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The Experiments for the Enhancement of Regression Rate of Hybrid Rocket Fuel

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Many studies have been conducted to increase regression rate of solid fuel in hybrid rocket. One of them resorts to swirl flow since it can extend the residence time of oxidizer in the fuel grain. Also, metal wires may lead to increase the regression rate of solid fuel as shown in solid propellants. In this study, a series of experiments was designed to investigate the enhancement of regression rate of solid fuel by embedded metal wires and by fuel port grain. And fuel port was designed with a helical configuration to attempt to induce swirl flow. PMMA with gaseous oxygen is the solid fuel used for investigation. Test results showed that embedded metal wires turned out to be ineffective method because only 3-4% increases in regression rate were observed. However, fuel port grain configuration yields higher burning performance of up to 50% increase in regression rate. Also pitch number as well as total impulse was found to be a design variable.

Key Words : Regression Rate, Hybrid Rocket, Metal Wire, Helical Grain

Nomenclature

A_b : Burning surface area
F : Thrust
I_{tot} : Total impulse
L : Port length
p : Pressure
$\dot{r}$: Regression rate
r_1 : Initial port radius of PMMA
r_2 : Final port radius
t : Time
t_b : Burnout time
V : Port volume

1. Introduction

Hybrid rocket has been regained a spotlight not only by its safety features in combustion but also by its low cost for development although it's low density specific impulse and inferior changing efficiency (Sutton and Biblarz,, 2001). Thus the most researches are focused on the subject to increase the changing efficiency and to enhance the regression rate.

Two different approaches have been attempted in the society for this purpose. The first one is the method 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 could lead to increase the heat production in the hybrid fuel and consequently will increase the regression rate. George, Krishnan, Varkey, Ravindran, and Ramachandran (1998) conducted a series of experiments with solid fuel, HTPB modified by AP and Al additives. Test results showed the regression rate increased considerably up to 180% compared to that of baseline fuel (pure HTPB). Also, Frederick, Moser, Knox, and Josh (2004) tested hybrid propellants to evaluate the effect of the addition of AP on the augmentation of the regression rate of HTPB based fuel. Their results

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showed the similar results as observed in the reference (George et al., *1998*) and the addition of AP of up to 25% produced the increase of 150–300% in regression rate. Another effort to increase the regression rate was done by Risha, Boyer, Wehrman, and Kuo (2002). Their experiments were designed to evaluate the effect of the addition of nano-sized energetic powder on the regression rate augmentation. Test 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, however, the addition of AP/Al turned out 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 lower than the critical value at which the hybrid fuel is no longer safe.

Second 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 on the fuel surface in the port and this will lead to the increase in the regression rate. Tamura, Yuasa, and Yamamoto (1999), Yuasa, Shimada, Imamura, Tamura and Yamamoto (1999), and Yuasa, Yamamoto, Hachiya, Kitagawa, and Owada (2001) designed a swirl injector for oxidizer stream and tested the effect of swirl strength on the regression rate. Test results showed the average regression rate increased 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. And the rest of the fuel grain was not affected by the swirl flow causing the port unbalance after combustion. Thus it is not appropriate to adopt a simple swirl oxidizer flow to increase the regression rate unless the complimentary method to reduce the unbalance of fuel burning is implemented. In addition, Knuth, Chiaverini, Gramer, and Sauer (1998, 1999) invented vortex tube method where swirl flow intrinsically dominates over the whole fuel port and consequently leads to the substantial increase in regression rate of up to 150% compared to one without swirl flow. It should be noted that this method differs from the method of Tamura, Yuasa, and Yamamoto (1999) in that swirl effect can be sustained throughout the whole fuel port and regression rate increases much higher than that with simple swirl flow (Knuth et al., 1998; 1999). And vortex tube method is a patented method for the enhancement of regression rate of hybrid solid fuel.

As previously mentioned, although swirl effect is the effective method in increasing the regression rate, 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 real hybrid rocket. To this purpose, two different methods can be considered in this study. One of the methods is to use embedded metal wires in the fuel port. Metal wires are generally used in the solid rocket motor for the purpose of increasing burning rate at the selected location of propellant by enhancing heat transfer rate from combustion product into solid fuel. Thus, it is not surprising to expect that the similar effect of burning rate increase could be occurred in hybrid rocket fuel if metal wires are properly used. Another method utilizes the increase of surface area and probably swirl flow induced by the internal port grain configuration. Helical grain 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 motor.

In this study, two different methods were tested and evaluated the effectiveness on the augmentation of regression rate of PMMA fuel; embedded metal wires and swirl flow generated by helical grain configuration. Both methods are easy to apply to any locations along the fuel port where the enhancement is needed. To this purpose, baseline tests with gaseous oxygen were done with a simple circular grain fuel. And tests were conducted with metal wires, copper and silver wires, those are properly located along the grain port. Also several configurations with different pitches were tested at various oxidizer flux conditions. Results of each method are compared with baseline test results and analyzed.

2. Experimental Setup

Figure 1 shows the schematic of experimental setup and test configuration. The fuel used in the test is PMMA (Poly Methyl MethAcrylate) and the gaseous oxygen is used as an oxidizer. In the design stage of hybrid rocket motor, the combustion pressure is determined at 300 psi for safety reason. Table 1 summarizes the test conditions and fuel configuration. As seen in Fig. 1, solenoid and check valves can control oxidizer feeding time 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 for ignition purpose triggered by electric discharge. MFC (mass flow controller, SEGA) controls oxygen mass flow rate ranging from 10 g/s to 35 g/s to provide various test conditions for a given fuel configuration. And the data acquisition was done by a device of Druck pressure transducers for static pressure, a PCB accelerometer for dynamic pressure, a load-cell by CAS for thrust and K-type thermocouples. And National Instruments DAQ board and LabVIEW program is also used for data acquisition process. Also, Figure 2 shows a

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

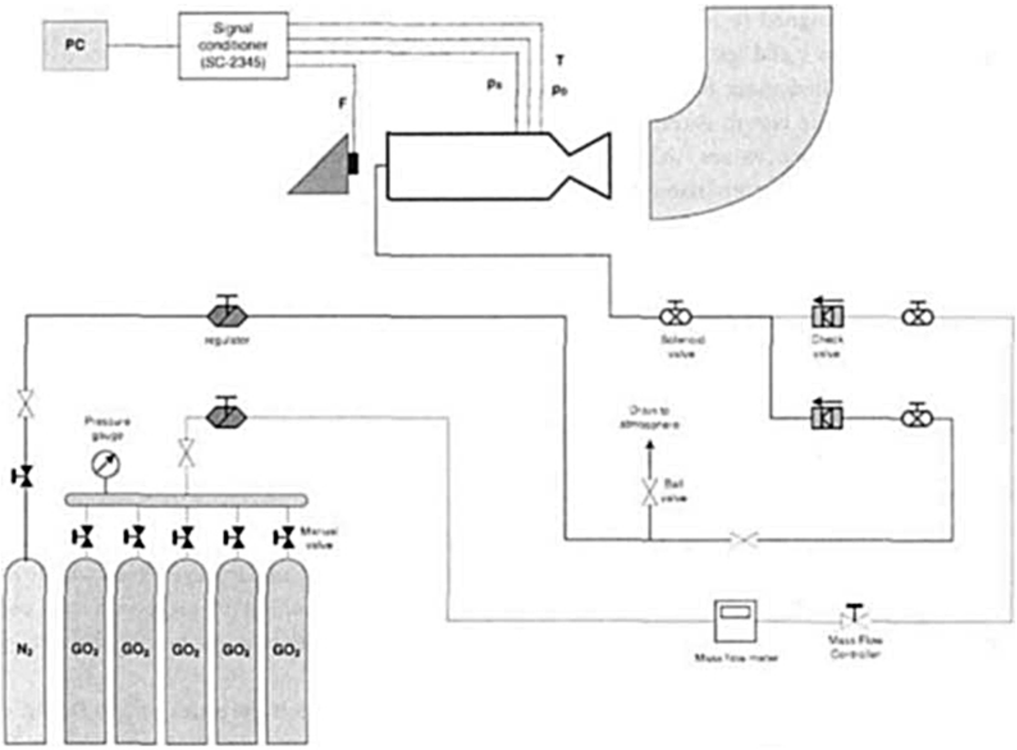


Fig. 1 Schematic of experimental setup

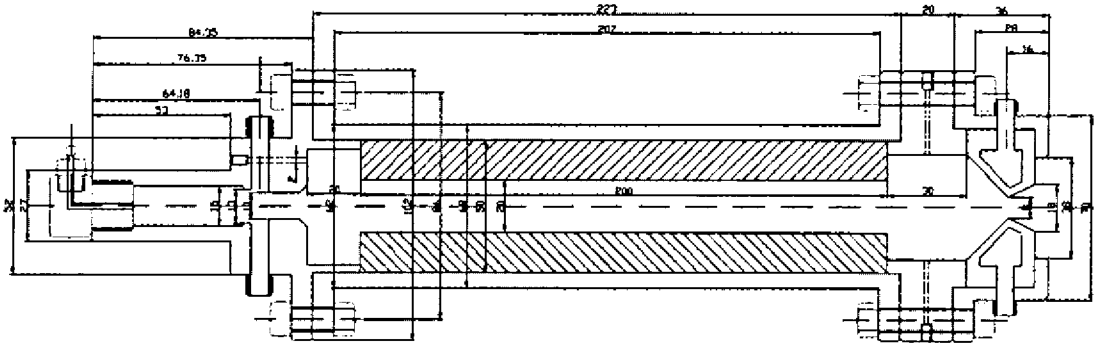


Fig. 2 Configuration of Test Motor

configuration of test motor.

2.1 Baseline test and results

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 the reference (Yuasa et al., 2001). Fuel used in the baseline test is designed to have a configuration as shown in table 1 and test time was set for 4 seconds. The specified mass flux ranges from 3 to 10 g/cm^2.sec in the test to directly compare results with the reference values (Yuasa et al., 2001). Figure 3 shows the comparison of baseline test results with previous one. As seen in the Fig. 3, test results show a quite good agreement with previous studies. So, this can verify the usefulness of the present test results.

It is worth noting that regression rate in the test is a time averaged regression rate and can be obtained by simple algebraic calculation with port volumes measured before and after the combustion 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 provide initial surface area A_{b1}. The initial port radius is then calculated by radius-area relation. So equations used are

$$A_{b1}=\frac{V_1}{L},\ A_{b1}=\pi r_1^2,\ r_1=\sqrt{\frac{A_{b1}}{\pi}} \tag{1}$$

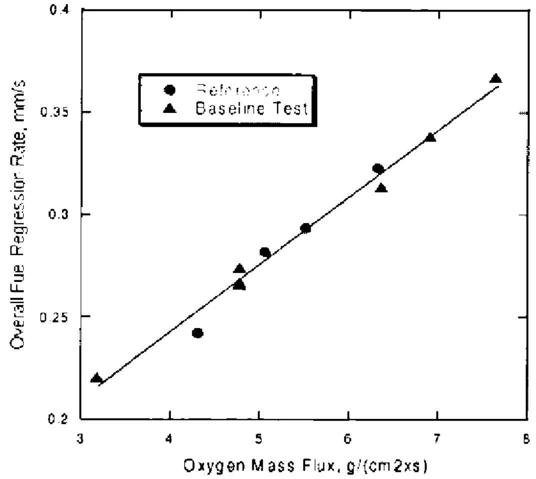


Fig. 3 The comparison of test result with previous one for verification

Similar method can be used to calculate final port radius r_2 from measured final port volume V_2. Then the average regression rate is determined by the average change in the radius divided by test time. So, it can be written as

$$\dot{r}\cong\frac{r_1-r_2}{\Delta t} \tag{2}$$

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

Figure 4 shows trajectories of thrust and combustion chamber pressure during the test. A load-cell is used to measure thrust and a dynamic

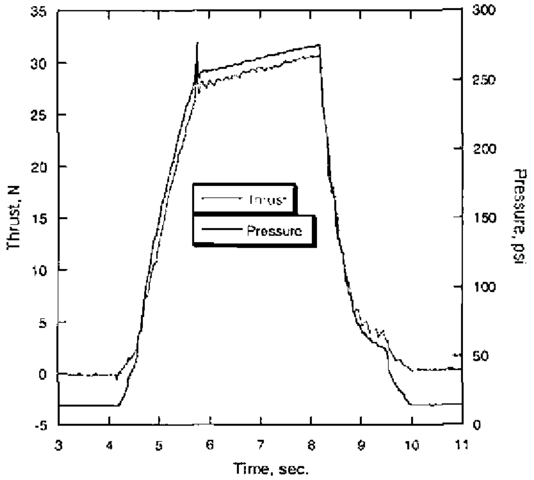


Fig. 4 Trajectory of thrust and combustion chamber pressure

pressure sensor picks up pressure signal. It should be noted that no discernible pressure oscillations due to combustion instability are observed in the pressure trajectory. A small oscillation in thrust curve with about 6 Hz frequency is attributed to unsmooth motion of slider on the test bed. And even though thrust trajectory did not return to the starting value at the end of test because of frictional hysterisis of slider in the test facility, thrust curve coincides with combustion chamber pressure in every aspect. Also, it is worth noting that the chamber pressure was observed about 250~290 psi, which is a little bit lower than the design pressure of 300 psi due to viscous and other dissipative mechanisms in the combustion chamber. However, this pressure level shows experimental setup along with fuel configuration was correctly well designed. Also, the initial peak at the beginning of the combustion is associated with the initial erosion of PMMA fuel.

2.2 Effect of metal wires on the regression rate

It is well known that metal wires can contribute to increase the burning rate of solid propellant by increasing the additional heat transfer rate through metal wires to fuel. For example, test results showed that silver wires of 0.6 mm in diameter could increase the burning rate of up to 400% compared to baseline case with no embedded metal wires. Similar test results showing up to about several hundred percentage increases in the burning rate could be obtained when different metal wires were used (Kubota et al., 1982 ; Zennin et al., 1969). Reference has details of theoretical explanation on the enhancement mechanism of metal wires (King, 1989). However, it is useful to review the basic mechanism how metal wires contribute to increase the burning rate in the solid propellant. Since metal wires have higher heat conductivity than solid propellant, metal wires can take a role of delivering larger amount of heat beneath the propellant surface. As heat flows through the wires, it liberates into the propellant in the normal direction to metal wires. Thus, it is not surprising to see the cross sectional view of location of metal wire is conical shape.

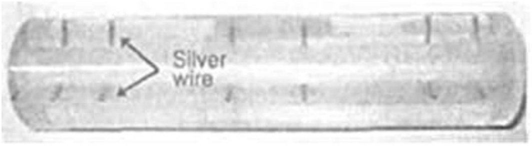


Fig. 5 PMMA fuel with embedded 12 silver wires of Ø2.0 mm

In this study, silver (Ag) and copper (Cu) wires are selected to be used in the test because these wires are easily available, highly heat conductive, and inexpensive materials. In the tests, silver wires have three different diameters of Ø1.5, 1.8 and 2.0 mm. And copper wires are Ø1.6 and 2.0 mm in diameter. Figure 5 is the picture of hybrid fuel, PMMA, prepared for combustion test with twelve embedded silver wires of Ø2.0 mm located various locations along the circular grain. In order to prevent the slippery of wires during the combustion test, each wire has 45 degree orientation with respect to vertical plane.

Figure 6 shows a typical example how metal wires affect the regression rate. As seen in the figure, the upper part of the hole where a metal wire was embedded has a larger diameter than the lower part after combustion and the overall shape becomes conical. However, the magnitude of conical shape is very small in size compared to

Fig. 6 Cross-sectional view at the location of metal wire regression rate

that observed in solid propellant even though wires with larger diameter were used in this test. Table 2 summarizes test results of metal wires for the increase in regression rate of PMMA fuel. In the results, it was found that total percentage of increase in regression rate with embedded wires ranges from 2.14% to 3.7%, which are negligibly small increases compared to those observed in the solid propellant. Silver wires were found to be more effective in enhancing the heat transfer rate to solid fuel compared to the regression rate with copper wires. And, it is obvious that metal wires with larger diameter shows relatively better performance in enhancing the regression rate because wire with larger diameter can be a better media for heat transfer. However, as can be seen in the table, the differences of regression rates between two metals are negligibly small. Thus, it is reasonable to summarize that embedded metal wires in hybrid rocket fuel, PMMA, are not effective in increasing the regression rate.

At this point, it is useful to try to explain why metal wires are less effective in hybrid rocket fuel than those in solid propellant. Basically, the exothermic reaction is dominant in the solid propellant combustion. Thus, the additional heat transfer through metal wires to the solid fuel can cause to accelerate the chemical reaction leading to the substantial increase in the burning rate of up to several hundred percentages. The hybrid fuel PMMA, however, is a pure polymer-based fuel and the endothermic reaction is dominant for melting and evaporating processes. It is, therefore, obvious that the enhancement of regression rate of hybrid fuel is possible only if a quite larger amount of heat transfer is available enough to overcome the required amount of heat absorption to solid fuel. So, this mechanism can explain why metal wires with larger diameter shows a better performance in increasing regression rate.

Table 2 Summary of test results of embedded metal wires on the increase in the regression rate of PMMA fuel

Wire	diameter mm	regression rate, mm/s	Increase in %
Baseline		0.2704	
Silver	1.5	0.2762	2.14
Silver	1.8	0.2781	2.77
Silver	2.0	0.2808	3.70
Copper	1.6	0.2770	2.38
Copper	2.0	0.2804	3.56

2.3 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 severely confined near the inlet part of fuel because swirl strength diminishes rapidly by viscous interactions with solid fuel surface as it flows downstream. A typical example of combustion with swirl flow in hybrid fuel can be found in reference (Tamura et al., 1999a ; Yuasa et al., 1999 ; 2001). And the burned volume along the axial direction shows a severely biased pattern. So, it is natural to seek a solution to overcome the disadvantage of unbalanced combustion volume of solid fuel by using other applicable options such as swirl generation and secondary oxidizer injection. In the aspect, this study concentrates on the subject to improve swirl effect over the whole length of the port by using the internal helical grain configuration.

Fuel grains with four different helical pitches were used in the experiment. Here, pitch is defined as the distance (in mm) between troughs of helical grain configuration. The pitch numbers of each fuel are of 3, 6, 12, and 18 as seen in Fig. 7. And, it should be noted a helical grain is imposed only over the aft half of fuel port to eliminate swirl effect produced by the oxidizer injection and to examine the effect of helical grain configuration on the combustion enhancement. And the pitch depth was fixed for all tests to simplify the test variables. However, it is not surprising to find that the additional grain configuration may lower the fuel charging efficiency because of additional vacancy by imposed helical groove in the port. Figure 8 shows the comparison of cross sectional view of PMMA fuel port with pitch 6 before and after a 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 obviously 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.

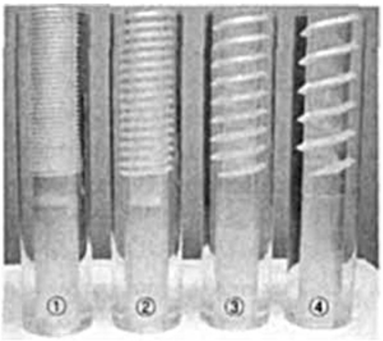


Fig. 7 Helical grain configuration of pitch 3, 6, 12, and 18

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 a combustion test.

As seen in the table 3, all fuels with helical configuration have the similar order of charging efficiency ranging from 98.94% to 99.39%, only 1 or 2% less than baseline case. However, it is found helical grain configuration can increase substantially the burning surface area (A_b) for all fuels ranging from 10% up to 50%. Thus it is expected the increase in surface area can lead nominally to the same order of percentage increase in volume burning rate ($\dot{V}$) enhancement if the regression rate remains unchanged. In other words, as shown in the equation (3), the increase in combustion volume ($\Delta \dot{V}$) is linearly proportional to the increase in burning surface area, if the regression rate ($\dot{r}$) is a specified constant at the given oxidizer flux.

$$\Delta \dot{V} = \Delta A_b \cdot \dot{r} \tag{3}$$

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

Fig. 8 Cross sectional view of solid fuel with pitch 6 before and after combustion test

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^3)	128.067 (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%)

to 35% increase compared to that of baseline case, which is less than surface area (A_b) increase of 50%. And the increase in volume burning rate becomes approximately equal to surface area increase as pitch number increases. So, for example, the difference between volume rate and surface area increase becomes almost negligible 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 ($\dot{V}$) of a fuel with pitch 18 shows only about 1% increase even though the increase in surface area was 10%. This implies other parameters rather than burning surface area are involved in controlling the volume burning rate of the fuel with pitch configuration. One of the possible parameter could be the generation of turbulence caused by helical configuration along axial flow direction. If the turbulence is generated by helical port configuration, turbulence causes the regression rate to be changed corresponding to the turbulence strength. 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. Thus, it is reasonable to summarize the optimal configuration exists for a given oxidizer flux.

Figure 9 summarizes test results of regression rate for fuels with different pitch numbers ranging from 3 to 18. Meanwhile, it is worth reviewing the method for the determination of the regression rate of each case from the measured grain volume. As previously mentioned 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 over 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 the section of "baseline test". Thus, results of regression rate in Fig. 11 were obtained from the calculation with fixed port length (L).

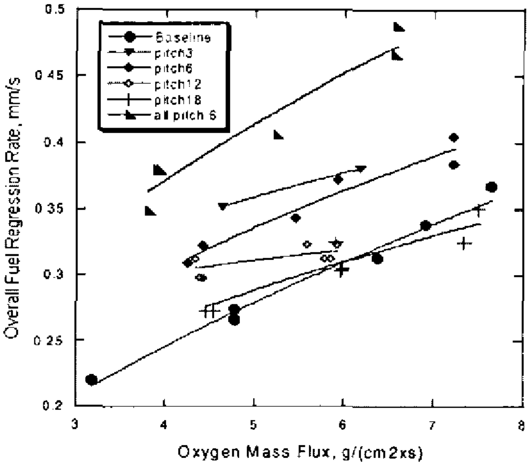


Fig. 9 Regression rates of several test cases for various pitch from 3 to 18

As seen in the figure, pitch number can be one of the major variables because it can change the turbulence level in the flow and affect the regression rate. It is interesting to see that a fuel with pitch 3 has 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 number is effective in increasing the regression rate of the fuel. However, the regression rate of the fuel with pitch 18 was found to be rather less than that of baseline case even though the burning surface area is 9% larger than that of 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. And this assumption needs to be verified by further study.

It is also interesting to observe in Fig. 9 that the overall gradient of regression rate curve 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 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. This means the optimal pitch number in maximizing regression rate exists. At this point, it is worth noting that a fuel designed to have with pitch 6 over the whole fuel port shows more than double increase in regression rate compared to that of a fuel with pitch over only half part. Thus, it can be concluded that the internal grain configuration may induce a swirl flow along the helical groove 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 10 is the picture showing the overall regression rate against pitch number at two different oxidizer mass flow rates of 15 g/s and 20 g/s. As seen in the figure, the optimal pitch number for the max regression rate is clearly located, as expected, at pitch 3 or so for all mass flow conditions. And Fig. 11 compares pressure trajectory of baseline case with those of fuel with various pitches. As seen in the figure, 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 pitch starts from lower pressure level than baseline. Then the pressure gradually recovers and finally the final pressure becomes higher than that of baseline pressure. However, it is interesting to observe the pressure for a fuel with pitch 18 is rather 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 high enough up to over 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 a pitch number as design variable in determining the optimal configuration for the maximum enhancement of regression rate.

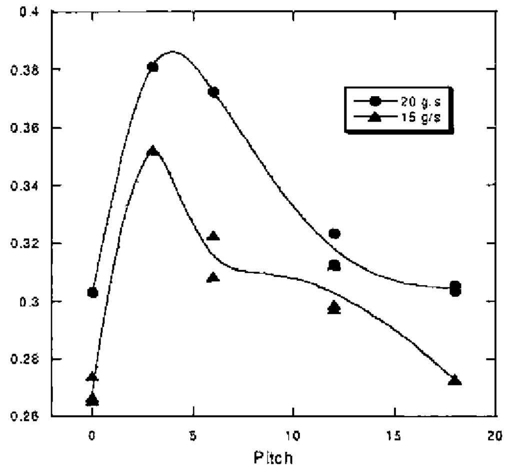


Fig. 10 Regression rate vs. pitch number at two different oxidizer mass flow rates

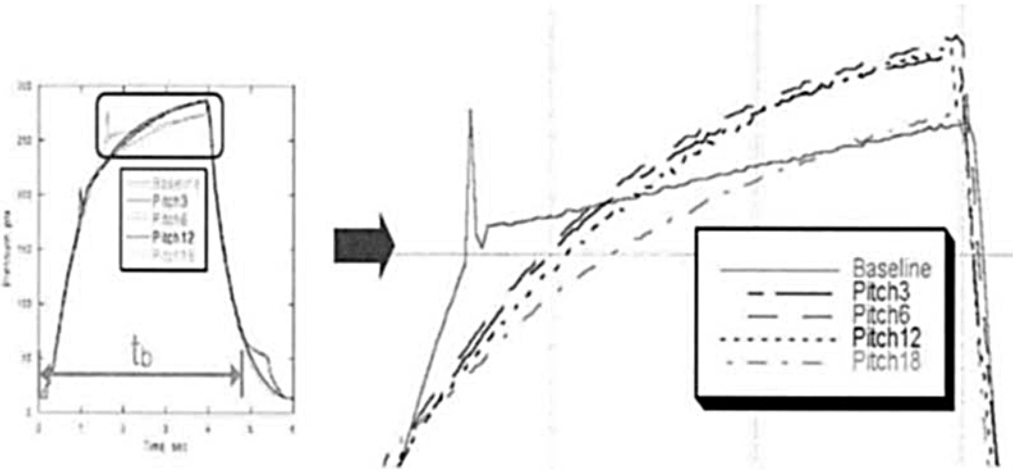


Fig. 11 Optimal pitch number of fuel grain at two different oxidizer mass flow rates

Figure 12 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 important performance index measuring the total amount of thrust during the combustion time and is defined by the integration of thrust over combustion time as

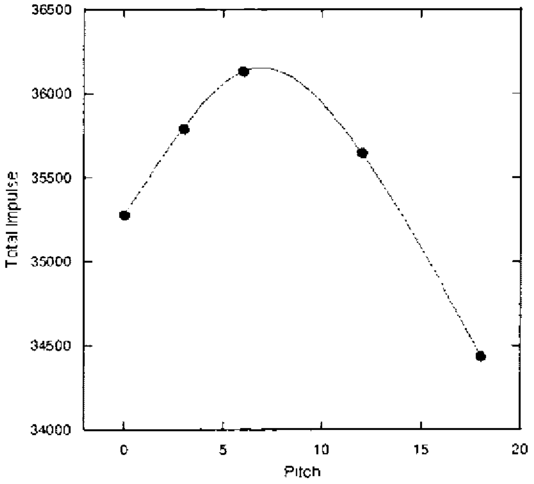
$$I_{tot}=\int F\,dt\cong\int p\,dt \qquad (4)$$

Even though the integration with pressure curve instead of thrust does not produce a physically correct dimension of total impulse, it will provide physical information which case shows the best impulse performance. Integration was done from the initial time t_0 to burnout time t_b. As shown in the figure, results show very interesting feature of dependence of total impulse on the pitch number. Total impulse has the maximum value of 36133 at pitch 6, which is equivalent to 2.4% increase compared to that of baseline. However, a fuel with pitch 3 shows only 1.5% increases in total impulse although the maximum increase in regression rate was observed in a fuel with pitch 3 among test cases. Figure 12 reveals the maximum total impulse is located around pitch 6 or 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 helical 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.

2.4 Summary and conclusion

This study aims to assess the effectiveness of various methods on the increase in the regression rate of hybrid rocket fuel, PMMA. Embedded metal wires and a helical fuel port grain configuration were experimentally tested. For metal wire method, two different metal wires such as silver and copper were used. Test results, however, showed only up to 3% increase in regression rate for all metal wires regardless of wire diameters and material types. The amount of increase in regression rate with metal wires is negligibly small when it is compared to that observed in solid propellant, which is in the order of several hundred percentage increase.

For the method with internal port grain configuration, a helical grain configuration can be an effective method to enhance the regression



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

Fig. 12 Pitch number vs. total impulse of a fuel with different pitch numbers

rate by simply increasing the burning surface area and resulting volume burning rate. Moreover, this internal grain configuration does sacrifice the charging volume with an acceptable level up to 1~2%. 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 observe that a fuel with pitch 6 has the maximum total impulse. 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.

Acknowledgments

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