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Comparative Study on Infrared Irradiance Emitted from Standard and Real Rocket Motor Plumes

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Abstract: The infrared irradiance signature from exhaust plume is essential for the design of solid rocket motors. To overcome the difficulty of conducting experiments using real rocket motors, experimental studies were carried out to compare standard rocket motors and real rocket motors of the same propellant. The static firing tests on standard and real rocket motors of NEPE and HTPB propellants were conducted. Despite different rocket motor size and methodology of spectro-radiometric measurement, the spectral characteristics of the infrared irradiance signature for both rocket motors were quite similar. The standard and real rocket motors of HTPB propellant showed similar tendency of steady infrared irradiance emission throughout the combustion, whereas both rocket motors of NEPE propellant showed a rapid emission in the midstream of combustion. The total infrared irradiance of NEPE was about 55 % less than that of HTPB propellant for both standard and real rocket motor experiments. Additionally, the relative amounts of chemical products produced during propellant combustion came out to be similar for both rocket motors. The experimental results indicated that the spectral characteristics of infrared irradiance and combustion products were quite similar for different sized rocket motors of same propellant and that a correlation of infrared irradiance signature exists between small-sized standard rocket motors and real rocket motors. Thus, the spectral characteristics of real rocket motors could be reasonably estimated from the results of standard rocket motors.

Keywords: Rocket exhaust plume · FT-IR irradiance · Solid rocket motor · Combustion products

1 Introduction

The exhaust plume is produced from the rocket motor due to the afterburning of the combustion products as they expand through the nozzle into the surrounding atmosphere. The smoke and infrared (IR) signatures emitted from the plume are used for the detection and tracking of the target that tactical missiles are required to have low plume irradiance and minimum smoke for survivability [1–3]. The plume irradiance originates from chemical reactions in the burning process and the afterburning phase where unburned combustion products react with ambient air [4,5]. Thus, the spectral characteristics of the irradiance signature are determined by the propellant formulation and the rocket motor of each propellant type has its own distinct plume irradiance. The IR irradiance signature contains spectral information of the target such as plume propagation, IR emission spectrum and gaseous combustion products [6–8]. Therefore, many experimental studies have been conducted to analyze the spectral characteristics of IR irradiance signature in detail. Blanc [9] used a spectrometer to measure the IR irradiance spectral characteristics of solid rocket motors of composite and double-base propellants. Devir [10] used a Fourier-transform infrared (FT-IR) spectrometer to measure the IR irradiance intensity of a small solid rocket motor. Wang [11] also used a FT-IR spectrometer to measure the IR irradiance signature of three kinds of double-base propellants.

However, conducting experimental studies using real rocket motor has many constraints such as a large-scale test site, high experimental cost and difficulty in IR irradiance measurement, which have limited the number of studies. Instead, experiments using flame, lab-scale rocket motors and standard rocket motors were conducted to simulate real rocket motors [7,10,12,13]. It would thus be of interest to determine the relationship between real rocket motors and standard rocket motors.

The objective of this study was to obtain a correlation of IR irradiance signatures between standard rocket motors and real rocket motors. Two kinds of solid composite propellants were selected for a comparative study and static

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firing tests of standard and real rocket motors of each propellant were conducted. The emitted IR irradiance signature ranging from 2 to 15 μm was measured with a FT-IR spectro-radiometer [7,14]. From the measured IR irradiance data, the spectral information contained in each rocket motor was analyzed and compared to find a correlation between standard and real rocket motors.

2 Experimental Section

2.1 Experiemental Set-Up

2.1.1 Propellant Formulation

Two kinds of solid propellants, minimum smoke NEPE (nitrate ester plasticized polyether) and reduced smoke HTPB (hydroxyl-terminated polybutadiene), were selected for this study. The NEPE propellant is composed of RDX/HMX oxidizer and PEG (polyethylene glycol) binder and the HTPB propellant contains AP oxidizer and HTPB binder. The formulation of both propellants is listed in Table 1.

For simplification, the standard and real rocket motors of the NEPE propellant were abbreviated as NEPE-S and NEPE-R. The standard and real rocket motors of the HTPB propellant were abbreviated as HTPB-S and HTPB-R, respectively.

Table 1. Propellant formulation.

Ingredient	NEPE [%]	Ingredient	HTPB [%]
RDX/HMX	57.0	AP	86.5
PEG	9.5	HTPB	12.5
Plasticizers	29.5	ZrC	1.0
ZrC	1.0		
Additives	3.0		

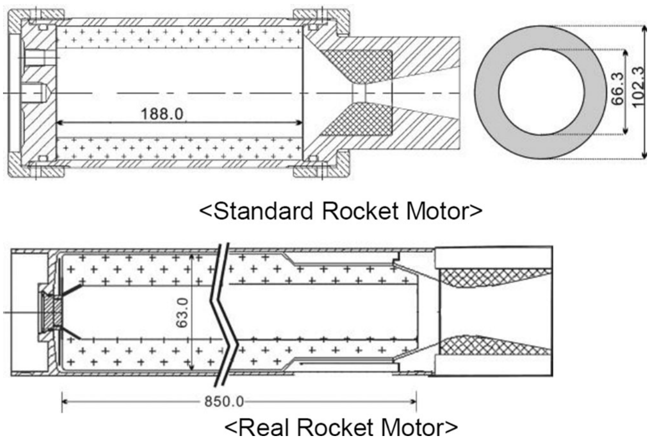

Figure 1. Schematic diagrams of solid rocket motors.

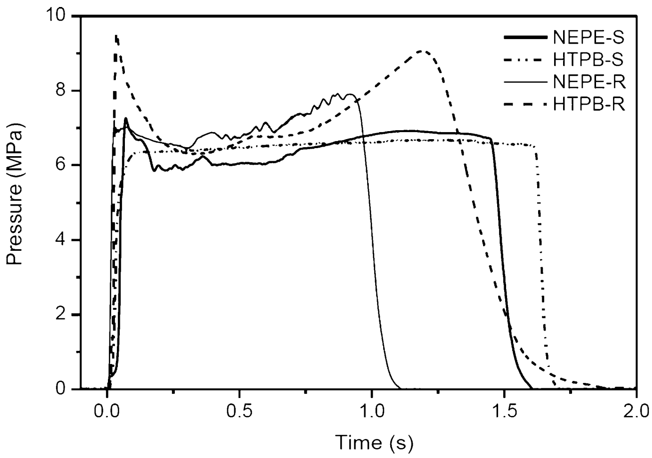

Figure 2. Chamber pressure vs. time of rocket motors.

2.1.2 Rocket Motor

For the comparative study of different rocket motor sizes, standard and real rocket motors loaded with solid propellant were used. The schematic diagrams of rocket motors are shown in Figure 1. The propellant grain of the standard rocket motor was cylindrical in shape with an inner diameter of 66.3 mm, an outer diameter of 102.3 mm, and a length of 188 mm. In contrast, the grain of the real rocket motor was star-shaped with 63 mm in outer diameter and 850 mm in length. The web thickness and number of star apexes in propellant grain were 13 mm and 8 for the NEPE-R motor, and 17 mm and 6 for the HTPB-R motor.

2.1.3 Static Firing Test

The plume signatures from standard and real rocket motors of both propellants were measured with the static firing test. Figure 2 shows the chamber pressure of standard and real rocket motors during the combustion. The average chamber pressure was about 6.5 MPa for the standard rocket motor and 7.3 MPa for the real rocket motor. The pressure spike at the beginning of combustion for HTPB-R motor in Figure 2 was taken place due to the erosive burning.

2.2 Test Instrument

A FT-IR spectro-radiometer of type ABB MR304LN was used to measure the IR irradiance signature emitted from exhaust plume. It featured simultaneous data acquisition from the IR detectors of MCT and InSb detectors which covered the spectral range from 2 μm to 15 μm [15]. The FOV (field of view) of the spectro-radiometer was 75 mrad and the spectral resolution was set to 4 cm^{-1}. Figure 3 shows the placement of the spectro-radiometer for the test. The spectro-radiometer was set differently for standard rocket and real rocket motors referring to previous studies [7,9–11]. For standard rocket motor tests, the spectro-radiometer was 3.17 m away from the axis line of the plume at a detection angle of 68.5°. The targeted plume spot was 1.31 m

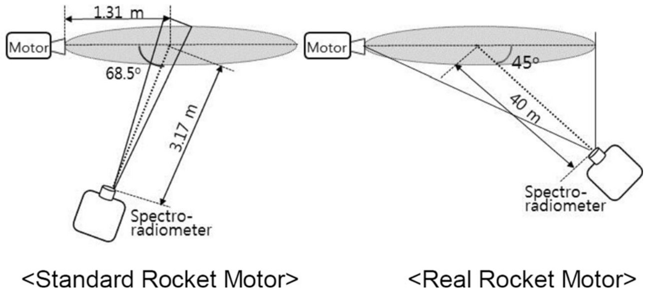

Figure 3. Placement of FT-IR spectro-radiometers.

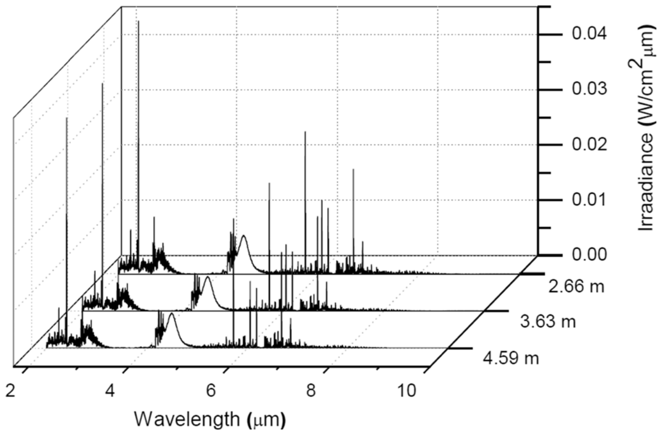

Figure 4. IR irradiance of NEPE-S at different distances.

from the nozzle exit. In contrast, the spectro-radiometer was 40 m away from the plume at an angle of 45° to measure the entire plume in real rocket motor tests.

The calibration of the spectro-radiometer was conducted using blackbody and background correction. The IR signature from blackbody source and background of the targeted plume spot were both measured with the FT-IR spectro-radiometer. These data were used to calculate the calibrated IR irradiance using FT-IR software called FTSW500. As a result, measurement distance and atmospheric absorption calibrated IR irradiance could be obtained from measured raw spectroscopic data.

The experiment was conducted in advance to confirm the calibration of measurement distance and atmospheric absorption using background correction. The standard rocket motor of NEPE propellant was measured at different distances of 2.66 m, 3.63 m, and 4.59 m from the spectro-radiometer. The measured IR irradiances are shown in Figure 4.

The results shown in Table 2 indicated that all three experiments have similar IR irradiances despite different measurement distances. Thus, these results clearly showed that the measurement distance and atmospheric absorption were well calibrated using background correction.

Table 2. IR irradiance of NEPE-S.

Propellant	Distance [m]	Irradiance [$W cm^{-2} \mu m^{-1}$]
NEPE-S	2.66	0.00498
NEPE-S	3.63	0.00448
NEPE-S	4.59	0.00453

Table 3. CEA calculated mole fraction at nozzle exit.

Propellant	H_2O	H_2	HCl	CO	CO_2
NEPE	0.1079	0.2557	–	0.2979	0.1177
HTPB	0.4013	0.0792	0.1914	0.0777	0.1494

2.3 Analysis Method

IR emission spectroscopy was applied in this study to analyze the IR irradiance signature emitted from exhaust plume. This methodology analyses the plume characteristics and the combustion products using a FT-IR spectro-radiometer [16]. Thus, the important IR irradiance participating species were analyzed [14].

In addition to the IR emission spectroscopy, the NASA Chemical Equilibrium with Applications (CEA) was applied to perform the theoretical calculation of combustion products at the nozzle exit [17]. Table 3 shows the calculated mole fraction by CEA code at a chamber pressure of 6.89 MPa and an exit pressure of 0.1013 MPa in equilibrium.

3 Results and Discussion

3.1 Plume Irradiance

The plume emitted from standard rocket and real rocket motors of NEPE and HTPB propellants were detected with a FT-IR spectro-radiometer at static firing tests. The total burning times were not similar since the rocket motor size and propellant formulation were different. The burning

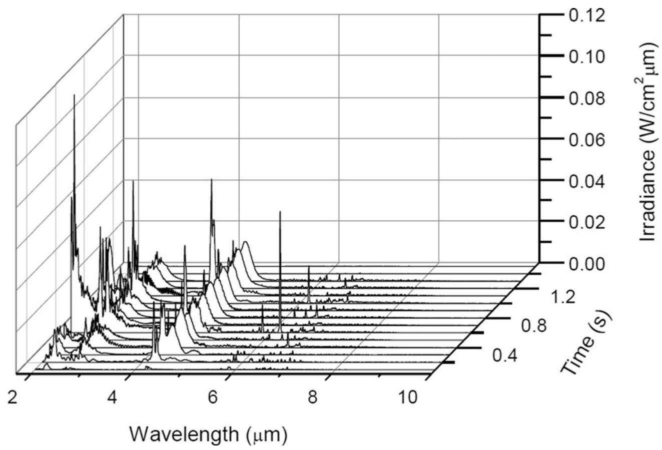

Figure 5. Time-resolved IR spectra of NEPE-S.

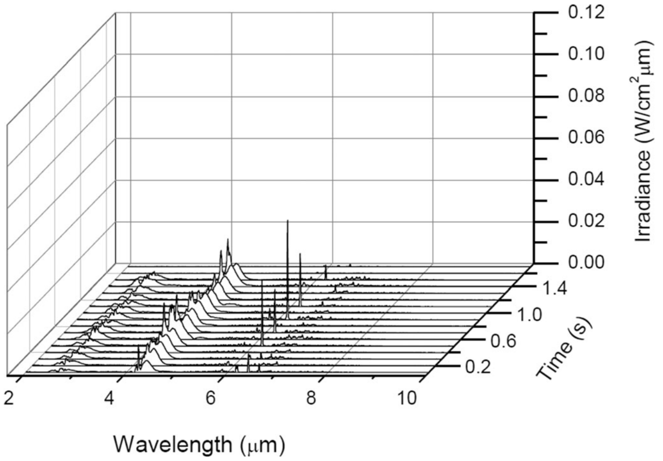

Figure 6. Time-resolved IR spectra of HTPB-S.

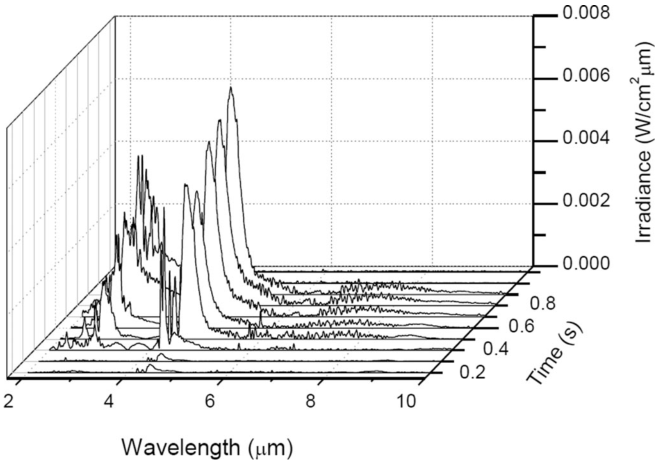

Figure 7. Time-resolved IR spectra of NEPE-R.

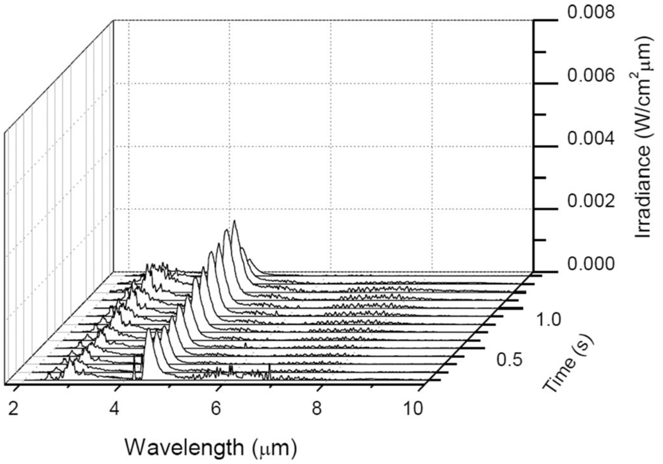

Figure 8. Time-resolved IR spectra of HTPB-R.

times of NEPE-S and HTPB-S were 1.55 s and 1.97 s, respectively, and the burning times of NEPE-R and HTPB-R were 0.97 s and 1.35 s, respectively. Thus, a comparative study was conducted according to the IR irradiance measured during the total burning times.

Table 4. IR irradiance and IR rate of rocket motors.

Propellant	NEPE-S	HTPB-S	NEPE-R	HTPB-R
Total irradiance [W cm^{-2}]	1.836×10^{-1}	0.967×10^{-1}	0.264×10^{-1}	0.146×10^{-1}
IR rate [%][a)]	100	52.7	100	55.3
Propellant weight [kg]	1.5		3.7	

a) IR rate $=100\times\frac{\text{total IR of HTPB propellant}}{\text{total IR of NEPE propellant}}$.

A set of time-resolved IR spectra obtained from the rocket motors are shown in Figure 5, Figure 6, Figure 7, and Figure 8. The IR irradiance of NEPE and HTPB propellants emitted from standard rocket motors are shown in Figure 5 and Figure 6. The IR irradiances emitted from real rocket motors are shown in Figure 7 and Figure 8.

Figures 5–8 clearly indicate that the plume irradiances differ according to the propellant type. For both standard rocket motor and real rocket motor experiments, NEPE propellant had a higher IR irradiance compared to HTPB propellants at every wavelength. Specifically, the mid-infrared (ca. 2–6 µm) region of spectra was significantly reduced in HTPB propellants. This has occurred due to the different amounts of combustion products emitted during the propellant combustion.

Each IR spectrum was integrated to calculate the total IR irradiance emitted during combustion. In addition, the IR rate was calculated by comparing the total IR irradiance of HTPB to that of NEPE propellant. The results of calculation are listed in Table 4.

Although the propellant weight of the real rocket motor is comparatively heavier than that of the standard rocket motor, the total IR irradiance of standard rocket motor came out to be much greater than that of real rocket motor due to different-distance placement of the spectroradiometer for the measurement. However, the IR rate between the NEPE and HTPB propellants were almost similar for both standard rocket motor and real rocket motor. The IR rate of the HTPB propellant was 52.7 % for the standard rocket motor and 55.3 % for the real rocket motor. Thus, the total IR irradiance difference between propellants of real rocket motor could be inferred from the measurement of standard rocket motor.

From Figures 5–8, it can be seen that the IR irradiance emitted from the exhaust plume varies throughout the total burning time. Both standard and real rocket motor of NEPE and HTPB propellants had different IR intensities at every 0.1 s interval of the burning time. Thus, the emitted IR rate was calculated to see the aspect of plume irradiance during combustion. Figure 9 shows the IR emission rate of NEPE and HTPB propellant standard rocket motors. Figure 10 shows the emission rate of real rocket motors.

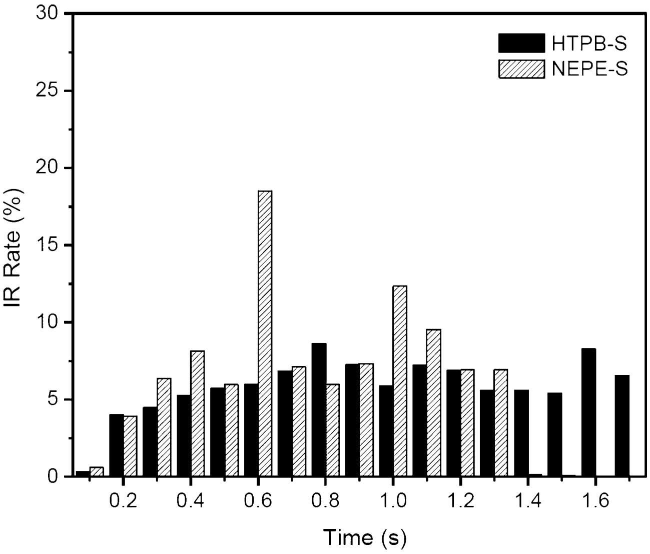

Figure 9. IR emission rates of standard rocket motors.

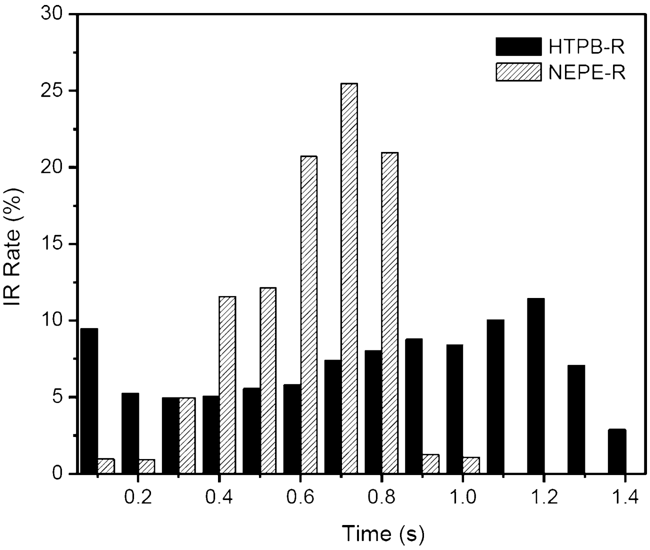

Figure 10. IR emission rates of real rocket motors.

According to both, standard and real rocket motor test, the HTPB propellant showed overall steady emission throughout the total burning time. In contrast, the IR emission rate from the NEPE propellant rocket motors was unstable compared to the HTPB propellant and most of the IR irradiance was rapidly emitted during 0.6–1.1 s for standard rocket motor and 0.4–0.8 s for real rocket motor. Thus, the results indicated that the similar aspect of IR emission rate exists between standard and rocket motor of same propellants.

3.2 Combustion Products Analysis

The exhaust plume is developed during the propellant combustion due to the after-burning process of fuel-rich

Table 5. Combustion mechanism.

$^{\bullet}$OH(radical)$^{\bullet}$OH(radical)$\leftrightarrow$$^{\bullet}$O(radical) + $\mathbf{H_2O}$(g)[a]
$^{\bullet}$OH(radical) + H_2(g)$\leftrightarrow$$^{\bullet}$H(radical) + $\mathbf{H_2O}$(g)
$^{\bullet}$OH(radical) + CO(g)$\leftrightarrow$$^{\bullet}$H(radical) + $\mathbf{CO_2}$(g)
$^{\bullet}NH_4ClO_4$(radical)$\rightarrow$$NH_3$(g) + **HCl**(g) + $2O_2$(g)
$C_xH_yO_z$(binder, s) + O_2(g)$\rightarrow$$\mathbf{CO}^{\bullet}$(radical) + **CO**(g) + $\mathbf{CO_2}$(g) + $\mathbf{C_xH_y}$(g)
ZrC(s)[b] + $2O_2$(g)$\rightarrow$$\mathbf{ZrO_2}$(s) + $\mathbf{CO_2}$(g)

a) (g): Gas phase. b) (s): Solid phase.

Table 6. Spectral range of main species.

Species	Spectral range [μm]
C_xH_y	2.50–3.00 (stretching peak of CH compounds)
H_2O	2.71–3.43 (bending vibration peak of OH and H_2O)
HCl	3.24–4.12 (HCl or HCl–H_2O)
CO_2	4.17–4.22, 4.29–4.55 (asymmetric vibration peak of CO_2)
CO	4.45–4.84 (asymmetric vibration peak of CO)
ZrO_2	4.85–5.00 (metal oxide or metal hydroxide)

products. The incomplete combustion of H_2 and CO gases in rocket plume participate in the oxidative reaction with atmospheric air and produce H_2O and CO_2, which are known as main emitters of IR intensity [4]. Additionally, gas components produced during the combustion of NEPE and HTPB propellant emit IR intensity. Table 5 shows the combustion mechanism of the propellants and the combustion products measurable using IR spectroscopy are printed in bold. Each species has its characteristic emission band as listed in Table 6 [7].

Figure 11 shows the IR spectrum of NEPE-S at a burning time of 0.6 s and the emission amounts of each species were measured according to its characteristic spectral range. The amounts of main species from exhaust plume were measured at every time interval of 0.1 s and these were compared relatively to the amount of species mea-

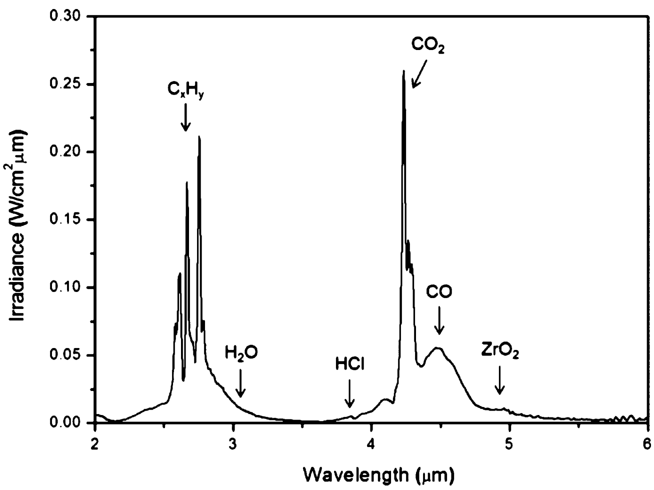

Figure 11. Characteristic spectral profile of NEPE-S at a burning time of 0.6 s.

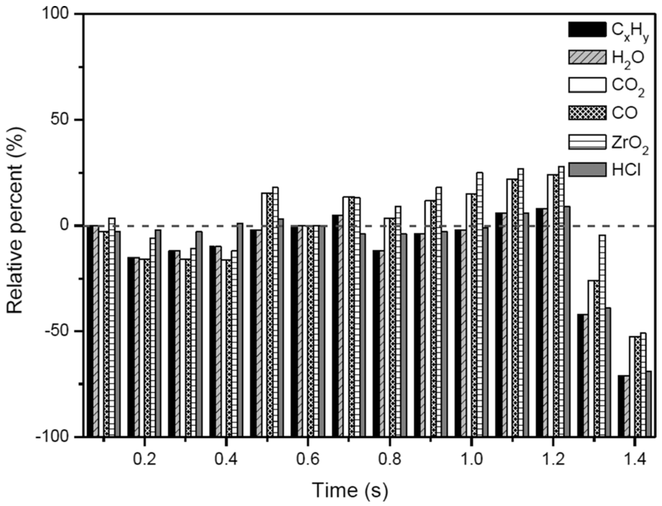

Figure 12. Time-resolved combustion products of HTPB-R.

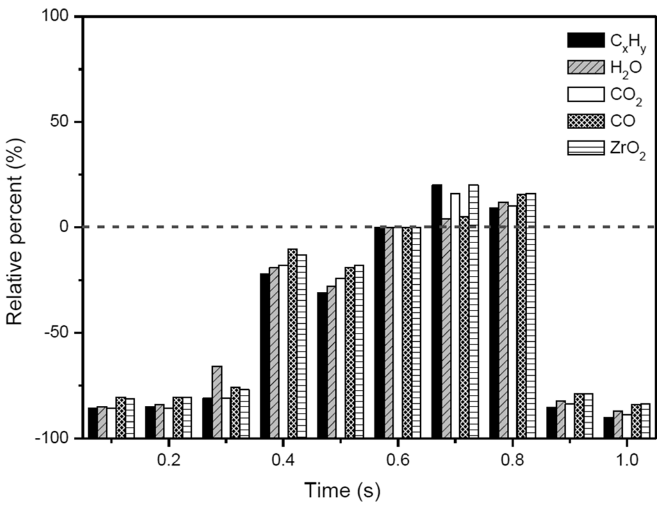

Figure 13. Time-resolved combustion products of NEPE-R.

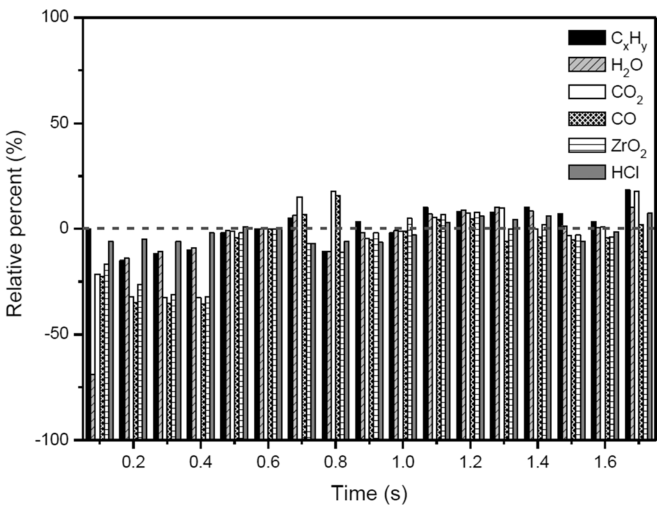

Figure 14. Time-resolved combustion products of HTPB-S.

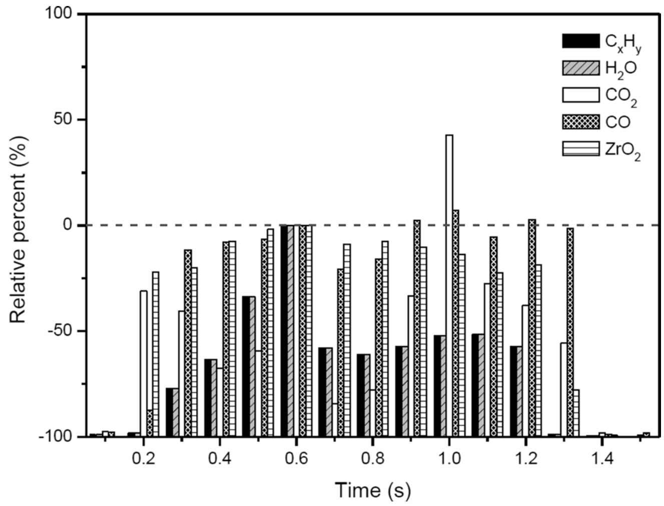

Figure 15. Time-resolved combustion products of NEPE-S.

sured at the reference burning time of 0.6 s. The results are shown in Figure 12, Figure 13, Figure 14, and Figure 15.

The main combustion products are the main emitters of IR spectrum that the relative amounts of emission throughout burning time show similar combustion tendency compared to the IR emission rate shown in Figure 5, Figure 6, Figure 7, and Figure 8. The amounts of species emitted from standard and real rocket motor of HTPB propellants were relatively stable. In contrast, the emission amounts of species were unstable for both rocket motors of NEPE propellant. The relative amounts and presence of species between NEPE and HTPB propellants came out to be similar for both standard and real rocket motor measurements. For example, HCl, which is known as a combustion product of HTPB propellant combustion, was only measured in standard and real rocket motors of HTPB propellant [6].

The measurement of combustion products is of importance to identify the solid propellant because each propellant has different combustion products according to propellant formulation. The similar results on amounts and presence of combustion products emitted from both standard and real rocket motors of same propellants indicated that the comparative study between standard and real rocket motor in addition to IR spectroscopy is reasonable.

4 Conclusions

An experimental study on the IR irradiance signatures emitted from exhaust plume of standard and real rocket motors was conducted. IR spectroscopy was used to analyze the IR spectrum and combustion products in this study.

Despite different rocket motor size, the results indicated that the spectral characteristics of IR irradiance signature of standard rocket motor and real rocket motor were quite similar. Specifically, combustion tendency, total IR irradiance, and combustion products were found to be similar between standard and real rocket motors of same propellant. The emitted amounts of species and IR emission rate of HTPB propellant were stable throughout total burning time, whereas the emission of NEPE propellant was unstable. The relative IR irradiance between HTPB and NEPE propellant was also similar for both standard and real rocket motor tests.

According to the experimental results obtained from this study, it is suggested that the correlation of the IR irradiance signature exists between the standard rocket motor and real rocket motor. Thus, the spectral characteristics and combustion products emitted from real rocket motor could be reasonably estimated from the results of standard rocket motor. Since conducting an experiment using real rocket motor has many constraints, it is suggested that the standard rocket motor could be used to study the characteristics of IR irradiance signature and combustion products of real rocket motor, which is comparatively easier to conduct experiments.

Acknowledgments

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FULL PAPERS

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