Effects of inlet pressure and inlet flow rate on the flow field in a pressure-swirl atomizer

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The dual-fuel circuit pressure-swirl atomizers are numerically studied by the finite volume method with the inside kerosene flowing under the boundary condition of mass-flow-inlet (300L/h~580L/h) and pressure-inlet (1.44MPa~3.04MPa) respectively. It is suggested that the velocity magnitude of the area near the wall of outlets, as significant parts of the internal flow filed of the atomizer, increases nearly linearly with the flow rate and the pressure of inlets. Furthermore, outlet flow rate slowly increases with the increasing inlet pressure under the pressure-inlet boundary condition and the fuel supply pressure of vice orifice increases fast with the increasing inlet flow rate under the mass-flow-rate boundary condition. Therefore, the inlet pressure and flow rate significantly affect the performances of atomizers.

Keywords: Swirl atomizers, inlet flow rate, inlet pressure, atomization performance

0 Introduction

Due to recent trends toward direction of higher thrust to weight ratio, high power to weight ratio, high reliability and low fuel consumption of aero-engine technology, how to improve the performance of the engine is still the focus of research in the field of the aviation. The atomizer of aviation engine is an inevitable necessity component due to fuel into the combustion chamber of the aviation engine in the form of droplets or spray is burned, the characteristics of atomization directly determine the combustion efficiency and stability of aero-engine. This process involves the fuel atomization performed by centrifugal atomizer. There are many types of centrifugal atomizers, which highlight the advantages of large fuel adjustment range, and ensure that better fuel atomization quality can still be obtained at the condition of low volume, meeting the requirements of the stability and complete combustion of the aviation turbine in different altitude. It is believed that in-depth study of the dual centrifugal atomizer to improve engine performance has a crucial role.

During the last decade, a number of numerical and experimental researches by many scholars were conducted on the atomizer considering different perspective and methods. [Jain M et al.(2014)] conducted a detailed experimental study to understand the role of Reynolds number and geometry on the flow coefficient, spray angle and droplet size in a spray atomizer. [Chen et al.(2010)] experimentally compared the effects of different operating conditions under which primary and secondary fuel line working at the same time on spray angle, indicating that the gap between the two situations is obvious. [Tratnig, A et al. (2010)] carried out an experimental study to evaluate mean diameter of liquid droplet caused by physical properties of working fluid. Although researches on the atomizer has achieved some profound understandings [C. J. Wang Et al. (2009); Zhang Et al. (2003); Chatterjee S et al. (2014); M. Yue Et al. (2003); Y. D. Kong Et al. (2007); Han Z et al. (1997); Datta AFan Y, et al. (2000); Fan Y et al.(2014)], due to small size of atomizer and the complexity of its internal flow field, significant details of the flow field cannot be captured only relying on experiments. And researches regarding the effects of inlet pressure, inlet flow on the flow field inside the atomizer are not deep enough and comprehensive. Henceforth, this study is devoted to investigate the law of dependence of inlet pressure, inlet flow on the flow field inside the atomizer using FLUENT software of computational fluid dynamics.

1 Physical model and calculation methods

1.1 computational model

A schematic of structure of the double line pressure swirl centrifugal atomizer and fuel flow inside the atomizer is shown in Fig. 1. Primary and secondary fuel line is consist of swirl chamber, swirl groove and fuel orifice respectively. When it is working, fuel is accelerated in swirl groove of primary and secondary fuel line and then rotated in swirl chamber and finally sprayed to orifice in the form of rotating film which is spread into a cone by centrifugal force. The fuel becomes relatively small particles under the effect of the air.

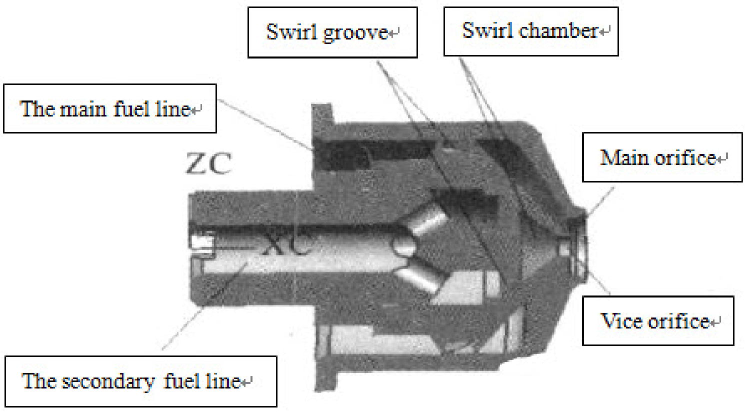


Figure 1. A schematic of cross-section of the atomizer and fuel flow inside it[C. J. Wang Et al. (2009))]

1.2 numerical calculation method

Due to fuel was injected into the atomizer at a relatively high speed at the inlet and then generated high-speed rotation at swirl chamber, the flow belonged to turbulent flow. Therefore, numerical simulation of the flow field of fuel in the atomizer also involves turbulence model, and standard $k-\varepsilon$ turbulence model was selected in this study. To analyze the flow characteristics of this three-dimensional model and simplify the problem, the following assumptions of the flow are adopted: (1)

incompressible;（2）gravity cannot be ignored. The governing equations are expressed as follows:

Continuity equation:

$$\nabla\cdot(\rho\vec{\upsilon})=0 \tag{1}$$

Momentum equation:

$$\rho\left[\frac{\partial_{\vec{\upsilon}}}{\partial_t}+(\vec{\upsilon}\cdot\nabla)\vec{\upsilon}\right]=\rho\vec{f}-\nabla p+\mu\nabla^2\vec{\upsilon} \tag{2}$$

Turbulence equations:

$$\begin{aligned}\frac{\partial(\rho k)}{\partial_t}+\frac{\partial(\rho k u_i)}{\partial_{x_i}}&=\frac{\partial}{\partial_{x_j}}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial_{x_j}}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k\\ \frac{\partial(\rho\varepsilon)}{\partial_t}+\frac{\partial(\rho\varepsilon u_i)}{\partial_{x_i}}&=\frac{\partial}{\partial_{x_j}}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial_{x_j}}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon\end{aligned} \tag{3}$$

$C_{1\varepsilon}$、$C_{2\varepsilon}$、$C_{3\varepsilon}$ is empirical constant and $C_{1\varepsilon}=1.44$、$C_{2\varepsilon}=1.92$ is the default value in FLUENT. Where ρ is density; μ is kinematic viscosity; $\vec{\upsilon}$ is velocity vector; p is pressure; $\vec{f}$ is combined external force.

1.3 mesh-independent verification

In the current work, CFD (Computational fluid dynamics, CFD) FLUENT software was used for numerical simulation. In order to improve the efficiency and accuracy, structural hexahedral mapped mesh generated by the pre-processing software ICEM was used, as shown in Figure 2. By comparing the amount of each of the grid 1.247 million and 1.181 million, the velocity magnitude of the line y = o through diameter at the outlet is shown in Figure 3, indicating that two lines almost overlap by the mesh-independent verification. Therefore, using 1.181 million mesh could meet the requirements of numerical simulation and analysis.

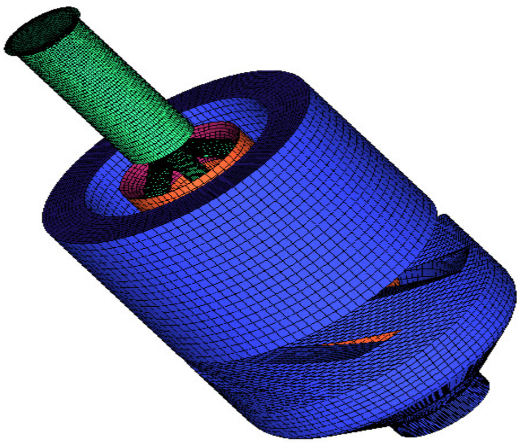


Figure 2. Mesh of calculated domain

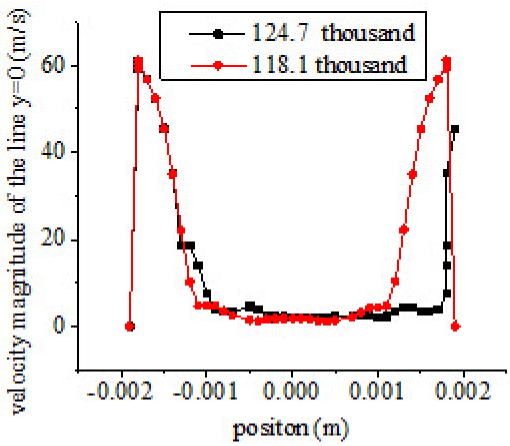


Figure 3. Mesh independence verification

1.4 boundary conditions

During the calculation, the 3rd aviation kerosene is used as the working medium. The properties of the 3rd aviation kerosene used in the computation are a density =800kg/m^3, the dynamic viscosity coefficient=0.00144Pa.s, the surface tension =0.0268N/s, the boundary conditions are as follows:

（1） The inlet pressure is 1.44, 1.84, 2.04, 2.64, 3.04Mpa respectively;

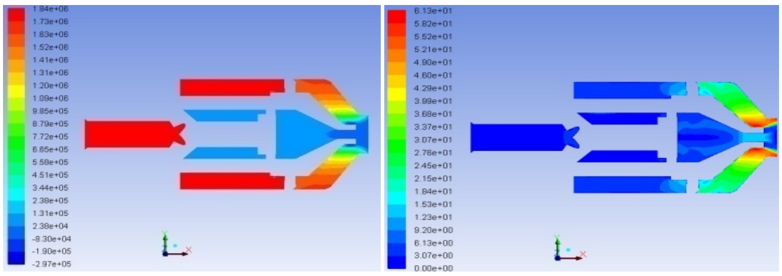
（2） The inlet flow rate is 300, 370, 440, 510, 580 L/h respectively;

（3） Total Guage pressure is 0MPa at the outlet;

2 Results and discussion

2.1 local flow field (pressure, velocity distribution) inside atomizer

Internal filed of the atomizer under the condition of primary and secondary fuel supply pressure as the same 370MPa was numerically calculated. The pressure and velocity distribution is shown in Figure 4 wherein Figure (a), Figure(b) displays the contours of the pressure and velocity in plane of Z=0 respectively. It can clearly be seen from Fig. 4 that the pressure has an apparent gradient in swirl chamber of primary and secondary fuel line, furthermore, due to the large pressure gradient in the secondary fuel line, there is an obvious area of low pressure in the center of swirl chamber. Correspondingly, after the fuel inflowing the inlet, velocity of the fuel was gradually increased, and increased rapidly after flowing into swirl groove and then fuel generated the acceleration and rotation in swirl chamber, finally was sprayed in a cone under the centrifugal force. The velocity maldistribution of the fuel in the swirling groove is dedicated to a sudden contraction of flow channel and its irregular structure. The geometric structure of the swirl chamber is gradually tapered, thus velocity magnitude of the fuel increases rapidly, reaching a maximum at the outlet, which provides the necessary conditions for the fuel in form of droplets into the combustion chamber.



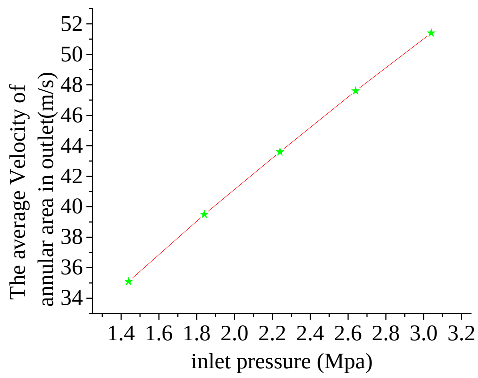
(a) Contours of pressure (b) Contours of velocity

Figure 4. Schematic of flow field in the atomizer

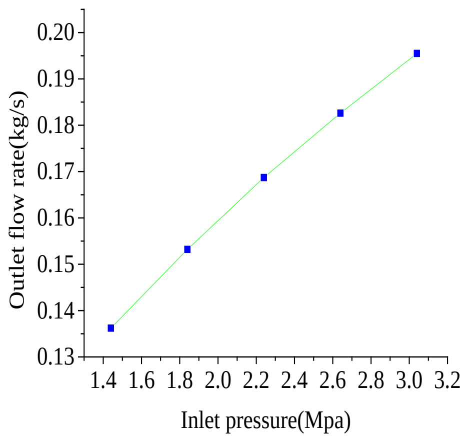
2.2 Effect of inlet pressure on average velocity of annular area at outlet and outflow rate .

Jet speed at the outlet where near the central area of the outlet is air and near the edge of the annular area of the outlet is the fuel directly determines the fuel atomization quality. The average velocity of the area was extracted to explore the dependence of fuel inlet pressure and inlet flow rate on it. Figure 5 (a) is the curve of the effect of inlet pressure on average velocity of annular area at outlet. It shows that, when the inlet pressure is 1.44, 1.84, 2.24, 2.64, 3.04Mpa, the average velocity in the annular area is 35.1, 39.5, 43.6, 47.6, 51.4 m/s correspondingly. When the inlet pressure equally spaced (0.4Mpa) increases, the velocity increases 4.4, 4.1, 4.0, 3.8 m/s separately. Namely as the inlet pressure (1.44-3.04Mpa) increases, the velocity magnitude of annular area at outlet is almost linearly increased, however the growth rate of velocity slows gradually. Therefore, in the situation of sufficient fuel supply and complete combustion, increasing inlet pressure of atomizer, the more fuel into the combustion chamber, greater combustion power can be generated. However, increasing the inlet pressure is not completely converted to an increase of the average velocity. Accordingly, when design the atomizer, a fact that with increased pressure (a range), the increasing trend of combustion power became slowly should be fully considered.

Outlet flow rate is one of the most critical indicators of the performance of the atomizer. Exploring the influence of geometric parameters or different operating conditions (inlet pressure) on the outflow rate has an important significance to guide the design and development of the atomizer. This paper focused on the effects of inlet pressure on the outlet flow rate, as shown in Figure 5 (b). It apparently demonstrates that when the inlet pressure is1.44, 1.84, 2.24, 2.64, 3.04Mpa, outlet flow rate is 0.136, 0.153, 0.169, 0.183, 0.196 kg/s respectively. When the inlet pressure equivalently spaced (0.4Mpa) increases, the outlet flow rate increases 0.017, 0.016, 0.014, 0.013 kg/s accordingly. That is, as the inlet pressure (1.44-3.04Mpa) increases, outflow rate is almost linearly increased. but a trend of the increase rate gradually becoming slower has appeared. It is proved once again that a fact that with inlet pressure (a range)increased, the trend of increase of burning power becoming slower should be took full account when design atomizer.



(a) Velocity of annular area of the orifice changes with inlet pressure



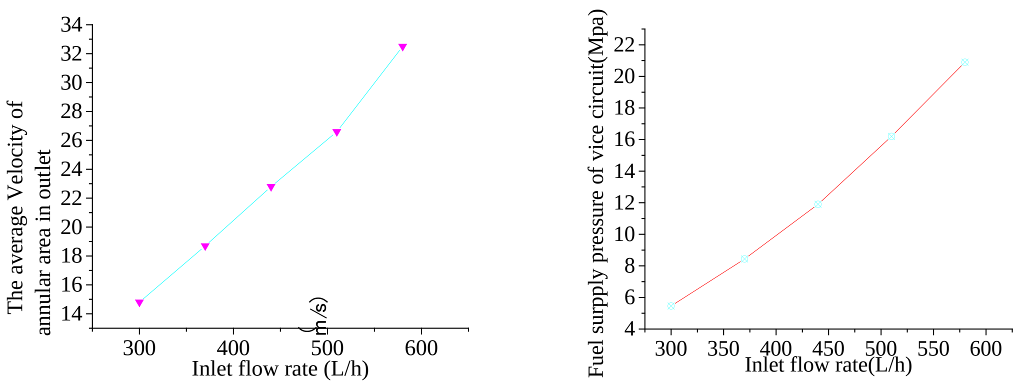
(b) The outflow rate changes with inlet pressure

Figure 5. The effect of inlet pressure on the local flow field

2.3 Effect of inlet flow rate on the average velocity of annular area of the outlet and fuel supply pressure of the secondary line

As described in section 2.2, studying the average velocity of annular area of the outlet has great significance. The law of the impact of the inlet flow rate on the velocity is shown in Fig 6(a). Seen from the figure, when the flow rate of the inlet is 300, 370, 440, 510, 580L/h, the average velocity of annular area of the outlet is 14.8, 18.7, 22.8, 26.6, 32.5 m/s separately. While the inlet flow rate equally spaced (70L/h) increases, the velocity increases 3.9, 4.1, 4.8, 5.9 m/s respectively. That is with the increase of the inlet flow rate (300-510L/h), the velocity of annular area of the outlet is gradually increased, and the increase rate becomes gradually faster. Consequently, in condition of combustion chamber is large enough and fuel combustion is compete, compared to adjust the inlet pressure, adjusting inlet flow rate (in a range) can remarkably enhance the combustion efficiency .

Fuel supply pressure is one of the indicators of the performance evaluating the atomizer, maximization of fuel supply efficiency in the atomizer is one of the fundamental purposes of numerous researches. The relationship between flow rate and supply pressure of the fuel in the secondary line was considered in this paper as shown in Figure 6(b).It is shown that when the inlet flow rate is 300, 370, 440, 510, 580L/h, supply pressure of the fuel of the secondary line is 5.5, 8.4, 11.9, 16.2, 20.9Mpa respectively. While the inlet flow equally spaced (70 L/h) increases, supply pressure of the fuel of the secondary line increases 2.9, 3.5, 4.3, 4.7Mpa respectively. That is, with inlet flow rate (300-510L/h) increased, the supply pressure of the fuel of the secondary line increases, and the increase rate gradually becomes faster. It can be explained that the fuel in the secondary domain, the more fuel supplied to the inlet passage (300-510L/h) ,leading to area of air contact with fuel is larger, the flow resistance is increased accordingly. It is seen that, when the primary and secondary fuel line operate simultaneously, a consideration that the increasing the flow rate (a range) makes the resistance of secondary fuel line increase and the effect that increase rate becomes faster should be premeditated in design of the atomizer.



(a) Average velocity of annular area in the outlet with inlet flow rate changes

(b) Supply pressure of the fuel in the secondary line changes with inlet flow rate

Figure 6. The effect of inlet flow rate on the local flow field

3 Conclusions

（1） With inlet pressure (1.44-3.04Mpa) increased, the average velocity of annular area of the outlet almost linearly increases, slightly emerging a trend that as the pressure increases, the increase rate will be slower. But the velocity sharply increases with the increasing inlet flow rate (300-510L/h), while the increase rate gradually goes up. Compared to adjust the inlet pressure (a range) , changing the inlet flow rate(a range) can more validly enhance combustion efficiency in the time of atomizer design.

（2） With the inlet pressure (1.44-3.04Mpa) increased, the outlet flow rate almost linearly increases, effect of air resistance on the fuel also reveals a relationship of linear increase, but increase of the flow rate tends to be slower. When improve combustion efficiency of the atomizer, this effect that increasing pressure (a range), the outlet flow increases correspondingly, but the increase rate slows down should be given full consideration.

（3） With the increasing inlet flow rate, the fuel supply pressure of secondary line increases, but the increase rate gradually becomes faster. The more fuel supplied to secondary passage, the greater chance of fuel contacting with air is, and the air resistance on the fuel becomes larger. Designing a atomizer especially primary and secondary passage operates at the same time, it is concentrated on the fact that with inlet flow rate increased, resistance of secondary line is increased and the growth rate becomes faster.

References

Jain M, John B, Iyer K N, et al. Characterization of the full cone pressure swirl spray atomizers for the nuclear reactor containment spray system[J]. Nuclear Engineering and Design, 2014, 273: 131-142.

J. Chen Et al. Experimental investigation of spray characteristics of a double line pressure-swirl atomizer [J]. Journal of Aerospace Power, 2010 (4): 774-779.

Tratnig A, Brenn G. Drop size spectra in sprays from pressure-swirl atomizers[J]. International Journal of Multiphase Flow, 2010, 36(5): 349-363.

C. J. Wang Et al. Numerical study of the cone angle of dual centrifugal atomization atomizer [J]. Energy Conservation, 2009, 28(2): 11-13.

Z. Zhang Et al. Experimental study on spray characteristics of dual-orifice pressure-swirl atomizer[J]. Journal of Engineering Thermophysics, 2003, 24(1): 153-156.

Chatterjee S, Das M, Mukhopadhyay A, et al. Effect of Geometric Variations on the Spray Dynamics of an Annular Fuel Sheet in a Hybrid Atomizer[J]. Atomization and Sprays, 2014.

M. Yue Et al. Numerical study of two-phase flow in atomizer [J]. Journal of Engineering Thermophysics, 2003, 24(5): 888-890.

Y. D. Kong Et al. Numerical Simulation of Spray Angle in Aero engine Combustor Swirl Atomizer [J]. Computer Simulation, 2007, 24(10): 45-47.

Han Z, Parrish S, Farrell P V, et al. Modeling atomization processes of pressure-swirl hollow-cone fuel sprays[J]. Atomization and Sprays, 1997, 7(6).

Datta A, Som S K. Numerical prediction of air core diameter, coefficient of discharge and spray cone angle of a swirl spray pressure atomizer[J]. International Journal of Heat and Fluid Flow, 2000, 21(4): 412-419.

Fan Y, Hashimoto N, Nishida H, et al. Spray characterization of an air-assist pressure-swirl atomizer injecting high-viscosity Jatropha fuels[J]. Fuel, 2014, 121: 271-283.