Atomization Characteristics by Impingement of Circular Arranged Triple Jets: Off-center Effects

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Abstract

Atomization characteristics by impingement of circular arranged triple-jets is experimentally investigated in the present study with emphasis on the off-center impinging effects. Corresponding experimental apparatus was established to spatially and temporally capture the atomization process by employing a high-speed camera and Phase Doppler Particle Analyzer (PDPA). Jet impinging parameter, *B*, is defined to quantitatively describe the off-center effect, and the desired value of *B* is guaranteed by the intelligent 3D-printing manufacturing technology. From the experimental results, the structure of liquid sheet and ligament formed by head-on and off-center impingement were both observed. It is found that firstly, there exists two types of the structure of the liquid sheet, i.e., closed rim and open rim, in the interested range of impinging conditions. Transition between the two regime is substantially affected by the combination of impinging *We* and *B*. Specifically, smaller *B* would be needed to achieve the open rim at larger impinging *We*. The results show that the larger value of *B* leads to smaller SMD of droplets

Keywords

atomization, jet impingement, spray characteristics, SMD, off-center effect.

Introduction

Atomization by impingement of two or multiple cylinder jets provides certain advantages in terms of the effectiveness of spray and mixing between the ejecting liquids. Such property is responsible for the wide utilization of jet-impinging spray in liquid-fueled combustors, especially in liquid rocket propulsion engines where the fuel and oxidizer need to mix with each other before burning. In order for a desired mixture ratio of fuel/oxidizer, various arrangements of the number of impinging jets may hold applicability, while the type of injector equipped with triplet-jet has been tested as the best one with regard to both the mixing performance and combustion stability[1, 2].

Compared to the double-jet impingement, atomization by triple impacting jets called relati vely limited awareness due to its intrinsic complexity and the asymmetric trait. Understanding of such spray process necessitates further efforts despite the existing results that can be inherited from those in double-jet impingement [3-11]. Among the finite number of papers on such problems, Riebling et al. [12] first tested the mixing efficiency of triplet-jet injector and reported that the parameter of ratio of the liquid flow rate plays a critical rule in the mixing between the impinging jets. Yoon et al. [13] further examined the spray mixing characteristics of liquid bi-propellants in a fuel-oxidizer-fuel (F-O-F) type of impinging injector. By measuring mass distribution of both oxidizer and fuel, the mixing efficiency was verified higher in triplet-jet injector than in other types. Nevertheless, as the jets in their study were arranged in a line within the plane that contains them, the liquid sheet formed was observed confined inside a flat surface perpendicular to the ejecting plane and the atomized droplets thus distributed mainly within a narrow area at each cross-section of the liquid sheet. Panão proposed a three dimensional structure of the liquid sheet formed by impingement of three pieces of jets where the orifices are arranged circumferentially in space [14]. A type of injector integrated with such pattern of jet orifices was reported in their serious studies [15-17], where the structure of liquid sheet was captured and the dispersion pattern of size and velocity of the atomized droplets was measured. Being with an investigation background of depositing liquid onto a solid surface, the authors mainly focus on development of droplet dispersion pattern with regard to time at specific operating conditions. While for the application in combustors, the dependence of steady tri-dimensional spray characteristics on various dynamical impacting parameters is of great importance with regard to droplet distribution, of which a pattern will affect the subsequent spatial configuration of the fuel/oxidizer vapors and heat release during combustion.

Among the predominant dynamical parameters effecting in jet impingement emerges one factor that quantifies the relevance of head-on impact of jets to the off-center impingement that tends to shear apart the interacting jets. A similar topic also arises in the investigation of binary droplet collisions, whereby a correlating nondimensional parameter, *B*, has been well defined and employed to describe the off-center collisions. It is found in these studies that *B* will facilitate the formation of liquid ligament and thus the smaller satellite drops, and gain interaction and mixing between the colliding droplets through shear stretching force [18]. Concerns to the off-center impacting effects in jet-impingement atomization are consequent upon the inevitable existence of misalignment of the impinging jets, which is caused by the limited accuracy of manufacture [17]. *H.gadgild* et al. [19] quantified the fraction of skewness of the impinging jets by the ratio of the offset distance to the jet diameter. In virtue of measuring the mass distribution and the atomizing *Sauter Mean Diameter*, a non-zero component of the moment in the direction of jet propagation was certified leading the formed liquid sheet to deflection when two misaligned jets impinged at one point. *S.Bimal* et al. reported the allowable maximum misalignment of the jets and concluded that if the jet skewness exceeds some certain value, it turns to act as a controlling parameter to the atomization [20]. Despite the existing results, systematic investigation of the misaligned impinging effects on liquid sheet and atomization characteristics still merits efforts.

Based on the earlier mentioned gaps in literature, the present work intends to contribute with experimental evidence and physical understanding to the liquid sheet structure and droplet distribution in atomization by impingement of circumferentially arranged triple jets under the off-center impacting effects. Following this brief introduction to the problem, the experimental setup is presented in Section 2. Afterwards the analysis and discussion of the experimental phenomena presented in Section 3. Finally, concluding remarks are draw pointing to the future work.

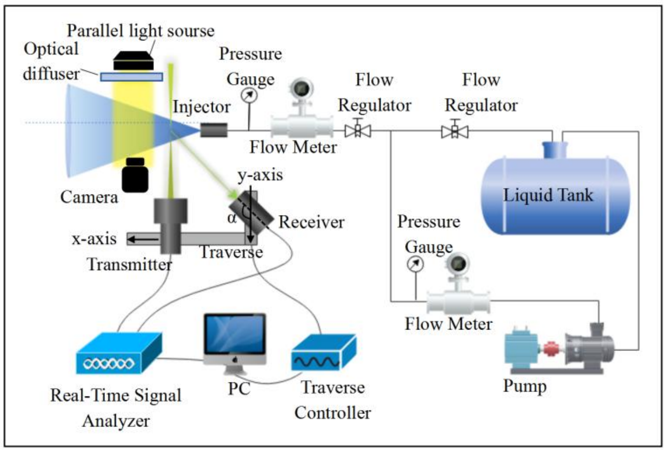
2. Experimental apparatus and measurement methodology

Figure 1a schematizes all the experimental facilities applied in the present work, including the fluid controlling system, jet-impinging injector, and measurement system. High-speed camera and the Phase Doppler Particle Analyzer (PDPA) are employed to record the configuration of jets, liquid sheet, liquid ligament and droplets and to measure the droplets size, velocity and their spatial distribution, respectively.

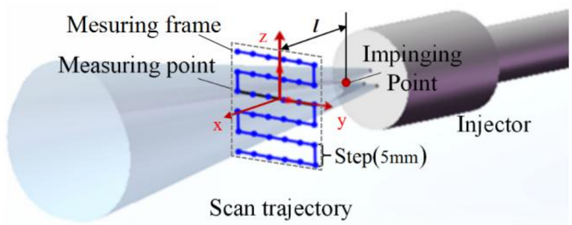
As to liquid controlling system, water is supplied to the injector from a 500 dm^3 volumetric tank, and a piston pump is utilized to pressurize the water up to 3.0 MPa. Diameter of the feedlines of the liquid controlling system is fourfold as that of the orifice of injector to ensure a negligible pressure drop along the pipes. After being pumped, the testing pressurized water branches into two separated passes. The main pass is directing toward the injector, while the other leading back to the liquid tank. The mass flow rate in the main flow-pass is precisely regulated by adequately switching the needle volve set on each flow-pass. The exact value of flow rate and pressure of the supplied water are monitored and measured through flowmeter and pressure gauge respectively. Volumetric flow rate in the present work ranges from 2 to 14g/s, and the ejecting pressure over 1~2MPa.

Visualization of the atomization process is achieved by a set of high speed of camera of Phantom V711 with the recording rate at 5000fps and the exposure time being of 10μs which is assured short enough to freeze the motion on image in one shoot. The lighting source equipped with a 200 mm × 200 mm sized optical diffuser is an intensive halogen lamp.

The PDPA system used herein consists of a 3-D traversing displacement integrated with three mutually perpendicular arms, laser transmitter, laser receiver, a Real-Time Signal Analyzer (RSA) and controller, as shown in Fig. 1a. Four laser beams from the transmitter lies at two kinds of the wavelength of 561nm (referred to yellow light) and 532nm (referred to green light). A commercial software helps to analyze the information acquired from the laser beams. Both the laser transmitter and the receiver are mounted on the traverse arms, whose movement are controlled by the traverse controller. The laser transmitter is installed perpendicular to the traverse arm, and the receiver is oriented at an angle of 147°.



(a)



(b)

Figure1. (a) Schematic diagram of experimental system; **(b)** Measuring point layout

As the major focus in present lies on the steady character of the spray, presentative measuring cross section is selected at a distance $l = 50d$, from the injector facet, as shown in Fig. 1b, under the consideration of practical atomization length in combustors. A measuring frame squared by 100mm×100mm in Y-Z plane ensure all the features of the spray being covered within detecting area of PDPA. Figure.1b shows the specific layout of measurement points and scan trajectory of PDPA in the measuring frame. A strategy of circuitous arrangement of the measuring point is applied with one measuring step of 5mm to suffice the requirement of spatial resolution of the acquired spray structure. The measurement errors from PDPA herein, caused by broadening phenomenon of the Doppler frequency in the measurement, are within 1% and 3% for droplet velocity and size respectively.

3. Definition of off-center impact parameter

Figure 2a illustrates the arrangement of jets that impacting onto one point. The orifices of three jets distribute equally around a circle contained in Z-Y plane (the injector facet). In order for unambiguous description of how the jets interact with each other, we adopt two projected directions, namely view T and view L, to the impingement structure. In view T, the off-center trajectory of impinging jets can be presented that each jet pivot to some certain angle θ, as shown in Fig. 2b, clockwise around the central axis of its orifice. For small values of θ, distance between each two adjacent off-center impinging jets approximately equals to the chord length, Δd, as shown in view L. Therefore, the ratio of misaligned distance between the impinging jets to jet radius appropriately serves as the parameter, B that quantitatively describes the off-center impacting effects as:

$$B = \frac{\Delta d}{d} = \frac{2l\sin\theta}{d} \tag{1}$$

where l is the jet pre-impingement distance; θ is the angle of jet deflection; and D is the jet diameter.

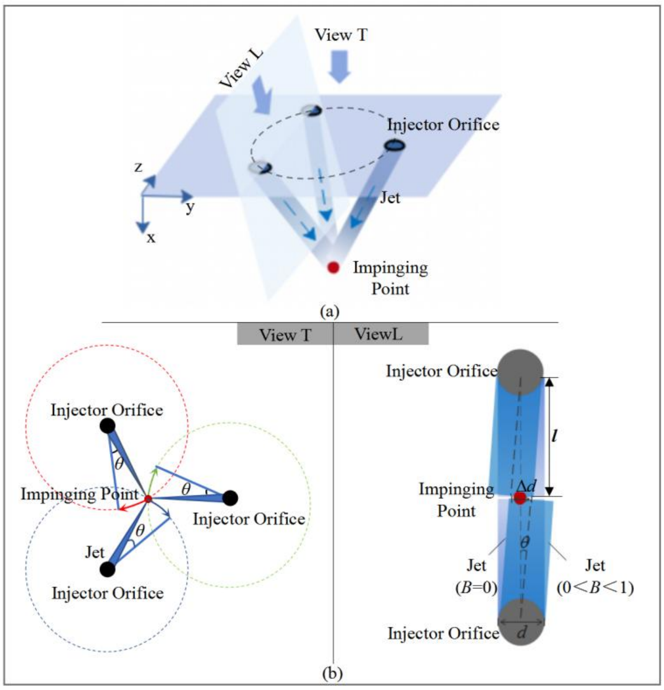


Figure 2. Schematic of off-center impingement system. **(a)** Head-on impingement, **(b)** off-center impingement

Results and Discussion

3.1 The off-center effects on atomization behavior

Regarding the definition of B, the previous chapter gave a detailed explanation. The content of the present study is mainly on experimentally investigating atomization modes by multiple jets impingement under deferring off-center impact parameter, B. Injector integrated with three water jets is employed herein to provide the impinging event. Fabrication of these injectors with different off-center impact parameters are guaranteed by virtue of the intelligent manufacturing technology. Observe the atomization behavior under the same camera view as that of the head-on impingement. It can be seen from Figure 3 that triple jets merged into a fishbone-like liquid sheet .Under various forms of instability, liquid sheet breakup into ligaments, and then disintegrate into drops. And under the same *We*, as *B* increases, the tip of the liquid sheet no longer be closed. Figure 4 shows the relation between the sheet configuration and the *We* and *B*. It can be seen that open tip or closed tip is in turn influenced by the combination of impinging *We* and *B*. The larger *B* is , It is easier to achieve the open tip of the liquid sheet, that is,increasing *B* will promote the formation of liquid ligaments.In particular, it can be found that, the central spine—the projection of the third liquid sheet is no longer in the middle, but is off-center to the left (when *B* is small) or right (when *B* is large).

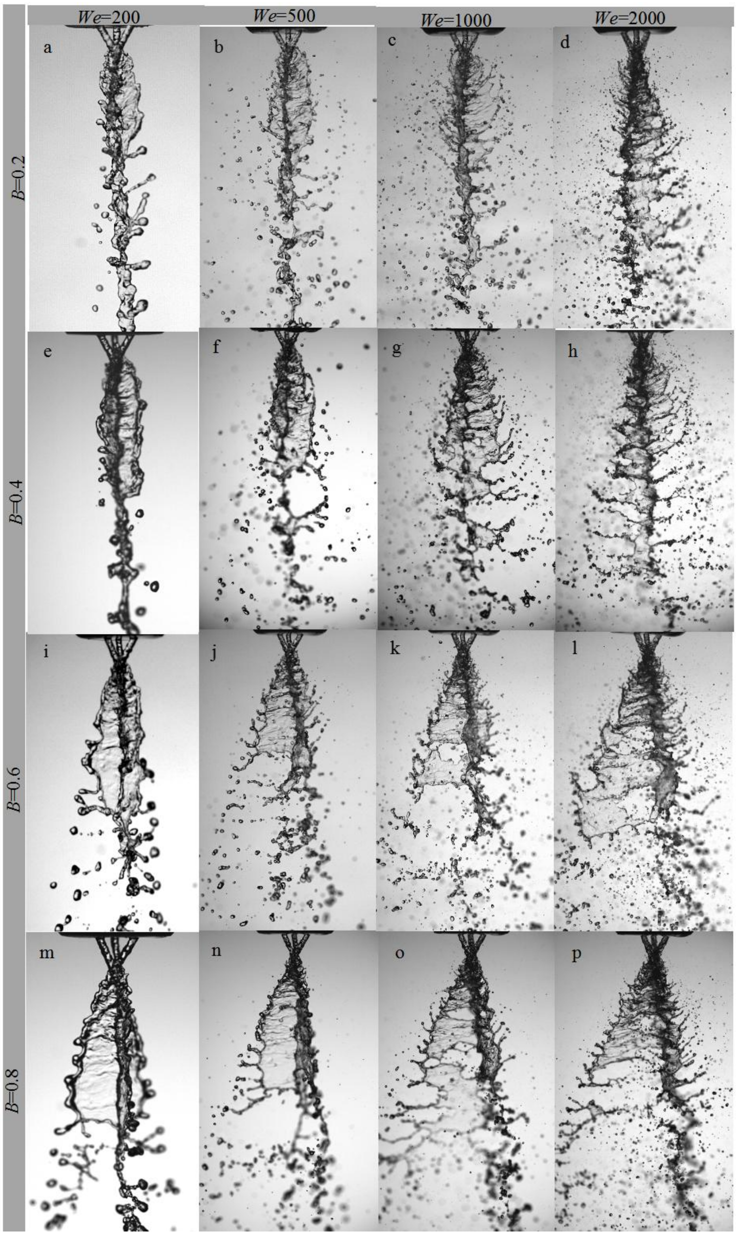


Figure 3. Breakup of sheet formed by off-center impingement under different impinging *We*s

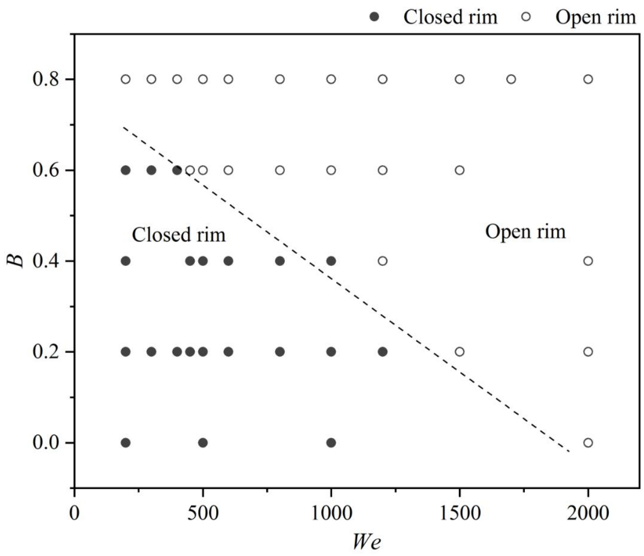


Figure 4. Relation between the sheet breakup regime and the *We* and *B*

In order to explain this phenomenon, we make reasonable guesses. Take the liquid sheet produced by the off-center impingement atomization with *B*=0.2 and *B*=0.8 as an example,shown as fig. 5a. When *B*=0.2, a little part of the jet not collide at the impinging point has an inertial force in the jet direction, which changes the liquid sheet original extension direction. In the view T shown in Figure 5b, the liquid sheets appears to deflect clockwise. When *B* is large(*B*=0.8), there is only a small part of each jet used for the head-on impingement, most of the jets are not involved in the collision, and the shear effect between the two parts produces a shear stretch force in the opposite direction,causing the sheets counterclockwise deflection from the original extension direction, as shown in Figure b. When the impinging *We* increases and the shear tensile force is greater than the surface tension, the liquid sheet is rapidly stretched and breakup into ligaments and drops.

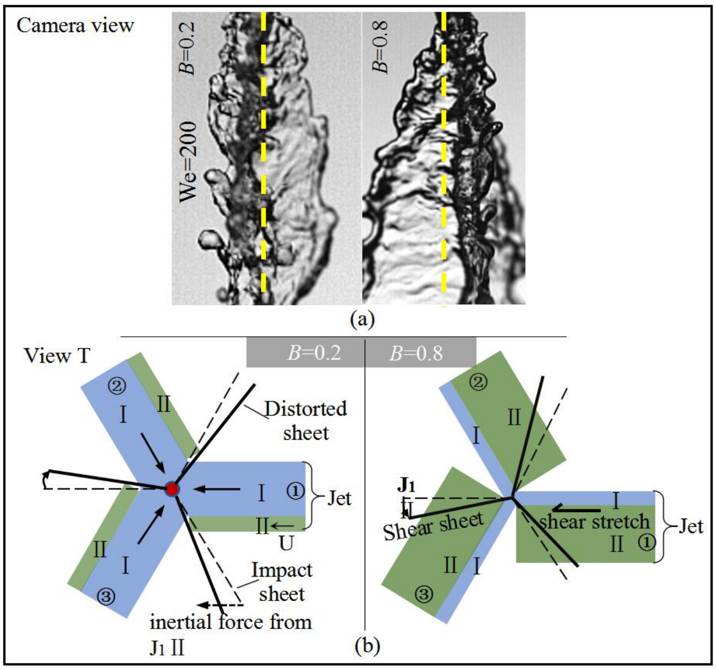


Figure 5. Diagram of off-center effect on liquid sheet

3.2 The off-center effects on atomization droplets characteristics

In the field of atomization, the droplets size and distribution are direct factors to measure the quality of atomization. Using the same working conditions as the above-mentioned liquid sheet characteristics research experiment, within a measuring frame of 100×100mm, the spray droplet size and spatial distribution information are obtained by PDPA measurement.

Figure 6 is a cloud diagram of the spray droplets number distribution with different off-center impingement parameters (*B*=0,0.2,0.6,0.8) under the fixed impinging *We*. To some extent, it shows the spatial distribution of atomized particles on the horizontal slices of the spray. It can be seen that there are three obvious flow concentration zones in the figure, and the distribution is similar to the liquid sheet structure shown in the view T in Figure 5b. That is, in a head-on impingement, the three flow concentration zones are distributed symmetrically and equidistantly. Under the influence of *B*, the three zones will be twisted counterclockwise or clockwise.

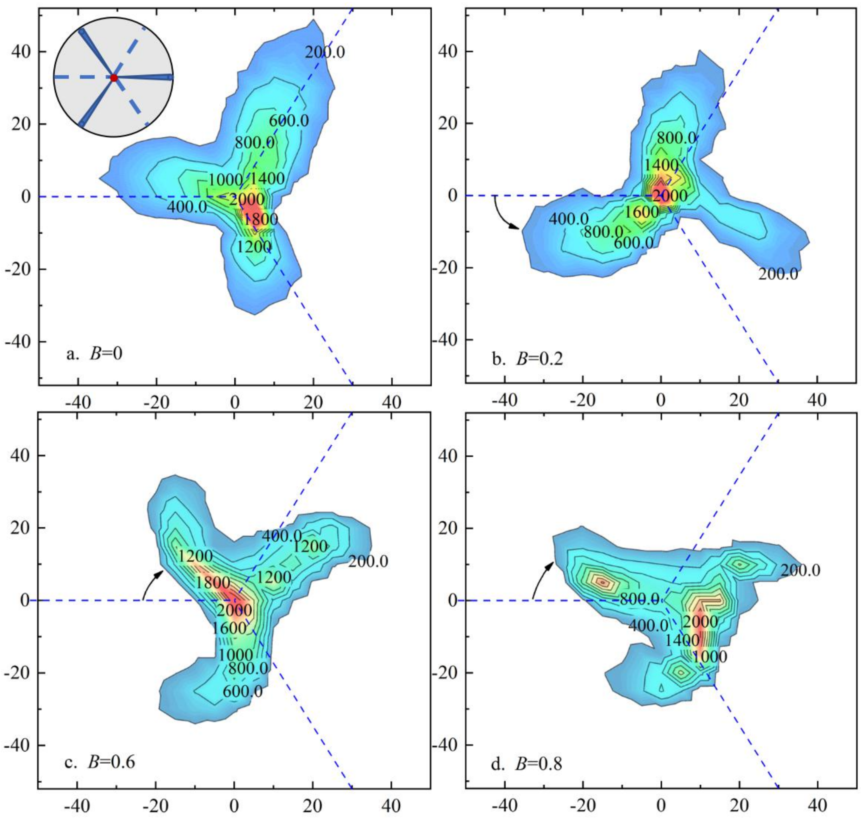


Figure 6. Spacial distribution cloud diagram of the spray droplets number with various *B*s under *We*=1000: **a.** *B*=0;**b**. *B*=0.2; **c.** *B*=0.6; **d.** *B*=0.8

the *Sauter Mean Diameter* (SMD) is an important parameter to measure the quality of atomization. Figure 7 shows the variation of SMD with off-center impinging parameters under different impinging *We*s. It can be seen from the figure that increasing the *B* can reduce the SMD, so it can be concluded that if the SMD is used as a measurement standard, increasing the eccentricity is beneficial to atomizing smaller droplets.

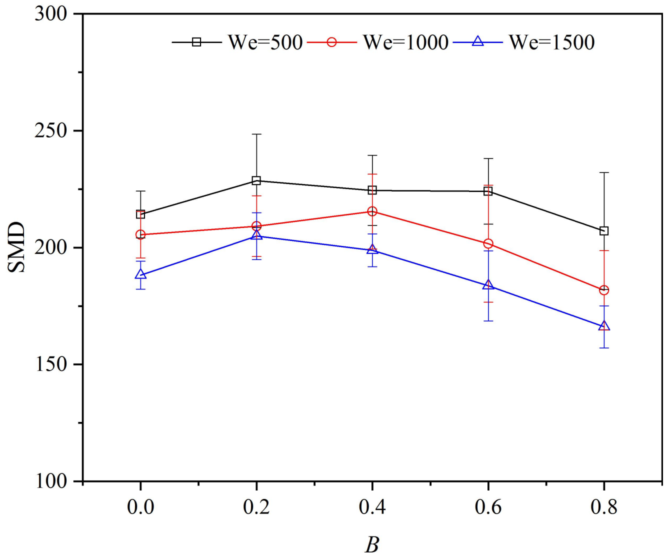


Figure 7. SMD vs. Off-center parameter and impinging *We*

Conclusions

(1) Sheet breakup regime is in turn influenced by the combination of impinging *We* and *B*. The larger *B* is , It is easier to achieve the open tip of the liquid sheet, that is,increasing *B* will promote the formation of liquid ligaments.

(2) Comparing with the liquid sheet formed by head-on impingement atomization, the location of the three sheets is changed. When *B* is small, a little part of the jet not collide at the impinging point has an inertial force in the jet direction, which changes the liquid sheet original extension direction, and the liquid sheets appears to deflect clockwise. When *B* is large, there is only a small part of each jet used for the head-on impingement, most of the jets are not involved in the collision, and the shear effect between the two parts produces a shear stretch force in the opposite direction, causing the sheets counterclockwise deflection from the original extension direction.

(3) Increasing off- center effect parameter *B* can obtain smaller SMD.

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