Short Communication

Propellants, Explosives, Pyrotechnics

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Combustion of Ytterbium Metal

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Dedicated to Dr. Bernard E. Douda on the occasion of his retirement and in appreciation of his contributions to pyrotechnics

Abstract: Ytterbium metal powder burns with a luminous vapor phase diffusion flame in oxygen. Consolidated stoichiometric mixtures with both polytetrafluoroethylene and hexachloroethane upon ignition yield intense luminous flames. With UV/Vis spectroscopy of the combustion flames Yb, YbO, YbCl, and YbF species have been identified contributing to the selective emission in the green spectral range. The flame temperatures of ytterbium combustion in oxygen and with halocarbon based oxidizers are in the same range as for comparable magnesium based systems.

Keywords: Ytterbium · Vapor-Phase combustion · Lanthanides · Pyrolants · UV/Vis spectroscopy

1 Introduction

Magnesium is the most important metallic fuel in pyrotechnic compositions. It is mainly used in signaling [1] and illuminating compositions [2] as well as in black body flare compositions for infrared decoy flares [3]. Its supremacy over many other metallic [4] fuels stems from its high combustion enthalpy and a low boiling point and very high boiling points of its oxidation products known as compliance with Glassman's criterion for metal combustion which enables extended vapor-phase diffusion flames [5].

In research for other metals compliant with Glassman's criterion it has been found that the rare earth metals: samarium, europium, thulium and ytterbium should in principle yield luminous vapor-phase diffusion flames with oxygen and fluorine based oxidizers as well (Table 1) [6].

However there is very little prior knowledge on the combustion properties of the lanthanide metals. The impact initiation behavior of mixed metal (Ce, La, Sm, Nd) fragments and their alleged use in thermites has been reported [7–9]. Sturman proposed to use lanthanide metals as possible fuels to obtain colored sparks in firework applications [10]. The oxidation of scandium, yttrium and lanthanum has been investigated by Ivanov recently [11].

As ytterbium shares very similar properties with magnesium and is not very prone to corrosion [12] it was decided to investigate its combustion behavior under oxygen and in combinations with halocarbon type oxidizers.

Under pressurized oxygen (0.2 MPa) in a window bomb [17] bulk layers of ytterbium powder burn with formation of an orange glowing oxide melt with a green luminescent vapor-phase flame segregated above (Figure 1a). The green gas phase flame is surrounded by aerosol clouds yielding a bluish scatter. The temperature of the flame as determined by NIR spectroscopy [17] ranges between 2000–2200 K and is even below the solidification temperature of the oxide (mp: 2450 K). This calls for a significant dissociation of the oxide already in this temperature range which is confirmed by the spectroscopic detection of YbO in the green flame with distinct bandheads at $\lambda = 477$ and 485 nm (Figure 2) [13]. In line with the visual perception of the green flame the UV/Vis spectrum of the Yb/O_2 flame reveals a series of lines and bands that on top of YbO can be assigned to ytterbium [14].

To probe the combustion behavior of ytterbium as a fuel in pyrolants it was tested in stoichiometrically balanced combinations with both polytetrafluoroethylene and hexachloroethane as shown below.

$$2\ Yb_{(s)} + C_2Cl_{6(s)} \rightarrow 2\ YbCl_{3(s)} + 2\ C_{(s)} + 1719.4\ \text{kJ} \quad (1)$$

$$4n\ Yb_{(s)} + 3\ (C_2F_4)_n \rightarrow 4n\ YbF_{3(s)} + 6n\ C_{(s)} + n\ 3850.4\ \text{kJ} \quad (2)$$

In comparison to analogous reactions of magnesium with the same oxidizers the gravimetric reaction enthalpy is lower due to the much higher atomic mass of ytterbium. However due to the high density of ytterbium the volumetric reaction enthalpies are comparable to magnesium-based compositions (Table 2).

Consolidated pellets of mixtures **1** and **2** (95% TMD) are easily ignited with a non-luminous propane torch and burn steadily. The linear burn rates under ambient pressure at-

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Table 1. Physical properties of Mg, Sm, Eu, Tm, Yb and their oxides and fluorides.

Metal	Density /g cm^{-3}	Mp /°C	Bp /°C	Δ_{melt}H /kJ mol^{-1}	Δ_{vap}H /kJ mol^{-1}	Bp Oxide /°C	Bp Fluoride /°C
Mg	1.738	649	1105	9.0	127	3600	2264
Sm	7.520	1072	1788	8.6	166	4024	2331
Eu	5.243	822	1525	9.2	144	3920	2389
Tm	9.321	1545	1944	16.8	191	3945	2312
Yb	6.965	824	1192	7.7	128	4070	2307

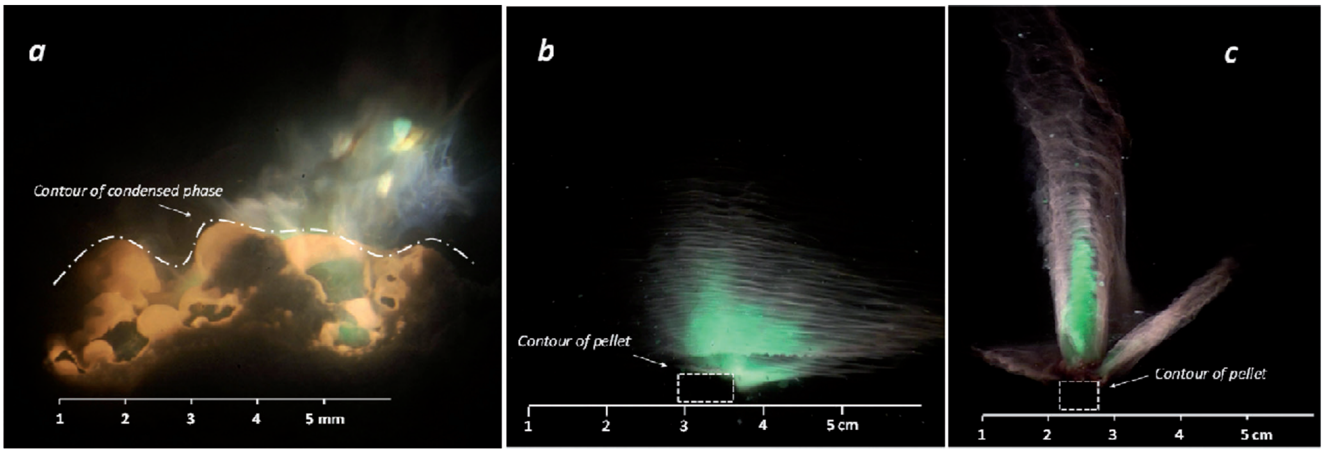

Figure 1. a) Combustion flame of ytterbium powder under O_2 (0.2 MPa); b) Combustion flame of Yb/polytetrafluoroethylene (PTFE); c) Combustion flame of Yb/hexachloroethane (HC).

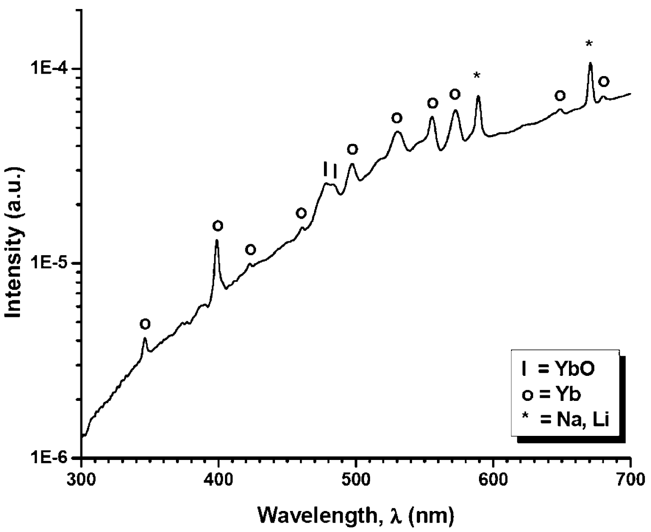

Figure 2. UV/Vis Spectrum of Yb/O_2 flame.

Table 2. Calculated Reaction enthalpy, $\Delta_f H$ (kJ g^{-1}), (kJ cm^{-3}) and theoretical maximum density of compositions for stoichiometric mixtures of Yb and Mg with hexachloroethane and Polytetrafluoroethylene.

Metal	Metal/Oxidizer (wt.-%/wt.-%)	$\Delta_f H$ /kJ g^{-1}	$\Delta_f H$ /kJ cm^{-3}	TMD /g cm^{-3}
1	Yb/C_2Cl_6 (59/41)	2.9	10.3	3.55
2	Yb/$(C_2F_4)_n$ (70/30)	4.2	18.2	4.33
Mg 1	Mg/C_2Cl_6 (24/76)	5.6	11.2	1.98
Mg 2	Mg/$(C_2F_4)_n$ (33/67)	9.7	20.2	2.07

mosphere are 4.5 mm s^{-1} and 2.6 mm s^{-1} for mixtures **1** and **2** respectively. In contrast the corresponding mixtures based on magnesium **Mg 1** and **Mg 2** do not exhibit a stable burn and eventually extinguish some time after ignition. The combustion of ytterbium with both oxidizers yields extended white-green luminous flames. With composition **1** the green emission is partly covered by luminous carbon particles but is distinct in the center of the core (Figure 1c). With composition **2** only scarce carbon luminosity is seen indicating a faster afterburn reaction (Figure 1b).

The UV/Vis spectra of both flames show a grey body-trace superimposed from a number of lines and bands in the wavelength range between $\lambda = 450–580$ nm (Figure 3). These signals can be assigned to Yb, YbO, YbCl and YbF respectively [13,15,16]. The temperatures of the flames (Table 3) are in accordance with the exothermic behaviors of both reactions (Table 2). With composition **1** the flame temperature is lower than the boiling point of $YbCl_3$ (2173 K). Likewise with composition **2** the flame temperature is much lower than the boiling temperature of the fluoride. This indicates substantial dissociation of the halides as is evidenced by the detection of its monohalides.

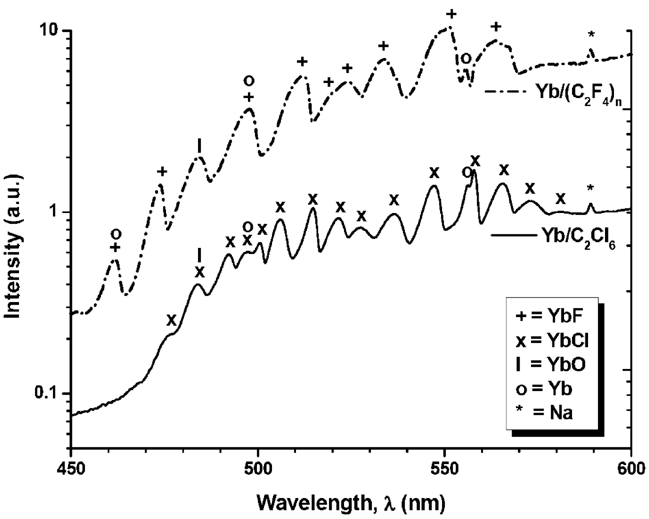

Figure 3. UV/Vis Spectra of both Yb/PTFE and Yb/HC.

Table 3. Spectroscopically determined grey body temperatures for aerobic flames.

Metal	Experiment/K
1	1700 ± 200
2	1975 ± 200
Mg 1	1850 ± 200
Mg 2	1730 ± 200

Ytterbium is a metallic fuel that is able to undergo vapor phase diffusion combustion similar to magnesium yielding an extended luminous flame. It has a similar volumetric energy content as magnesium and due to its strong selective emissions in the green spectral range ($\lambda = 450–550$ nm) it could be used in green burning pyrotechnics such as volume restrictive applications e.g. tracers. Currently, the performance of ytterbium in specialized infrared flare composition is explored.

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