EFFECT OF INDUCED SWIRL FLOW ON REGRESSION RATE OF HYBRID ROCKET FUEL BY HELICAL GRAIN CONFIGURATION

Changjin Lee, Jaewoo Lee, and Yungwhan Byun
Konkuk University, Korea

Sungtaik Lee
Hanwha Corporation, Korea

The oxidizer swirl flow is the efficient method to extend the residence time of oxidizer in the solid fuel of hybrid rocket. In this study, a series of experimental tests has conducted to investigate the optimal conditions of oxidizer swirl flow and grain configuration for enhancement of regression rate of solid fuel. And a helical fuel grain configuration is not only designed to increase the burning surface area and also to induce turbulences to enhance heat transfer rate. PMMA with gaseous oxygen is the solid fuel for investigation. Test results show that fuel port configuration yields higher burning performances up to 50% increase in regression rate. And pitch number total impulse can be design variables in determining overall regression rate. Also numerical simulations revealed that a helical grain induces swirl flow and turbulences along the helical grain.

I. Introduction

Hybrid rocket has been regained a spotlight not only by its excellent safety in combustion process but also by its advantage in development cost although its low density specific impulse and inferior changing efficiency[1-2]. Thus the most researches are focused on the subject to increase the changing efficiency and to enhance the regression rate.

The one of the popular method is to use additives such as AP (Ammonium Perchlorate) and Al (Aluminum) powder in the fuel compositions. It is well known these materials are major components of composite solid propellant. And the addition of AP and Al will increase the heat release in the hybrid fuel and consequently will lead to increase the regression rate. Krishnan *et al.* [3] conducted a series of experiments with solid fuel, HTPB modified by AP, Al additives. Test results showed the regression rate increased considerable up the 180% compared to the regression rate of baseline fuel (pure HTPB). Also, Frederick et al. [4] tested a mixed hybrid propellants to evaluate the effect of the addition of AP up to 25% on the augmentation of the regression rate of HTPB based fuel. They obtained the similar results as observed in the previous results in reference [3] and the addition of AP could yield up to 150–300% increase in regression rate. Another effort to increase the regression rate was done by Risha et al. [5]. Their experiments were designed to evaluate the effect of the addition of nano-sized energetic powder on the regression rate augmentation. Results revealed that the addition of 13% of energetic powders showed an increase of up to 63% in mass burning rate compared to the pure HTPB fuel. Although the addition of AP/Al proved to be an effective method in increasing regression rate, it should be noted the use of additives may deteriorate the safety feature of hybrid fuel. In this regard, the maximum percentage of the additives has to be limited less than the critical value at which the hybrid fuel is no longer safe.

Another approach to increase the regression rate resorts to swirl flow of liquid oxidizer injected into the fuel port. The swirl flow can increase the residence time (or contact time) of oxidizer stream with fuel surface in the port. Thus this will lead to the increase in the regression rate. Yuasa et al.[6-8] designed a swirl injector for oxidizer injection and tested the effect of swirl strength on the regression rate. Test results revealed the average regression rate showed an increase up to 200% as swirl number increases. However, it was also found that the enhancement of regression rate is severely localized near the inlet of fuel port. Thus it is not appropriate to adopt a simple swirl oxidizer flow to increase the regression rate unless the complimentary method is implemented. In addition, Knuth et al. invented vortex tube method where swirl flow intrinsically dominates the overall fuel port and consequently leads to the substantial increase in regression rate up to 450% compared to one without swirl flow. It should be noted that this method differs from the method of Yuasa et al. in that swirl effect can be sustained throughout the whole fuel port and regression rate increases much higher than that with simple swirl flow [9-11]. And vortex tube method is a patented method for the enhancement of regression rate of hybrid solid fuel.

As mentioned, a swirl flow is effective in increasing the regression rate. However, the complimentary method should be used simultaneously to extend swirl effect throughout the whole fuel grain if this method could be applied into a practice in the real hybrid rocket. In this regard, Helical grain in the fuel port can lead to generate swirl flow even though this method has disadvantage of not only pressure drop due to turbulent generation from oxidizer flow but also low charging volume for the augmentation of regression rate. Generally solid propellant rockets did not use the internal port design to generate swirl flow because no oxidizer flow is involved in the combustion. Thus, the swirl generated by internal port configuration may be a unique way in hybrid rocket combustion. In this study, a couple of port grain configurations were tested to investigate the optimal conditions for increasing the regression rate. Also numerical simulations have been done with cold flow within the fuel port to investigate the flow characteristics of internal. Results of each method are compared with baseline test results and analyzed.

II. Experimental Setup

The fuel used in the test is PMMA (Poly Methyl MethAcrylate) and the gaseous oxygen is used as an oxidizer. The chamber pressure is determined at 300 psi for safety reason. Table 1 summarizes the test conditions and fuel configuration. Fig. 1 shows the schematic of experimental setup. As seen in Fig. 1, solenoid and check values control oxidizer feeding time

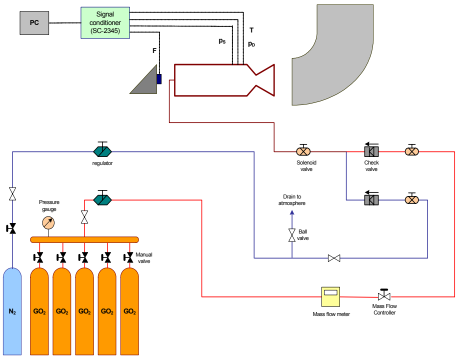


Fig. 1. Schematic of experimental setup

and nitrogen gas flow rate to purge after the combustion by using PLC (programming logic controller) control. Ignition of solid fuel is usually a difficult problem to achieve. This test utilizes a model rocket propellant triggered by electric discharge for ignition purpose. Sega MFC (mass flow controller) controls oxygen mass flow rate from 10g/s to 35g/s to provide various test conditions for a given fuel configuration. The data acquisition devices are Druck pressure transducers for static pressure, a PCB accelerometer for dynamic pressure, a loadcell by CAS for thrust, and K-type thermocouples. And National Instruments DAQ board and LabVIEW program is also used for data acquisition process. Fig. 2 shows a configuration of test motor.

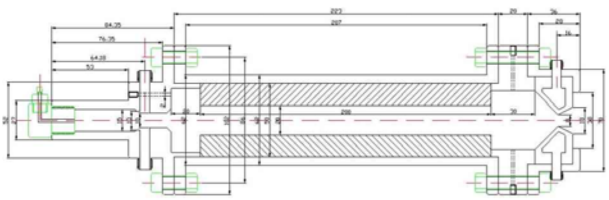


Fig. 2. Configuration of Test Motor

Table 1

Test conditions and fuel configuration

Solid Fuel	Oxidizer	Length	Outer Dia.	Inner Dia.	Chamber pressure
PMMA	GOx	200 mm	50 mm	20 mm	300 psi

III. Results

A. Baseline test

A baseline test was conducted with PMMA fuel and gaseous oxygen in order to verify experimental setup and test procedure. Yuasa et al. conducted a series of experiments to assess the swirl effect on the regression rate increase with PMMA and gaseous oxygen. Thus, baseline test results in this study are compared with results in reference. In the range of specified mass flux from 3 to 10 g/(cm^2·s) [8]. Fuel used for the baseline test is designed to have a configuration as shown in the table 1 and test time was fixed for 4 seconds. Figure 3 shows the comparison of baseline test results with previous one in [8]. As seen in the Fig. 3, test results show a quite good agreement with previous studies.

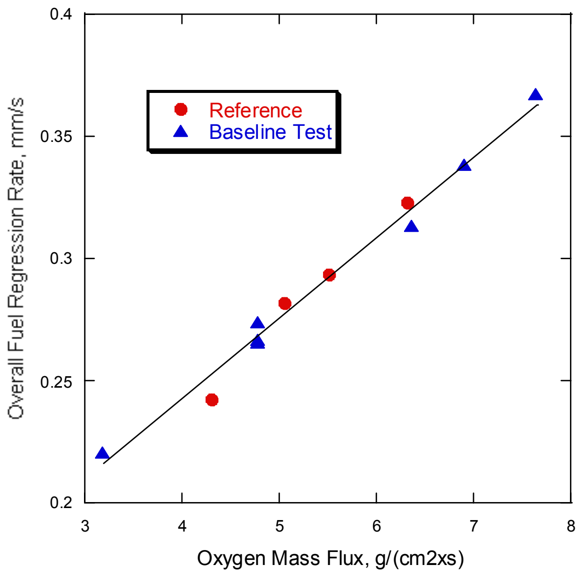


Fig. 3. Comparison of baseline test results with previous one [8]

The average regression rate was obtained by simple algebraic calculations with port volumes measured before and after the test. The procedure to calculate the average regression rate begins with the measurement of port volume before test. If the initial volume (V_1) is divided by port length (L), it will give an initial surface area A_{b1}. The initial and final port radius are then calculated by radius-area relation. So equations used are

$$r_1 = \sqrt{\frac{A_{b1}}{\pi}} \ , \ A_{b1} = \pi r_1^{\,2} \ , \ A_{b1} = \frac{V_1}{L} \quad \dot{r} \cong \frac{r_1 - r_2}{\Delta t}$$

This method provides the average regression rate with a quite good accuracy for the fuel for simple circular grain port. However, it should be noted that the determination of regression rate can be complicate if the port is not a circular one.

B. *Regression rate increase associated with internal grain configuration*

Swirl flow induced by injector is known to increase the regression rate by increasing the contact time between oxidizer and solid fuel. It is, however, generally known that the effect of swirl flow is only limited near the inlet part of fuel port because swirl strength diminishes by the viscous interaction with solid fuel surface as it flows downstream. A typical example of combustion with swirl flow in hybrid fuel can be found in reference [6-9]. Even though the regression rate showed the increase with swirl flow, only the inlet part of the fuel experienced swirl effect. And, the burning volume of along the axial direction shows a severely biased pattern. So it is natural to seek a method not only to minimize the disadvantage of swirl injector but to overcome the negative effects by using other applicable options. In this respect, this study concentrates on the improvements of swirl effect by using the internal grain configuration.

Four different pitches are adopted in the experiment. These are pitch of 3, 6, 12, and 18 as shown in Fig. 4. Here, pitch is defined as the distance (in mm) between troughs of helical grain configuration. And, it should be noted a helical grain is imposed only over the aft half of the port to examine the effect port grain configuration on the combustion enhancement. And the pitch depth was fixed for all tests to simplify the test variables. It is not surprising to find that the additional grain configuration can lower the charging efficiency because of additional vacancy of fuel by helical groove along the port. Fig. 5 shows the comparison of cross sectional view of PMMA fuel port of pitch 6 before and after test when the oxidizer mass flow rate was specified at 15 g/s.

As can be seen in the bottom picture, the enhancement of regression rate is achieved by the result of evenly distributed increase in burning rate along the flow direction. It is worth noting that the inlet port of fuel port shows severely biased burning due to initial strong swirl effect of oxidizer flow.

Table 3 summarizes initial charging efficiencies, initial burning surface areas, and volume burning rates of fuel with various pitch numbers. Initial fuel port volume was measured by using water before combustion test.

As found in the table 3, all fuels with pitch have the similar order of charging volume only 1 or 2 % less than baseline. However, the burning surface area (A_b) increases substantially by adopting helical grain configuration for all fuels ranging from 10% up to 50%. Thus it is expected the increase in surface area can lead nominally to the same percentage increase in volume burning rate ($\dot{V}$) enhancement if the regression rate remains unchanged as shown in the equation;

$$\Delta\dot{V} = \Delta A_b \cdot \dot{r}$$

Test results, however, showed that a fuel with pitch 3 revealed at most the highest increase in volume burning rate ($\dot{V}$) of 5.075 cm^3/s equivalent to 35% increase compared to

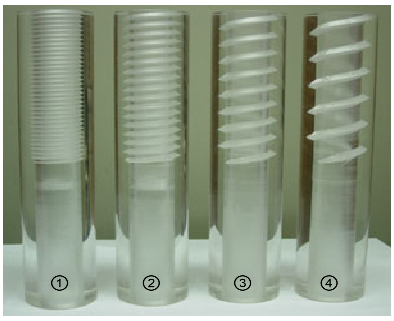


Fig. 4. Helical grain configuration of pitch 3, 6, 12, and 18

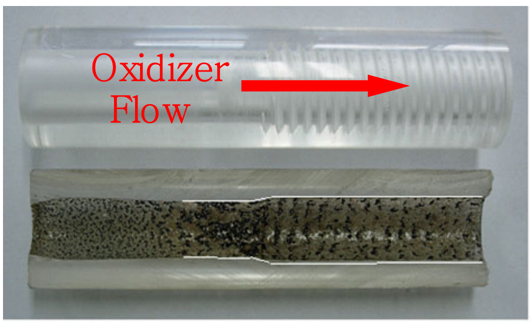


Fig. 5. Cross sectional view of pitch 6 before and after combustion test

that of baseline case, which is less than that of surface area (A_b) increase of 50%. And the increase in volume burning rate becomes approximately the same as surface area increase as pitch number increases. So, for example, the difference between volume rate and surface area increase becomes almost negligibly at pitch 12 showing 114.6% in surface area and 116.4% in volume burning respectively. However, it is interesting to observe volume burning rate ($\dot{V}$) at pitch 18 shows only about 1% increase rather less than surface area increase of 10%. This implies other mechanisms other than surface area and regression rate are involved in controlling the volume burning rate of the fuel with pitch configuration. One of the possible parameter can be the generation of turbulence caused by helical configuration against axial flow direction. The less is pitch number, the more resistance to axial flow. And consequently the stronger generation of turbulence in the flow may aggravate the volume burning rate.

Table 3

Summary of charging efficiency and surface area of various test fuels

	Baseline	Pitch 3	Pitch 6	Pitch 12	Pitch 18
charging vol. (cm^3)	329.67 (100 %)	326.16 (98.94 %)	326.66 (99.09 %)	326.96 (99.18 %)	327.66 (99.39 %)
A_b (surface area, mm^2)	128.06 (100 %)	191.15 (149.3 %)	165.82 (129.5 %)	146.80 (114.6 %)	140.67 (109.8 %)
Vol. burning rate (cm^3/s)	3.753 (100 %)	5.075 (135%)	4.500 (120%)	4.368 (116.4%)	3.793 (101%)

Figure 6 summarizes test results of regression rate of test cases with different pitch numbers from 3 to 18. Meanwhile, it is worth reviewing the method to determine the regression rate of each case from the measured grain volume. As mentioned previously in the part "baseline test", the initial port surface area can be calculated by dividing measured volume over port length (L). However, it is ambiguous to calculate the real burning surface area from measured port volume by using port length of the fuel with pitch because a helical grain is imposed only after half of the grain. Nevertheless the ambiguity, it is useful to calculate regression rates of various fuel cases by using the simple relation of measured port volume, surface area and port length (L) as mentioned in previous section of "baseline test". Thus, regression rates in Fig. 6 were obtained from the calculation with fixed port length (L). As seen in the Fig. 6, pitch number can be one of the major variables affecting the regression rate.

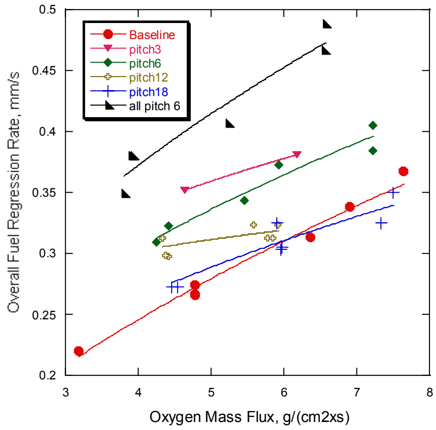


Fig. 6. Regression rates of several test cases with different pitch number from 3 to 18

It is interesting to see that a fuel with pitch 3 shows the biggest increase in regression rate up to about 30% among test cases over the wide range of oxidizer flux from 3.2 g/(cm^2·s) to 7.6 g/(cm^2·s). And test results show that a fuel with smaller pitch is effective in increasing the regression rate of the fuel. However, the regression rate of the fuel with pitch 18 was found to be less than that of baseline case even though the burning surface area is 9% larger than that in the baseline. This means that the increase in surface area is not directly proportional to the increase in the regression rate. Presumably, pitch number and turbulence strength generated by grain configuration are the simultaneously affecting factors to determine the characteristics of regression rate behavior. It is also interesting to observe that the overall gradient of regression rate line becomes smaller as pitch number increases. For example, the gradients for fuel with pitch 12 and 18 are much less than that of baseline case. And regression rate of fuels

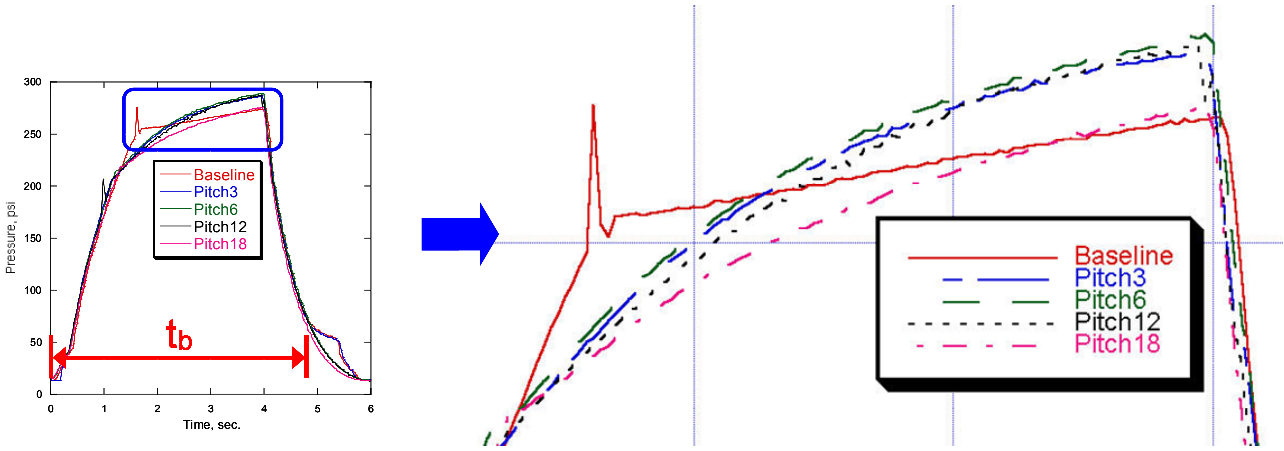


Fig. 7. Pressure trajectory of baseline case with those of fuel with various pitches

with pitch 12 and 18 can be less than that of baseline case. This result, therefore, implies that the internal port configuration with larger pitch may even deteriorate the regression rate. And it means the optimal pitch exists in maximizing regression rate. At this point, it is worth noting that a fuel with pitch 6 imposed over the whole part shows more than double increase in regression rate compared to that of a fuel with pitch over only half part. Thus, the internal grain configuration may induce a swirl flow near the entrance of the port. Unfortunately, no physical evidences are available for this assertion, and further researches are needed with fuel having various orientations of helical grain.

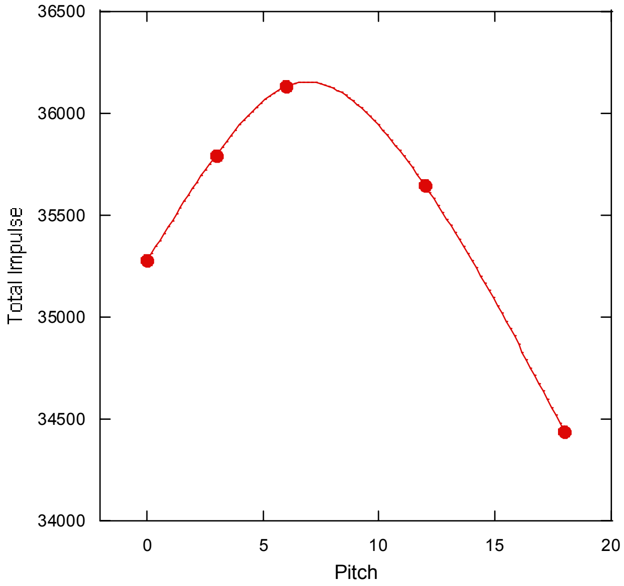
Figure 6 is the picture showing the overall regression rate against pitch number at two differferent oxidizer mass flow rates of 15g/s and 20g/s. As seen in the Fig. 6, the optimal pitch number for the max regression rate is clearly located, as expected, at pitch 3 or so for all mass flow conditions.

Figure 7 compares pressure trajectory of baseline case with those of fuel with various pitches. As seen in the figures, the solid line is a pressure trajectory of baseline case.

The pressure trajectories for fuel with pitch show smooth curve while the baseline pressure is a linear straight line. Also the initial pressure for fuel with pitches starts from lower pressure level than baseline. Then the pressure gradually increases across the baseline pressure and finally the final pressure becomes larger than that of baseline pressure. However, it is interesting to observe the pressure for a fuel with pitch 18 is less than that of baseline during whole combustion time. And the initial pressure drop in the fuel with pitches may be caused by the generation of turbulences due to internal port configuration. However, the chamber pressure becomes quite big up to almost 300 psi because the increase in regression rate consequently overcomes the pressure losses by turbulences in the combustion region. Thus, it is not appropriate to use solely a pitch number as design variable in determining the optimal configuration for the maximum enhancement of regression rate.

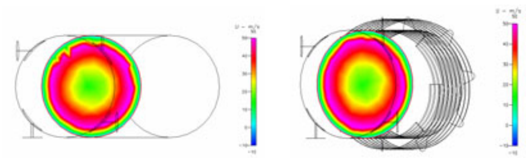
Figure 8 reveals another aspect in determining the optimal configuration of internal port pitch. Since it is well known that thrust trajectory coincides with the chamber pressure curve, the pressure trajectory can be used as an alternative of thrust curve to evaluate the total impulses for several test cases. Total impulse is one of the performance index measuring the total amount of thrust during the combustion and is defined by the integration of thrust over combustion time as

$$I_{tot} = \int F\,dt \cong \int p\,dt$$

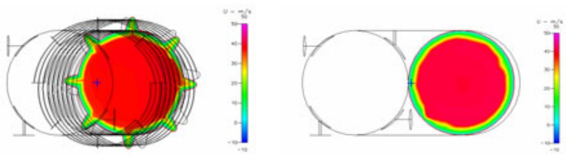


Pitch	I_{Tot}
Baseline	35280 (100%)
3	35795 (101.5%)
6	36133 (102.4%)
12	35643 (101.0%)
18	34440 (97.6%)

Fig. 8. Pitch number vs. total impulse of a fuel with different pitch numbers



Axial velocity profiles at 50 mm



Axial velocity profile at 190 mm

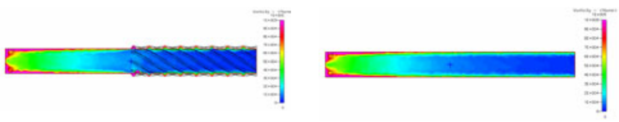
Fig. 9. Axial velocity profiles at two different locations within circular and helical port

Even though the quantity from the integration with pressure curve instead of thrust does not have a physically correct dimension of total impulse, it will provide physical interpretation which cases shows the best impulse performance. Integration was done from the initial time t_o to burnout time t_b. As shown in the Fig. 8, results show very interesting dependence of total impulse on the pitch number. Total impulse has the maximum value of 36133 (psi·s) at pitch 6 equivalent to 2.4% increase compared to baseline. However, a fuel with pitch 3 shows only 1.5% increases in total impulse although a fuel with pitch 3 showed the maximum increase in regression rate among test cases. Figure 14 reveals the maximum total impulse is located around pitch or pitch 7. So, it can be concluded a simple comparison of regression rate with other cases does not provide the information what pitch number is an optimal one for a given fuel conditions. In this regard, further studies with experiments and numerical calculations are needed to understand the basic mechanism of the enhancement of regression rate by internal grain configuration. Nevertheless the lack of understanding, the grain configuration should be determined by accounting for both the increase in regression rate and the total impulse.

C. Numerical Simulation for Cold Flow in the grain port

Numerical simulations have been done to investigate the flow characteristics in the fuel port and the effect of helical grain configuration on the generation of swirl component of internal flow over the after part of the grain. A commercial software, CFD-ACE, was used for the numerical calculation. Experiments revealed the oxidizer swirl effect could influence only near the inlet part of the fuel and resulted in the biased burning of solid fuel. So, numerical simulations attempts to focus on the extension of swirl effect along the port grain by using the helical grain. In the simulation, inlet condition and geometry configuration were chosen to be the same as shown in table 1. And the mass flow rate of 0.015kg/sec was fixed as the inflow condition and this was provided through four tangential directions with equal amount of mass flow rate. Simulations investigated the flow characteristics with two different flow cases; swirl inlet flow with pure circular grain port, and swirl inlet flow with helical grain port having 30 degree orientation with respect to axial direction. Figure 9 shows the axial velocity profile at the location of 50mm from the inlet.

Since the helical grain begins at the location of 100mm, no differences in velocity profile were found for both configurations at this location. However, the velocity profile at 190 mm reveals that the helical grain may take a role of distributing high flow momentum from the core to solid wall along the grain. Also, as shown in figure 10, the vorticity distribution within the helical grain shows that the helical grain produces more vorticities near solid wall.



Circular grain   Helical grain

Figure 10. Vorticity profiles along the axial direction within circular and helical port

This may implies that turbulence generated by the helical grain becomes intensive near solid wall surface due to helical groove. The increase in the regression rate with helical grain attributes to the increase in the vorticity near solid wall and results in the increase in heat transfer to solid fuel

IV. Summary and conclusion

For the method with internal port design, a helical grain configuration can be an effective method to enhance the regression rate by simply increasing the burning surface area and by resulting in the increase in heat transfer to solid wall due to the enhancement of heat transfer. Even though further research efforts should be required to investigate the optimal matching condition between inflow swirl strength and the helical grain orientation, the helical grain configuration does sacrifice the charging volume with an acceptable level up to 1~2% and increases dramatically the regression rate without resort to any additional devices. Also, it was found that the smallest pitch number 3 showed the best performance in the increase in regression rate among test cases. However, it is interesting to find that a fuel with pitch 6 has the maximum total impulse, which relates to the maximum thrust performance. Thus, the optimal grain configuration should be determined by considering both regression rate behavior and total impulse characteristics. And further study will focus on the issue what configuration of fuel port is suitable to generate swirl flow as well.

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