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Study on self-pulsation characteristics of gas centered shear coaxial injector for supercavitating underwater propulsion system

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ABSTRACT: *In order to design a shear coaxial injector of solid particles for underwater propulsion system, basic experiments on gas-liquid shear coaxial injector are necessary. In the gas-liquid coaxial injector self-pulsation usually occurs with an intense scream. When self-pulsation occurs, mass flow rate oscillation and intense scream are detected by the interactions between the liquid and gas phase. Self-pulsation must be suppressed since this oscillation may cause combustion instabilities. Considerable research has been conducted on self-pulsation characteristics, but these researches are conducted in swirl coaxial injector. The main objective of this research is to understand the characteristics of self-pulsation in shear coaxial injector and reveal the mechanism of the phenomenon. Toward this object, self-pulsation frequency and spray patterns are measured by laser diagnostics and indirect photography. The self-pulsation characteristics of shear coaxial injector are studied with various injection conditions, such as the pressure drop of liquid and gas phase, and recess ratio. It was found that the frequency of the self-pulsation is proportional to the liquid and gas Reynolds number, and proportional to the L/d.*

KEY WORDS: Self-pulsation; Shear coaxial injector; Recess ratio; Momentum flux ratio.

NOMENCLATURE

d_O : orifice diameter of inner injector
$\dot{m}$: mass flow rate
$\dot{Q}$: volume flow rate
Re_g : gas Reynolds number
Re_l : liquid Reynolds number
J : momentum flux ratio
RR : recess ratio
L_R : recess length

INTRODUCTION

In order to design a shear coaxial injector for a supercavitating underwater vehicle, propellant of that system is made of hydro-reactive solid particles with sea water. When the vehicle proceeds under the water, cavitation occurs on the surface develops rapidly with increasing velocity, and if the cavitation grows large enough to wrap the whole body, the underwater subsequently vehicle escapes from the high drag force of the water, and can potentially reach high speed over 400 *km/h*. Supercavitating underwater vehicle using the hydro-reactive solid particle as a propellant has a higher propulsive efficiency per unit volume as compared to conventional underwater vehicles because the surrounding water can be directly used as an oxidizer. In the combustion reaction of water and hydro-reactive particles, Foote et al. (1996) reported that uniform mixing performance of the water and the hydro-reactive particles causes the decrease of the ignition temperature and the increase of the flame propagation speed which indicate an increase in the specific impulse. Aluminum oxide (Al_2O_3) and Magnesium oxide (MgO_2) are commonly used as the hydro-reactive propellant, these solid particles are doesn't move itself without other liquid or gas phase matters. Therefore basic experiments were conducted in gas-liquid shear coaxial injector, instead of solid-liquid coaxial injector. Coaxial injector and impinging injector is widely used, coaxial injector classified by swirl coaxial injector and shear coaxial injector. Among these injector shear coaxial injector characteristics is low pressure drop, high reliability and easy to design (Bayvel, 1993).

From the few earlier studies of gas centered injector (Lee et al. 1991; Camatte et al. 1993), it was observed that the centered gas flow makes more effective for the liquid sheet breakup than outer gas flow. A gas centered gas-liquid shear coaxial injector has an annular liquid steam that is injected through the annular gap between the inner and outer injectors. The centered gas stream disrupts the liquid sheet by striking it at a high velocity. Because the gas velocity is higher than liquid sheet, the pressure of inner liquid sheet is lower than ambient pressure. So spray gathered together through centerline,

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because of this spray angle of shear coaxial injector is very narrow (Lefebvre, 1989). Supercavitation underwater propulsion system required small combustion chamber and high propellant penetration length. Because of this requirements shear coaxial injector was used in this research.

The interaction between the gas and liquid phase at specific condition, self-pulsation occurs with intensive scream and strong mass flow rate oscillation. Self-pulsation can cause harmful disturbance on the acoustic field and make a heat release oscillation. Thus that affects unstable combustion, so this phenomenon must be controlled. In the mid-1970s Russia, self-pulsation phenomenon was discovered during a test of reduced rating conditions in a LOX-hydrogen engine (Bazarov, 1978; Bazarov, 1998). Bazarov (1995) conducted experimental study on the influence of operation condition and design parameters such as ambient pressure, pressure drop and recess length. According to his results, the LOX post recess length was most important parameter to determine self-pulsation characteristics, and he suggests some idea to suppress self-pulsation phenomena. Zhou et al. (1996) studied the flow rate and the acoustic characteristics of hydrogen/oxygen gas-liquid swirl coaxial injector. They found gas velocity is the main parameter of causing the scream and recess length and annular passageway length are also decisive factor of scream. Sivalumar et al. (2011) investigated self-pulsation frequency in gas centered swirl coaxial injector. They found that strouhal number is constant without momentum flux ratio.

But these results are conducted using swirl coaxial injector that different from shear coaxial injector using in this study. Shear coaxial injector stabilities of an centered gas stage was studied in detail (Kendall 1986: Carvalho and Heitor 1998; Wahono et al. 2008). Kendal (1986) studied in very low gas velocity regime, from his result the annular liquid sheet disintegrates as spherical bubbles in a periodic manner depending on the pressure difference across the liquid sheet and liquid sheet density. However, previous research mainly focused on the swirl coaxial injector self-pulsation characteristics did not reveal the self-pulsation characteristics of gas centered shear coaxial injector.

The main object of this study is to understand characteristics of self-pulsation and reveal the mechanism of this phenomenon. For this injection condition such as gas and liquid momentum, and geometric parameter like recess ratio were used in this study. Laser diagnostics used to measure the spray oscillation frequency. And compared to this result high speed image was also used. From these experimental techniques self-pulsation frequency, spray shape, break-up process and self-pulsation boundary were obtained.

EXPERMENTAL METHODS

Experimental techniques

The spray patterns were analyzed using instantaneous spray profiles imaged with and indirect photographic technique. The stroboscopic light was illuminated through a translucent paper. A digital camera was used and synchronized with a stroboscopic light that light freeze the spray images. High speed camera was used for capture the change of spray patterns with time. Frame rate of high speed camera is 8000 *fps* and resolution 256×512. Using the He-Ne laser and photo detector, the frequency of spray oscillation were obtained. As shown in Fig. 1 laser beam passed through the center of oscillating spray, the laser signal was attenuated until it reached the photo detector. This attenuated signal linearly proportional to the amount of liquid volume, that signal varied with time, and using this signal FFT analysis was applied to calculated the frequency of spray oscillation.

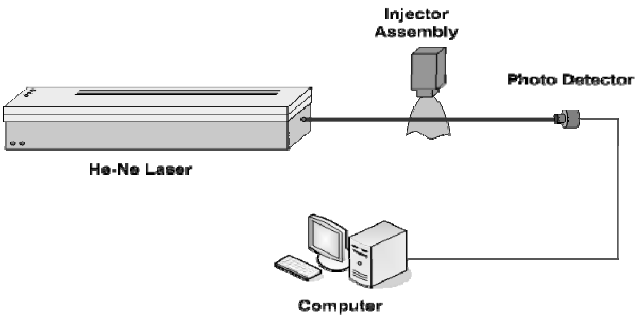
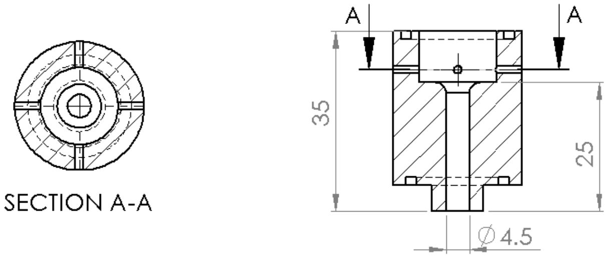


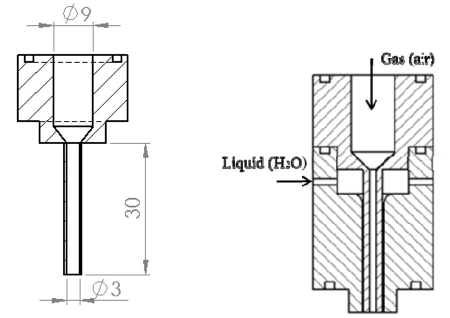
Fig. 1 He-Ne laser and photo detector system to measure the frequency of spray oscillation.

Experimental conditions

As shown in Fig. 2 gas centered shear coaxial injector was used in this study. It consisted of two parts: the outer oxidizer injector (liquid phase), and the inner fuel injector (gas phase). The inner orifice diameter of gas injector was 3.0 *mm*. And inner orifice diameter of liquid injector was 4.5 *mm*. Four entries were located every 90° to produce a uniform liquid supply.



Outer liquid injector



Inner gas injector Injector Assembly

Fig. 2 Schematic of a swirl coaxial injector (in *millimeters*).

Fig. 3 shows the geometric parameters used in this study. Recess is geometrical configuration where the length of inner injector orifice is located from the outer injector face, definition in Eq (1).

$$BR = \frac{L_R}{d_O} \tag{1}$$

Recess is known to augment mixing efficiency and affect flame stabilization through the internal mixing of propellants (Mayer et al. 1996), but it induced self-pulsation and thermal deformation at injector face. As you see in the table. 1, to investigate the effects of recess length on the self-pulsation characteristics, three inner injectors were manufactured with different orifice length.

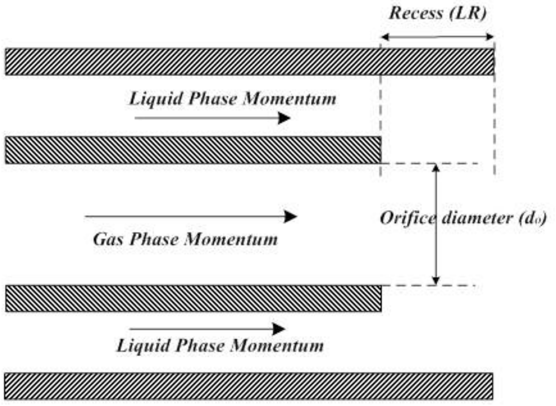


Fig. 3 Schematic of geometric parameters.

The experimental conditions are summarized in Table 1 Water and air was used to simulate the sea water (oxidizer) and particle carrier gas (fuel side). The mass flow rate of water was between 15.1~78.4 *g/s*, and a mass flow rate of air was 0.79~3.16 *g/s*, air gas controlled by a mass flow controller. Momentum flux ratio and Reynolds number were experimental parameter of this study. The momentum flux ratio is the momentum transfer from gas to liquid vice versa, defined Eq (2), that is known to be one of the most important parameters in liquid atomization process (Rehab 1997).

$$J = \frac{\rho g U_g^2}{\rho g U_L^2} \tag{2}$$

Table 1 Experimental conditions.

	Water	Air
△P (*MPa*)	0.05~1.0	0.008~0.3
Mass flow rate (*g/s*)	15.1~78.4	0.79~3.16
Reynolds number	4981~22307	18086~180868
Momentum flux ratio (*J*)	0.03~1.5	
Recess ratio (*RR*)	0, 1.25, 2.5	

RESULTS

Spray Patterns

Self-pulsation phenomena are observed at certain injection condition and certain injector geometry. From Bazarov's result in 1995, self-pulsation cause server change in spray mass distribution, atomization quality and acoustic fields. Fig. 4 shows that the self-pulsation phenomena at fixed liquid Reynolds number of 17,279 and fixed recess ratio of 0 that are suppressed as gas velocity increased. At low gas Reynolds number (Fig. 4a~c), strong self-pulsation phenomena were observed but at high Reynolds number (Fig. 5d), self-pulsation disappeared. When self-pulsation phenomena occurred (Fig 4a~c) mass oscillation of the spray observed and spray angle become larger than stationary spray (Fig 4d)

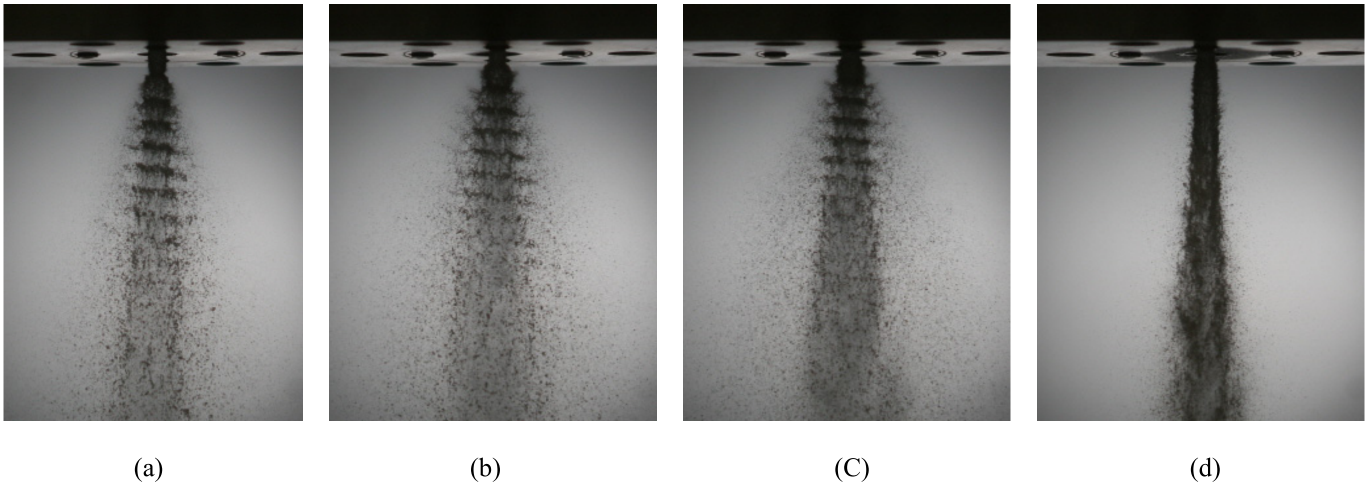


Fig. 4 Spray patterns with the gas Reynolds number at Re_l=17,279 and no recess with self-pulsation and no pulsation case: (a) self-pulsation, Re_g=28,597 (J = 0.083); (b) self-pulsation, Re_g=40,443 (J = 0.167); (c) self-pulsation, Re_g=49,532 (J = 0.25); (d) no pulsation, Re_g=63,946 (J=0.417).

At low gas Reynolds case, gas momentum can't resist high momentum of annular liquid sheet. As the gas velocity increases, however, the gas phase momentum becomes large enough to resist disturbance of the annular liquid phase outside of gas phase; therefore self-pulsation becomes suppressed. If the self-pulsation wave length is defined as the length between the dense parts within the spray images, then can measured wavelength of spray oscillation. This method used by laser diagnostics, He-Ne laser signal pass through the center of the spray, than attenuation laser signal will be detected by photo detector. From this method self-pulsation frequency increased with gas Reynolds increased. This result will be discus subsequently.

Fig. 5 shows spray patterns according to recess ratio, in the case with low recess ratio 1.25 (Fig. 5a and 5b), self-pulsation phenomena observed, but in the case with high recess ratio (Fig. 5c), self-pulsation is not detected, and the self-pulsation frequency decrease with increasing recess ratio.


(a) (b) (c)

Fig. 5 Spray patterns with the recess ratio at Re_l=17,279 , Re_g=28,597 and J = 0.083 with self-pulsation and no pulsation case: (a) self-pulsation, recess ratio (RR) = 0; (b) self-pulsation, recess ratio (RR) = 1.25 ; (c) no pulsation, recess ratio (RR) = 2.5.

High speed image were used, 8000 *fps*, to obtain detail initial self-pulsation breakup regime The dynamics of pulsation sprays discharging from gas centered shear coaxial injectors have been investigated earlier (Kendall 1986, Wahono 2008). Kendall (1986) reported that a liquid shell formation mechanism, shell formation frequency and shell volume in gas centered shear coaxial injector at low Reynolds number. Kendall argued liquid shell formation frequency increased with gas volume flow rate increased. The self-pulsation spray in Fig. 4a~c, shows strong periodic spray oscillation, and the onset of self-pulsation can be determined from the spray image.

As shown in Fig. 6, from the outer injector, liquid ejected from outside of injector was generated within the hollow core by the downward flow of liquid. Because of surface tension, downward flow of liquid will be solid jet not hollow core. Accordingly that solid jet blocked gas flow from the centered orifice, when the gas flow blocked by the annular liquid column, at momentum of the gas lower than surface tension force of liquid sheets, a radial displacement of the cylindrical surface of the liquid (Fig. 6a). After that bulbous liquid feature were made like liquid balloons with gas inside. At same liquid Reynolds number gas Reynolds number increased (Fig. 6b), surface tension force of liquid bubble does not resist the momentum of gas, so liquid bubble ruptured, thereby creating radially spreading liquid ligaments were made (see Fig 4a~c). The rupturing process of liquid bubble is the main mechanism of self-pulsation phenomenon of gas centered shear coaxial injector, and that may be makes a severe noise of the injector.

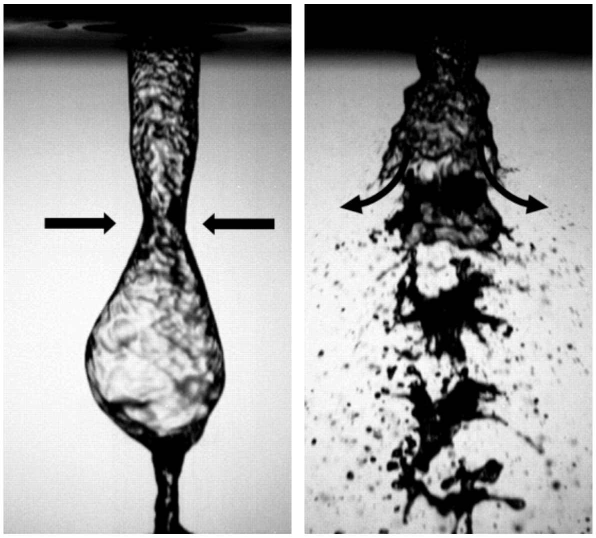

(a) (b)

Fig. 6 Spray patterns with the gas Reynolds number at Re_l =4981, $\dot{V}$ =15.13cm^3/s and RR=0: (a) Re_g =18086, $\dot{Q}$=665.6cm^3/s (b) Re_g=22878, $\dot{Q}$=688.8cm^3/s.

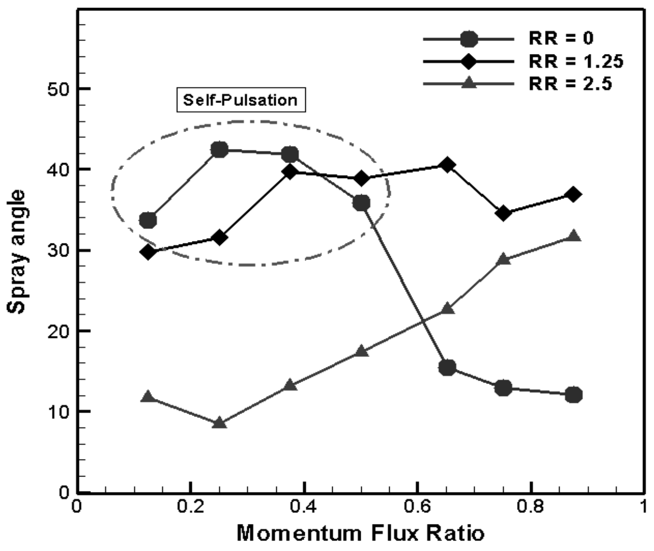


Fig. 7 Spray angle with the momentum flux ratio at Re_l =14108.

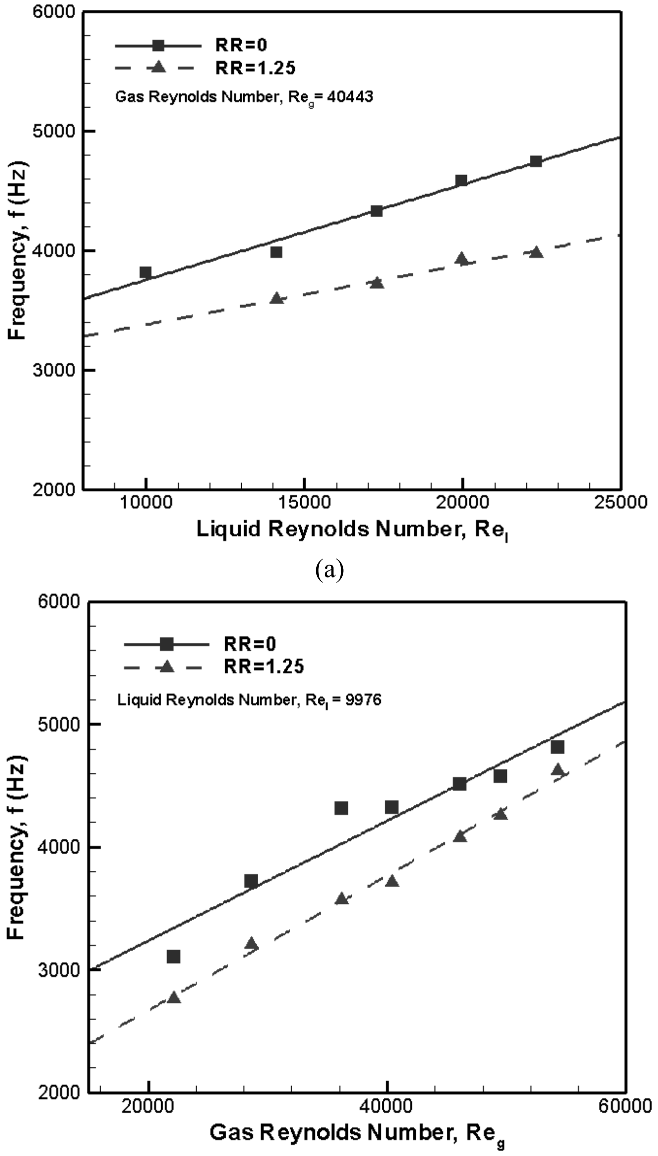
Self-Pulsation Characteristics

Normally self-pulsation phenomenon can effect on the combustion instability, because pressure oscillation by self-pulsation match the pressure oscillation in the combustion chamber, by this process spray oscillation may initiate combustion instabilities.

He-Ne laser pass through the center of the spray then detected by photo detector to measure a spray oscillation frequency with the gas and liquid Reynolds number. If a laser beam passed through a spray, attenuation will be greater in dense parts and less in the sparse area. This attenuation laser signal analyzed by FFT method, from this process the frequency of spray oscillation obtained.

Figure 8 shows the characteristics frequencies according to the liquid and gas Reynolds number. Fig 8(a) shows a self-pulsation frequency at a constant gas Reynolds number of 40443, as liquid Reynolds number increase as self-pulsation frequency also increase. However recess number increase 0 to 1.25 self-pulsation frequencies decreased in all experiments case conducted in this study. Furthermore, Fig. 8(b) shows a self-pulsation at a constant liquid Reynolds number of 9976, in this case self-pulsation frequencies linearly proportional to the gas Reynolds number, and also recess number increased, then self-pulsation frequencies decreased.

Kendal (1986) was reported frequencies of produced liquid bubble were linearly proportional to the gas and liquid volume flow rate. Volume flow rate is proportional to the Reynolds number at the same injector geometry. In the previous section of self-pulsation mechanism, this liquid bubble produced process is occur self-pulsation. Therefore result of self-pulsation frequencies from in this study agree with the Kendal's result. Im et al. (2009) studied the pulsation characteristics of sprays from gas-liquid swirl coaxial injector discharging central swirling liquid sheets. The authors observed that the self-pulsation spray frequency is exactly the same as acoustic frequency at the same injection condition. Zhou et al. (1996) observed instability in LOX/H2 engine may be related to the acoustic oscillation from self-pulsation in coaxial injector from the comparison with some instability tests of liquid rocket engine. From these results, self-pulsation of gas centered shear coaxial injector may be induced combustion instability in underwater propulsion system.



(a)

(b)

Fig. 8 Characteristic frequency of self-pulsation with (a) gas Reynolds number fixed (Re_g =40443) (b) liquid Reynolds number fixed (Re_l=9976).

Fig. 9 shows frequencies of self-pulsation sprays, both case self-pulsation frequencies increased with increase multiplication of liquid and gas Reynolds number, and recess ratio increased spray oscillation frequency decreased. This tendency may be connected with *L/d* of inner gas injector.

Spray oscillation have a frequency range of 2.6-5 *kHz*, which may be the first tangential mode of combustion instability. So spray mass oscillation at the range of 2.6-5 *kHz*. This oscillation can lead to heat release oscillation at the same frequency range of the first tangential mode of the combustion instability.

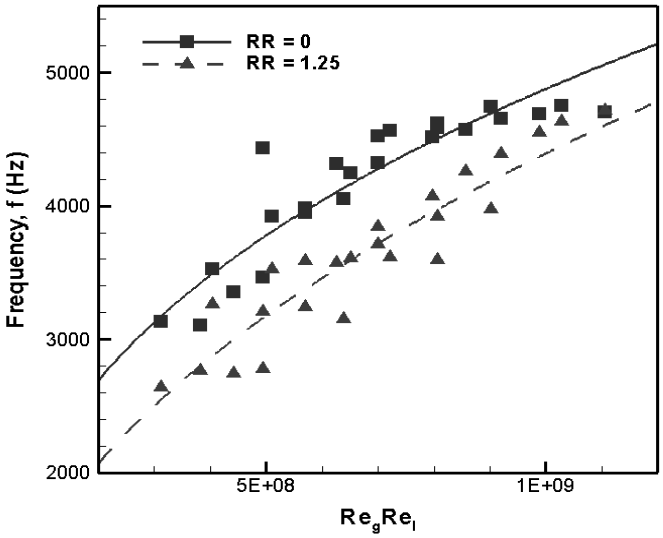


Fig. 9 Characteristic frequency of self-pulsation with Re_g and Re_l.

Result from previous section (by indirect photography and laser attenuation method), the onset of self-pulsation associated with the gas and liquid momentum is plotted in Fig. 10. As you see in Fig. 10 self-pulsation boundary lines plotted inversely with respect of with or without recess. Injector with recess, severe interaction occurred between liquid and gas phase, so in recessed case, the growth of liquid bubble (see Fig 6a) will be limited. Because of this self-pulsation boundary increased with at high liquid momentum flux in recess ratio 1.25 than without recess.

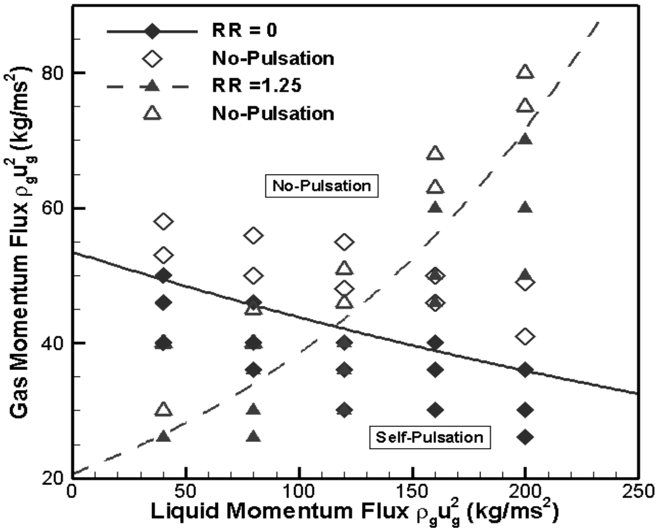


Fig. 10 Self-Pulsation Boundary with *RR* at various momentum flux.

CONCLUSIONS

The self-pulsation characteristics of a gas centered shear coaxial injector were investigated by measuring spray patterns (indirect photography and high speed image), spray oscillation characteristics, and the self-pulsation boundary.

Strong mass oscillation of spray and severe noise observed. At the time of self-pulsation phenomenon observed, spray angle higher than no pulsation. Because self-pulsation process based on the liquid bubble rupturing process, when liquid bubble ruptured, gas momentum has as radial direction momentum.

The self-pulsation characteristics frequencies are measured according to the liquid and gas Reynolds number and the recess ratio. The self-pulsation frequency according to the liquid and gas Reynolds number increases. Furthermore decreases with recess ratio increased. Spray oscillation have a frequency range of 2.6-5 kHz, which may be the first tangential mode of combustion instability. So spray mass oscillation at the range of 2.6-5 kHz. This oscillation can lead to heat release oscillation at the same frequency range of the first tangential mode of the combustion instability.

The self-pulsation boundary is obtained according to the liquid, gas momentum flux and recess ratio. The occurrence of self-pulsation phenomenon is determined by taking indirect photography and absorbing laser attenuation signal. The self-pulsation boundary lines plotted inversely with respect of with or without recess. Because, severe interaction occurred between liquid and gas phase in recessed case. Therefore, the growth of liquid bubble will be limited that is main factor of self-pulsation phenomenon in gas centered shear coaxial injector used in this study.

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