

## Research Article

# Effect of Low Ambient Pressure on Spray Cone Angle of Pressure Swirl Atomizer

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Pressure swirl atomizers are widely used in gas turbine combustor; this paper is aimed at researching the effect of low ambient pressure (0.1 MPa to 0.01 MPa, lower than an atmosphere) on the spray cone angle of pressure swirl atomizer. The spray angle is captured by high-speed photography; then, an image post program is used to process the spray angle magnitude. A mathematical model of a single droplet's movement and trajectory based on force analysis is proposed to validate the spray angle variation. The maximum variation of the spray cone angle, which is observed when fuel supply pressure drop through the atomizer is 1 MPa as the ambient pressure decreases from 0.1 MPa to 0.01 MPa, is found to be 23.9%. The experimental results show that the spray cone angle is expected to increase with the ambient pressure decrease; meanwhile, mathematical results agree well with this trend.

## 1. Introduction

Pressure swirl atomizers are widely used in liquid rocket engines, internal combustion engines, and aircraft engines; it has unique advantages over other atomizers. The spray cone angle is important in determining combustion performance in terms of combustion efficiency, soot formation, and temperature distribution [1]. And the effective fuel/air mixing influenced by the fuel spray angle is one of the pivotal issues determining the ignition performance.

There are two parts affecting the spray angle: one is the geometry of the atomizer self; another is the ambient pressure that fuel is injected into [2]. A large number of works have also been conducted focusing on the spray cone angle of pressure swirl atomizers about those parts.

About the influence of the geometry structure, Rizk and Lefebvre [3] studied the effect of different structural parameters on the spray cone angle for a single swirl atomizer, within

which the influence of ambient gas pressure on the spray cone angle is not involved. Shim et al. [4] conducted a numerical and experimental study of the spray characteristics of a high-pressure swirl injector at ambient pressures. The droplet diameters increase while the spray penetration, spray width, and axial velocity decrease with the ambient pressure increases. Chen et al. [5] studied the initial tip structure evolution of diesel fuel spray under various injection and ambient pressures experimentally and numerically; the results show that (1) the ambient pressure exhibited a significant impact on the maximum size of the observable droplets and (2) the spray penetration decreased by approximately 10% with the increment of 0.5 MPa in ambient pressure, while increased by about 9% with 10 MPa injection pressure increment. Zhang et al. [6] worked at studying the spray characteristics of kerosene-ethanol blends discharging from a pressure swirl nozzle. The spray cone angle, discharge coefficient, breakup length, and velocity distribution were

obtained by particle image velocimetry, while droplet size is acquired by particle/droplet imaging analysis.

Ambient pressure plays a role part in forming the spray angle, and many research focused on this point tries to reveal the relationship between ambient pressure and spray angle. Wang and Lefebvre [7] focused on high ambient pressure, and the result shows that the basic effect of an increase in air pressure is to improve atomization, but this trend is opposed by contraction of the spray angle which reduces the relative velocity between the drops and the surrounding air and also increases the possibility of droplet coalescence. Sovani et al. [8] studied the spray cone angle in high ambient density environment for different injection pressures and ambient pressure. Kim et al. [9] investigated the influence of ambient gas pressure on the spray cone angle of single swirl atomizer and liquid sheet fragmentation experimentally; the result shows that the measured spray angles according to the ambient gas density differed before and after the sheet broke up and put forward a kind of boundary mathematical model of spray cone suggesting that density of gas has a deep influence on the spray cone angle. Chen and Yang [10] studied the effect of ambient pressure on the flow dynamics of a liquid swirl injector by means of a combined theoretical and numerical analysis; the result suggests that the pressure drop across the liquid sheet downstream of the nozzle exit increases, thereby suppressing the liquid expansion in the radial direction and decreasing the spreading angle. Kenny et al. [11] studied the flow inside the swirl atomizer and the spray cone angle with combustor of high pressures by experiments, the cone angle decreases when ambient gas pressure increases, but no specific analysis for the causes of the change was provided. Chen et al. [12] studied the spray characteristics of swirl atomizer by using a high-speed shadowgraph system under high ambient pressure; the results show that spray is suppressed by ambient pressure, a critical pressure value was found at which the spray structure converts from a wide hollow cone to a narrow contracting bell, and the discharge coefficient increases while the spray cone angle decreases. Lee et al. [13] reveal that high ambient pressure decreases the vertical extent of the spray penetration and its area.

Compared with existing literature, the ambient pressure is a very important module to affect the spray angle. However, the ambient pressure in most research is higher than atmospheric pressure. The ambient pressure is lower than an atmosphere when the aircraft is operated at high altitude reflight condition; the characteristics of the spray angle are strikingly different at high altitude. It is meaningful to reveal this variation trend, no matter for the atomizer or the ignition of combustor.

Another phenomenon which is noticeable is that when a pressurized bubbly mixture is driven out through an orifice, the mixture pressure abruptly drops and the bubbles undergo a rapid expansion process, which under some circumstances results in rapid disintegration of the liquid bulk into small droplets (atomization) [14]. The bubbles' explosion in the droplet is called microexplosion in vacuum ambient, which leads to very distinctive atomizing performance [15].

According to the above discussion, it can be seen that the spray cone angle is significantly affected by ambient pressure when ambient pressure is higher than an atmosphere, and the combustion characteristics are also affected significantly [16]; however, little work has been done to reveal this effect at low ambient pressure. Meanwhile, a totally different atomization mechanism called microexplosion has been ascertained with vacuum environment, which would lead to different spray performance in terms of droplet diameter and spray cone angle. In this context, it would be very interesting to see what would happen when the ambient pressure lies in 0-0.1 MPa and how the spray performance would be affected as ambient pressure varies in this range. The present work focuses on this effect in terms of spray cone angle.

## 2. Experimental Setups and Technique Method

**2.1. Experimental Setup.** The experimental setup, as shown in Figure 1, consists of 4 parts: a pressure vessel, kerosene supply system, vacuum pump, measurement system. The pressure vessel, of which the frame is made of stainless steel, has the dimensions of 200 mm × 200 mm × 500 mm. Three sides of the vessel are optically accessible. The kerosene supply system includes a high-pressure nitrogen bottle, a tank, pipes, and a solenoid valve. The vacuum pump has the volume rate of 8 L/s and minimum pressure of 0.06 Pa, with the help of a buffering tank and the valve on the vessel. The vacuum pump could adjust the pressure of the vessel tank to the desired value. The measurement system consists of a high-speed camera (IDTVISION Y5), two pressure sensors, and a temperature sensor. The resolution rate of the camera is 2336 × 1728, the maximum frequency is 69000 fps, and the minimum exposure time is 1 μs. The pressure sensors have a measuring range of 0-0.1 MPa with an accuracy of ±0.4%. The temperature sensor has a measuring range of -15-80°C with an accuracy of ±0.8%.

Properties of liquid are shown in Table 1, and the test conditions are listed in Table 2.

**2.2. Tested Pressure Swirl Atomizers.** Pressure swirl atomizers have been widely used in practical applications. In a pressure swirl atomizer, fuel is fed into a swirl chamber through tangential ports that give it a high angular velocity, thereby creating an air-cored vortex. The outlet from the swirl chamber is the final orifice, and the rotating fuel flows through this orifice under both axial and radial forces to emerge from the atomizer in the form of a hollow conical sheet.

Two different pressure swirl atomizers are tested to make the results more convincing, and the schematic and images of the atomizers are listed in Table 3.

### 2.3. Data Processing

**2.3.1. Spray Cone Angle Measurement.** The spray of a pressure swirl atomizer is usually in the form of a hollow cone of wide angle, with most of the drops concentrated at the periphery. A major difficulty in the definition and measurement of the cone angle is that the spray cone has curved boundaries, owing to the effects of air interaction with the spray. To overcome this problem, the cone angle is often

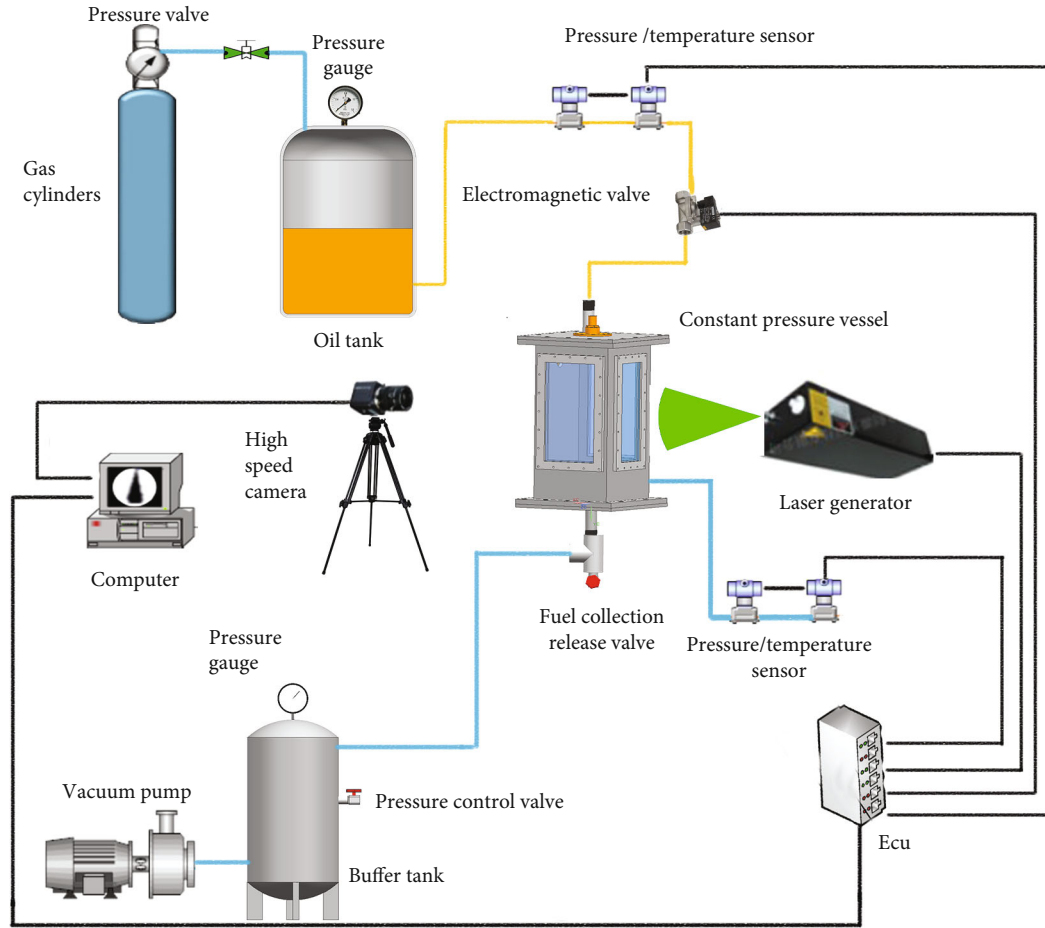


FIGURE 1: Schematic of the experimental facility.

TABLE 1: Properties of fuel (RP-3).

Density ( $\text{kg/m}^3$ )	Specific heat ( $\text{J/kg}\cdot\text{K}$ )	Viscosity ( $\text{kg/m}\cdot\text{s}$ )	Surface tension ( $\text{N/m}$ )
784	2090	0.0024	0.026

given as the angle formed by two straight lines drawn from the discharge orifice to cut the spray contours at some specified distance from the atomizer face. In the present work, this distance is 25 mm.

The vessel is lighted up by a laser sheet with thickness of 0.5 mm. The spray images are captured by a high-speed camera at the frequency of 900 Hz and the exposure time of 100  $\mu\text{s}$ . 1800 images are recorded for each experiment case, and these images are then averaged by the MATLAB program. The averaged image is then transformed into a binary image; the threshold value is ascertained by the OTSU method. Figures 2(a)–2(d) show the transient image, the averaged image, the binary image, and the boundary of the spray, respectively.

**2.3.2. Fuel Volume Concentration.** Koh et al. [17] designed an optical line patternator to get the original distribution of the

dense spray injected from a swirl injector at high ambient pressure. The optical line patternator is a combined technique of laser extinction measurement and image processing for spray characterization. The spray was scanned with the laser beam, and the line image of Mie scattering was captured simultaneously in the path of each laser beam by using a high-speed camera. A photodiode was used to obtain the transmission data that was the amount of the incident laser beam passing through the spray region. The distribution of the attenuation coefficients in the spray was obtained by processing the transmission data and Mie scattering distribution data by an algebraic reconstruction technique.

An image taken by a high-speed camera consists of pixels with different gray values; when the liquid goes through the red box region shown in Figure 3, the region that contains more mass of liquid is brighter than that containing less liquid under the same laser intensity, so that the gray value of the corresponding region in the image is larger than others. For a specific vertical position, the image is divided into  $n+1$  parts designated  $A_0, A_1, \dots, A_n$ , respectively; in Figure 4, each of these parts contains 20 pixels. The representing gray value of each part is obtained averaging the gray values of the 20 pixels.

TABLE 2: Test conditions.

Parameters	Value
Pressure drop through atomizer $\Delta P$ (MPa)	0.5, 0.7, 0.8, 0.9, 1.0
Ambient gas pressure $P_g$ (MPa)	0.01, 0.02, 0.04, 0.06, 0.08, 0.1

TABLE 3: The schematic and images of atomizers.

Number	Schematics of the atomizer	Image of the atomizer
1 <sup>#</sup> atomizer	<p>1 Swirl chambe 2 Convergent sectio 3 Throat 4 Divergent section 5 Tangent inlet</p>	
2 <sup>#</sup> atomizer	<p>A Nozzle housing C Nozzle cone D Orifice disc H Filter S O-ring holder</p>	

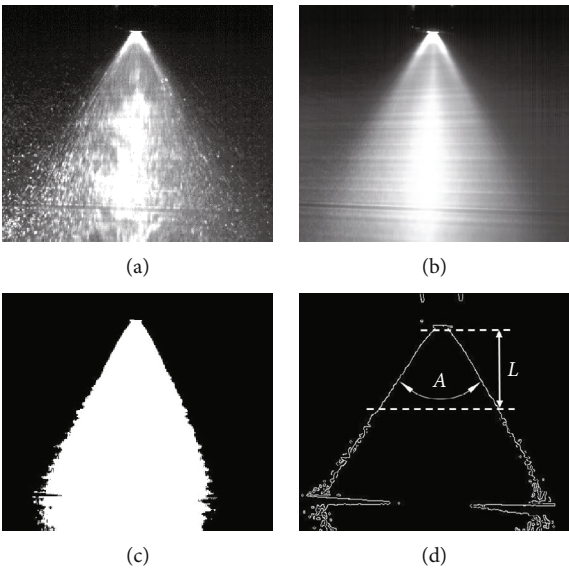


FIGURE 2: Postprocessing of images: (a) transient image; (b) average-time image; (c) binary image; (d) boundary of spray.



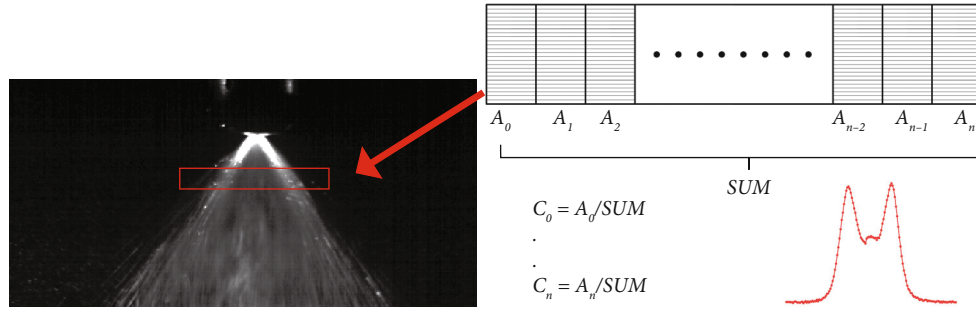


FIGURE 3: Postprocessing for volume concentration information.

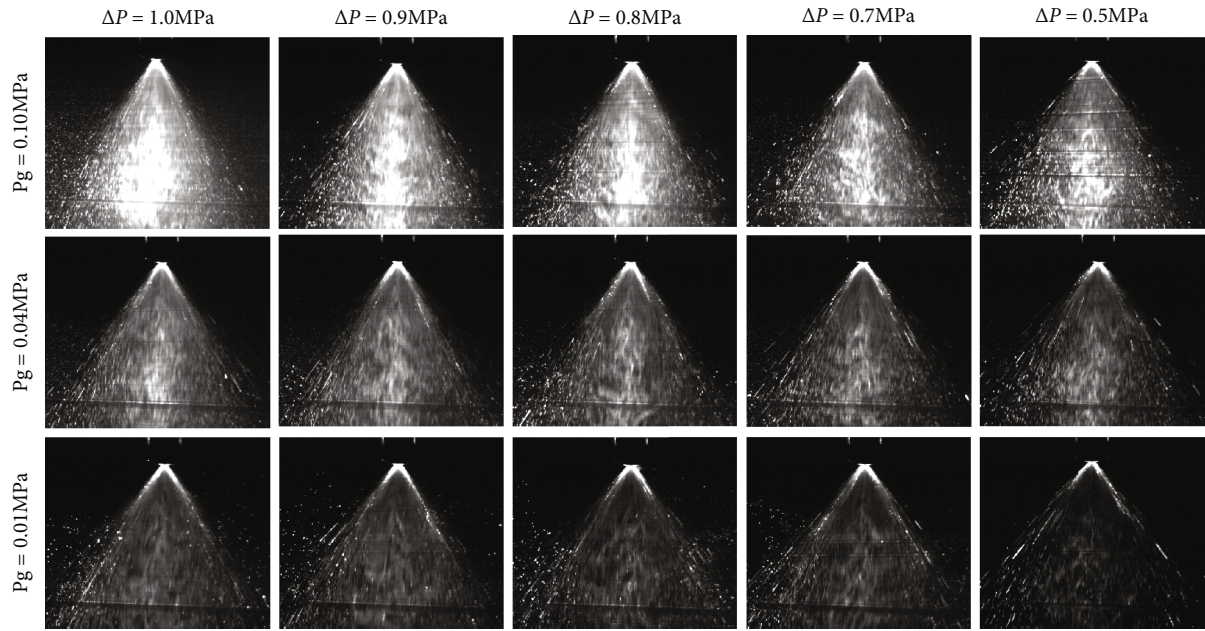


FIGURE 4: Spray images of 1# atomizer.

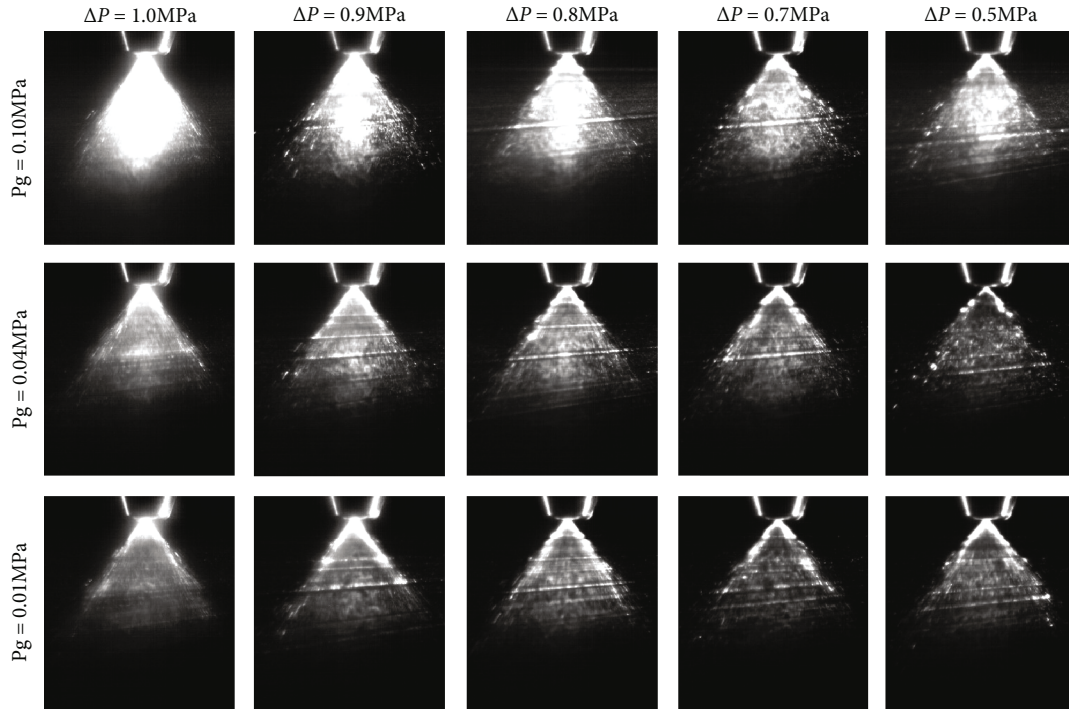
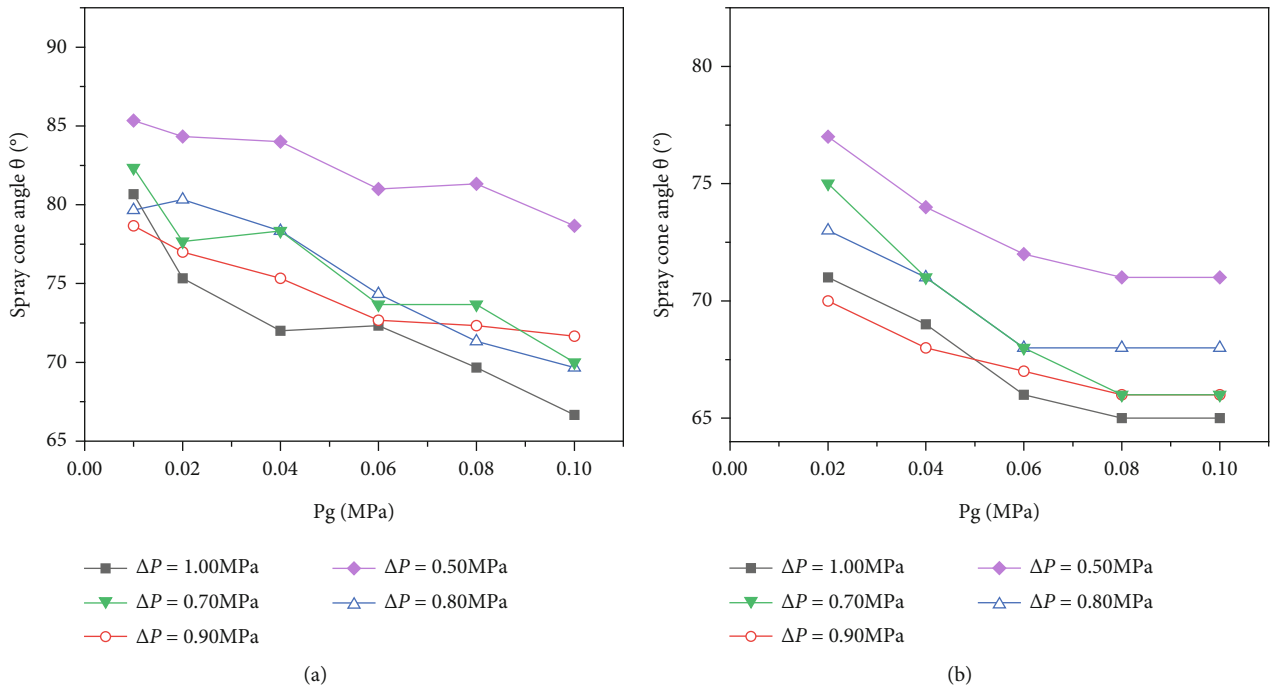
### 3. Results and Discussion

**3.1. Images of Spray Cone Angle.** The mass flow rate of an atomizer is constant at a fixed fuel supply pressure. Figures 4 and 5 show the transient images obtained with different ambient pressures and fuel supply pressures. The ambient pressures vary from 0.1 MPa to 0.01 MPa. The brightness of the area inside the spray cone reduces obviously as the ambient pressure decreases. Lower ambient pressure features lower air density, and the extrusion effect of gas molecules on the spray cone becomes weak; the droplet groups spread outward; therefore, the liquid mass inside the spray cone decreases. It is verified in five groups of experimental images of different pressure differential across atomizer.

**3.2. Spray Cone Angle.** The effect of low ambient pressure on the spray cone angle of the two atomizers is shown in Figures 6(a) and 6(b), respectively. The results of the two atomizers show the same trends that as the ambient pressure decreases from 0.1 MPa to 0.01 MPa, the spray cone angle increases significantly.

The maximum variation of the spray cone angle for 1# atomizer is obtained at  $\Delta P = 1.00$  MPa; the angle is  $66^\circ$  when the ambient pressure is 0.1 MPa, while the angle is  $82^\circ$  when the ambient pressure is 0.01 MPa which indicates an increase of 23.9%. Compared to the angle of atmospheric pressure, the minimum variation when  $\Delta P = 0.50$  MPa is  $5^\circ$ ; the amplitude is 6.0%, respectively. As for 2# atomizer, the maximum variation of the spray cone angle is obtained at  $\Delta P = 0.70$  MPa; the angle is  $66^\circ$  when the ambient pressure is 0.1 MPa, while the angle is  $75^\circ$  when the ambient pressure is 0.01 MPa which indicates an increase of 13.6%.

**3.3. Dimensionless Fuel Volume Concentration.** The dimensionless liquid volume concentration distribution of 1# atomizer is shown in Figure 7; the ambient pressures are 0.1 MPa, 0.04 MPa, and 0.02 MPa; the fuel supply pressures are 1.0 MPa, 0.9 MPa, 0.7 MPa, and 0.5 MPa, respectively. All the curves share a common feature that a bottom is found in the "0" radial position, and two peaks are found at specific positions corresponding to the peripheries.

FIGURE 5: Spray images of 2<sup>#</sup> atomizer.FIGURE 6: Spray cone angle with ambient gas pressure: (a) 1<sup>#</sup> atomizer; (b) 2<sup>#</sup> atomizer.

It is noteworthy that as the ambient pressure decreases, the peaks of the curve move outwardly. Besides, as the ambient pressure decreases, the dimensionless liquid volume concentration in the “0” position decreases, and that in the peaks increases. Both of the abovementioned indicate an increase in spray cone angles, as ambient pressure decreases.

#### 4. Theoretical Analysis

When a sheet of liquid emerges from an atomizer, its subsequent development is influenced mainly by its initial velocity and the physical properties of the liquid and the ambient gas. Three velocities are obtained when the liquid is accelerating

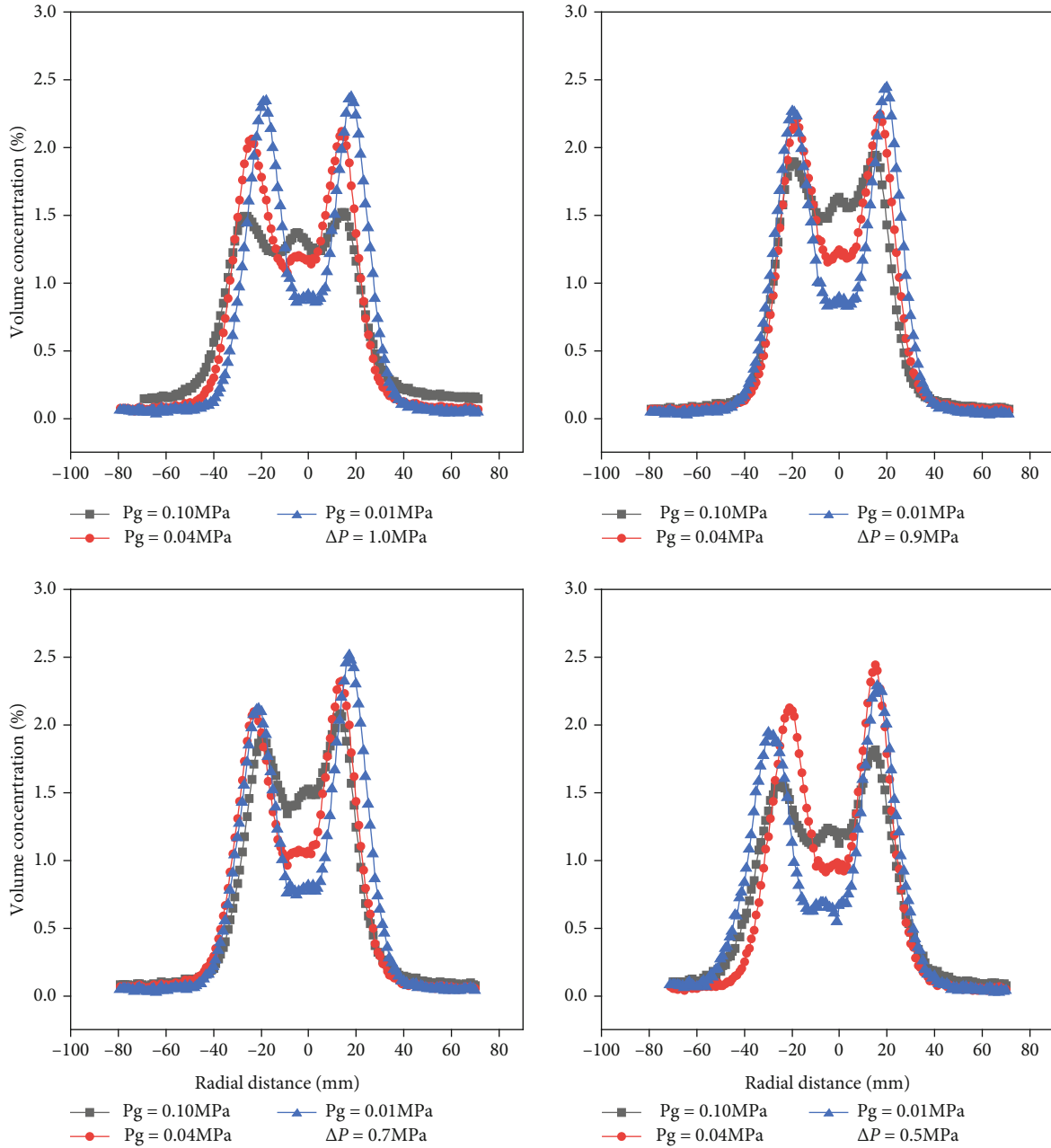


FIGURE 7: Distributions of dimensionless fuel volume concentration.

in swirl chambers, and then, it interacts with the surrounding air after leaving the atomizer; air molecules add resistance forcing liquid fragments or particles and change their trajectory. Thus, it is reasonable to analyze a single liquid droplet's movement and trajectory.

**4.1. Mathematical Model.** A single droplet with initial velocity is selected to carry out force analysis in environments with different pressures. Two assumptions are made as follows: (1) there is no mass loss during the droplet's movement and (2) the droplet has no spinning.

The motion of a droplet in a static environment can be described by Newton's second law; according to equilib-

rium of forces, the mathematical equation can be listed as follows [18]:

$$m \frac{\partial V}{\partial t} = F_D + F_A + F_B + F_G, \quad (1)$$

where  $m$  is the mass of the droplet (kg),  $V$  is the velocity of the droplet (m/s),  $F_D$  is the drag force (N),  $F_A$  is the additional mass force (N),  $F_B$  is buoyancy (N), and  $F_G$  is the gravity (N):

$$F_D = \rho_g |U - V| (U - V) \frac{C_D \pi d^2}{8}, \quad (2)$$

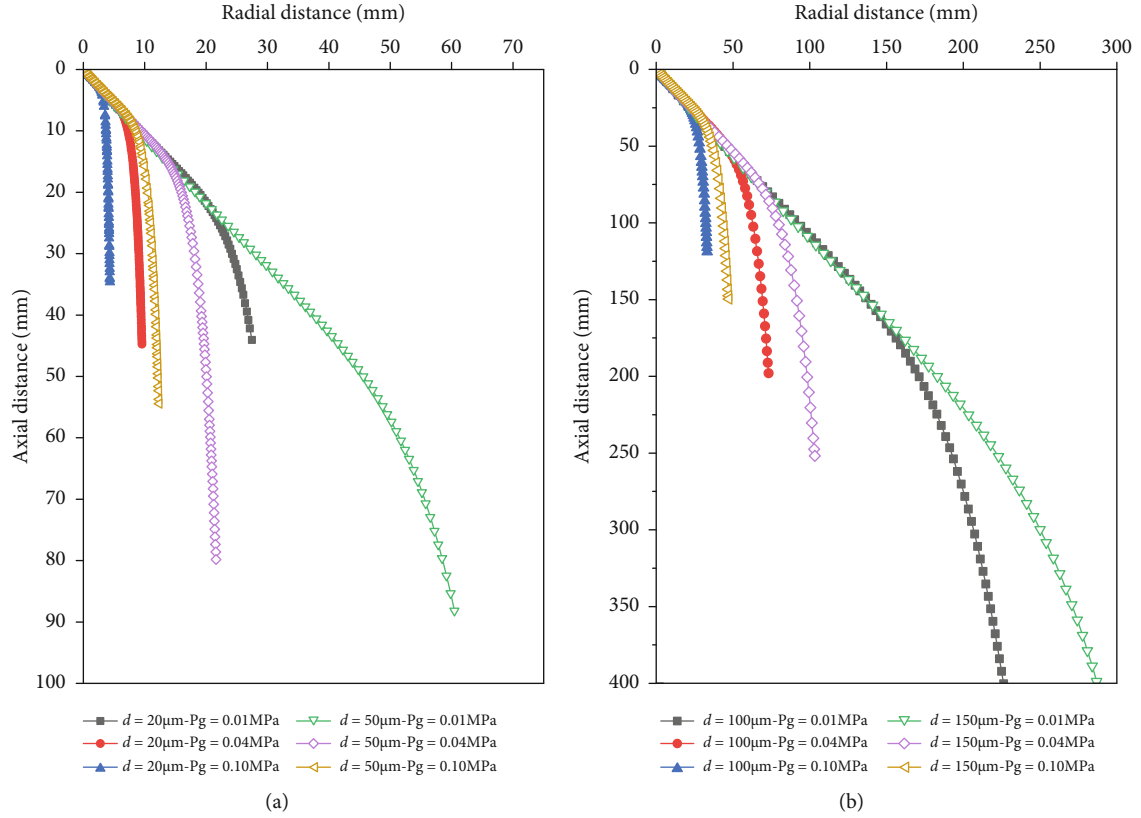


FIGURE 8: Trajectory of droplet with different diameters: (a)  $d = 20 \mu\text{m}$ ,  $d = 50 \mu\text{m}$ ; (b)  $d = 100 \mu\text{m}$ ,  $d = 150 \mu\text{m}$ .

where  $\rho_g$  is the density of gas ( $\text{kg/m}^3$ ),  $U$  is the velocity of gas ( $\text{m/s}$ ),  $d$  is the droplet diameter ( $\text{m}$ ), and  $C_D$  is the drag coefficient. Some more parameters are needed to be considered including droplet viscosity, looped flow inside droplet, droplet Reynolds number, and the impact of inertial effect in the  $C_D$  calculation; drag coefficient  $C_D$  is calculated as below:

$$C_D = C_{D0} \times \frac{2\mu_g + 3\mu_d + k}{3\mu_g + 2\mu_d + k} \times h. \quad (3)$$

$C_{D0}$  is

$$C_{D0} = \begin{cases} \frac{24}{\text{Re}_d}, & \text{Re}_d < 50, \\ 10 \text{Re}_d^{-1/2}, & 6.2 \leq \text{Re}_d < 500, \\ \frac{24}{\text{Re}_d} (1 + 0.15 \text{Re}_d^{0.687}), & 500 \leq \text{Re}_d < 800, \\ 0.44, & 800 \leq \text{Re}_d < 2 \times 10^5, \\ 0.1, & 2 \times 10^5 \leq \text{Re}_d. \end{cases} \quad (4)$$

$\text{Re}_d$  is

$$\text{Re}_d = \rho_g |U - V| \frac{d}{\mu_g}, \quad (5)$$

where  $\mu_g$  is the gas dynamics viscosity ( $\text{N}\cdot\text{s}\cdot\text{m}^{-2}$ ),  $\mu_d$  is the liquid dynamics viscosity ( $\text{N}\cdot\text{s}\cdot\text{m}^{-2}$ ),  $k$  is related to looped flow inside droplet (it is 0 in this paper),  $h$  is the droplet deformation,  $h = [1, \infty]$  (it is 1 in this paper), and  $\text{Re}_d$  is the droplet Reynolds number.

Virtual mass force shows

$$F_A = \pi d^3 \frac{\rho_g [\partial(U - V)/\partial t]}{8}. \quad (6)$$

Buoyancy:

$$F_B = \frac{-\pi d^3 \rho_g g}{6}. \quad (7)$$

Gravity:

$$F_G = \frac{\pi d^3 \rho_d g}{6}. \quad (8)$$

Axes are designated as follows:  $y$  axis is along the atomizer spray direction and  $x$  axis is vertical to the spray direction. Four forces are applied on a droplet in motion equation and then resolve into  $x$  and  $y$  directions.

$x$  direction shows

$$m \frac{dv_x}{dt} = F_{Dx} + F_{Ax}. \quad (9)$$



y direction shows

$$m \frac{dv_y}{dt} = F_{Dy} + F_{Ay} + F_B + F_G. \quad (10)$$

The differential equation of velocity shows

$$\begin{cases} \frac{dv_x}{dt} = -\frac{3\rho_g C_D}{2d(2\rho_d + \rho_g)} v_x^2, \\ \frac{dv_y}{dt} = \frac{2(\rho_g - \rho_d)g}{2\rho_d + \rho_g} - \frac{3\rho_g C_D}{2d(2\rho_d + \rho_g)} v_y^2. \end{cases} \quad (11)$$

According to the differential equation of velocity,  $C_D$  is related to  $Re_d$ , and  $Re_d$  is related to the droplet velocity, which makes it very difficult to get an analytical solution by directly integrating. The differential equations are usually solved by a numerical method, the displacement is obtained by carrying out integral for the time with velocity, and then, the trajectory curve is achieved. The ode45 function in MATLAB is used to solve the differential equation of velocity based on the *Runge-Kutta* algorithm.

Four droplet diameters are considered  $d = 20 \mu\text{m}$ ,  $50 \mu\text{m}$ ,  $100 \mu\text{m}$ , and  $150 \mu\text{m}$ , with initial velocity  $v_x = 19 \text{ m/s}$ ,  $v_y = 21 \text{ m/s}$  [19]. According to the ideal gas state equation  $P = \rho RT$ , when ambient gas pressure decreases, ignore the change of temperature; pressure is the function of density. Figure 8 shows the trajectories obtained with different droplet diameters. The results show that the droplet moves outward as the ambient pressure decreases, which indicates large spray cone angles with low ambient pressures.

## 5. Conclusion

The ignition performance is imperative at high altitude reflight condition for usual aircraft engine combustor. The effective fuel/air mixing influenced by the fuel spray angle is one of the pivotal issues determining the ignition. In this paper, an experiment was conducted to investigate the effect of ambient pressure (0.1 MPa to 0.01 MPa, lower than an atmosphere) on spray cone angles.

The results show that the spray cone angle increases as the ambient pressure decreases from 0.1 MPa to 0.01 MPa. The maximum variation of the spray cone angle, which is observed when fuel supply drop through atomizer is 1 MPa, is found to be 23.9%. A mathematical model of a single droplet's movement and trajectory based on force analysis is proposed, and the mathematical results agree well with the experimental results. Both experiment and mathematical model results show that the spray angle increases with ambient pressure decrease.

It should be noted that a very detailed observation of the process of low ambient pressure atomization is needed for a deeper understanding; however, this is beyond the scope of the current work. Such diameter of a droplet will be investigated in our future works.

## Nomenclature

$\Delta P$ :	Pressure drop through atomizer
$P_g$ :	Ambient gas pressure
$M$ :	Mass of the droplet
$V$ :	Velocity of the droplet
$F_D$ :	Drag force
$F_A$ :	Additional mass force
$F_B$ :	Buoyancy force
$F_G$ :	Gravity
$\rho_g$ :	Density of gas
$U$ :	Velocity of gas
$d$ :	Droplet diameter
$C_D$ :	Drag coefficient
$\mu_g$ :	Gas dynamics viscosity
$\mu_d$ :	Liquid dynamics viscosity
$k$ :	Looped flow inside droplet
$h$ :	Droplet deformation
$Re_d$ :	Droplet Reynolds number.

## Data Availability

The research article data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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