Quantification of the Transient Mass Flow Rate in a Simplex Swirl Injector

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Abstract

When a heat release and acoustic pressure fluctuations are generated in a combustor by irregular and local combustions, these fluctuations affect the mass flow rate of the propellants injected through the injectors. In addition, variations of the mass flow rate by these fluctuations bring about irregular combustion, which is associated with combustion instability, so that it is very important to identify a mass variation through the pressure fluctuation on the injector and to investigate its transfer function. Therefore, quantification of the variation of the mass flow rate generated in a simplex swirl injector via the injection pressure fluctuation was the subject of an initial study. To acquire the transient mass flow rate in the orifice with time, the axial velocity of flows and the liquid film thickness in the orifice were measured. In an effort to understand the flow area in the orifice, the liquid film thickness was measured by an electric conductance method. In the results, the mass flow rate calculated by the axial velocity and the liquid film thickness measured by the electric conductance method in the orifice were in good agreement with the mass flow rate acquired by the direct measuring method in a small error range within 1 percent in the steady state and within 4 percent for the average mass flow rate in a pulsated state. Also, the amplitude(gain) of the mass flow rate acquired by the proposed direct measuring method was confirmed using the PLLIF technique in the low pressure fluctuation frequency ranges with an error under 6 percent. This study shows that the our proposed method can be used to measure the mass flow rate not only in the steady state but also in the unsteady state(or the pulsated state). Moreover, this method shows very high accuracy based on the experimental results.

Introduction

Combustion instability is known to prevent a stabilized energy supply, to generate incomplete combustion and to induce the destruction of the combustion engine itself [1-3]. Various countries have long attempted to understand the phenomenon of this combustion instability; however, these efforts have yet to show a breakthrough owing to the highly complex phenomena generated in a combustor.

Essentially, when unstable combustion is generated via bad-mixing and by the vaporization of the propellants in a combustor, fluctuations in the heat release and acoustic pressure are generated due to the unstable combustion in the combustor. If the phases between the heat release and acoustic pressure are in-phase and are amplified, combustion instability is generated. Moreover fluctuation of the heat release has an effect on propellants injected into the combustor, an action that brings about the fluctuation of the mass flow rate. In addition, unstable propellants injected into the combustor by this process again generate unstable combustion that pulsates the heat that is released by the combustion. Hence, it is clearly necessary to understand the variations of the mass flow rate that are caused by pressure fluctuations in the combustion chamber. However, studies regarding mass variations of propellants that are injected from an injector in this unsteady state have not been reported as they pertain to a swirl injector until recently. This research field is known as injector dynamics [4-6]. In order to study injector dynamics, it is initially important to understand the transient variation of the mass flow rate with time when pressure fluctuations are generated.

D'souza et al. derived a transfer matrix related to the dynamic pressure and the velocity of a hydraulic line with a small diameter using a basic Navier-Stokes'-equation [7]. Lei et al. suggested two different non-intrusive methods for measuring the thickness of a thin falling film: a chromatic confocal imaging method and a fluorescence intensity technique [8]. However, these methods can not be applied directly to a swirl injector owing to the particular part known as the vortex chamber, which is characterized as having a swirling motion. Therefore, a new method is developed in this study through theoretical and experimental approaches. Quantification of the variation of the transient mass flow rate in the unsteady state is tested with this new method.

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Theoretical Approach

Figure 1 shows the schematic of a simplex swirl injector. The notations of the pressures and the velocities are redefined as injector parts, and the Bernoulli equation was applied in the manifold and in the orifice.

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

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

where P_m and P_o are the pressures in the manifold and orifice, and $u_{o,th}$ and $w_{o,th}$ are the axial and tangential velocities in the orifice, respectively.

Generally, the mass flow rate of a fluid injected into an injector is only related to the axial velocity passing through the flow line. However, because equation (1) includes the axial and tangential velocities, the tangential velocity was substituted for the axial velocity in this study. The spray cone half angle in the steady state can be written as follows [9].

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

Hence, equation (1) represents equation (3) by equation (2), and it is possible at this point to acquire the mass flow rate passing the orifice if the cross-section area of the flowing fluid at the orifice is known.

$$\dot{m}_o = \rho C_d u_{o,th} A_o = \rho C_d \sqrt{\frac{2(P_m - P_o)}{\rho(1+\tan^2\theta)}}\,A_o \qquad (3)$$

Here, C_d denotes a discharge coefficient to offset the theoretical mass flow rate.

In equation (3), the cross-section area of the fluid in the orifice, A_o, can be acquired directly with the proposed measurement method using the electric conductance proposed by Lefebvre et al. The real mass flow rate can be measured directly as well. Therefore, the real value of the axial velocity in the orifice can be written as

$$u_o = C_d u_{o,th} = C_d \sqrt{\frac{2(P_m - P_o)}{\rho(1+\tan^2\theta)}} \qquad (4)$$

For a steady state, the pressures in the manifold and in the orifice are constantly maintained with time. However, if pressure fluctuations are generated in the injector, the pressures in these two positions have difference in values because a phase difference exists between the pressures in the manifold and in the orifice. Therefore, it was necessary to substitute P_m for P_o in equation (4) as the second step.

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

$$P_m = C_p P_o \qquad (5)$$

where C_p is a correction factor to offset the pressures between the manifold and the orifice. Its value is 6.348 for this injector.

$$u_o = C_d \sqrt{\frac{2(C_p - 1)P_o}{\rho(1+\tan^2\theta)}} \qquad (6)$$

Finally, it was necessary to substitute a spray cone angle for the pressure in the orifice as the spray cone angle is commonly known to be proportional to the injection pressure. Rizk et al. derived from a theoretical approach the fact that the spray cone angle, θ, is proportional to the pressure in the manifold in a steady state [10].

The spray cone angle in equation (6) can be expressed as an equation for the pressure in manifold, as shown by equation (7). Figure 2 (b) shows the experimental results regarding the relation between the spray cone angle and the pressure in the manifold, as expressed by equation (7).

$$\tan^2\theta = C_A \tan^2\left(P_m^{0.11}\right) \tag{7}$$

Here, C_A denotes a correction factor to offset the relation between the spray cone angle and the pressure in the manifold. Its value is 163.631 for this injector.

From above three stages, it was possible to acquire the final equation for the actual axial velocity in the orifice on the basis of the inviscid theory.

$$u_o = C_d \sqrt{\frac{2(C_p - 1)P_o}{\rho(1 + C_A \tan^2(P_m^{0.11}))}} \tag{8}$$

The method to measure the mass flow rate in the orifice using equation (8) is termed the Direct Pressure Measuring Method (DPMM).

Materials and Methods

Hydrodynamic mechanical pulsator

A hydrodynamic mechanical pulsator to generate pressure fluctuations in a flow line was designed, as shown in Fig. 3 (a). The inside of the pulsator consists of two parts: a rotating disk and a connector. If the holes in the rotating disk meet the hole of the connector, fluid in the pulsator is divided into the injector and the outside. However, if this does not occur, all of the fluid in the pulsator moves into the injector. As the process of this type of rotating disk does not have an effect on the working liquid that flows into the injector, physical phenomena such as bubbles or cavitations in the pulsator are not generated. The device consists of four different sizes of rotating disk and connector each, and can generate the frequency range of the pressure fluctuation from 5 to 300 Hz. This device was designed in cooperation with Prof. Bazarov in Russia [4,6].

Electric conductance method

A special injector was produced to measure the thickness of the liquid film in the orifice. The injector used in this paper is a simplex swirl injector with three tangential entries, as shown in Fig. 3 (b). Two electrodes are installed onto the orifice exit to measure the thickness of the liquid film in the orifice.

The thickness of the liquid film was here measured via the electric conductivity between two electrodes in the orifice, as in Lefebvre's method. As the electric conductance of water flowing between two electrodes of a fixed distance only varies with the thickness of the liquid film, this thickness in the orifice can be measured by varying the voltage between two electrodes. The electrode used here consisted of a thin stainless steel sheet and insulation material was placed between two electrodes [11,12].

Table 1 shows the experimental conditions of the simplex swirl injector used in this study. The data acquisition system was used to measure the transient pressures in the manifold and in the orifice as well as the thickness of the liquid film in the orifice simultaneously. Water was used as a working fluid and 10000 samples per second were acquired.

Results and Discussion

Steady State

The variables required to establish the mass flow rate in the orifice are the density, the axial velocity and the cross-section area of the liquid that passes through the orifice. Thus, the actual data was compared to the calculated data in a steady state for the mass flow rate to determine the accuracy of the DPMM, as the axial velocity and the cross-section area were acquired using the DPMM.

Figure 4 shows the accuracy of the mass flow rate by the DPMM in the orifice. The square and the circle denote DPMM and the actual data, respectively. The accuracies of the DPMM are defined as the values that divide the

DPMM data by the directly measured actual data, and the result was greater than 99 percent higher. Hence, the mass flow rate by the DPMM was determined and it was possible to use the DPMM to acquire the mass flow rate in the pulsated state.

Pulsated State

An experiment using two bundled conditions from 5 to 25 Hz and from 100 to 300 Hz in a pulsated state was conducted. Figure 5 illustrates the accuracies of the mass flow rate acquired by the DPMM in the orifice in the range of 5 to 25 Hz and in the range of 100 to 300 Hz. The filled symbols and non-filled symbols denote the DPMM data in the pulsated state and the actual data, which are obtained by direct measuring during specific time as average value, in the steady state from Figure 5. The error of the DPMM compared to the actual data was calculated using the average value of each pressure fluctuation frequency condition, as the actual data for the pulsated state could not be measured directly in real time.

Although only the average mass flow rate was compared, the mass flow rate in the pulsated state was found to obtain the high accuracies of greater than 97 percent for the range of 5 to 25 Hz and 96 percent for the range of 100 to 300 Hz, as shown in Fig. 5.

Amplitude comparison

Finally, the amplitude accuracy of the mass flow rate acquired by the DPMM was identified. It is very important to acquire the amplitude of the fluctuation in order to understand the dynamic characteristics of the transfer function of any specific system for all related research fields. Therefore, precision evaluation to estimate the amplitude accuracy of the mass flow rate obtained by DPMM was done with the non-intrusive laser technique known as PLLIF in the low-frequency range of the pressure fluctuation.

PLLIF technique can measure the quantitative mass flow rate because the fluorescence signal intensity of a spray drop is proportional to the volume of a drop which includes the fluorescent molecules [13-15]. However, this laser technique requires sufficient exposure time by the sheet beam of a continuous laser in order to acquire sufficient laser intensity. Hence, this laser technique was used with a high-speed camera(FASTCAM SA-1, Photron) to ensure good sensitivity in the low-frequency range of pressure fluctuation because it is difficult to obtain uniform laser intensity under a sufficient exposure time if pressure fluctuation is generated. The exposure time of the high-speed camera was 1/60s, and 60 images were acquired per second.

Figure 6 shows the mass waves during 1 period (a), for the result of condition with 5 Hz as the pressure fluctuation frequency, and 2 periods (b), for that with 10 Hz as the pressure fluctuation frequency, acquired by the PLLIF and DPMM in the pulsated state. The dashed and solid lines denote the result for the PLLIF method and that for the DPMM, respectively. The Y axis of Fig. 13 is defined as the accumulated mass, which means the total mass collected during 1/60s. Although the condition of the mass flow rate acquired by the PLLIF technique, which can measure the quantitative mass, is in the low-frequency range of the pressure fluctuation as 5 Hz (a) and 10 Hz (b), the mass wave acquired by the DPMM shows a low error for the amplitude size compared with the result acquired by the PLLIF technique, as shown in Fig. 10; the error was less than 6 % in both 5 and 10 Hz conditions as a result by least squire analysis.

Nomenclature

P	*pressure, bar*
u, w	*axial, tangential velocities, m/s*
ρ_L	*density of the liquid, kg/m3*
$\dot{m}$	*mass flow rate, kg/sec*
A_o	*cross-section area of the liquid with ring shape in orifice, m2*
θ	*maximum spray cone half-angle, degrees*
d_o	*discharge orifice diameter, m*
μ	*absolute viscosity, kg/ms*

Subscrpts

o	*orifice*
m	*manifold*
L	*Liquid*

th *theoretical*

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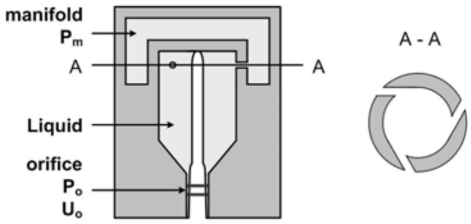


Figure 1. Definitions for a simplex swirl injector

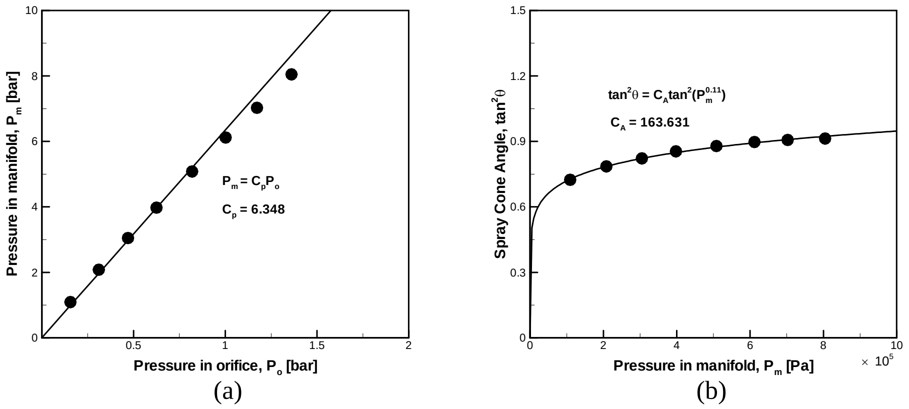
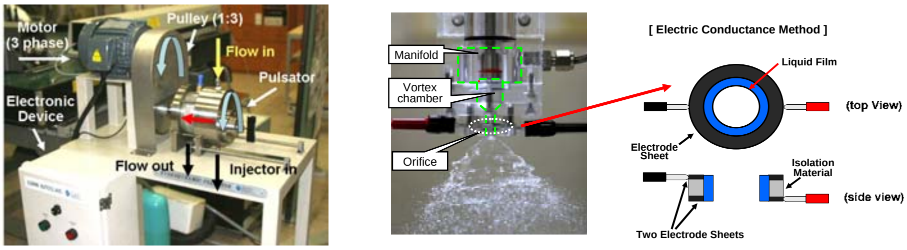


Figure 2. (a) the relation between the pressure in the manifold(P_m) and the pressure in the orifice(P_o) (b) the relation between the spray cone angle(Θ) and pressure in the manifold(P_m).



(a) (b)

Figure 3. (a) Hydrodynamic mechanical pulsator designed to generate the pressure fluctuation in the flow line (b) the electric conductance method to measure the thickness of the liquid film in the orifice

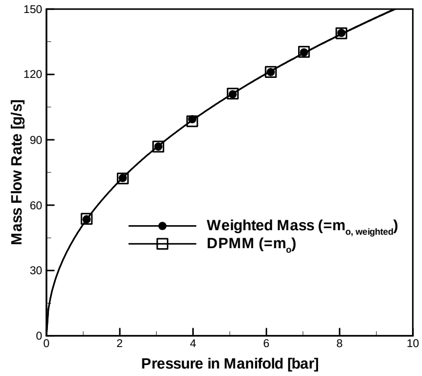
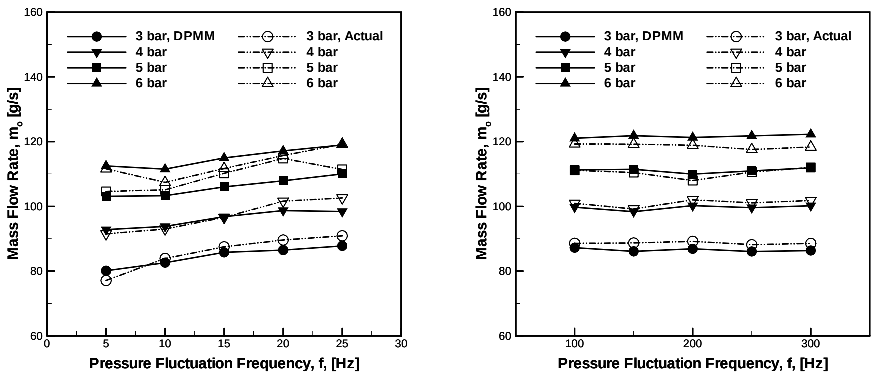
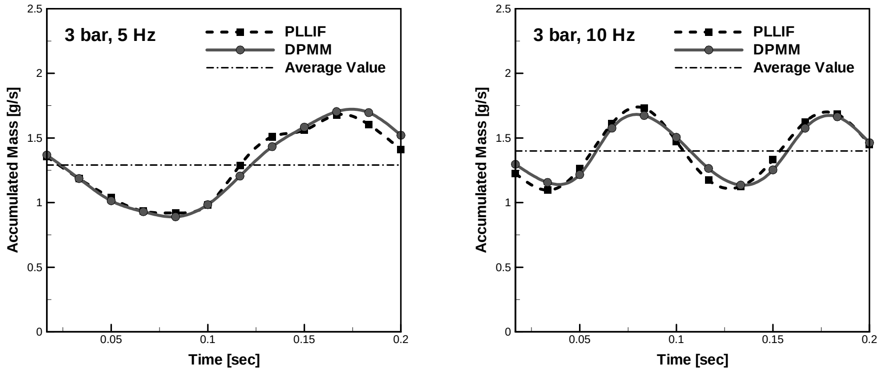


Figure 4. The accuracy of the mass flow rate by the DPMM in the orifice.



(a) (b)

Figure 5. The comparison of the actual average value of the mass flow rate in the steady state with the average value of the mass flow rate calculated by DPMM in the range of (a) 5~25 Hz and (b) 100~300 Hz.



(a) (b)

Figure 6. Amplitude comparison of results by PLLIF with those by DPMM in the pulsated state; (a) 3 bar, 5 Hz; (b) 3 bar, 10 Hz

Table 1. The experimental conditions

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