Influence of Mg and Si content on infrared radiation performance of AP/HTPB system in each band

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Abstract. The limited effort in this paper is focused on studying the effects of different contents of high-energy additives on infrared radiation performance of AP/HTPB systems in each band. A Spectraline SC7000 imaging spectrometer was used to test the radiation performance of each band. The test results show that when the magnesium (Mg) content increases from 0 to 30%, the near-infrared radiation intensity is greatly increased. The near-infrared radiation energy increases from 19 to 125W/Sr by 558%, the mid-infrared radiation energy increases from 32 to 85W/Sr by 166%, and the far-infrared radiation energy increased from 9.4 to 12.8W/Sr by 36%. The ratio of θα/β/λ changed from 0.59:1:0.29 to 1.47:1:0.15. The increase of silicon (Si) content from 0 to 30% has a great contribution to the increase of the radiation intensity in the far-infrared band. The intensity of near-infrared radiation increased from 19 to 97W/Sr by 411%, the energy of mid-infrared radiation increased from 32 to 64W/Sr by 82%, and the energy of far-infrared radiation increased from 9.4 to 40W/Sr by 326%. The ratio of θα/β/λ has changed from 0.59:1:0.29 to 1.52:1:0.63.

1. Introduction
With the development of optoelectronic countermeasures technology, modern national defense has put forward higher requirements for decoy agents [1-3]. The decoy agent not only be required to maintain a near-mid-far infrared spectral distribution (0.6:1:0.25) that matches the target [4-5], but also be expected to provide a stable thrust for the steering device [6-7]. Therefore, the concept of propulsion bait is proposed. AP/HTPB composition is widely used in solid propellants for its stable combustion and large specific impulse[8-9]. In view of the fact that the combustion product CO2 has a high emissivity at 4.38μm in the mid-infrared, the overall infrared spectrum of AP/HTPB is characterized by low near-far infrared and high mid-infrared[10]. In order to enhance the infrared radiation performance and improve the near-mid infrared radiation ratio of AP/HTPB agent, the international researchers have made a lot of effort, mainly focused on adding a high-energy combustible or a burning rate catalyst.[11 -14]. Nielson[15] tried to add magnesium to partly replace Ammonium Perchlorate(AP) in the AP/HTPB system and obtained a better near-to-mid infrared ratio(θα/β) close to that of aircraft when the Mg content was 22%.

As we known that Si is a very old material and has been used as a high-energy combustible in pyrotechnics for a few years traced back to 1950s. The combustion product of silicon has a high emissivity in the far infrared during the formation of silicon dioxide, which is expected to increase the far infrared radiation intensity of the agent. However, researchers have found that the oxidation of Si is greatly affected by the oxygen content in the system. When in the anaerobic system, Si is more present as a reaction catalyst without an energy provider, which leads to a waste of energy. For example, in Silicon/Teflon/viton (SiTV) and Silicon/magnesium/Teflon/viton (Si/MTV) [16-17] systems, Si will not
be oxidized to form SiO2 and SiF2, but exists as Si and SiC. On the contrary, in negative oxygen systems such as Silicon/AntimonyOxide/Potassium Nitrate(Si/Sb2O3/KNO3), Silicon/Iron Oxide/Tin Oxide (Si/Fe2O3/SnO2)[18-20]. Si will be oxidized to silica (SiO2) and increase the far infrared radiation energy. In view of the oxygen dependence of Si, in this experiment, the zero oxygen balance formula with an AP/HTPB ratio of 79/13 was used as the basic formula. With the gradually increase of the content of silicon and magnesium, the influence of the content of which on the radiation performance of the agent in each band was studied.

2. Experimental Section

2.1. Preparation of pyrotechnic powder
Zero oxygen balance formula of AP/HTPB/TDI/DOS/TPB(mass ratio 79/13/5/2/1) was chose as the basic formula. The experimental formula is shown in Table 1, and the sample preparation flow chart is shown in Figure 1. AP (Nanjing Jiaoziteng Chemical Company, 100mesh, 99%purity), HTPB (Tianyuan Chemical Group, mass fraction $\geq 97.5\%$), TPB (Shanghai Merrill Group, 100 mesh, 99% purity), TDI (Shanghai Jiujiang Group, 100-120 mesh, 99% purity), DOS (Beijing Sinopharm Group, 100-120 mesh, 99% purity), Mg (Beijing Sinopharm Group, 200-300 mesh, 99% purity), Si (Beijing Sinopharm Group, 100-120 mesh, 99% purity).

| Table 1 | Summary of pharmaceutical formulations. |
|---------|-----------------------------------------|
|         | AP (mass %) | HTPB (mass %) | DOS (mass %) | TDI (mass %) | TPB (mass %) | Addition |
| Blank   | 79          | 13           | 5            | 3            | 1            | 0        |
| Si-1    | 69          | 13           | 5            | 3            | 1            | 10% Si   |
| Si-2    | 59          | 13           | 5            | 3            | 1            | 20% Si   |
| Si-3    | 49          | 13           | 5            | 3            | 1            | 30% Si   |
| Mg-1    | 69          | 13           | 5            | 3            | 1            | 10% Mg   |
| Mg-2    | 59          | 13           | 5            | 3            | 1            | 20% Mg   |
| Mg-3    | 49          | 13           | 5            | 3            | 1            | 30% Mg   |

![Figure 1](image_url) The preparation process of samples.
2.2. Experimental test
A Spectraline SC7000 imaging spectrometer was used to test the radiation performance of each band. The combustion tower has a horizontal diameter of 0.6m and a height of 1m. After the pellets were completely burned, the exhaust fan was turned on to smoke out to prevent the effect of the instrument's test. The response band range of the spectral radiometer (Spectraline SC7000 imaging spectrometer) is 1.28μm-13.88μm and the field angle is 4.7o. The test distance was 14m and the test frequency was 25Hz. DY-HT4 high temperature black body (800-1600℃) was used to calibrate the spectrometer and radiant intensity in different bands. The calibration temperature is 1000℃, the light source is full of the instrument's field of view calibration, and the calibration curve has stable fluctuations.

3. Result and Discussion
The spectral radiant intensity curves of agents with different contents of magnesium and silicon in each band are shown in Fig. 2. The summary of the radiation intensity of compositions at each band and the mass burning rate are listed in Table 2.

It can be seen from Fig. 2 that for Mg-containing compositions, the characteristic peaks of the infrared spectrogram changed very little. But as the Mg content increased from 0 to 30%, it can be seen that the heat radiation energy, especially the energy of near-infrared heat radiation was greatly improved. This is because Mg combustion released a large amount of energy, which greatly increased the combustion temperature of the agent, thereby increasing the heat radiation energy. In addition, the combustion of Mg would produce Magnesium oxide (MgO), which has a higher emissivity than the gaseous products of the AP/HTPB system, which also contributed to the increase of heat radiation. As for Si-containing compositions, with the increase of Si content, selective infrared radiation peaks appeared at 8-10 μm in the far-infrared band. This is because the combustion of Si would produce silicon dioxide (SiO2), which has high emissivity in far infrared. In addition, it can be seen that the heat radiation energy had a more obvious increase than the selective absorption peak of CO2 in the mid-infrared band. This is because as the Si content increased, the combustion time is prolonged and the mid-infrared band absorption peak decreased with the less CO2 mass produced per unit time. While the heat radiation energy still increased without effected, which made heat radiation the decisive factor.

With the Mg content increased from 0 to 30%, the burning time reduced from 9.8s to 8.2s, and the mass burning rate increased from 0.51g/s to 0.61g/s. The near-infrared radiation energy increased from 19W/Sr to 125W/Sr by 558%, the mid-infrared radiation energy increased from 32W/Sr to 85W/Sr by 166%, and the far-infrared radiation energy increased from 9.4W/Sr to 12.8W/Sr by 36%. The intensity of near-infrared radiation increased much greater than that in the mid-infrared and far-infrared bands for the energy mainly provided by heat radiation energy. It is widely known that heat radiation follows Planck's law, then the wavelength shift to the shortwave direction as the temperature increases and the ratio of θα/β/λ changed from 0.59:1:0.29 to 1.47:1:0.15.

With the Si content increased from 0 to 30%, the burning time increased from 9.8s to 11.5s, and the mass burning rate decreased from 0.51g/s to 0.43g/s. This is because the ignition temperature of Si is as high as 1400℃, and the combustion of Si requires a process of surface liquefaction, resulting in the burning time prolonged. Secondly, it can be seen that the intensity of near-infrared radiation increased from 19W/Sr to 97W/Sr by 411%, the energy of mid-infrared radiation increased from 32W/Sr to 64W/Sr by 82%, and the energy of far-infrared radiation increased from 9.4W/Sr to 40W/Sr by 326%. The addition of Si has significantly improved the far-infrared radiation. This is because the combustion product SiO2 has a high emissivity in the far-infrared, and the θα/β/λ ratio changed from 0.59:1:0.29 to 1.52:1:0.63. It can be seen that Mg increases heat radiation more than Si in the near-mid-infrared band. On the one hand, the combustion of Mg can provide more heat radiation. On the other hand, the increases of mass burning rate lead to the increase of the radiation intensity per unit time. The increase in infrared radiation of Si in the far-infrared band is higher than that of Mg, because the combustion product SiO2 have a high emissivity in the far-infrared radiation band.

In summary, the addition of high-energy additives such as Mg and Si can greatly increase the radiation energy of AP/HTPB. But it’s still insufficient only relying on the AP/HTPB system to improve
the spectral distribution of bait agents. The addition of high-energy additives will greatly increase the heat radiation energy, but the energy of CO2 selective radiation is not significantly increased. When the heat radiation energy far exceeds the CO2 selective radiation peak, it is inevitable that the near-infrared radiation energy is much higher than the mid-infrared and far-infrared radiation energy.

![Figure 2](image)

**Figure.2** Spectral radiant intensity curves of agents with different contents of magnesium and silicon.

**Table 2** Summary of the radiation intensity of compositions at each band and the mass burning rate.

| Sample | α(1.28-3μm) | β(3-5μm) | λ (8-14μm) | βα/βλ | T/ s | Vm / g·s⁻¹ |
|--------|-------------|---------|-------------|-------|-----|-----------|
| Sample | 19          | 32      | 9.4         | 0.59:1:0.629 | 9.8  | 0.51  |
| Mg-1   | 35          | 48      | 10          | 0.73:1:0.21 | 9.2  | 0.54  |
| Mg-2   | 90          | 72      | 9.5         | 1.25:1:0.13 | 8.8  | 0.57  |
| Mg-3   | 125         | 85      | 12.8        | 1.47:1:0.15 | 8.2  | 0.61  |
| Si-1   | 26          | 44      | 17.9        | 0.59:1:0.41 | 10.3 | 0.49  |
| Si-2   | 75          | 62      | 33          | 1.21:1:0.53 | 11.2 | 0.45  |
| Si-3   | 97          | 64      | 40          | 1.52:1:0.63 | 11.5 | 0.43  |

**4. Conclusion**

(1) The addition of Mg and Si will greatly increase the radiation energy of AP/HTPB agent. The addition of Mg makes a large amount of heat radiation during combustion and increases the radiation energy in the near and mid infrared bands. The addition of Si helps to improve the spectrum of the AP/HTPB-based composition by increasing the 8-14μm radiation intensity.

(2) The addition of Mg will increase the burning rate of the agent and reduce the burning time for the reason that the combustion of the agent increases the combustion temperature and accelerates the...
reaction. The addition of Si will reduce the mass burning rate and increase the burning time. This is because the ignition temperature of Si is as high as 1400°C, and the combustion of Si requires a process of surface liquefaction, resulting in the burning time prolonged.

(3) The experimental results show that Mg increases infrared radiation more than Si in the near-mid-infrared band, and the increase of Si infrared radiation in the far-infrared band is higher than that of Mg. The research provided ideas for the design of thrust decoys and made practical tests, but only relying on the AP/HTPB system to improve the spectral distribution of bait agents is still insufficient.

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