AIAA 81-1207R

Combustion Processes of Propellants with Embedded Metal Wires

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Research was made with double-base propellants with embedded metal wires to understand how the burning rate changes along the silver wire and to obtain what factors control the burning rate of the propellants. The burning rate along the wire is influenced greatly by the kind of metal wire, wire size, and propellant compositions. With double-base propellants having varied burning characteristics, burning rate along the silver wire was measured and the effects of the luminous flame, dark zone, and the fizz zone were studied. By means of microthermocouples, the temperature profiles in the propellant near the silver wire were measured. Based on the test results, it was clear that the factors which control the burning rate along the silver wire are the temperature gradient in the fizz zone and the temperature in the dark zone. The luminous flame zone that stands above the burning surface affects neither the burning rate of the propellant nor the burning rate along the silver wire.

I. Introduction

THE desirable characteristics of solid propellant include higher specific impulse, reduced temperature sensitivity of burning rate, and smokeless combustion products. Recent research in propellant combustion technology has been conducted to achieve these requirements by the addition of lead compounds and nitramine particles within double-base propellants. However, double-base propellants still have a zone between the thrust and the burning rate that, from the aspect of burning rate and burning area of propellant grain in a rocket motor, is not attainable.[1] Thus, it is necessary to expand the burning rate regime by making the propellant burning rate extremely high or low. The research to augment the burning rate, reported in this paper, employed propellant with embedded metal wires (mainly silver wires) to increase the heat transfer to the unburned part of the propellant and to augment the burning rate.

Propellant with embedded metal wires is divided in two types.[2] One type has the fine wires scattered at random in the propellant. The other uses a long metal wire embedded along the burning direction of the propellant grain. The second method is applied to end-burning-type rocket motors.

The second method was employed in the test reported here. Tests were done to see the effect on the burning rate along the embedded silver wire. Silver wires of various diameters and wires of different materials were used to determine what factors in the combustion wave of propellant burning would control the burning rate. A double-base propellant was chosen as a reference sample. The reference sample was specially formulated so as to be transparent. This sample made it possible to observe how the burning surface regresses along the metal wire.

Presented as Paper 80-1207 at the AIAA/SAE/ASME 16th Joint Propulsion Conference, Hartford, Conn., June 30-July 2, 1980; submitted Sept. 12, 1980; revision received July 1, 1981.

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II. Experimental

Several types of propellants were made in order to understand the mechanism of the augmentation of the burning rate along the metal wires. The detailed propellant compositions used in this study are shown in Table 1. The sizes of the propellant samples used were 7×7 mm in the cross-sectional area and length ranged from 70 to 140 mm. For the ignition of the propellant samples, an electrically heated nichrome wire was used.

Observation of Burning Surface Structure

A chimney-type strand burner, that has four transparent qualtz windows mounted on the side of the burner, was used to observe the burning processes of the propellant samples. The burner was pressurized with nitrogen gas. A motor drive 35-mm camera (5 frames/s) with a close-up lens and a 16-mm high-speed camera (2000 frames/s) were used to take photographs of the burning surface structure of the propellants with the embedded metal wires.

For observation of the burning surface structures, propellant samples of three types were prepared. Sample I was propellant with a silver wire embedded in its center, so as to observe how the silver wire would change a flat burning surface. Sample II was prepared to observe the flow of the burned gas around the silver wire, which could not be observed from the photographs of sample I. Sample III was prepared with various metal wires each embedded in one side of the propellant surface. These three types of the samples

Table 1 Propellant compositions

Propellant	NC[a]	NG[b]	DEP[c]	EC[d]	AP[e]	Ni[f]
1	44.0	43.0	11.0	2.0	–	–
2	42.0	41.0	10.0	1.9	5.0	–
3	39.6	38.7	9.9	1.8	10.0	–
4	35.2	34.4	8.8	1.6	20.0	–
5	51.8	36.5	9.7	–	–	–
6	50.7	35.8	9.5	–	–	2.0
7	25.3	65.0	9.7	–	–	–

[a]Nitrocellulose. [b]Nitroglycerin. [c]Diethylphthalate. [d]Ethyl centralite. [e]Ammonium perchlorate (200 μm in diameter). [f]Nickle (0.5 μm in diameter).

were made with propellant of high transparency to enable photographic observation of the propellant during burning.

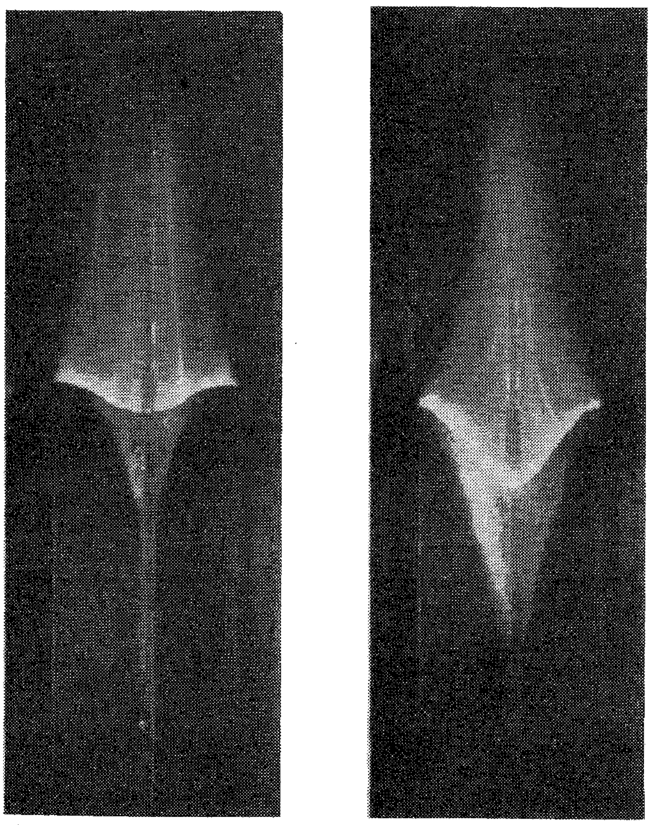
Temperature Profile Measurements

Temperature profiles of the silver wire and the propellant around the silver wire were measured using Pt-PtRh 13% thermocouples (wire size was 50 μm or 12.5 μm in diameter) embedded along the silver wire and in the propellant around the silver wire. The samples used to measure the propellant temperature around the silver wire were made in the following manner. Sample I of the strand-size was cut into two equal parts along the burning direction. One part had embedded silver wire. A thermocouple was embedded along with the silver wire in one of the parts. Then, the two parts were put together again with acetone. The sample was kept in an electric furnace at 40°C for 72 h to ensure there was no electric conduction between the silver wire and the thermocouple.

The procedure for making the sample to measure the temperature of the silver wire was the same as that for the sample to measure the propellant temperature around the silver wire, except the thermocouple consisted of the silver wire (original wire for burning rate augmentation) and a platinum wire. The platinum wire (50-μm diam) was welded to the silver wire before it was embedded in the propellant sample to augment the burning rate. Thus the temperature was measured by the thermoelectricity generated by the silver wire and the platinum wire during propellant burning.

Burning Rate Measurements

The burning rate was measured by means of a fuse-wire method in a chimney-type strand burner. The pressure in the burner ranged from 5 to 110 atm. Nitrogen was used to pressurize the strand burner. The samples used to measure the burning rate were made in the following manner. Propellant samples of strand size 7×7×140 mm were cut into two equal parts parallel to the burning direction. Three pieces of fuse-wires (0.2-mm diam) were placed on the half containing embedded silver wire. The two parts were put together again with acetone. Then, it was kept in an electric furnace at 40°C for 72 h to remove the acetone from the sample and to homogenize the propellant. These fuse-wires were placed 3 cm apart and perpendicular to the silver wire.



a) b)

Fig. 1 Cone shaped burning surfaces around a silver wire; combustion of propellant 1 with embedded 0.8-mm diam silver wire, a) 0.8 s after ignition and b) 1.2 s after ignition.

III. Experimental Results and Discussion

Burning Surface Structure

Figure 1 shows burning surfaces of a propellant strand with embedded silver wire. The burning surface makes a cone shape, rather than a common flat burning surface, around the silver wire, and the combustion progresses rapidly along the wire. To observe the burned gas flow which was not visible in the tests of sample I, the burning surface of sample II, with an embedded silver plate instead of a silver wire, was photographed. The burned gas flowed vertically from the burning surface, turned when it came close to the metal plate, and flowed downstream almost parallel with the metal plate. Therefore, the heat transfer from the burned gas to the metal plate or metal wire must play a significant role in augmenting the burning rate of the propellant.

Figure 2 shows successive regressing burning surfaces of various metal wires embedded in sample III. Pictures were obtained with high-speed microphotographs. When the samples were ignited at the top, the burning surfaces were flat and the burning rates were approximately identical for all the samples shown in Fig. 2. However, a significant burning-rate difference along the wire was seen among the samples as the burning progressed. The burning surface makes a cone shape with the metal wire as its axis. The burning rate perpendicular to the burning surface changes little while the burning rate along the metal wire becomes larger as burning progresses. Therefore, it is evident that the effect of the metal wire is only on the thin layer of the propellant around the metal wire. The cone angle of the burning surface around the metal wire is large at first, but gradually becomes smaller as burning progresses. A larger burning surface transition rate is obtained with a finer silver wire. Furthermore, the burning surface transition rates caused by silver, copper, and iron become larger according to the thermal diffusivity of the metal wire. The thermal diffusivity of silver, copper, and iron are 0.595, 0.370, and 0.064 (m^2/h), respectively. These results are consistent with the results obtained by Caveny et al.[2]

Burning Rate Measurements

Based on the results of the burning surface observations, it was clear that the metal wire only affects the burning rate of the propellant around it and that the part of the propellant a

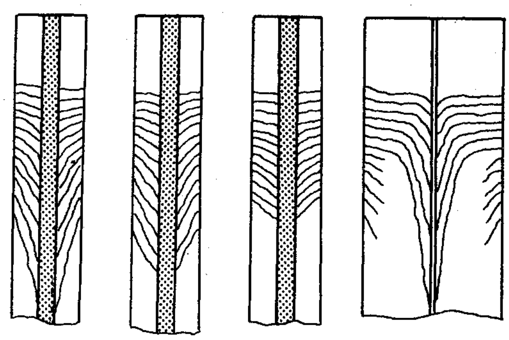


Fig. 2 Burning surface transition rates varied by metal wires; each line interval indicates 0.2 s.

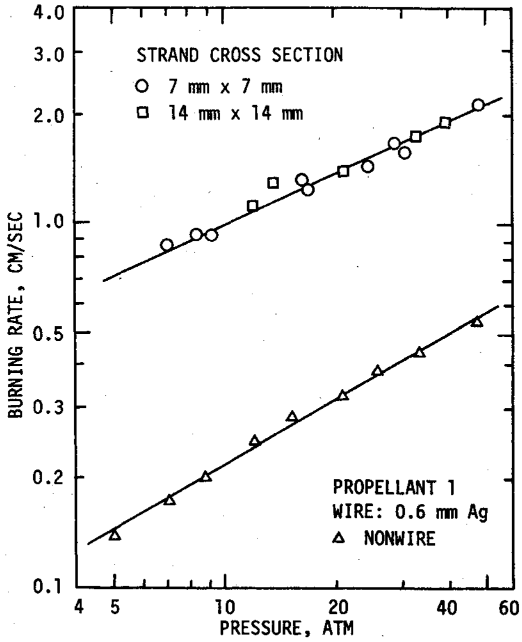


Fig. 3 Size effect on strand samples showing no clear dependence on the size of the sample.

little distance from the wire burns with its normal propellant burning rate. Therefore, the measurements of the burning rate were performed only along the metal wire, r_w.

Since r_w is given as a result of the heat transfer by the metal wire, experiments were conducted first to determine the effects of the size of the strand sample used in this study on r_w. Figure 3 shows the measurement results of the size effect of propellant strand on r_w. On two strand samples with embedded silver wire, whose cross sections were 7×7 mm and 14×14 mm, respectively, the obtained r_w did not show a clear difference. This indicates that there was no size effect of the strand within the sizes tested in this study. Therefore, mainly the strand samples of 7×7-mm cross section were used to measure r_w in this study. It is important to note that the effect of the heat transfer from the silver wire to the propellant occurs adjacent to the silver wire.

A test was performed to determine the propellant length that is required for the r_w to reach a steady-state value within the pressure range between 6 and 50 atm. This test was performed to determine where the fuse wire should be set to measure the transient and steady-state burning rates. Propellant strands with embedded 2.0-mm silver wire and with 2.0-mm iron wire were prepared. Figure 4 shows that the r_w reached a steady-state value at approximately 3 cm from the top of the strand for both the silver wire and the iron wire. Thus, the fuse wires were positioned further than 3 cm from the ignition point of the strand and r_w was measured.

Figure 5 shows the relation between r_w, various metal wires, and the burning pressure. The results obtained in this study agreed with the results obtained by Caveny et al.[2] The larger the thermal diffusivity of the metal wire, the higher the r_w is. However, the results obtained from three kinds of metal wires did not confirm the results reported previously. The r_w was not always higher according to the melting point of the metal wire.

The transient r_w from ignition to steady state was also determined. As shown in Fig. 4, the r_w increased gradually along the strand length until a steady state was reached. This result is different from that of Caveny et al.[2] who reported the r_w overshot on the earlier stage of combustion, and then calmed down to a steady-state value.

Variation of r_w by the Size of Silver Wire

Figure 6 shows a variation of the r_w/r_0 by wire size at 40 atm. The burning rate with no embedded wire is denoted by r_0. As the wire size decreases, the r_w/r_0 increases when the wire size is larger than d_c. However, the r_w/r_0 decreases when the wire size is smaller than d_c. Thus, the r_w/r_0 becomes a maximum when the wire size is d_c. In this experiment, a very fine silver wire (5-μm or 50-μm diam) was embedded in propellant 4 strand. However, no cone shaped burning surface along the silver wire was seen. Thus, the results indicate that r_w becomes smaller when the size of the embedded wire becomes smaller than a certain value, d_c. This agrees with the results reported by Summerfield et al.[3] which qualitatively explain the relationship between r_w and wire size.

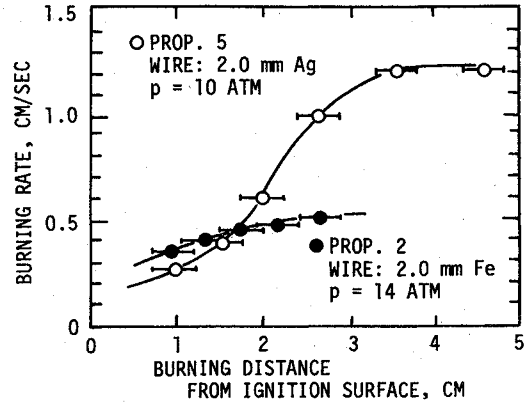


Fig. 4 Variation of r_w by strand length.

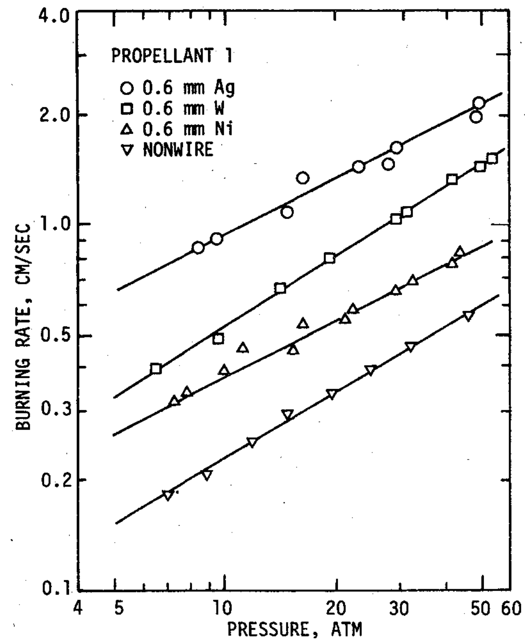


Fig. 5 Variation of r_w by different kinds of metal wires.

Temperature Profiles of Propellant and Silver Wire

The temperature profiles of the propellant around the silver wire were measured to observe whether the silver wire affects the propellant around it. Figure 7 shows typical results of the measurements. The temperature increased smoothly from the initial temperature of the propellant to the temperature in the gas phase. Since the temperature at the burning surface of double-base propellants is approximately 300°C,[4] it was found that the temperature starts to rise at about 20 mm below the burning surface of the propellant with the embedded silver wire, while the temperature of the propellant without the wire starts to rise at about 1 mm below the burning surface. Based on this, it is clear that the propellant deep inside below the burning surface is heated by the silver wire through thermal conduction.

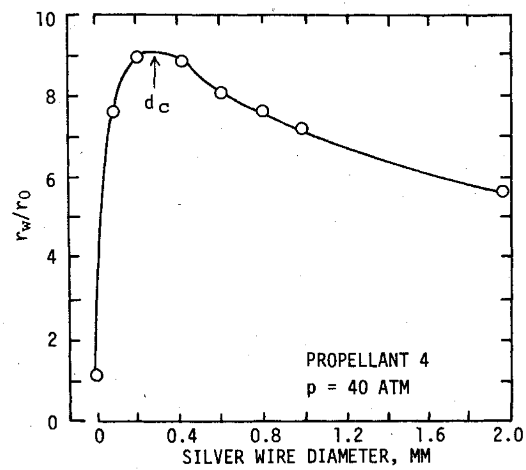


Fig. 6 Variation of r_w by wire size; r_w is the burning rate along the silver wire and r_0 the burning rate without silver wire.

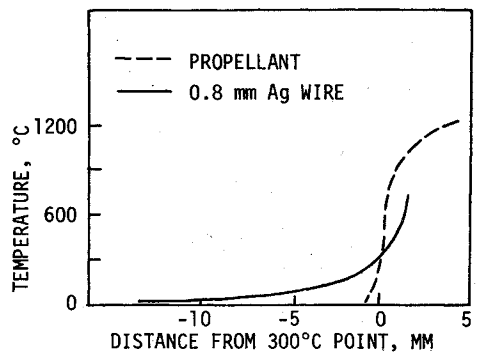


Fig. 7 Temperature profiles of propellant and silver wire; propellant 1 at 21 atm.

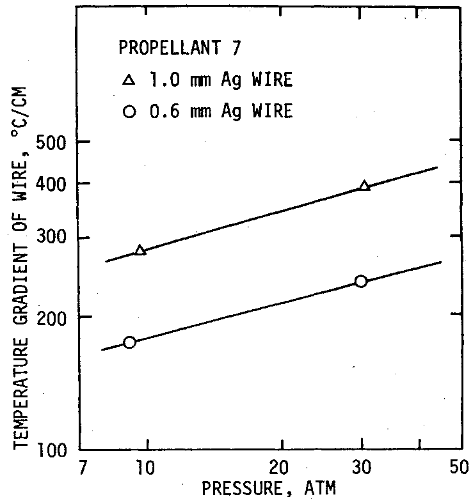


Fig. 8 Temperature gradient of wire vs pressure.

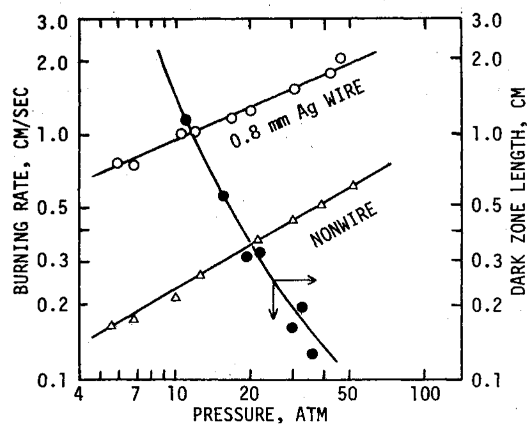


Fig. 9 Influence on r_w by the luminous flame zone of propellant 1.

The observations of the burning surfaces made it clear that an embedded silver wire changes the burning rate of the propellant only nearby. The thermal influence of an embedded silver wire does not reach further than 70-100 μm around the wire.[2] Therefore, it is considered that the increased burning rate around the wire is just the same as the burning rate by the increased initial temperature of the propellant.

The temperature gradient of the silver wire inside the propellant at the burning surface was measured. As shown in Fig. 8, the temperature gradient decreased when the wire size was decreased from 1.0 to 0.6 mm. This indicates that the heat penetrates deeper inside the propellant through the wire as the wire size becomes smaller. Thus, the temperature of the propellant around the wire increases. It is important to note that the temperature gradient of the wire inside the propellant at the burning surface is significantly lower than the temperature gradient of the propellant at the burning surface.

Effect of Gas Phase Structure on r_w

Since the burning rate of a propellant depends on the heat transferred back from the gas phase to the burning surface of the propellant, r_w of the propellant with an embedded silver wire is determined by how much heat is transferred by the silver wire to the unburned portion of the propellant around the wire. Figure 7 makes it clear that the propellant around the embedded silver wire is heated by the wire. Thus, the heat needed to heat the propellant must be transferred by the silver wire that is protruding into the gas phase. Therefore, it is important to determine the heat transfer mechanism from the gas phase to the silver wire.

The combustion wave structure of double-base propellants consists of successive reaction zones: subsurface reaction, fizz, dark, and luminous flame zones. The luminous flame zone appears some distance above the burning surface. The flame standoff distance increases with decreasing pressure, and the flame disappears completely below 7 atm.[4,5] Although the temperature reaches the maximum in the luminous flame zone, the luminous flame does not play a dominant role in controlling the burning rate.[5,6] The temperature gradient in the fizz zone just above the burning surface dominates the heat feedback from the gas phase to the burning surface. Thus, the burning rate of double-base propellants is determined by the reaction in the fizz zone.[5,6]

In this section, the effect of the luminous flame zone on r_w is discussed using propellants that have various gas phase characteristics. Figure 9 shows the influence on r_w by the luminous flame zone. The dark zone on propellant 1 has become shorter as the burning pressure becomes higher, and its length has become about the same as the diameter of the silver wire used in this test at 50 atm. When the pressure is 8 atm or lower, there is no luminous flame zone, just fizz burning. Even when the pressure of the propellant with embedded silver wire is so low that there appears to be no existence of a luminous flame, the value of r_w is at least four times that of the burning rate, r_0, which is obtained from the propellant with no embedded silver wire. The r_w obtained when the pressure is in the region where a luminous flame zone appears, is also four times that of r_0. The r_w, obtained when the pressure is in or out of the region where the luminous flame zone appears, are plotted approximately on a straight line on the log (pressure) vs log (burning rate).

Propellants of two different types in the dark zone structure were chosen in order to determine the effect of dark zone on r_w. As shown in Fig. 10, the luminous flame standoff distances on the two propellants differ significantly. On

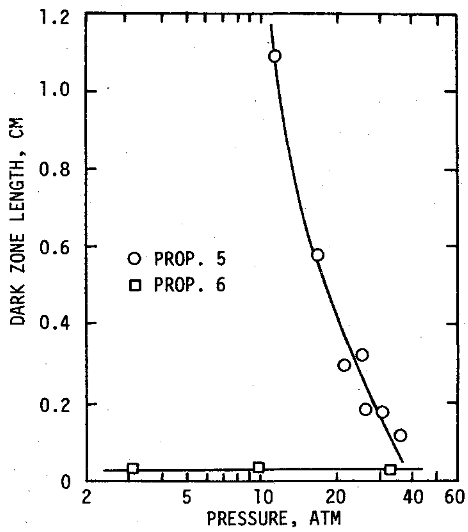


Fig. 10 Dark zone length vs pressure showing that the addition of Ni decreases the length and the luminous flame approaches the burning surface at low pressure.

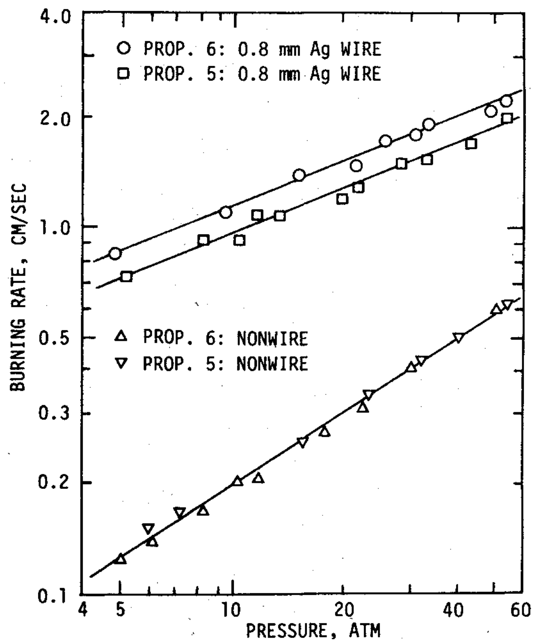


Fig. 11 Effect of luminous flame zone on r_w.

propellant 6, the luminous flame zone appears very close to the burning surface, when the pressure is 1 atm or more, and the distance changes little by pressure or by the burning rate. On propellant 5, there is no luminous flame zone when the pressure is 7 atm or lower, and when the pressure becomes higher, the luminous flame zone appears at a distance from the burning surface and comes closer to the burning surface. Therefore, if the luminous flame zone is one of the factors that has a decisive influence on r_w, the r_w of propellant 6 must be larger than that of propellant 5 because the luminous flame zone of propellant 6 stands much closer to the burning surface. As shown in Fig. 11, the r_w of both propellants increased significantly at low and high pressure regions. However, little difference in r_w between propellants 5 and 6 was observed. The r_w of propellant 6 was slightly higher than that of propellant 5. It is considered that the luminous flame zone of propellant 6 contributes more toward increasing the rate of heat transfer from the gas phase to the silver wire than that of propellant 5. Consequently, the burning rate of propellant 6 increases more than that of propellant 5. However, the augmented burning rate of propellant 6 was not large,

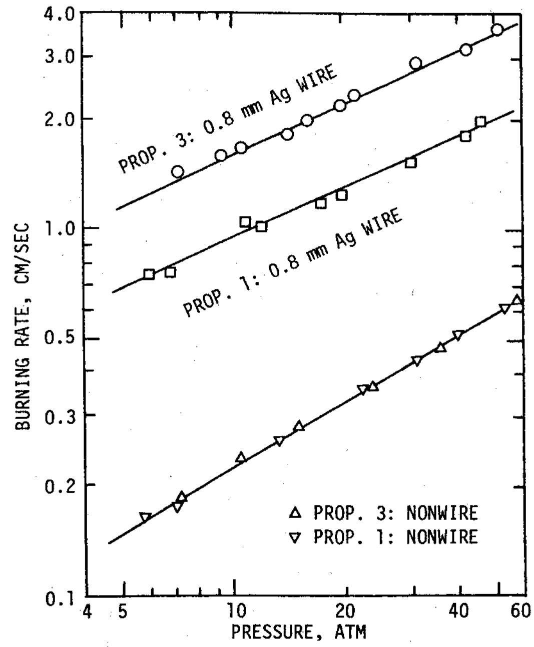


Fig. 12 Difference of r_w obtained with propellants having different dark zone characteristics.

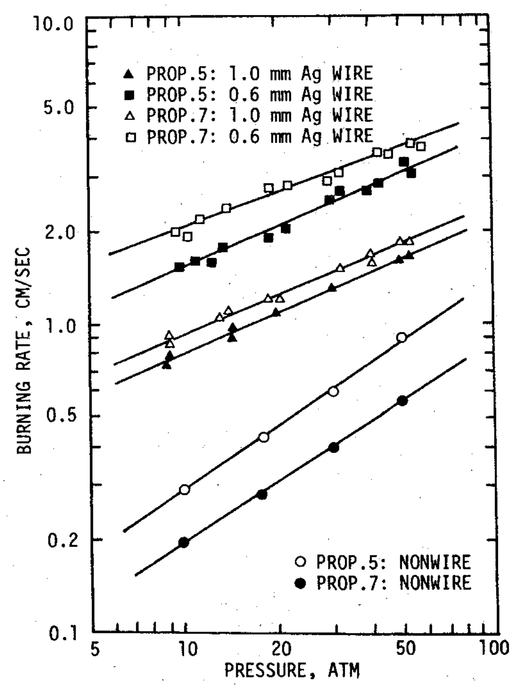


Fig. 13 Effect of propellant burning rate on r_w.

although the luminous flame zone approached the burning surface. Thus, it was found that the r_w is dominated by the reaction zone where it is much closer to the burning surface than the luminous flame zone.

A result similar to that just described was obtained when the dark zone structures were different. Since propellant 3 contains 10% of ammonium perchlorate (200-μm diam), the flame structure of propellant 3 becomes different from that of propellant 1. Based on the combustion flame model proposed by Kubota and Masamoto,[7] the dark zone temperature of propellant 3 is considered to be increased by the addition of the ammonium perchlorate, caused by the diffusion flame produced by the ammonium perchlorate monopropellant flame and the decomposition flame of the double-base propellant. However, the fizz zone reaction just above the burning surface may not be affected by the addition of the

10% of ammonium perchlorate.[7] Consequently, the burning rate of propellant 3 appeared to be approximately the same as that of propellant 1. Measurement results are shown in Fig. 12.

However, when silver wires (0.8-mm diam) were embedded in both propellants, a significant burning rate difference was observed, as shown in Fig. 12. The r_w of propellant 3 was increased by the addition of ammonium perchlorate. This result indicates that the r_w largely is dependent on the temperature in the dark zone.

To determine the effect of fizz zone on r_w, two different types of propellants were prepared. Propellant 7 contains more nitroglycerin than that of propellant 5. Therefore, the temperature gradient in the fizz zone and the temperature in the dark zone are larger than those of propellant 5.[8] Consequently, the burning rate of propellant 7 is higher than that of propellant 5, as shown in Fig. 13. The results of the measurements of r_w showed that the r_w of propellant 7 for 0.6- or 1.0-mm-diam embedded silver wire was higher than the r_w of propellant 5 for the same embedded wire diameter. It is evident that the r_w is largely dependent on the temperatures in the fizz and dark zones.

IV. Conclusions

The burning rate along the metal wire, r_w, is dependent largely on the kind of wire, wire size, and propellant flame structure. The r_w is controlled by the temperature profile in the fizz and dark zones. The luminous flame zone that stands above the burning surface does not affect the r_w even though the temperature reaches the maximum in the luminous flame zone. When the temperature gradient in the fizz zone or the temperature in the dark zone is increased, the heat flux from the gas phase to the metal wire increases.

The heat transferred from the gas phase to the metal wire penetrates deep inside of the propellant along the wire. For example, the propellant temperature around a silver wire starts to rise at about 20 mm below the burning surface, while the temperature of the propellant without the embedded wire starts to rise at about 1 mm below the burning surface. Thus, the propellant around the wire ignites rapidly and the burning rate along the wire appears to be increased significantly.

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