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Spray and droplets characteristics of air assisted nozzle under extreme low fuel temperature

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Abstract: To extend the range of unmanned aerial vehicles (UAVs), internal combustion engines using aviation kerosene are utilized because of its high efficiency and power density. The air assisted nozzle are used in the engines of UAVs due to the requirement of light weight. But the extreme low temperature at high altitude pose a great challenge to the air assisted nozzle because of the high viscosity and low volatility of fuel under low temperature. In this paper, a cryogenic fuel injection system coupled with an air assisted nozzle are utilized to realize the injection under low fuel temperature down to – 55 °C. The high-speed imaging and Phase Doppler Particle Analyzer (PDPA) technologies are employed to analyze the spray and droplets characteristics. Results showed that large visible droplets come out of the nozzle under low temperature, indicating the incomplete breakup inside the nozzle. The Sauter mean diameter (SMD) significantly increase from 14 μm to 25.4 μm with the fuel temperature decrease from 25°C to – 55°C, leads to deterioration in atomization and evaporation. Furthermore, increasing assisted air injection pressure and duration can reduce the large droplets and improve the atomization. Results indicate that eliminating the large visible droplets is a key issue to improve the atomization performance. The design of fuel storage grooves or threads on the inside surface of the nozzle may reduce the fuel accumulation in the exit of the nozzle and reduce the incomplete breakup.

Key words: air assisted nozzle; low fuel temperature; spray characteristics; droplets measurement; unmanned aerial vehicles (UAVs)

Abbreviations: ASOI: After start of injection; SMD: Sauter mean diameter; UAV: unmanned aerial vehicle.

1 INTRODUCTION

The internal combustion engine is a highly efficient and high power density power source. Due to the widespread use of the unmanned aerial vehicles (UAV), internal combustion engines are also commonly used as a power source for UAVs to extend their range. In recent years, aviation kerosene can be used as the fuel for

UAVs [1]. Considering the need for lightweight engines for UAVs, the air assisted nozzle is used for fuel injection in engines. However, the low-temperature environment at high altitude pose a great challenge to the atomization of the air assisted nozzle, due to the high viscosity and low volatility of kerosene in low fuel temperature. Therefore, it is particularly important to investigate the spray characteristics and atomization of the entrained-air injection system under low-temperature conditions.

For the study of spray characteristics and atomization, Boretti et al. investigated the spray and mixing using experiments and simulation [2]. The results showed that the Sauter Mean Diameter (SMD) is less than 10 μm, and adequate fuel and air distribution in the combustion chamber. Wu et al. using high-speed imaging and Phase Doppler Particle Analyzer (PDPA) in a constant volume chamber [3]. The study finds flash boiling enhances atomization in air-assisted injectors by increasing spread and reducing droplet size, while longer fuel injections duration lead to larger droplets by reducing spray velocity. Hu et al. investigated the spray characteristics of kerosene and gasoline in air-assisted fuel injection systems, revealing that varying ambient pressures influence spray angle of kerosene, while the spray angle of gasoline remain unchanged [4]. Wu et al. investigated kerosene sprays of air assisted nozzle in varying ambient temperature and pressure conditions [5]. Results showed that penetration decreases with higher pressure but increases with temperature, due to the change of density. Yu et al. studied the air assisted kerosene sprays using high-speed imaging and PDPA [6]. They found that the increase of air flow rate can increase the spray angle and improve the atomization. Pressure et al. tested the spray and combustion of air assisted nozzle [7]. Results indicated that the increase of air flow speed improve the vaporization of fuel and increase the flame intensity. Liao et al. studied the atomization and combustion of air assisted nozzle using numerical simulation [8]. They found that the air flow can increase the turbulence inside the cylinder and improve the vaporization, the knock can be suppressed using the double injections strategies. Zhao et al. studied the inner and outer flow of air assisted nozzle using numerical simulation, indication the fuel and air interactions at the exit of the nozzle dominant the breakup process [9]. Zhao et al. also simulated the SMD of inner and outer flows and compared it with the experiment in room temperature [10]. Results showed that the SMD inside the nozzle is 40 – 60 μm, and decrease to 20 μm in the outer flows. In conclusion, the injection parameters including assisted air pressure, ambient pressure, fuel injection duration and type of fuels greatly affect the spray and droplet characteristics, therefore impact the air and fuel distribution and combustion process. However, the current experiments of air assisted nozzle using kerosene is operated in room temperature. The effect of low fuel temperature on spray and droplets characteristics is not clear.

For the effect of fuel temperature, Pan et al. investigated the fuel film characteristics in fuel temperature ranges from 20 °C to -18 °C [11]. Results showed that the thickness of the fuel film increase with the decrease of fuel temperature. Park et al. explored the spray characteristics of diesel under cold start conditions [12]. Results showed that the injection quantity decreased about 50 % with the fuel temperature decrease from 313 K to 243 K due to the increase of viscosity, the evaporation and fuel and air interactions are also decreased, causing the difficult of cold start. Hwang et al. did further study of the spray and combustion characteristics of diesel injection under cold start conditions [13]. They found that the liquid penetration increase and spray angle decrease with the fuel temperature decrease from 313 K to 243 K, and partial misfire were observed in the cold start condition. Zigan et al. investigated the direct injection of the spark ignition engine, results showed that the decrease of viscosity can increase the flow speed inside the nozzle ,thus increase the liquid penetration and enhance cavitations [14]. Park et al. studied the spray characteristics of diesel with fuel temperature ranges from

60 to 120 °C [15]. Results showed that the injection delay, injection profiles and spray development speed is affected by the change of fuel propertied in varied fuel temperatures. Park et al. studied the spray and droplets characteristics of biodiesel with fuel temperature ranges from 300 to 360 K [16]. Results showed that the increase of fuel temperature increase the evaporation rate of droplets and decrease the number of droplets. Pandey et al. investigated the effect of fuel temperature on biodiesel injections [17], indicating that the increase of fuel temperature can decrease the viscosity and improve the atomization. Kim et al. evaluated the effect of fuel properties on the spray characteristics, indicating that the liquid fuel density, viscosity, vapor pressure, and specific heat had significant impact on liquid penetration [18]. In conclusion, the physical properties of fuel change with the decrease of fuel temperature, resulting in drastic changes in spray and droplets characteristics, which is significant to optimize the combustion in cold start conditions. However, the lowest fuel temperature extended to – 30 °C in current researches, which is not enough for high altitude conditions for UAVs. The effect of fuel temperature on spray and droplets characteristics of kerosene is still not clear.

In summary, low fuel temperatures can deteriorate the atomization of the fuel injection process. However, the spray and droplets characteristics of air assist nozzle using kerosene at extreme low temperatures remain unclear. In this paper, high-speed imaging and Phase Doppler Particle Analyzer (PDPA) technology are utilized to investigate the spray and droplets characteristics of air assisted nozzle using aviation kerosene. A cryogenic injection system is built to realize the low fuel temperature down to – 55 °C, which is same as the environment temperature at altitude of 10000 m. Results indicating that the decrease of fuel temperature significantly increase the SMD, but increasing assisted air injection pressure and duration can reduce the large droplets and improve the atomization.

2 Experimental Setup

2.1 High-speed Imaging with cryogenic injection system

In the presented research, a cryogenic injection system is built, and the schematic diagram of the system is shown in Figure 1. The cryogenic refrigerator outputs the cryogenic medium as cryogenic ethanol, which is divided into two flows, one flows to the heat exchanger to cool the kerosene in the heat exchanger. The other flows to the nozzle adaptor to cool the adaptor and the air assisted nozzle. Most low-temperature ethanol and fuel pipes are wrapped with insulations to minimize heat transfer losses. The structure of the air-assisted nozzle is shown in Figure 2. Fuel and air are injected and mixed in the mixing chamber. After that the fuel-air mixture flow down through the channel around the needle to the nozzle outlet. High-velocity air flow is generated in the O-ring shaped nozzle outlet and break the liquid fuel into small droplets.

In this experiment, RP3 aviation kerosene is used for testing. As shown in Figure 1, the fuel is pressurized by the fuel pump and pumped to the heat exchanger to be cooled by low temperature ethanol. The cooled fuel flows through the pipeline to the air chuck nozzle, which is installed with thermocouples and pressure gauges to measure the fuel temperature and pressure, and the return fuel from the air assisted nozzle flows back to the tank through the pipeline. The cooling system can cool the fuel to -55°C to reach the requirements of low-temperature experiments. A compressed air cylinder is used to supply air to the air assisted nozzle, and pressure regulators are used to control the air pressure. The air inlet of the constant volume chamber is connected to the atmosphere, and the exhaust pipe is connected to the vacuum pump. The vacuum pump is used to remove the fuel droplets in the constant volume chamber after injections. This experiment uses LED light source and high-speed camera for imaging. A diffuser is placed in front of the optic window to uniformize the image background. The imaging parameters are shown in Table 1. During the test, the fuel pump is keep working to maintain the circulation of fuel, to ensure the efficient cooling in the heat exchanger and the stable of the fuel temperature. The assisted air injection signal is synchronized to the high-speed camera to capture the images of sprays.

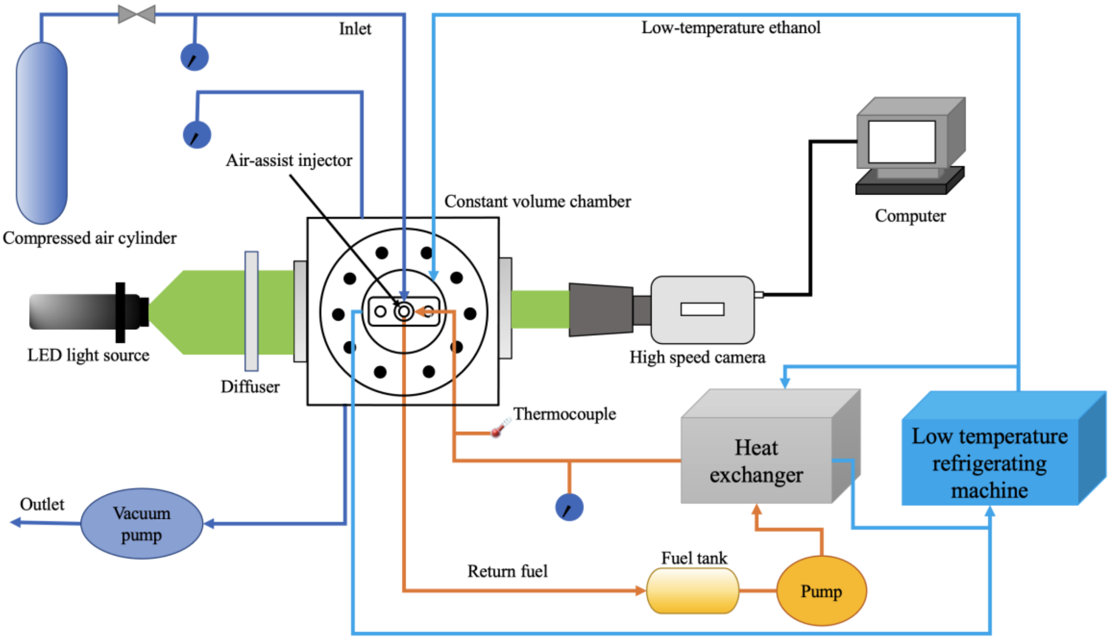


Figure 1 Schematic diagram of the low-temperature injection imaging system

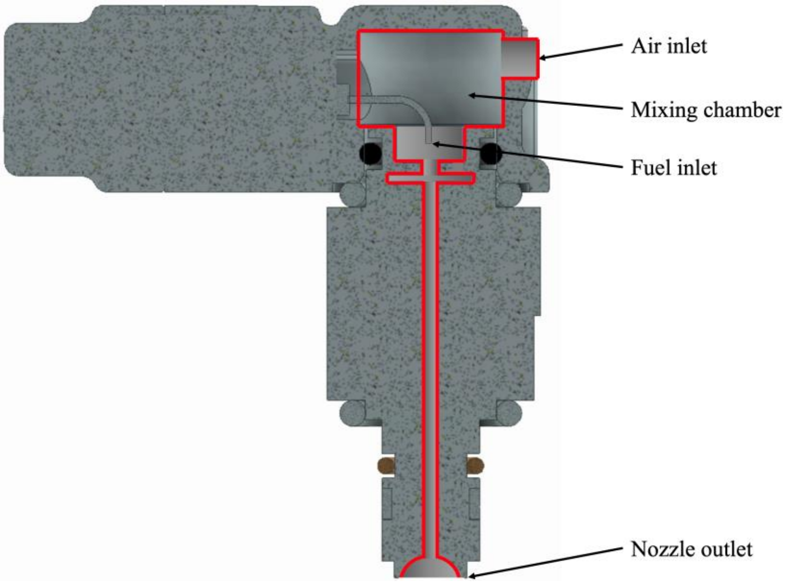


Figure 2 The structure of the air-assisted nozzle

Table 1 Imaging parameters

Items	Parameters
Frame speed (frame/second)	20000
Exposure time (μs)	10
Image resolution (pixel)	1024 x 1024
Pixel size (μm/pixel)	120

2.2 Phase Doppler Particle Analyzer (PDPA) System

The cryogenic injection droplet test system consists of a cryogenic injection system and a PDPA system, illustrated in Figure 3. The PDPA system consists of an argon ion laser, a Bragg unit, a transmitter, a receiver, a PDPA processor and a computer. The laser from the argon ion laser is divided into two beams after passing through the Bragg unit and is transmitted to the transmitter by an optical fiber. The laser light is focused by the lens in the transmitter to form two beams of cross-incidence laser light, forming interference fringes at the intersection point, which is the measurement point. When a droplet passes through the measurement point, the laser light is scattered by the droplet, and the scattered light is received by the receiver and transmitted by the optical fiber to the PDPA processor for analysis, which determines the droplet velocity from the frequency of the scattered light and the droplet size from the phase difference of the scattered light in the different sensors. In this experiment, the laser wavelength used was 514.5 nm, and the transmitter and receiver were placed in a 3-dimensional coordinate frame, which controlled the position of the measurement points. The transmitter and receiver were placed at an angle of 110° from each other to receive the strongest scattered light signal. The detailed setup of the PDPA system is same as the previous work [19]. During the test, each measurement point of the sprays is measured by moving the 3-dimensional coordinate frame, which is controlled by the program of computer. The assisted air injection signal is synchronized to the PDPA processor to obtain the droplet data of each injection.

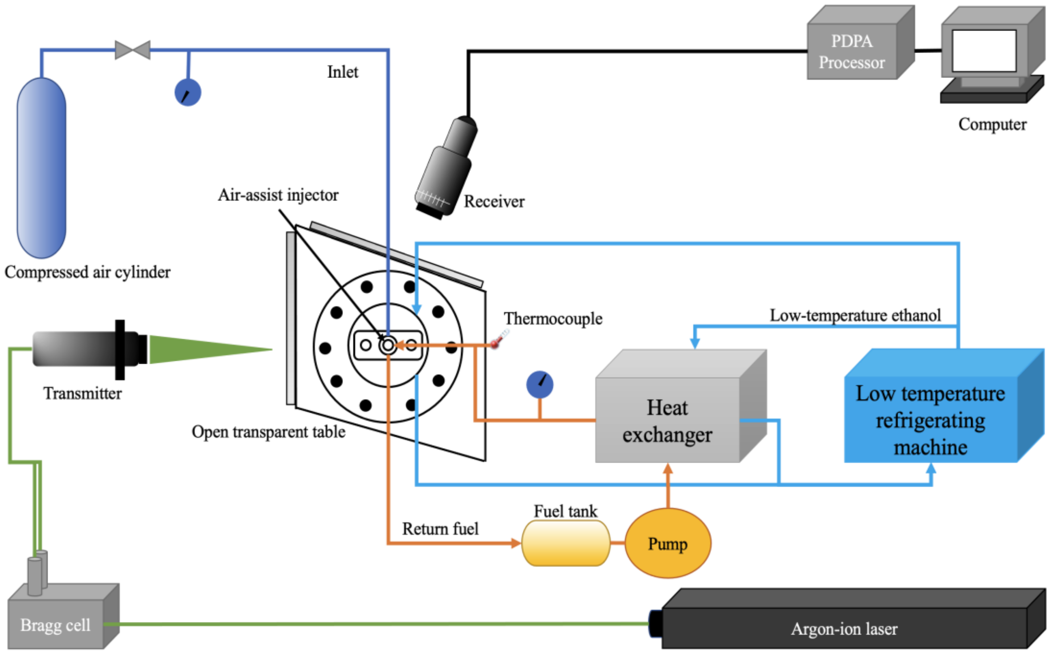


Figure 3 Schematic diagram of cryogenic injection droplet test system

2.3 Experimental Conditions

In order to analyze the spray and atomization of air assisted nozzles under different conditions, experiments are carried out under varied fuel temperature, assisted air injection duration, fuel injection duration and assisted air pressure. The experimental conditions are shown in Table 2. The typical assisted air pressure is 3 – 6.5 bar [9, 10]. The assisted air pressure in the presented paper is set to 3 – 6 bar to exam the effects of low and high pressure on the spray and droplets characteristics. The lowest fuel temperature is decided by the typical cruising altitude of airplanes and UAVs. On the typical cruising altitude of 10000 m, the environment temperature drops to –

55 °C. The viscosity of RP-3 kerosene under low temperature measured by Zhang et al. is shown in Table 3 [20]. The decrease of fuel temperature significantly increases the viscosity. The kinetic viscosity of kerosene increase about 5 times with the fuel temperature decrease from 20 °C to – 30 °C.

Table 2 Experimental conditions

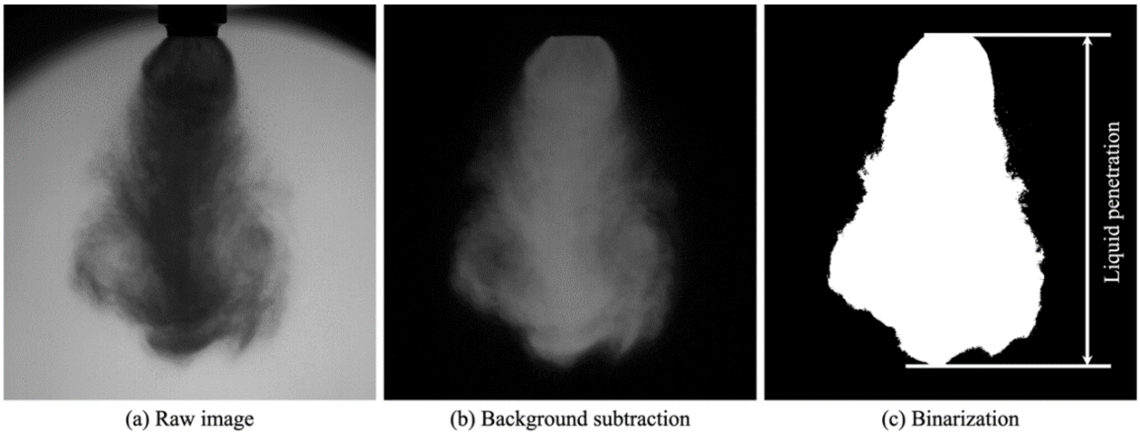
Parameters	Ranges
Assisted air pressure (P_{air}, bar)	3, 4, 5, 6
Assisted air injection duration (t_{air}, ms)	1.5, 2.5, 3.5
Fuel injection pressure (P_{fuel}, bar)	5.5, 6.5, 7.5, 8.5
Fuel injection duration (t_{fuel}, ms)	6, 12
Fuel temperature (T_{fuel}, °C)	25, -45, -55
Pressure difference (P_{fuel} - P_{air}, bar)	2.5
Fuel and air interval (ms)	10
Ambient pressure (bar)	1
Ambient temperature (°C)	25
Assisted air temperature (°C)	25

Table 3 Viscosity of RP-3 kerosene under low temperature [20]

Temperature (°C)	Kinematic viscosity (mm^2/s)
-30	6.7089
0	2.5451
20	1.7688

2.4 Image and Data Processing

The images are processed with background subtraction and binarization to calculate the liquid-phase penetration of the spray using MATLAB codes. The method of image processing is same as the previous work [21]. As shown in Figure 4, the raw image is subtracted by the background to eliminate extraneous features such as the nozzle and window boundary. After that the image is binarized using adaptive threshold. The liquid penetration is measured using the binarized image.



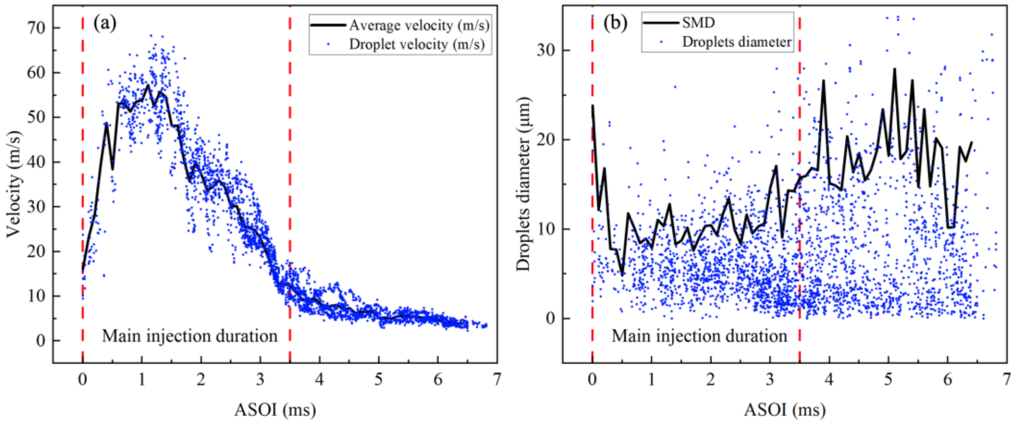
(a) Raw image (b) Background subtraction (c) Binarization

Figure 4 Image processing

For the post processing of the PDPA experiment. The droplet velocity and diameter distribution obtained from a single measurement point are shown in Figure 5, the measured droplet velocity first rises and then decreases after start of injection (ASOI). The low velocity droplets after 3.5 ms are suspended droplets, which do not belong to the main injection duration. When calculating the Sauter mean diameter (SMD), the suspended droplets are not considered, only the droplets in the main injection duration is included into calculations. The SMD and average velocity are calculated using Eq. 1 and 2.

$$SMD = \frac{\sum_{i=1}^{n} d_i^3}{\sum_{i=1}^{n} d_i^2} \qquad \text{Eq. (1)}$$

$$V = \frac{\sum_{i=1}^{n} v_i}{n} \qquad \text{Eq. (2)}$$



P_{fuel} = 8.5 bar, P_{air} = 6.0 bar, t_{fuel} = 12.0 ms, t_{air} = 3.5 ms, T_{fuel} = 25 °C, radial distance (x) = 5 mm, axial distance (z) = 30 mm

Figure 5 Droplets velocity and diameter distribution, (a) velocity, (b) diameter

3 RESULTS and DISCUSSIONS

3.1 Spray Characteristics

3.1.1 Effects of Fuel Temperature

The effect of fuel temperature on spray morphology is shown in Figure 6 and Figure 7. The spray gradually becomes sparser as the fuel temperature decreases, which is caused by the increase of fuel viscosity that reduces the fuel flow rate. Large droplets still occur under longer t_{fuel} conditions. Under the lower P_{air} conditions in Figure 6, large droplets come out at the exit of the nozzle under low fuel temperature, indicating the incomplete breakup in the nozzle. The incomplete breakup may cause by high viscosity and serve fuel accumulation in the exit of the nozzle. The effect of fuel temperature on the penetration distance is shown in Figure 8. The fuel temperature has a great influence on the liquid penetration, and the penetration distance is lower at low fuel temperatures due to the increase in the viscosity of the fuel which leads to a decrease in the actual amount of fuel injected. The liquid penetration of 6ms t_{fuel} is higher than 12 ms, which is caused by the increase of resistance of fuel. In summary, eliminating the large visible droplets is a key issue to improve the atomization performance. The design of double nozzle structure similar to Boretti's research [2] may suppress the incomplete break inside the nozzle. The design of fuel storage grooves or threads on the inside surface of the nozzle may also reduce the fuel accumulation in the exit of the nozzle and reduce the incomplete breakup.

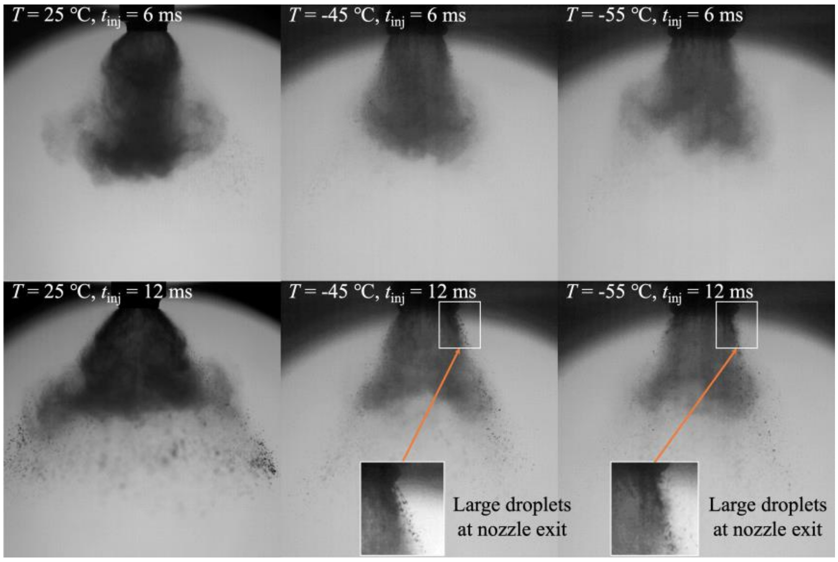


Figure 6 Effect of fuel temperature on spray morphology, P_{air} = 5 bar, t_{air} = 2.5 ms, ASOI = 1.5 ms

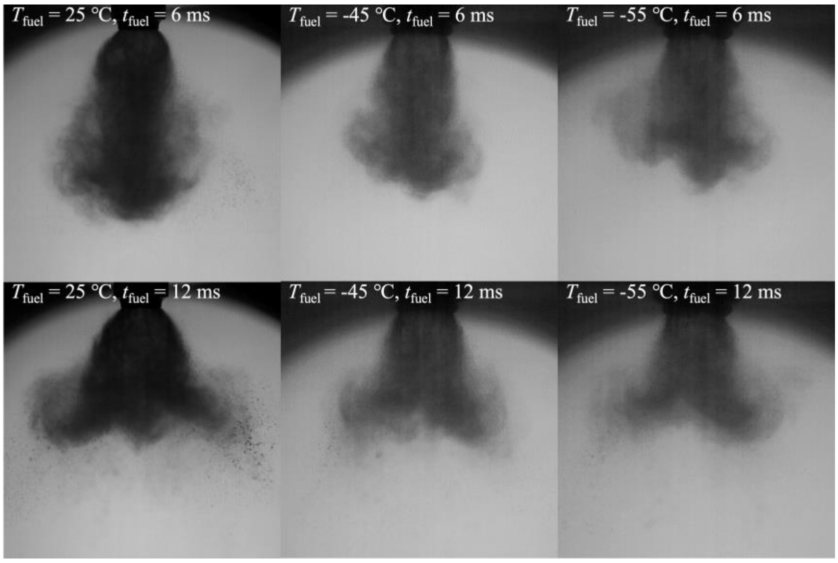
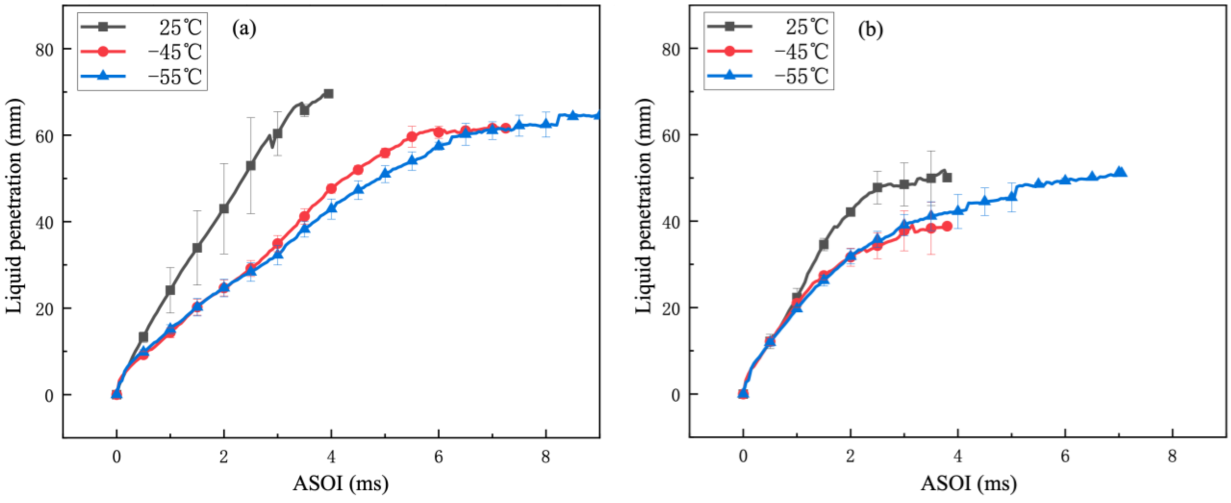
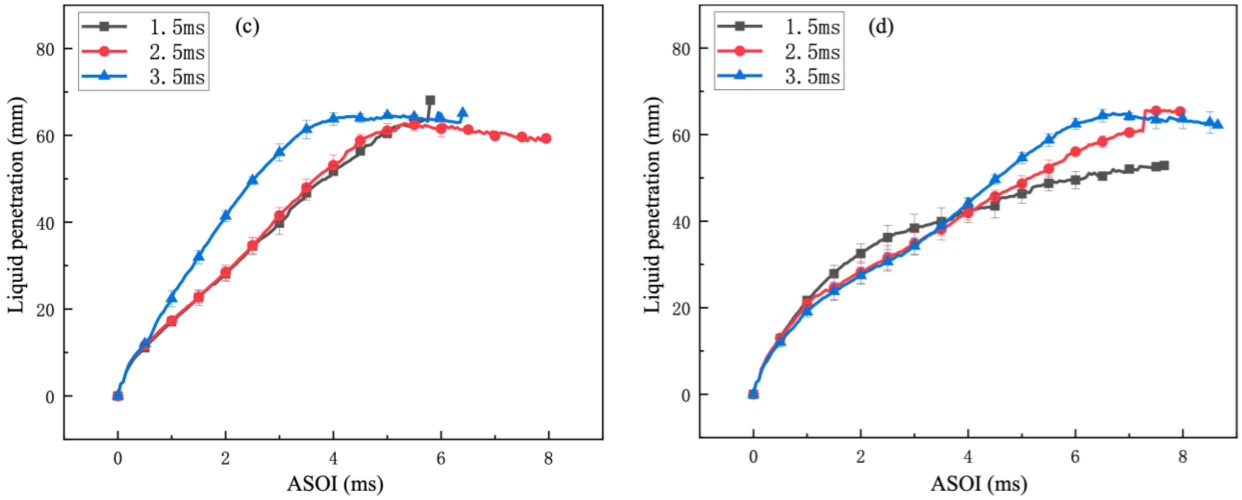


Figure 7 Effect of fuel temperature on spray morphology, P_{air} = 6 bar, t_{air} = 2.5 ms, ASOI = 1.5 ms



(a) P_{air} = 5 bar, t_{fuel} = 6 ms (b) P_{air} = 5 bar, t_{fuel} = 12 ms



(c) P_{air} = 6 bar, t_{fuel} = 6 ms (d) P_{air} = 6 bar, t_{fuel} = 12 ms

Figure 8 Effects of fuel temperature on liquid penetration,

3.1.2 Effects of Assisted Air Pressure

The effects of assisted air pressure (P_{air}) on spray morphology at low fuel temperature conditions are shown in Figure 9.When P_{air} equal to 3 bar, some large droplets occur due to the high viscosity of kerosene in low temperature, indicating the incomplete breakup of fuels. With the increase of assisted air pressure, the large droplets are gradually reduced, and the atomization are improved. The effect of P_{air} on liquid penetration at low temperature is shown in Figure 10, with an overall higher penetration distance at high P_{air}.

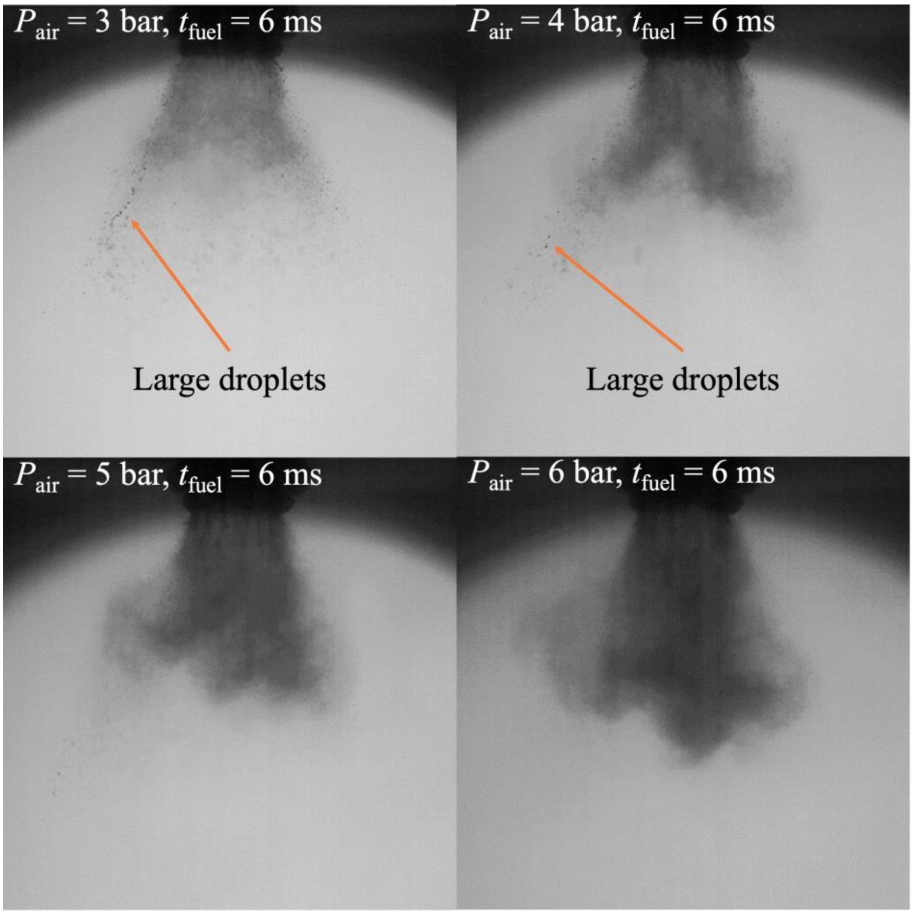


Figure 9 Effects of assisted air pressure on spray morphology at low fuel temperatures of – 55 °C

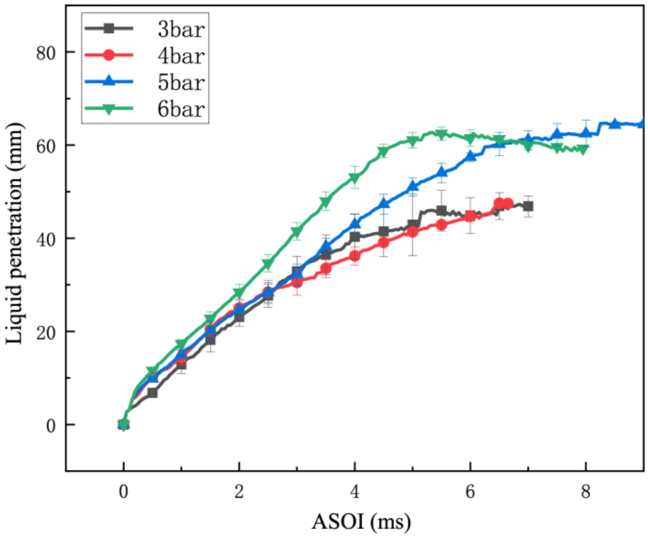


Figure 10 Effects of assisted air pressure on liquid penetration at low fuel temperatures of -55 °C

3.1.3 Effects of Assisted Air Injection Duration

Under the fuel temperature of -55 °C, the effect of assisted air injection duration (t_{air}) on spray morphology is shown in Figure 11. Increasing the t_{air} can basically eliminate the large droplets in cases of longer fuel injection duration (t_{fuel}). The effect of jet pulse width on the penetration distance is shown in Figure 12. The effect of t_{air} on the liquid penetration is not obvious. The penetration distance grows lower under 6ms jet pulse width, indicating more amount of fuel results in large suppression at the nozzle exit.

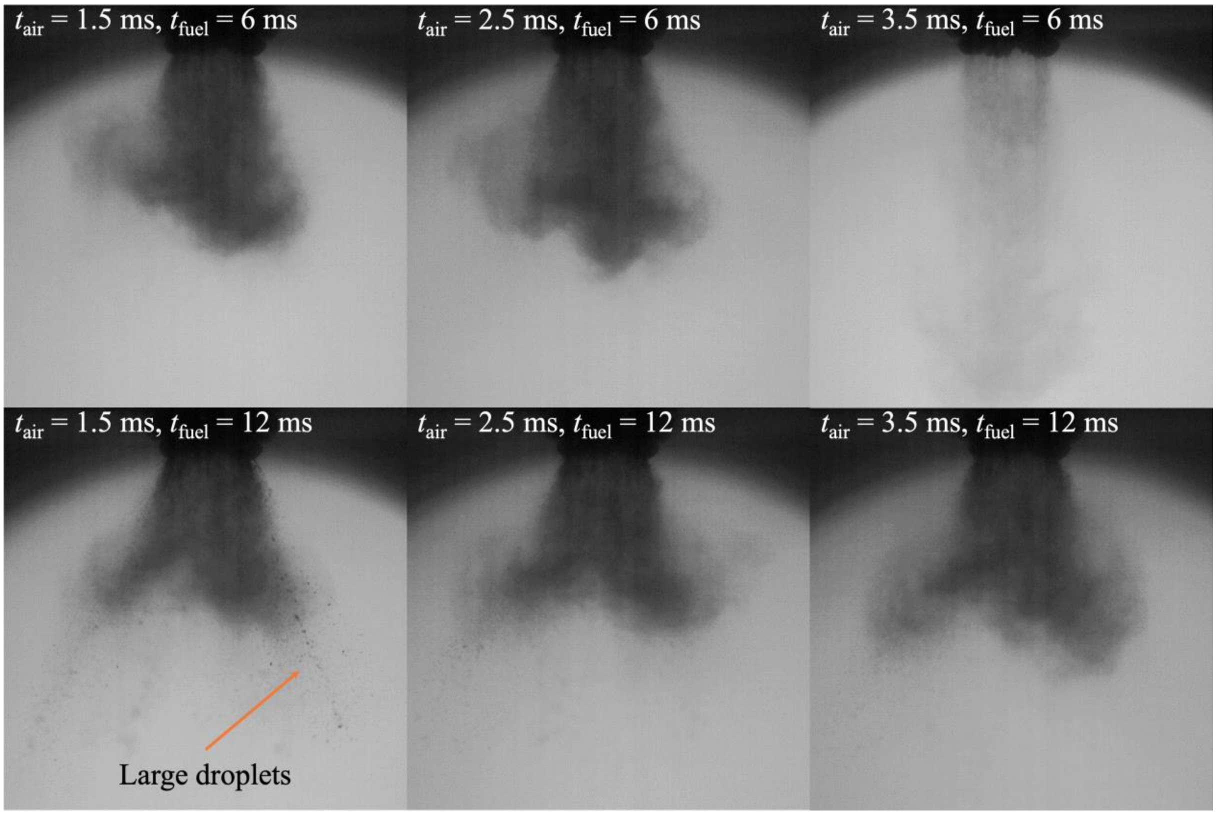
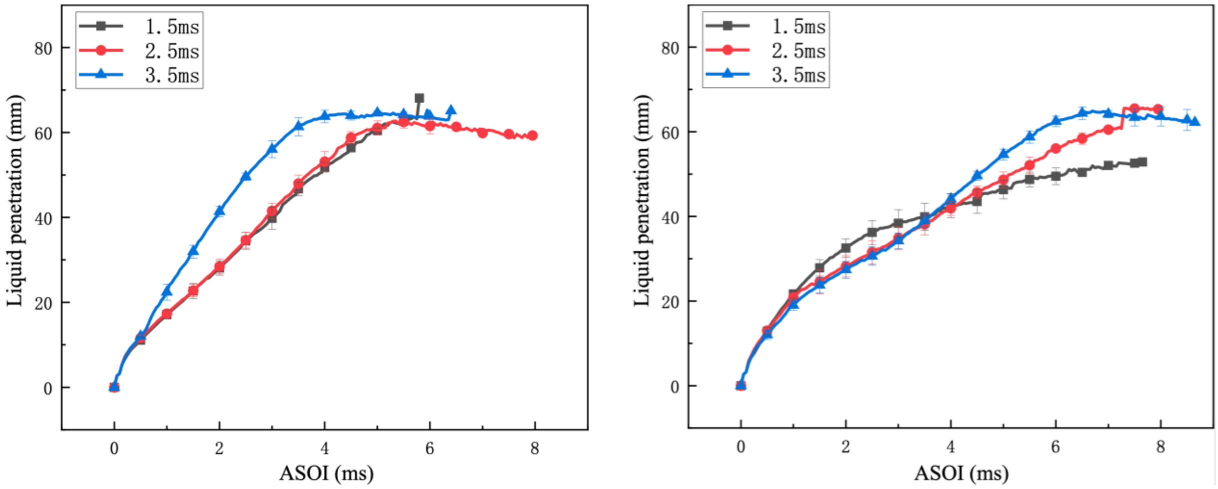


Figure 11 Effects of assisted air injection duration on spray morphology at low temperature, P_{air} = 6 bar, ASOI = 1.5ms, T_{fuel} = - 55 °C

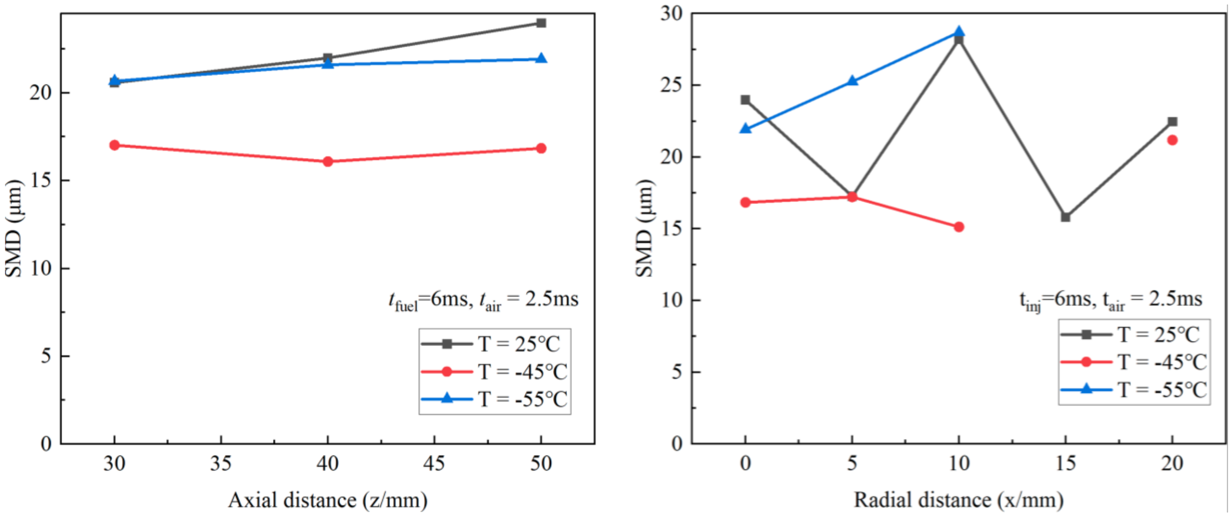


(a) t_{fuel} = 6 ms (b) t_{fuel} = 12 ms

Figure 12 Effects of assisted air injection duration on liquid penetration, P_{air} = 6 bar

3.2 Droplets Characteristics

The distribution of SMD at different temperatures is shown in Figure 13. The SMD is analyzed using the average values due to the non-uniform distribution of droplet sizes.



(a) t_{fuel} = 6 ms (b) t_{fuel} = 12 ms

Figure 13 SMD spatial distribution, P_{air} = 3 bar, t_{air} = 2.5 ms

3.2.1 Effects of Fuel Temperature

Figure 14 shows the effect of fuel temperature on SMD when the assisted air injection duration is 2.5ms. The SMD in room temperature is around 10 μm according to Boretti's research [2], which is similar to the results in the presented paper. However, the SMD significantly increase about 47 % (20.54 μm) when the fuel temperature decreases from 25 °C to – 55 °C. Elevating the fuel temperature can significantly reduce the SMD. The active heating of the fuel supply pipeline and injector is an effective means to promote atomization, but still need to cooperate with the optimization of the assisted air injection pressure and duration to achieve stable atomization effect.

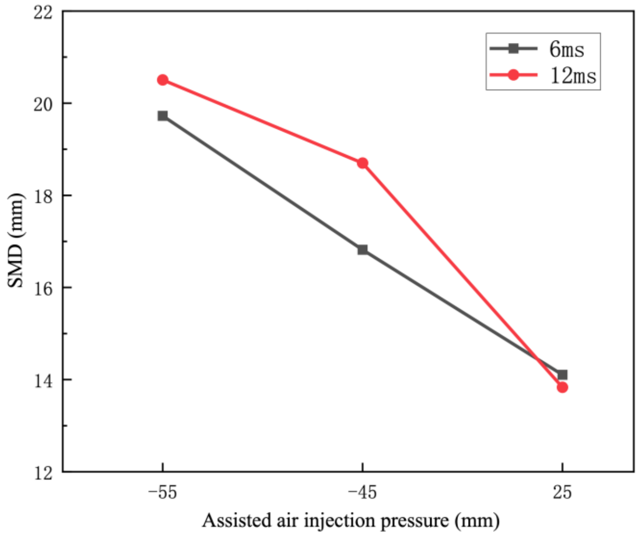


Figure 14 Effects of fuel temperature on SMD, t_{air} = 2.5 ms, P_{air} = 6 bar

3.2.2 Effects of Assisted Air Pressure

Figure 15 shows the effect of jet pressure on the average SMD at 2.5ms jet pulse width. Under -55°C of fuel temperature, the SMD shows an overall increasing trend, and the droplet atomization deteriorated, and on the other hand, the SMD decreases with the increase of the assisted air injection pressure. Droplets with high SMD may appear under very low fuel temperature conditions during the injection process.

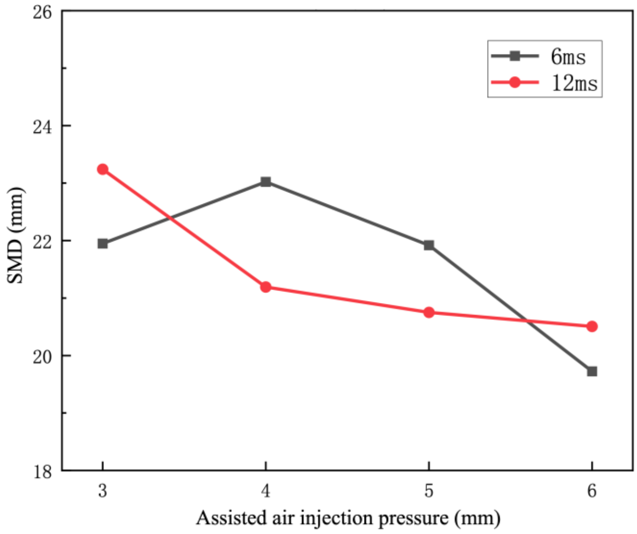


Figure 15 Effects of assisted air injection pressure on SMD, t_{air} = 2.5ms, T_{fuel} = - 55 °C

3.2.3 Effects of Assisted Air Injection Duration

Figure 16 gives the effect of jet pulse width on the SMD under the condition of oil temperature of -55°C. The SMD shows a decreasing trend with the increase of assisted air injection duration in general. It should be noted that, the increase of assisted air injection duration from 2.5ms to 3.5ms has limited effect on SMD reduction, which may be related to the fact that more liquid has already been swept out of the nozzle in the early stage.

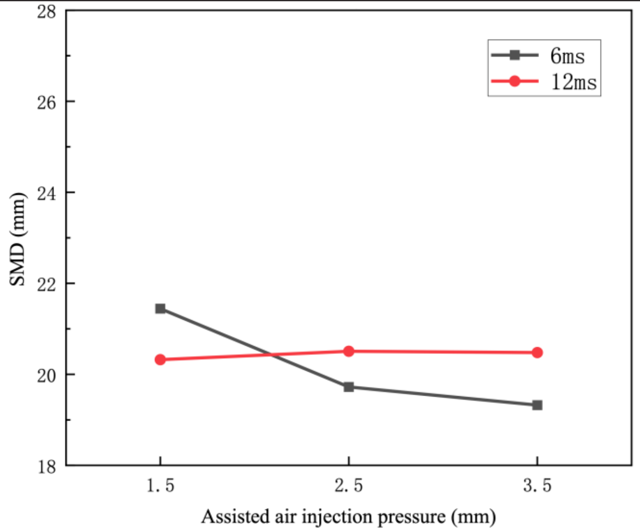


Figure 16 Effect of assisted air injection duration on SMD, t_{fuel} = - 55 °C, P_{air} = 6 bar

4 CONCLUSIONS

The low fuel temperature can significantly impact the spray and droplets characteristics in fuel injection process, which is important for optimize the engines of UAVs at high altitude. In this paper, the spray of air assisted nozzle with fuel temperature as low as -55°C was investigated using high-speed imaging and PDPA technologies. The spray and droplets characteristics under low fuel temperature conditions are analyzed. the main conclusions are as follows:

(1) Large visible droplets come out at the exit of the nozzle under low fuel temperature, indicating the incomplete breakup in the nozzle. The incomplete breakup may cause by high viscosity and serve fuel accumulation in the exit of the nozzle.

(2) Increasing the assisted air injection pressure can reduce large droplets and reduce the SMD in low fuel temperature.

(3) Lowering the fuel temperature will increase the SMD because due to the increase of the viscosity, resulting in the appearance of large droplets with a diameter equal to or larger than 30 μm, resulting in a poor atomization effect.

This paper provides important spray and droplets data under extreme low fuel temperature, which is valuable in engine optimization and simulation verification. The results prompt that eliminating the large visible droplets is a key issue to improve the atomization performance. The design of double nozzle structure similar to Boretti's research [2] may suppress the incomplete break inside the nozzle. The design of fuel storage grooves or threads on the inside surface of the nozzle may also reduce the fuel accumulation in the exit of the nozzle and reduce the incomplete breakup. In future, researches of different fuels and nozzle geometry combined with numerical simulation may reveal the effects of internal flows and improve the low temperature performances.

Compliance with Ethical Standards

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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