Research Article

Experimental Investigation on the Effects of Injection Parameters on the Air-Assisted Diesel Spray Characteristics

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The air-assisted fuel injection (AAFI) system may be installed in the spark ignition aviation piston engine for the atomization of heavy fuels. However, studies on the effects of injection parameters on the spray characteristics are insufficient, which affects the improvement of AAFI engine performance. In this study, air-assisted diesel spray characteristics are investigated experimentally using a high-speed backlit imaging technique. The effects of main air-assisted injection control parameters such as fuel injection pressure, fuel temperature, and fuel injection duration on the spray characteristics are examined. The results show that spray shape changes from “spindle” to “cone” with an increase in fuel injection pressure. As the fuel injection pressure increases to 1.0 MPa, both the spray penetration and spray width increase significantly. “Protrusions” appear on the spray edge at high fuel temperatures. When the fuel temperature drops to 268 K, the spray penetration and spray width increase slightly. The spray shrinks significantly in both the axial and radial directions with an increase in fuel injection duration. Key parameters that directly affect air-assisted spray characteristics include the difference between the fuel-air mixture injection pressure and the ambient pressure, the density of fuel-air mixture in the air-assisted injector premixed chamber, and the kinetic energy density of the fuel. The former two parameters affect the spray penetration while the latter affects the spray width. The study is beneficial for the design of AAFI engines.

1. Introduction

Unmanned aerial vehicles (UAVs) are widely used in civil and military fields because of their low cost and high efficiency [1, 2]. UAVs with a service ceiling of less than 10,000 m and a payload of less than 1,000 kg are usually driven by low-power piston engines. Since spark ignition piston engines have a higher power-to-weight ratio and a smaller geometric size than compression ignition piston engines at this power level, piston engines for UAVs are mostly spark ignition engines. In the past few decades, aviation gasoline has always been the main fuel for aviation piston engines. Gasoline has low flash point and high volatility, which makes it easy to explode when exposed to flames or sparks. Recently, spark ignition aviation piston engines are facing a transition from being powered by aviation gasoline to being powered by heavy fuels (diesel and kerosene) that can be more safely stored and transported [3–5].

However, due to the high viscosity and low saturated vapor pressure of heavy fuels [6], the atomization quality of the conventional fuel system (carburetor and port fuel injection) degrades when supplied with heavy fuels rather than gasoline, which markedly affects the power and cold start performance of the spark ignition aviation piston engine [7, 8]. Direct injection is required to efficiently atomize heavy fuels.

Traditional direct injection is characterized by extremely high injection pressure and good atomization quality [9]. However, the high-pressure fuel pump and fuel rail reduce the power-to-weight ratio of the engine, and the high-pressure fuel also increases the risk of fuel leakage, which cannot meet the requirements of aviation engines [10, 11]. By contrast, the air-assisted fuel injection (AAFI) system, which is a low-pressure direct injection system developed by Orbital Inc., uses the expansion of compressed air bubbles to shear fuel droplets. Hence, it can achieve the

atomization quality of traditional direct injection at a relatively low injection pressure. According to Cathcart et al. [12], the overall Sauter mean diameter (SMD) of the air-assisted spray is approximately $5\text{ }\mu\text{m}$.

An AAFI system mainly consists of a metering fuel injector and an air-assisted injector, as shown in Figure 1. The metering fuel injector is first triggered to inject the fuel into the air-assisted injector premixed chamber. The premixed chamber is connected to the compressed air channel and is filled with compressed air. After a certain time interval, the air-assisted injector is triggered to inject the fuel-air mixture into the combustion chamber [13, 14]. The AAFI system requires a supply of pressurized air and fuel. The air pressure is generally lower than 0.7 MPa and the fuel pressure is usually 0.1 MPa higher than the air pressure. The injection sequence and injection pulse width of the two injectors are controlled by an electronic control unit (ECU). The low injection pressure and flexible control strategy not only reduce the cost of the AAFI system but also improve its safety [15, 16]. Therefore, the AAFI system can be integrated into the spark ignition aviation piston engine to achieve high-quality atomization of heavy fuels. The integrated engine is then called the AAFI engine.

A good match between the AAFI system and the spark ignition aviation piston engine requires a full understanding of the spray characteristics of the AAFI system, and the optical diagnostic methods are generally used to investigate the characteristics of fuel spray [17]. Due to the obvious advantages of the AAFI system in improving fuel atomization, a series of studies have been conducted over the past decades. Diwakar et al. [18] studied the liquid and vapor fuel distributions of air-assisted spray. They found that a low-pressure region beneath the poppet causes the air-assisted spray to collapse downstream. Boretti et al. [19] investigated the transient behavior of air-assisted spray to find that the AAFI system can produce a cone spray with a fine atomization and a low penetration. Sureshkumar et al. [20] found that the recirculation area in the air-assisted spray flow field significantly affects the spray shape. Jin et al. [21] found that the ambient gas density significantly influences the penetration and overall SMD of the air-assisted spray; the vortex ring shed from the injector outlet implies a strong coupling between the gas and liquid phases. Subsequently, Wu et al. [22] studied the formation of vortex ring and its influences on air-assisted spray characteristics.

Hu et al. [23] compared the air-assisted spray characteristics of gasoline and kerosene under different test conditions to find considerable differences between the two in spray penetration, spray angle, droplet size, and velocity. Gao et al. [24] and Wu et al. [25] investigated the flash boiling phenomenon of air-assisted gasoline and kerosene spray, respectively. They found that a decrease in ambient pressure or an increase in fuel temperature may induce flash boiling of air-assisted spray, and the flash boiling greatly promotes atomization by increasing droplet spreading and reducing droplet size. Based on the above understandings, Gao et al. [26] studied the trajectory deviation of air-assisted gasoline spray under different conditions. It was found that the radial expansion of air-assisted spray occurs under specific

FIGURE 1: AAFI system.

differences between the ambient pressure and fuel-air mixture injection pressure; an increase in ambient temperature leads to the trajectory deviation near the spray edge. Subsequently, Wu et al. [27] studied the air-assisted kerosene spray characteristics under various in-cylinder conditions. They found that as the ambient pressure increases from 0.5 bar to 3.5 bar , the spray penetration and spray volume decrease significantly. There is no significant difference in kerosene vapor penetration when the ambient temperature changes from 400 K to 500 K . A summary of the literature related to air-assisted spray characteristics is shown in Table 1.

Based on the above literature review, it can be seen that researchers have explored the typical characteristics of air-assisted spray and discussed the influences of ambient conditions on air-assisted spray characteristics, but to date there has been no systematic study on the effects of main air-assisted injection control parameters (injection pressure, fuel-air mixture temperature, and injection pulse width) on spray characteristics. However, these control parameters significantly impact air-assisted spray characteristics by affecting the state of a large number of air bubbles in the spray. The lack of such research affects the design of new AAFI engines. Specifically, the selection of fuel-air mixture injection pressure and the determination of AAFI system control strategies during cold start lack theoretical basis. Therefore, to guide the design of new AAFI engines, in the present study, the effects of these control parameters on air-assisted spray characteristics are examined.

In this paper, air-assisted diesel spray characteristics under a wide range of fuel injection pressures, fuel temperatures, and fuel injection durations were investigated experimentally. The effects of each control parameter on the spray characteristics were discussed in detail. In particular, spray characteristics under high fuel injection pressure (1.0 MPa) or low fuel temperature (268 K) were considered compared with previous works. Key parameters that directly affect the penetration and width of air-assisted spray were

TABLE 1: A summary of the literature related to air-assisted spray characteristics.

Serial number	Author and reference	Type of fuel	Main contents
Serial number 1-7: Typical characteristics			
1	Diwakar et al. [18]	Gasoline	Liquid and vapor fuel distributions
2	Boretti et al. [19]	Gasoline	Spray shape and penetration
3	Sureshkumar et al. [20]	Gasoline	Spray shape
4	Jin et al. [21]	Gasoline	Vortex ring
5	Wu et al. [22]	N-heptane	Vortex ring
6	Gao et al. [24]	Gasoline	Flash boiling phenomenon
7	Wu et al. [25]	Kerosene	Flash boiling phenomenon
Serial number 8: Differences between fuels			
8	Hu et al. [23]	Gasoline and kerosene	Differences in spray characteristics
Serial number 9-10: Ambient conditions			
9	Gao et al. [26]	Gasoline	Ambient pressure and temperature
10	Wu et al. [27]	Kerosene	Ambient pressure and temperature

FIGURE 2: Schematic diagram of experimental apparatus.

determined after careful analysis of the experimental results. This work may provide a valuable reference for the design of new AAFI engines and the in-depth understanding of the atomization mechanism of AAFI systems.

The remainder of this paper is organized as follows. The experimental specifications are introduced in Section 2. Sections 3.1–3.3 provide phenomenological descriptions of the effects of control parameters on air-assisted spray characteristics. Key parameters that directly affect these characteristics

are discussed in Section 3.4. Section 3.5 presents a comparative study on the previous findings. Section 4 provides a brief summary and conclusion.

2. Methodology

2.1. Experimental Setup. Figure 2 shows a schematic diagram of the experimental setup used in this study to record the air-assisted spray characteristics. An electronic controlled

FIGURE 3: Control signal sequence.

FIGURE 4: Real time image of the spray experiment.

FIGURE 5: Internal structure of the air-assisted injector.

TABLE 2: Properties of diesel (at 298 K).

Parameter (unit)	Value
Density (kg/m^3)	840.1
Kinematic viscosity (mm^2/s)	4.35
Surface tension (mN/m)	28.3
Vapor pressure (hPa)	<1
Heat of evaporation (kJ/kg)	280

TABLE 3: Test condition matrix.

Serial number	Test abbreviation	Fuel injection pressure (MPa)	Fuel temperature (K)	Fuel injection duration (ms)
1	Reference	0.8	298	4.0
2	0.7 MPa	0.7	298	4.0
3	0.9 MPa	0.9	298	4.0
4	1.0 MPa	1.0	298	4.0
5	268 K	0.8	268	4.0
6	328 K	0.8	328	4.0
7	358 K	0.8	358	4.0
8	6.0 ms	0.8	298	6.0
9	8.0 ms	0.8	298	8.0
10	10.0 ms	0.8	298	10.0

TABLE 4: Engine main parameters.

Parameter (unit)	Value
Engine type	Opposed four-cylinder two stroke, spark ignition, diesel engine
Cooling system	Water-cooled type
Fuel system	AAFI system
Displacement (cm ³)	1350
Bore (mm)	82
Stroke (mm)	64
Effective compression ratio	8
Rated speed (rpm)	6000
Rated power (kW)	80

TABLE 5: Uncertainty analysis of measuring equipment.

Serial number	Measuring equipment	Uncertainty
1	Gas pressure regulator	± 0.0092
2	Fuel pressure gauge	± 0.0104
3	Temperature sensor	± 0.0072
4	High-speed camera	± 0.0038

AAFI system was installed on the top of the chamber. A vacuum pump was connected to the chamber through a three-way ball valve to remove the residual fuel of the previous test. A high-intensity Xenon lamp (300 W rated power) was used to illuminate the spray. A high-speed camera (SA4, Photron) was used to record spray shadowgraph images. The frame rate of the camera was set to 10,000 fps. The resolution of the spray image was set to 768×512 pixels. Synchronization between the high-speed camera and the AAFI system was achieved by an ECU. A laptop was used to modify the control programs of the ECU and store the images.

During the experiments, an air cylinder with a pressure regulator was used to supply compressed air to the AAFI system. An electric fuel pump was used to pressurize the fuel. A differential pressure valve was used to maintain a fuel pressure of 0.1 MPa higher than the compressed air pressure. A metering fuel injector and an air-assisted injector were mounted on an aluminum alloy manifold block. The fuel outlet of the metering fuel injector was located near to the fuel inlet of the air-assisted injector. The manifold block has a fuel channel, a compressed air channel, and a methyl silicone oil channel. The fuel channel was connected to the fuel inlet of the metering fuel injector and the compressed air channel was connected to the air inlet of the air-assisted injector. Both ends of the methyl silicone oil channel were, respectively, connected to the outlet and inlet of the high/low temperature circulating pump (temperature range: -20°C – 100°C , flow rate: 20 L/min).

The temperature of fuel and air was adjusted indirectly by adjusting the temperature of methyl silicone oil. Temperature sensors (PT100) were installed near the fuel inlet of the metering fuel injector and the air inlet of the air-assisted injector to monitor fuel and air temperatures in real time. The fuel injection duration, fuel-air mixture injection duration, and time interval between two injec-

tions were adjusted by the ECU. The sequence of the injection control signals is shown in Figure 3. The driving modes of the metering fuel injector and the air-assisted injector were both “peak-hold.” The air-assisted injector was driven separately for a period after each mixture injection to remove the residual fuel that may remain inside the air-assisted injector. The real-time image of the spray experiment is shown in Figure 4.

The internal structure of the air-assisted injector is shown in Figure 5. Before the metering fuel injector injects fuel, the air-assisted injector premixed chamber is already filled with air of a specific pressure. The compressed air originates from the compressed air channel and enters the premixed chamber through the air inlet. The fuel is first injected to the premixed chamber. After a certain time interval, the drive circuit supplies power to the coil of the injector, which induces a magnetic field inside the injector. When the electromagnetic force acting on the needle valve is greater than the spring force acting on the needle valve, the needle valve moves downward along the injector axis. The air-assisted injector opens and the fuel-air mixture is ejected. The displacement of the needle valve depends on the gap between the needle valve and the valve seat. After a period of time, the drive circuit stops supplying power to the coil and the electromagnetic force acting on the needle valve is reduced to zero. The needle valve returns to its initial position under the action of the spring force and the injection process ends.

Equipment that need to be calibrated in this study include: a gas pressure regulator for adjusting and measuring the air rail pressure, a fuel pressure gauge for measuring the fuel rail pressure, an ECU for controlling the injection pulse width, temperature sensors for measuring the temperature of the fuel and air, and a high-speed camera for recording the transient development of the air-assisted spray. The calibration method of the gas pressure regulator is to connect it in series with the corresponding standard pressure gauge and adjust the pressure gauge of the gas pressure regulator based on the reading of the standard gauge. The calibration method of the fuel pressure gauge is similar to the calibration method of the gas pressure regulator. An oscilloscope was used to calibrate the output signal of the ECU. The thermostatic water tank was used to calibrate the temperature sensor. A

FIGURE 6: Spray image processing procedure and definitions of spray diffusion area, spray penetration, and spray width.

customized rotating code disc standard device was used to calibrate the frame rate of the high-speed camera.

2.2. Test Condition. Diesel adopted in this test is a mixture of hydrocarbons ($C_{10}\sim C_{22}$), which is composed of alkanes, cycloalkanes, and aromatics. It has good ignitability and low-temperature fluidity and is the fuel for compression ignition high-speed diesel engines. The production process of diesel used in this study includes: the straight-run diesel is first obtained from the crude oil through atmospheric and vacuum distillation, and then the straight-run diesel is hydrotreated to obtain the product-grade diesel. The main properties of the diesel are listed in Table 2.

The design matrix of the test conditions is shown in Table 3. The fuel-air interval and fuel-air mixture injection duration of all test conditions are 0.5 ms and 3.0 ms, respectively. The ambient conditions are room temperature and atmospheric pressure. Based on the above test conditions, the main parameters of the AAFI engine to be simulated in this study are shown in Table 4.

2.3. Spray Image Post-Processing. The processing software attached to the high-speed camera was used to extract the original spray images frame-by-frame. Subsequently, a spray image processing program was operated in MATLAB. A typical image processing process is shown in Figure 6. The

TABLE 6: Uncertainty analysis of experimental results.

Test conditions		Spray penetration			Spray width (2.5 ms)			Spray diffusion area ratio		
		0.5 ms	1.5 ms	2.5 ms	25 mm	50 mm	75 mm	0.5 ms	1.5 ms	2.5 ms
Reference condition		±0.0254	±0.0227	±0.0108	±0.0278	±0.0218	±0.0309	±0.0451	±0.0338	±0.0103
Fuel injection pressure (MPa)	0.7	±0.0166	±0.0324	±0.0185	±0.0309	±0.0208	—	±0.0261	±0.0445	±0.0466
	0.9	±0.0287	±0.0259	±0.0197	±0.0181	±0.0151	±0.0414	±0.0405	±0.0292	±0.0314
	1.0	±0.0608	±0.0414	±0.0208	±0.0305	±0.0233	±0.0217	±0.0302	±0.0092	±0.0938
Fuel temperature (K)	268	±0.0264	±0.0211	±0.0134	±0.0427	±0.0173	±0.0265	±0.0925	±0.0233	±0.0468
	328	±0.0196	±0.0347	±0.0233	±0.0271	±0.0352	±0.0235	±0.0152	±0.0181	±0.0211
	358	±0.0244	±0.0142	±0.0157	±0.0247	±0.0235	±0.0419	±0.0316	±0.0198	±0.0143
Fuel injection duration (ms)	6.0	±0.0098	±0.0160	±0.0774	±0.0597	±0.0162	±0.0435	±0.0287	±0.0484	±0.0257
	8.0	±0.0203	±0.0243	±0.0225	±0.0213	±0.1184	—	±0.0336	±0.0293	±0.0374
	10.0	±0.0270	±0.0461	±0.0202	±0.0248	±0.0252	—	±0.0176	±0.0301	±0.0187

background of the original spray image shown in Figure 6(a) was subtracted and the image was processed as a grayscale image as shown in Figure 6(b). The grayscale image was then binarized according to a gray threshold determined based on the Otsu method [28], as shown in Figure 6(c). Finally, an edge detection algorithm was used to determine the spray penetration and spray widths at different positions (Figure 6(d)). In addition, the spray diffusion area ratio of the spray image was calculated to quantify the spray diffusion. This parameter is the ratio of the number of pixels contained in the white area (spray diffusion area) in Figure 6(c) to the number of pixels in the entire spray image. It should be pointed out that all the original spray images were cropped to a size of 360×270 pixels before further processing.

2.4. Uncertainty Analysis. Uncertainty analysis can be used to evaluate the reliability of experimental results, so it is necessary to carry out uncertainty analysis. The calculated uncertainties of measuring equipment are listed in Table 5. Each test condition was repeated several times in this study; the measurements of three tests under each test condition were subjected to uncertainty analysis to evaluate their reliability. Uncertainty was first calculated as follows:

$$U = \pm \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n(n-1)}}, \quad (1)$$

where U is the uncertainty, n is the number of measurements, x_i is the value of each measurement, and $\bar{x} = \sum_{i=1}^n x_i / n$ is the average measurement [29]. Subsequently, the ratio of the uncertainty to the average measurement was calculated to obtain a dimensionless analysis result (Table 6). The uncertainty values of most measurements are below 5%; thus, the measurements are reliable.

3. Results and Discussion

In this section, “ P_f ,” “ T_f ,” and “ ΔT_f ” in figures indicate “fuel injection pressure,” “fuel temperature,” and “fuel injection duration,” respectively. Error bars in figures indicate the

standard error. “Axial direction” refers to the direction of the air-assisted injector axis. “Radial direction” refers to the direction of the radial axis. The injector axis and radial axis are marked in Figure 6(d).

3.1. Effect of Fuel Injection Pressure on Spray Characteristics.

As mentioned above, during the tests, the difference between the fuel injection pressure and the fuel-air mixture injection pressure was fixed at 0.1 MPa. Therefore, the fuel injection pressure affects the air-assisted spray characteristics by changing the difference between the fuel-air mixture injection pressure and the ambient pressure. Figure 7 shows the temporal evolution of spray shapes under four different fuel injection pressures (Test conditions (1)~(4)). As shown, an increase in fuel injection pressure causes the spray to expand significantly in both the axial and radial directions at all stages of spray development. This is because an increase in fuel injection pressure causes both the initial spray velocity and droplet radial velocity to increase. The detailed reasons will be discussed in subsequent paragraphs. In addition, when the fuel injection pressure is 1.0 MPa, there is an obvious radial expansion at the spray tip and the spray shape is “cone.” When the fuel injection pressure is lower than 1.0 MPa, the spray shape is “spindle.” This difference can be attributed to the fact that the size of the fuel droplets in the spray field is generally small under high fuel injection pressure [26, 30]. Small droplets are more susceptible to ambient gas than large droplets due to their smaller inertia. The resistance of ambient gas to gas-liquid two-phase spray flow is large at the front of the spray [31, 32]. A portion of small droplets deviate from their initial trajectories and move away from the injector axis, creating the radial expansion that is observable at the front end of the spray.

Figure 8 shows the spray penetration under different fuel injection pressures. It is found that the spray penetration increases as fuel injection pressure increases. The spray penetration mainly depends on the initial spray velocity, which can be expressed as follows:

$$V0 = C_F \sqrt{\frac{2(P_{inj} - P_{amb})}{\rho_l}}, \quad (2)$$

FIGURE 7: Time sequence of spray images under different fuel injection pressures ($T_f = 298\text{ K}$, $\Delta T_f = 4.0\text{ ms}$).

FIGURE 8: Spray penetration under different fuel injection pressures ($T_f = 298$ K, $\Delta T_f = 4.0$ ms).

FIGURE 9: Spray width at different axial positions under different fuel injection pressures ($t = 2.5$ ms, $T_f = 298$ K, $\Delta T_f = 4.0$ ms).

FIGURE 10: Spray diffusion area ratio under different fuel injection pressures ($T_f = 298$ K, $\Delta T_f = 4.0$ ms).

where V_0 is the initial spray velocity, C_F is the discharge coefficient, P_{inj} is the injection pressure, P_{amb} is the ambient pressure, and ρ_l is the fuel density [33]. Therefore, the initial velocity of the air-assisted spray is mainly determined by the difference between the fuel-air mixture injection pressure and the ambient pressure, as well as the density of the fuel-air mixture in the air-assisted injector premixed chamber.

Due to the fixed difference between the fuel injection pressure and the compressed air pressure, the increase in fuel injection pressure means the increase in compressed air pressure. Therefore, the mass of compressed air in the premixed chamber will increase according to the ideal gas law shown in Formula (3). At the same time, the fuel under the current pressures (0.7 MPa–1.0 MPa) can be regarded as an incompressible fluid [34]. The pressure difference between the inside and outside of the metering fuel injector is always 0.1 MPa under any fuel injection pressure; hence, the mass of fuel injected into the premixed chamber does not vary with fuel injection pressure. Ultimately, an increase in fuel injection pressure causes the mass of the fuel-air mixture in the premixed chamber to increase; that is, there is an increase in the density of the fuel-air mixture in the premixed chamber. According to Formula (2), the initial spray velocity will decrease. However, the increase in fuel injection pressure also increases the difference between the fuel-air mixture injection pressure and the ambient pressure. According to Formula (2), the initial spray velocity will increase. Figure 8 shows that under the current fuel injection pressures, the increase in pressure difference has a greater impact on the initial spray velocity than the increase in fuel-air mixture density.

$$PV = nRT, \quad (3)$$

where P is the pressure of the gas, V is the volume taken up by the gas, n is the number of moles of the gas, R is the gas constant, and T is the temperature of the gas [35].

The axial distribution of the spray width at 2.5 ms after the start of injection under different fuel injection pressures is shown in Figure 9. The spray width increases significantly as fuel injection pressure increases. This is because the spray width depends on the radial component of the droplet velocity. For the air-assisted spray, the radial velocity of the fuel droplet is mainly determined by the kinetic energy that the droplet obtains from the compressed air bubbles. An increase in fuel injection pressure leads to an increase in the pressure and mass of compressed air in the premixed chamber, which means that in the subsequent spray development process, the kinetic energy that a unit mass of fuel obtains from the expansion and bursting of the compressed air bubbles will increase. Therefore, the radial velocity of the fuel droplets will increase, which manifests as an increase in the spray width.

The spray diffusion area ratios under different fuel injection pressures were calculated to further quantify spray diffusion characteristics, and the results are shown in Figure 10. The spray diffusion area ratio increases substantially as fuel injection pressure increases. This is due to the increases in the penetration and width of the air-assisted spray with the increase in fuel injection pressure, which results in a significant increase in the spray diffusion area. Therefore, increasing the fuel injection pressure can spread the spray across a wider space, which helps to achieve a uniform mixing of fuel and air in the cylinder.

3.2. Effect of Fuel Temperature on Spray Characteristics. The introduction of compressed air makes the spray characteristics of the AAFI system very sensitive to temperature. As the

FIGURE 11: Time sequence of spray images at different fuel temperatures ($P_f = 0.8$ MPa, $\Delta T_f = 4.0$ ms).

AAFI engine is operated, the temperature of the AAFI system may fall below 273 K (cold start) or exceed 343 K (large load) [36, 37]. It is important to understand the air-assisted spray characteristics at different fuel temperatures. In particular, since the internal temperature of the AAFI system is uniform when the AAFI engine is running, the experiments conducted in this study maintained the uniformity of the internal temperature of the AAFI system. The “fuel temperature” mentioned here can actually be understood as the temperature of the entire AAFI system.

Figure 11 shows the changes in spray shape over time at four different fuel temperatures (Test conditions (1), (5)~(7)). As the fuel temperature increases, the spray shrinks slightly in both the axial and radial directions. This is because an increase in fuel temperature causes both the initial spray velocity and droplet radial velocity to decrease. This phenomenon will be explained in the following paragraphs. Furthermore, in the later stage of spray develop-

ment, the spray edge of the low-temperature case (268 K) and normal-temperature case (298 K) is relatively smooth and the spray front in both cases is arrow-shaped. In the other two high-temperature cases (328 K and 358 K), irregular “protrusions” appear on the spray edge and the spray front has an irregular shape. This difference can be understood in this way. High fuel temperature causes some of the fuel droplets located at the edge of the spray to evaporate in the process of interacting with the ambient gas, which destroys the integrity of the spray boundary [38, 39].

The spray penetration at different fuel temperatures is shown in Figure 12. Spray penetration decreases slightly as fuel temperature increases. This is because the increase in fuel temperature means that the temperature of compressed air in the premixed chamber also increases. However, the pressure of compressed air in the premixed chamber remains constant. According to Formula (3), the mass of compressed air in the premixed chamber will decrease. The

FIGURE 12: Spray penetration at different fuel temperatures ($P_f = 0.8\text{ MPa}$, $\Delta T_f = 4.0\text{ ms}$).

FIGURE 13: Spray width at different axial positions at different fuel temperatures ($t = 2.5\text{ ms}$, $P_f = 0.8\text{ MPa}$, $\Delta T_f = 4.0\text{ ms}$).

FIGURE 14: Spray diffusion area ratio at different fuel temperatures ($P_f = 0.8$ MPa, $\Delta T_f = 4.0$ ms).

change in fuel temperature also affects the density and viscosity of the fuel, so the mass flow rate of the metering fuel injector changes. The mass flow test proves that the increase in fuel temperature causes the mass of fuel injected into the premixed chamber to increase, and the increase in fuel mass is greater than the decrease in compressed air mass. Hence, the density of the fuel-air mixture in the premixed chamber will increase. According to Formula (2), the initial spray velocity will decrease, thus decreasing the spray penetration.

Figure 13 shows the spray width at 2.5 ms after the start of injection at different fuel temperatures. Spray width appears to decrease slightly as fuel temperature increases. This phenomenon can be explained by that, an increase in fuel temperature causes a decrease in the mass of compressed air in the premixed chamber and an increase in the mass of fuel in the premixed chamber, so the kinetic energy obtained by a unit mass of fuel from the compressed air bubbles in the subsequent spray development process will decrease. Therefore, the radial velocity of the fuel droplets will decrease, and the spray will shrink in the radial direction.

The spray diffusion area ratio, as shown in Figure 14, decreases slightly as fuel temperature increases. This is because as fuel temperature increases, the spray penetration and width both decrease. Therefore, increasing the fuel temperature does not help the spread of air-assisted spray in the cylinder. However, increasing the fuel temperature reduces the SMD of air-assisted spray [24]. Compared with increasing the fuel temperature, increasing the fuel injection pressure promotes the spread of air-assisted spray and reduces the SMD of spray at the same time. Hence, among all alternative strategies for improving the cold start performance of AAFI engines, priority should be given to increasing the fuel injection pressure rather than heating the fuel system.

3.3. Effect of Fuel Injection Duration on Spray Characteristics. As discussed in the Introduction, the injection process of the AAFI system includes fuel injection, fuel-air mixing, and mixture injection. The duration of fuel injection is defined as the fuel injection duration. Therefore, the fuel injection duration affects the air-assisted spray characteristics by affecting the mass of fuel injected into the premixed chamber [40]. Figure 15 shows the changes in spray shape with time under four different fuel injection durations (Test conditions (1), (8) ~ (10)). As the fuel injection duration increases, the spray shrinks significantly in both the axial and radial directions. This is because with the increase of the fuel injection duration, both the initial spray velocity and droplet radial velocity decrease. A more detailed analysis is given below.

The spray penetration under different fuel injection durations is shown in Figure 16. Spray penetration decreases as fuel injection duration increases, because the increase in fuel injection duration leads to an increase in the mass of fuel in the premixed chamber, while the mass of compressed air in the premixed chamber remains basically unchanged. This ultimately causes an increase in the density of the fuel-air mixture in the premixed chamber. According to Formula (2), the initial spray velocity will decrease, which means a decrease in spray penetration.

The spray width at 2.5 ms after the start of injection under different fuel injection durations is shown in Figure 17. Spray width decreases as fuel injection duration increases, as the increased duration causes the mass of fuel in the premixed chamber to increase, while the pressure and mass of compressed air in the premixed chamber remain basically unchanged. Therefore, in the subsequent spray development process, the kinetic energy obtained by a unit mass of fuel from the expansion and bursting of

FIGURE 15: Time sequence of spray images under different fuel injection durations ($P_f = 0.8$ MPa, $T_f = 298$ K).

compressed air bubbles will decrease. Hence, the radial velocity of the fuel droplets will decrease, which means that the spray width will decrease.

Figure 18 shows the spray diffusion area ratio under different fuel injection durations. The spray diffusion area ratio decreases as fuel injection duration increases, which is related to the contraction of air-assisted spray in axial and radial directions. Therefore, for AAFI engines, when the fuel delivery of the engine needs to be increased under large load, in addition to increasing the fuel injection duration, increasing the fuel injection pressure should be considered to ensure favorable fuel atomization quality. The adjustment of fuel injection pressure during engine operation can be achieved by canceling the air pressure limiting valve and redesigning the air pump [41, 42]. Figure 18 also shows that increasing the fuel injection

duration does not help to improve the cold start performance of AAFI engines.

3.4. Key Parameters That Directly Affect the Air-Assisted Spray Characteristics. The effects of typical air-assisted injection control parameters on spray characteristics are discussed above. Although the types of these control parameters are different, they actually affect the spray characteristics by impacting three distinct parameters: the difference between the fuel-air mixture injection pressure and the ambient pressure, the density of the fuel-air mixture in the premixed chamber, and the kinetic energy density of the fuel. The spray penetration is mainly affected by the first two of these three. According to Formula (2), increasing the difference between the fuel-air mixture injection pressure and the ambient pressure or

FIGURE 16: Spray penetration under different fuel injection durations ($P_f = 0.8\text{ MPa}$, $T_f = 298\text{ K}$).

FIGURE 17: Spray width at different axial positions under different fuel injection durations ($t = 2.5\text{ ms}$, $P_f = 0.8\text{ MPa}$, $T_f = 298\text{ K}$).

FIGURE 18: Spray diffusion area ratio under different fuel injection durations ($P_f = 0.8\text{ MPa}$, $T_f = 298\text{ K}$).

reducing the density of the fuel-air mixture in the premixed chamber will increase the initial spray velocity, which in turn leads to an increase in spray penetration. The spray width is mainly affected by the kinetic energy density of the fuel. This parameter is defined as

$$\rho ke = \frac{E_a}{m_f}, \quad (4)$$

where ρke is the kinetic energy density of the fuel, E_a is the total kinetic energy released when all compressed air bubbles expand and burst, and m_f is the fuel mass. When the kinetic energy density of the fuel is high, a unit mass of fuel obtains more kinetic energy from the compressed air bubbles; fuel droplets have higher radial velocity and the spray width increases.

Figure 19 shows a comparison of spray shapes at 2.5 ms after the start of injection under four different test conditions. The spray development of the four test conditions during the entire fuel-air mixture injection duration is shown in Figure 20. The spray shape under the reference conditions is shown in Figure 19(a). It can be observed that the spray is in an elongated spindle shape with a relatively smooth edge. Figure 19(b) shows the spray shape under high fuel injection pressure (1.0 MPa). The increase in fuel injection pressure changes the difference between the fuel-air mixture injection pressure and the ambient pressure as well as the density of the fuel-air mixture in the premixed chamber at the same time, which eventually leads to an increase in the initial spray velocity and spray penetration. Meanwhile, the increase in fuel injection pressure also means an increase in the pressure and mass of compressed air in the premixed

chamber, so the total kinetic energy released when all compressed air bubbles expand and burst will increase. Since the mass of fuel in the premixed chamber remains basically unchanged, the kinetic energy density of the fuel will increase, thus increasing the spray width. Therefore, compared with the spray under the reference conditions, the spray under high fuel injection pressure expands significantly in axial and radial directions.

Figure 19(c) shows the spray shape at high fuel temperature (358 K). On the one hand, the increase in fuel temperature increases the density of the fuel-air mixture in the premixed chamber. According to Formula (2), the initial spray velocity will decrease, which means that the spray penetration will decrease. On the other hand, the increase in fuel temperature reduces the mass of compressed air in the premixed chamber, which decreases the total kinetic energy released when all compressed air bubbles expand and burst. Since the mass of fuel in the premixed chamber increases as fuel temperature increases, the kinetic energy density of the fuel will decrease. The spray width will also decrease. Therefore, compared with the spray under the reference conditions, the spray at high fuel temperature shrinks slightly in axial and radial directions.

The spray shape under long fuel injection duration (10.0 ms) is shown in Figure 19(d). The increase in fuel injection duration causes an increase in the density of the fuel-air mixture in the premixed chamber. According to Formula (2), the initial spray velocity will decrease; hence, the spray penetration will decrease. In addition, the mass of fuel in the premixed chamber also increases as fuel injection duration increases. Since the total kinetic energy released by compressed air bubbles is basically unchanged, the kinetic energy density of the fuel will decrease. This means that the

FIGURE 19: Continued.

FIGURE 19: Comparison of spray shapes under different air-assisted injection control parameters ($t = 2.5$ ms).

spray width will decrease. Therefore, compared with the spray under the reference conditions, the spray under long fuel injection duration shrinks in axial and radial directions.

3.5. Comparative Study. In previous works, most of scholars studied the air-assisted spray characteristics under low fuel injection pressures (below 0.8 MPa) due to the high atomization quality of the AAFI system under this pressure level [25,

26]. They found that as the fuel injection pressure increases from 0.6 MPa to 0.8 MPa, the spray penetration and penetration growth rate both increase significantly. Few people investigated the air-assisted spray characteristics under high fuel injection pressures (over 0.8 MPa). However, as the AAFI system is integrated into the spark ignition two-stroke aviation piston engine, the low fuel injection pressure forces the AAFI system to inject fuel before the exhaust port

FIGURE 20: The spray development of the four test conditions during the fuel-air mixture injection duration.

is completely closed and part of the fuel is directly discharged without being burned, which ultimately leads to the high fuel consumption of the AAFI engine.

An effective way to solve this problem is to increase the fuel injection pressure of the AAFI system, so it is necessary to fully understand the air-assisted spray characteristics under higher fuel injection pressure. In this study, the spray characteristics under a wide range of fuel injection pressures were considered. The experimental results show that as the fuel injection pressure increases from 0.8 MPa to 1.0 MPa, the spray penetration increases significantly, but the penetration growth rate increases at a slower rate than earlier. The radial spread of the spray is more obvious. Hence, a moderate increase in fuel injection pressure will not significantly increase the risk of wall impingement. It is feasible to reduce the fuel consumption of the AAFI engine by appropriately increasing the fuel injection pressure.

At present, there are few studies related to the effects of fuel temperature on the air-assisted spray characteristics, and these studies mainly focus on gasoline and high temperature [23, 24]. No researchers have studied the air-assisted

spray characteristics at low temperatures, which greatly affects the design of the cold start control strategies of the AAFI system. This work investigated the air-assisted diesel spray characteristics at multiple temperatures, it is found that the penetration and width of the air-assisted diesel spray at low fuel temperature (268 K) are slightly larger than that at room temperature. Therefore, heating the AAFI system under low temperature condition does not help the spread of air-assisted spray in the cylinder. This finding may provide a reference for the design of the control strategies of the AAFI diesel engine.

In addition, discussions on the penetration and width of air-assisted spray in previous works are insufficient. Researchers generally believed that the difference between the mixture injection pressure and the ambient pressure is the main parameter that affects the spray penetration [27], and the air/fuel ratio affects the spray width [22]. In this work, after analyzing the experimental results of different test conditions, three key parameters that directly affect the penetration and width of air-assisted spray were determined, which helps people understand the atomization mechanism of AAFI systems.

4. Conclusions

In this study, visualization measurements were undertaken to analyze the effects of main injection control parameters on the air-assisted spray characteristics. Compared with previous works, the spray characteristics under high fuel injection pressure or low fuel temperature were considered. Three key parameters that directly affect the spray characteristics were obtained. The main findings can be summarized as follows.

- (1) As the fuel injection pressure increases from 0.7 MPa to 1.0 MPa, the spray shape changes from “spindle” to “cone,” both the spray penetration and spray width increase significantly. An appropriate increase in the fuel injection pressure of the AAFI engine can help to achieve a uniform mixing of fuel and air in the cylinder
- (2) As the fuel temperature increases from 268 K to 358 K, “protrusions” appear on the edge of the spray, the spray penetration and spray width decrease slightly. The change of fuel injection duration has little effect on the spray shape. The spray penetration and spray width decrease with an increase in fuel injection duration from 4.0 ms to 10.0 ms. Therefore, heating the fuel system or increasing the fuel injection pulse width does not help the spread of air-assisted spray in the cylinder
- (3) The penetration of the air-assisted spray is mainly affected by the difference between the fuel-air mixture injection pressure and the ambient pressure, as well as the density of the fuel-air mixture in the premixed chamber, while the width of the air-assisted spray is mainly affected by the kinetic energy density of the fuel

Data Availability

The spray image, spray penetration, spray width, and spray diffusion area data of all cases used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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