pore size, crossflow velocity and physical property parameters on droplet size distribution under subsonic flow by using phase Doppler particle analyzer(PDPA). It was believed that the momentum ratio had a great influence on droplet size distribution. Li[9] studied the atomization of liquid jet under supersonic crossflow, and analyzed the influence of injection drop and pore size on droplet velocity and droplet size spatial distribution by using laser particle size analyzer (PDA) and Malvern. Lin K C et al.[10] studied jet atomization under the crossflow Mach number=1.94 by using PDPA. The research show that when x/d is 100, the atomization process is basically completed. SMD is about 10 μm. The droplet size is S type. For penetration, shadow method, schlieren method [11], PDPA [12] and other measurement methods are mainly used for research. Kolpin and Horn found forward inclination (jet Angle <90°) could not improve penetration [13], while backward inclination (jet Angle >90°) could reduce penetration [14,15]. Wang et al. [2] studied the penetration depth of kerosene under crossflow based on PLIF technology, analyzed the influence of momentum ratio and Weber number on penetration, and fitted the empirical formula of penetration about momentum ratio, Weber number and axial distance. Liu et al. [11] measured the spray' penetration by using schlieren method and fitted out the corresponding empirical formula for penetration. They believed that momentum flux ratio and pore size are the main factors affecting penetration. Lee [16] believed that at low Weber number, momentum flux ratio, Weber number and liquid viscosity have influences on penetration. The penetration will decrease when the increase of Weber number and liquid viscosity. Tong et al. [17] studied the effect of combined injection on penetration by using partical image velocimetry. The result show that the spanwise and along combination can improve the penetration of jet.

There are many factors influencing the size of spray. Researchers mainly studied the pore size, pressure drop, velocity and position of crossflow, nozzle configuration and physical parameters of the liquid. However, due to different test methods and working conditions, the results have some distinction, but the trend is the same. When measuring the penetration, due to the different experimental environments and measurement methods, the formula of penetration obtained by different researchers is different. Analyzing the research status, it can be seen that previous studies on the mechanism of atomization are relatively few, and the mechanism of jet atomization is not clear yet. This paper mainly studies the atomization characteristics and penetration of kerosene under the condition of crossflow. Then the mechanism of kerosene was analyzed by using the test results.

2. Experimental system and working conditions

2.1 Experimental system

The atomization characteristics and penetration of kerosene were studied in this experiment. The system consists of subsonic/supersonic flow system, optical observation chamber, kerosene supply system and test and control system. Subsonic/supersonic flow system includes pressurized air storage tank, equipment throat, movable tail cone and so on. The pressure intensity of the pressurized air storage tank is 4~6MPa, and the adjustable range of the inlet flow is 0.5~ 2.5Mpa after the rectifier and decompression device. The measurement method is non-contact optical measurement. PDA was used to measure the size and distribution of atomized droplets. And high-speed photography and schlieren method was used to shoot the trajectory of atomized kerosene in the flow field. The selected optical

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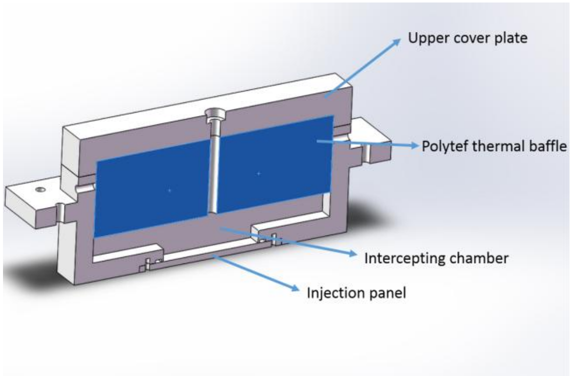
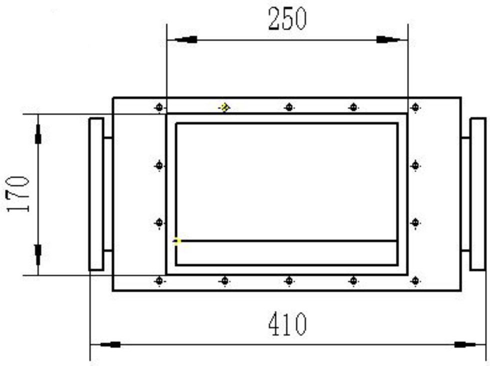
observation chamber runner size is 50mm*100mm*410mm. The specific structure of the optical observation chamber is shown in figure 1. Kerosene supply system selected the extruded supply system. It includes fuel storage tank, stop value, filters, flow meters and injectors. Programmable logic controller (PLC) is used in the test and control system to precisely control the air inlet flow, fuel jet flow, heating system and blowing system. At the same time, the pressure of each transfer section, equipment throat, optical observation chamber and supply system is collected, so as to accurately obtain the engine combustion chamber and upstream wall pressure.



a. Three-dimensional section view of insulation spray structure



b. The design drawing of optical observation chamber

Figure 1: The structural drawing of optical observation chamber

The schlieren test system used in this paper is shown in figure 2. PDA test system and high-speed photography system are similar to schlieren test system, while are not listed here.

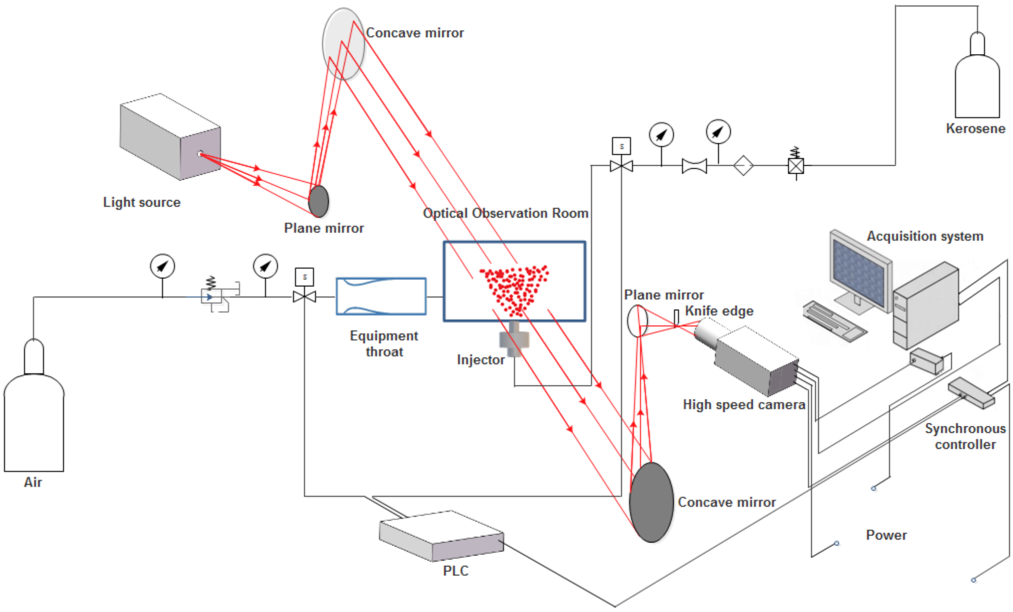


Figure 2: Schlieren system under supersonic flow

2.2 Experimental content

The atomization characteristics and penetration of kerosene under crossflow were studied by means of various

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influencing factors, such as pore size and number, configuration, flow rate and inlet Mach number, etc. The atomization characteristics mainly measure the size and distribution of droplet size. From the micro point of view, the sauter mean diameter and relative size range of spray under different influencing factors are obtained by

Table1: injection panel information

group	**1**	**2**	**3**	**4**#	**5**##
pore size/mm	0.7	0.5	0.4	0.4	0.4
pore number	1	1	1	3	3
mass flow rate (P=1MPa)/g • s-1	12.3	6.28	4	12	12
mass flow rate (P=2MPa)/g • s-1	17.4	8.88	5.68	17.1	17.1

#: Linear distribution. ##: equilateral triangle distribution

Table 2: Test setting

conditions	**injection panel**	**△P/MPa**	**Inflow Mach number/Ma**
GKY1-0.7	1	1	0.6
GKY2-0.4	3	2	0.6
GKY2-0.4L	4	2	0.6
GKY2-0.4S	5	2	0.6
GKY2-0.5	2	2	0.6
GKY2-0.7	1	2	0.6
GKC1-0.7	1	1	2
GKC2-0.7	1	2	2

Notes, GKY-subsonic, GKC-supersonic, “1,2”-pressure drop, “0.4,0.5,0.7”-pore size, L-orifices were distributed in a straight line, S-orifices in an equilateral triangle, X-fuel injection preferred.

using PDA. For penetration, high-speed photography and schlieren method are mainly used to obtain the kerosene atomization track, and the collected images are processed to fit the empirical formula of penetration. The influence of different factors was studied by using the control variable method, and different injection panels were designed for testing. The information of the injection panel is shown in table 1. Due to the unstable compressed air power of the

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gas storage tank, subsonic flow was mainly selected as the main state of crossflow when setting test conditions, and a small number of supersonic conditions were selected for comparison. Meanwhile, in order to make the experimental results more obvious, the pore size of 0.7mm was selected as the diameter of jet hole for multi-factor comparison. The working conditions are set as shown in table 2.

3. Experimental results

3.1 Analyzing atomization characteristics

This paper selects SMD(D32) and relative size range(Δ_s) to evaluate atomization characteristics. The ambient temperature was 270K. According to the total pressure, static pressure and total temperature, the static temperature and Mach number was calculated, and the momentum flux ratio was calculated according to the injection pressure drop. Where, the momentum flux ratio is the dynamic pressure ratio of the jet to crossflow, as shown in equation (1). The test results under different working conditions are shown in table 3.

$$\mathrm{q} = \frac{\frac{1}{2}\rho_l v_l^2}{\frac{1}{2}\rho_g v_g^2} = \frac{2\Delta P}{PMa^2} \quad \textbf{(1)}$$

In equation (1), q is jet to crossflow momentum flux ratio. ρ_l , ρ_g is the density of kerosene and crossflow,

Table 3: Measurement results of atomization characteristics

conditions	**injection panel**	**△P/MPa**	**Ma**	**q**	**SMD(mm)**	Δ_s
GKY1-0.7	one	1.02	0.65	8.62	37.09	2.24
GKY2-0.4	three	2.03	0.5	16.74	18.93	1.23
GKY2-0.4L	four	1.73	0.63	11.32	14.87	0.77
GKY2-0.4S	five	1.68	0.63	12.09	14.55	1.19
GKY2-0.5	two	1.9	0.57	14.09	18.18	1.14
GKY2-0.7	one	1.83	0.64	14.18	13.17	0.89
GKY2-0.7X	one	1.86	0.67	18.02	12.88	1.3
GKC1-0.7	one	1.05	2	0.55	30.89	1.84

g/cm^3 . v_l , v_g is velocity of kerosene and crossflow, m/s . ΔP is pressure drop of kerosene, MPa. P is static pressure, MPa. P0 is total pressure, MPa. It can be seen from equation (1) that the momentum flux ratio is related to the total pressure, static pressure and fuel injection pressure drop. Jet to crossflow momentum flux ratio can be control directly by control the fuel injection pressure drop.

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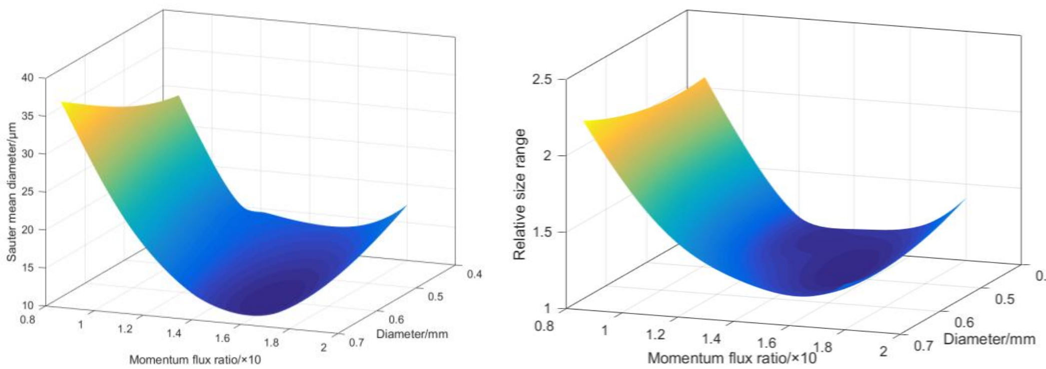
Analyzing the results, the Mach number of subsonic flow is about 0.6, the speed of supersonic flow is controlled by the equipment throat at Mach 2. The above conditions were grouped according to different factors. The sauter mean diameter is taken as the standard to evaluate atomization, and the relative size range is taken as the index of dispersion degree of kerosene atomization to analyze atomization process. Preliminary analysis of table 3 shows that the arrangement of pore and the sequence of incoming flow have little influence on the average diameter and relative size range of liquid droplets. Therefore, pore size and momentum flux ratio are taken as the main influencing factors for analysis in the drawing. Figure 3 shows the variation trend of the sauter mean diameter and relative size range of spray with the pore size and momentum flux ratio under different working conditions.

(1) Injection pressure drop

In order to study the influence of injection pressure drop on droplet size, the injector with an aperture of 0.7mm was tested at 1MPa and 2MPa. The incoming Mach number was basically the same. By analyzing GKY1-0.7 and GKY2-0.7, it can be obtained as the pressure drop increases, the speed of jet exit increases, which strengthens the air-liquid interaction and is beneficial to the droplets to overcome the surface viscosity force and enhance the shear force, so as to improve the atomization effect and improve the uniformity of atomization. According to the test results, SMD and relative size range of liquid droplets both decrease with the increase of injection pressure drop.

(2) Pore size and momentum flux ratio

When analyzing the influence of pore size on droplet size, since hasn’t control other variables to be a certain value, comprehensive analysis of multiple factors is required. Figure 3 shows the variation trend of atomization characteristics with pore size and momentum flux. It can be seen that the sauter mean diameter and relative size range of droplets decreases with the increase of momentum flux ratio and increase with the increase of pore size. When the momentum flux ratio increases to a certain extent, the growth trend of sauter mean diameter gradually flattens out, and the influence of momentum flux ratio on atomization is much greater than pore size. The main reason is that with the decrease of pore size, the flow rate of the jet decreases, and the concentration of the atomized droplet group decreases, which increases the interaction between gas and liquid. However, when the momentum flux ratio increases, the surface fragmentation of droplets increased, which leads to better atomization effect.



a. SMD b. Relative size range

Fig.3 The variation trend of droplet atomization characteristics

(3)The nozzle arrangement

By studying GKY2-0.4L and GKY2-0.4S, the influence of nozzle arrangement on droplet size can be analyzed. As can be seen from table 3, the sauter mean diameters of the two types are not significantly different, but their relative size ranges are greatly different. The design of multiple pores in the direction of central flow has better atomization uniformity than that arrange in the spanwise. In principle, although wider spanwise atomization is more conducive to

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making full use of shear effect of crossflow field, the influence of wall boundary layer on mixing must be considered at the same time, which will lead to uneven droplet size. In the practical design, the center line of combustion chamber should be reasonably used to arrange the pores in the spanwise, which is more conducive to the uniformity of atomization.

(4)The nozzle number

According to the information of the injection panel, the flow rate of the injector with an aperture of 0.7mm is similar to that of the injector with three apertures of 0.4mm. So the GKY2-0.4L and GKY2-0.7 were selected to study the influence of nozzle number. Compared with the measured results, the sauter mean diameter of single orifice is slightly larger and the atomization uniformity of single orifice are slightly better. Analysis of the results, compared to single-hole jet injection, The flow field in the downstream of porous jet injection are quite different from those in the upstream. The inflow velocity before the upstream jet is larger, while the flow field before the downstream jet is mixed with a large number of liquid droplets after passing through an oblique shock wave. As a result, the flow velocity before the downstream jet decreases, and the liquid-to-gas momentum ratio of downstream jet decreases. Therefore, the spray atomization performance of porous jet holes is slightly worse than that of single jet hole.This is consistent with the conclusion of literature [20].

(5)Inflow Mach number

Compared with GKY1-0.7 and GKY2-0.7, the influence of subsonic and supersonic crossflow on the size of atomized droplets was analyzed. It can be seen that the larger the Mach number, the smaller the atomized droplet size and the better the droplet uniformity. The reason is that the larger the Mach number, the greater the shearing effect relative to the kerosene jet, and the greater the dynamic pressure. The increase of crossflow pressure will increase the degree of surface breakage, which greatly improves the atomization performance.

According to comprehensive analysis of 8 groups of data, the size of atomized droplets increases with the increase of pore size, injection pressure drop, momentum flux ratio and crossflow Mach number. The injection pressure drop and the momentum flux have a greater influence on the droplet size. In terms of atomization uniformity, the most uniform distribution is the porous structure arranged according to the center line, indicating that the nozzle arrangement has a great influence on the atomization uniformity. When designing the injector, the influence of the pore size, pressure drop, etc. on the atomization performance should be combined to select the best conditions for the atomization effect.

3.2 Analysis of penetration measurement results

The fuel penetration generally refers to the depth at which the fuel penetrates into the crossflow. After research and development, it is defined as the vertical distance between the outermost contour of the spray at the jet center section and the bottom surface. The penetration of the jet reflects the mixing degree of fuel and the mainstream. The greater the penetration, the deeper the fuel jet penetrates into the mainstream, and the better the atomization effect [11].

In this paper, schlieren method and optical photography method were used to measure the fuel penetration, and superimposed records were made on the entire flow field to obtain the trajectory and distribution diagram of atomized kerosene in the flow field. Through image processing technology, kerosene penetration curve was extracted, and then the data was fitted by least square method to get the penetration empirical formula.

3.2.1 The penetration measurement results of atomized kerosene

The conditions selected for the measurement of penetration are consistent with those for the measurement of atomization characteristics. During the test, real-time measurement and collection of total pressure, static pressure and pressure drop of fuel injection were carried out. After the end of each group of experiments, it was need to blow the runner and replace the injection panel. At the same time, absorbent cotton and anhydrous ethanol were used to

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clean and wipe the glass of observation chamber. Finally, the penetration measurement graph under eight conditions is obtained, including two schlieren conditions and six high-speed photography conditions. Figure 4 and 5 are schlieren and high-speed photography photos of GKY2-0.5 respectively.

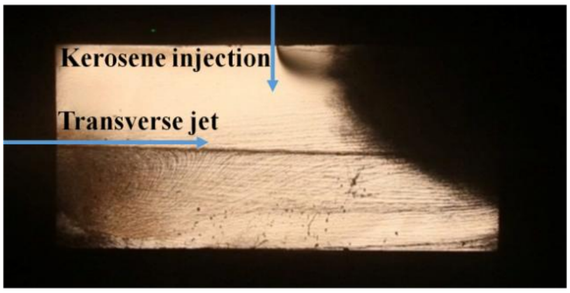

Figure 4: Schlieren photos

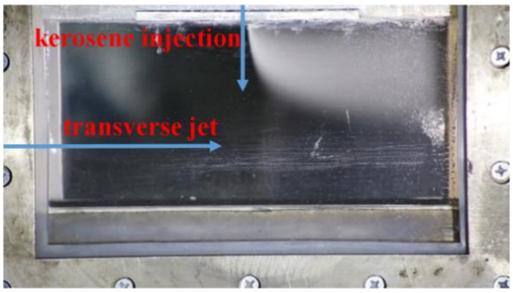

Figure 5: High-speed photography photos

It can be seen from figure 4 and 5 that there is a large amount of kerosene attached to the glass at the exit end of the optical observation chamber under the subsonic condition, while there is no kerosene at the supersonic condition, and the flow field is relatively stable. It is speculated that under subsonic, the square circle transfer segment and movable tail cone were assembled at the exit of the optical observation chamber, which resulted in the decrease of the exit area and the accumulation of kerosene. The kerosene penetration can be clearly observed from the figure 4 and 5. The accumulation of kerosene does not affect the measurement of penetration. The pressure, pressure drop, momentum flux ratio and other parameters in each working condition are shown in table 4.

Table 4: Test parameters under different working conditions

	conditions	**injection panel**	**P0/MPa**	**P/MPa**	**△P/MPa**	**q**
1	GKY1-0.7	one	1.86	0.74	1.21	9.11
2	GKY2-0.4	three	1.67	1.39	2	8
3	GKY1-0.7	one	1.89	1.23	1.09	4.89
4	GKY2-0.4	three	1.87	1.35	2	9.33
5	GKY2-0.5	two	1.91	1.19	1.9	8.89
6	GKY2-0.7	one	2.24	1.05	2.09	11.11
7	GKY1-0.7	one	1.84	0.75	0.97	7.22
8	GKC2-0.7	one	2.06	0.84	1.77	1.05

Notes, “1-2” is schlieren, “3-8” is high-speed photography.

According to the parameter Settings of each working condition in table 4, the influences of injection pressure drop, pore size and momentum flux ratio on the penetration can be analyzed. When measuring the influence of one of the variables, it’s difficult to control other factors. Therefore, when analyzing the effects of these variables on penetration, multiple factors need to be combined.

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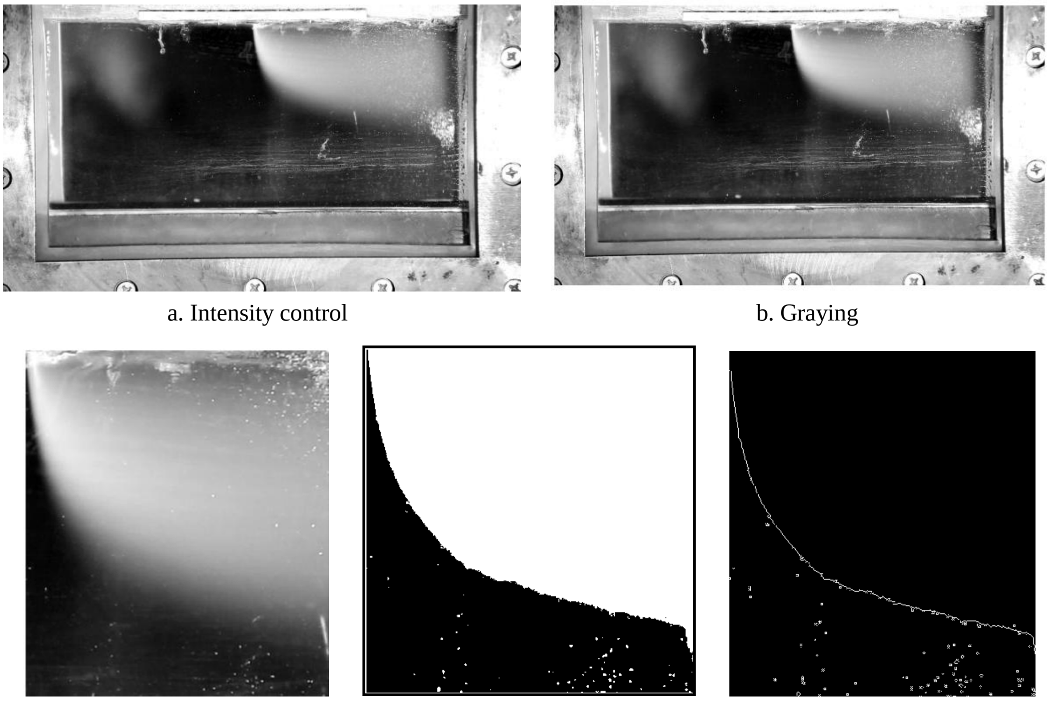
3.2.2 Image processing and penetration fitting

This paper mainly uses Matlab software to process the penetrating image, and the main processing process is as follows. (1) Dimension calibration. Since the default coordinate system in the image is the pixel coordinate system, rather than the real length coordinate system, the image needs to be calibrated. That is, through the real size convert pixel coordinate system to real coordinate system. (2) Adjust brightness and contrast through brightness adjustment function to enhance the color difference between background color and atomization area. (3) Grey processing, transforming the atomized image from color image to grayscale image. (4) Intercept the image of atomized region to avoid the influence of other regions on data extraction. (5) According to the definition of kerosene penetration depth, an appropriate threshold value was selected for binarization. (6) The boundary is extracted from the binarization image. (7) Extract and process the data points of boundary, and remove the isolated points. (8) The empirical formula of penetration is obtained by using the least square method to fit the data. Taking GKY2-0.7 as an example, the processing process picture is listed in figure 6.



a. Intensity control b. Graying

c. Atomization area d. Binaryzation e. Boundary extraction

Figure 6: Image processing of jet atomization

The experimental data show that momentum flux ratio and axis distance have the largest influence on penetration, which is consistent with previous research results [2,11-13,21]. Therefore, the empirical formula of penetration fitted in this paper is shown in equation (2).

$$\frac{h}{d} = a * q^{b} * \left(\frac{x}{d}\right)^{c} \tag{2}$$

Where a, b and c are constant.

In the process of public fitting, the momentum flux ratio and constant are fitted as a constant to reduce the loss caused by the fitting, and then the momentum flux ratio under each working condition is substituted into the formula for quadratic fitting. The first fitting results are shown in table 5. Because of the difference of measuring method and crossflow Mach number, the penetration formula is different. Therefore, this paper only makes a quadratic fitting to

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the subsonic penetration curve obtained by high-speed photography. When the crossflow Mach number is 0.6, the penetration empirical formula is :

$$\frac{h}{d} = 3.365 * q^{0.429} \left(\frac{x}{d} \right)^{0.393} \quad \textbf{(3)}$$

Where h is penetration, d is pore size, q is momentum flux ratio and x is abscissa. The above formula shows the change trend of penetration with momentum flux ratio and flow direction. Other conditions being the same, the greater the momentum flux ratio is, the greater the penetration is.

Figure 7 shows the fitting curve of penetration obtained by high-speed photography, indicating the variation trend of penetration with the direction of flow under different working conditions. It can be seen that the variation trend of penetration is consistent in all working conditions. The penetration of GKY2-0.4 is the largest, that is, the smaller the pore size and the greater the pressure drop, the deeper the penetration. These two factors are related to the momentum flux ratio, indicating that the momentum flux ratio has the greatest influence on the penetration. By analyzing the penetration depth of gky1-0.7 and gkc2-0.7, it can be known that the penetration depth of supersonic inflow is larger, which is consistent with the conclusion of literature [22].That is, when the crossflow Mach number increases, the penetration increases.

Table 5: The first fitting formula of penetration under each working condition

conditions	**Penetration empirical formula**
Schlieren GKY2-0.4	$\frac{h}{d} = 9.071*\left(\frac{x}{d}\right)^{0.345}$
Schlieren GKY2-0.5	$\frac{h}{d} = 10.21*\left(\frac{x}{d}\right)^{0.336}$
High-speed photography GKY1-0.7	$\frac{h}{d} = 6.407*\left(\frac{x}{d}\right)^{0.376}$
High-speed photography GKY2-0.4	$\frac{h}{d} = 11.54*\left(\frac{x}{d}\right)^{0.4}$
High-speed photography GKY2-0.5	$\frac{h}{d} = 7.08*\left(\frac{x}{d}\right)^{0.439}$
High-speed photography GKY2-0.7	$\frac{h}{d} = 8.444*\left(\frac{x}{d}\right)^{0.367}$
High-speed photography GKC1-0.7	$\frac{h}{d} = 8.59*\left(\frac{x}{d}\right)^{0.355}$
High-speed photography GKC2-0.7	$\frac{h}{d} = 9.732*\left(\frac{x}{d}\right)^{0.386}$

In general, the penetration of spray increases obviously with the increase of injection pressure drop. And with the increase of pore size and crossflow Mach number, the penetration also increases gradually. The influence of jet

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pressure drop and crossflow Mach number is greater. When the penetration of spray is relatively small, the distance between the edge of spray and the wall surface is very small, and adherent flow appears. Some droplets will collide with the wall surface, which is not conducive to atomization and mixing. Therefore, the occurrence of adherent flow should be avoided as far as possible.

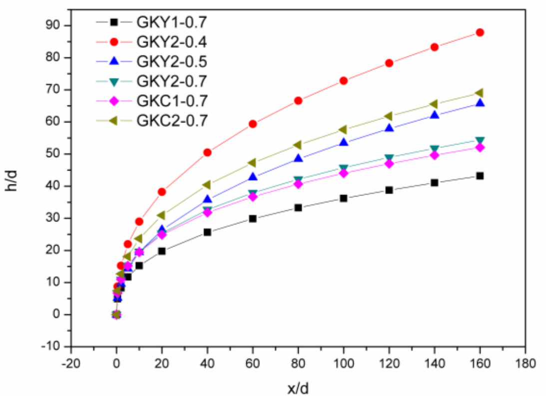

Figure 7: The fitting curve of penetration under different conditions

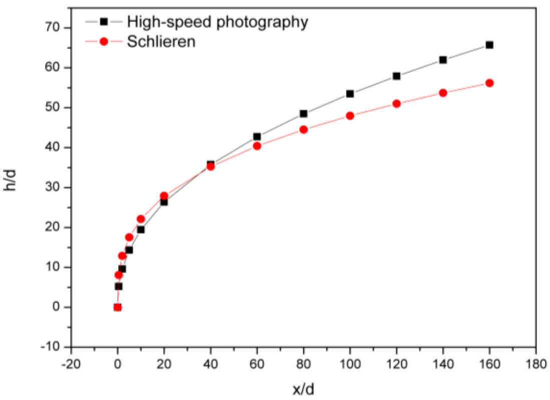

Figure 8: Comparison chart of penetration between the two measurement methods

Table 6: The commonly used penetration empirical formula

Date	Author	Method	Ma	empirical formula
1998	Wu,Kirkendall[13]	PDPA	0.2-0.4	$\frac{h}{d}=4.3*q^{0.33}*\left(\frac{x}{d}\right)^{0.33}$
2002	Lin，Kennedy[12]	PDPA	0.3	$\frac{h}{d}=2.42*q^{0.48}*\left(\frac{x}{d}\right)^{0.24}$
		PDPA	0.2-0.4	$\frac{h}{d}=3.17*q^{0.33}*\left(\frac{x}{d}\right)^{0.40}$
2004	Lin[21]	PDPA	1.94	$\frac{h}{d}=4.73*q^{0.30}*\left(\frac{x}{d}\right)^{0.3}$
2008	Liu[11]	Schlieren method	2	$\frac{h}{d}=3.14*q^{0.29}\left(\frac{x}{d}\right)^{0.38}$
2013	Sun[21]	NPLS	2.7	$\frac{h}{d}=1.16*q^{0.72}*\left(\frac{x}{d}\right)^{0.32}\theta^{0.11}$
2015	Wang[2]	PLIF	—	$\frac{h}{d}=3.134*q^{0.422}\left(\frac{x}{d}\right)^{0.32}We^{-0.06}$

Figure 8 shows the fitting curve of penetration of gky2-0.5 in the same working condition photographed by high-speed photography and schlieren method. It can be seen from the figure that the schlieren method has larger measurement results in the near field area, while the high-speed photogrammetry results in the far field area are

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larger. But overall, the penetration is close. For different measurement methods, the penetration fitting formulas are different. Table 6[13] lists some empirical formulas of penetration that obtained by different test methods.

The empirical formula of penetration fitted by this paper is compared with the empirical formula of penetration fitted by previous researchers. The exponential of momentum flux ratio is 0.492, which is similar to the data in the literature. It is found that the exponential of the momentum flux ratio is very close to the exponential of the flow position, indicating that the momentum flux ratio and the flow position have close influence on the penetration. There are certain differences in the penetration formula in various literatures, which are related to the test method, crossflow Mach number [23] and other factors. Suppose the pore size is 0.5mm and the momentum flux ratio is 10. The penetration fitting curves obtained in this paper are compared with some penetration fitting curves in table 6, as shown in figure 9.

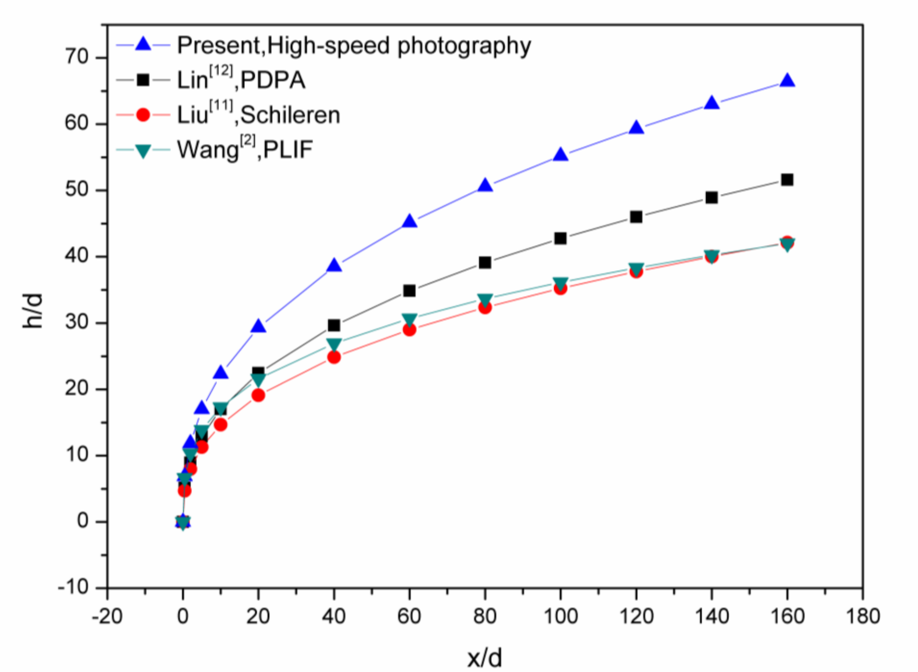

Figure 9 Comparison of penetration curves

Figure 9 compares the penetration curves fitted by four test methods, including PDPA, schlieren, high speed photography and laser induced fluorescence (PLIF). It can be seen that the penetration obtained in this paper is higher than other literatures, and the measurement results of PDPA are higher than schlieren method and PLIF. This is related to the test philosophy. PDPA is to obtain the distribution of spray through laser scanning the entire flow field, with higher measurement accuracy. Schlieren method uses the density gradient of spray field to cause the change of light intensity, and then to judge the distribution of spray. For fine particles on the surface of spray, the density gradient is small and the light intensity is weak. PLIF uses laser to incident fluorescent substances to obtain the distribution of spray in the flow field, where the concentration of spray is high, the fluorescence signal is strong, and where the concentration is low, the fluorescence signal is weak. However, high-speed photography uses the principle of optical imaging to quickly and repeatedly sample high-speed objects in a short time, so that the image becomes visualized and clear. However, the electric signal is weak and penetration is not obvious in the places with small concentration of spray. Therefore, schlieren method, PLIF and high speed photography measurement results tend to be small. In this paper, when processing high-speed photographic images, small particles around the spray are also fitted as part of the penetration, which leads to a higher penetration than other literatures. Table 6 shows that, even with the same test method, penetration obtained by different researchers is different to some extent. This is because the differences in testing media, test conditions and image processing methods will result in different jet

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penetration. This is also the reason why different researchers cannot reach a uniform empirical formula of penetration.

4. Conclusion

In this paper, the atomization characteristics and penetration of kerosene under crossflow are studied respectively, and the main conclusions are as follows.

(1) PDA was used to study the atomization characteristics of kerosene. It was found that the SMD of atomized droplets was smaller with the increase of injection pressure drop, momentum flux ratio and crossflow Mach number. However, the larger the pore size and the multiple orifice are arranged in the direction of flow, the better the uniformity of atomized droplets.

(2) The penetration is positively correlated with the momentum flux ratio, pore size and crossflow Mach number, and is most affected by the momentum flux ratio.

(3) The penetration of subsonic and supersonic crossflow was measured by schlieren method and high-speed photography. And compared with the formulas that obtained by other researchers. It is found that the overall trend of penetration is the same, but the empirical formula of penetration obtained by different researchers is different due to the influence of different factors.

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