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Thermal characterizations of the paraffin wax/low density polyethylene blends as a solid fuel

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ABSTRACT

Thermal characterizations of a novel solid fuel for hybrid rocket application, based on the paraffin wax blends with low density polyethylene (LDPE) concentration of 5% (SF-5) and 10% (SF-10) were conducted. Both the increased regression rate in comparison with the polymeric fuel, and the improved combustion efficiency in comparison with the pure paraffin fuel reveal that the blend fuels achieve higher combustion performance. The morphology of the shape stabilized paraffin wax/LDPE blends was characterized by the scanning electron microscopy (SEM). Although the SEM observation indicated the blends have uniform mixtures, they showed two degradation steps confirming the immiscibility of components in the crystalline phase from thermogravimetric analysis (TGA). The differential scanning calorimeter (DSC) results showed that the melting temperature of LDPE in the blends decreased with an increase of paraffin wax content. The decreasing total specific melting enthalpy of blended fuels with decreasing paraffin wax content is in fairly good agreement with the additive rule. In thermomechanical analysis (TMA), the linear coefficient of thermal expansion (LCTE) seems to decrease with an increase of LDPE loading, however, the loaded LDPE do merely affect the LCTE in case of the blends with low LDPE concentration. It was found that a blend of low concentration of LDPE with a relatively high concentration of paraffin wax can lead to a potential novel fuel for rocket application, a contrary case with respect to the field of phase change materials (PCM) where a blend of high concentration of LDPE is usually used with low concentration of paraffin wax.

1. Introduction

Paraffin waxes, usually known as fuels for candle, are mixtures of saturated hydrocarbon composed of numerous alkanes. Because of their high latent heat, low vapor pressure in the melt, chemically inert and low acquisition cost (without mentioning all their positive characteristics), paraffin wax has been one of the best candidates for the phase change materials (PCM) for thermal storage applications and electronic cooling devices [1–4]. In the other hand, hydrocarbon polymers releasing a lot of thermal energy are widely used as fuels in various industrial areas [5–7]. In particular, polymers such as hydroxyl-terminated polybutadiene (HTPB), polyethylene (PE), polymethylmethacrylate (PMMA) and polypropylene (PP) have shown potential possibilities as solid fuels for hybrid rocket motor (HRM) [8–10] in aerospace industry. However, these typical polymers have relatively slower burning speed with respect to the composite fuels which are widely used in solid rocket system provoking low thrust performance. Typically, this slow burning speed is associated to the intrinsic combustion mechanism of the hybrid rocket. The burning speed known as regression rate is defined as the rate the fuel surface recedes and it is a key parameter for the hybrid rocket motor design. Therefore, a lot of research efforts [10–13] have been conducted to enhance the fuel regression rate.

Karabeyoglu et al. [14] have suggested that paraffin wax can be a promising solid fuel for overcoming the low regression rate of HRM fuel because its regression rate has been found to be 3–4 times higher than that of conventional polymeric fuels. Fast regression rate of these paraffin-based fuels results from the important phenomenon of two-phase mass transfer by the gas and liquid, which is different from gas phase mass transfer of conventional polymeric fuels.

Fig. 1 is an illustration of two-phase mass transfer mechanism by the paraffin wax from the fuel surface. First, the heated paraffin wax fuel forming a melted liquid layer over the solid fuel surface generates unstable wavelets in which some portions are vaporized to the gas phase. Secondly, the substantial liquid fuel droplets which are generated at the tips of the wavelets are entrained into

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Nomenclature

A_t	Nozzle throat area (m^2)
c^*_{exp}	Experimental characteristic velocity (m/s)
c^*_{theo}	Theoretical characteristic velocity (m/s)
h	Melt layer thickness (m)
$\dot{m}_{ent}$	Entrained fuel mass flux from fuel surface (kg/m^2 s)
$\overline{\dot{m}}_o$	Time averaged oxidizer mass flow rate (kg/s)
P_c	Chamber pressure (Pa)
P_d	Dynamic pressure (Pa)
t_b	Burning time (s)
α	Dynamic pressure exponent
β	Thickness exponent
γ	Viscosity exponent
η_{c*}	Efficiency of characteristic velocity
Δm_f	Mass difference between initial and final fuel grain (kg)
μ_l	Liquid layer viscosity (Pa s)
π	Surface tension exponent
σ	Surface tension (N/m)

the gas stream where this entrained mass of the liquid droplets is known to be a dominant mechanism leading to the increase of the regression rate.

However, manufacturing of large fuel grain using paraffin-based fuel is a difficult task. Kilic et al. [15] have reported that poor mechanical characteristics and low melting temperature of the pure paraffin fuel can lead to a serious deformation under storage, handling or operating conditions. In their study of large fuel grain for space shuttle booster, fuel storage life time was limited due to the slump deformation for temperature range above 45 °C. In addition, combustion efficiency of the paraffin fuel is lower than the usual polymeric fuel because fuel droplets generated from the melted liquid layer are not completely burned during the passage of the fuel grain port and through the exhaust nozzle [16,17]. In many reports and papers [12,18–21], use of heterogeneous materials are presented where energetic metal particles and carbon black powders were added to pure paraffin wax to improve the mechanical strength, combustion efficiency and fuel density. Nevertheless, adding such additives to paraffin wax has often been a problem since it occasionally leads to combustion instability [21–23], chamber pressure sensitivity and non-uniform concentration of added material during mixing and casting process.

In this respect, this paper suggests an effective solid fuel by blending pure paraffin wax and polyethylene with different objective of PCM application. The motivation of this research is due to the following reasons. Firstly, paraffin-LDPE blended fuels may have many potential advantages compared to pure paraffin wax which includes additives. The fact that both paraffin wax and LDPE can be considered as a series of homologous materials, the proposed blended fuel may behave as a uniform material if mixed and prepared properly. Secondly, paraffin-LDPE blended fuels can improve the mechanical strength and the combustion efficiency of pure paraffin fuel since the physical properties of blended fuel are better than the paraffin itself [24].

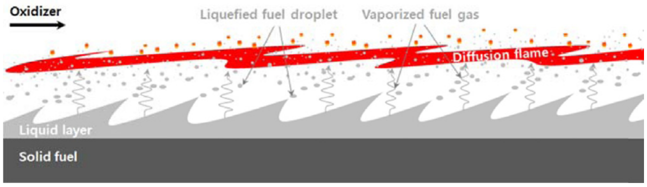

Fig. 1. Combustion mechanism of paraffin-based liquefying solid fuel.

Many researchers have already been focused on the paraffin wax/LDPE blend solution which is one of the best candidates as a phase change materials (PCM) for thermal storage applications [1–4]. Usually, the LDPE containing range in the blends for PCM application [1] is over 40%.

In our previous study [24] on the mechanical strength and combustion performance of blends, an entirely different range from that of blends for PCM has been tried. The paraffin wax blends containing less than 10% of LDPE have been found to be very effective for hybrid rocket fuel application with sufficient burn rate. Consequently, understanding the thermal characterizations of blends containing less than 10% of LDPE would be necessary to investigate.

In this paper, to evaluate good potentiality required for hybrid rocket application, paraffin wax blends with low density polyethylene were prepared and tested. The propulsion performances based on the solid fuel regression rate and combustion efficiency were compared by burning tests using lab-scale hybrid combustor. In order to examine the uniformity of the new blends fuel, the structure of blends was investigated using scanning electron microscopy (SEM). Thermal properties, such as crystallization temperature, melting temperature and specific melting enthalpy obtained from the differential scanning calorimeter (DSC) were discussed to describe the behavior of liquid layer. During the thermogravimetric analysis (TGA), decomposition temperature was obtained to determine the onsets of drastic thermal history while the thermal stability is analyzed to highlight the degradation behavior. Also, in order to consider a possible thermal deformation, thermal expansion behavior is examined by the thermomechanical analysis (TMA). In the present paper, thermal properties of paraffin wax/LDPE blends with low LDPE content are investigated and discussed especially for the standpoint of hybrid rocket fuel application.

2. Paraffin wax/LDPE blends as hybrid rocket fuel

2.1. Effective LDPE concentration

The conventional HRMs storing the solid fuel and liquid oxidizer separately gain their thermal energy from the turbulent diffusion combustion mechanism occurring in the boundary layer over the solid fuel surface. Usually the heat transfer from the flame zone to the fuel surface is transferred by convection and radiation, and leads to vaporization of solid fuel. At this point, slow regression rate of HRM fuel is due to the decreased heat transfer by the blocking effect which is triggered by the radial blowing of decomposed fuel from the solid fuel surface to the flame zone [25].

As mentioned before, Karabeyoglu et al. [14] showed that the paraffin wax can be an effective solid fuel to innovatively enhance the low regression rate of HRM fuel. This high regression rate of paraffin wax fuel is achieved by not only gasified mass transfer as in conventional polymeric fuels, but also additional mass transfer by shear driven liquid droplets.

In order to model and scale the entrainment rate of liquid droplets, Karabeyoglu et al. [14] suggested an empirical formula (Eq. (1)) which includes the gas dynamic pressure in the combustion chamber, the melt layer thickness, the surface tension and the viscosity of the liquefied paraffin at the fuel surface.

$$\dot{m}_{ent} \propto \frac{{P_d}^{\alpha} h^{\beta}}{{\mu_l}^{\gamma} \sigma^{\pi}} \tag{1}$$