

文章编号:1000-8055(2012)04-0890-10

Numerical simulation of flow in swirl injector for power-law fluid

WANG Feng¹, FU Qing-fei², YANG Li-jun²

(1. School of Astronautics,
Northwestern Polytechnical University, Xi'an 710072, China;

2. School of Astronautics,
Beijing University of Aeronautics and Astronautics, Beijing 100191, China)

Abstract: In order to investigate the flow characteristics of swirl injectors for gelled propellants, which actually behaved as non-Newtonian power-law fluid, a swirl axisymmetric model was established to solve Navier-Stokes equations and VOF (volume of fluid) equation, and the power-law constitutive equation was used to describe the rheology characteristics of the gelled propellants. The film thickness and velocity distribution in the swirl injector under different flow conditions were studied numerically. The simulation results show that the increased geometry characteristic parameter of the swirl injector contributes to the decrease of liquid film thickness. The liquid film thickness is almost independent of the pressure drop. The rheologic parameters have great influences on the inner flow of swirl injector; by increasing the fluid consistency index K and power index n , both the axial and the swirl velocities decrease dramatically; higher fluid consistency index K and power index n make the liquid film thickness increase. When the viscosity is large enough, the air core in the injector would vanish.

Key words: numerical simulation; gelled propellants; power-law fluid; swirl injector; inner flow

CLC number: V439

Document code: A

Nomenclature

A	geometric characteristic constant	R	radius
D	diameter	U	velocity
i	number of tangential inlets	$\dot{\gamma}$	shear rate
K	fluid consistency index, $\text{Pa} \cdot \text{s}^n$	η	apparent viscosity
L	length	ρ	density
n	power index	τ	shear stress
Q	volume flow rate		

Subscripts

l	liquid	s	swirl chamber
n	nozzle	t	tangential inlet
r	radial direction	θ	tangential direction

Liquid swirl injectors are widely used in the preparation for the combustion mixtures of high energy release devices such as rocket engines and jet engines because they provide good spray and also they are relatively simple and inexpensive to

manufacture^[1]. As shown in Fig. 1, a swirl injector is consisted of three parts, namely the tangential inlets, the swirl chamber and the nozzle. In a swirl injector, the liquid enters the tangential inlets under the supply pressure and an-

Received:2011-05-09; **revision received:**2012-01-13

Foundation item:Beijing Natural Science Foundation (Support number:8112026)

E-mail:rich1983@gmail.com

gular momentum is imposed on the liquid to form a swirling motion. Under the action of centrifugal force, the liquid spreads out in the form of a conical sheet as soon as it leaves the nozzle. It is well known that the disintegration of the liquid sheet is due to the growth of the unstable wave at the interface between the ambient gas and the liquid sheet. A relative velocity between the liquid and gas promotes the growth of disturbances until the disturbance reaches the most unstable state and the liquid sheet disintegrates into fragments, which rapidly contract into unstable ligaments under the effect of surface tension. Finally, the ligaments are broken into a multitude of droplets.

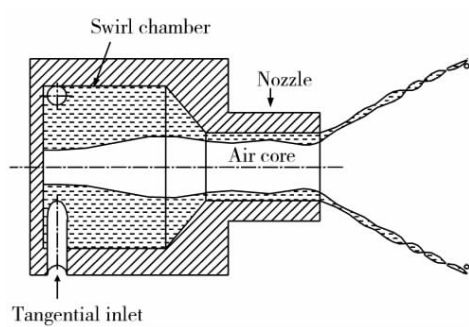


Fig. 1 Schematic of a liquid swirl injector

As can be seen, the liquid film thickness has direct influence on the final droplets size. Hence, a number of investigations have been made to study the annular liquid film in the swirl injector. Before the advent of computational fluid dynamics (CFD), a number of workers attempted to determine the liquid film thickness within the nozzle by modeling the liquid as inviscid and the flow irrotational. A review of these works has been made by Chinn^[2] recently. Experimental investigations have generally reported measurements of spray angle, pressure drop, and mean drop size with Newtonian liquids, essentially parameters that can be measured outside the injector. This is because the swirl injector sizes are extremely small which makes direct flow field measurements inside the injector extremely difficult. A few studies were carried out on the measurement of film thickness in the noz-

zle^[3-5]. Large-scale injectors were also used to enable measurement of film thickness in the orifices of the injector and velocity fields in the swirl chamber^[6-7]. In recent years, the development of CFD made an insight into the flow condition in the swirl injector^[8-9] by tracking the gas-liquid interface accurately.

All the literatures cited above focused on the flow of Newtonian fluid inside swirl injector. As we known, gelled propellant is promised in future aerospace application because it combines the advantages of the solid propellant with those of the liquid propellant. From the view of fluid mechanics, gels behave as time dependent non-Newtonian power-law fluids. The rheological properties of gel made the flow in injectors and atomization of gelled propellants much different with that of Newtonian fluids. Some investigations^[10-12] have been performed to study the spray characteristics and flow dynamics of the gelled propellant in several types of injectors, such as the impinging jet injectors, the air-blast injectors and so on. However, the spray and flow characteristics of the gelled propellants (or power-law fluid) in swirl injectors are yet to be studied. Hence, the motivation of the present study is to understand the flow condition of gelled propellant in swirl injectors.

In this paper, we employed Herschel-Bulkley model to describe the rheology of the fluid, combining the VOF (volume of fluid) method to predict the liquid film thickness and velocity distribution in a pressure swirl injector with power-law fluid. The effect of injector geometry and rheological parameters on the liquid film thickness and velocity distribution was also studied.

1 Numerical framework

The governing equations of the two phase flow in pressure-swirl injector are conservation of mass (continuity) and conservation of momentum (Navier-Stokes) equations. In the VOF model, a single set of momentum equations is shared by the fluids while the volume fraction of each of the fluids in each computational cell is

tracked throughout the domain. The viscosity and density for each cell are evaluated as volume-fraction-weighted-average of the corresponding properties of the individual phases. An equation for the phase volume fraction is solved simultaneously with the mass and momentum conservation equations on a fixed Eulerian structured grid and the volume fraction of each of the phases in each computational cell is tracked throughout the domain. For flow with two-phases, the volume fraction of the cell is denoted as $\alpha=1$ for a cell containing only the first phase; $\alpha=0$ for a cell with only the second phase, and $0<\alpha<1$ when a cell contains the interface between the first and second phase. An equation for the volume fraction $\frac{\partial \alpha}{\partial t} + \mathbf{u} \cdot \nabla \alpha = 0$ is solved simultaneously with the conservation equations governing the flow.

The conservation equations governing the flow are

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla P + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{f} \tag{2}$$

For distinct applications, the viscosity characteristic of power-law fluids is often described by two-parameter power-law equation:

$$\eta = K\dot{\gamma}^{n-1} \tag{3}$$

The fluid is shear-thinning fluid for $n<1$; Newtonian fluid for $n=1$; and shear-thickening fluid for $n>1$.

However, in some applications such as gelled fuels, this equation can only describe the medium shear rate range with sufficient accuracy. Both in the range of low shear rates, relevant for storage and feeding, and the range of high and very high shear rates, which occur in injectors, the power-law equation cannot be used. The use of an extended version of the Herschel-Bulkley equation (HBE), which is presented in Eq. (4), takes both the yield stress τ_0 and the constant viscosity γ_∞ into account. This HBE equation describes the viscosity/shear-rate dependence in the whole propulsion relevant shear rate range. HBE model was also

used in the present study.

$$\eta_{\text{HBE}} = \tau/\dot{\gamma} = \tau_0/\dot{\gamma} + K\dot{\gamma}^{n-1} + \eta_\infty \tag{4}$$

In order to get a preliminary understanding of flow field in swirl injector, commercially available CFD solver Fluent 6.3 with the pressure based solver VOF method is used to solve the governing equations with the geometric reconstruction scheme. In the present case of study, the flow was transient and was considered as constant density, laminar and swirl axisymmetric. The discretization scheme used for pressure was PRESTO (pressure staggering option) and for pressure-velocity coupling was the SIMPLE (semi-implicit method for pressure-linked equations) method. The Geo-Reconstruct scheme for volume fraction discretization was used. The second order upwind schemes were used for the momentum equations.

A numerical model of a power-law fluid swirl injector was simulated using geometric parameters as shown in Table 1, where $A = 4(R_s - D_t/2) \cdot R_n/iD_t^2$ indicates the geometric characteristic constant. Fig. 2 showed the basic parameter of the calculation domain inside the swirl injector.

Table 1 Geometric parameters of model injectors

Parameters	1	2	3	4
D_t/mm	2	2	1.5	1.5
L_k/mm	7	7	7	7
R_s/mm	9	9	9	9
L_s/mm	20	20	20	20
R_n/mm	2	1.5	2	1.5
L_n/mm	1.5	1.5	1.5	1.5
i	2	2	2	2
A	4	3	7.3	5.5

The computational domain included the entire interior of the swirl injector. The inlet width was taken the tangential inlet diameter, thus the inlet radial velocity can be calculated from the flow rate equation: $U_{i,r} = Q/(2\rho\pi R_s D_t)$, and the inlet tangential velocity was given from the swirl momentum conservation: $U_{i,\theta} = 2QD_t/(\rho\pi R_s D_t^2)$.

At the outlet cross-section, pressure outlet boundary was prescribed. All wall boundaries were taken as no-slip. For all cases, the fluids are viscous incompressible air and specified power-law fluid.

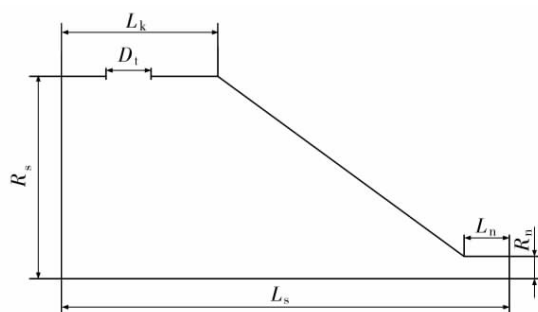


Fig. 2 Calculation domain and interfaces

For Newtonian flow through a pressure swirl injector the geometric characteristic constant and the pressure drop have been shown to have a significant impact on injector performance. Moreover, the rheological parameters greatly influence the flow condition. In view of these findings, we have considered A , Δp , K and n to examine the influence of these parameters on the injector performance with a power law fluid.

2 Results and discussion

2.1 Analysis of a typical flow field

Fig. 3 showed the axisymmetric contour of volume fraction of gel and velocity for injector 3 under the pressure drop of 0.6 MPa, K and n are $0.1 \text{ Pa} \cdot \text{s}^n$ and 0.389 respectively. It is observed in Fig. 3(c) that the tangential velocity increases from the wall to the center line of injector. This relationship between tangential velocity and radius means that the tangential velocity is highest at small radii, so that according to the pressure-velocity relationship of Bernoulli, the pressure there reduces to match that of the ambient medium into which the liquid is subsequently ejected. This allows the ambient medium to enter along the axis of the injector to form a hollow “air” core, which is shown in Fig. 3(a). Fig. 3(b) showed velocity direction of air core is oriented to the inside of injector, i. e., the ambient air flows into the swirl chamber.

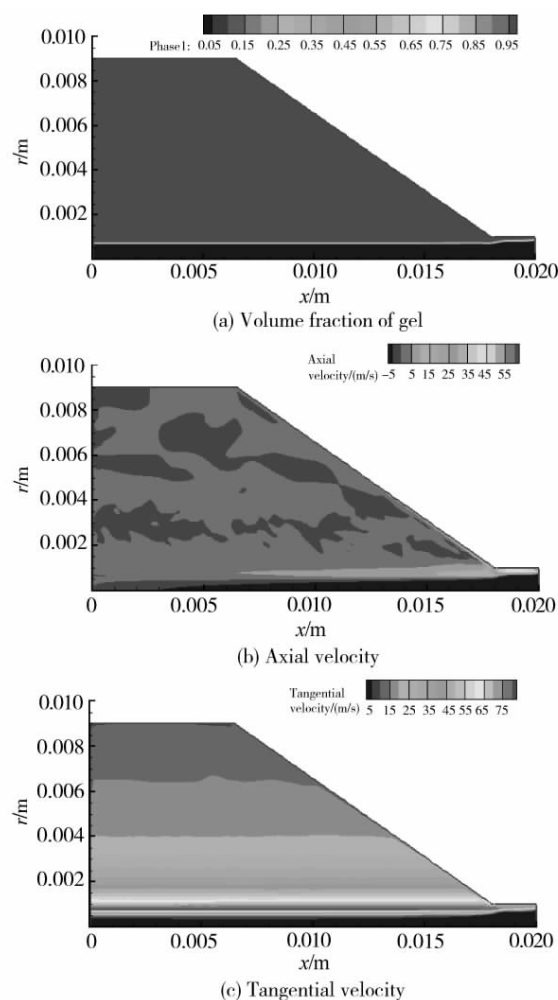


Fig. 3 Contour of volume fraction and velocity

The streamtrace plot for the flow inside injector for the case same as Fig. 3 was shown in Fig. 4. Fig. 4 showed there were several separated recirculation zones in the swirl chamber. A large recirculation zone was found in the near-wall region. Therefore the axial velocity was reversed near the chamber wall. There are several

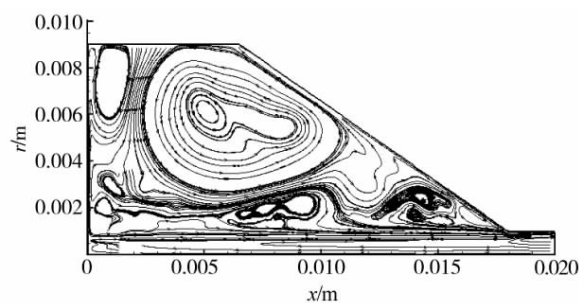


Fig. 4 Stream trace plot for injector 3 under the pressure drop of 0.6 MPa

smaller recirculation zones near the gas-liquid interface. The large and smaller recirculation zones rotate in opposite directions. The recirculation zones reduce the effective axial flow cross-section in the swirl chamber.

2.2 Effect of geometric characteristic constant

Figs. 5–7 showed the volume fraction of gel, axial velocity and swirl velocity distribution on the section $x=5, 10, 15$, and 20 mm respectively. The radial velocities were not shown here because the radial velocity was much smaller than axial velocity and tangential velocity. The simulation was conducted for injector No. 1–4. Pressure drop across the injector is held constant in all cases. Hence, the velocity inlets were set according to the measured mass flow rate under the constant pressure drop for the four injectors. The rheological parameters of gel K and n are $0.1 \text{ Pa} \cdot \text{s}^n$ and 0.389 respectively. In the present study, the gas-liquid interface was defined as the position where the volume fraction of gel is 50% . Hence, the liquid film thickness can be obtained from reading the radius of the gas-liquid interface. It can be seen from Fig. 5 that the liquid film thickness of 3# injector is the least while that of 2# injector is the largest, i. e., the larger geometric characteristic constant corresponds to the decreased liquid film thickness. This coincides with the trend of Newtonian fluid. That's because the geometric characteristic constant

$$A = \frac{4(R_s - D_t/2)R_n}{iD_t^2} = \frac{\frac{4Q}{i\pi D_t^2} \times \frac{(R_s - D_t/2)}{R_n}}{Q/\pi R_n^2} = \frac{\text{tangential velocity} \times \text{arm coefficient}}{\text{axial velocity}} \quad (5)$$

It can be seen from Eq. (5) that the liquid tangential velocity or arm of force increase as “ A ” increases, that is, the moment of momentum increase, the liquid in the swirl injector swirls more intensively. Therefore, “ A ” denotes the swirl strength of liquid flow in the swirl injector. Increased A means the decreases liquid film thickness because of the centrifugal force. Furthermore, we can see that the liquid film

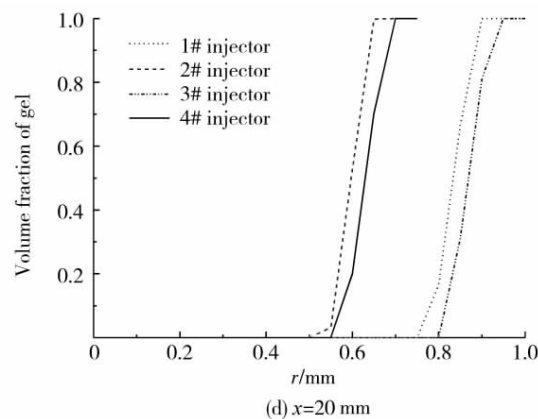
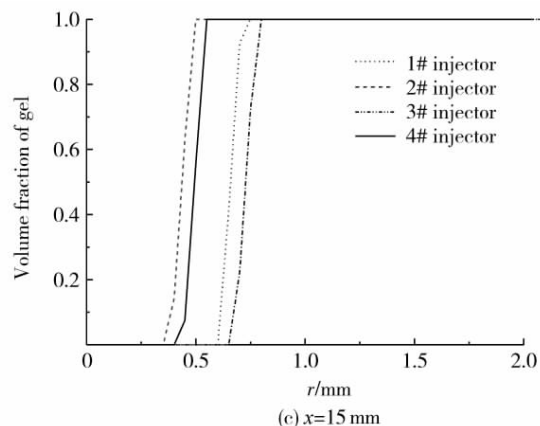
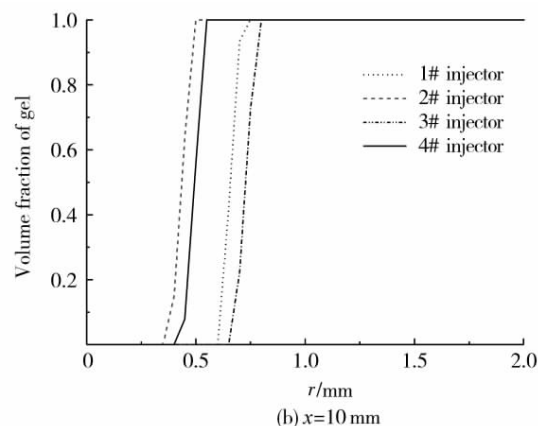
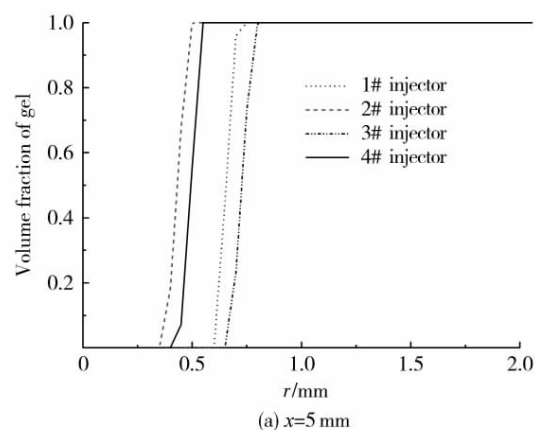


Fig. 5 Volume fraction of gel on different cross-sections

thickness didn't vary greatly along the axial position except profile which was very close to the injector exit ($x=20$) where the liquid film was accelerating. In order to match the conservation of mass flow rate, the liquid film got thinner.

The profiles of the axial velocity were plotted in Fig. 6. The axial velocity distribution near the wall appeared the profile of a turbulent boundary layer. The obvious inflection point was the position of the gas-liquid interface. The axial velocity profile of the gas part at the interface appeared reverse profile of boundary layer which reached inflection point at the centerline of the injector. The axial velocity on these sections didn't vary greatly except the section near the injector exit. The liquid film accelerated when it reached the injector exit, which can be seen from Fig. 6(d) (the amplitude of the axial velocity on this section is larger than that on other sections). It can be seen at the gas-liquid interface, the axial velocity of 3# injector was the least and that of 2# injector was the largest, i. e., the geometric characteristic constant increased, the axial velocity of liquid film decreased.

Fig. 7 showed the tangential velocity profiles at various axial locations for different injectors. The tangential velocity increased with increased radius in the air core region and reached a maximum value at the gas-liquid interface; thereafter, it decreased with increased radius. Based on the tangential velocity profile, the cross section can be divided into four regions: wall region, free vortex zone, transition zone and forced vortex zone. Near the wall, the tangential velocity got zero rapidly, forming a wall boundary layer. At the free vortex region, the angular momentum is conserved, i. e., the tangential velocity is given by $U_\theta = \Gamma/2\pi R$ (where Γ is the circulation). The tangential velocity at forced vortex region can be obtained by $U_\theta = \omega R$, where ω is the angular velocity and R is the radial distance from the centerline. The angular momentum $U_\theta r$ increased with the increased radius at the forced vortex region. It is interesting to

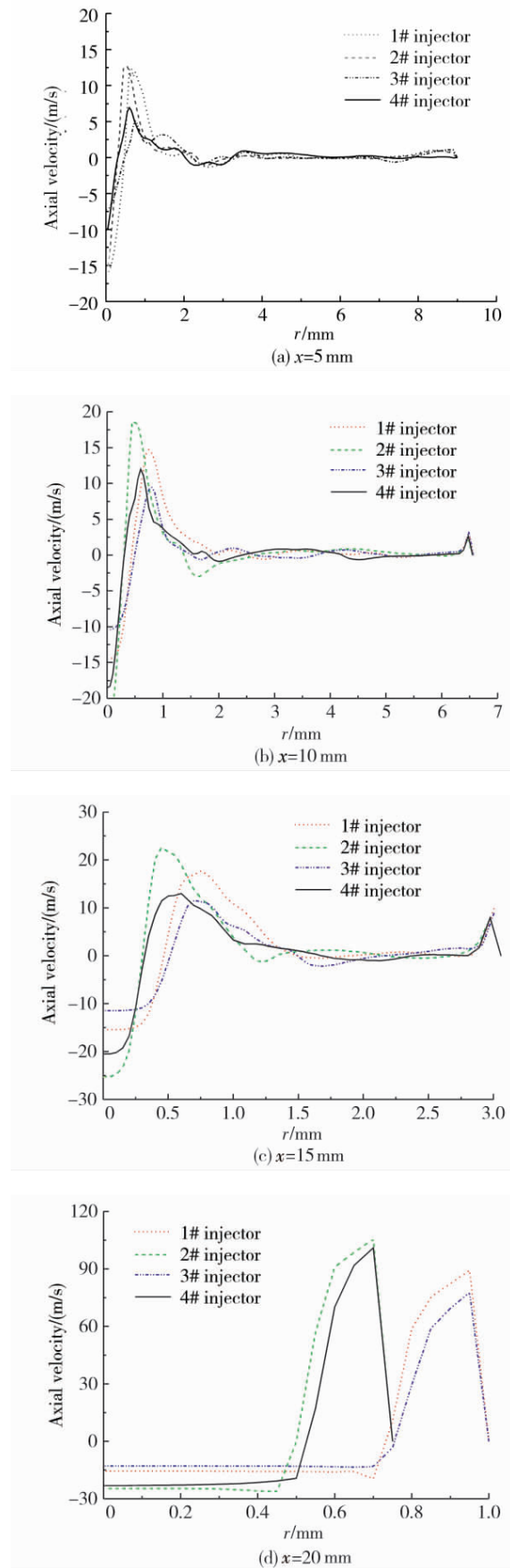


Fig. 6 Axial velocity distribution on different cross-sections

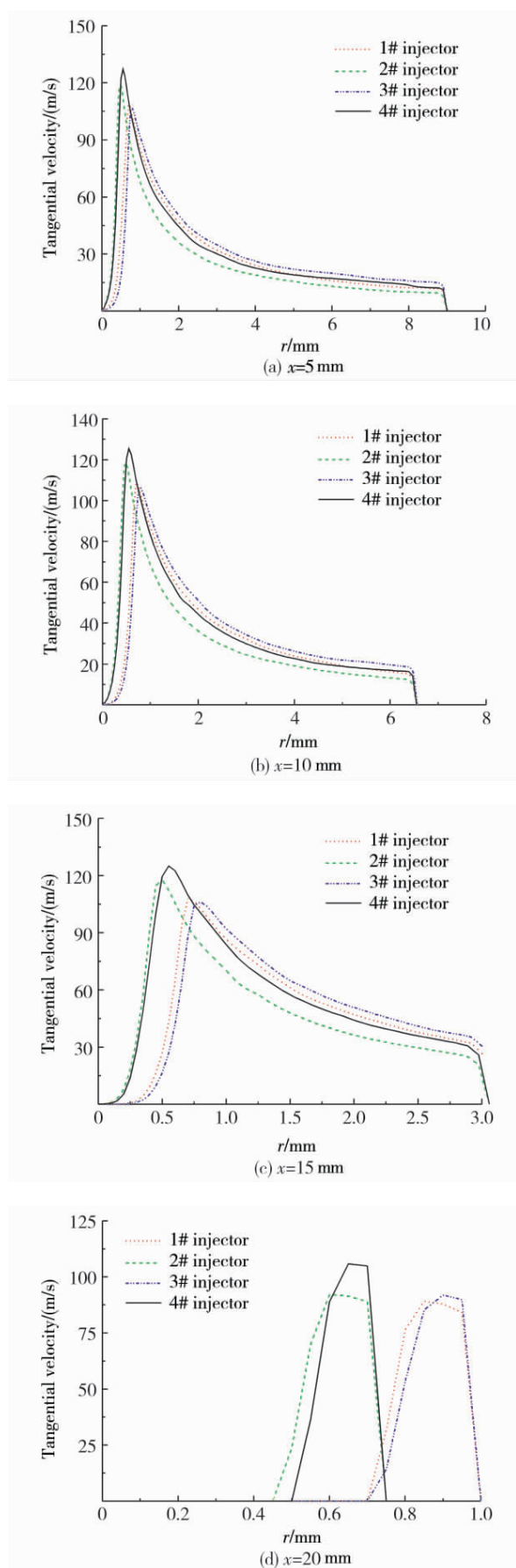


Fig. 7 Tangential velocity distribution on different cross-sections

notice that the boundary between transition zone and forced vortex zone is at the interface. The transition zone can be attributed to the shear between the gas and liquid phase.

It also can be seen from Fig. 7 that the geometric characteristic constant influence the maximum tangential velocity greatly. The tangential velocity of liquid film increased as the geometric characteristic constant A increased. That's because the geometric characteristic constant denotes the swirl strength of the liquid. However, the trend of the tangential velocity versus geometric characteristic constant in air core region is opposite with that of liquid film.

2.3 Effect of pressure drop

Effect of pressure drop on the flow parameters at the injector exit can be found in Fig. 8. The simulation was conducted with injector 3#. The rheological parameters of the gel used in the simulation were $K = 0.1 \text{ Pa} \cdot \text{s}^n$, $n = 0.389$. It can be observed from Fig. 8(a) that the liquid film thickness is almost independent of the pressure drops because the variation of liquid film thickness is of the magnitude of 0.01 mm . Fig. 8(b)-Fig. 8(c) showed that the maximum axial velocity and tangential velocity increases with the pressure drop increases. The amplitude of maximum axial velocity varies from 50 m/s to 100 m/s as pressure drop increases from 0.6 MPa to 1.6 MPa , while that of maximum tangential velocity varies from 60 m/s to 120 m/s . The radial location of maximum axial velocity and tangential velocity didn't vary with the pressure drop.

2.4 Effect of fluid consistency index K

Effect of fluid consistency index K on the flow condition in the swirl injector 3# was tested and shown in Fig. 9. The velocity at the inlet was held constant in all cases. The power index n was set to be 0.389 . It is clear that by increasing the fluid consistency index K , the maximum axial and swirl velocities decrease. The amplitude of maximum axial velocity varies from 30 m/s to 20 m/s as K increases from 6 to 10 ,

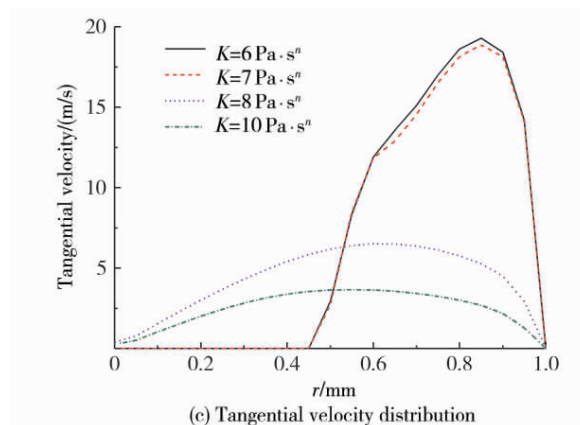
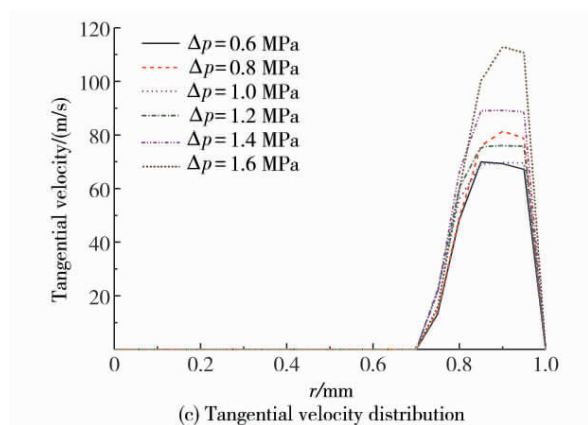
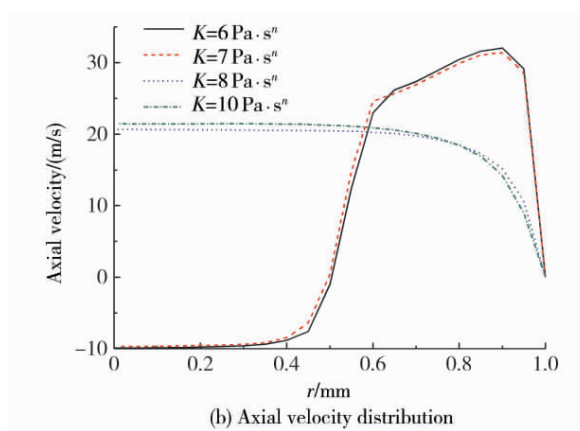
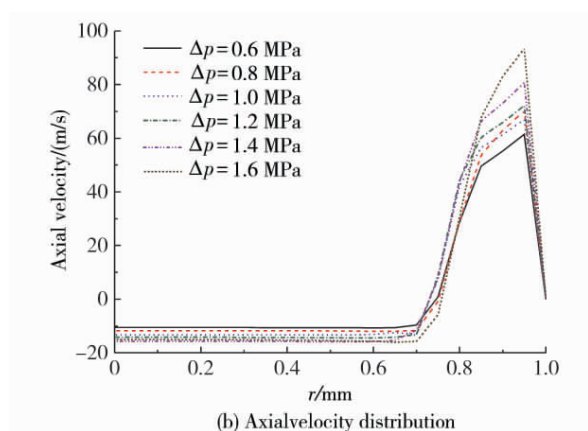
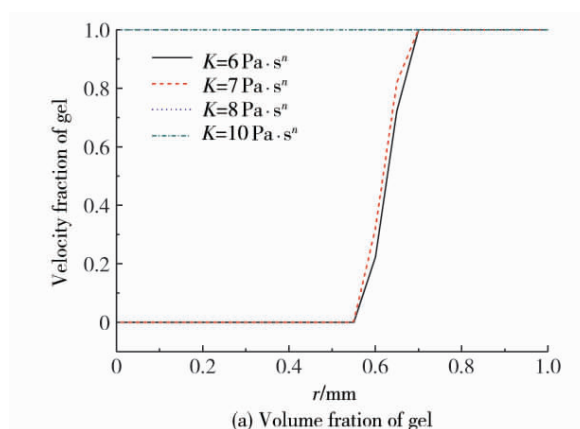
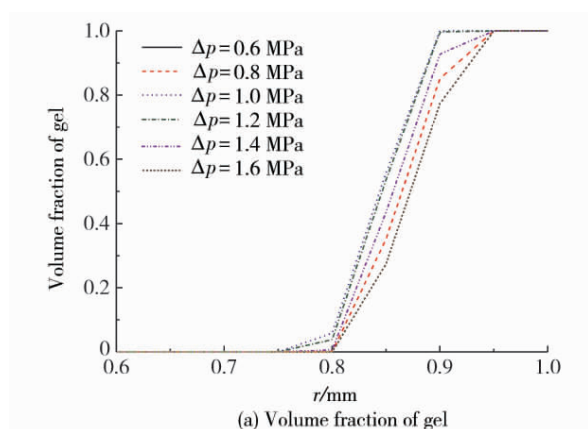


Fig. 8 Flow parameter profiles at the injector exit
($x = 20$ mm)

Fig. 9 Flow parameter profiles at the injector exit
($x = 20$ mm)

while that of maximum tangential velocity varies from 20 m/s to 5 m/s. But the variations of the axial velocity and tangential velocity are small as K increases from 6 to 7. The axial and tangential velocity decreases dramatically as K increases from 7 to 8 and 10.

Moreover, it is interesting to observe from Fig. 9(a) that while K increases to 8 and 10, the air core vanishes. The entire injector exit was filled by the liquid. That's because the decreased

velocity caused by higher apparent viscosity made the pressure higher than the ambient pressure, even at the center line of injector. For this reason, it is impossible to form an air core. For the case of $K = 8$ and $K = 10$, the axial velocity profiles looks like a duct flow velocity profile. It showed in Fig. 9(c) that the free vortex and forced vortex region still exist although the entire exit was filled by the power-law fluid. The transition from the free vortex region to forced

vortex region became smooth compared to the tangential velocity profile for smaller value of K .

2.5 Effect of power index n

Injector 3 # was selected to test the effect of variation in power index on the inner flow condition of swirl injectors. The velocity at the inlet was held constant in all cases. The fluid consistency index K was set to be $0.001 \text{ Pa} \cdot \text{s}^n$. Fig. 10 showed the effects of shear-thinning fluids ($n=0.6, 0.8$), viscous Newtonian ($n=1$)

fluids and shear thickening fluids ($n=1.2$) on injector performance (liquid film thickness and velocity distribution). Due to the viscosity, it is clear that for shear-thinning fluid with $n=0.6$ and 0.8 the magnitude of velocity higher than shear thickening fluid ($n=1.2$). The amplitudes of maximum axial velocity and tangential velocity decrease from 80 m/s to 30 m/s and 20 m/s respectively while n increases from 0.6 to 1.2 . Larger value of n corresponds to the increased viscosity and results in an increasing decay of swirl energy. In order to match the conservation of mass, the liquid film thickness increases as the power index increases, which can be seen from Fig. 10(a).

3 Conclusions

In this study, by using power-law equation to describe shear stress terms in the Navier-Stokes equations, the numerical model was used to calculate power-law fluid flow inside the swirl injectors. A two-dimensional swirl axisymmetric model based on the VOF method was developed to predict the power-law flow within swirl injectors. The time-independent purely viscous power-law fluids flow in swirl injectors was simulated. The effects of shear-thinning fluids ($n < 1$), viscous Newtonian ($n = 1$) fluids and shear thickening fluids ($n > 1$) have been considered on injector performance. The numerical results show that the liquid film thickness decreases as the geometric characteristic constant of swirl injector increases. The liquid film thickness is almost independent of the pressure drop across the injector. Under constant pressure drop by increasing the fluid consistency index K and power index n , both the axial and the tangential velocities decrease dramatically. On the other hand due to increase in shear viscosity with increasing K and n , the film thickness increases at the orifice exit. The air core would even vanish when the fluid consistency index and power index were large enough.

Acknowledgements

This research was supported by Beijing

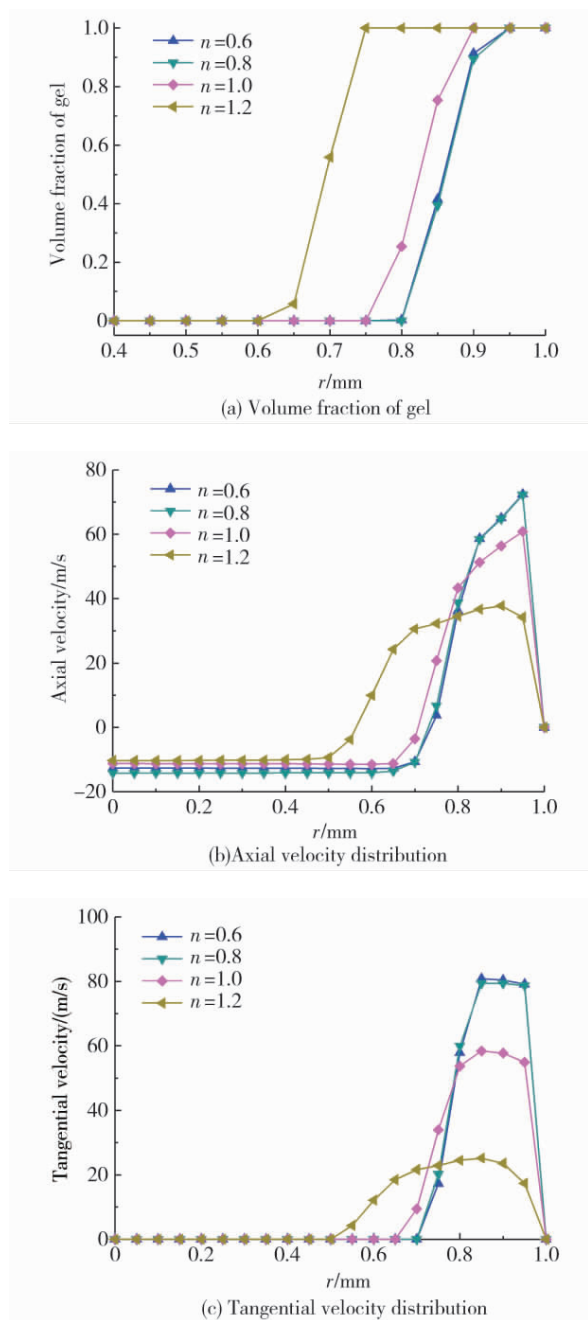


Fig. 10 Flow parameter profiles at the injector exit
($x = 20 \text{ mm}$)

Natural Science Foundation (Support number: 8112026).

References:

- [1] Lefebvre A H. Atomization and Spray[M]. New York; Hemisphere Publishing Corporation, 1989.
- [2] Chinn J J. An appraisal of swirl atomizer inviscid flow analysis, part 1: the principle of maximum flow for a swirl atomizer and its use in the exposition and comparison of early flow analyses[J]. Atomization and Sprays, 2009, 19(3): 263-282.
- [3] Suyari M, Lefebvre A H. Film thickness measurements in a simplex swirl atomizer[J]. Journal of Propulsion and Power, 1986, 2(6): 528-533.
- [4] Fu Q, Yang L, Qu Y. Measurement of annular liquid film thickness in an open-end swirl injector[J]. Aerospace Science and Technology, 2010, 15(2): 117-124.
- [5] Kim S, Kim D, Khil T, et al. Effect of geometry on the liquid film thickness and formation of air core in a swirl injector[R]. AIAA 2007-5460, 2007.
- [6] Wang D, Ma Z, Jeng S M, et al. Experimental study on large-scale simplex nozzle[R]. AIAA 1999-2401, 1999.
- [7] Kenny R J, Hulka J R, Moser M D, et al. Effect of chamber backpressure on swirl injector fluid mechanics[J]. Journal of Propulsion and Power, 2009, 25(4): 902-913.
- [8] Liao Y, Sakman A T, Jeng S M, et al. A comprehensive model to predict simplex atomizer performance[J]. Journal of Engineering for Gas Turbine and Power, 1999, 121(2): 285-294.
- [9] Dash S K, Halder M R, Peric M, et al. Formation of air core in nozzles with tangential entry[J]. Journal of Fluids Engineering, 2001, 123(4): 829-835.
- [10] Von Kampen J, Alberio F, Ciezki H K. Spray and combustion characteristics of aluminized gelled fuels with an impinging jet injector[J]. Aerospace Science and Technology, 2007, 11(1): 77-83.
- [11] Mansour A, Chigier N. Air-blast atomization of non-Newtonian liquids[J]. J. Non-Newtonian Fluid Mech., 1995, 58(2/3): 161-194.
- [12] Chernov V, Natan B. Effect of periodic disturbances on non-Newtonian fluid sprays[J]. Atomization and Sprays, 2008, 18(8): 723-738.