Numerical Simulation of Internal Flow and External Atomization in Pressure Swirl Nozzle

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Abstract. A computational fluid dynamics (CFD) study is carried out on the internal flow characteristics of pressure swirl nozzle and the breakup of external liquid film outside the nozzle. The numerical simulation of two-phase flow shows the unsteady characteristics inside the nozzle and the breaking mechanism of liquid film outside the nozzle. In the nozzle, the numerical simulation reveals the three-dimensional velocity distribution in the swirl chamber and the nozzle outlet. At the same time, the study shows that the breakup of liquid film is caused by the circumferential disturbance wave produced by R-T instability under the condition of 0.7 MPa inlet pressure. The influence of inflow characteristics on the instability of liquid film is pointed out.

1. Introduction

Liquid atomization is the process of liquid breaking to produce a large number of small droplets. It is widely used in fuel injection, spray drying and agricultural spraying. It aims at producing high surface area in liquid phase. For example, in gas turbine, fuel atomization can enhance the mass and energy transfer between liquid fuel and circumferential gas, and make the fuel air mixture more homogeneous and increase combustion efficiency.

As a device to realize atomization, pressure swirl nozzle has been widely used because of its good atomization quality and relatively simple geometric structure. Its working principle is to depend on the hydraulic pressure to atomize. The liquid is forced to rotate in the nozzle under pressure and form air core. Then the nozzle is ejected in the form of rotating liquid film. Under centrifugal force, the nozzle expands outward into a conical liquid film, and finally breaks up into oil droplets under the combined action of external aerodynamic force and internal force of the liquid flow.

Figure 1. Atomization principle of pressure swirl nozzle
Vladimir used CFD to study the influence of different nozzle geometric characteristics on atomization characteristics, the calculated internal velocity distribution is in qualitative agreement with the experimental results [1]. Laurila studied the internal flow of swirl atomizer with asymmetric intake structure by computational fluid dynamics (CFD). It was found that the internal flow exhibited completely different characteristics under laminar, transitional and complete turbulence conditions [2]. Amini built the velocity field analysis model of pressure swirl nozzle through theoretical analysis [3]. The study of Ashgriz shows that instability first breaks the liquid film into ligament, and then breaks into droplets [4]. Ponstein studied the instability growth of disturbance theoretically and derives the dispersion relation of disturbance growth in inviscid fluid [5]. Seneca studied the effect of disturbance growth on breakup in a planar liquid film [6].

The atomization characteristics of liquid fuel, such as velocity distribution and external liquid film breakage, are the key factors affecting the performance of the system. A thorough understanding of the flow characteristics and external atomization mechanism is bound to provide important help for the development of high-performance atomization nozzles.

2. Numerical method

2.1. Turbulence Equation

The turbulence model RNG K-ε is chosen in this paper, considering the effect of eddy current on turbulence, to improve the simulation accuracy of rotating flow. The equation form is as follows:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b + \rho \varepsilon - \frac{\rho \varepsilon}{\tau} Y_M S_k
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left( \alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} \left( G_k + C_{3\varepsilon} G_b \right) - C_{2\varepsilon} \frac{\rho \varepsilon^2}{k} - \frac{\rho \varepsilon}{\tau} R + S_\varepsilon
\]

2.2. VOF method

The principle of pressure swirl atomization involves gas-liquid two-phase flow. In this paper, VOF interface capture method is used to capture the phase interface in the inner and outer regions of the nozzle. When air is the main phase, water is the secondary phase and the volume fraction of liquid phase in a cell is \( \alpha \), there are three situations: \( \alpha = 0 \): there is no liquid phase in the cell, and all the cells are air; \( 0 < \alpha < 1 \): the gas-liquid mixture phase in the cell; and \( \alpha = 1 \): all the cells are liquid. The volume fraction equation can be expressed as:

\[
\frac{1}{\rho_q} \frac{\partial}{\partial t} \left( \alpha_q \rho_q \right) + \nabla \cdot \left( \alpha_q \rho_q \vec{v}_q \right) = S_{\alpha} + \sum_{p=1}^{n} \left( \dot{m}_{pq} - \dot{m}_{qp} \right)
\]

2.3. Geometric Model and Computational Mesh

The computational domain consists of two parts: 1) the upper part is a pressure swirl nozzle, including four inlet passages, swirl chamber, convergence section and outlet section; 2) the lower part is a cylindrical computational domain outside the nozzle. The nozzle uses tetrahedral unstructured mesh, the entrance wall and swirl chamber wall use prism mesh to refine boundary layer, and the nozzle uses hexahedral structured mesh outside, and improves the mesh density. The adaptive mesh method AMR is used to refine the mesh to capture the two-phase interface, obtain the best accuracy and shorten the calculation time.
The curvature-based adaptive mesh refinement method (AMR) is used to capture the two-phase interface, obtain the best accuracy and shorten the calculation time. The AMR mesh area is chosen as the cylindrical space below the nozzle outlet to ensure that the area related to atomization breakup can be covered at the same time. The refinement interval is 10 time steps. With the secondary AMR level, the basic grids in the cylindrical computing domain are about 700,000 before refinement, and the refined grids can reach 5 million at most.

3. Numerical Study

3.1. Internal Velocity Analysis

The velocity vector can be decomposed into axial velocity, tangential velocity and radial velocity. Under the condition of 0.7 MPa inlet pressure, the cross section of \( Y = 13.5 \) mm in the swirl chamber is selected, and the three-dimensional velocity distribution is shown in the figure3. The tangential velocity inside the nozzle shows a bimodal distribution. From the wall to the section center, the tangential velocity first increases and then decreases rapidly along the radius direction. The location of the peak is the gas-liquid interface. In addition, the tangential velocity of the liquid is much larger than the axial and radial velocities, so the motion of the liquid in the swirl chamber is a spiral motion dominated by the tangential velocity.

The radial velocity in the swirl chamber is much smaller than the tangential velocity. From the curve, it can be seen that the fluctuation is small on the zero scale line. Because of the existence of air core inside the nozzle, the axial velocity field in the middle region is negative, which is contrary to the downward axial velocity of the liquid. This is consistent with the actual phenomenon of air sucking into the nozzle from the center of the nozzle outlet caused by pressure difference.
The velocity distribution of the liquid film at the nozzle outlet has a great influence on the atomization breakup, because the velocity fluctuation at the outlet will cause the initial disturbance of the liquid film, leading to subsequent breakup. Compared with the inner part of the swirl chamber, the tangential velocity of the outlet section decreases, the proportion decreases, the peak value drops to 10.52 m/s, and the tangential velocity of the middle part of the air core approaches zero. On the contrary, the maximum axial velocity of liquid phase increases to 13.17 m/s. Due to the existence of negative pressure zone, gas reflux occurs, and the axial velocity at the center decreases rapidly and shows negative value, the axial velocity in the middle of the gas core is quite different from that in the swirl chamber. The radial velocities of liquid and gas phases are very small, similar to those in the swirl chamber, and both oscillate slightly at the zero scale.

Figure 3. Velocity Distribution in Swirl Chamber

Figure 4. Velocity Distribution in Nozzle outlet section
3.2. Internal Velocity Analysis

There are many factors affecting the breakup of liquid film, such as the uneven distribution of velocity, the oscillation of air core and the instability caused by the interaction with surrounding gases. Moreover, because of the complexity of the breakup process, it can not be attributed to a single breakup mechanism. As shown in the figure, the key characteristics of liquid film breakage under 0.7 MPa condition are analyzed.

As shown in the figure, the hollow conical liquid film near the nozzle exit is basically intact, but due to the non-uniformity of the velocity field, there is an irregular disturbance (I) on the surface of the liquid film, which results in the local perforation of the liquid film, as shown in figure (II). At the same time, the fluctuation along the circumferential distribution on the surface of the liquid film can be clearly seen. This circumferential fluctuation Rayleigh-Taylor instability leads to a typical mode of liquid film rupture and instability, which is essentially due to the density difference between the gas phase and the liquid phase. Galbiati also found similar circumferential fluctuations through direct numerical simulation of DNS [7]. The continuous development of fluctuations leads to insufficient surface tension to suppress fluctuations, which makes the liquid film thinner. When the thickness of the liquid film decreases to a certain extent, the breakdown between the two peaks will occur, resulting in the appearance of annular strip liquid structure, as shown in (III). Under the action of aerodynamic force, the large-scale liquid belt is stretched and fractured into a shorter one. Under the action of surface tension, the discrete small size strip liquid structure shrinks and wraps into large spherical droplets, as shown in (IV). The size of the strip is related to the diameter of the liquid strip. Detailed details of liquid film breakdown are obtained by numerical calculation. It can be qualitatively considered that the R-T unstable wave is the main factor leading to the breakup of liquid film into liquid ligament and droplet.

![Figure 5. Breakup of Conical Liquid Film](image)
4. Conclusion
In this paper, the characteristics of velocity distribution in pressure swirl nozzle are studied by computational fluid dynamics (CFD). The velocity distribution shows a drastic change at the phase interface. In addition, numerical simulation captures the details of liquid film rupture well. The conical liquid film first breaks into strips under the action of R-T instability. Under the action of perturbation and gas shear, the thickness of some liquid film surfaces gradually becomes thinner, and the liquid film shrinks to form holes, which then expand rapidly. The liquid membranes break up and form sheet liquid membranes, which gradually shrink into liquid belts under the action of surface tension, and finally break into droplets under the action of aerodynamics.

References
[1] Vladimir. Bazarov, Hinckel, J, N, H. F. Villa Nova, and. CFD analysis of swirl atomizers[C]. Aiaa Joint Propulsion Conference & Exhibit 2013.
[2] Laurila E, Roenby J, Maakala V, et al. Analysis of viscous fluid flow in a pressure-swirl atomizer using large-eddy simulation[J]. International Journal of Multiphase Flow, 2018.W. Strunk Jr., E.B. White, The Elements of Style, third ed., Macmillan, New York, 1979.
[3] Amini G. Liquid flow in a simplex swirl nozzle[J]. International Journal of Multiphase Flow, 2015, 79:225-235.
[4] Ashgriz, Nasser. Handbook of Atomization and Sprays [M]. Springer US, 2011.P.G. Clem, M. Rodriguez, J.A. Voigt and C.S. Ashley, U.S. Patent 6,231,666. (2001)
[5] Ponstein J. Instability of rotating cylindrical jets[J]. Applied Scientific Research, 1959, 8(1):425-456.
[6] Senecal P K, Schmidt D P, ouar I, et al. Modeling high-speed viscous liquid sheet atomization[J]. International Journal of Multiphase Flow, 1999, 25(6-7):1073-1097.
[7] Galbiati, C., Ertl, M., Tonini, S., Cossali, G.E., Weigand, B., 2016a. DNS investigation of the primary breakup in a conical swirled jet[J]. Springer International Publishing, Cham, pp. 333–347. doi: 10.1007/978-3-319-24633-8.