Quantifying the Variation of Mass Flow Rate generated in a Simplex Swirl Injector by the Pressure Fluctuation for Injector Dynamics Research

Taeock Khil, Sunghyuk Kim, Seongho Cho and Youngbin Yoon
School of Mechanical and Aerospace Engineering, Seoul National University Affiliation
San 56-1, Shillim-dong, Gwanak-gu, Seoul, Korea, 151-742
ybyoon@snu.ac.kr

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Abstract

When the heat release and acoustic pressure fluctuations are generated in the combustor by irregular combustion, these fluctuations affect the mass flow rate of the propellants injected through the injectors. Also, the variations of the mass flow rate by these fluctuations again bring about irregular combustion and furthermore that is related with combustion instability. Therefore, it is very important to identify the mass variation for the pressure fluctuation on the injector and to investigate its transfer function. So, we first have studied quantifying the variation of mass flow rate generated in simplex swirl injector by injection pressure fluctuation. To acquire the transient mass flow rate in orifice with time, we have tried to measure of the flow axial velocity and liquid film thickness in orifice. The axial velocity is acquired through theoretical approach after measuring the pressure in orifice and the flow area in the orifice is measured by electric conductance method. As results, mass flow rate calculated by axial velocity and liquid film thickness measuring in orifice accorded with mass flow rate acquired by direct measuring method in the small error range within 1 percents in steady state and within 6 percents as average mass flow rate in pulsated state. Hence this method can be used to measure the mass flow rate not only in steady state but also in unsteady state because the mass flow rate in the orifice can acquire with time and this method shows very high accuracy based on the experimental results.

Introduction

Combustion instability was discovered both solid and liquid rockets in the 1930's. Although the efforts to control the combustion instability have not acquired the large outcome in 1940's, F-1 engine development used in Apollo Project in the 1960's provided the motive for the combustion instability research[1)]. At this time many technical reports and papers about theoretical, experimental researches as engine development have published from early 1950's to early 1970's and space shuttle main engine was successfully developed on the basis of these efforts[2)]. In Russia, high frequency instability was generated at the RD-0110 engine equipped Soyuz spacecraft and it has solved by the change of the injector geometry and the rib function as baffle[3)]. In addition, it has been performed an effort to directly control pressure pulsation using the swirl type injectors generating uniform mixing distribution by V. Bazarov in 1970's and he has analyzed the dynamics of the injector through theoretical and experimental researches[4-5)]. However, it is discovered the self-pulsation phenomenon that can cause high frequency combustion instability on the swirl-coaxial injectors and then study to solve this phenomenon is now in progress[6)]. In Europe, combustion instability researches really started by Ariane Program and then French-German Research & Technology program has performed to understand physical mechanism of combustion instability in rocket system by National Space Institute and CNRS and ONERA in French and DLR in Dutch, and SNECMA and ASTRIM in industries had been participated in this program[7)].
Combustion instability is known to prevent stabilized energy supply, to generate incomplete combustion and to induce the destruction of the combustion engine itself. Various countries have tried to understand the phenomenon of this combustion instability for a long time and yet have not solved until the present owing to very complex phenomena generated in the combustor.
Actually when the unstable combustion is generated by a bad-mixing and the vaporization of propellants in the combustor, it is generated the fluctuations of the heat release and acoustic pressure due to the unstable combustion in the combustor. If the phases between the heat release and acoustic pressure are in-phase and amplified, combustion instability is generated. Also, the fluctuation of the heat release is given an effect on propellants injection injected into the combustor, which brings about the fluctuation of the mass flow rate. In addition, unstable propellants injected in combustor by previous process again generate unstable combustion to pulsate the heat release by the combustion. In other words, this process forms one of feedback loop in combustor. On this account it is certainly necessary to understand variations of mass flow rate by pressure fluctuation in the combustion chamber. However, studies on the variations of mass flow rate injected from the injector in this unsteady state have not been reported in the case of swirl injector till recently. This research is called as injector dynamics. In order to study injector dynamics, we have firstly to know transient variation of mass flow rate with time when the pressure fluctuation is generated.

D'souza et al. derived a transfer matrix related the dynamic pressure and velocity for hydraulic lines with small diameter through the basic Navier-Stokes's

equation and concluded that the dynamic response of small-diameter lines can be predicted correctly by the viscous theory developed in their paper[8]. Yokota et al. proposed method for measurement of unsteady mass flow rate using pressure measured at an arbitrary external portion between two pressure measuring points, $P_1(t)$ and $P_1(t)$, in hydraulic line with circular shape[9]. Lei et al. suggested two non-intrusive, different methods for measuring the thickness of thin falling film: a chromatic confocal imaging method and a fluorescence intensity technique[10]. However, these methods could not be directly applied to swirl injector owing to particular part called vortex chamber. Therefore, we have been developed new method through theoretical and experimental approaches and have tried the qualification of transient mass flow rate in unsteady state with this new method.
Variables composed mass flow rate are an axial velocity and a cross-section area. In steady state, the axial velocity was acquired by the empirical correlation proposed in this paper through theoretical and experimental approaches, and the cross-section area was measured by electric conductance method using Lefebvre's technique with accuracy[16,17]. Two variables were multiplied after they separately measured by these ways. And then, it found error rate to estimate accuracy of axial velocity and mass flow rate through comparison with real data directly measured in steady state. Lastly transient mass flow rate is measured with this method and is analyzed a little information when the forced pressure fluctuation is generated in a simplex swirl injector.

Theoretical Approach

Prior to explanation of method developed to measure the mass flow rate of the fluid injected through a swirl atomizer, we tried two methods using laser diagnostic technique as non-intrusive method: a laser intensity attenuation method and a PLLIF method[11]. The laser intensity attenuation method is to estimate attenuation degree of laser signal intensity with photo detector after the laser sheet beam built by concave and convex lenses passes over the spray region, and PLLIF method is to measure quantitative mass flow rate using the fluorescent signal intensity proportional to the volume of drop. In unsteady state the former could not measure transient velocity of axial or moving direction on the spray and the latter needed complex work to sum experimental data for a long time because transient signal intensity of fluorescence is very weak. Therefore, we conceived new method to be able to directly measure axial velocity of fluid existed air core of circular shape in the orifice.
Figure 1 shows the schematic of a simplex swirl injector. We redefined notations of the pressures and the velocities as the injector parts and assumed that Bernoulli equation was applied in the manifold and in the orifice.

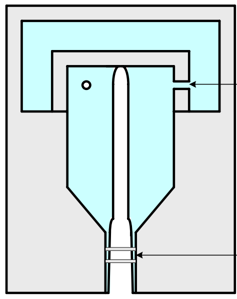


Fig. 1 Definitions for a simplex swirl injector

If Bernoulli equation applies to simplex swirl injector as shown in Fig. 1, the velocity in the orifice becomes

$$P_m = P_o + \frac{\rho u_{o,th}^2}{2} + \frac{\rho w_{o,th}^2}{2} \tag{1}$$

where P_m and P_o are pressures in the manifold and orifice, and $u_{o,theoretical}$ and $w_{o,theoretical}$ are axial and tangential velocity in the orifice, respectively[12].
Generally mass flow rate of the fluid injected the atomizer is only related in a axial velocity passing through the flow pipe. However, because equation (1) includes the axial and the tangential velocity, we firstly tried to work that the tangential velocity substitutes for axial velocity component. The spray cone half angle in the steady state can be written as follows[12].

$$\tan\theta(Spray\ Cone\ Angle) = \frac{w_o}{u_o} \tag{2}$$

Hence equation (1) is represented equation (3) by equation (2) and we can acquire the mass flow rate passing the orifice if we know cross-section area of flowing fluid the orifice.

$$u_{o,th} = \sqrt{\frac{2(P_m - P_o)}{\rho(1+\tan^2\theta)}} \tag{3}$$

$$\dot{m}_o = \rho C_{do} u_{o,th} A_o = \rho C_{do} \sqrt{\frac{2(P_m - P_o)}{\rho(1+\tan^2\theta)}} A_o \tag{4}$$

Here C_{do} means discharge coefficient to compensate for theoretical mass flow rate.
In equation (4), the cross-section area of flowing fluid the orifice, A_o, can acquire directly with our measurement method using electric conductance proposed by Lefebvre et. al. and real mass flow rate also can measure directly. Therefore, the real value of axial velocity in the orifice can be written

$$u_o = C_{do} u_{o,thl} = C_{do} \sqrt{\frac{2(P_m - P_o)}{\rho(1+\tan^2\theta)}} \tag{5}$$

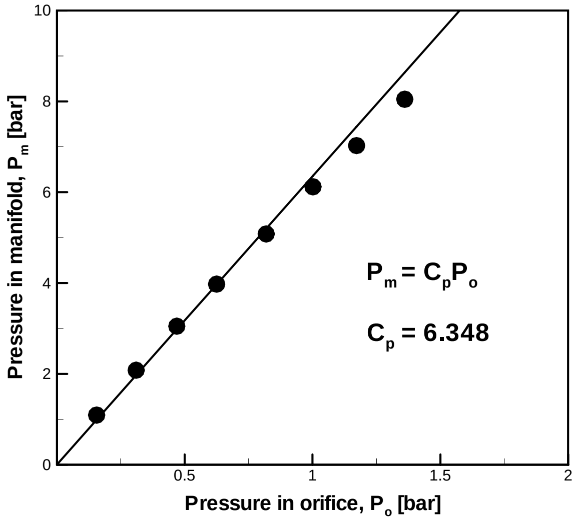


Fig. 2 The relation between the pressure in the manifold and the pressure in orifice

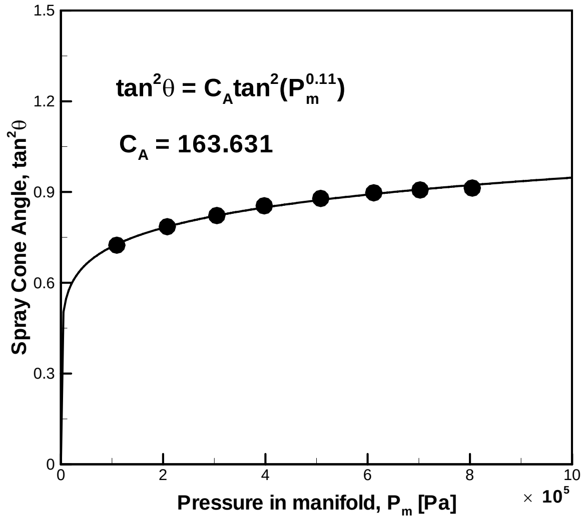


Fig. 3 Relation between the spray cone angle and the pressure in the manifold

and discharge coefficient, C_{do} , is changed the correction factor to compensate for theoretical axial velocity.

For the steady state, pressures in the manifold and orifice keep up with time constantly. However, if the pressure fluctuation is generated in the injector, pressures in above two positions have different in values because the phase difference exists between pressures in the manifold and the orifice. Therefore, we performed work to substitute P_m for P_o in equation (5) as second process.

Figure 2 shows the relation between pressure in manifold, P_m , and pressure in the orifice, P_o , acquired by experiment in steady state. Pressure in the orifice, P_o , is proportional to the pressure in the manifold as shown in Fig. 2 and its equation becomes

$$P_m = C_p P_o \tag{6}$$

where C_p means the correction factor to compensate for pressures between in the manifold and in the orifice and its value is 6.348 in our injector.
The real value of axial velocity in equation (5) can be expressed by equation (6) as follows.

$$u_o = C_{do}\sqrt{\frac{2(C_p-1)P_o}{\rho(1+\tan^2\theta)}} \tag{7}$$

Finally we performed the work to substitute the spray cone angle for the pressure in orifice because spray cone angle is proportional to the injection pressure as widely publicized. Rizk et. al. derived from theoretical approach the fact that the spray cone angle, θ, is proportional to pressure in the manifold on steady state[13)].

$$2\theta = 6K^{-0.15}\left(\frac{\Delta P_L d_o^2 \rho_L}{\mu_L^2}\right)^{0.11} \tag{8}$$

From equation (8) the spray cone angle in equation (7) can be expressed an equation for pressure in manifold as equation (9). Figure 3 shows the experimental results about relation between spray cone angle and pressure in the manifold as equation (9).

$$\theta \sim P_m^{0.11} \qquad \tan\theta \sim P_m^{0.11} \Rightarrow \tan\left(P_m^{0.11}\right)$$
$$\tan^2\theta \sim P_m^{0.22} \Rightarrow \tan^2\left(P_m^{0.11}\right)$$
$$\tan^2\theta = C_A \tan^2\left(P_m^{0.11}\right) \tag{9}$$

Here C_A means the correction factor to compensate for relation between spray cone angle and pressure in the manifold and its value is 163.631 in our injector.
From above three stages we can acquired the final equation for real axial velocity in the orifice on the basis of the inviscid theory.

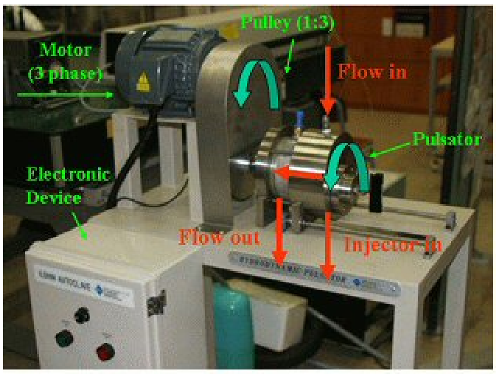
$$u_o = C_{do}\sqrt{\frac{2(C_p-1)P_o}{\rho\left(1+C_A\tan^2\left(P_m^{0.11}\right)\right)}} \tag{10}$$

The method to measure the mass flow rate in the orifice using an equation (10) is called the Direct Pressure Measuring Method (DPMM).

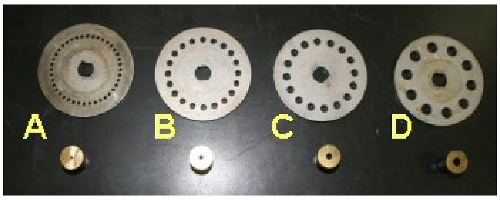
Experimental Methods

Hydrodynamic mechanical pulsator

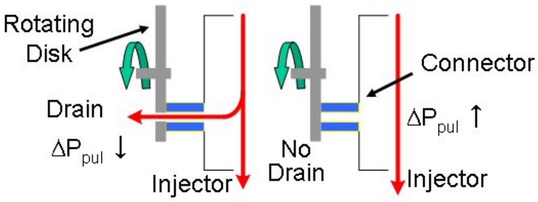
The hydrodynamic mechanical pulsator to generate pressure fluctuation in flow line was designed as shown in Fig.4. The inside of the pulsator consists of two parts; rotating disk and connector. If the holes in the rotating disk meet the hole of connector, fluids flowed in pulsator exhaust outside through the hole of connector as shown in Fig.4 (b). But, if it is not, all fluid flowed in pulsator move toward the injector.



(a) the front view of a pulsator



(b) the rotating disks and the connectors



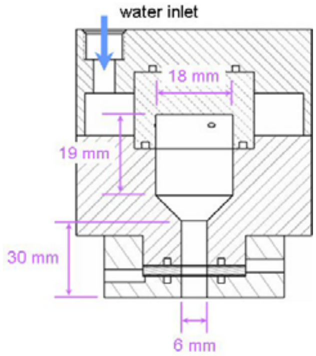
(c) the working mechanism for the pulsator

Fig. 4 Hydrodynamic mechanical pulsator designed to generate the pressure fluctuation in the flow line. (a) the front view of a pulsator ; (b) two components of the pulsator inside ; (c) the working mechanism for the pulsator

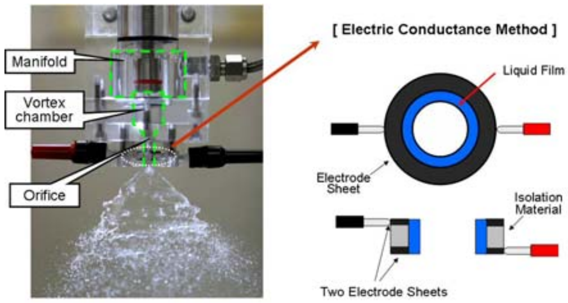
Because the process of this rotating disk type did not affect working liquid which flow the injector, physical phenomena such as bubbles or cavitations in pulsator are not generated. The rotating disks and connectors are 4 types of different size and numbers of holes and can generate the frequency range of the pressure drop from 10 Hz to 400 Hz. The frequency ranges of the injection pressure fluctuation used in this experiment are two bundle conditions from 5 to 25 Hz and from 100 to 300 Hz. The numbers of holes are 10 units and diameter of rotating disk and connector are 6 mm, respectively. This device was designed in cooperation with Prof. Bazarov in Russia[4)].

Electric conductance method

It was produced specially designed injector to measure the liquid film thickness in orifice. The injector used in this paper is a single swirl injector and has 3 tangential entries as shown in fig.5. Two electrodes are equipped at orifice exit to measure the liquid film thickness in orifice. Measurement of the liquid film thickness in a swirl injector is certainly necessary to understand spray characteristics of swirl injector such as spray cone angle, breakup length and droplet size.



(a) the geometric conditions for a simplex swirl injector



(b) the electric conductance method to measure the liquid film thickness in orifice

Fig. 5 Schematics of (a) a simplex swirl injector and (b) the electric conductance method used in the experiment

Until now some methods have been suggested to measure liquid film thickness in orifice of pressurized swirl atomizer. However, it relied on numerical or theoretical method because it is very difficult to identify the exact value of liquid film thickness by experiment. Kutty et.al used a photographic technique in order to understand the variation of spray cone angle and air core diameter as a function of injection pressure[14)]. Jeng et.al measured liquid film thickness of a large-scale transparent atomizer using a photographic method[15)]. Suyari & Lefebvre measured liquid film thickness using the variation of the electric conductivity between two electrodes placed the end of orifice[16)].

Liquid film thickness is measured by electric conductivity between two electrodes in orifice like as Lefebvre's method. Because electric conductance of water flowing between two electrodes of a fixed distance varies only with the liquid film thickness, the liquid film thickness in orifice can be measured by voltage variation between two electrodes.

Table 1 the experimental conditions

Injection Pressure, P_m, [bar]	3, 4, 5, 6
Pressure fluctuation frequency, f, [Hz]	0 (steady) 5, 10, 15, 20, 25 100,150,200,250,300

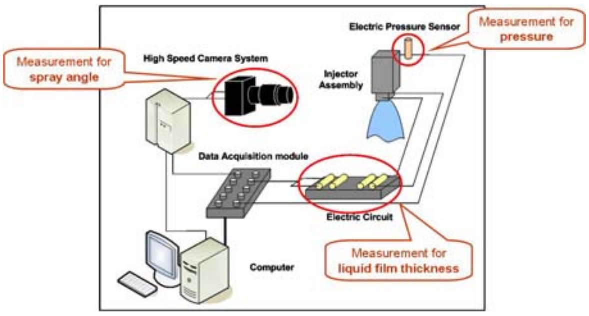


Fig. 6 The data acquisition system to obtain data for spray image, pressures in manifold and in orifice and liquid film thickness in orifice simultaneously

The electrode was made of thin stainless steel sheet and isolation material is placed between two electrodes. Table 1 shows the experimental conditions of a simplex swirl injector using in this paper. Also, figure 6 shows the schematic of data acquisition system used in order to measure transient pressures in the manifold and in the orifice and liquid film thickness in the orifice simultaneously. We used water as a working fluid.

Experimental Results

In order to take the quantitative estimation for DPMM, we compared the error rate between the real data measured directly and the data calculated by DPMM as tested frequency for the axial velocities and mass flow rates in steady state and in unsteady state.

Steady State

Variables required in order to know the mass flow rate are a density, the axial velocity and the cross-section area of the liquid passed through in the orifice. In the first place, we compared the real data with the calculated data in the steady state for the axial velocity and the mass flow rate to know an accuracy of DPMM. Figure 7, 8 and table 2 show the accuracies of the axial velocity and the mass flow rate by DPMM in the orifice and the symbols of the squire and the circle mean DPMM and the real data, respectively. The real data of axial velocity acquired by equation of the mass flow rate like as $u_{real} = \frac{\dot{m}_{measured}}{\rho_L A_o}$ where A_o means the cross-section area in the orifice measured by our electric conductance method[17]. The accuracies of DPMM are defined as value to divide DPMM data by the real data both the axial velocity and the mass flow rate and then its results appeared over 99 percents highly. Hence we could confide for the axial velocity and the mass flow rate by DPMM and could use DPMM to acquire the mass flow rate in the pulsated state.

Pulsated State

We made an experiment in two bundle conditions from 5 to 25 Hz and from 100 to 300 Hz for the pulsated state.

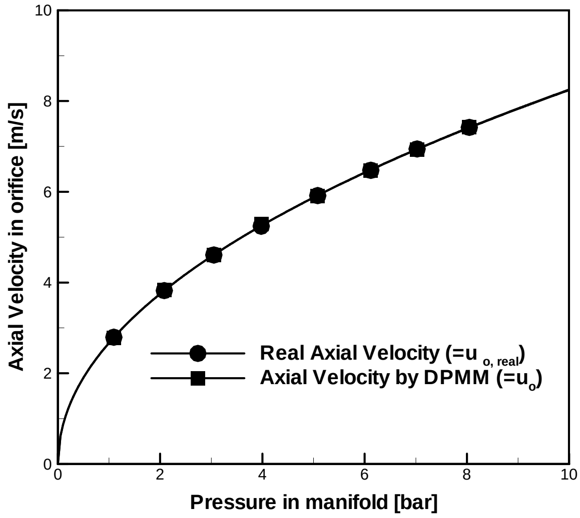


Fig. 7 The real axial velocity measured directly and the axial velocity calculated by DPMM in steady state

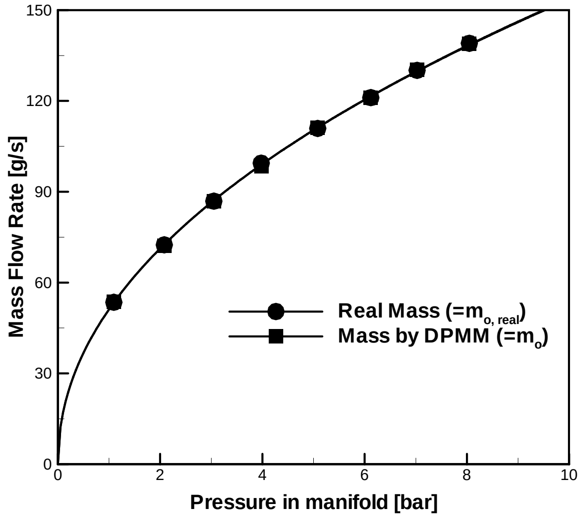


Fig. 8 The real mass flow rate measured directly and the mass flow rate calculated by DPMM in steady state

Table 2 Errors of the axial velocity and the mass flow rate by DPMM in steady state

Pressure in manifold, P_m, [bar]	2	4	6	8
Error of the axial velocity by DPMM, [%]	0.27	0.94	0.07	0.11
Error of the mass flow rate by DPMM, [%]	0.27	0.94	0.07	0.11

Figure 9 shows the real data when the pressure fluctuation is generated in the feeding line and the pressure condition and the fluctuation frequency are 3bar and 5 Hz, respectively. Upper image in figure 9 means the pressure fluctuation in the injector inlet, which is call the manifold after this. Low image in figure 9 means the parameters in the orifice which are affected by the pressure fluctuation in the injector inlet: the pressure (blue line), the liquid film thickness (pink line), the axial velocity (green line) and the mass flow rate (violet line).

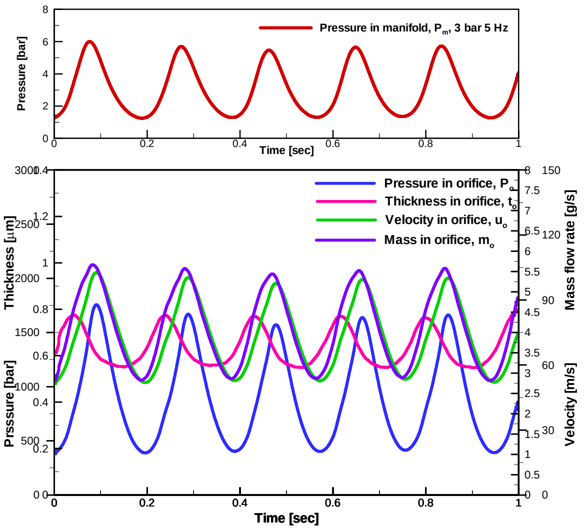


Fig. 9 the pressure fluctuation in the injector inlet (upper image) and the parameters in the orifice (low image) which are affected by the pressure fluctuation in the injector inlet: the pressure (blue line), the liquid film thickness (pink line), the axial velocity (green line) and the mass flow rate (violet line)

As shown in figure 9, it can know that the differences of a phase and an amplitude between the pressure in the manifold and the parameters, a pressure, a liquid film thickness, an axial velocity and a mass flow rate, in the orifice although the parameters is simultaneously measured in the manifold and in the orifice. Therefore, it needs to know the value of the parameter in the injector outlet with time in order to understand injector dynamics. Figure 10 and 11 and table 3 show the accuracies of the axial velocity acquired by DPMM in the orifice for the range of 5 to 25 Hz and for the range of 100 to 300 Hz, respectively. The symbols of the squire and the circle mean DPMM data in pulsated state and real data in steady state in figure 10 and 11, respectively. Error rate of DPMM for the real data was calculated using an average value of each condition because the real data for the pulsated state could not directly measure with time. Mass flow rates have to be constant both in steady state and in pulsated state in order to only know a frequency effect of the pressure fluctuation when the pressure fluctuation is generated in the swirl injector. Therefore, a total and an average mass flow rate are constant both in steady state and in pulsated state for a one pressure condition and the error rate of DPMM for the real data is calculated using average value of each state as follows:

$$Error\ rate_{pulsated\ state} = \frac{average\ velocity\ in\ pulsated\ state - velocity\ in\ steady\ state}{velocity\ in\ steady\ state} \quad (11)$$

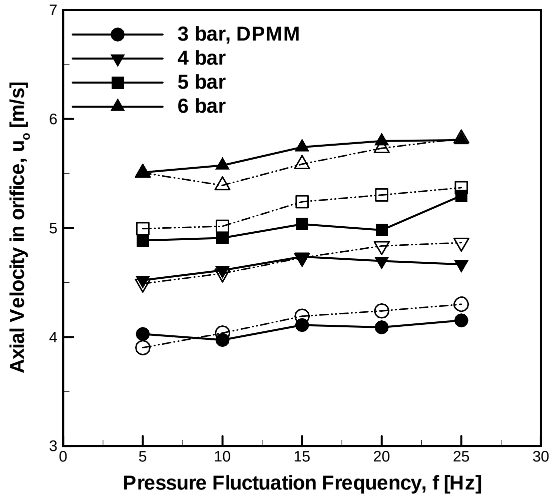


Fig. 10 Comparison of the average axial velocity measured directly with that calculated by DPMM in the range of 5~25 Hz

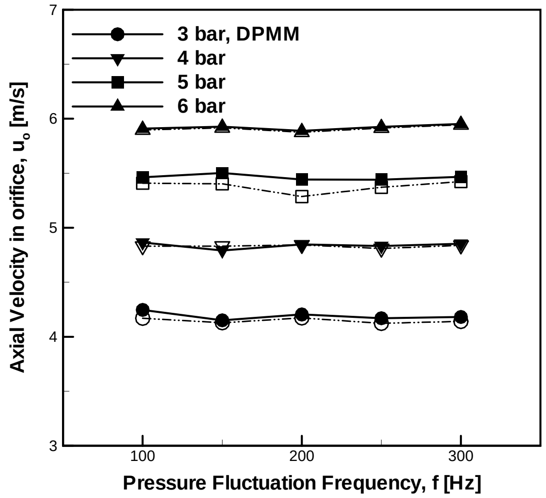


Fig. 21 Comparison of the average axial velocity measured directly with that calculated by DPMM in the range of 100~300 Hz

Table 3 Errors of the axial velocity and the mass flow rate calculated by DPMM in the range of 5~25 Hz and in the range of 100~300 Hz

Pressure in manifold, P_m, [bar]	3	4	5	6
Error of the axial velocity by DPMM, 5~25 Hz, [%]	2.7	4.0	6.1	1.8
Error of the axial velocity by DPMM, 100~300 Hz, [%]	0.8	0.4	0.4	0.9

Table 4 Errors of the axial velocity and the mass flow rate calculated by DPMM in the range of 5~25 Hz and in the range of 100~300 Hz

Pressure in manifold, P_m, [bar]	3	4	5	6
Error of the mass flow rate by DPMM, 5~25 Hz, [%]	1.4	0.9	3.0	1.7

Error of the mass flow rate by DPMM, 100~300 Hz, [%]	2.4	1.4	0.6	2.5

For the pulsated state, an average velocity means average value of all pressure fluctuation frequency for one pressure condition. Although it was compared its average velocity, the axial velocities in pulsated state could also get the high accuracies over 94 percents for the range of 5 to 25 Hz and 99 percents for the range of 100 to 300 Hz as shown in table 3.
Table 4 shows the accuracies of the mass quantification in the range of 5 to 25 Hz and in the range of 100 to 300 Hz, respectively. In the same manner the accuracy of the mass flow rate also computed using an average value of each condition because the real data for the pulsated state could not directly measure with time and the mass flow rate could get the high accuracies over 97 percents for all conditions.

Conclusion

In this work, we performed study on quantifying the variation of the mass flow rate generated by the pressure fluctuation in a simplex swirl injector as a preliminary research for injector dynamics. The laser diagnostic techniques were occurred with the serious problems that could not measure the liquid velocities in the orifice or into the external spray when the pressure fluctuation is generated in the swirl injector, and these methods could not be used to measure transient mass flow rate. Therefore, new method using the pressure and the liquid film thickness directly measured in the orifice was developed, and the equation for the axial velocity was proposed through theoretical approach that is applied Bernoullie equation based on inviscid theory and function suggested by Rizk et al[12-13].
To verify the equation for axial velocity, tests of two types were conducted as follows: comparisons real data with data calculated by DPMM for axial velocity in steady state and in pulsated state. In steady state, accuracy of the axial velocity calculated by DPMM showed high quality over 99 percents from results comparing with real axial velocity acquired by direct measuring method, $u_{real} = \frac{\dot{m}_{real}}{\rho_L A_o}$, under assumption that neglects an error of the liquid area obtained by electric conductance method. In pulsated state, the accuracies of the axial velocity calculated by DPMM using average value showed also the high quality over 94 percents for the range of 5 to 25 Hz and 99 percents for the range of 100 to 300 Hz resulted from comparison with values in steady state and the accuracies of the mass flow rate using the axial velocity by DPMM appeared to 96 percents for all frequency conditions. From these facts, the axial velocity acquired through DPMM proposed to this paper can be used to measure the mass flow rate varied transiently in the swirl injector with high accuracy.

Acknowledgments

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Nomenclatures

P_m	pressure in manifold (bar)
P_o	pressure in orifice (bar)
u, w	axial, tangential velocities (m/s)
ρ_L	density of the liquid (kg/m^3)
C_{do}	discharge coefficient (Non-dim.)
C_p	correction factor for pressure
C_A	correction factor for spray cone angle compensated by experiment
$\dot{m}$	mass flow rate (kg/sec)
A_o	cross-section area of the liquid with ring shape in orifice (m^2)

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