OBSCURANT AND EMISSION CHARACTERISTICS OF THE SCREENING SMOKE COMPOSITIONS USED IN NAVAL SHIPS

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Abstract: *Obscurant and optronic decoy compositions are the pyrotechnic formulations that are an effective way to protect naval ships from optical guided missile seekers. In this work, the obscurant characteristics (i.e. the transmittance and the extinction coefficient) and the infrared emission characteristics (i.e. the infrared emission distribution and the radiance) of the obscurant and optronic decoy compositions were described. The results showed that the obscurant cloud made from the mixture of red phosphorus, $Ba(NO_3)_2$ and Viton rubber has a low transmittance, high extinction coefficientwith 1.06 µm laser and strong infrared emission in the wavelength range of 8.0 to 14.0 µm. On the other hand, the infrared emission radiance (in the wavelength range of 2.5 to 5.0 µm) of the optronic decoy composition based on Mg-Al, hexachloroethane and Viton rubber reaches maximum values (i.e. 17.77E-3 $W.cm^{-2}.Sr^{-1}$) at about of 17 wt% Mg-Al. Finally, the above obscurant and optronic decoy compositions can be usedcombinationin in naval ships against the anti-ship missile.*

Keywords: Obscurant; Decoy flare; Red phosphorus; Metal-Chlorocarbon; Screening smoke.

1. INTRODUCTION

Guided weapons such as laser-guided missiles and infrared-guided missiles are themost used widely electro-optically guided precision weapons to attack several military targets (i.e. naval ships, main battle tanks, aircraft, etc.) [1-4]. To protect these targets, optronic decoys and obscurant clouds were used as a countermeasure to infrared-guided and laser-guided missiles, respectively. Optronic decoys set up a false optical target near the protected ship in the form of a smoke-screen which ensures retargeting of the homing heads of the attacking projectiles [5-7]. Meanwhile, the purpose of obscurant clouds is to scatter and absorb laser radiation and thereby to interrupt the line of sight between the target and observer [8].

Over the last 50 years, a lot of optronic decoy compositions (i.e. metal/halocarbon compositions, metal/aromatic-compound compositions, etc.) and obscurant compositions (i.e. HC-based mixtures, phosphorus-based mixtures, etc.) have been developed, manufactured and used for the military purpose [9-13]. These compositions can be used individually or in combination to increase the ability to protect the target, especially with large-sized targets such as the naval ships, which have distinct sources of infrared radiation provided by the chimney and the exhaust plume (i.e. primarily in the range of 2.5 to 5.0 µm and 8.0 to 14.0 µm) [10, 14].

This work aims to investigate the infrared emission and the obscurant characteristics of optronic decoy formulation (based on Mg-Al alloy/hexachloroethane mixture) and obscurant formulation (based on red phosphorus) using in naval ships. The infrared radiation characteristics (i.e the infrared emission spectrum and the infrared radiance in the range of 2.5 to 5.0 µm and 8.0 to 14.0 µm) of these compositions were determined using a spectroradiometer. On the other hand, the absorption and scattering of a screening smoke at 1.06 µm laser radiation were also determined.

2. MATERIALS AND METHODS

2.1. Materials

The Mg-Al alloy powder (with average particle sizes below 63 μm) was obtained from Sichuan Hermus Industry Co., Ltd. Hexachloroethane fine powder (with an average particle size of 100 μm); red phosphorus fine powder (with an average particle size of 100 μm) and barium nitrate powder (with an average particle size of 60 μm) were provided by Xilong Scientific Co., Ltd. Viton A rubber (i.e. vinylidene fluoride-hexafluoropropene copolymer is an elastomer with a fluorine content of 66%, and a density of 1.81 $g.cm^{-3}$) was commercially obtained from Dupont company.

2.2. Methods

2.2.1 Sample preparation

Optronic decoy composition: Viton rubber was dissolved in acetone and kept overnight to obtain a homogeneous solution. The binder solution was mixed with hexachloroethane powder in a mixer with a stirring rate of 600 rpm. Then, Mg-Al alloy powder was added to the suspension and mixed for about 30 minutes. The final mixture was covered on both sides of a 50x50 mm fiberglass fabric and was vacuum-dried at 60 °C for 3 hours to remove the solvents.

Obscurant composition: Viton rubber was dissolved in acetone and kept overnight to obtain a homogeneous solution. The binder solution was mixed with red phosphorus powder and barium nitrate powder in a mixer with a stirring rate of 700 rpm for about 30 minutes. The final mixture was covered on both sides of a 50x50 mm fiberglass fabric and was vacuum-dried at 60 °C for 3 hours to remove the solvents. The formulations of optronic decoy and obscurant composition are expressed in Table 1.

Table 1. *The formulations of optronic decoy and obscurant composition.*

Materials	Content (wt%)	
	Optronic decoy composition	Obscurant composition
Mg-Al alloy (Mg_4Al_3)	10.0 ÷ 20.0	-
Hexachloroethane, C_2Cl_6	60.0 ÷ 70.0	-
Red phosphorus, RP	-	65.0 ÷ 75.0
Barium nitrate, $Ba(NO_3)_2$	-	10.0 ÷ 20.0
Viton A	20.0	15.0

2.2.2. Experimental techniques

The heat of combustion (Q) was measured by the Parr 6200 calorimeter (Parr Instrument Company, US). 2.0 grams powder of samples were prepared and the combustion processes were initiated by the electrically heat igniter.

The burn rate of samples was determined by high-speed digital camera Fastcam SA 1.1 RV (Photron, Japan) with a recording speed of 500 fps, if the time interval needed for the flame front to travel the known distance through the sample was recorded, the burning rate is calculated. The samples were prepared in the form of a sheet with a size of 10x100 mm.

To evaluate the performance of the obscurant composition, the mass extinction coefficient α_λ ($m^2.kg^{-1}$) can be considered as figures of merit. According to the Lambert-Beer law, the mass extinction coefficient α_λ can be expressed as [1,8]:

$$\alpha_\lambda = \frac{-\ln T_{obs}}{c.L} \quad (1)$$

where c is the concentration of obscurant aerosol in the obscurant cloud ($g.m^{-3}$); L is the optical path-length through the obscurant cloud (m); T_{obs} is the degree of transmission determined by[12]:

$$T_{obs} = \frac{I_{\min}}{I_0} \quad (2)$$

where I_0 and I_{min} are the initial radiant intensity without smoke and the minimum value of radiant intensity transmitted after passing the obscurant cloud. The spectral extinction was measure by burning a known amount of obscurant composition in the test chamber. A continuous-wave (CW) laser source is used with an output power of 22.0 mW and a beam diameter of 2.0 mm. The path-length through the aerosol was 600 mm. The experimental setup used to measure the mass extinction coefficient of 1.06 µm laser radiation is shown in Figure 1.

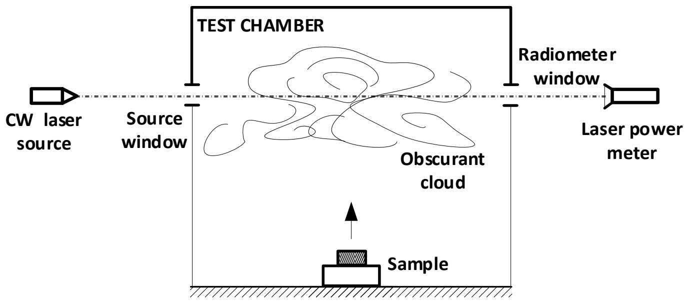


Figure 1. *Setup used to measure the mass extinction coefficient.*

The emission characteristic of the optronic decoy composition was determined using the Spectral Master 12-550 Mark III Radiometer (US) with a spectral range from 2.5 to 14.5 µm. 5.0 grams of the sample (i.e. five 50x50 mm thin plates) were burned in the test chamber by an electric prime, and the optronic decoy cloud was opposite the lens. The infrared radiance and the infrared radiation intensity were determined by the built-in software. The experimental setup used to measure the emission characteristic is shown in Figure 2.

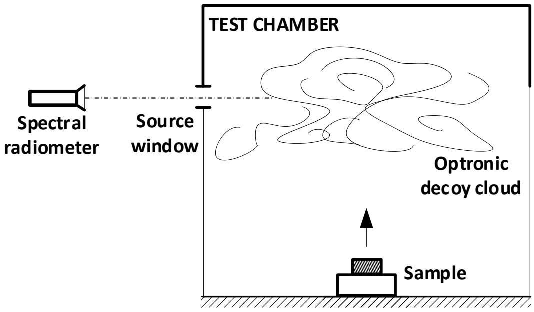


Figure 2. *Setup used to measure the emission characteristic.*

3. RESULTS AND DISCUSSION

3.1. Combustion characteristics

Before the experiments, the heat of combustion (Q_v) of the mixture was measured. The theoretical temperature flame (T_f) and the composition of its combustion products were calculated using the REAL software based on the chemical balance according to the principle of minimizing free energy [15, 16]. The T_f and the Q_v values of the obscurant composition or the optronic decoy composition were determined as a function of red phosphorus or Mg-Al alloy weight content, respectively. The burn rate of both compositions was also determined. The results are given in table 2 and figure 3.

Table 2. *Combustion characteristics of the screening smoke composition.*

Component (%)	Q_v (kcal/kg)	T_f (K)	Burn rate (mm.s^{-1})	Main ingredients of smoke (mol/kg)
RP - 60; $Ba(NO_3)_2$ - 25; Viton - 15	445	1610	2.80	P_2: 0.78; P_4: 3.97; C: 1.12
RP - 65; $Ba(NO_3)_2$ - 20; Viton - 15	415	1465	2.42	P_2: 0.27; P_4: 4.63; C: 1.89
RP - 70; $Ba(NO_3)_2$ - 15; Viton - 15	395	1340	2.10	P_4: 5.12; C: 2.91
RP - 75; $Ba(NO_3)_2$ - 10; Viton - 15	370	1220	1.40	P_4: 5.50; C: 3.98
RP - 80; $Ba(NO_3)_2$ - 5; Viton - 15	310	910	1.25	P_4: 5.95; C: 3.51
Mg_4Al_3 - 10; C_2Cl_6 - 70; Viton - 20	465	2235	12.6	C: 11.52; $MgCl_2$: 1.55; MgF_2: 0.70; AlF_3: 0.60
Mg_4Al_3 - 12; C_2Cl_6 - 68; Viton - 20	500	2420	14.2	C: 11.33; $MgCl_2$: 2.38; AlF_3: 0.71; MgF_2: 0.31
Mg_4Al_3 - 15; C_2Cl_6 - 65; Viton - 20	625	2975	16.5	C: 11.08; $MgCl_2$: 3.00; MgF_2: 0.34; AlF_3: 0.53
Mg_4Al_3 - 17; C_2Cl_6 - 63; Viton - 20	690	3250	18.0	C: 10.81; $MgCl_2$: 2.28; MgF_2: 0.39; AlF_3: 0.43
Mg_4Al_3 - 20; C_2Cl_6 - 60; Viton - 20	720	3335	22.2	C: 10.25; $MgCl_2$: 3.56; MgF_2: 0.46; AlF_3: 0.34
Mg_4Al_3 - 25; C_2Cl_6 - 55; Viton - 20	700	3190	25.5	C: 9.76; $MgCl_2$: 3.80; MgF_2: 0.53; AlF_3: 0.25

Obscurant composition: Figure 3 shows that when the content of red phosphorus increases, the adiabatic flame temperature T_f and the heat of combustion Q_v decrease due to the oxygen balance becomes more negative. Therefore, the burning rate of composition also decreases when the content of red phosphorus increases.

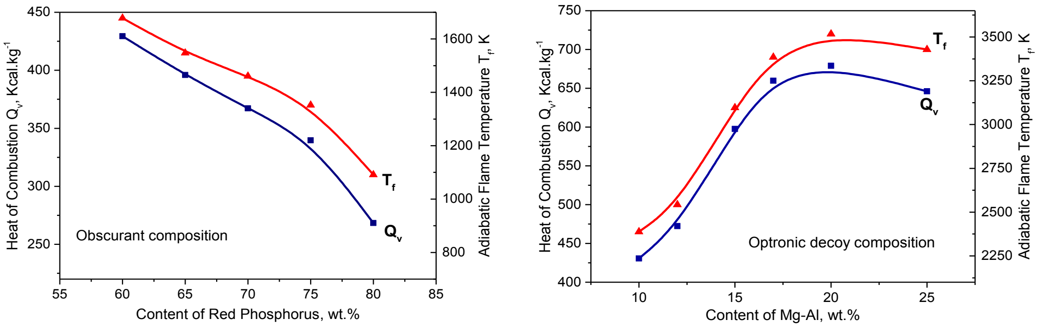


Figure 3. *The T_f and the Q_v values of smoke compositions.*

Optronic decoy composition: When Mg-Al content increases, the adiabatic flame temperature T_f and the heat of combustion Q_v increase. When the Mg-Al content is approximately 20% (i.e. the stoichiometric mixture), the T_f and Q_v values reach the maximum value. After that, the more Mg-Al content increase (i.e. the fuel-rich formulations), the values of T_f and Q_v tend to decrease. The more surprising correlation is with an increase in the content of Mg-Al alloy results in a higher burning rate. This may be due to the increase in Mg-Al alloy content which increases the thermal conductivity (i.e. efficient energy feedback) of the mixture from the reacting zone to the pre-reacting material, results in increasing the burning rate.

It can be assumed that for the obscurant composition, soot particles (i.e. Carbon) and P_4O_{10} particles formed in a reaction of P_2, P_4 with atmospheric oxygen are main components of the smoke; for the optronic decoy composition, soot particles and chloride/fluoride of magnesium/aluminum are main components of the smoke [17].

3.2. Obscurant characteristics

To determine the performance of obscurant compositions, 0.20 g samples were ignited to produce smoke inside the chamber. After 10 seconds (to get uniform mixing of smoke), 10-values of radiant intensity, which transmitted after passing the obscurant cloud, were recorded every 10 seconds. The minimum value of radiant intensity (I_{min}) was used to calculate the transmittance (T_{obs}) according to the Eq. (2), and then the mass extinction coefficients were calculated according to the Eq. (1). These results are expressed in table 3.

It can be seen that the aerosol concentration of the obscurant mixture increases with the increasing of red phosphorus content (i.e. from 60 to 80 wt%), which reduces the transmittance. The measurement results of the transmittance show that the mixtures tested provide good attenuation of 1.06 μm laser radiation. Interestingly, when the red phosphorus content increases from 60 to 70 wt%, the extinction coefficient increases from 3.1 to 3.5 m^2.g^{-1}, but at a higher red phosphorus content, the extinction coefficient has a constant value. This may be due to the relationship between the aerosol concentration and the transmittance in the Eq. (1). It is noteworthy that the values of the extinction coefficient are also equivalent to the values of the RP/$NaNO_3$/Binder mixture previously reported by E-C. Koch [11].

Table 3. *Results of the mass extinction coefficient measurements.*

Component (%)	**Aerosol concentration c (g.m^{-3})**	**Transmittance T_{obs} (%)**	**Extinction coefficient α_λ (m^2.g^{-1})**
RP - 60; $Ba(NO_3)_2$ - 25; Viton - 15	1.16	11.3	3.1
RP - 65; $Ba(NO_3)_2$ - 20; Viton - 15	1.27	7.7	3.4
RP - 70; $Ba(NO_3)_2$ - 15; Viton - 15	1.39	5.2	3.5
RP - 75; $Ba(NO_3)_2$ - 10; Viton - 15	1.49	4.3	3.5
RP - 80; $Ba(NO_3)_2$ - 5; Viton - 15	1.60	3.3	3.5

3.3. Infrared emission characteristics

The infrared spectral distributions of Mg-Al/C_2Cl_6/Viton mixtures were measured and the results are shown in figure 4.

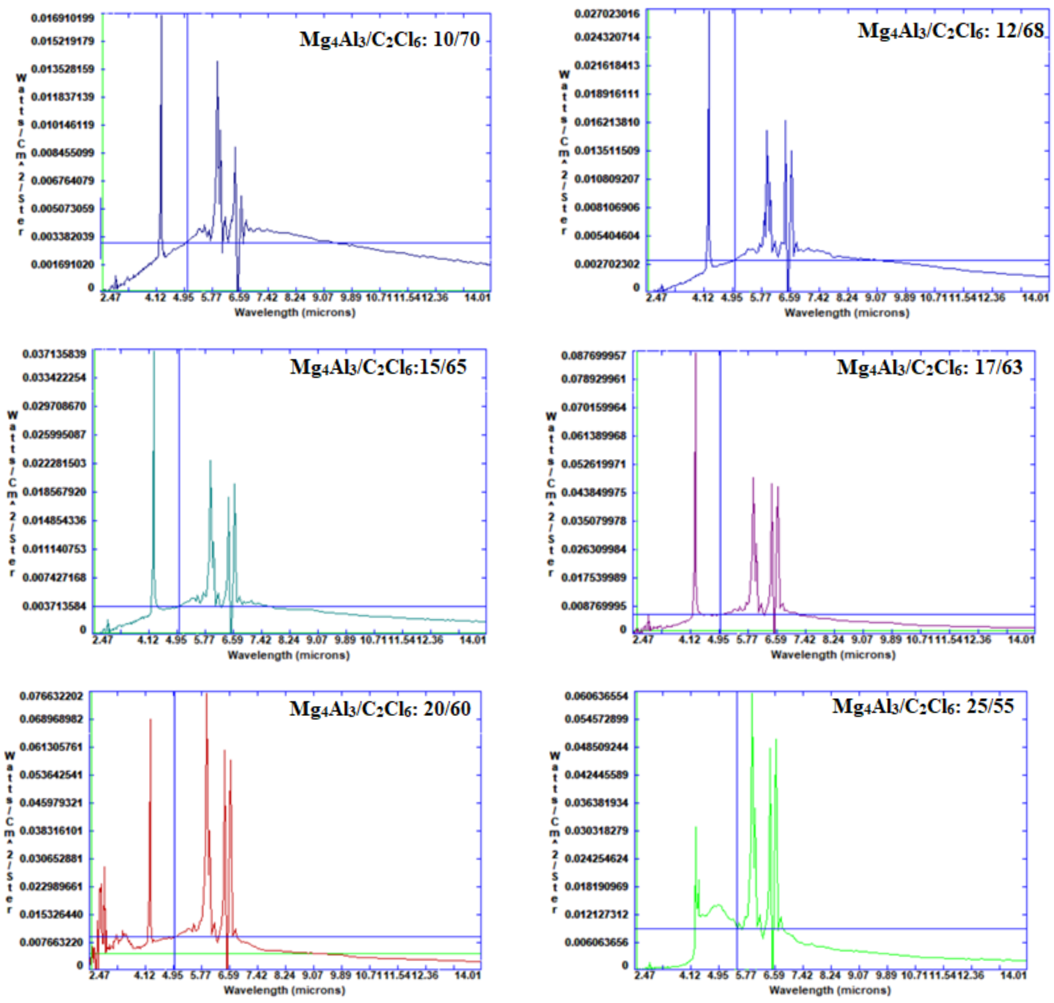


Figure 4. *Infrared radiance distribution of Mg-Al/C_2Cl_6/Viton mixtures with different Mg-Al/C_2Cl_6 ratios.*

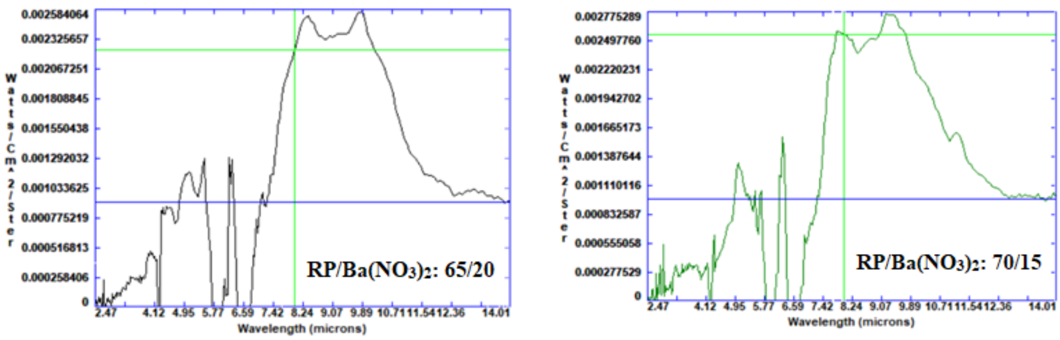
As shown in fig. 4, the infrared emission spectra distributions of all samples are similar and more radiant at infrared near- and medium-wavelength radiation area. To make a comparison, the average values of the radiance of all samples in the range of 2.5 to 5.0 µm are summarized in table 4.

Table 4. *Radiance average values of Mg-Al/C_2Cl_6/Viton mixtures with different Mg-Al/C_2Cl_6 ratios.*

Ratio of Mg-Al/C_2Cl_6/Viton	**Radiance x10^{-3} ($W.cm^{-2}.sr^{-1}$)**
10/70/20	4.85
12/68/20	5.14
15/65/20	9.75
17/63/20	17.77
20/60/20	17.21
25/55/20	12.65

When the content of Mg-Al alloy increases, the burning rate of composition also increases. The increased burning rate leads to generated combustion products increased, so the intensity of infrared emission increases. When the Mg-Al content is approximately 17%, the emission radiance reaches the maximum value (i.e. 17.77E-3 $W.cm^{-2}.sr^{-1}$). However, when the Mg-Al content increases by more than 20%, the emission radiance tends to decrease. The reason is that the increase in Mg-Al content resulting in the burning rate increases but the burning temperature decreases, thus the infrared emission distribution tends to shift to the longer wavelengths (i.e. out of range of 2.5 to 5.0 µm) according to the Wien displacement law [2, 18].

The most surprising aspect is the radiance distribution of obscurant compositions. As seen in Fig. 5, all obscurant mixtures have a strong emission intensity in the wavelength of 8.0 to 14.0 µm. These signals can be used as a false target to simulate the chimney of naval ships. The emission radiance (i.e. in the range of 8.0 to 14.0 µm) of the obscurant mixtures containing 65, 70, 75, 80 wt% of red phosphorus were 10.10E-3, 10.48E-3, 11.14E-3 and 11.44E-3 $W.cm^{-2}.sr^{-1}$, respectively. These results are not significantly different since the difference in its burning rates is not large (i.e. from 1.0 to 2.5 $mm.s^{-1}$).



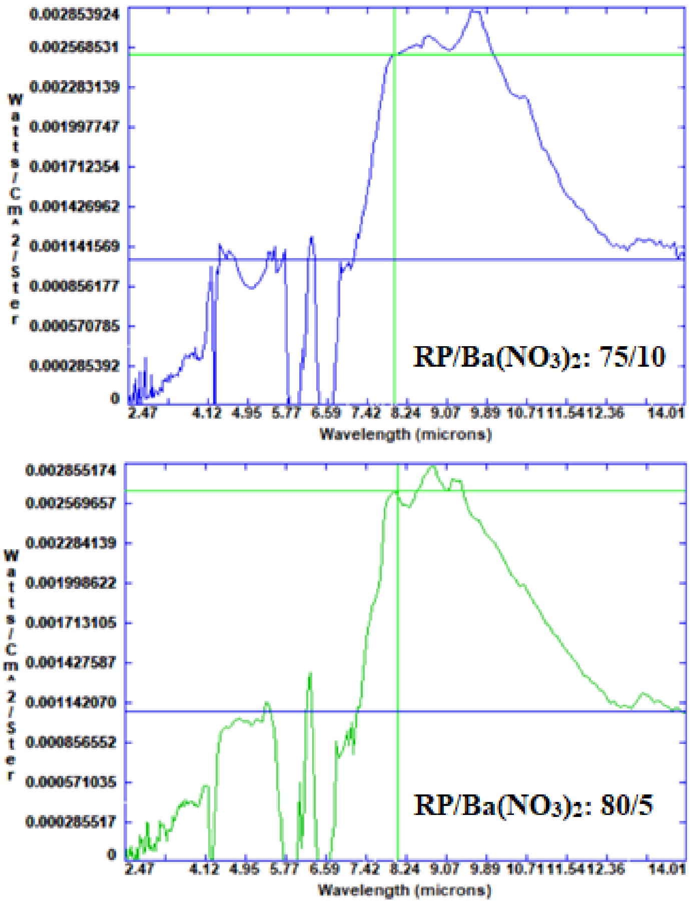


Figure 5. *Infrared radiance distribution of RP/Ba(NO_3)$_2$/Viton mixtures with various RP/Ba(NO_3)$_2$ ratios.*

4. CONCLUSION

Several characteristics (include combustion, obscurant and infrared emission characteristic) of the obscurant composition (RP/Ba(NO_3)$_2$/Viton) and the optronic decoy composition (Mg-Al/C_2Cl_6/Viton) were investigated. In particular, the burning rate of optronic decoy composition is much higher than that of the obscurant composition due to the difference in the thermal conductivity of two compositions.

The cloud smoke from RP/Ba(NO_3)$_2$/Viton composition has a low transmittance, high extinction coefficient for 1.06 µm laser radiation, thus, the smoke screening of this composition can be used to defend the naval ship from the laser-guided missile. Besides, while the optronic decoy composition performs high infrared emission in the wavelength of 2.5 to 5.0 µm, the obscurant composition emits a strong emission at a wavelength of 8.0 to 14.0 µm. Thus, the combination using both compositions is a highly effective counter measure against infrared-guided missiles.

Further work needs to be carried out to assess the effect of environmental conditions on the obscurant and emission performance of two compositions.

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TÓM TẮT

CÁC ĐẶC TRƯNG CHE PHỦ VÀ PHÁT XẠ CỦA HỖN HỢP TẠO MÀN KHÓI SỬ DỤNG TRONG CÁC TÀU HẢI QUÂN

Các hỗn hợp che phủ và nghi trang quang học là những thành phần hỏa thuật được sử dụng hiệu quả để bảo vệ các tàu hải quân khỏi sự tấn công của các tên lửa dẫn đường bằng quang học. Trong nghiên cứu này, các đặc trưng che phủ (độ truyền qua, hệ số che phủ) và các đặc trưng phát xạ hồng ngoại (phân bố phát xạ và năng lượng bức xạ) của các hỗn hợp che phủ và nghi trang được khảo sát. Kết quả nghiên cứu cho thấy, các đám mây che phủ của hỗn hợp trên cơ sở Phốt pho đỏ, $Ba(NO_3)_2$, Viton có độ truyền qua thấp, hệ số che phủ cao đối với laze 1,06 µm và phát xạ hồng ngoại mạnh trong vùng 8.0 đến 14.0 µm. Mặt khác, năng lượng bức xạ hồng ngoại trong vùng 2.5 đến 5.0 µm của hỗn hợp nghi trang trên cơ sở hợp kim Mg-Al, C_2Cl_6, Viton đạt giá trị cao nhất $17,77.10^{-3} W.cm^{-2}.Sr^{-1}$ với hàm lượng 17% Mg-Al. Cuối cùng, các hỗn hợp che phủ và nghi trang quang học kể trên có thể được sử dụng kết hợp để bảo vệ các tàu hải quân khỏi các tên lửa chống hạm.

Từ khóa: Che phủ; Nghi trang; Phốt pho đỏ; Kim loại-Clorua cacbon; Màn khói.

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