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Procedia Engineering 99 (2015) 930 – 938
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“APISAT2014”, 2014 Asia-Pacific International Symposium on Aerospace Technology, APISAT2014

Numerical Simulation of the Atomization Process of a Like-doublet Impinging Rocket Injector

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Abstract

A numerical simulation is conducted to characterize the atomization process of like-doublet injector with two different impingement angles. Using the coupled Level-Set/Volume-of-Fluid (CLSVOF) method for capturing the liquid/gas interfaces, liquid sheet characteristics were efficiently captured, and the simulations were found to agree well with experiment results for both breakup characteristics and Sauter Mean Diameter (D_{32}). This method combines the mass conservation properties of the volume-of-fluid method with the accurate surface reconstruction properties of the Level-Set method for a 3D atomization process simulation of the like-doublet injector. Since the velocity profiles around the stagnation point and impingement point greatly affects the sheet characteristics, the velocity profiles of different axial locations on the cross section for two different impingement angles cases are studied. It shows that the velocity difference caused by the impact of liquid jets is one of the important factors which directly affect the formation of surface wave and the breakup of sheet

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Keywords: Liquid rocket engine; Like-Doublet injector; Impingement angle; Atomization; CLSVOF

1. Introduction

Impinging jet injector elements are the preferred injector geometry for both boost and orbit transfer rocket engines because of its simple fabrication and good spray and mixing characteristics, especially for the engines which use storable propellants or liquid hydrocarbons. It delivers both fuel and oxidant into the combustion chamber and

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Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)
doi:10.1016/j.proeng.2014.12.624

provides mixing through fine atomization and good space distribution. In this configuration, two or more liquid jets with the same properties impinge on one another at a certain impingement angle to form a thin liquid sheet. The liquid sheet thins with the radial distance from the impingement point, and the fluctuation of the liquid continues to increase until reaching the breakup point, at which the liquid sheet disintegrates into large liquid clumps and then disintegrates into finer droplets downstream[1].

Extensive numerical, experimental and theoretical studies have been carried out on the mechanism of the impinging jets atomization. Taylor[2] modeled analytically the shape and thickness of liquid sheet formed by liquid jets, and compared the results with the experimental data. Dombrowski and Hopper[3] studied the factors influencing the break-down of sheets formed by the impingement of liquid jets. It was shown that waves on the liquid sheet are influenced by the impact force of two liquid jets, and the characteristics of spray atomization are determined by the growth and breakup of these waves. Anderson et al.[4] conducted an experiment to characterize the formation and effect of impact waves on the atomization process. Relations between the breakup periodicity and combustion instability are presented by comparing the breakup frequency with instability frequencies of actual rocket combustors. Kihoon Jung et al.[5]focused on the effects of the orifice inner flow characteristics and found that the effects of turbulence inside the sharp-edged orifice are significant for the breakup of liquid sheet, and the cavitations tends to increase the turbulence strength. Ri Li and Nasser Ashgriz[6] conducted an experimental investigation of liquid sheets formed by the impingement of two capillary liquid jets, and the breakup mechanism of the sheets is categorized into two regimes and five sub-regimes based on the experimental observations. G.Bailardi et al.[7] investigated the atomization characteristics of various Newtonian fluids with a like-doublet impinging jet injector under ambient pressure and temperature conditions and jet velocities up to 80m/s.

In most of the studies mentioned above, the impinging-jet injector sprays have mainly been characterized experimentally and theoretically, because the atomization processes of such injectors are complex and strongly three-dimensional. Nowadays, with the rapid development of computer technology and calculation method, the simulation techniques have been applied to simulate the primary atomization of impinging jet[8,9]. Inoue et al.[10]used a cubic-interpolated propagation hybrid level set method (CIP-LSM) and a multi-interface advection and reconstruction solver (MARS) technique to capture the liquid surface and showed the formation of the characteristics fan-shaped sheet. Li at al.[11] demonstrated the effectiveness of coupling the Combined Level Set Volume of Fluid (CLSVOF) formulation with the Lagrangian tracking of the spray on a dynamically adaptive, block-structured grid. Qiang Hong-fu et al.[12] used the Smoothed Particle Hydrodynamics (SPH) method to simulate the atomization process of impinging jets. Xiaodong Chen et al.[13]used an accurate adaptive solver for surface-tension-driven interfacial flows, and investigated the physical mechanism of formation of impact wave and mixing process in the atomization of impinging jets. The effect of impact wave on mixing process of both miscible and immiscible impinging jets is also addressed. Dong-Jun Ma et al.[14] performed a high fidelity numerical simulations to study the atomization patterns and breakup characteristics of liquid sheets formed by two impinging jets. A fully three-dimensional Volume-of-Fluid method is used with the adaptive mesh refinement (AMR) based on octree meshes. In conclusion, the numerical analysis has the potential to be a helpful tool in simulating the atomization process of liquid rocket injectors. However, there are few analyses that treat the atomization process of impinging jet injector with different impingement angle.

This present study focuses on the detailed atomization process of liquid sheet, where experimental measurement is different. The objective is to investigate the primary atomization of the like-doublet injector with two different impingement angles. To clarify the flow inside the sheet, the velocity profiles are varies and the effects on breakup are investigated in detail. In addition, the experimental results were used to validate the numerical method.

2. Numerical method

An important aspect of numerical simulation of atomization process of like-doublet injector is accurate capturing the liquid/gas interfaces. In this paper, we choose CLSVOF method to simulate the 3D moving interface of liquid sheet. The description of the CLSVOF method can be found elsewhere, together with several validation studies.15-17 This method combines the VOF method with the LS method, and generally superior to either method alone. Here, the interface-tracking method is introduced as follows.

Considering a viscous and incompressible flow assumption, the three dimensional incompressible, variable-density, conservation equations with surface tension can be written as:

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\rho(\partial_t \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}) = -\nabla p + \nabla \cdot (2\mu \boldsymbol{D}) + \sigma\kappa\delta_s \boldsymbol{n} \tag{2}$$

$$\nabla \cdot \boldsymbol{u} = \boldsymbol{0} \tag{3}$$

Where $\boldsymbol{u} = (u, v, w)$ is the fluid velocity, $\rho \equiv \rho(x,t)$ is the fluid density, $\mu \equiv \mu(x,t)$ is the dynamic viscosity, and $\boldsymbol{D}$ is the deformation tensor defined as $D_{ij} \equiv (\partial_i u_j + \partial_j u_i)/2$. The Dirac delta function δ_s express the fact that the surface tension term is concentrated on the interface; σ is the surface tension coefficient, κ and $\boldsymbol{n}$ are the curvature and normal to the interface, respectively.

The coupled level-set and VOF method is introduced to trace the two-phase interface, which combines the mass conservation properties of the volume-of-fluid method with the accurate surface reconstruction properties of the level-set method.[15,16] The level-set function ϕ is defined as a signed distance to the interface. Accordingly, the interface is the zero level-set $\phi(x,t)$, and can be expressed as $\Gamma(t) = \{x \in \Omega : \phi(x,t) = 0\}$ in a two-phase flow system:

In the level-set method, the interface is captured and tracked by the level-set function and defined as a signed distance from the interface:

$$\phi(x,t) = \begin{cases} +K(x, \Gamma(t)), x \in \Omega_1 \\ 0, x \in \Gamma \\ -K(x, \Gamma(t)), x \in \Omega_2 \end{cases} \tag{4}$$

For this function, it is zero at the interface, positive in one side of the interface and negative in the other side. K is the distance from the interface, Ω_1 and Ω_2 represent the area of two different phase respectively.

The normal and curvature of the interface, which is needed in the computation of the surface tension force, and can be estimated as:

$$\boldsymbol{n} = \frac{\nabla\phi}{|\nabla\phi|}\Big|_{\phi} = 0 \tag{5}$$

$$\kappa = \nabla \cdot \frac{\nabla\phi}{|\nabla\phi|}\Big|_{\phi} = 0 \tag{6}$$

And the evolution of the level-set function can be given in a similar fashion as to the VOF model:

$$\frac{\partial\phi}{\partial t} + \nabla \cdot (\boldsymbol{u}\phi) = 0 \tag{7}$$

Where $\boldsymbol{u}$ is the underlying velocity field.

The momentum equation can be written as:

$$\frac{\rho\partial\boldsymbol{u}}{\partial t} + \rho\boldsymbol{u} \cdot \nabla\boldsymbol{u} = -\nabla p + \nabla \cdot \mu[\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T] - \sigma\kappa\delta(\phi)\nabla\phi + \rho\boldsymbol{g} \tag{8}$$

$\delta(\phi) = \dfrac{1+\cos(\pi\phi / a)}{2a}$ if $|\phi| < a$ and $\delta(\phi) = 0$ if $|\phi| > a$. $a = 1.5h$ （h is the grid spacing）, ρ , p , g for the density, pressure and acceleration of gravity respectively.

3. Injector dimensions and operating conditions

For like-doublet injectors, the primary atomization process consists of the collision of two liquid jets forming a liquid sheet, which subsequently disintegrates into ligaments and droplets some distance downstream of the impingement point. And the formation of the liquid sheet is believed to be caused by the creation of a high-pressure stagnation region at the impingement point where the momentum of the two jets towards each stopped and the liquid is forced to spread outward in the lateral direction from the impingement point[1].

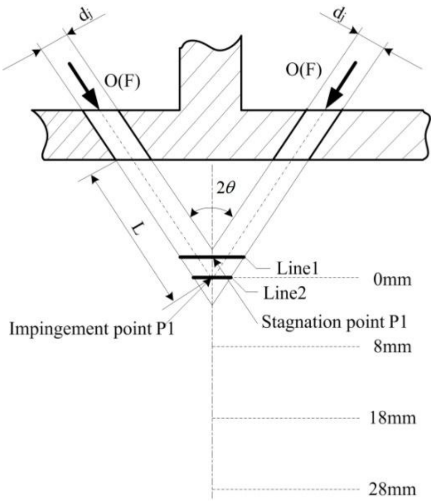


Fig.1 The schematic of like-doublet injector

Figure 1 shows a representative drawing of a like-doublet impinging injector. For the present work the impingement angle (2θ) of 50 deg and 80 deg and a pre-impingement length (L) of 5mm have been chosen. The diameter (d_j) of the two jets is takes the common value of 1mm. As can be seen in Figure 1, the velocity profiles of two different locations on the cross section were chosen for investigated, Line 1 near the stagnation point while Line 2 near the impingement point.

Since the atomization and mixing processes of the like-doublet injectors are strongly three-dimensional, we consider the full size three-dimensional simulation of the atomization process. Figure 2 shows the grid system, X, Y, Z axis are defined as illustrated in the figure. The computational domain consists of $x \times y \times z = 35mm \times 24mm \times 10mm$ stencils. Two liquid jets collide with each other in the cross section of z=0. Several grid systems were investigated and the results shown in this paper used 2100,000 computational cells. To capture the characteristics of the liquid sheet, finer grids were arranged around the plane of Z=0, the minimum grid size is 40 um. The nozzle radius was resolved with 72 grids of 0.5mm in width.

Besides numerical simulations, the present research composes several corresponding experiments, and the simulation results are verified by the experimental results. The corresponding experiments also chosen water as the working fluid and were conducted using the optical measurement system under the condition of atmospheric environment. The behavior of the liquid sheet was observed using the high-speed video camera. The D_{32} was measured at different planes along the X axis. (50 deg case chose X= 8, 18, 28 mm, while the 80 deg case chose X= 10, 20, 30 mm). The final D_{32} results at different planes were get after an average of data obtained from different position on the plane.

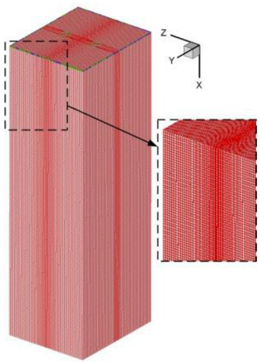


Fig. 2 Computational Grid System

The properties of the working fluids and the boundary conditions are shown in table 1. The inertia force, surface tension, viscous force and gravity force have been taken into account in the present flow model.

Table 1. Physical properties and boundary conditions.

Physical properties		Boundary conditions	
Fluid	Water	Ambient pressure	1atm
ρ [kg/m^3]	998.2	Mass flow rate	20g/s
μ [$Pa \cdot s$]	0.001003	Re	25389
σ [mN/m]	72.5	We	8948

4. Results and analysis

4.1. Liquid sheet formation process

Figure 3 compares the snapshots obtained from experiments and the numerical simulation for a spray generated by the like-doublet injector. Similar flow patterns are observed for direct image comparison, mainly in the zones near the impingement point. General features of atomization such as the breakup length are well represented and the surface wave downstream the impingement point are captured.

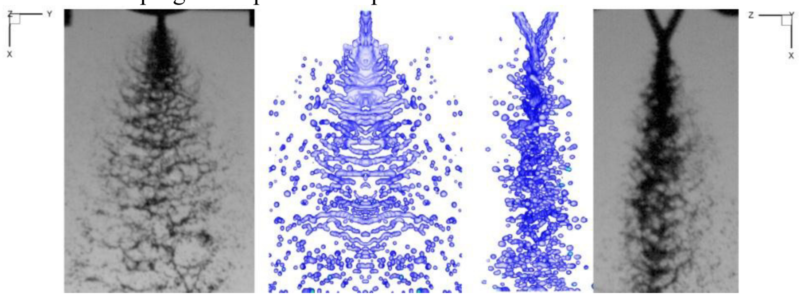


Fig.3 Liquid sheet characteristics at different instants of time.

Figure 4(a) and (b) shows the characteristics of liquid sheet at different instant times in the atomization process of like-doublet injector. As can be seen from the figures, the whole atomization processes are dominated by violent impact waves that form at the impingement point and propagate down the length of the sheet. The whole process can be divided into three stages. The first stage starting at the impact of two liquid jets, this causes a thin sheet to form perpendicular to the two impinging jets; The second stage starting at the moment of forming liquid ligaments. In this stage, the liquid sheet deformed by surface waves which caused by aerodynamic waves and hydrodynamic force. The third stage begins after the second stage with the formation of numerous drops shed from the ends of the ligaments. The phenomenon observed by present simulation results are consistent with the experimental results described in literature [1].

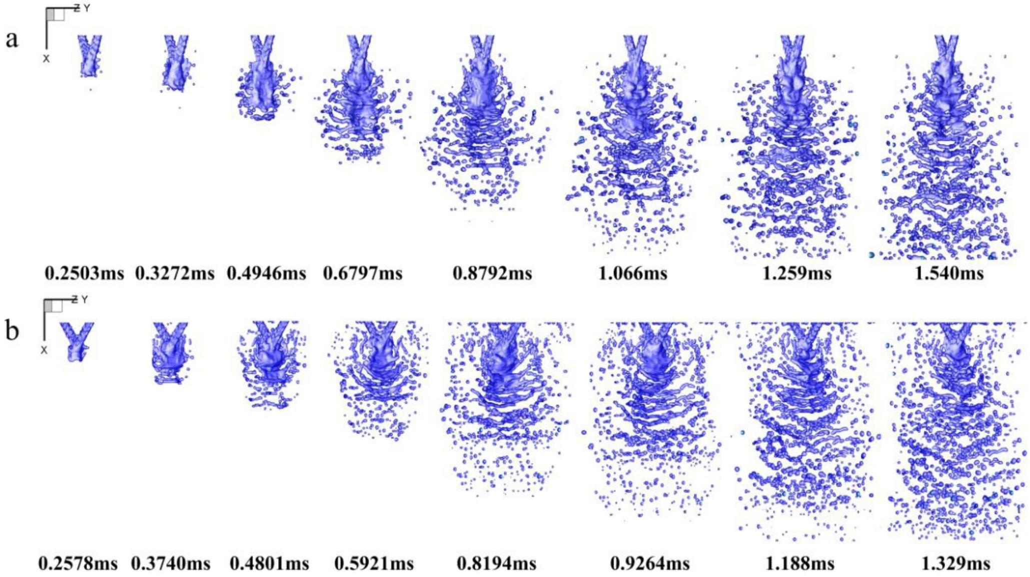
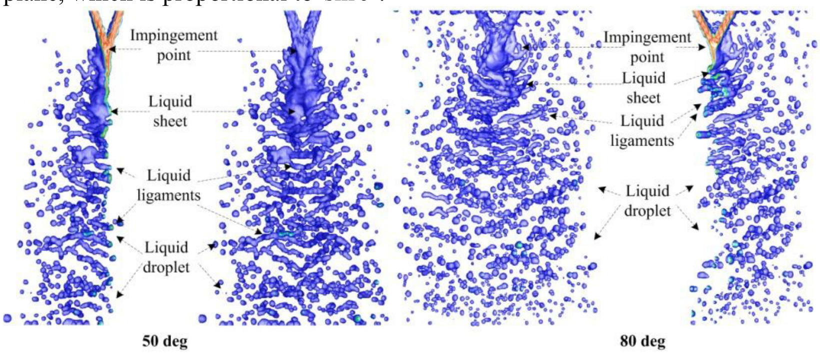


Fig.4 Liquid sheet characteristics at different instants of time. (a)50 deg; (b) 80 deg.

4.2. Characteristics of liquid sheet

Figure 5 and Figure 6 shows a comparison of two different shapes of liquid sheet formed by 50 deg and 80 deg respectively. Due to the fluctuation of liquid sheets, the shapes of sheets will be somewhat different at various instant of times, so figure 5 and figure 6 just represent the sheets of a single moment. As can be seen from figure 5 , it is obvious that two cases have a greater similarity in liquid shape and breakup mode. The width of sheet and the amplitude of surface wave on the sheet of 80 deg case are larger than those of 50deg case. Longer breakup length and smaller liquid droplets distribution around the impingement point are show up in the 50 deg case. Sheet breakup of 80deg case is more intense than that of 50 deg case and result in smaller ligaments and droplets. From Figure 6 we can see the side view of the two cases, this results shows that the 80 deg case has larger liquid distribution in XZ plane, which is proportional to $\sin\theta$.



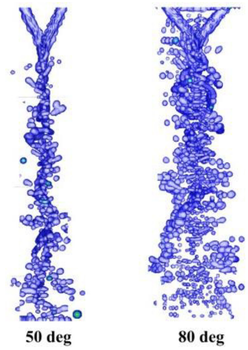


Fig.5 Overview of liquid sheets

Fig.6 Side view of liquid sheets

Figure 7 shows liquid distributions in 3 planes along X direction from the face plate. The position on the X direction are 8, 18 and 28mm. It could be seen that the ranges of liquid distribution on YZ planes are increase with the increasing distance away from impingement point, which corresponding with the atomization process. The liquid sheet formed after the impact of two liquid jets each other around the X=8mm plane, and then it largely deforms with dispersion of liquid ligaments from the edge of sheet around X=18mm plane. At the downstream plane of X=28mm, the liquid sheet and ligaments totally breakup into drops. It can be observed that the size of liquid drops of 80 deg case is smaller than that of 50 deg case.

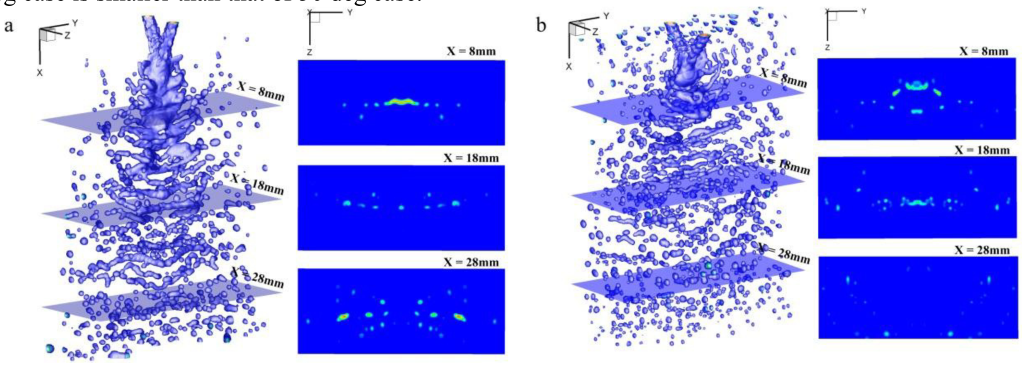


Fig.7 Liquid distribution at different planes along the X axis. (a) 50deg; (b) 80deg.

4.3. Sauter Mean Diameter (D_{32})

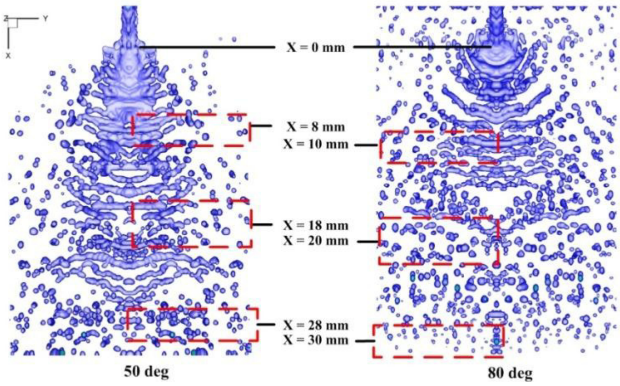


Fig.8 Droplets selection area at different position

Table 2. Comparison of the simulation results and experimental results.

Impingement angle (deg)		50			80		
Distance from the Impingement point (mm)		8	18	28	10	20	30
D_{32}	Experimental results (μm)	125	141	139	129	125	127
	Numerical results (μm)	168.3	158.2	161.6	147.1	149.2	140.9
Relative error (%)		34.64	12.19	16.26	14.03	19.36	10.94

According to the simulation results, we select a rectangular area at different position corresponding to the experimental measurement position (Figure 8). The D_{32} was statistically measured by averaging 5 set of data obtained at different instant of times. The D_{32} after atomization of impinging jet injector under different impingement angle is shown in table 3 comparing with experimental data. And the results show that the numerical values are larger than the experimental values, while the relative deviation were less than 20% except one position of the 50 deg case. It indicated that the model can reflect the atomization process and the numerical method has a certain rationality and feasibility. The reasons of the exitence of error mainly has the following several aspects. Firstly, the boundary conditions of numerical simulation have certain difference with the experimental work condition because the flow process inside of the injector has not been taken into account. Secondly, the measurement errors exist in the experimental data. Thirdly, effects due to limited grid resolution cannot be completely ruled out in the results, which consistently underestimate the size of drops.

4.4. Velocity profile analysis

Figure 9 shows the velocity profiles of different axial locations on the cross section. Line 1 is near the stagnation point, while Line 2 is near the impingement point. Figure 9 (a) and (b) shows the velocity profile and component velocity in the Z direction around location 1. It is clear that the velocity is the lowest at the center, and velocity on both sides of Line 1 is approximately equal to the jet velocity for two cases. Velocity at the center of 50 deg case is larger than that of 80 deg case. From Figure 9 (b) we can see that the component velocity in the Z direction for both cases is almost the same on the two sides of Line 1, but in the opposite direction. It has been found that the component velocity in the Z direction of 80 deg case is larger, this is due to the greater momentum generated, which is also proportional to $\sin\theta$.

The velocity profile and component velocity in the Z direction on Line 2 were shown in Figure 9 (c) and (d). On this position, the velocity profile at the center increases slightly, and the velocity on both sides of Line 2 also approximately equal to the jet velocity. For both cases, the points with the lowest velocity are slightly off center, which caused by the fluctuation of liquid sheet.

Through above analysis, we can infer that the reason for the shorter breakup length of 80 deg case due to the greater impact force generated. The velocity difference around the stagnation point and impingement point is an important factor of the liquid sheet instability and may be the major causes of surface wave which directly affects the breakup of liquid sheet. Different impingement angles result in different component velocity in the Z direction on Line 1 and Line 2, which influences the amplitude of the surface wave and the liquid distribution at Z direction.

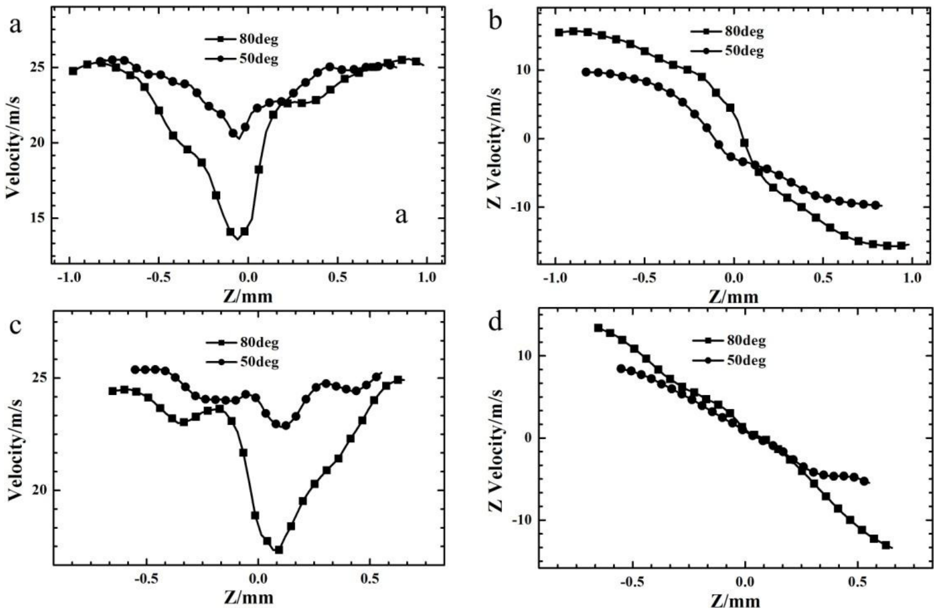


Fig.9 Velocity distribution around the stagnation point and impingement point. (a) Velocity profile of line 1; (b) Component velocity in the Z direction of line 1; (c) Velocity profile of line 2; (b) Component velocity in the Z direction of line 2.

5. Conclusions

This study establishes the CLSVOF method as a tool for predicting spray atomization of two different impingement angles without empiricism. The characteristics of the liquid sheet breakup and the formation of surface wave and D32 from this method show overall agreement with both trends and magnitudes of the experimental results. The CLSVOF method has been verified not only qualitatively but also quantitatively through the simulation of atomization process like-doublet injector. The numerical results show that the formation of surface wave significantly affects the breakup of liquid sheet, which has a great relationship with impingement angle. For larger impingement angle, higher impact force generated, which directly affects the amplitude of surface wave and the velocity profile around stagnation point and impingement point.

In this paper, liquid distributions from injector face plate were visualized. It found that the size of droplets is smaller in axial direction with spreading in the cross section for larger impingement angle case. The velocity difference around the impact point strongly affects liquid distributions of atomized ligaments and drops at downstream.

Further research is necessary in order to clarify the relationship between the atomization characteristics of liquid sheet and the impingement angle for like-doublet injector.

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