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Transition of Combustion Instability by Swirl Injection in Hybrid Rocket

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Abstract
In this study, the effect of swirl injection on the combustion stability was investigated with experimental tests and numerical calculation. As a result, swirl injection seems to modify two main physical processes responsible for the occurrence of the LFI. With swirl injection, even the frequency characteristics of p′ and q′ of both 20Hz and 500Hz band were not changed. However, as the swirl intensity increases, the phase difference p′ and q′ in 500 Hz band showed an increase above π/2 showing a totally independent relation between p′ and q′. Therefore, it is believed that phase shift happened as the result of the complicate interaction of strong rotational flow structure near core region and the additional combustion in post chamber.

1. Introduction

Two types of flow structure characterize the swirl flow; rotational velocity component near surface and an axial velocity along the central region. Sometimes, swirl injection can be applied as an effective role to achieve mixing enhancement between fuel and oxidizer. Lilley [1] reports that swirl flow is widely used in conventional combustion system because it is efficient in stabilizing combustion. It is mainly used in gasoline engine, diesel engine, gas turbine, industrial furnace, utility boiler and so on. Also, Iudiciani et al [2] found that the swirl flow stabilizes the combustion by the formation of recirculation zone where the combustion product preheats combustible mixture in the front of the flame, and it serves as an ignition source to incoming mixture.

Combustion and flow in hybrid rockets, on the other hand, show very unique characteristics compared to other chemical rockets. The hybrid rocket combustion exhibits non-premixed flame that performs passive chemical reaction with a variable regression rate depending on oxidizer mass flux. Also the interaction of axial oxidizer flow and fuel vaporization flow makes a very complicated flow and vortices generation near surface region. Recent studies that investigated the wall blowing effect in the pipe flow with a large-eddy simulation (LES) confirmed that turbulence structures change its characteristics spatially and temporally due to the complicated interaction between the oxidizer flow and the fuel vaporization flow[3].

Also, Hybrid rocket combustion shows very unique features of combustion instability; sudden amplification of combustion pressure, limit cycle behavior and pressure fluctuations with very low frequency less than 100Hz. At a certain condition, combustion pressure is suddenly amplified and develops into low frequency instability (LFI). According to Kim et al [4], LES results show that modified boundary flow containing small scale vortices flows into the post chamber producing a the shear layer, and flow fluctuations along the shear layer is the source of pressure oscillations of 500 Hz in the post-chamber. Park et al. [5] also conducted a series of combustion tests to investigate the effect of chamber configurations on the initiation of pressure oscillations of 500 Hz band. Their results show that the pressure oscillations of 500 Hz band suddenly pops up during the combustion. Interestingly, this frequency band remained unchanged in the magnitude in the experiment with rear ring attached to the fuel end. However, the pressure oscillations of 500 Hz band were not detected in the experiment with increased post-chamber length. In addition, Moon et al. [6] experimentally investigated how the combustion oscillations with the same frequency band as the pressure oscillations in 500 Hz band interfere with each other and develop into the LFI. They observed that LFI of 20 Hz band occurs when the phase difference between the pressure and heat release fluctuations of 500 Hz becomes less than 90 degree, so called positive coupling. This suggests that the positive coupling between 500Hz p′ and 500Hz q′ seems to be the necessary and sufficient condition for the LFI occurrence. Note that details of physical process of LFI occurrence are remained unveiled at this moment.

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Meanwhile, visualizing results of combustion flow in a hybrid rocket using a swirl injection show that near surface flow structure and the core flow structure, which are characteristics of the general swirl flow, also appear. When the swirl injection is applied, the stratification of the flow occurs inside the combustion chamber and is divided into the flow near the surface and the flow near the center. In this regard, Masugi et al. [7] visualized the flame distribution and behavior when axial and swirl oxidizer injection was applied to the combustion of hybrid rocket fuelled with polypropylene (PP) and poly methyl methacrylate (PMMA), respectively. They reported that swirl injection induced helical velocity component near the surface region whereas rotating component appears around the centerline. This helical velocity component enhanced convectional heat transfer to solid fuel and increased regression rate.
The reason for applying swirl injection in hybrid rocket combustion may be another purpose other than to increase regression rate. Recent studies have found that swirl oxidizer injection can stabilize combustion in hybrid rockets. Bellomo et al. [8] reported that the application of swirl injection resulted in 4.2% reduction in average pressure oscillations compared to those with axial injection. Pucci et al. [9] also experimentally studied combustion stability of a hybrid rocket with swirl injection. First, they observed that the pressure fluctuations of 20 Hz and 600 Hz bands were amplified when the swirl intensity was less than a certain value or none. And they reported that if the swirl intensity is larger a certain value, central toroidal recirculation zone (CRTZ) is formed in the central part, and claimed that the formation of CTRZ is responsible for stable combustion by preheating the incoming oxidizer flow. Jerome et al. [10] also investigated the combustion instability of a hybrid rocket using swirl injection. According to their results, the pressure oscillations in the combustion chamber using axial oxidizer injection are closely related to the formation of vortex shedding near surface region. When swirl injection was applied, it is suggested that small size vortex generation and shedding on the wall are reduced, thereby contributing to stabilization of combustion by decreasing the amplitude of the pressure fluctuations of 500 Hz band. They also reported that the flow structure modified by the swirl injection contributed to the improve mixing in the post-combustion chamber. Although all of the studies mentioned here have reported that swirl injection produces a very positive effect on combustion stabilization, no detailed physical study has yet been done on how the swirl flow contributes to combustion stabilization.
Many studies already showed that the application of swirl injection could not only increase the regression rate of solid fuel but also reduce the amplitude of the combustion pressure. And the combustion could be stabilized with the appropriate swirl intensity. In hybrid rocket combustion, swirl injection may alter the flow structures near surface region and core region and this modification may affect the occurrence of the LFI through unknown flow and combustion interactions. Therefore, this study investigates how the flow structure changes when swirl injection was applied and focuses to analyze how these changes in flow structure contribute to combustion stabilization.
To this end, a series of experimental test was done. Each case has different swirl injection angles, which can control the swirl intensity. During the test, combustion pressure and intensity were measured to analyze the interaction of the combustion pressure and the chemical reaction when the swirl injection was applied, and the influence on the combustion instability was also investigated. The light intensity emitting from the combustion chamber was also measured by PMT to monitor the oscillatory behavior of the combustion reaction. With this configuration, the influence of the swirl intensity on the combustion instability can be experimentally examined. Also numerical calculations for non-reactive flows were performed using the LES method to examine the change in flow structure caused by the interaction of wall blowing and swirl injection. The calculation results were also used to investigate the qualitative effects on combustion instability.

2. Experimental setup

Table 1: Summary of combustion tests

	Test A (Baseline)	**Test B**	**Test C**
Swirl angle (degree)	0	7	10
Main chamber length (mm)	400	400	400
Post-chamber length (mm)	75	75	75
Mass flow rate (g/s)	20	20	20
Remarks	LFI	Intermediate stable	Stable

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Table 1 summarizes details of test configurations and remarks of each case. Gaseous oxygen (GOx) was used as an oxidizer and PMMA was the solid fuel. Chamber lengths of main, pre and post-chamber were fixed as 400 mm, 45 mm and 75 mm respectively, whereas a fuel diameter was 50 mm in all test cases. Pressure was measured at the pre-chamber. Three different cases are designed for hot firing test. Test A was designed to study the basic features of pressure and luminosity fluctuations in the LFI. Test B was the case where swirl injection angle is fixed as 7 degrees. Test C was prepared to study the effect of swirl intensity on the change in flow and combustion structure by increasing swirl angle from 7 to 10 degrees.

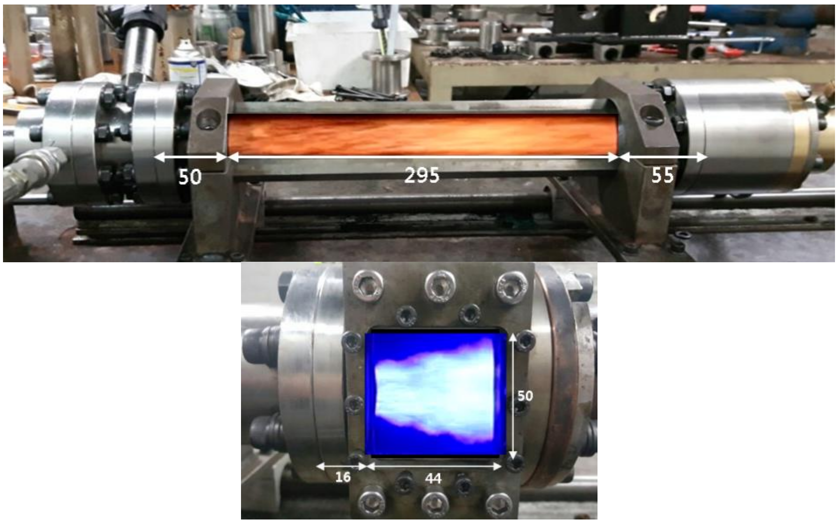

Figure 1: Configuration of main and post-chamber for visualization

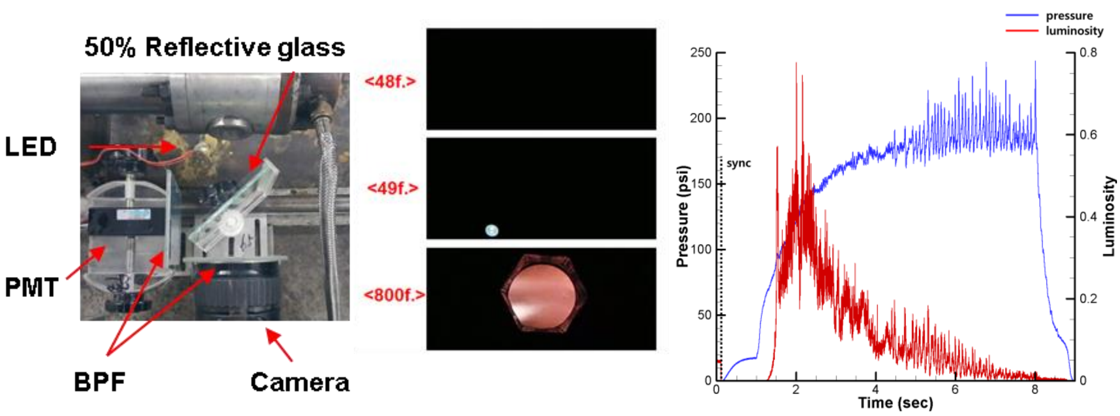

Figure 2: Synchronization setup for pressure and flame luminosity measurement [11]

Figure 1 shows the test setup for visualizing the combustion in main chamber. One side of main chamber was modified to visualize the combustion flow inside the fuel. Total 295mm of main chamber was cut out. The change in the flow with swirl injection cannot be clearly observed because the oxidizer enters the pre-chamber and corresponds to the impingement. In addition, the length of the front part of the fuel gradually decreased over time due to the combustion, so that the front 50 mm and the rear 55 mm were regarded as offset to prevent a flame from spurting out. In the post-chamber, a quartz window was installed to try to visualize the flame dynamics. A special glass with a reflectance of 50% was installed in front of the window, and the light generated by the combustion reaction was divided into two directions. The divided light was photographed using Casio Ex-1 camera and photomultiplier tube (PMT) H10722 manufactured by Hamamatsu. Camera and PMT have the same shooting area, and are synchronized. Event-based synchronization technique, which uses LED as trigger is used to synchronize pressure and high-speed image data. Visualization tests were conducted in complete darkroom in order to minimize the noise in the PMT. In addition, a band pass filter (BPF) for 430 nm wavelengths was attached to the front of the camera and the PMT to clearly capture the combustion reaction. The shooting speed of the camera is 1200 fps, and this speed can measure changes with frequency characteristics up to 600 Hz. The visualization method is the same for

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both the main chamber and the post-chamber. Details regarding validation of post-chamber configuration, extraction of the light intensity from the visualization images, and the image post-processing are consulted from reference [11].

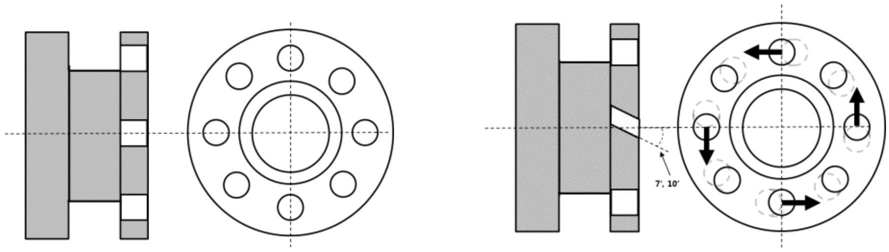

Figure 3: Schematics of top and cross-section view of axial and swirl injector

There are two ways to control the swirl intensity. Kitagawa [12] claimed that the regression rate increases with the increase in the number of LOX (liquid oxygen) injection holes and the cross-sectional area. Their study reported that the combustion instability is stabilized when the swirl intensity is above a certain value. In the present study, the axial injector was used as the baseline case and the swirl intensity was controlled by the variation of the swirl injection angle, the number of holes. The swirl angle was selected from three parameters: 0˚ (axial injection; baseline), 7˚, 10˚. Figure 3 shows schematics of an axial (Test A) and swirl (10˚) injectors.

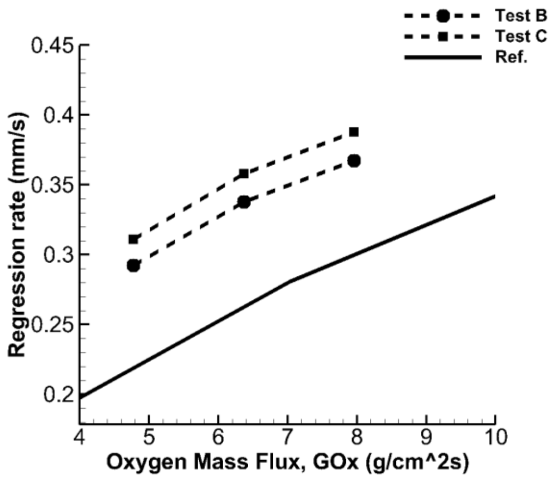

Figure 4: Comparison of regression rates in Test B and C with that of reference [13]

In ref [14], with PMMA as a fuel and GOx as an oxidizer, tests were conducted as the swirl intensity increased by increasing the number of holes and the cross-sectional area. As a result, it was observed that the regression rate increases with increasing swirl intensity. Figure 4 shows the comparison of regression rates in Test B and C with that in ref [13]. As shown in the figure, the regression rate of this study using swirl injection agrees well with that of the reference and validates the methodology used in this study.
Rayleigh criterion is generally used as a mathematical tool for determining whether there is a correlation between combustion pressure (p′) and heat release fluctuations (q′). The phase difference between the two fluctuations is a critical factor in the criterion, which states that if pressure and heat release fluctuations are in positive coupling, the combustion pressure is amplified by the coupling process [15]. Mathematical formulation of the criterion can be expressed as

$$\int_{cycle} p'q'dt > 0 \quad \textbf{(1)}$$

By measuring the phase difference between the two fluctuations, it is possible to define a positive coupling in which the amplitude gradually increases over time leading to combustion instability. On the other hand, the negative coupling is the case where the amplitude gradually decreases. A transfer function F(f) between

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combustion pressure and luminosity fluctuations is an effective way of estimating the phase angle ϕpq. Equation (2) defines the transfer function in the frequency domain using the FFT analysis from combustion pressure and luminosity time signals

$$F(\mathrm{f}) = \frac{(p'/\bar{p})}{(L'/\bar{L})} = G(\mathrm{f})\, exp(j\, \phi(\mathrm{f})) \qquad \textbf{(2)}$$

where p′/p(f) is the Fourier transform of pressure and L′/L(f) is that of luminosity. G is the modulus or the transfer function gain, while ϕ_{pq} is its phase angle. And the positive coupling is defined as the case where the phase angle $|\phi_{pq}|$ is less than $\pi/2$. And a negative coupling is the case where ϕ_{pq} is larger than $\pi/2$.

3. Test Results

3.1 Pressure and heat release oscillations

The combustion instability refers to the case where the amplitude of the combustion pressure becomes higher than 5% of mean pressure level. Figure 6 shows the pressure measurements with three different swirl injectors. As the swirl intensity increases, the amplitudes of the combustion pressure are decreasing from 23.5% at the LFI, 14.4% and 2.3% in Test A, Test B, and Test C respectively. Test results confirmed that combustion became stabilized by gradually increasing the swirl intensity. In the rest of the study, the effect of swirl flow on the LFI was investigated through the visualizations of main and post-chamber and the comparison of phase angle between p′ and q′. Note that the visualization time was limited by 12 seconds due to the accumulation of soot on the visualization window.

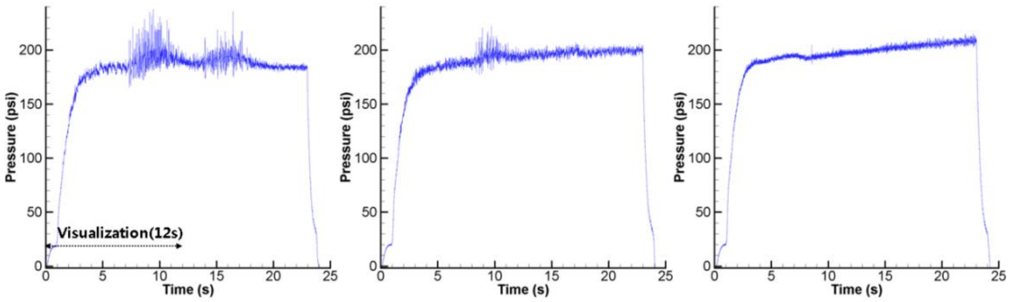

Figure 5: Trajectory of combustion pressure oscillations

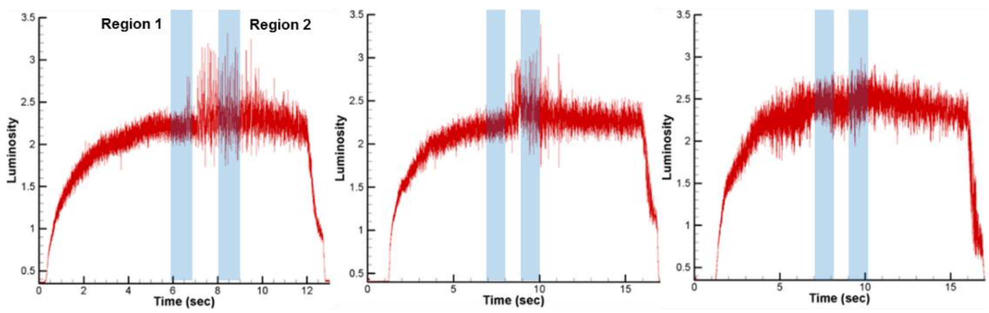

Figure 6: Trajectory of combustion luminosity (heat release) oscillations

From the literature studies, it is assumed that the swirl injection may affect the heat release fluctuation in the post chamber. And the variation of light intensity from post chamber was also measured by PMT to investigate the heat release fluctuation as swirl intensity increases.

As the swirl intensity increases, heat release fluctuation is amplified at the same frequency band as those of pressure oscillations. And FFT results are shown in Fig. 6. In the Figure, it is observed that the peak amplitudes of p′ decreased as the swirl intensity increases. It is a very interesting to see that combustion

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pressure and luminosity fluctuations of 500 Hz were observed in all combustion conditions regardless of the occurrence of the LFI. In addition, as the swirl intensity increases, the amplitude of the LFI decreases, and the amplitude of the overall combustion pressure decreases as well showing a very stable combustion. This result may suggest the application of swirl injection induces some changes in both flow structures and combustion characteristics even though these are not yet completely understood. Probably, swirl injection affects the temporal and spatial distribution of heat release in post chamber and resulted in the occurrence of the LFI at a certain combustion condition.

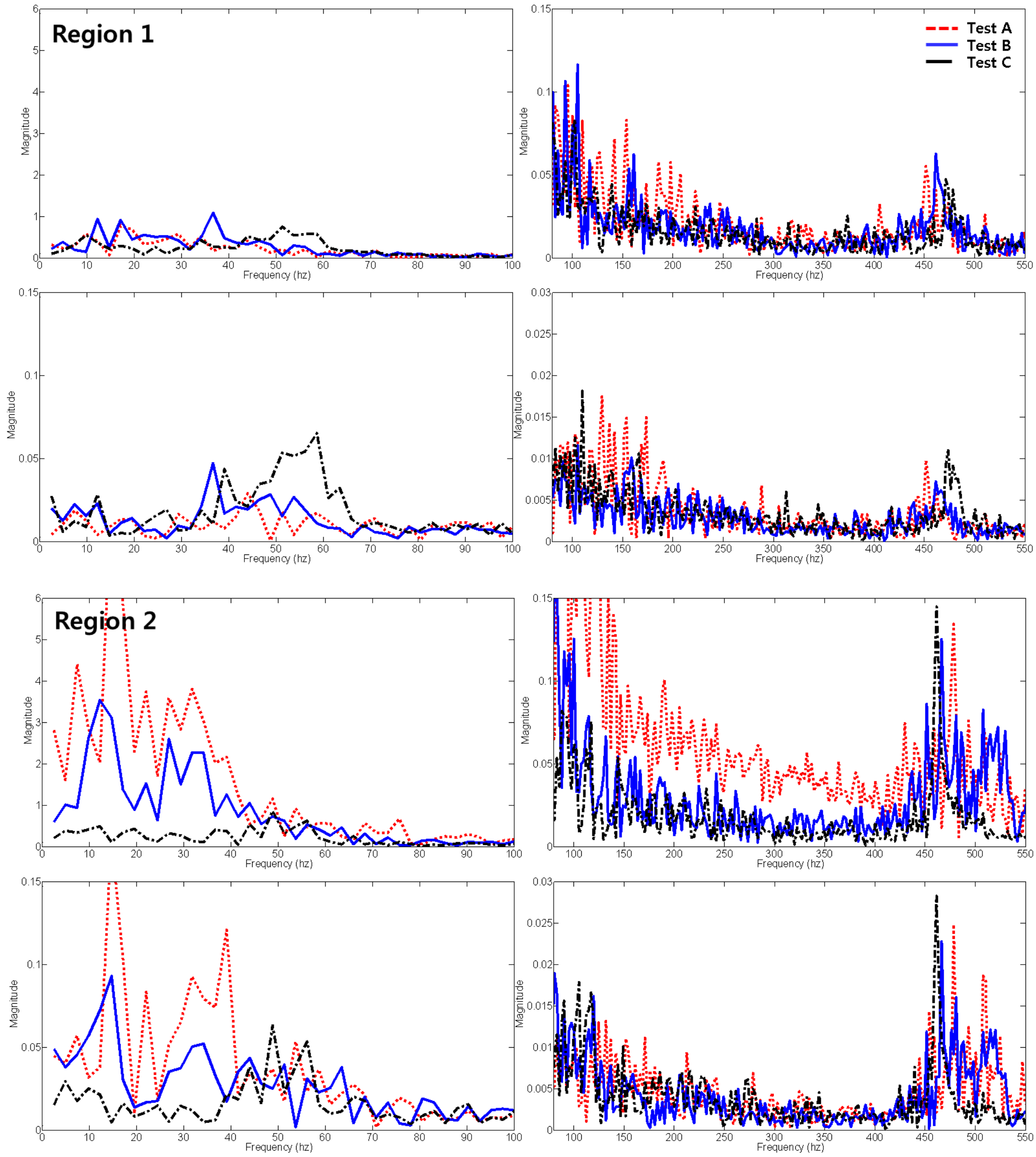

Figure 7: Frequency characteristics of p′ (top) and q′ (bottom) of 20 Hz and 500Hz band in region 1, 2

Figure 7 shows frequency characteristics of pressure and heat release fluctuations of 20Hz and 500Hz band in region 1 and 2 respectively. In region 1 (displaying stable combustion behavior), pressure oscillations of 20 Hz bands in all cases do not amplify. Meanwhile, in Test A, a small peak of heat release oscillations was shown up at about 70 Hz, and no specific peak frequency was observed. However, heat release oscillations showed a peak frequency near at 30-40 Hz for Test B and 50-60 Hz for Test C. This result confirmed that the swirl injection affected to shift p′ and q′ of low frequency band simultaneously. It is also interesting to

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observe that p′ and q′ of 500 Hz band appeared during the combustion even though the amplitudes are not fully noticeable compared to those of 20Hz oscillations. This shift in frequency band is presumably due to the application of swirl injection and the modification of flow structure. In Test A, we could observe that p′ of 20 Hz band amplifies significantly, whereas Test B produces a relatively weak amplification of p′. This biased amplification of p′ seems to be the effect of swirl injection at the front part of main chamber. Note that q′ shows a tendency of oscillation amplitudes similar to that of p′.

Examining p′ and q′ of 500 Hz band, we can see that the pressure and heat release oscillations are amplified even in region 1. Test A and B have broad frequency characteristics ranging from about 400 to 550 Hz centering on the peak frequency, while Test C has a peak frequency of a narrow band between 450 and 500 Hz. The difference in frequency band range is presumably related to the changes in flow structure induced by swirl injection, which will be discussed in more detail in the next section.

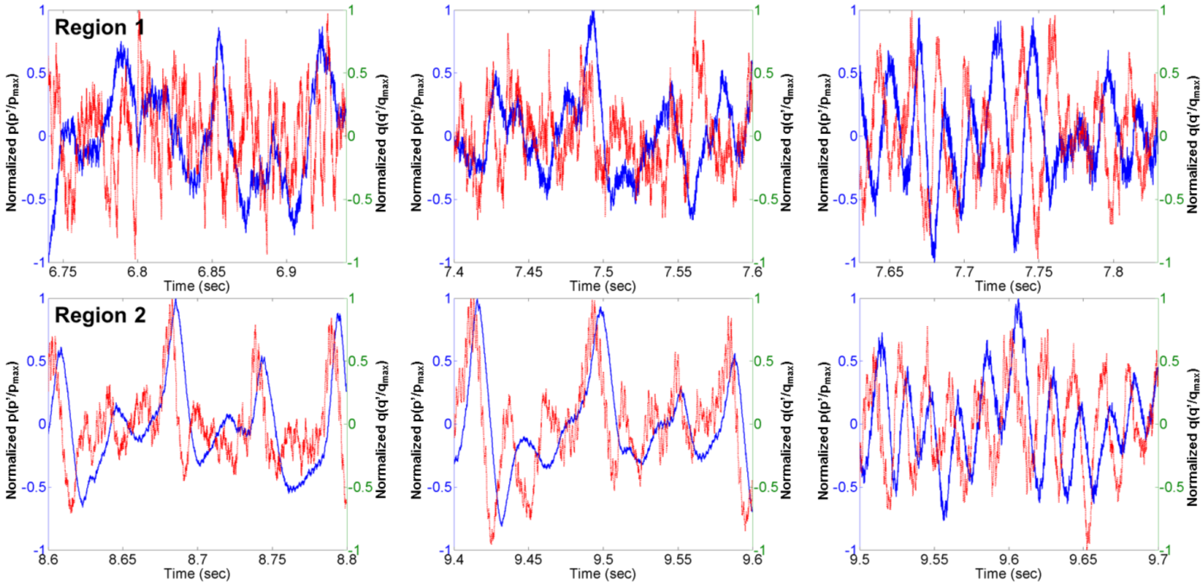

Figure 8: Overlay of p′-q′ trajectory in the 20 Hz band, region 1 (top) and 2 (bottom)

In the previous analysis, it was found that LFI occurred only when the phase difference of p′ and q′ in 20 Hz band is less than 90 degrees. In addition, p′ and q′ in the 500 Hz band displayed a positive coupling at the same time. From this, it is estimated that the phase difference of pressure and heat release oscillations in the 500 Hz band seems to play an important role in occurrence of the LFI [16]. Therefore, the effect of swirl injection on the phase difference between p′ and q′ has been investigated.

Figure 8 shows that trajectory of p′ and q′ in the 20 Hz band. For the trajectory in region 1, Test A and B exhibit a very large amplification of pressure oscillations in the 20 Hz band, whereas q′ was observed to have various frequency bands at the same time. However, in Test C, the frequency of p′ and q′ does increase from the dominant one of 20Hz observed in Test A and B. Moreover, it is very interesting to see that pressure and heat release perturbations in region 1 do not show any correlation in all cases. Interestingly, p′ and q′ of 20 Hz band in region 2 were positively coupled with each other in Test A and B. On the other hand, no positive coupling was found in Test C even measured in region 2.

Figure 9 compares the phase difference quantitatively. As mentioned, the phase difference between p′ and q′ of 20 Hz band in Test A and B is less than 90 degrees. However, in Fig. 8, it is expected that the heat release oscillation of 20 Hz band have no physical significance because of negligibly small amplitude. Also, pressure and heat release fluctuations of 30-40 Hz was observed in Test B showing phase difference larger than 90 degrees. On the other hand, phase difference of fluctuations of 20 Hz band in Test A and B are less than 30 degrees and about 45 degrees respectively. Although the weak swirl injection was applied, the phase difference between p′ and q′ seems exceeded over π/2. In Test C, the heat release oscillation of around 50 Hz was also observed both in regions 1 and 2. However, the phase difference was approximately 90 degrees or more. Thus, as the swirl intensity increases, we found that the phase difference between p′ and q′ increases and resulted in the coupling shift from positive to negative. Therefore no LFI was developed in Test C.

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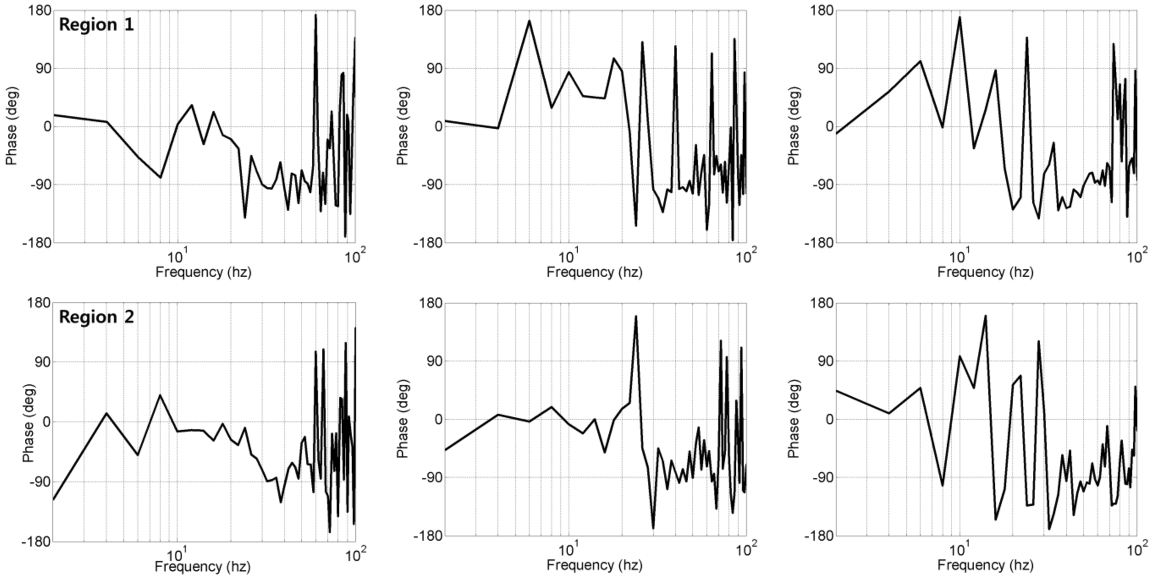

Figure 9: Representations of phase diagrams, region 1 (top) and 2 (bottom)

The phase difference between the pressure oscillation and the heat release fluctuation due to the change of swirl intensity, thereby stabilizing the combustion instability was investigated. According to previous study, it is possibly assumed that a positive coupling between pressure and heat release fluctuation in 500 Hz band is strongly related to occurrence of combustion instability [6]. Based on the present results, swirl seems to affect the phase difference of the two oscillations somehow.

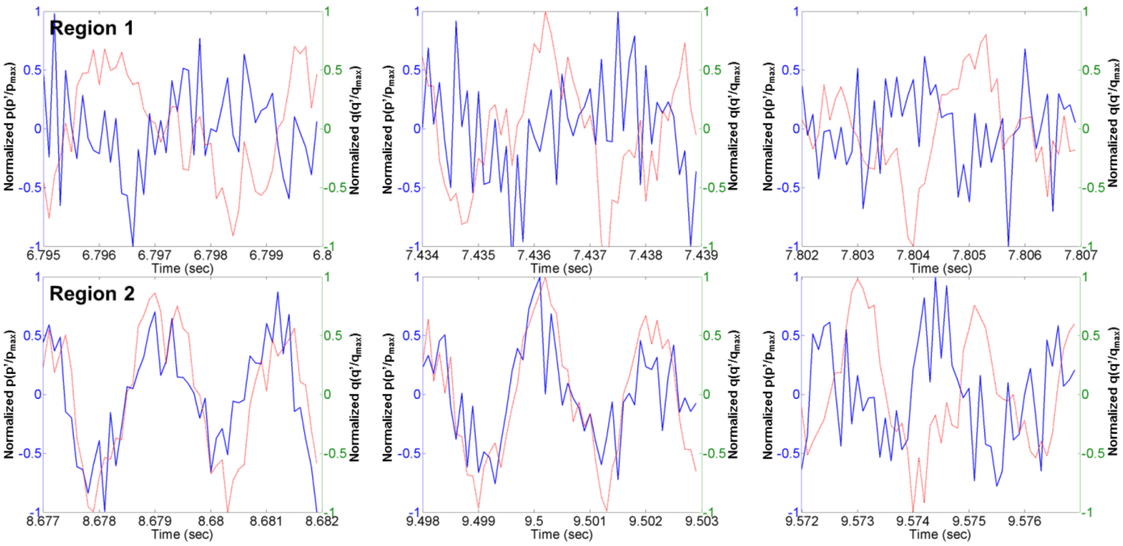

Figure 10: Overlay of p′-q′ trajectory in the 500 Hz band, region 1 (top) and 2 (bottom)

Figure 10 is a diagram showing the overlap with the pressure and heat release fluctuations normalized by each maximum value. Note that the pressure and heat release fluctuations were measured simultaneously at the same time using the event-based synchronization for sending an electrical signal. In Region 1, Test A, B, and C all have a 500 Hz band of pressure and heat release oscillations, and each has negative coupling. However, in Region 2, a completely different result can be observed. In Test A, B, pressure oscillation and heat release fluctuation in the 500 Hz band have the positive coupling. In Test C, on the other hand, it can be observed that pressure and heat release fluctuation in the 500 Hz band is completely out of phase, Therefore, as the swirl intensity is increased, the phase difference of pressure oscillation and heat release fluctuation changes, resulting in stabilization of combustion.

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By analyzing the flow structure changes in the main chamber with swirl, we expect to understand the physical process related to phase shift between p′ and q′. Especially, as the swirl intensity increases, the phase difference of p′ and q′ of 500 Hz band suddenly increases from less to larger than π/2. Thus, the change in the flow structures due to swirl injection prior to entering to post chamber plays an important role in achieving combustion stabilization. And combustion visualization in main chamber was done to further investigate the details of flow structure changes.

3.2 Flow structure in main chamber

Two types of flow structure characterize swirl injection; the flow structure near surface and rotating flow in central core region. Visualizing combustion in the main chamber shown in Fig. 11, the spiral trajectory of the flow was observed near surface region. The spiral trajectory near the wall varies in angle and range depending on the strength of the swirl intensity. In Test A, visualizing images show that flow trajectory is elongated with some wrinkles in the axial direction. This elongated trajectory near surface is the typical feature of surface flow in case of pure axial flow.

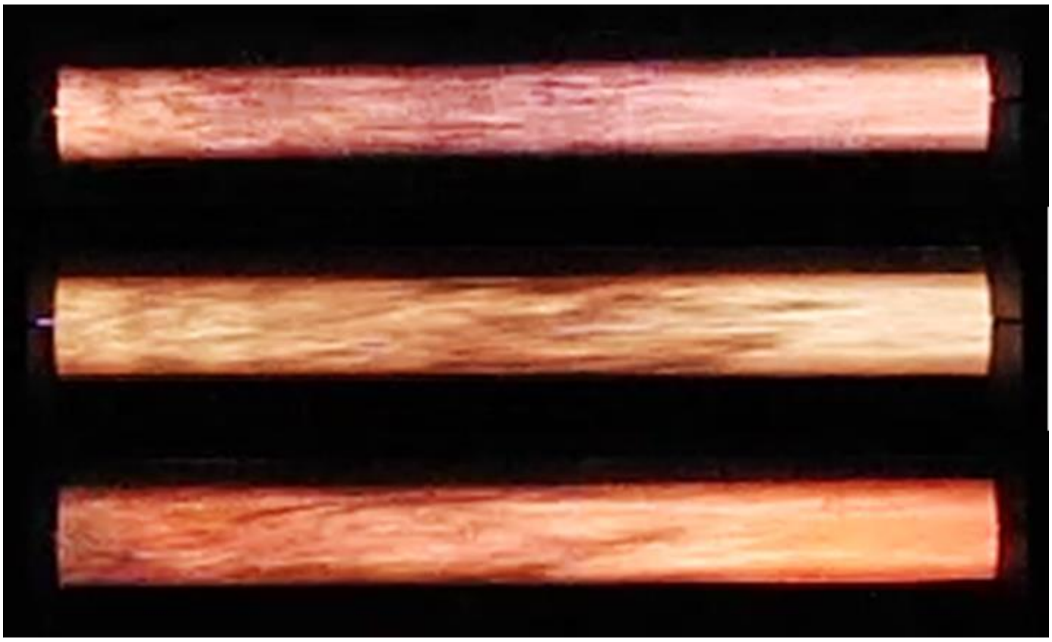

Figure 11: Visualization of main chamber with different swirl angle

On the other hand, in Test B, spiral trajectory of surface flow is clearly visible up to the 1/3 location of the main chamber, and the helical trajectory progresses into the axial one as the swirl strength weakens (Test B). However, the spiral trajectory was observed up to the end of solid fuel due to the application of strong swirl injection (Test C). Thus, the application of swirl injection gradually induces flow stratification as swirl intensity increases; helical flow near surface region and rotating flow in core region. At the same time, combustion region is mainly formed near surface and chemical reaction was seldom found in the core region due to biased mixing enhancement of fuel and oxidizer by swirl injection. In Test A and B, flame images are relatively bright near the center of the main chamber and near the fuel surface as well. However, in Test C, the flame images near the center region seem less bright than the rest of fuel region. Yuasa et al. [17] observed that the combustion reaction does not develop in the core region when the swirl injection is applied [7]. In this regard, brightness difference in visualization images is the result of biased combustion reaction developed near core region.

Such changes in the core and surface regions can be observed in detail through recent LES study [18]. Figure 12 compares the flow inside the main chamber with the Q criterion distribution, and a similar appearance can be observed. From these results, it was concluded that the LES results show the qualitative description of flow structure. According to the LES results, the axial flow interacts with the wall blowing and this generates small vortices near the wall surface. However, the swirl injection induces a strongly rotating flow in core region. The calculation results with swirl injection in Fig. 13 confirm that the small size vortices generation

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near the wall is reduced and the vortices size is also smaller. Meanwhile, the stratification of the flow into the core region and surface region due to swirl injection seems to be a unique feature only observed in Test C as shown in Fig. 11. Therefore, a strong rotational flow developed in the core region expects to flow into the post chamber. Even the details of the interaction of rotating flow and additional combustion of unburned fuel is not understood, the presence of rotating flow may be related to the initiation of the LFI.

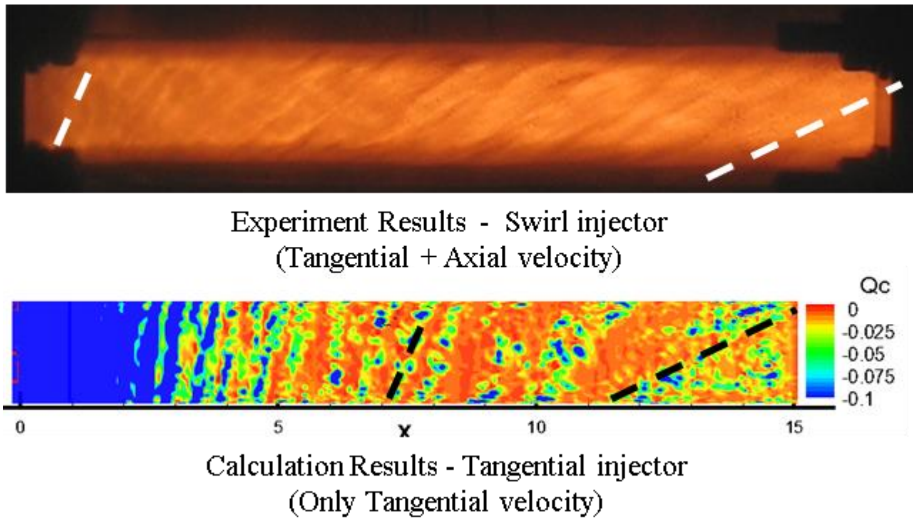

Figure 12: Visualization of swirl flow in chamber (top) and Q-criterion on the surface for tangential injector (bottom)

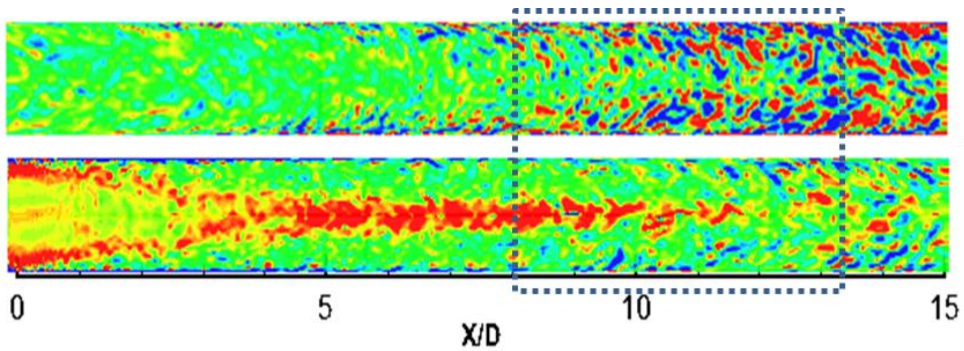

Figure 13: Axial vorticity, axial (top) and swirl (bottom) injector

Also, as the swirl intensity increases, the rotational flow of the core region and the swirl effect of the surface region are observed near the rear of the main chamber. Fig. 14 shows the vortices distribution in main chamber with increasing swirl intensity. As the rotation component in core region becomes stronger and continues to exist up to the rear end, the number of vortices generated near the surface region is decreasing. Examining the fuel surface flow, it can be indirectly observed that the number of vortices decreases in the surface region. Thus, the application of swirl injection induces a change in turbulence structure through interacting and mixing process with the fuel vaporization and the wall blowing prescribed along the surface.

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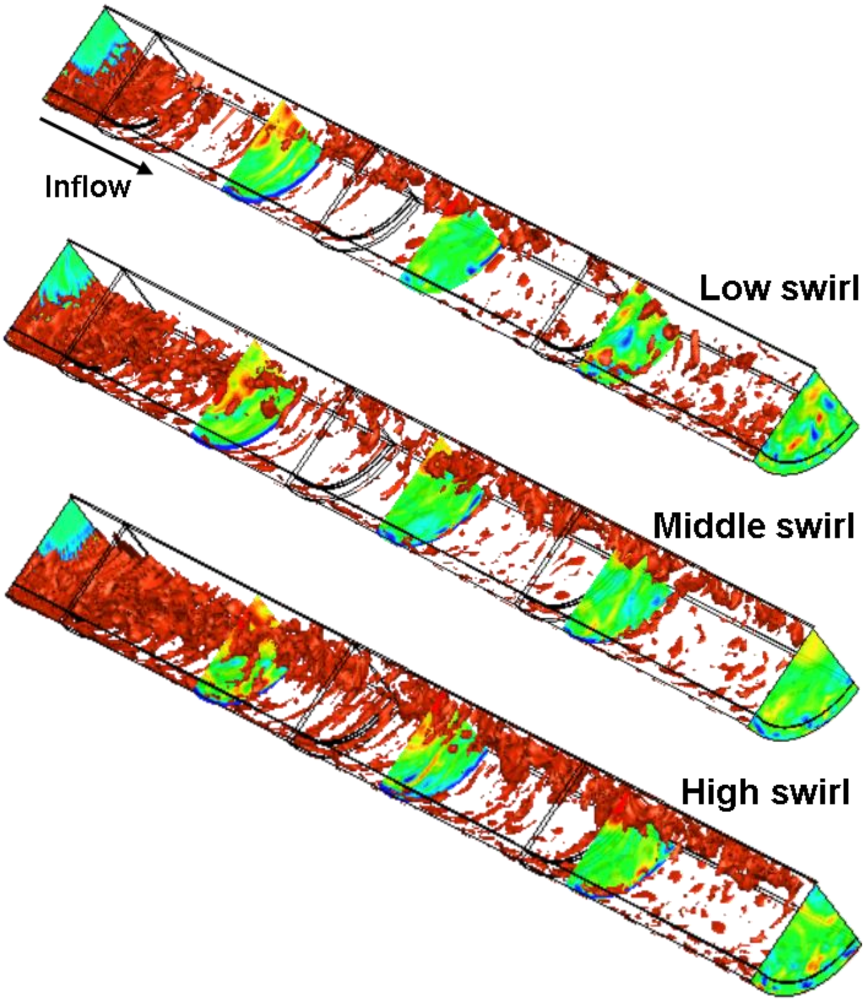

Figure 14: Iso-contour of Q criterion along with vortices distribution

3.3 Flow structure in post-chamber

In previous study, it was reported that small vortices from main chamber were interacted with the shear layer and turbulence structures were modified along the shear layer regardless of combustion conditions; stable or unstable [6]. As mentioned in section 3.2, turbulent flow structures near the outlet of the main chamber were determined depending on the swirl intensity, which may affect the additional combustion behavior in terms of combustion fluctuation frequency and phase along the shear layer in post-chamber.

Figure 15 compares time-averaged flame image using visualization inside post-chamber in Test A and Test C. For baseline case at region 1 (no swirl injection in Test A), the flame distribution shows a steady structure elongated in the axial direction, exhibiting a chamber-axis symmetric distribution, and gradually spreads to the wall after passing the location of 1/3 of post-chamber length from inlet. However, in Test C, the flame spreads to the wall from the post-chamber inlet. This seems to be related to the flow structure which is affected by swirl injection near surface region in the main chamber, resulting reduction in recirculation region size and hence reattachment length. In the Test C, the surface region is also formed up to the end of the fuel, which was suddenly expanded in the post-chamber due to the additional rotational momentum. Also, as the swirl intensity increases, the boundary layer of the flame was found to rotate in post-chamber. Flame image in Fig. 15 confirmed that additional combustion of unburned fuel occurred along the rotating shear flow when swirl intensity was strongly increased. Thus, the change in momentum distribution due to swirl injection in the main chamber significantly affects flame behaviour and turbulence structure in post-chamber.

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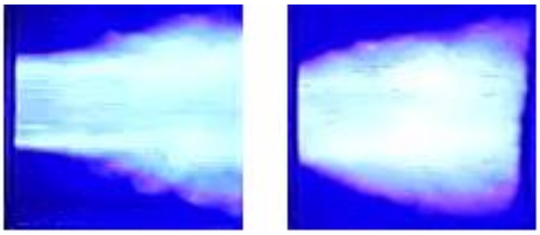

Figure 15: Comparison of flame raw images, Test A (left) and Test C (right)

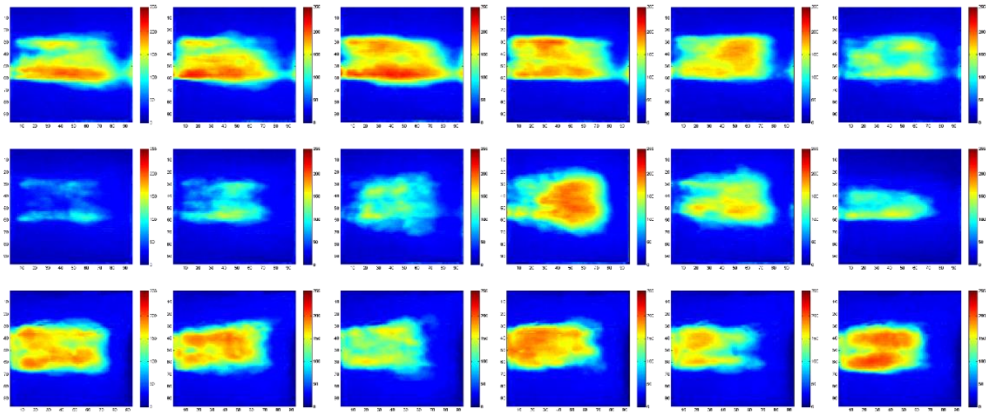

Figure 16: Sequence of averaged flame images for one cycle at region 1(top; stable), region 2 (middle; LFI) in Test A and Test C (bottom; stable)

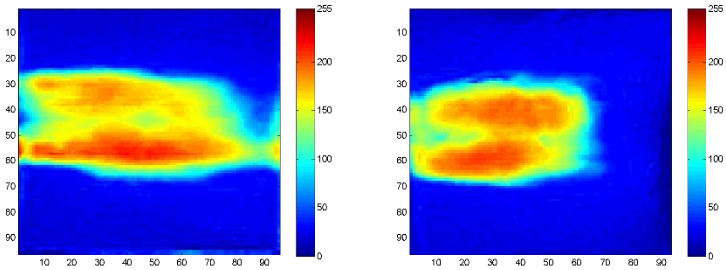

Figure 17: Exemplary image at region 1 (left) in Test A and Test C (right)

Figure 16 compares the flame structure inside the post chamber. From the top, it shows the change of 20 Hz 1 cycle in Test 1 region 1, region 2, and Test C region 1 in order. Each image averaged 3 images (500 Hz 1 cycle) to clearly compare the periodic changes in the 500 Hz band. In region 1 of Test A, there is almost no chemical reaction in the central part in the axial direction, and elongated steady flames form above and below the central axis. In region 2, the stratified flame gradually weakens, and a flame structure with a large vortex shape is observed. Choi reported that this periodic flame decay and LFI develop [16]. However, in Test C, a slightly different flow structure appears to develop. As mentioned above, a core region that is rotated by the swirl flow develops inside the main chamber. It is assumed that a strong rotational flow is introduced into the post chamber and the flame is formed at the axial center.
Shown in Figure 17, unlike region 1 in Test A, where no chemical reaction occurred at the axial center, flame can be observed in the center as well as along the shear layer. It is considered that the heat release oscillation is developed due to the additional combustion interacted with modified turbulence structure by swirl injection. It can also be deduced that the axial velocity component decreases. Further studies will be needed to understand the details of physical mechanism why the phase of the heat release oscillations does shift in this circumstance. Nevertheless, it is considered that the rotating flow of the core region flows into the post combustion chamber, and the modified turbulent flow structure plays an important role to stabilize combustion suppressing the occurrence of the LFI.

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4. Conclusion

The application of swirl flow was found as an effective method to increase the combustion stability and to enhance combustion efficiency in conventional propulsion system including gas turbine engines. In recent experiments, it is also observed that swirl injection plays an important role in stabilizing of hybrid rocket combustion. When the swirl is applied, the occurrence of the LFI could be suppressed developing stable combustions even in the same combustion conditions. In this study, the effect of swirl injection on the combustion stability was investigated with hot tests and numerical calculation. To monitor the substantial changes in flow structure due to swirl, the main chamber and the post chamber were visualized, and also the phase shift was estimated in the analysis.

As a result, the application of swirl injection seems to modify the two main physical processes responsible for the occurrence of the LFI, that is, the generation of the heat release oscillations of 500 Hz band and the establishment of positive coupling between p′ and q′ of 500 Hz band. When the swirl injection was applied, even the frequency characteristics of p′ and q′ of both 20Hz and 500Hz band were found unchanged, and the positive coupling p′ and q′ of 500Hz was barely established or not. However, as the swirl intensity increased above the critical value, the phase difference p′ and q′ in 500 Hz band showed an increase above pi/2 showing totally independent behaviors of p′ and q′.

Therefore, it is believed that phase shift was the result of the complicate interaction of strong rotational flow structure near core region and the additional combustion in post chamber. At the LFI occurrence, visualization images confirmed that stratified isolated flames in the post chamber were also observed accompanied with periodic flame extinction in baseline case. However, flame regions were mainly observed near central region instead when the swirl injection was applied. It is presumed that the unburned fuel and the oxidizer are reacted by the strong rotational flow structure near the centerline in post chamber and ultimately contribute to resulting in combustion stabilization.

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