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Effects of Mg-Al Alloy Powder on the Combustion and Infrared Emission Characteristics of the Mg-Al/PTFE/Viton Composition

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ABSTRACT

Metal-Fluorocarbon compositions are the pyrotechnic formulations which have been widely used in infrared decoy flares to protect aerial targets from infrared guide missile seekers. In this work, the effect of Mg-Al alloy powder (i.e. the particle size and the content) on the combustion and the infrared emission characteristics (i.e. the infrared emission distribution and the infrared radiance) of the pyrotechnic composition based on Mg-Al alloy, polytetrafluoroethylene (PTFE) and Viton rubber are described. The results show that the high burning rate (with the values of 4.0 $mm.s^{-1}$ to 10.0 $mm.s^{-1}$, depend on the compression density) of this composition is achieved with a high content of Mg-Al alloy or when using fine Mg-Al alloy particles as well as coarse PTFE particles. On the other hand, the infrared emission radiance (in the wavelength range of 2.5 µm to 5.0 µm) of Mg-Al/PTFE/Viton composition reaches maximum values (i.e. 17.7 $W.cm^{-2}.Sr^{-1}$ and 21.0 $W.cm^{-2}.Sr^{-1}$ with the size of Mg-Al particles are 20 µm and 120 µm, respectively) at 60 wt% Mg-Al alloy. Finally, the Mg-Al/PTFE/Viton composition has a similar combustion and emission characteristics as the Mg/PTFE/Viton composition.

Keywords: Infrared decoy flares; Metal-fluorocarbon; Mg-Al alloy; Teflon; Viton

1. INTRODUCTION

Aircraft are distinct sources of infrared radiation, in which the intense radiation provided by the turbine blades, hot tailpipes and the exhaust plume (i.e. primarily in the range of between 2.5 µm and 5.0 µm) that infrared-guided missiles have been developed to fight aerial targets[1-3]. Infrared decoy flares are used as a countermeasure flare by many military aircraft to protect against the attack by heat-seeking missiles such as surface-to-air as well as air-to-air missiles[3,4]. Currently, the pyrotechnic compositions used in infrared decoy flares are often solid mixtures of magnesium, PTFE (polytetrafluoroethylene) and Viton (vinylidene fluoride-hexafluoropropene copolymer)[5-14]. These are commonly called MTV-flares. MTV compositions are widely used in infrared decoy flares because of their high energy compared to other compositions, low hygroscopicity, low dependence of burning rate on pressure and temperature[3,15].

Along with the use of Mg, the MTV compositions have high energy density. However, the improvement of the MTV composition performance is limited due to the high sensitivity of the mixture to mechanical impulses, the smallest available Mg particle size powder, and the composition may deteriorate because of the reaction of Mg powder with moisture[2,16]. To address these issues, Mg-Al alloy can be used as a replacement for Mg in the MTV composition, which still meets the performance of the composition. Cudzilo[17] and Chen[18] reported that the burning rate of Mg-Al/PTFE/Viton increases with increasing metal content. However, there is little published data on the infrared decoy flares based on Mg-Al/PTFE/Viton, and the effect of Mg-Al alloy on the performance of this mixture still needs further research.

This study focused on investigating the effect of the content and the particle size of the Mg-Al alloy (i.e. the mass ratio of 50:50) on the burning rate and the infrared radiation performance of Mg-Al/PTFE/Viton composition. The Mg-Al/PTFE/Viton compositions were compressed into steel cylindrical tubes to determine the burning rate using a high-speed digital camera, and the infrared radiation properties (i.e the infrared emission spectrum and the infrared radiance) using a spectroradiometer. The results obtained were compared with the characteristics of the MTV composition to evaluate the effectiveness of the use of Mg-Al in infrared decoy flare applications.

2. MATERIALS AND METHODS

2.1 Materials

The Mg-Al alloy powder (i.e. the Mg/Al ratio of 50/50 by weight, with average particle sizes approximately of 20 µm and 120 µm) was obtained from Sichuan Hermus Industry Co,. Ltd. PTFE fine powder (with average particle sizes approximately of 10 µm and 180 µm) was produced by Beijing Starget Chemicals Co., Ltd. Photomicrographs for two material particles were shown in Fig. 1. Viton A rubber (i.e. vinylidene fluoride-hexafluoropropene copolymer with a fluorine content of 66%, and a density of 1.81 $g.cm^{-3}$) was commercially obtained from Dupont company.

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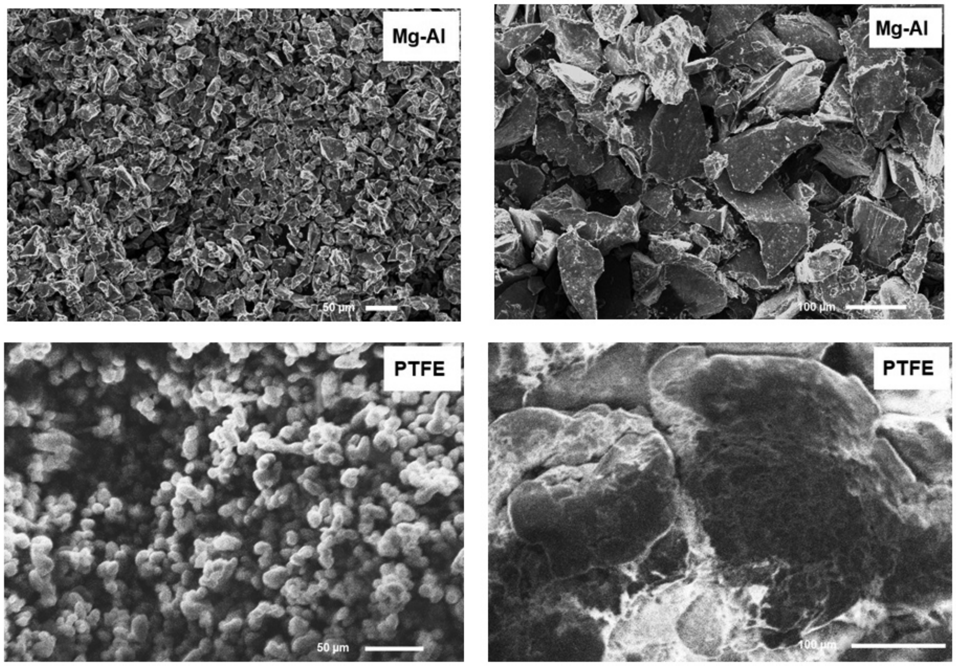


Figure 1. Scanning electron micrographs of Mg-Al and PTFE particles.

2.2 Experimental Techniques and Methods

2.2.1 Sample Preparation

Viton rubber was dissolved in acetone with the polymer/solvent ratio of 1/15 (w/v) and kept overnight to obtain a homogeneous solution. The binder solution was mixed with Mg-Al alloy powder in a mixer with a stirring rate of 700 rpm. Then PTFE powder was added to the suspension and mixed for about 30 min. The final mixture was dried for 30 min in the air and then granulated through a 250 µm sieve. After that, the mixtures were vacuum-dried at 60 °C for 3 h to remove the solvents. The compositions of these Mg-Al/PTFE/Viton samples are expressed in Table 1.

Table 1. The composition of Mg-Al/PTFE/Viton samples

Material	Content (%.wt)				
	M1	M2	M3	M4	M5
Mg-Al alloy	30	40	50	60	70
PTFE	65	55	45	35	25
Viton A	5	5	5	5	5

2.2.2 Experimental Techniques

To determine the burning rate of the pyrotechnic mixture, the Mg-Al/PTFE/Viton compositions were compressed into a cylindrical steel tube with an inner diameter of 15 mm, a thickness of 1.5 mm and a length of 100 mm using the hydraulic compressor with the compression pressure of 1000 kgf to 1500 kgf. Two observation windows were placed at a distance of 50 mm on the wall of the tube. The composition was ignited by an electric primer. The burning rate of these compositions was measured by high-speed digital camera Fastcam SA 1.1 RV (Photron, Japan) with a recording speed of 1000 fps. If the time interval (t) needed for the flame front to travel the known distance (L) through the sample is determined, the burning rate (u) is calculated according to the equation:

$$u = \frac{L}{t} \tag{1}$$

Each experiment was carried out three times and took the average value. The experimental setup used to measure the burning rate of the flares composition is shown in Fig. 2.

The radiation characteristic of the mixture was determined using the Spectral Master 12-550 Mark III Radiometer (M^3 Measurement Solution Inc., US) with a spectral range from 2.5 µm to 14.5 µm. The compositions were compressed into a cylindrical tube with a diameter of 35mm and a length of 150 mm using the hydraulic compressor. The tube was placed on the test-line about 15 m in front of the instrument, and the burning surface was opposite the lens (Fig. 3). The infrared radiance and the infrared radiation intensity were determined by the built-in software.

3. RESULTS AND DISCUSSIONS

3.1 Combustion Characteristics

3.1.1 Thermochemical Properties

The flame temperature T_c, the heat of combustion Q_v of the mixtures and the composition of its combustion products were calculated as a function of Mg-Al weight content. The calculation was based on the modified REAL thermodynamic code, which determines the chemical balance according to the principle of minimizing free energy[19,20]. In which, the process examined was treated as an adiabatic and isochoric condition. The results were shown in Table 2 and Fig. 4.

From Table 2 and Fig. 4, it can be seen that at the stoichiometric ratio Mg-Al/PTFE (the content of Mg-Al is about 30%, i.e. the oxygen balance is close to zero), the main combustion products are soot particles (i.e. $C_{(S)}$), MgF_2 and AlF_3 with the concentration of 12.1 mol.kg^{-1}, 5.9 mol.kg^{-1} and 3.6 mol.kg^{-1}, respectively, at the maximum values of the

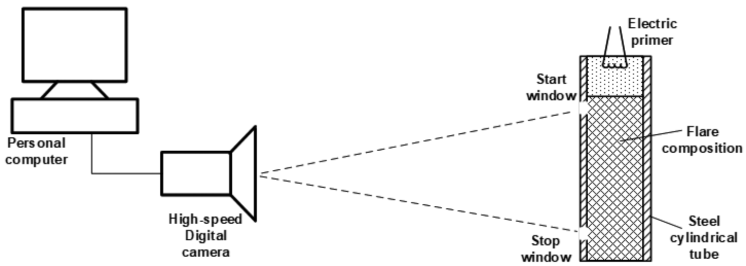


Figure 2. The experimental setup used to measure the burning rate.

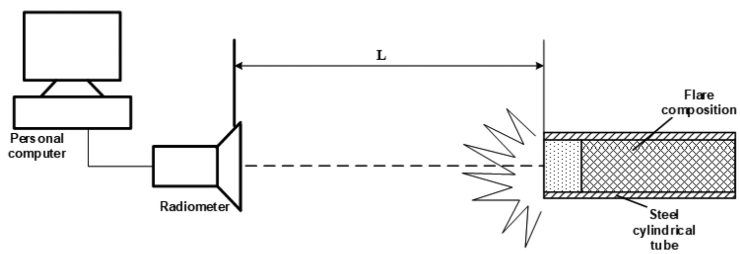


Figure 3. The experimental setup for infrared emission recording.

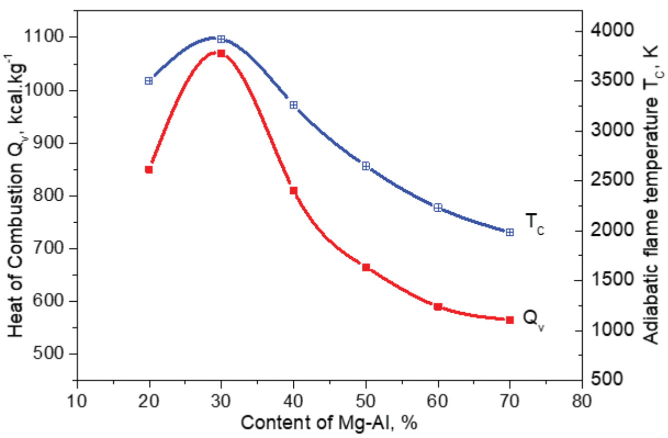


Figure 4. Adiabatic flame temperatures and the heat of combustion of Mg-Al/PTFE/Viton mixtures.

adiabatic flame temperature T_C and the heat of combustion Q_V. The concentrations of $C_{(S)}$, MgF_2 and AlF_3 decrease, and the concentrations of $Mg_{(G)}$ and $Al_{(G)}$ increase with increasing of the Mg-Al content. The flame temperature and the heat of combustion also decrease rapidly as the content of Mg-Al increase above 30% (i.e. the oxygen balance becomes more negative/or fuel-rich formulations).

3.1.2 Burning Rate Properties

The effect of the content and the particle size of Mg-Al alloy and PTFE at several compression densities on the burning rate of the Mg-Al/PTFE/Viton are shown in Figs. 5 (a)-5(c). It is observed that an increase in the content of Mg-Al alloy results in a higher burning rate, as Kubota & Serizawa[7] has noted. At low Mg-Al content (below 50%), the burning rate increases quite slowly, while at high Mg-Al content, the burning rate increases rapidly.

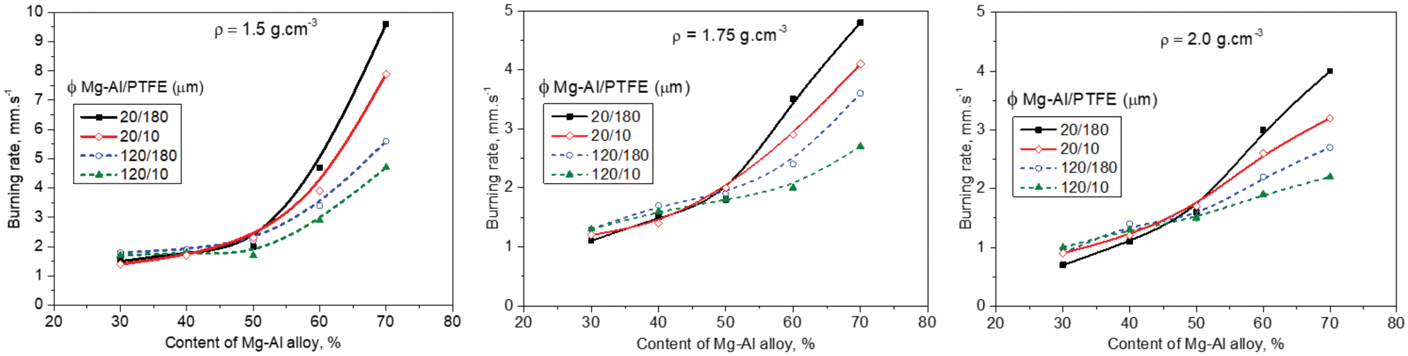
Interestingly, the relationship between the burning rate and the flame temperature as well as the heat of combustion of Mg-Al/PTFE/Viton appears to be in contrast to the conventional propellants (i.e. the single-base, double-base and composite propellant). It is noteworthy that the burning rate of conventional propellants often increases with the increasing of the flame temperature and the heat of combustion. This is the significant difference in the combustion characteristic of Mg-Al/PTFE/Viton composition compares to the conventional propellants. It is important to note that this relationship of Mg-Al/PTFE/Viton mixture similar to the MTV mixtures reported by Kubota & Serizawa[7]. 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.

Figure 5 also shows that the burning rate increases with decreasing the particle size of Mg-Al alloy. The reason is that smaller Mg-Al particle size has a larger specific surface area, and therefore have a larger contact area with fluorides (generated from PTFE decomposition), resulting in increased reactivity[21]. Besides, the burning rate depends not only on the particle size of Mg-Al but also on the particle size of PTFE. At low content of Mg-Al alloy, the mixtures using fine PTFE particles have a high burning rate and the mixtures using coarse PTFE particles have a low burning rate. However, at high content of Mg-Al alloy, fine PTFE particles affect a low burning rate and coarse PTFE particles cause a high burning rate. Thus, high burning rate values of Mg-Al/PTFE/Viton composition are achieved with fine Mg-Al alloy particle size, coarse PTFE particle size, and high content of Mg-Al alloy.

As the compression density increases, the burning rate of the mixtures tends to decrease. Figure 6 shows the relationship of the compression density against the burning rate of Mg-Al/PTFE/Viton mixtures with different Mg-Al contents using the

Table 2. Main ingredients of the Mg-Al/PTFE/Viton combustion product

Ratio of Mg-Al/PTFE	Oxygen balance	Main ingredient of combustion products ($mol.kg^{-1}$)
20/75	18.1%	C-10.5, MgF_2-3.9, AlF_3-3.4, F-0.4, C_2F_2-1.5, CF_2-1.6
30/65	-4.3%	C-12.1, MgF_2-5.9, MgF-0.7, AlF_3-3.6, AlF_2-1.0, AlF-0.4
40/55	-31.7%	C-11.1, MgF_2-4.9, MgF-2.4, AlF_3-1.5, AlF_2-1.4, AlF-3.8, Mg-1.7
50/45	-60.2%	C-10.3, MgF_2-4.3, MgF-1.4, AlF_3-0.4, AlF_2-0.6, AlF-7.4, Mg-5.6
60/35	-88.6%	C-5.5, MgF_2-4.4, MgF-0.4, Al_4C_3-0.9, AlF-6.2, Mg-8.6
70/25	-116.1%	MgF_2-4.9, Al_4C_3-2.1, AlF-1.7, Mg-10.6, Al-1.6



(a) (b) (c)

Figure 5. The burning rate of the Mg-Al/PTFE/Viton mixtures at (a) 1.50, (b) 1.75 and (c) 2.0 g.cm^{-3}.

20 µm Mg-Al alloy and the 180 µm PTFE. Similar effects are observed for the mixtures using other grades of Mg-Al and PTFE.

In Fig. 6, it can be observed that at low Mg-Al content, the density of composition affects low the burning rate, and at high Mg-Al content (over 50 %), the difference in the burning rate at different densities is quite large. The reason is that by increasing the compression, the spaces between the grains decreases, the ability to penetrate of hot gases through the solid composition decreases, leading to a decrease in burning rate.

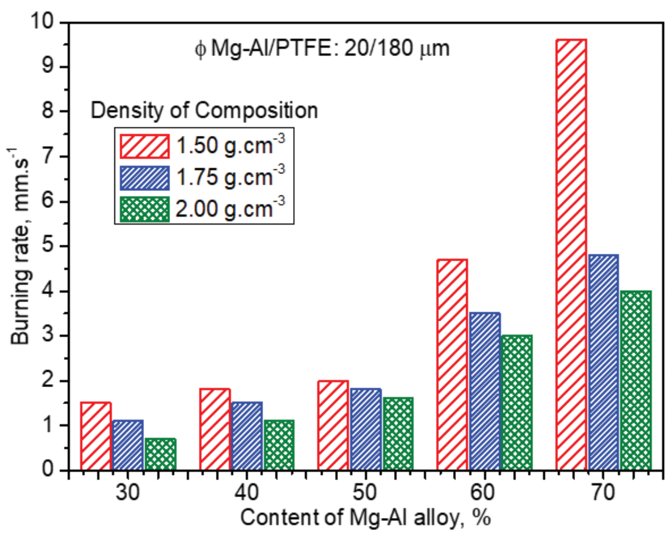


Figure 6. Comparison of burning rates at different densities.

3.2 Infrared Emission Characteristics

The infrared spectral distributions of Mg-Al/PTFE/Viton mixtures (with two grades of Mg-Al alloy particle sizes, and 180 µm PTFE) were measured using the Spectral Master 12-550 Mark III Radiometer, and the results are shown in Fig. 7.

As shown in Fig. 7, the infrared emission spectra distributions of all samples are similar and more radiant at infrared near- and medium-wavelength radiation area. In particular, the Mg-Al/PTFE/Viton samples using fine Mg-Al alloy powder have a stronger infrared emission intensity than those using coarse Mg-Al alloy powder. Because of this, in the same composition, the infrared radiance of mixture with fine alloy powder is about 20 % higher than that of the mixture with coarse alloy powder (Table 3). The difference in radiance values might due to the difference in the burning rate of compositions when using different particle sizes of Mg-Al alloy powder. Besides that, the fine Mg-Al particles contact better with PTFE so the combustion process is more complete, thus the burning temperature will be higher[21].

Table 3. Radiance average values of several Mg-Al/PTFE/Viton mixtures

Ratio of Mg-Al/PTFE/Viton	Radiance (W.cm^{-2}.sr^{-1})	
	Fine Mg-Al (20 µm)	Coarse Mg-Al (120 µm)
30/65/5	12.06	9.90
40/55/5	14.99	12.58
50/45/5	19.06	16.20
60/35/5	21.00	17.70
70/25/5	19.68	16.60

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, thus the intensity of infrared emission increases. However, the intensity of infrared emission does not increase as fast as the burning rate. 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 (according to the Wien displacement law[1,22]). The emission radiance reaches the maximum value of 17.7 and 21.0 W.cm^{-2}.sr^{-1} with the 120 µm Mg-Al and 20 µm Mg-Al, respectively, at 60 wt% Mg-Al powder. These emission radiance values are also equivalent to the values of the MTV mixture previously reported by Du[21], *et al.* If the Mg-Al content increases by more than 60 %, the emission radiance tends to decrease.

Thus, it can be found that to improve the infrared emission performance of Mg-Al/PTFE/Viton mixtures in the range of 2.5 µm to 5.0 µm, the burning rate should be increased by using the burning catalysts or resizing the component particles instead of increasing the Mg-Al content too high. Therefore, the burning rate, the adiabatic flame temperature and the heat of combustion meet the requirements, and the infrared emission distribution will not be shifted to the longer wavelength area (i.e. out of range of 2.5 µm to 5.0 µm).

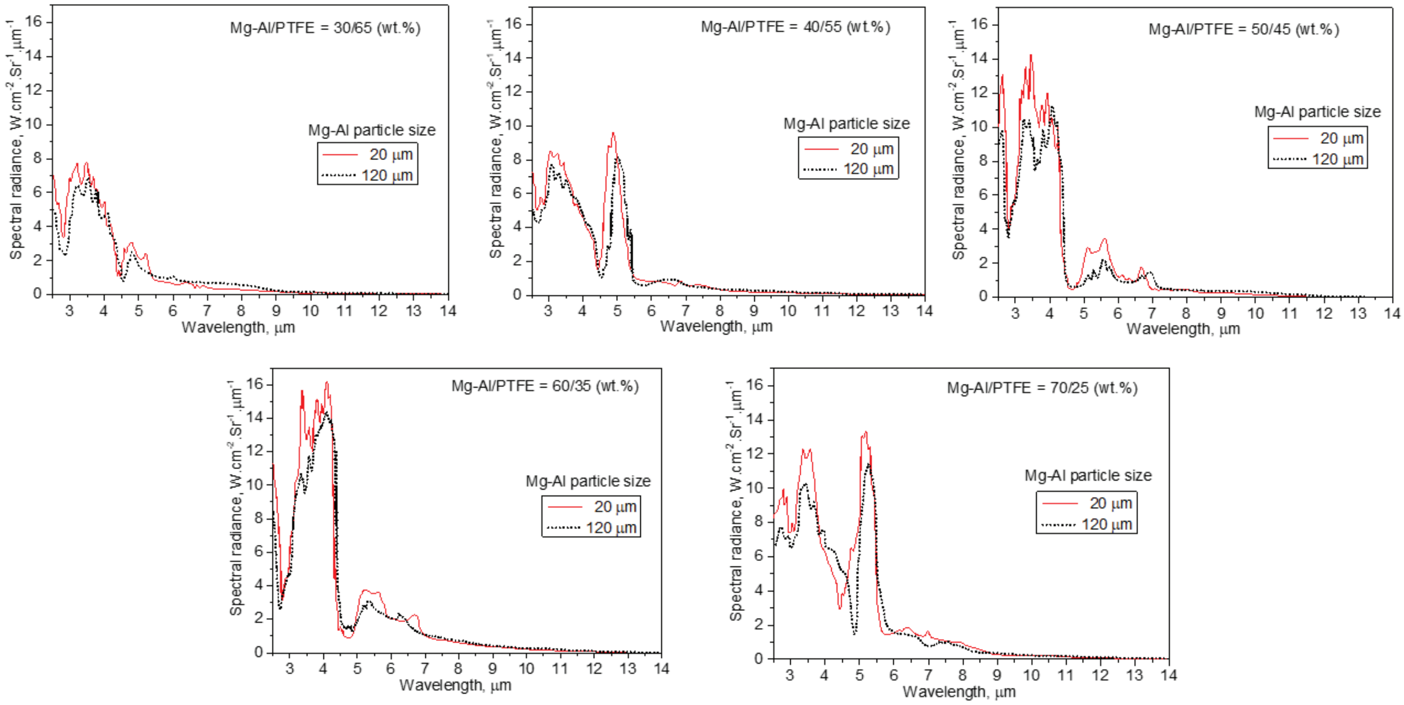


Figure 7. Infrared radiance distribution of several Mg-Al/PTFE/Viton samples.

4. CONCLUSIONS

The maximum values of the adiabatic flame temperature and the heat of combustion of Mg-Al/PTFE/Viton formulation are obtained at the stoichiometric Mg-Al/PTFE/Viton formulation (i.e. the ratio of Mg-Al/PTFE/Viton is approximately 30/65/5). However, the burning rates of those mixtures increase with increasing the content of Mg-Al from 30 % to 70% due to the increase of the thermal conductivity. On the other hand, high burning rates can be achieved when using fine Mg-Al and/or coarse PTFE particles.

To increase the infrared emission performance in the wavelengths of 2.5 µm to 5.0 µm, the burning rate of these mixtures should be increased by using 20 µm Mg-Al powder, and the emission radiance reaches the maximum value of 21.0W.cm^{-2}.sr^{-1} at 60 wt% Mg-Al.

The Mg-Al/PTFE/Viton mixture has a similar combustion and emission characteristics as the MTV mixture, thus the Mg-Al/PTFE/Viton can be used as a replacement for MTV mixture in infrared decoy flares to set up a false optical target of hot tailpipes and the exhaust plume of an aircraft.

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