Experimental Study on the Internal Flow Stability for Tangential Entry Conditions in a Swirl Injector

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Abstract

In swirl injector, the internal flow is significantly influenced by the tangential entry conditions. Because the tangential entry conditions have influenced on the liquid film thickness, air core formation, spray angle and mass flow rate, it can be said to one of the most important parameters of swirl injector. From the previous study, we confirm that air core shape and liquid film thickness are directly related. Thus, it is possible to investigate the internal flow characteristics for various tangential entry conditions through the visualization of air core in the swirl chamber and the measurement of the liquid film thickness in the orifice. The measurement of liquid film thickness and the visualization of air core formation were conducted using a specially designed injector based on the electrical conductance method and a high-speed camera system, respectively. The relation between the variations of liquid film thickness in the orifice and the pressure fluctuations in manifold were analyzed by FFT(Fast Fourier Transform) method. The fluctuations in manifold pressure showed a same tendency with that of liquid film thickness. We analyzed the stability of internal flow with respect to initial inlet angular momentum. From these results, the stability boundary map for the internal flow presented.

Introduction

Air core formed in the swirl chamber becomes the fundamental determiner of liquid film thickness. Usually, the spray phenomenon of the exterior of the injector is easy to observe, but the air core in the swirl chamber is difficult to visualize. Thus, research has mainly been conducted by way of numerical analysis. Som et al. [1] noted that the air core is one of the most significant parameters in the swirl spray nozzles because the air core diameter determines the liquid film thickness at the orifice, which plays an important role in determining the average drop size in the process of atomization. Dash et al. [2] observed that the air core in a conical nozzle remains nearly axisymmetric with increased diameter near the nozzle exit, but it can attain a complex helical shape in a cylindrical nozzle so that the jet at the nozzle exit does not have a circular but rather an elliptical cross-section. Cooper et al. [3] visualized the air core in pressure swirl atomizer and waves on the liquid surface using a high-speed image and LDA(Laser Doppler Anemometer) method, they noted that three distinctive types of waves were detected; helical, low amplitude random ripples and low frequency stationary waves. Also, they noted that the disturbances on the air core/liquid surface caused by these ‘waves’ manifest themselves in the exit region of the atomizer by the liquid film breaking down locally, with the air core itself impinging on the wall of the atomizer. Donjat et al. [6] suggested that the unsteadiness of internal flow is originated by a precession movement of the air core due to the inlet jet diffusion and a rotating double helix wave through the numerical results and laser spectrum analysis. Lavante et al. [7] carried out numerical analysis using commercially available computer codes(FLUENT, COMET), they noted that the flow at the air core interface has been shown to be unsteady, with waves generated at the nozzle top end and propagating towards the open end. However, these analysis results were mostly limited to specified injector geometry, various geometric parameters of injector were not considered in these researches for unsteadiness or instability of internal flow.

In this study, we measured the liquid film thickness in the orifice and visualized the air core in the swirl chamber to analyze the internal flow in a swirl injector. The liquid film thickness was measured by the electrical conductance method of Kim et al.’s [4]. This method is similar to Suyari and Lefebvre’s [5], however, we designed an injector that would enable us to visually investigate the relation between variations of the air core in the swirl chamber and the liquid film thickness, allowing us to calibrate various liquid film thickness for more accurate measurement.

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In addition, replacing the part of the injector is possible to investigate the variation of liquid film thickness for the geometric parameters of the injector.

Experimental Equipment and Methods

2.1 Experimental Equipment

Figure 1 shows the structure of simple swirl injector used in this study. Fundamentally, the injector has a measurement section for the liquid film thickness and it is organized to have easily replaceable parts for the tangential entry number or diameter and the swirl chamber length or diameter. The parts of injector were made of colorless and transparent acrylic for the visualization of internal flow.

The swirl flow formed inside of the injector and the liquid film thickness was obtained by measuring the electrical conductance between two electrodes located in the discharge orifice. The liquid film formed by the movement of the air core is not a perfect cylindrical shape. Thus, the data of liquid film thickness measured by the electrical conductance method are average values. The average liquid film thickness could be converted by the voltage for the film thickness in the orifice because the electrical conductivity of water is known. The electrodes were made from a thin stainless steel sheet, separated from each other by an acrylic disk of high electrical resistance. The electrode and an acrylic disk are joined with each other with elastic adhesives in order to prevent an exfoliation of adhesion surface. However, the external surface of electrodes is not attached to the orifice parts; they are combined with the orifice parts by o-ring without adhesion. The liquid film formed in the orifice is very thin with its thickness normally about several hundred micrometers. Even a small leak of water through the electrode surface may cause a substantial error in output voltage. Therefore, the external surface of electrodes is treated with a parylene insulation coating.

Experimental equipments consisted of a function generator, an electric circuit, DAQ, injector and high-speed camera system, as shown in fig. 2. The function generator supplied the electric circuit an AC voltage of 10 kHz frequency with constant amplitude. The voltage for liquid film thickness was measured through the electrodes inside of the orifice. The internal flow was analyzed by the images of 4000 frame/s using a high-speed camera (FASTCAM SA1.1 model 675K-C2), manifold pressure and liquid film thickness are measured simultaneously.

2.2 Experimental Methods

Geometric parameters of injector used in experiment were established as shown in Table 1. The schematics of the swirl injector were illustrated in fig. 1, the basic length and diameter of the swirl chamber were 19 and 18 mm, respectively. And the basic diameter of the tangential entry was 1 mm, the number of tangential entry was three. The diameter of the tangential entry can be changed to 0.5, 2, 3, 4 mm in the fixed entry number of three. And the number of the tangential entry can be changed to 2, 4, 5, and 6 in the fixed entry diameter of 1 mm. These conditions of the tangential entry can be applied to the parameter of the swirl chamber length related to the stability of the internal flow. In case that the swirl chamber diameter is 12 and 15 mm, the tangential entry diameter of 1 and 3 mm was applied.

Injection pressure was directly measured at the manifold of the injector, the liquid film thickness in the orifice was measured by the sampling rate of 200 kHz simultaneously. The experiment was conducted under constant water injection pressure(ΔP = 1, 2, 4, 6, 8, 12, 16 bar), as mentioned, the experimental conditions are shown in table 1. However, the injection pressure was controlled adequately because the mass flow rate under the specific entry condition is too much.

Results and Discussion

3.1 Mass flow rate for tangential entry conditions

Figure 3 shows the mass flow rate for the tangential entry conditions, an increasing rate of the mass flow for the entry conditions shows a various tendencies. In case that the tangential entry number (n_T) is from 2 to 6, the entry diameter is 1 mm, the mass flow rate increased regularly as the entry number increase. In case that the tangential entry diameter (d_P) is 0.5, 2, 3 mm, the entry number is three, an increasing rate of the mass flow showed substantially different tendency than the entry number increase. This is a natural result because the mass flow rate is proportional to the entry cross section area. However, the range of mass flow rate was established variously through the change of the tangential entry condition in order to investigate the stability of the internal flow for the change of the swirl chamber length.

3.2 Variations of the internal flow and liquid film thickness for geometric parameters

In swirl injector, the air core formation and the liquid film thickness are directly related each other. Fig. 4 shows the variations of internal flow for the tangential entry conditions under constant injection pressure (ΔP = 4 bar) when the swirl chamber length was 37 mm. In case of fig. 4(a) and (b), unstable behavior occurred on the air core, it seemed to be a rotating double helical shape. This is because the sufficient mass flow was not supplied due to the narrow entry area and decrease of the entry number, respectively. Fig. 4(c), (d), (e) shows that the air core in the swirl chamber remain axisymmetric. In case of fig. 4(c), the mass flow rate have quadrupled than fig. 4(b) due to the increase of entry area, 2 mm. Also, an increasing rate of mass flow rose because the entry number increased to 3 and 4 ea, respectively.

Dash et al. [2] noted that air core has a complex helical shape in a cylindrical nozzle. This phenomenon was also evident in our study, as a helical shape was detected in specific cases. They mentioned the necessity of a high-speed camera to capture the instantaneous formation of air core because the development process is very rapid, but they used a numerical analysis method instead due to the heavy expense. They have observed a phase of the air core shape varying with an inlet Reynolds number. Also, they noted that the development of an air core takes place only at a sufficiently high inlet velocity or mass flow rate. Considering this reference, we increased the water injection pressure to 16 bar, the formation of air core was still unstable due to the tangential entry conditions. The mass flow rate increased as the water injection pressure increased ($\propto P^{0.5}$), on the other hand, an increasing rate of mass flow decreased. Thus, the limit point of increase in mass flow rate can be changed by the tangential entry conditions. This trend of unsteady internal flow showed through the visualization of air core in the swirl chamber and the variation of liquid film thickness in the orifice, as shown in fig. 5.

3.3 Variations of the liquid film thickness and manifold pressure

Khil et al. [8] measured and quantified the mass flow variation at the discharge orifice when the pressure pulsation of specific frequency is generated in the mass flow feed line using devices for excitation of periodic pressure pulsation so-called a Mechanical Pulsator. In liquid rocket engine, low frequency fluctuation can be generated from the propellant supply unit and the pressure fluctuation in the combustion chamber. For this problem, perceptive study must be conducted because the relation between the low frequency fluctuation and combustion instability have not established clearly.

Generally, if the pressure pulsation in the mass flow feed line is generated, internal flow and external spray of injector are influenced by this. In this study, a factor of external pulsation was excluded from water tank to injector manifold. Fig. 6 shows the relation between the variations of liquid film thickness in the orifice and manifold pressure in case of 46 mm swirl chamber when the tangential entry number or diameter is changed. In case of fig. 6(b), the liquid film thickness measured constant, and specific fluctuation was not detected in manifold pressure.

The internal flow stability can be analyzed by the variations of liquid film thickness, the fluctuations of about 10 kHz were detected in specific tangential entry conditions. At this time, the variation of manifold pressure shows a same tendency with that of liquid film thickness. In liquid rocket engine, the pressure in combustion chamber is so high. Thus, it is thought to be good possibility that the pressure fluctuations in combustion chamber have an effect on the inside of injector and manifold.

3.4 Stability boundary map for internal flow

Figure 7 shows the stability boundary map for geometric parameters under constant water injection pressure (ΔP = 2, 4, 6, 8 bar). Sufficient initial momentum from the tangential entry is an essential element for stable internal flow and air core. In fig. 7, angular momentum is multiply initial momentum ($\dot{m}^2 / \rho A$, A : tangential entry area) by mean radius of inlet flow (R) as shown in Eq. (1), which is significantly influenced by an increasing rate of mass flow.

$$\dot{m}uR = \frac{\dot{m}^2}{\rho A}R = \frac{4\dot{m}^2}{\rho n \pi d_p^{\,2}}R \qquad (1)$$

Figure 7 shows the range of mass flow for stable internal flow through the change of tangential entry condition at the specific *L/D* (the ratio of swirl chamber length to swirl chamber diameter). Also, the stability boundary was formed at high angular momentum as the injection pressure increased. This is because the mass flow have a general tendency to increase as the injection pressure increased although the limit point of increase in mass flow rate can be changed by the tangential entry conditions. Thus, the optimum design of tangential entry must be considered for the formation of stable internal flow in a swirl injector. This can be a very useful method for an injector length tuning to damp the resonant frequency causes combustion instability or an adjustment of the swirl chamber length by the modification of manifold size. The stability domain can be shifted by the difference of injector geometry, of course, an evaluation method of internal flow stability through the calculation of initial inlet angular momentum is thought to have a merit.

Conclusions

In swirl injector, the effect of tangential entry conditions on the stability of internal flow was analyzed by the change of swirl chamber length. The stability of internal flow for the tangential entry conditions was judged by the visualization method, liquid film thickness measurement and angular momentum calculation. It is true that the mass flow rate increased as the water injection pressure increased, the stability of internal flow and the limit point of increase in mass flow rate can be changed by the tangential entry conditions. Unstable internal flow was detected by visualizing air core formation and the liquid film fluctuations of about 10 kHz were detected in specific tangential entry condition. The relation between the variations of liquid film thickness in the orifice and the pressure fluctuations in manifold were analyzed by FFT(Fast Fourier Transform) method. The fluctuations in manifold pressure showed a same tendency with that of liquid film thickness. We analyzed the stability of internal flow with respect to initial inlet angular momentum. From these results, the stability boundary map for the internal flow presented. It is thought that these results are applied to a scaling of injector geometric parameter such as manifold size and swirl chamber length.

Acknowledgement

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Table 1. Specification of swirl injector

Variable parameter	Value				
Swirl chamber length (mm)	19	28	37	46	55
Swirl chamber diameter (mm)	12	15	18	21	24
Tangential entry diameter (mm)	0.5	1	2	3	4
Tangential entry number (ea)	2	3	4	5	6

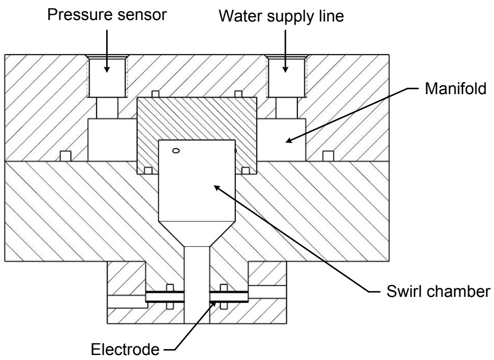


Figure 1. Schematic of swirl injector

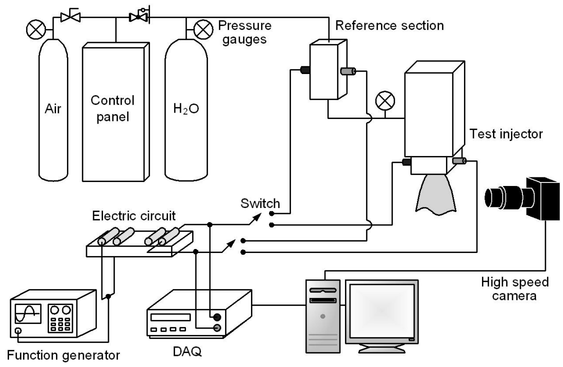


Figure 2. Experimental apparatus

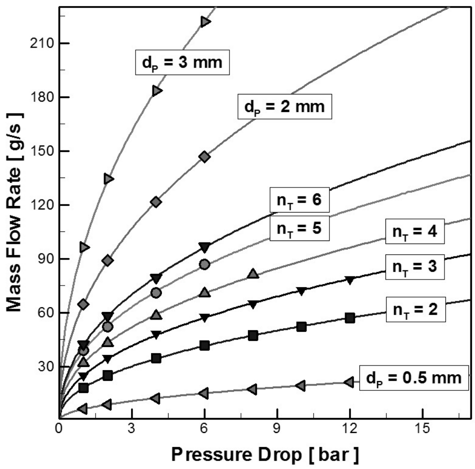


Figure 3. Mass flow rate for tangential entry conditions (d_P : tangential entry area, n_T : tangential entry number)

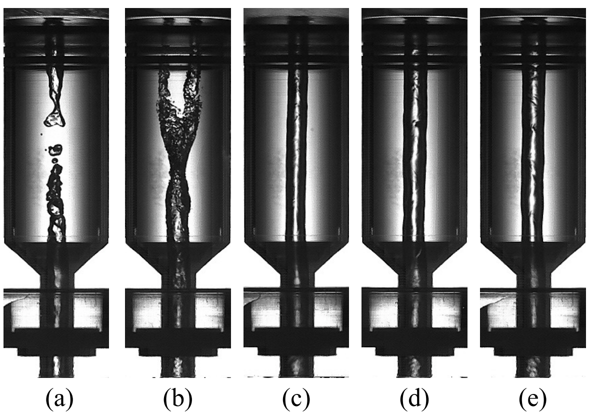


Figure 4. Formation of the air core in the swirl chamber ; (a) d_P = 0.5 mm, (b) n_T = 2 ea, (c) d_P = 2 mm, (d) n_T = 3 ea, (e) n_T = 4 ea (d_P : tangential entry diameter, n_T : tangential entry number, ΔP = 4 bar)

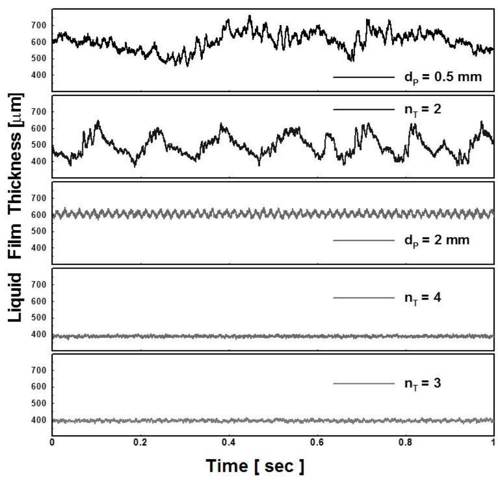
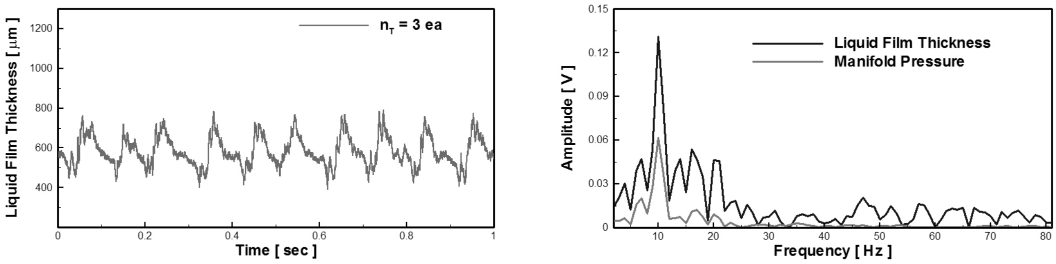
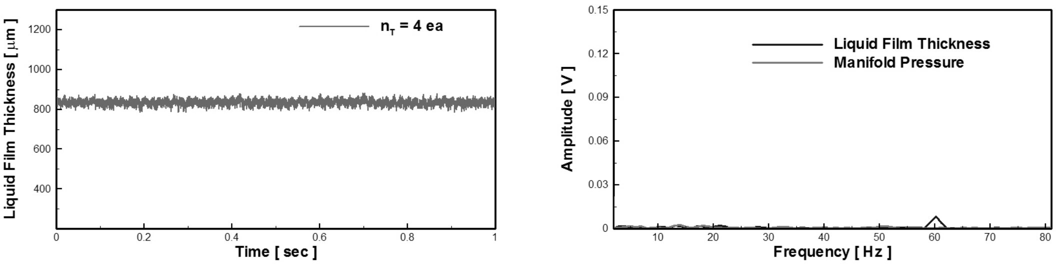


Figure 5. Variations of the liquid film thickness in the orifice for tangential entry diameter and number

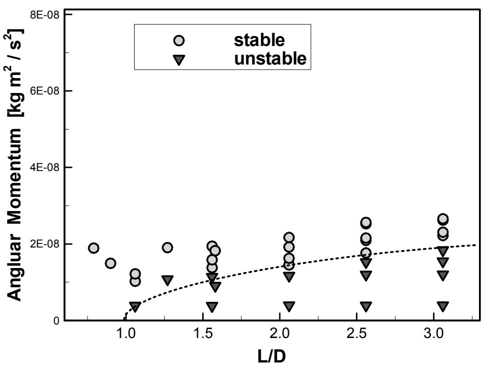


(a)

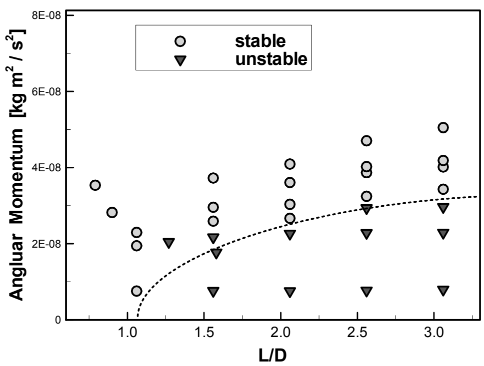


(b)

Figure 6. Liquid film thickness variations and FFT analysis (ΔP = 6 bar, L_S = 46 mm) ; (a) n_T = 3 ea, (b) n_T = 4 ea, (n_T : tangential entry number)



(a)



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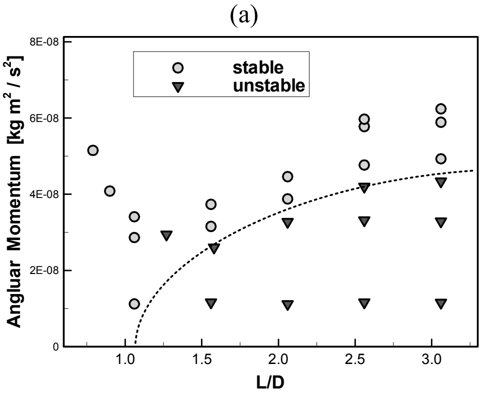
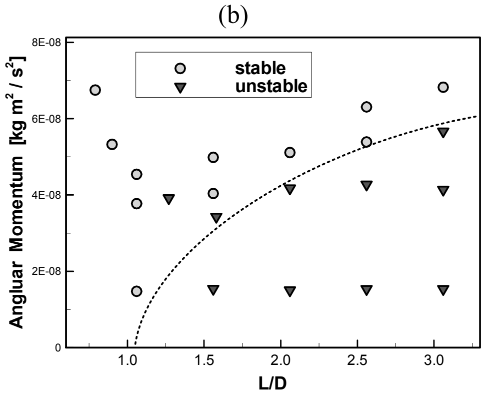


(c)



(d)

Figure 7. Stability boundary map for internal flow in the swirl chamber ; (a) ΔP = 2 bar, (b) ΔP = 4 bar, (c) ΔP = 6 bar, (d) ΔP = 8 bar (*L/D* : the ratio of swirl chamber length to swirl chamber diameter)