Research on Fuel atomization technology in aero engine

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Abstract. Recently, fuel combustion-related performances of aero engines are increasingly demanding, and their combustion quality directly affects their power, economy and emission characteristics, and a series of key performance indicators. The fuel atomization is the key link to determine the combustion condition**.** Therefore, this paper clarifies the mechanism of fuel atomization in aero-engines, studies the characteristics and methods of fuel atomization in aero-engines, and analyzes the influencing factors in the this process. The results indicate that lower fuel viscosity, smaller surface tension and appropriate temperature pressure, nozzle geometry, etc. can better enhance the fuel atomization performance. Herein, good atomization effect is the premise of efficient combustion, and it is important for energy saving and environmental protection. For the future development of engines, the rational organization of combustion is essential to improve their performance**.**

Keywords: Fuel Atomization; Aero Engines; Combustion Performance.

1. Introduction

The emission problem has always been a challenge for the development of aero engine technology. Especially in recent years, regulations related to emissions have been increasing launched, and emissions standards are getting stricter, thus requires people to solve emission problem on root [1]. For aero engines, the combustion quality impacts its power, economy, emission characteristics and various other key performance indicators directly, and the fuel atomization is a critical stage in determining the combustion condition. Thus, perfect atomization effect is a premise for high-effect combustion for its vital importance for energy saving and environment protection [2]. Therefore, identifying the fuel atomization mechanism, and exploring the mixing process between spray and air are critical to improve the aero engine performance.

The aero engine mainly consists of several parts, such as fan, compressor, combustion chamber and turbine [3]. Thermal energy released by fuel combustion can be converted into mechanical energy in it, and the thrust generated by the kinetic and potential energy difference from the inlet and outlet ensures the proper operation of the engine [4]. The current aero engines include ramjet engines, piston engines, turbojet engines, turbofan engines and many other types, and this paper mainly focuses on the turbofan engine as an example to explore. In the working process, the air is pressurized by the fan into the compressor, and the fuel is sent to the combustion chamber through the pipe. Then mixes with high-pressure come from the outlet of compressor. The mixture flows into the combustion chamber for combustion and heating, turning into high-temperature and high-pressure combustion exhaust. Then. the energy of exhaust flows into the follow-up sections and converts into kinetic energy to push the turbine blades to do work. Therefore, the combustion chamber is one of the key components of an aero engine, and its combusting performance is influential for the performance of the whole engine [5]. Therefore, it is critical to clarify the fuel atomization mechanism of aero engines and investigate the measures to improve fuel atomization performance [6].

In the fuel atomization process, the fuel flows out from the nozzle under high pressure, broken into thinly atomized particles under the high-speed air flow, which consists of primary atomization and secondary atomization. Primary atomization takes place as the jet breaks up, and the fuel dissociates into ligaments or larger particle. In the secondary atomization stage, the fuel ligament or large particles are refined into thinner particles by the force of gas disturbance, and then mixed with gas to achieve combustion requirements [7]. This process is shown in Figure 1.

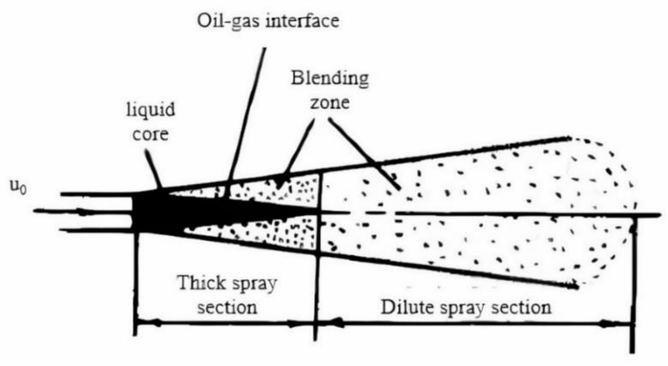

Figure 1. The process of fuel atomization [7].

Herein, the atomization of fuel is influenced by a variety of factors. The nozzle structure, spraying conditions, liquid surface tension and viscosity are effective for the atomization process. The nozzle structure and spraying conditions affect the primary atomization, while the surface tension and viscosity affect the fragmentation of fuel particles. In conclusion, the atomization effect is a combination of various factors. However, there is still a lack of research in this area, so this paper investigates the effect of fuel viscosity, surface tension, temperature and pressure, nozzle geometry and size on the atomization effect of fuel.

2. Fuel atomization

The principle of fuel atomization technology is to make the fuel ejected from the nozzle, and broken into discrete droplets by use pressure nozzles. The droplets then flow at high speed into the ambient gas and are burned with it. Primary atomization refers to the jet-breaking process during injection, while secondary atomization refers to the collision of broken droplets or mutual energy exchange and continues to split to form a fine liquid mist. In short, fuel atomization is a liquid flow-breaking process under the joint influence of internal and external forces.

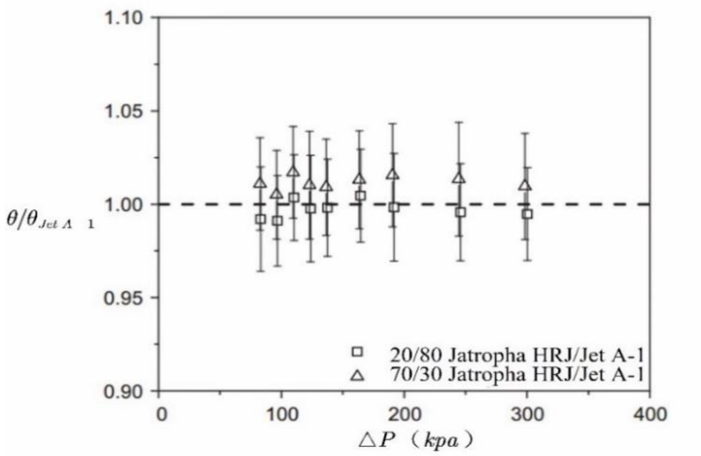

Figure 2. The variation of normalized full spray cone angle with the simplex swirl atomizer [8].

Energy exchange usually accompanies the process of fuel atomization. In this process, liquid fuel is injected into the combustion chamber space, and a field of a multi-phase mixture of the liquid column, oil droplets, oil vapor, and air is formed. On the one hand, the surface tension of the liquid forces it to form a small sphere for the minimum surface energy. On the other hand, the aerodynamic force acting on the liquid's surface causes it to burst. If the sum of the aerodynamic forces is greater than the sum of the surface tension and viscous forces, the liquid may break up. It appears that the main factors affecting atomization are surface tension and fuel viscosity. In addition, atomizing conditions are affected by the size and shape of the atomizing orifice, the liquid to be atomized and the atomizing conditions. Sivakumar et al.[8] Optimized the fuel selection, and the test results showed that the primary and secondary spray characteristics of newer alternative fuels, such as Jatropha vegetable oil and Jet A-1 fuel, are nearly equivalent in existing injectors. Slight differences could be attributed to differences in fuel properties. However, flame intensity and carbon vapor release decreased significantly as the mix ratio of these new fuels increased. This way decreases environmental pollution and satisfies the growing demand for futural fuels as shown in Figure 2.

In recent years, researchers have done a lot of research on the fuel atomization characteristics inside the combustion chamber using numerical simulations, simulation experiments, and theoretical analysis [9]. The design of the pressurized vortex nozzle is an essential factor affecting the atomization efficiency [10]. The inlet and outlet orifice diameters, inlet orifice orientation, vortex chamber diameter, and vortex chamber height affect the atomization efficiency, with the inlet and outlet orifice diameters having a greater influence. Geometric differences have been found to have a significant effect on spray characteristics such as spray angle and sauter mean diameter (SMD) at the same flow rate and pressure. Specific nozzle configurations can be adapted to suit actual requirements. Analysis of the data showed that spray angle is related to the number of vortices and SMD is related to the turbulent kinetic energy. By fitting the data, equations were developed to predict spray angle and SMD. The estimated fit equations for the atomization angle and the average diameter were within the 15% and 10% error limits, respectively. The key fluid-side factors that affect spray characteristics are fluid viscosity, surface tension, etc.

However, many pressure cyclonic atomization models are still based on simple centrifugal nozzle structures. But the internal structure of the centrifugal nozzle (e.g., scrambling slot, cyclonic reinforcement structure, etc.) can also affect the atomization performance, which is usually not considered in the models. Also, with the refined design of nozzle structures, there are limitations to the generalizability of traditional models.

3. Factors impact on fuel atomization performance

3.1. The effect of spray hole shape on atomization performance

In engines, nozzle design affects fuel combustion and exhaust gas emission, and the geometry of the nozzle orifice has an important effect on the air-fuel mixing and fuel atomization performance. Yicheng Deng et al.[11] Numerically investigated the multiphase flow inside and outside V-shaped and Y-shaped cross-hole nozzles using the volume of fluid large eddy simulation (VOF-LES). The cross-hole nozzles have an overall flow loss is 24-37% lower than that of the cylindrical nozzle, and its jet has a 50% wider diffusion angle and 27% smaller droplet size than that of the cylindrical orifice nozzle. The results show that the use of V and Y cross-hole nozzles has greater fuel atomization performance. The schematic diagrams of the V and Y nozzles are shown in Figure 3.

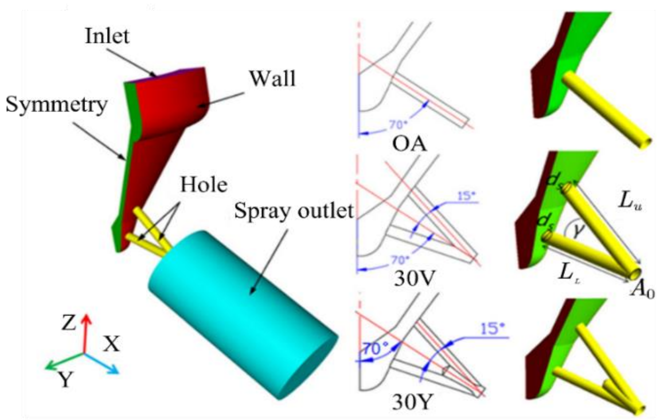

Figure 3. The geometry model of the nozzle and boundary definition [11].

Xianyin Leng et al.[12] Designed a spiral grooved hole (SGH) nozzle with multiple helical arc grooves on the inner wall of the nozzle's conical bore. A Volume of Fluid, Large Eddy Simulation (VOF-LES) method was used to calculate the multiphase flow in and out of the SGH nozzle. An SGH nozzle and a non-spiral grooved nozzle (NSH) with specified injection pressure and ambient pressure were used in the calculations. Numerical results show that, due to the effect of the near-wall direction of the spiral grooves in the SGH nozzle orifice, the fluid flows partially spirally outside the nozzle orifice, resulting in significant centrifugal forces in the fluid core and adding dynamics to the aerodynamic effects of the fluid jet break-up. Partial spiral flow also caused a much larger near-field propagation angle and smaller droplets than with the NSH nozzle, but has the disadvantage of an 11.8% lower discharge coefficient, as shown in Figure 4.

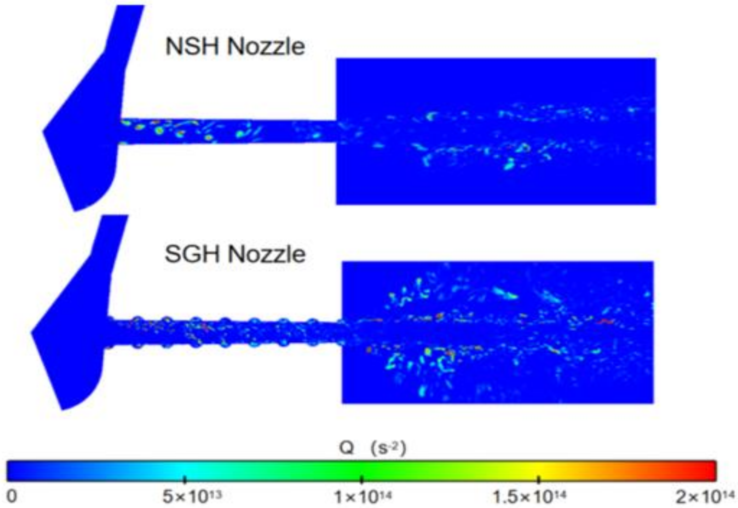

Figure 4. Comparison of the Q for different nozzles [12].

O. O. Taskiran et al. [13] conducted a comparative study on the atomization performance of sharp inlet nozzles and round inlet nozzles. Higher flow coefficients can be obtained using round inlet nozzles. The flow coefficients of sharp inlet nozzles are 0.07 and 0.08 lower than round inlet nozzles at 50 Mpa and 100 Mpa injection pressures respectively. Also, longer liquid core areas can be obtained using round inlet nozzles that with better atomization performance.

Therefore, optimizing nozzle geometry is an effective way of improving fuel atomization characteristics. V-shaped and Y-shaped nozzles have better atomization performance than round-hole nozzles, while nozzles with round inlets have higher flow coefficients than sharp inlet nozzles under experimental conditions of 50 Mpa-150 Mpa. In addition, the tilting nozzle has an inhibiting effect on the atomization performance, and the selection of the appropriate nozzle geometry under different working conditions is the direction and goal of the researchers concerned.

3.2. The Effect of spray hole size on atomization performance

Many researchers are interested in the fuel atomization performance to reduce fuel consumption and harmful emissions for energy saving and emission reduction, and the size of atomizing holes is an important factor affecting the fuel atomization performance.

Mohammad Nikouei et al. [14] investigated the spray kinematics of nozzles of specific geometries at a range of injection pressures. They found different spray kinematic properties for two-orifice nozzles with inlet internal diameters of 224 µm (TH-A) and 219 µm (TH-B) at an inlet pressure of 1600 bar. At a spray time of 40 µs, the velocity of the TH-A nozzle spray decreases faster in the frontal OX direction from 400 m/s to 150 m/s at 2 mm, and the velocity of the TH-B nozzle spray even increases from 150 m/s to 250 m/s as shown in Figure 5.

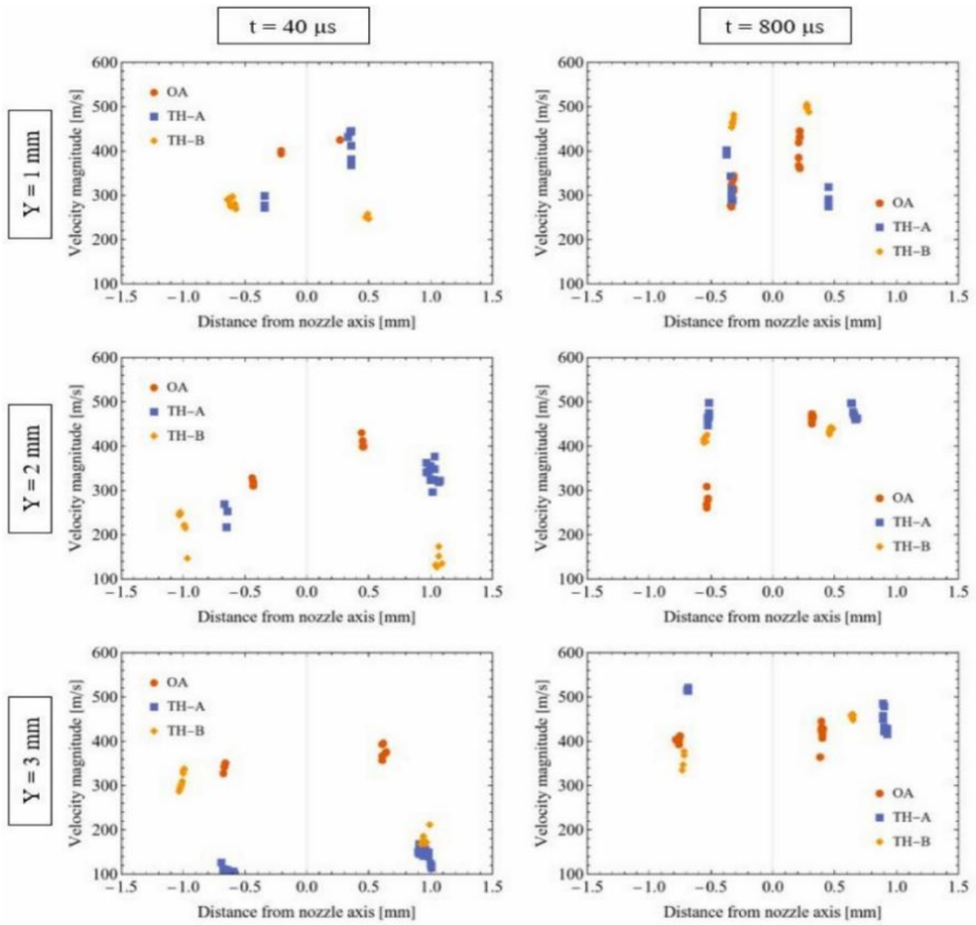

Figure 5. Average velocity magnitude for TH and OA nozzles [14].

G. R. Kothiwale et al.[15] Used multi-hole injectors with different orifice sizes to study the emission characteristics of DC-CI diesel engines. Under the same load and pressure conditions, a three-hole injector with a diameter of 0.2 mm showed a maximum reduction of 0.005 ppm in CO emissions and a maximum reduction of 6.5 ppm in HC compound emissions compared to a four-hole injector with a diameter of 0.25 mm. The smaller the nozzle diameter, the better the injection characteristics. The smaller the size of the atomized fuel droplets, the greater the fuel atomization performance. It also reduces the emission of pollutants to some extent.

The specific effect of spray hole size on atomization performance varies for different engines. Overall, the important research work is to find the most suitable orifice size for a particular engine to obtain excellent fuel atomization characteristics.

3.3. The effect of fuel surface tension on atomization performance

In the future, bio-alcohols have a great potential to replace conventional diesel as a premium biofuel for blending, especially in the heavy transport sector where electrification is not yet fully developed. During high-pressure injection, the surface tension of the liquid fuel has a greater influence on atomization than the viscosity. It affects the quality of spray formation (penetration and charring) in the engine combustion chamber, which in turn affects combustion characteristics and emissions. However, unlike viscosity, surface tension is not restricted by fuel quality standards. In addition, surface tension also exhibits strong non-linearities after mixing. The aim of this study is to determine which of the surface tension prediction models proposed in the literature is best suited to samples composed of diesel and biodiesel-alcohol blends. To distinguish between the different models, three criteria have been defined, which can be used separately or in combination: best fit, minimum number of settings and physical basis of the model. Rayda et al. [16] found that of all the models tested, the Connors-Wright model was the most suitable for such mixtures due to its simplicity and accuracy. Some selected models are shown in Figure 6.

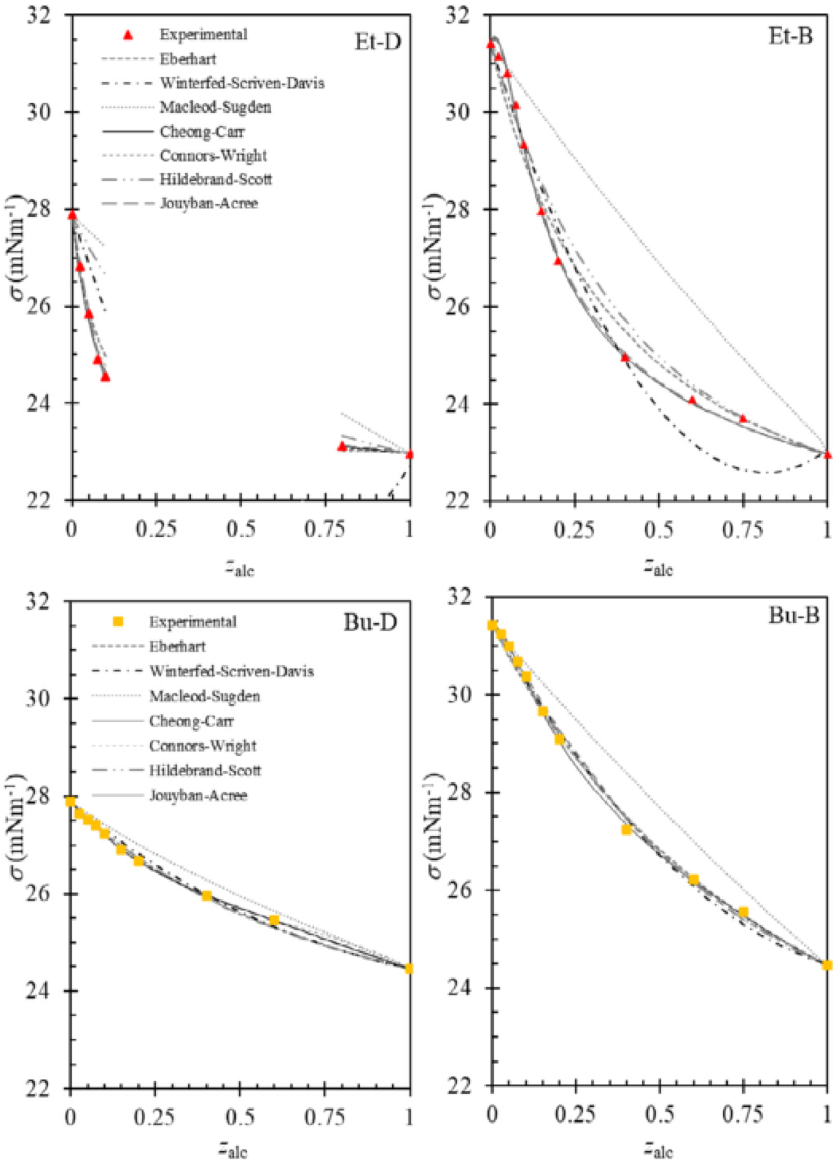

Figure 6. Comparison of experimental surface tension and selected models [16].

Sauter mean diameter (*SMD*) shows the average specific surface coverage of fuel droplets. It is related to the evaporation capacity and normally used to measure the atomization performance and can be viewed in formula (1).

$$SMD = \frac{\sum d_i^3}{\sum d_i^2} \tag{1}$$

The aggregation of liquid is normally caused by surface tension. This is the macroscopic manifestation of molecular gravity, acting to prevent the liquid from dispersing. Therefore, breaking such aggregation to get atomized liquid, the effect of surface tension is not negligible.

Finally, the reduction of fuel surface tension is positive related to the droplet refinement and the expansion of droplet space distribution. The smaller surface tension is also beneficial to obtain higher atomized droplet velocity. However, the change of droplet refinement effect with surface tension is not obvious.

Shin, J. et al. [17] studied the influence of density and surface tension on the fuel atomization process, discovering the rise of surface tension increased fuel beam unfolding angle and *SMD*. However, the effect is smaller than the variation in fuel density caused by operating conditions. The testing results are shown in Figure 7.

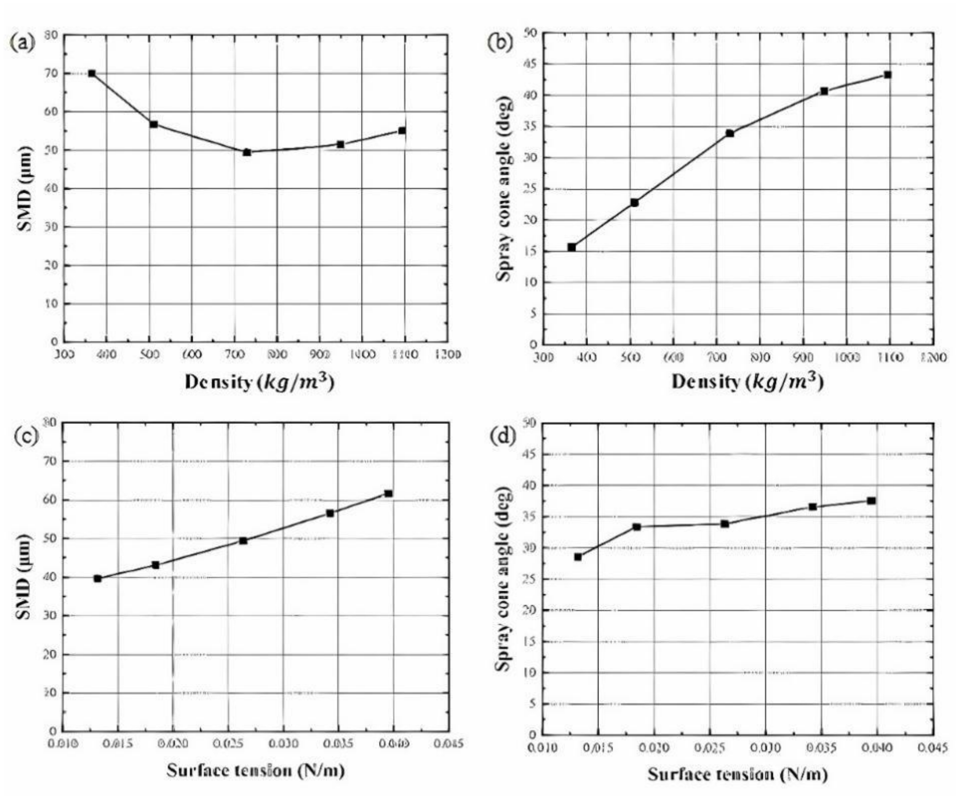

Figure 7. Comparison of the effect on SMD and spray angle [17].

The study of E. Ejim et al. [18] shows that the gas/liquid two-phase mixing atomization consists of two stages. First, liquid phase is broken into ligaments by bubble expansion, and ligaments turn into droplets under the air flow action. Controlling other conditions, *SMD* can be viewed in formula (2).

$$SMD \propto \sigma^{0.69} \quad (2)$$

So, the surface tension has a positive but insignificant effect. C. Park, S. H. et al. [20] blended gasoline with diesel in diesel engines. concluding that increasing gasoline content reduced the surface tension of the fuel mixture, and the surface tension decreases approximately linearly with the growth of gasoline volume content, moreover, average diameter decreases. The results identified that surface tension is one restriction against the improvement of atomization quality. The relations of *SMD*, spray cone angle is shown in Figure 8.

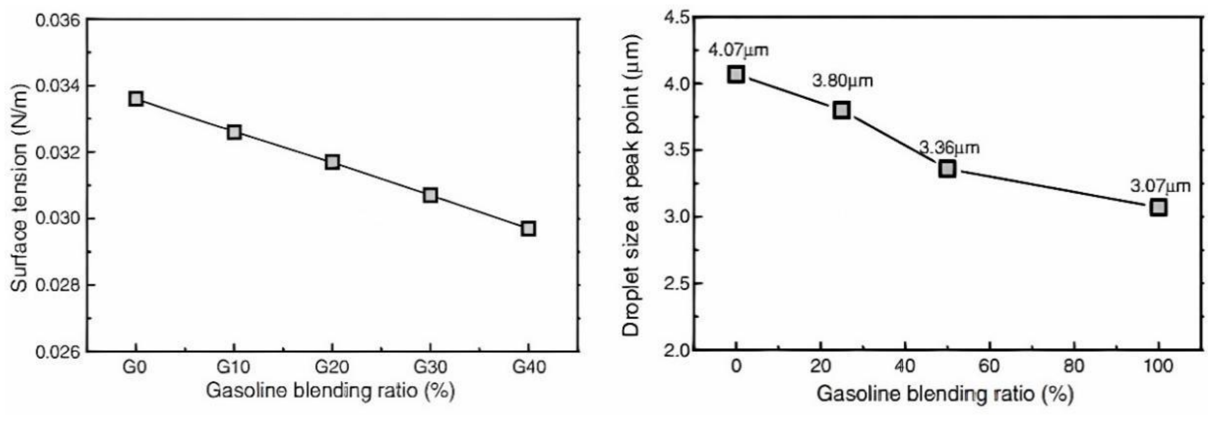

Figure 8. Variation of fuel surface tension and SMD with gasoline volume content. (a) Mixed fuel surface tension; (b) *SMD* [19].

The study results of various common fuels indicate that the fuel atomization performance falls due to the increase of surface tension, but surface tension has a small effect and is not a major factor.

3.4. The effect of fuel viscosity on atomization performance

Due to the viscosity, the mechanical movement of the liquid is obstructed, causing the atomization effect to move away from the ideal situation. The design of existing fuel atomizers is based on a certain viscosity, however, the instability of both the temperature in the engine combustion chamber and the chemical composition of the fuel can change the viscosity. Therefore, the influence of fuel viscosity on atomization performance needs to be considered.

The atomization performance of commonly used petroleum-based fuels is generally indirectly affected by changes in working temperature. Dafsari et al. [20] proved that the relative rate of change of surface tension and density with temperature is tiny, and the effect of viscosity can be focused on. The viscosity altered remarkably with temperature, decreasing in an approximate exponential manner. Moreover, as the fuel temperature decreases, its Sauter mean diameter (*SMD*) gets larger, as shown in Figure 9.

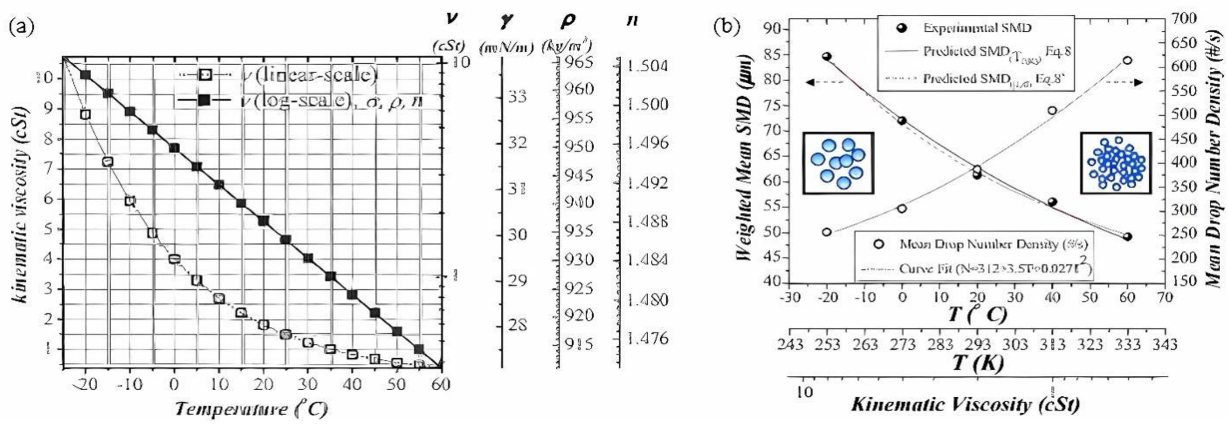

Figure 9. The relations between the viscosity of a fuel, SMD after atomization and its temperature. (a) Tested fuel physical properties; (b) Inverse relation of weighted mean SMD and mean drop number density [20].

From the discussion of the surface tension in 3.3, the change of *SMD* could not be regarded as an effect of surface tension alone, with the role of viscosity needs to be considered.

Some researchers proved that low viscosity increases the difference of droplet dispersion velocity and facilitates full space diffusion and combustion. Feng et al.[21] Concluded that blending gasoline reduces the viscosity of diesel. In formula (3)

$$\upsilon = \frac{\tau}{\rho} \Big/ \frac{\mathrm{d}u}{\mathrm{d}r} \tag{3}$$

It indicates that the reduction of viscosity weakens the resistance to shear stress which is reflected in the reduction of the atomization cone angle. Take 20bar and 40bar injection pressure as examples, as shown in the Figure 10.

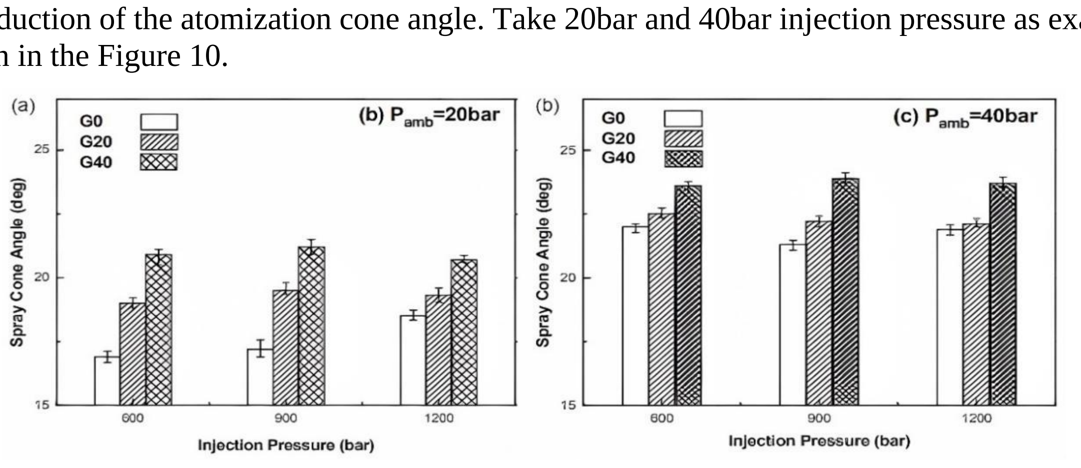

Figure 10. The averaged spray angle for diesel and gasoline blends at different blending ratio and injection pressure. (a) 20 bar; (b) 40 bar [21].

Hazar et al. [22] studied combustion characteristics of biodiesel, it was demonstrated that preheating the high-viscosity fuel to reduce its viscosity improved poor combustion, high exhaust emissions, and improved power and economy. As shown in Figure 11, the viscosity of DF, O20, O50, RRO gradually decreases under the certain temperature and combustion conditions. There are following phenomena: (1) The exhaust temperature increases in order, meaning that with the decrease of viscosity, the combustion is more complete, and more heat is released; (2) The volume fraction of NOx and CO emitted basically decreases gradually, indicating that the mixture between fuel with air gets more complete, then fuel combusts more completely. So, the incomplete combustion product reduces gradually.

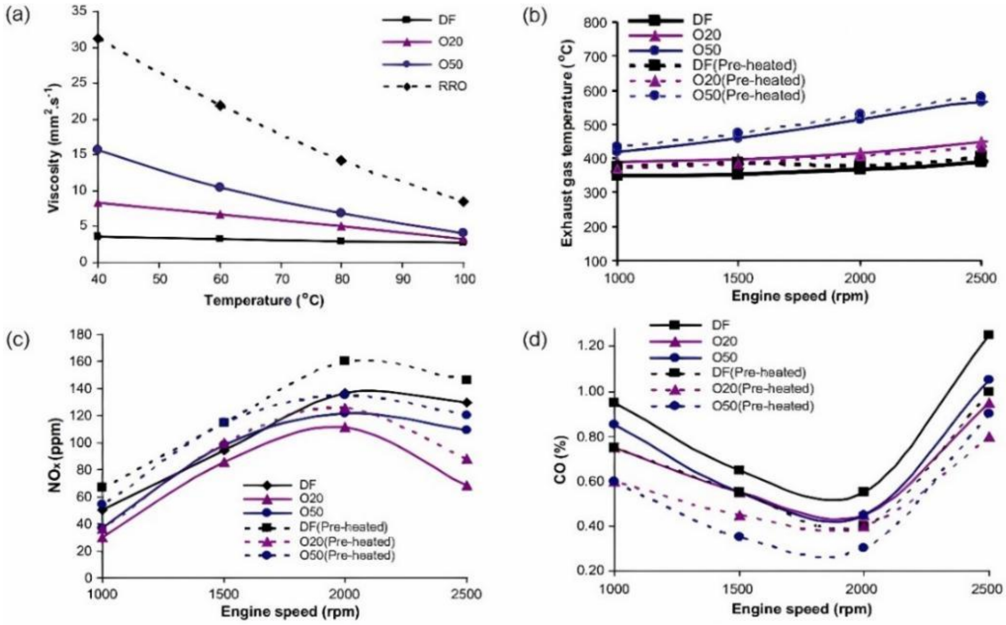

Figure 11. Relations between viscosity of several fuels and exhaust temperature, emission NOx and CO volume fraction for four varieties of biodiesel [22].

Yang et al. [23] demonstrated that the atomization performance gets more influential under high pressure conditions than low pressure. Considering multi-boost stages in modern aero engines, the impacts of viscosity cannot be neglected. the viscosity impacts the actual atomization performance of the fuel used in aero engines.

Therefore, viscosity varies considerably with working conditions and affects the atomization performance remarkably, and the fuel is easily unable to meet the usage needs when the viscosity is too high.

3.5. The effect of fuel temperature on fuel atomization

The fuel temperature also has an effect on fuel atomization. In order to cope with the wide range of applications for aircraft engines, so that the aero-engine in very cold or hot conditions, normal operation, the effects of different temperatures of fuel need to be considered. Especially low-temperature fuel on the nozzle atomization performance of the urgent need to study the impact. The low-temperature nature limits the range of use of aero engines. The freezing point is not low enough for aero engines to work in very cold environments. Meanwhile, the freezing point is too low for the availability of aviation kerosene to be limited.

Qing Zhang et al. [24]found that the fuel injection dynamics in the vicinity of the injector can be represented by a dimensionless parameter and this parameter is particularly sensitive to the fuel temperature. This general scaling suggests that cavitation can be used to improve the efficiency of air-hydrokinetic energy conversion. This is important for better fuel atomization and engine combustion performance. This enhancement result has important consequences for the combustion of low-emission alternative fuels with high saturation vapour pressure, as shown in figure 12.

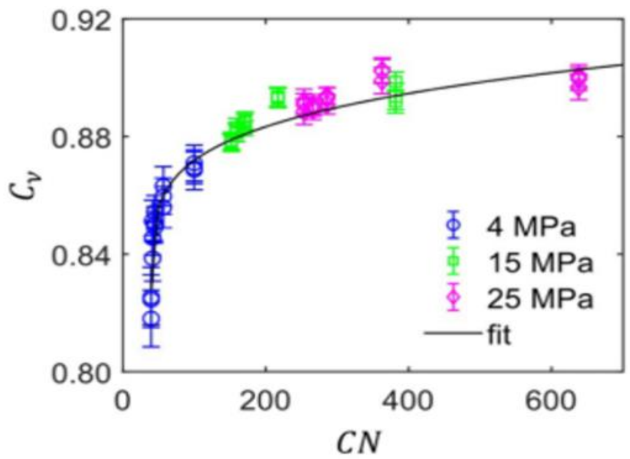

Figure 12. Linear ratio of the velocity coefficient *Cv* to the cavitation number *CN* [24].

3.6. The Effect of injection pressure on fuel atomization

With the increasingly stringent emission regulations, the reduction of harmful emissions has become the focus and difficulty of internal combustion engine research. Research shows that the use of high injection pressure can effectively improve the combustion process and reduce pollutant emissions. This has become a development trend. Increasing the injection pressure can improve the penetration capacity of the oil beam, reduce the particle diameter and improve the quality of atomization. Due to the increase in the amount of air involved in the oil beam and air disturbance, the formation of the mixture was accelerated. Meanwhile, a rapid and good combustion is achieved, the combustion and emission quality are improved, especially the reduction of the emission of particulates. In addition, increasing the injection pressure can reduce the requirements of air movement in the cylinder. Considered the performance of the engine at high and low speed conditions, it also brings many advantages to improve the efficiency of inflation.

Xuan Wang et al. [25] investigated the effect of injection pressure on the injection characteristics and fuel atomization. Xuan Wang studied a series of tests with three different concentrations of dual biodiesel blends in a single-cylinder engine at four different scenarios of injection pressure (180 MPa, 200 MPa, 220 MPa and 240 MPa). 240 MPa compared to other injection pressures, the mixing rate was higher and the spray intensity of the blended fuel was higher, while emissions increased. According to the numerical study, as the injection pressure continues to increase, the injection range and injection cone angle vary. Thus, optimizing the injection pressure had a great potential to improve combustion efficiency while reducing environmental problems.

3.7. The effect of pressure and temperature on fuel atomization

During the actual operation of a gas turbine, the ambient temperature and pressure change dramatically. The changes in ambient pressure and temperature cause changes in physical parameters such as air density and dynamic viscosity, which in turn affect the atomization characteristics of the fuel.

Dongyun Shin et al. [26] found that a higher ambient gas density leads to an increase in the drag and inertial forces of the liquid, resulting in a decrease in droplet size. However, the effect of ambient pressure on droplet size decreases with increasing ambient pressure. In addition, at higher ambient pressure, atomization tends to produce monodisperse droplets. Droplet sizes are larger for fuels with higher viscosity and higher surface tension, as shown in Figure 13. The axial velocities of the droplets are similar at all ambient pressures, but droplet velocities near the edge of the spray slower with increasing pressure. As can be seen from the figure, more small droplets were observed at higher pressures.

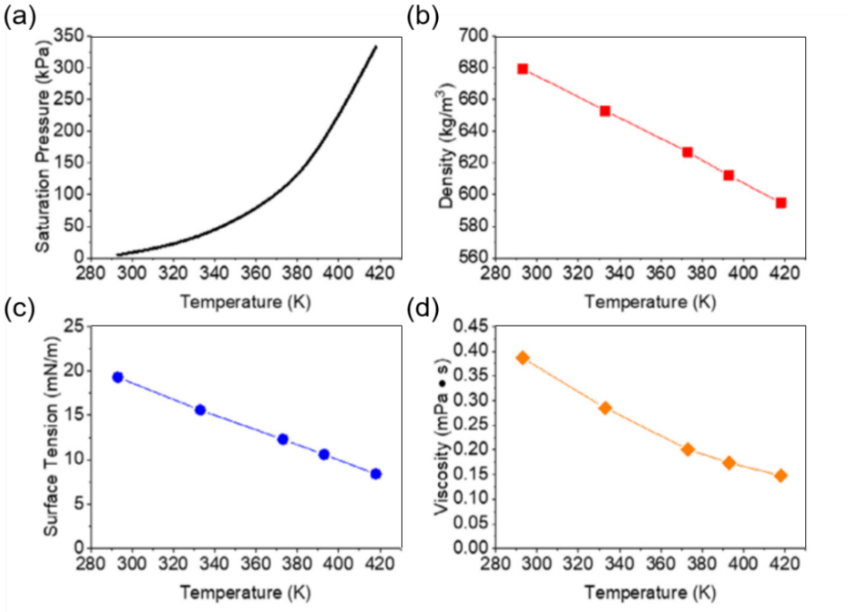

Figure 13. Effect of fuel temperature on different fuel properties[26].

Omer Farooq Atak et al. [27] carried out a comparative study at different ambient to saturation pressure ratios (*Pa/Ps*) in order to investigate the effect of high fuel temperature and low ambient pressures together in combination to achieve a certain superheated condition on the characteristics of transient boiling aerosols. Firstly, he predicted the bubble growth rate. The initial dispersion angle and droplet size distribution were then analyzed using X-ray imaging. As predicted by the Rayleigh-Plesset equation, for the same degree of superheat, the bubble growth rate was higher for increasing the fuel temperature (T_f) compared to decreasing ambient pressure (Pa) at the same superheat rate. As X-ray shown in Fig. 14, the larger the T_f, the greater the initial flow dispersion and the smaller the droplet size.

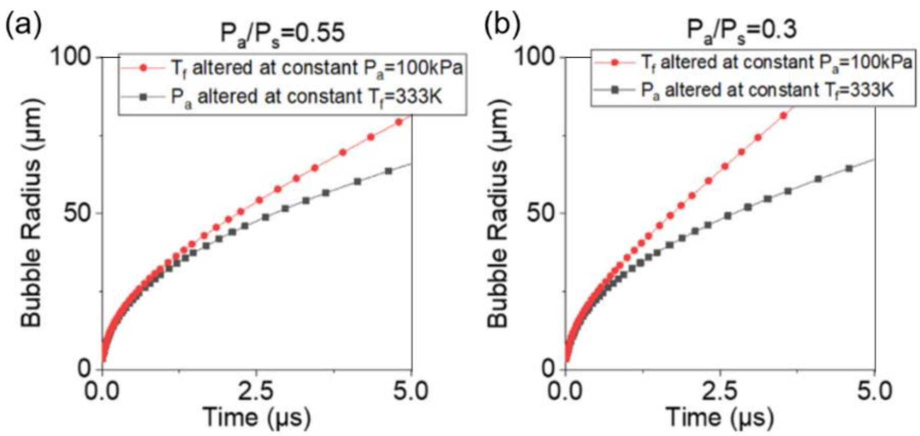

Figure 14. Effect of ambient pressure and fuel temperature on the growth rate of bubbles in fuel [27].

In general, the injection parameters have an important influence on fuel atomization. The injection parameters mentioned in this paper are nozzle size and shape, fuel temperature, injection pressure. This paper also compared the mutual effects of the parameters, and learned that in different environments, the temperature and pressure parameters on fuel atomization is not the higher the better, but there is some optimal value. And the determination of the optimal value needs a large number of experiments to explore. The shape of V, Y and circular nozzles is optimized for fuel atomization in different aspects. In addition, the influence of surface tension and fuel viscosity in fuel properties was also analyzed. Although the increase of surface tension is positive, it has little effect. The increase of viscosity obviously reduces the atomization effect and needs to be controlled.

4. Conclusions

Engine is the core component of an aircraft, and the fuel atomization process of an aircraft engine is critical to combustion efficiency and engine performance. Stricter emission standards and the high-performance requirements of the new generation of aero-engines make the improvement of combustion performance a future development direction, and fuel atomization is a key influence on combustion performance. In this paper, the effects of fuel viscosity, surface tension, temperature and pressure, and nozzle geometry on fuel atomization performance are investigated. The results show that smaller fuel surface tension, lower fuel viscosity and proper fuel or ambient temperature and pressure, V and Y nozzle geometry, and proper nozzle size enhance the fuel atomization performance significantly. Finally, the good and stable fuel atomization performance not only responds positively to the national energy saving and emission reduction policy, but also plays a role in protecting the environment.

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