

STUDY ON THE ATOMISATION PERFORMANCE OF FUEL ATOMISING SPRAY NOZZLE WITH NON-EQUILIBRIUM PLASMA EXCITATION

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The atomisation performance of fuel nozzles is a key factor affecting combustion efficiency. In this study, an experimental investigation was conducted on the atomisation performance of a plasma-excited fuel atomising nozzle. The effects of air flow rate and discharge voltage on the spray angle and Sauter Mean Diameter were systematically examined. The results demonstrated that increasing the air flow rate and discharge voltage improved the fuel atomisation performance. Compared with the case without plasma excitation, the spray angle was increased by up to 29.24%, and the SMD was decreased by up to 11.95% with plasma excitation. The plasma excitation effect was observed only when the discharge voltage exceeded a certain threshold. Furthermore, the improvement in fuel atomisation performance due to plasma excitation exhibited a limit; beyond a certain level, the atomisation performance remained unchanged with further increase in plasma excitation intensity.

Keywords: Non-equilibrium Plasma; Spray angle; Sauter Mean Diameter; Atomisation

1. Introduction

Fuel atomisation marks the initial stage of the engine combustion process. Effective atomisation increases the specific surface area of the fuel droplets, enhancing fuel-air mixing, shortening the time required for complete combustion, and reducing pollutant emissions. Consequently, improving the fuel atomisation level facilitates more efficient and cleaner engine combustion, contributing to energy conservation, emission reduction, and enhanced combustion efficiency. As a critical component of the combustion chamber, the atomisation performance of the spray nozzle significantly influences its overall performance, including combustion efficiency, stability, outlet temperature field, and exhaust pollution levels[1]. Therefore, investigating nozzle atomisation theory, advancing atomisation technology, improving atomisation performance, and enabling precise control of the spray field are of paramount research importance.

Currently, fuel atomisation nozzles can be categorised into pressure-swirl, pneumatic, and hybrid

atomisers[2]. Numerous scholars have conducted extensive research on the structural design and atomisation performance of these nozzles. Among them, Chen et al.[3] proposed a combined duplex atomizer with an air cyclone and experimentally investigated the effect of auxiliary atomizing air on its atomization characteristics. The results indicated that the fuel flow rate and atomization quality of the centrifugal nozzle could be independently controlled using a small amount of auxiliary air. Chen et al.[4] employed the Volume of Fluid (VOF) method with adaptive mesh refinement, combined with experiments, to study the atomisation characteristics of RP-3 and RP-5 aviation kerosene in a centrifugal nozzle. They analysed the effects of fuel physical properties and flow rate on liquid film fragmentation, gas-liquid two-phase distribution, and the size and velocity distributions of droplets throughout the flow field. Shi et al.[5] utilised a Mie scattering and PLIF laser measurement system to investigate the atomisation characteristics of a fan nozzle in high temperature, high speed environment. They obtained the variation patterns of fuel trajectory, evaporation distance, and gas-liquid two-phase distribution under different inlet temperatures, inlet Mach numbers, and fuel flow rates, and fitted empirical formulas for the penetration depth. Chen et al.[6] experimentally investigated the influence of jet parameters on transverse jet atomisation, discussed the effects of gas-liquid ratio, nozzle orifice diameter, and transverse air flow rate on the atomisation characteristics of transverse jet of air atomisation nozzles.

Plasma discharge technology[7] is an emerging technology with a wide range of applications. Macheret et al.[8] explored a technique where fuel is injected as a liquid jet into the core flow, and droplets are electrostatically charged using a low-power electron beams, thereby controlling droplet breakup, atomization, mixing, and ignition. This method demonstrates potential for controlling fuel atomization. Matveev et al.[9] presented the development and experimental study of the Plasma Fuel Nozzle (PFN) concept, a promising tool for implementing plasma-assisted combustion in various heat engines. Their work reported on the selection and optimization of the plasma source, consideration and comparison of fuel atomizer options, and the impact on the combustion process parameters. Experiments results indicated that the PFN is an advanced solution for lean burn and low-Btu fuel combustors, STIG cycle turbines, flexi-fuel systems, and gasification units for liquid and gaseous feedstocks. Yang et al.[10] carried out an optical diagnosis of a helium plasma jet using emission spectroscopy and explored the effects of the peak voltage and working gas volume flow rate on the spray cone angle and SMD of the fuel spray. Their results showed that the helium plasma significantly excited the fuel spray field. Khasare et al.[11] numerically simulated the effects of annular plasma actuators mounted on an orifice plate in non-premixed burners. Their results indicated that activating the plasma actuator reduced the spatial mixing defect (SMD) value by an average of 12.75%, demonstrating improved mixing efficiency.

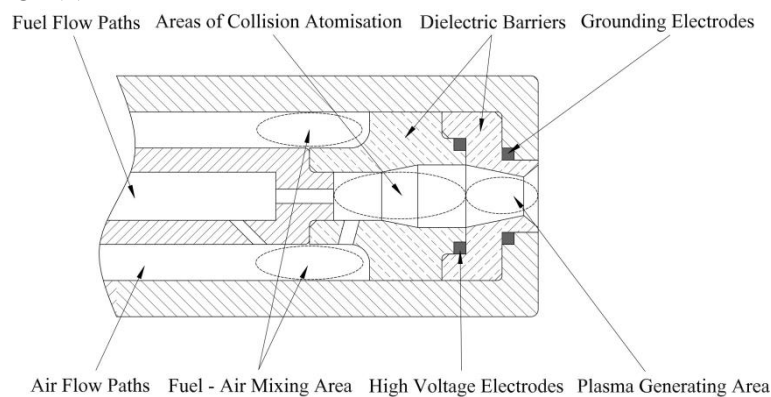
As evidenced by the literature, while significant research has been conducted on fuel atomisation technology, studies combining plasma discharge technology with fuel atomization technology remain limited. This is primarily because plasma-excited fuel atomisation technology necessitates careful consideration of fuel line routing, discharge electrode arrangement, and ensuring effective plasma interaction with the fuel spray, posing significant challenges for atomiser structural design. Therefore, this study designed a plasma-excited fuel atomisation spray nozzle that integrates pneumatic atomisation technology with plasma discharge technology. This design not only enhances fuel atomisation performance but also ensures the stable plasma discharge operation through dual atomisation mechanisms. This paper presents a detailed experimental study on the atomisation characteristics of the plasma-excited fuel atomisation nozzle, investigating the influence of the plasma excitation on fuel atomisation characteristics, thereby providing a reference for research on the plasma-excited fuel

atomisation.

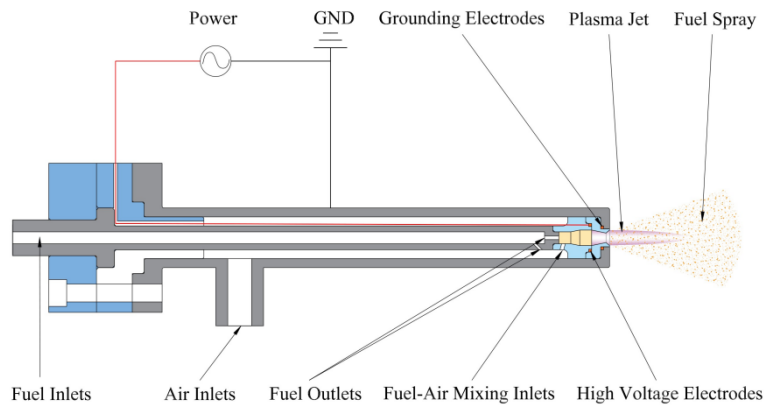
Although current studies on fuel atomisation technology are relatively abundant, research combining plasma discharge with fuel atomisation remains very limited, primarily due to the significant structural design challenges posed by the need for careful consideration of fuel circuit layout, discharge electrode arrangement, and ensuring effective plasma-spray interaction. Addressing this, achieving synergistic coupling of aerodynamic effects, collision atomisation, and plasma excitation within a pneumatic atomisation nozzle provides a novel approach to improving atomisation performance. Systematic experiments analysing the effects of discharge voltage and airflow rate on spray angle and SMD confirm that plasma excitation significantly enhances atomisation, but only above a certain voltage threshold, with performance improvements showing a saturation trend as voltage increases. This finding offers theoretical guidance for understanding plasma-droplet interactions and optimising discharge parameters, while also providing a scientific basis for the engineering application of plasma-excited atomisation technology. The plasma-excited fuel atomisation nozzle developed in this study can be widely applied in aerospace propulsion systems—such as aircraft turbine engines and ramjet engines—to enhance fuel atomisation, thereby improving fuel-air mixing, expanding lean combustion limits, increasing combustion efficiency, shortening combustion duration, and reducing exhaust emissions. Furthermore, this technology contributes to faster transient thrust response, lower exhaust infrared signature, and improved combustion stability, broadening the flight envelope and enhancing aircraft maneuverability and mission reliability. Consequently, this study holds significant importance for achieving highly efficient and clean combustion in aerospace engines and improving their overall performance.

2. Test equipment and test systems

Figure 1(a) illustrates the schematic of the plasma excitation coupled with pneumatic atomisation method proposed in this study. This approach primarily utilises aerodynamic force and collision atomisation for initial fuel atomisation, followed by plasma discharge to excite the initial atomised fuel-air mixture, thereby enhancing atomisation performance. Specifically, fuel is injected from one end outlet and five side outlets into the fuel-air mixing area and the collision atomisation zone, respectively. The two fuel streams mix within the collision atomisation zone to form a homogeneous air-fuel mixture. When this mixture flows through the plasma generation area, plasma is generated by the applied electric field, interacts with the fuel again, and is subsequently ejected from the nozzle outlet. In this experiment, the outlet size of the atomising spray nozzle was designed to be 10 mm, with a spray hole diameter of 2 mm, as shown in Fig.1(b).



(a) Schematic diagram of the coupling of plasma excitation and pneumatic atomisation technology.



(b) Structure of plasma-excited fuel atomisation spray nozzle.

Figure 1. Plasma-excited fuel atomisation spray nozzle.

The fuel atomisation characteristic test system used in this study is depicted in Fig. 2. It mainly consists of the fuel supply system, a gas supply system, a Phase Doppler Particle Analyser (PDPA), and an image acquisition system. The compressed air used was supplied by a compressor and stored in a gas tank, RP-3 aviation kerosene served as the test fuel, and its physicochemical properties are listed in Table 1. The fuel was sprayed directly into the ambient atmosphere under standard atmospheric pressure. The power supply used was a CTP-2000K low-temperature plasma power supply (Nanjing Suman Plasma Technology Co., Ltd), operated at a constant discharge frequency of 9 kHz throughout the experiments.

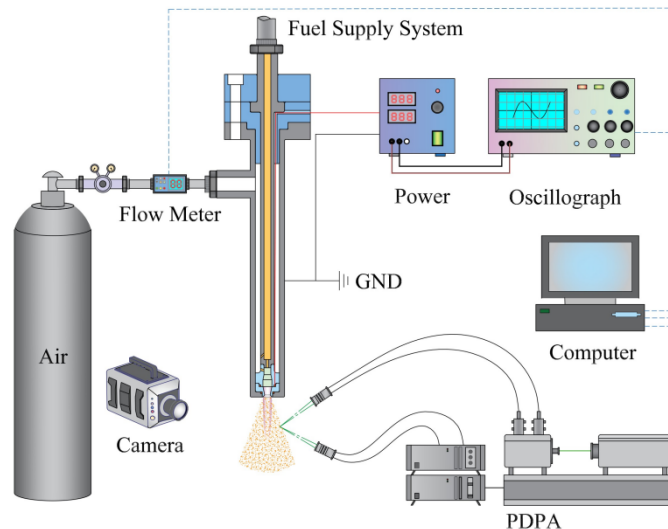


Figure 2. Schematic of the plasma excitation fuel atomisation test system.

Table 1. Physicochemical properties of RP-3 aviation kerosene.

Properties	RP-3
Chemical formula	$C_{10.5}H_{19.6}$
Molecular mass	145
Density [kg/m^3](20°)	806.0
Viscosity [mm^2/s]	$\geq 1.25, \leq 8.0$

Lower heating value [MJ/kg]	≥ 42.8
Auto-ignition temperature [°C]	> 425
C [% mass]	85.97
H [% mass]	13.43
O [% mass]	0
N [% mass]	0

A Sony ZV-E10L camera was employed to capture image of the atomisation field structure. The image processing procedure for spray angle measurement is shown in Fig. 3: (a) the original image of the fuel atomisation process; (b) conversion to a grayscale image; (c) binarisation of the image and extraction of the actual spray boundary; (d) determination of the spray angle based on the extracted boundary. For each operating condition, three images were captured. The spray angle was measured from each image using the described method, and the average value was calculated as the final spray angle for that condition.

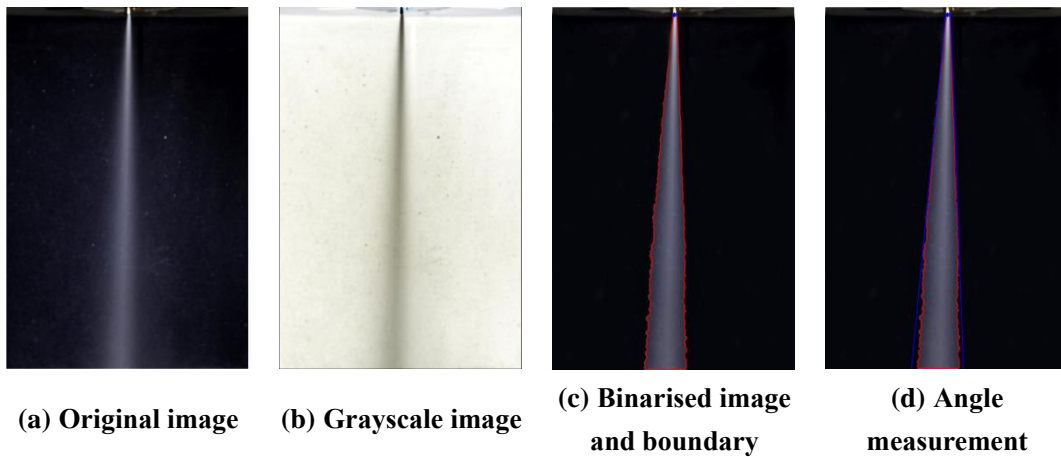


Figure 3. Procedure for spray angle measurement.

The Sauter Mean Diameter (SMD), characterising the ratio of the total droplet volume to the total surface, is a key metric for evaluating liquid atomisation effectiveness in spray combustion studies. As shown in Fig. 4, the PDPA was used to measure and record the droplet size distribution under each operating condition. The measurement positions for SMD are illustrated in Fig. 5. The nozzle orifice was set as the origin, the fuel injection direction as the Y-axis, and the spray diffusion direction as the X-axis. Preliminary measurements indicated that the SMD was low ($< 15 \mu\text{m}$) at $Y > 60 \text{ mm}$. Considering the fuel spray distribution and residence time in practical combustion chamber applications^[2], the cross-section at $Y = 60 \text{ mm}$ downstream of the nozzle orifice was selected. The SMD was measured at three positions along the X-axis: -12 mm , 0 mm , and 12 mm from the centre line, where $X = -12 \text{ mm}$ represents the left boundary of the fuel spray, $X = 12 \text{ mm}$ represents the right boundary, and $X = 0 \text{ mm}$ denotes the spray centre position. Three measurements were taken at each position under identical conditions, and the average value was used as the final SMD for that operating condition.

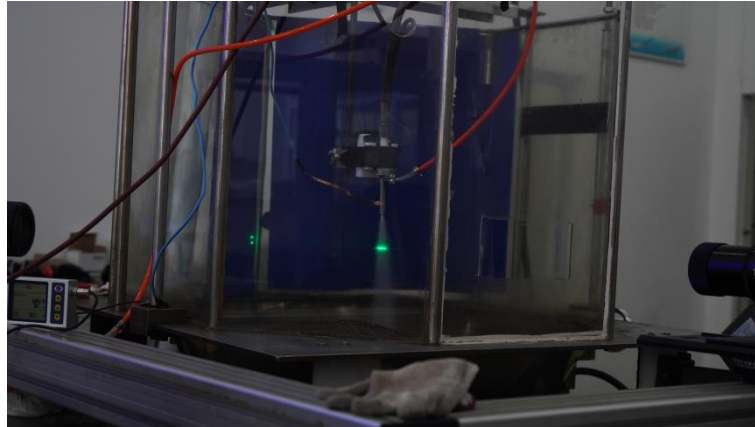


Figure 4. Fuel atomisation particle size measurement using PDPA.

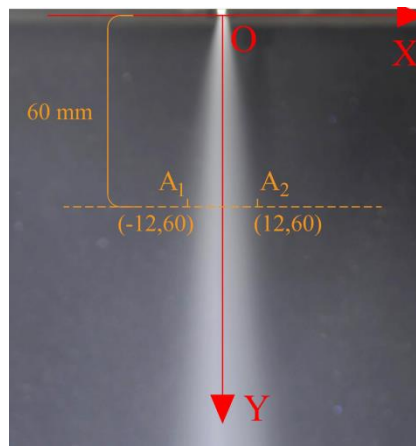


Figure 5. Schematic diagram of SMD measurement positions.

The supply pressure of fuel and air in this experiment are listed in Table 2. The experiment maintained equal fuel and air pressure ($P_{Oil}/P_{Air} = 1$). If P_{Oil}/P_{Air} is too high, fuel may flow back into the air pipe, obstructing the airflow. Reduced airflow affects plasma discharge stability and weakens initial atomisation. Since the plasma excitation effect is closely related to fuel droplet size, this subsequently impacts overall atomisation performance. Conversely, if P_{Oil}/P_{Air} is too low, the strong aerodynamic force improves preliminary atomisation but limits the potential for further enhancement via plasma excitation. Therefore, this study select a reasonable range of operating conditions to investigate the effect of plasma excitation on fuel atomisation characteristics.

Table 2. Plasma-excited fuel atomisation test matrix.

Parameter	Symbol	Numerical value
Fuel supply pressure (MPa)	P_{Oil}	0.3, 0.4, 0.5
Air supply pressure (MPa)	P_{Air}	0.3, 0.4, 0.5
Air flow rate (L/min)	Q_{Air}	20, 30, 40
Discharge voltage (kV)	U	1.35, 1.50, 1.65, 1.80, 1.95, 2.10

3. Results and discussion

3.1. Trends in spray angle of the atomizing nozzle

3.1.1. Effect of air flow rate on spray angle

Figure 6 shows the effect of air volume flow rate on the spray angle at a discharge voltage of 0 kV and $P_{Oil} = P_{Air}$. The spray angle increases with increasing Q_{Air} at the same supply pressure. This is attributed to the enhanced aerodynamic force acting on the fuel liquid column and the increased flow velocity in the fuel-air mixing channel, which intensified the collision atomisation effect in the collision atomisation region. The combined influence of these effects led to a significant improvement in the spray angle with increasing Q_{Air} .

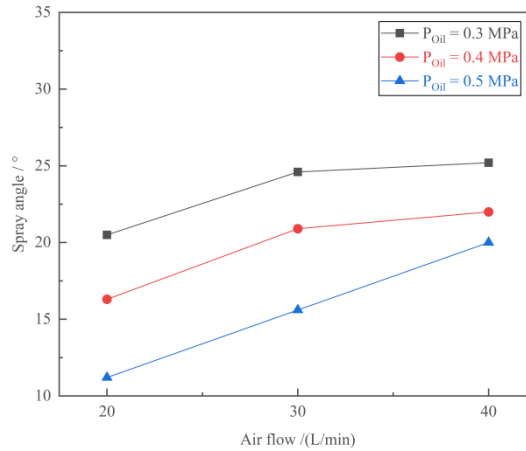
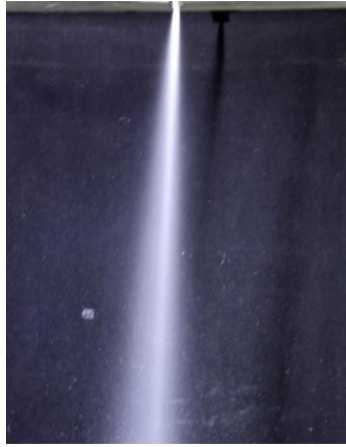


Figure 6. Effect of air flow rate on the spray angle at different operating conditions ($U = 0$ kV).

Furthermore, the enhancement of the spray angle due to increasing Q_{Air} became more pronounced as P_{Oil} increased. This is evident from the steeper slope of the curve at $P_{Oil} = 0.5$ MPa compared to that at $P_{Oil} = 0.3$ MPa. This study suggests that at higher supply pressures, the fuel flow rate increases, consequently requiring a higher air flow rate to achieve optimal atomisation. When the fuel supply pressure is low, the required air flow rate for effective atomisation is correspondingly lower. Further increasing the air flow rate under low fuel pressure conditions still improve aerodynamic and collision atomisation but demands disproportionately higher energy for marginal gains in atomisation performance.

3.1.2. Effect of discharge voltage on spray angle

Figure 7 shows real-time images of the plasma-excited fuel atomisation spray nozzle under different discharge voltages at $P_{Oil} = 0.4$ MPa and $Q_{Air} = 20$ L/min. The increased brightness of Fig. 7(b) compared to Fig. 7(a) is due to the presence of a significant amount of fine fuel mist in the measurement space at $U = 1.95$ kV, which altered the light scattering and thus the image intensity. A clear observation from Fig. 7 is that the spray angle with plasma excitation is substantially large than that without excitation.



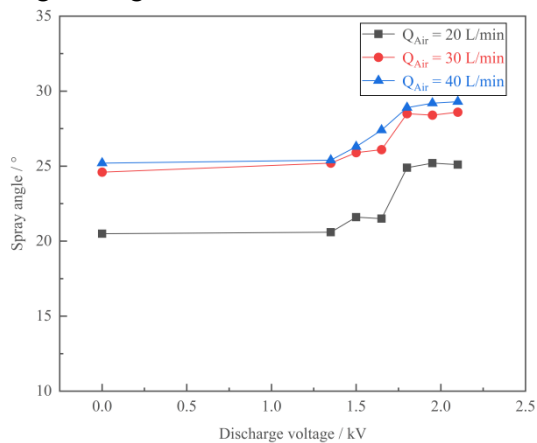
(a) $U = 0$ kV



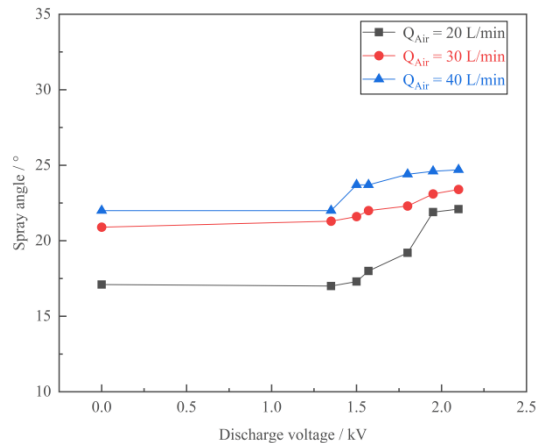
(b) $U = 1.95$ kV

Figure 7. Real image of fuel spray at $P_{Oil} = 0.4$ MPa and $Q_{Air} = 20$ L/min under different discharge voltage.

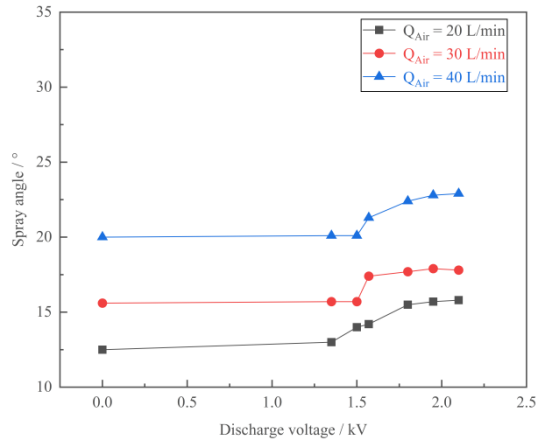
Figure 8 illustrates the effect of discharge voltage on the spray angle at different P_{Oil} . The spray angle exhibited a trend of initial increase, followed by a rapid rise, and finally stabilisation as U increased. The maximum spray angle was observed at $U = 2.1$ kV. Compared to the case without plasma excitation, the maximum increase in spray angle with plasma excitation was 29.24%. When P_{Oil} and Q_{Air} constant, the electron density of the plasma increases with rising U [12], enhancing the energy transfer between the plasma and fuel droplets drives physical breakup and atomisation **Error! Reference source not found.**, energy conversion triggers chemical fragmentation and elevates reactivity[13], while flow diffusion continuously perturbs the fuel-air mixing process **Error! Reference source not found.**. Simultaneously, contributing to the large spray angle. As U continues to increase, fuel atomisation is further enhanced. However, charged particles generated by the plasma discharge move and accumulate on the dielectric layer, creating a reverse electric field that weakens the effective electric field strength acting on the plasma. This counteracting effect diminishes the plasma's promotion of the spray angle at higher voltages. The combination of these factors results in a reduced rate of spray angle increase at high discharge voltage.



(a) $P_{Oil} = 0.3$ MPa



(b) $P_{Oil} = 0.4$ MPa



(c) $P_{Oil} = 0.5 \text{ MPa}$

Figure 8. Effect of discharge voltage on spray angle under different operating conditions.

3.2. Trends in SMD of atomizing nozzle

3.2.1. Effect of air flow rate on SMD

Figure 9 shows the effect of air flow rate on SMD under different operating conditions without plasma excitation. The SMD decreases gradually as the air flow rate increased. The SMD measured at the centre line ($X = 0 \text{ mm}$) was generally higher than the value at $X = -12$ and 12 mm .

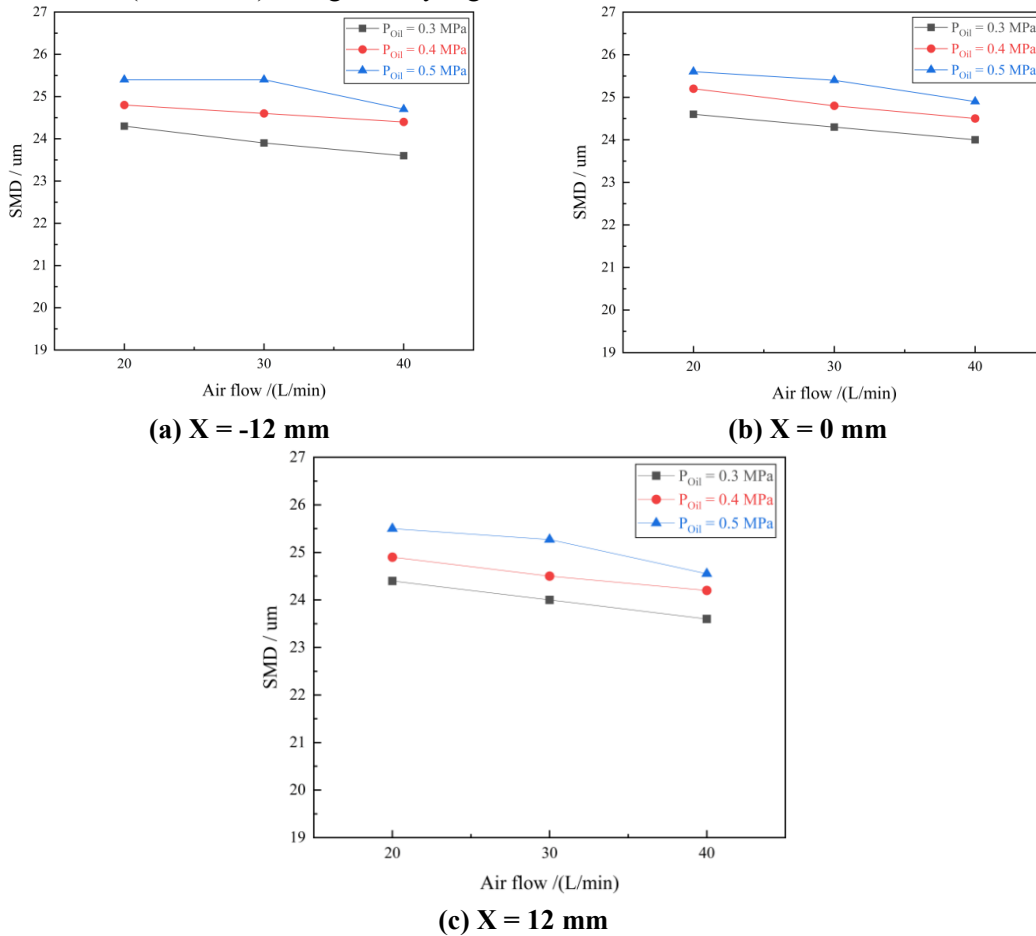
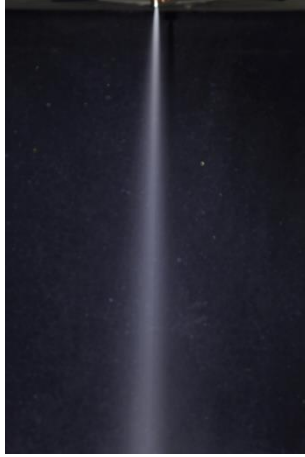


Figure 9. Effect of air flow rate on SMD ($U = 0 \text{ kV}$).

At a constant P_{Oil} , increased air flow enhances the atomisation effect in the collision atomisation zone. Furthermore, higher gas flow increases aerodynamic forces, intensifying the interaction between the fuel-air mixture exiting the nozzle and the ambient air. This leads to a faster breakup rate of fuel droplets at the interface between the spray and the ambient air is weaker compared to the off-center position ($X = \pm 12$ mm), resulting in a lower degree of atomisation and consequently a higher SMD. Figure 10 shows actual fuel spray images at different Q_{Air} values. A substantial amount of fine mist is observed at the spray boundary when the gas flow rate is high, confirming enhanced droplet breakup at the periphery.



(a) $P_{Oil} = 0.5$ MPa, $Q_{Air} = 20$ L/min



(b) $P_{Oil} = 0.5$ MPa, $Q_{Air} = 40$ L/min

Figure 10. Spray images illustrating the effect of air flow on atomisation and SMD.

3.2.2. Effect of discharge voltage on SMD

Figure 11 shows the variation of SMD with discharge voltage at $Y = 60$ mm under different operating conditions. The SMD initially decreased and then stabilised as U increased. Within the research scope of this paper, the minimum SMD was achieved at $U = 2.1$ kV. Compared to the case without plasma excitation, the SMD was reduced by a maximum of 11.95% with plasma excitation. This reduction is attributed to two main factors: firstly, free electrons and charged particles generated by air ionisation interact with fuel molecules under the combined influence of the electric and flow fields during plasma discharge promote the fragmentation of the fuel droplets, while plasma flow and diffusion disturb the fuel liquid column[16], enhancing its turbulence and prompting premature breakup. This plasma-induced fragmentation enhances the atomisation process, leading to a decrease in SMD with increasing U at constant P_{Oil} and measurement position.

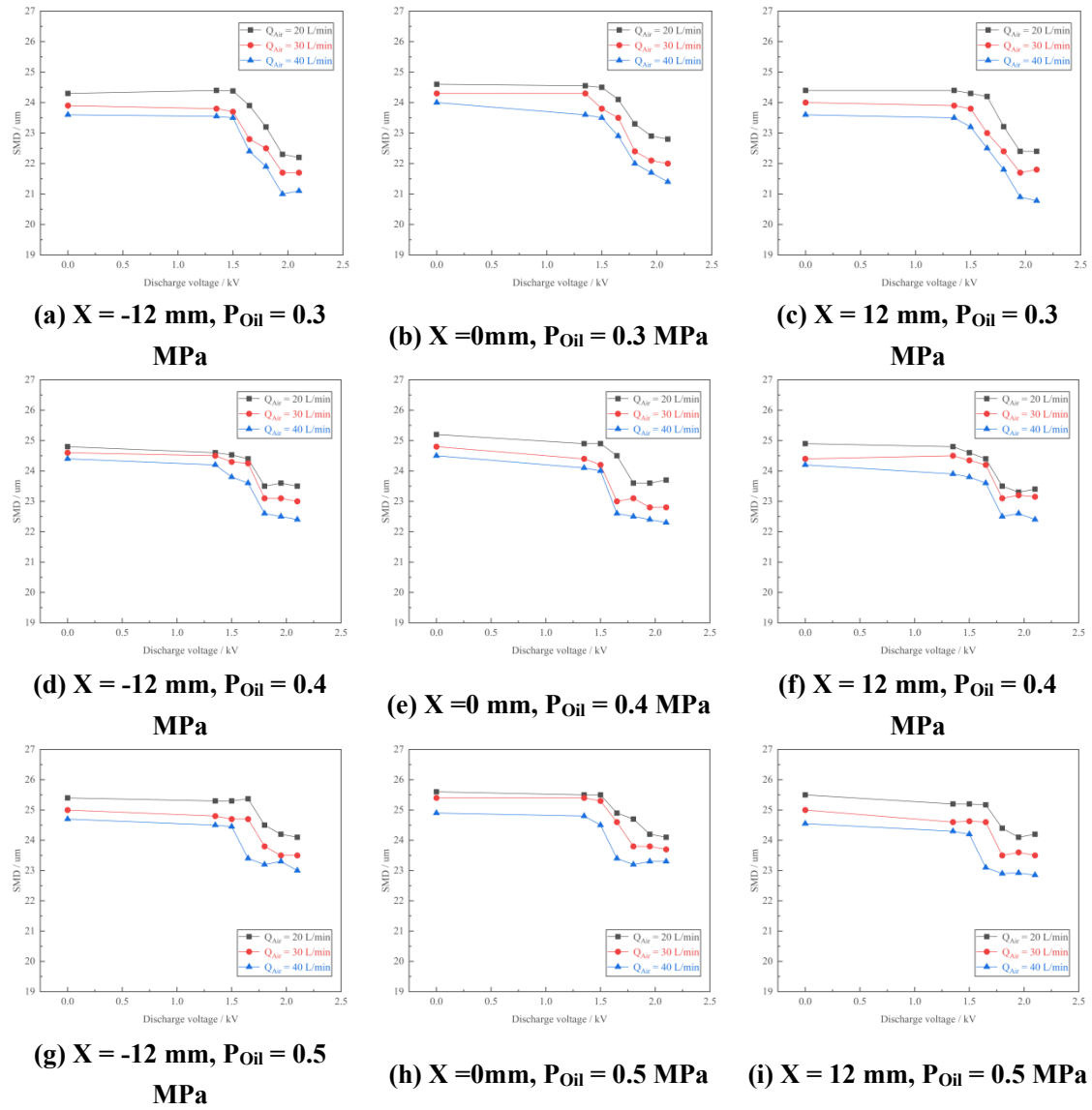


Figure 11. Variation of SMD with discharge voltage different measurement positions and supply pressures.

As evident in Fig. 11, the SMD remains nearly constant when plasma was initially generated ($U = 1.35$ kV). A significant decrease in SMD occurred only when U exceeded a certain threshold (approximately 1.8 kV). As U increased further, the rate of SMD reduction diminished noticeably. This study attributes this phenomenon to the insufficient energy of the nascent plasma to effectively excite fuel atomisation. Once the voltage threshold is surpassed, the plasma interacts with fuel droplets and breaks up the fuel droplets, reducing the SMD. With further voltage increase, although plasma electron density and temperature rise, the decreased SMD means the remaining droplets are smaller and more stable, requiring higher energy for further breakup. The energy provided by the plasma excitation eventually becomes insufficient to maintain the same rate of droplet fragmentation, leading to the observed saturation in SMD reduction.

Combining Fig. 8 and Fig. 11, the effects of plasma discharge voltage on the spray angle and SMD were respectively investigated. The results demonstrated that, compared with the case without plasma excitation (0 kV), the variations in fuel spray angle and SMD were marginal, or even imperceptible

under certain operating conditions, at a discharge voltage of 1.35 kV. However, when the discharge voltage reached 1.65 kV, significant improvements were observed in both the fuel spray angle and SMD. This indicates that the excitation effect on fuel droplets requires a minimum discharge power/energy and is not present immediately upon plasma initiation.

In summary, plasma excitation significantly enhances fuel atomisation performance. However, a noticeable change in SMD requires the discharge voltage to exceed a specific threshold. Although plasma excitation reduces SMD, the SMD does not decrease indefinitely with increasing discharge voltage but rather decreases initially and then stabilises.

Although this study achieved significant experimental results in plasma-excited fuel atomisation and revealed the influence patterns of discharge parameters on atomisation characteristics, there are still the following deficiencies in terms of research depth and completeness: First, in terms of mechanism explanation, the article repeatedly mentions the "interaction between plasma and fuel droplets," but fails to deeply reveal the microscopic physical processes of this interaction through more refined optical diagnostics or numerical simulation methods—for example, the penetration of charged particles on the droplet surface, Coulomb fission effects, and the disturbance mechanism of ion wind to the flow field remain at the qualitative description stage, lacking quantitative mechanical or energy analysis; Second, in terms of research scope, the experiment only selected RP-3 aviation kerosene as the test fuel, and all conditions were carried out in a stagnant environment at normal temperature and pressure, without considering the influence of different fuel physical properties (such as viscosity, surface tension, and conductivity differences) on plasma response characteristics, and also without simulating the high-temperature and high-pressure crossflow environment in actual combustion chambers, which limits the universality and engineering extrapolation of the conclusions to some extent; Finally, in terms of application orientation, although the effect of plasma on improving atomisation performance was demonstrated, the energy consumption of the plasma excitation itself was not evaluated, nor was the improvement in atomisation correlated with downstream combustion characteristics (such as ignition delay, flame stability, and emission formation), which leaves the final engineering value of the conclusion "enhancing atomisation performance" lacking a complete chain of supporting evidence.

4. Conclusions

(1) The atomisation characteristics of a plasma-excited fuel atomising nozzle are affected by both the air flow rate and the discharge voltage.

(2) The spray angle of the plasma-excited fuel atomising nozzle increases and then stabilises with increasing air flow rate. At a constant air flow rate, the spray angle increases and then plateaus with increasing discharge voltage. The SMD decreases and then stabilises with increasing air flow rate. Under constant air flow, the SMD initially decreases, then stabilises, and shows a slight potential to increase at very high voltages with plasma excitation. Compared to operation without plasma excitation, plasma excitation can increase the spray angle by up to 29.24% and reduce the SMD by up to 11.95% .

(3) The effect of the discharge voltage on the atomisation characteristics is not instantaneous. Significant changes in atomisation characteristics occur only after the discharge voltage exceeds a certain threshold. Increasing the discharge voltage improves the atomisation characteristics of the nozzle, but this improvement is not perpetual. Once the atomisation performance reaches a certain level, further increases in voltage yield negligible changes.

Nomenclature

P_{Oil} - Fuel supply pressure, [MPa]

P_{Air} - Air supply pressure, [MPa]

Q_{Air} - Air flow rate, [L/min]

U - Discharge voltage, [kV]

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