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Infrared Irradiance Reduction in Minimum Smoke Propellants by Addition of Potassium Salt

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Abstract: One of the plume characteristics of minimum smoke propellant is the infrared (IR) radiation signature, which may be useful for detection of rocket. The IR irradiance is known to be reduced by afterburning suppression in rocket plume by addition of potassium salt in propellant. The minimum smoke propellant with nitrate ester polyether (NEPE) binder system and nitramine oxidizers was researched for the afterburning and IR irradiance difference according to the content of potassium salt as afterburning suppressant in propellant formulation. The propellants were formulated to satisfy the level of AGARD smoke class AA and potassium sulfate was selected as afterburning inhibitor suitable for NEPE propellant. The afterburning flame length and mid-range IR intensity were measured, while conducting static firing tests of 6 inch (15.24 cm) standard rocket motors loaded with minimum smoke propellants of the different contents of potassium sulfate. The total IR irradiance of HMX/RDX propellant with 1.1 % potassium sulfate was reduced to about 23 % compared to the propellant without afterburning suppressant due to the inhibition of afterburning. Also, the total IR irradiance of the HNIW (30 %)/RDX propellant was found to be almost three times more than that of the HMX/RDX propellant although the content of potassium sulfate was the same of 1.1 % in both propellants.

Keywords: Infrared irradiance · Afterburning suppression · Minimum smoke propellant · Potassium sulfate

1 Introduction

The exhaust plumes of aircrafts or rockets radiate energy over a broad spectral range producing signatures that may be used for detection, identification, and targeting or for tracking and control. One of the plume characteristics is the IR radiation signature, which is useful for detection of rocket [1–3]. The solid rocket motor for tactical missile is favorably loaded with double base or minimum smoke propellant due to Advisory Group for Aerospace Research and Development (AGARD) smoke class AA not to show a visible primary and secondary smoke. But these kinds of solid propellants are essentially fuel-rich and about a half amount of combustion products consists of carbon mono oxide and hydrogen.

CO and H_2 formation in rocket plumes during propellant combustion make the oxidative reaction with oxygen in the ambient air entraining into the plume. This is called afterburning that could greatly increase release of CO_2, H_2O, temperature, and IR radiation intensity in the exhaust plume field [4]. The IR intensity of mid-range wavelength is known to increase with increasing CO_2 and H_2O content as well as flame temperature. One of the best ways to reduce the IR intensity of mid-range wavelength is to suppress the afterburning in the exhaust plume. And addition of potassium in propellant formulation is known to inhibit the afterburning such as the oxidation of CO and H_2 [5–12].

The effect of potassium on afterburning in double base propellants has been presented in several reports [6–8,10,11]. The potassium content in solid propellants results in the formation of K_2CO_3 during propellant combustion in rocket motor and K_2CO_3 in the plume could be a visible smoke of solid particles that is classified as a primary smoke. In order to reduce the IR intensity as well as a visible primary smoke, the potassium content in propellants should be controlled. The minimum smoke propellant com-

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prising of nitrate ester polyether (NEPE) binder and nitramine oxidizer is known to have higher specific impulse and density than double base propellant.

In this paper NEPE minimum smoke propellant with RDX, HMX, or HNIW is investigated to find the effect of potassium salt on the IR intensity in the plume using solid rocket motors. A potassium salt is selected as the afterburning suppressant suitable for NEPE minimum smoke propellant. Based on the satisfaction of AGARD primary smoke class A, some propellant formulations were selected and the flame length as well as IR irradiance was measured and accessed by the static firing of solid rocket motors with 154 mm in diameter.

2 Experimental Section

2.1 Selection of Afterburning Suppressants

To select one of potassium compounds for NEPE minimum smoke propellant, six potassium materials were considered as shown in Table 1 [13]. K_2SO_4, K_2CO_3, and KNO_3 are known to effectively suppress the afterburning of double base propellants [6,10,11]. Based on the result that the afterburning in rocket plumes decreases with increasing potassium content in the propellant [6], compounds with higher potassium content (c in Table 1) are considered to be more advantageous. The melting point of KNO_3 is 607 K below the burning surface temperature. Therefore, KNO_3 could change the burning surface structure of the propellant, which enhances the burning rate and reduces the pressure exponent [6,12]. $KClO_4$, $KClO_3$, and K_3AlF_6 are not applicable to minimum smoke propellant because chlorine or fluorine in these compounds could induce secondary smoke. K_2CO_3 showing the highest c value in Table 1 is very hygroscopic and could trouble about the urethane cure reaction of NEPE propellant. Therefore, K_2SO_4 was selected for a suitable afterburning suppressant in this study.

2.2 Preparation of Propellants

Basically, NEPE minimum smoke propellants are formulated not to contain chlorine or fluorine to satisfy the level of AGARD smoke class A in secondary smoke. ZrC used as the combustion instability suppressant of the propellant in this study produces the solid zirconium oxide after combustion that is classified as primary smoke material. Also the potassium sulfate in propellant formulation could cause the increase of the primary smoke by the production of solid potassium carbonate in rocket plume after propellant combustion. The selected propellant formulations were based on the satisfaction of AGARD smoke class AA, in which AGARDP is less than 0.35 for primary smoke classification and AGARDS is higher than 90% for secondary smoke classification [3].

The basic propellant formulation S0, as shown in Table 2, consisted of 37.1 mass-% of polyethylene glycol (PEG) binder, 2.9 wt-% of additives as stabilizer, burning rate modifier and etc, 59 wt-% of nitramine oxidizer (34% of RDX and 25% of HMX), 1.0 wt-% of ZrC as combustion instability suppressant. PEG binder system consisted of 8.1 wt-% of PEG polymer cured with triisocyanate N-3200 and 29 wt-% of nitrate ester plasticizer. By applying K_2SO_4 as afterburning suppressant, six formulations S1–S6 were set up, where the content of potassium sulfate was varied in the range of 0.6–1.7%.

As shown in Table 2, propellants S0–S4 consist of RDX and HMX as nitramine oxidizers, but propellants S5 and S6 are formulated with 30% of HNIW and RDX. The HNIW/RDX formulations are calculated to have higher temperature in rocket chamber and exit as well as specific impulse ($T_{chamber}$, T_{exit}, I_{sp} in Table 2) than the HMX/RDX formulations, since HNIW is more energetic and has higher oxygen content than RDX or HMX. The product compositions at the nozzle exit for the HMX/RDX propellants S0–S4 are nearly similar. The HNIW/RDX propellants S5 and S6 are calculated to have slightly more mole fraction for CO and CO_2 but a little less for H_2 in the exit products compared to the HMX/RDX propellants.

In order to satisfy the level of AGARD primary smoke class A, the content of ZrC was varied from 0.5 to 1.0 wt-% in propellants. The AGARDP values of all formulations based on AGARD method [3] were found to be less than 0.35 that satisfies the level of primary smoke class A. The significant materials affecting AGARDP in these formulations are K_2CO_3 and ZrO_2 at nozzle exit plane. To investigate the effect of HNIW content in NEPE minimum smoke propellant on AGARDP, Figure 1 shows AGARDP variation with HNIW content in formulation consisting of 57.9% of nitramines (RDX and HNIW), 1.0% of ZrC and 1.1% of K_2SO_4. AGARDP was decreased with increase of HNIW content and shown to be nearly a constant value of 0.21 in propellant with more than 40% of HNIW. It was because the products

Table 1. Properties of potassium compounds.

Chemicals	Melting point [K]	Molecular weight (a)	No. of K per mole (b)	$c = 100b/a$
K_2SO_4	1342	174.3	2	1.15
K_2CO_3	1164	138.2	2	1.45
KNO_3	607	101.1	1	0.99
$KClO_4$	883	138.6	1	0.72
$KClO_3$	643	122.6	1	0.82
K_3AlF_6	1273	258.3	3	1.16

Table 2. Selected formulations, thermodynamic properties, and AGARDP of minimum smoke propellants S0–S6.

		S0	S1	S2	S3	S4	S5	S6
Ingredient [wt-%]	PEG binder	37.1	37.1	37.1	37.1	37.1	37.1	37.1
	Additives	2.9	2.9	2.9	2.9	2.9	2.9	2.9
	RDX	34	34	34	34	34	27.9	27.6
	HMX	25	24.4	24.4	24.4	24.4	0	0
	HNIW	0	0	0	0	0	30	30
	ZrC	1.0	1.0	0.8	0.6	0.5	1.0	0.7
	K_2SO_4	0.0	0.6	0.8	1.0	1.1	1.1	1.7
Mole fraction at nozzle exit[a)]	CO	0.2884	0.2875	0.2863	0.2850	0.2844	0.3009	0.2985
	CO_2	0.1171	0.1177	0.1186	0.1195	0.1199	0.1241	0.1258
	H_2	0.2406	0.2395	0.2385	0.2374	0.2369	0.1993	0.1969
	H_2O	0.1249	0.1253	0.1265	0.1277	0.1283	0.1330	0.1352
	N_2	0.2258	0.2252	0.2254	0.2256	0.2257	0.2355	0.2355
$T_{chamber}$[a)] [K]		2727	2708	2702	2697	2694	2867	2849
T_{exit}[a)] [K]		1174	1174	1175	1175	1176	1263	1266
I_{sp}[a)] [Ns kg^{-1}]		2387.9	2375.1	2372.2	2370.2	2369.3	2399.6	2389.8
AGARDP		0.2407	0.3228	0.3318	0.3420	0.3489	0.2558	0.3445
Motor No.		SM0	SM1	SM2	SM3	SM4	SM5	SM6

a) Theoretical value calculated from CEA code [15] at 6.89 MPa of chamber pressure, 0.1013 MPa of exit pressure, equilibrium condition and optimum nozzle expansion.

of gaseous potassium and KOH were increased and K_2CO_3 was decreased at nozzle exit with increase in HNIW as shown in Figure 2. Also K_2CO_3 was found not to exist at nozzle exit of solid rocket motor containing more than 40% of HNIW. But ZrO_2 mol percentage at nozzle exit was calculated to be nearly constant.

All propellant formulations were mixed in a vertical planetary mixer from B&P Co. in USA having 8 L volume and cured in an oven heated by hot water for 10 d at 323 K.

2.3 Standard Rocket Motor and Static Firing Test

A standard rocket motor as shown in Figure 3 was employed for the static firing test to investigate the flame appearance and IR irradiance of rocket plume. The rocket motor was loaded with a cylindrical propellant grain with 127.0 mm in inner diameter, 152.4 mm in outer diameter, and 279.0 mm in length. The expansion half angle of the nozzle exit was 15 degree. The propellant weight was about 2.6 kg per motor. All rocket motors were fired after conditioning for longer than 24 h at 298 K. Figure 4 shows the pressure vs. time curves measured during firing tests of SM0–SM6 rocket motors. The pressure was measured to be 7.0–8.5 MPa and the total burning time was checked to be 1.0–1.4 s as shown in Figure 4. And the pressure oscillation during combustion was not observed in even rocket

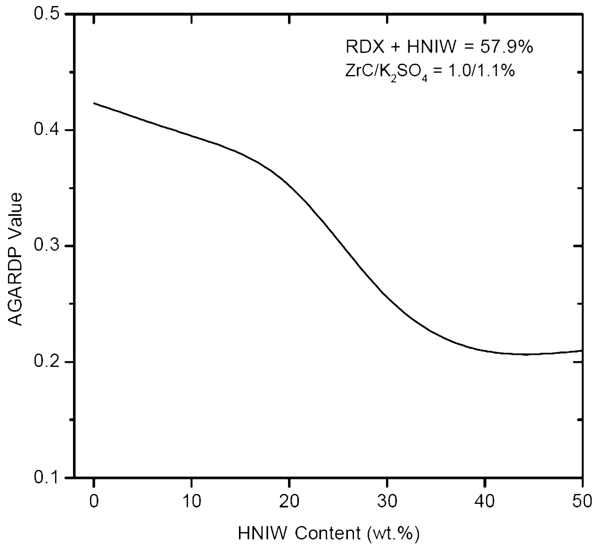

Figure 1. AGARDP variation according to the HNIW content.

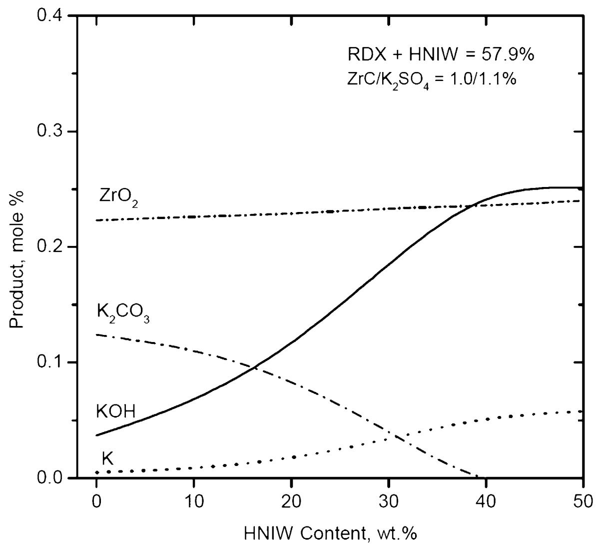

Figure 2. Mole percentage of potassium compounds and ZrO_2 at nozzle exit vs. HNIW content of propellant.

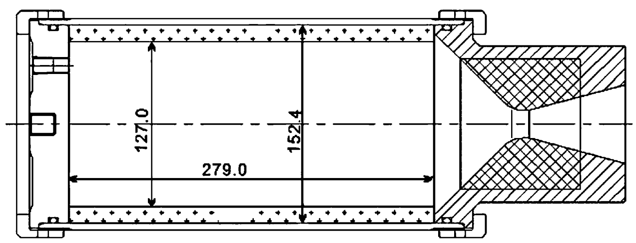

Figure 3. Configuration of the standard rocket motor (unit: mm).

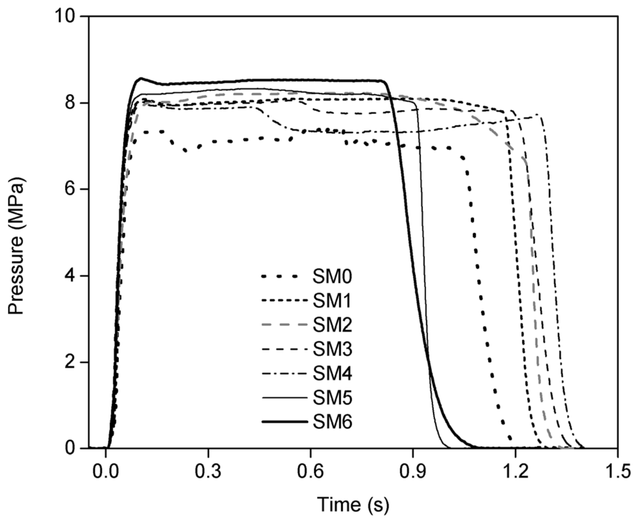

Figure 4. Chamber pressure vs. time of rocket motors.

motors with propellants less than 1.0% of ZrC as combustion instability suppressant. Moving pictures as well as IR irradiance of rocket plume were taken during the firing test.

2.4 Measurement of IR Irradiance

Several methods for the placement of spectrometer to measure the IR irradiance of rocket plume are provided in literature [3,14]. Figure 5 shows the arrangement of rocket motor and IR spectrometer, where the IR signature was positioned 131 cm from the rocket nozzle exit and the length from IR spectrometer to plume was 317 cm. The FT-IR spectrometer was a MR304LN Spectro Radiometer with 75 mrad of FOV (fields of view) from ABB in Canada. Therefore, the diameter of test spot area is 23.8 cm in the axis line of the plume. Liquid nitrogen was used to cool the IR detector and the neutral density filter 1/100 was applied in order to compare the IR intensity of each propellant for the mid-range wavelength of 2–6 μm.

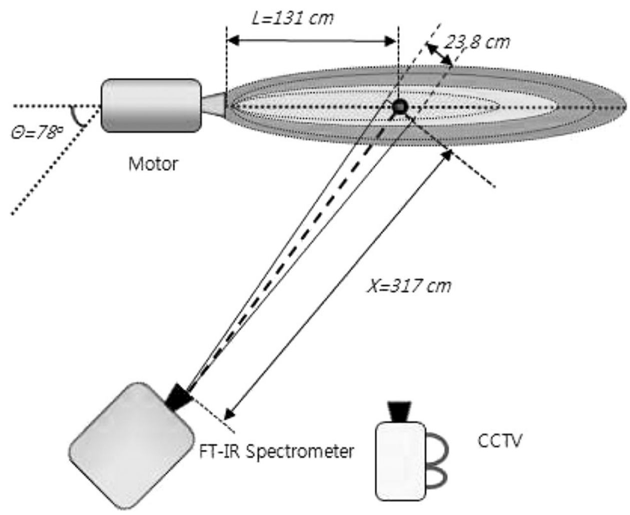

Figure 5. Arrangement for IR signature measurement.

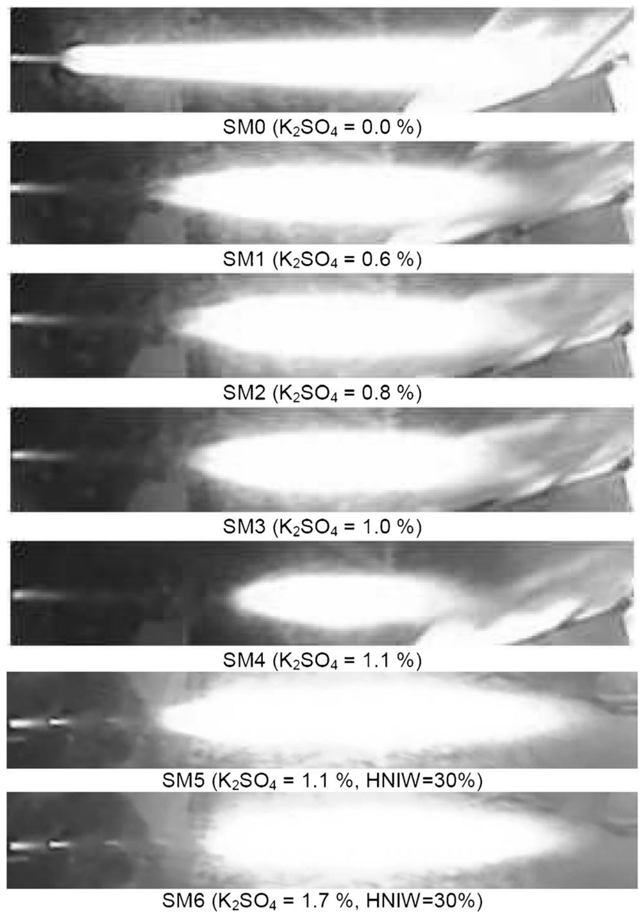

Figure 6. Photos of plumes after nozzle of rocket motors.

3 Results and Discussion

3.1 Plume Configuration

The plume shapes during combustion of rocket motors SM0–SM6 are shown in Figure 6 captured from the video pictures. As expected, the plume flame length of the SM0 motor charged with propellant without K_2SO_4 was found to be the longest and the flame lengths for the SM0–SM4 motors decreased with increasing K_2SO_4 content in the

HMX/RDX propellants. But the flame length of the SM5 motor with HNIW/RDX propellant was shown to be longer and wider than that of the SM4 motor with HMX/RDX propellant even though a similar amount of K_2SO_4 was used. The flame length of the SM6 motor with 1.7% of K_2SO_4 was slightly shorter than that of the SM5 motor with 1.1% of K_2SO_4 in HNIW/RDX formulation.

The plume flames are defined as shown in Figure 7 to access the flame length from video picture [6]. The exhaust plume could be divided into two flames, namely the primary and secondary flames. The primary flame is formed by the exhaust gas from the rocket motor without any influence of the ambient atmosphere. The secondary flame is formed by mixing of the primary flame gas with the ambient air and afterburning of this gas mixture. Lp and Ls in Figure 7 stand for the length from the nozzle exit plane to the starting point of the primary and the secondary flame lengths. Lt in Figure 7 means the sum of Lp and Ls.

Each plume flame length is given in Table 3. For the HMX/RDX propellants in motors SM0–SM4, the primary flame length was increased but the secondary flame length was reduced with increasing K_2SO_4 content. The Lp and Ls of the SM0 rocket charged with S0 propellant, which didn't contain K_2SO_4 were measured to be 30 cm and 323 cm. But Lp and Ls of the SM4 rocket charged with S4 propellant containing 1.1% K_2SO_4 were measured to be 117 cm and 149 cm, respectively

The secondary flame length of the SM5 motor with HNIW/RDX propellant was measured to be 257 cm, which is much longer than that of the SM4 motor (149 cm) with HMX/RDX propellant although the content of potassium sulfate was similar. This result could be explained by the fact that the secondary flame causes plume afterburning and a higher energetic propellant causes a stronger afterburning [14]. For the HNIW/RDX propellants, the secondary flame length of the SM6 motor loaded with 1.7% K_2SO_4 was slightly reduced compared to the SM5 motor loaded with S5 propellant containing 1.1% of K_2SO_4 as shown in Table 3.

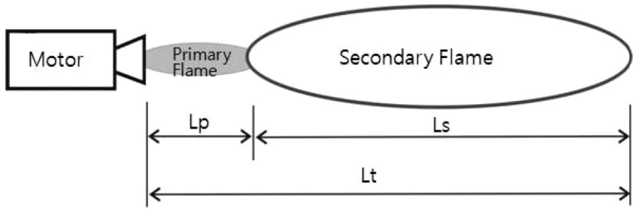

Figure 7. Definition of the flame length of rocket plume.

Table 3. Flame length of rocket plume.

Motor No.	Lp [cm]	Ls [cm]	Lt [cm]
SM0	30	323	353
SM1	82	230	312
SM2	94	212	306
SM3	100	194	294
SM4	117	149	266
SM5	83	257	340
SM6	109	224	333

3.2 IR Irradiance Analysis

The IR irradiance of the SM0 rocket motor, which was measured during firing test is illustrated in Figure 8. The IR plume spectrum shows a relatively stable figure during combustion after 0.3 s similar to that of the data reported by Devir [16]. To analyze the gas components, the IR irradiance of the SM0 motor plume vs. wavelength measured at 0.6 s after the beginning of combustion is shown in Figure 9. The point "a" of 2–2.5 μm wavelength in Figure 9 is assigned to the broad peak of the bending vibration of OH radical and H_2O. The point "b" of 2.5–3.0 μm wavelength is assigned to the stretching peak of CH com-

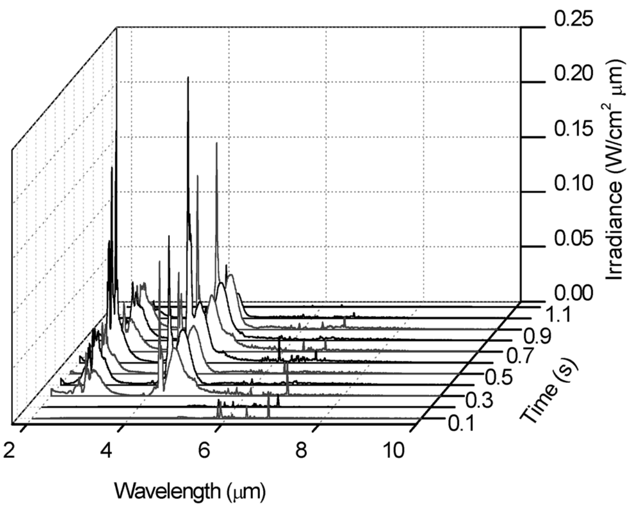

Figure 8. IR irradiance of the SM0 motor during combustion.

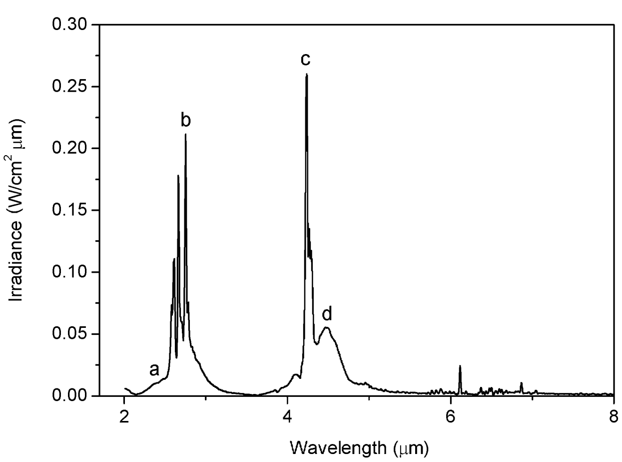

Figure 9. Analysis of IR spectrum at 0.6s after ignition of the SM0 motor.

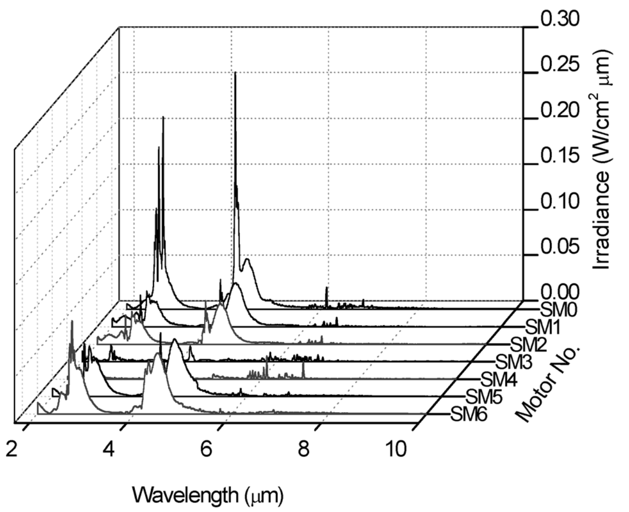

Figure 10. Comparison of IR irradiance measured at 0.6 s after ignition of solid rockets according to the propellant formulations.

pounds. The point "c" of 4.2 μm wavelength is assigned to the asymmetric vibration peak of CO and CO radical and the symmetric vibration of CO_2 occurs in 4.5 μm wavelength at the point "d" in Figure 9.

Figure 10 shows the IR intensity of the rocket plume measured at 0.6 s after ignition of seven rocket motors. The IR intensity was found to be reduced with increasing K_2SO_4 content in the propellants of rocket motors SM0–SM4. The IR irradiance peaks of SM5 and SM6 motors with HNIW/RDX propellant were shown to be fairly higher than those of SM2–SM4 motors even though they are smaller than that of SM0 motor without afterburning suppressant.

In order to quantitatively access the IR intensity of each motor, the total IR irradiance of mid-range wavelength, 2–6 μm was calculated by summation of each curve integral of 0.1 s interval for the total burning time as shown in Figure 8. The IR rate is defined as:

$$\text{IR rate } (\%) = 100 \times \frac{\text{IR irradiance of each motor}}{\text{IR irradiance of SM0 motor}}.$$

The results are shown in Table 4. The total IR intensity decreased with increasing K_2SO_4 content in the propellants of rocket motors SM0–SM4 and the IR rate of the SM4 motor containing 1.1% of K_2SO_4 in the propellant was found to be reduced to 22.64% compared to the SM0 motor containing the propellant without afterburning suppressant. The IR rate of the SM5 motor with HNIW/RDX propellant was 66.68%, which is about triple compared to SM4 with HMX/RDX propellant even though it contains a similar amount (1.1%) of K_2SO_4. The more energetic propellants with higher flame temperatures and specific impulses were found to produce much more afterburning and IR irradiance.

Table 4. Total IR irradiance of rocket plume.

Motor No	Irradiance [W cm^{-2}]	IR rate [%]
SM0	3.679×10^{-1}	100
SM1	1.921×10^{-1}	52.22
SM2	1.671×10^{-1}	45.42
SM3	1.024×10^{-1}	27.83
SM4	0.883×10^{-1}	22.64
SM5	2.453×10^{-1}	66.68
SM6	2.072×10^{-1}	56.32

4 Conclusions

The minimum smoke propellant with nitrate ester polyether binder system and nitramine oxidizers was studied for the afterburning and IR irradiance. Potassium sulfate was selected as the afterburning suppressant to NEPE minimum smoke propellant since it has no influence on the processibility and burning characteristic of the propellant. The propellants were formulated to satisfy the level of AGARD smoke class AA by tailoring the content of potassium sulfate and zirconium carbide in the propellant. Videos and IR irradiance were measured and accessed during the static firing tests of solid rocket motors loaded with seven different contents of potassium sulfate. The total IR irradiance of the HMX/RDX propellant with 1.1% of potassium sulfate was reduced to about 23% compared to the propellant without afterburning suppressant due to the inhibition of afterburning. Additionally, the total IR irradiance of the HNIW (30%)/RDX propellant was found to be almost three times higher than that of the HMX/RDX propellant although the content of potassium sulfate was similar.

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