

Effects of Viscosity on Droplet Entrainment and Combustion Characteristics in Hybrid Rocket Engines

Jungpyo LEE*, Seunghyun KIM**, Suhan KO***, Taeseon PARK*, and Heejang MOON***†

* School of Mechanical Engineering, Kyungpook National Univ.
Daegu, Republic of Korea

** School of Smart Air Mobility, Korea Aerospace Univ.
Gyeonggi-do, Republic of Korea

*** School of Aerospace and Mechanical Engineering, Korea Aerospace Univ.
Gyeonggi-do, Republic of Korea

jungpyo@knu.ac.kr – skyksh1014@kau.kr – ks0613h@naver.com – tsparkjp@knu.ac.kr – hjm@kau.ac.kr

† Corresponding Author

Abstract

This study investigates the effect of liquid paraffin viscosity on the burn rate in hybrid rocket combustion. Paraffin-based fuels were blended with low-density polyethylene to vary viscosity, and tests were conducted using a 2D plate engine at different oxidizer flow rates. Results show that while viscosity had little impact on droplet entrainment at low oxidizer flow rates, it significantly influenced the behavior of the liquid layer on the fuel surface. These findings enhance the understanding of combustion dynamics in paraffin-based hybrid fuels and support the development of high-performance hybrid propulsion systems.

1. Introduction

Hybrid rocket propulsion systems have garnered increasing interest due to their inherent safety, throttleability, and simplicity compared to traditional liquid and solid propulsion systems. These advantages result from their bipropellant configuration, in which a solid fuel and a liquid or gaseous oxidizer are stored separately, reducing the risk of accidental detonation and allowing for safer storage and handling. Moreover, the ability to control thrust by adjusting oxidizer flow makes hybrid systems suitable for missions requiring variable propulsion or restart capability. Among various fuel candidates, paraffin-based fuels have emerged as promising alternatives due to their relatively high regression rates and ease of processing. Unlike conventional polymeric fuels, paraffin exhibits a unique melting behavior during combustion. A distinctive feature of paraffin combustion is the formation of a thin liquid layer on the fuel surface, which leads to droplet entrainment into the oxidizer stream. This mechanism significantly enhances the fuel regression rate. As a result, paraffin has become a preferred fuel in high-performance hybrid propulsion applications. [1–5] Previous studies have identified the importance of this liquid layer in influencing combustion efficiency. Particularly, Ref. [6] highlights the significance of a newly identified combustion mechanism for paraffin-based fuels. In addition to the conventional vaporization regression and droplet entrainment, the study emphasizes the critical role of the liquid film regression occurring on the solid fuel surface, which substantially contributes to the overall regression rate. However, the detailed role of the liquid layer's physical properties—particularly liquid viscosity—on the entrainment and regression mechanisms remains insufficiently understood. Since viscosity governs the flow behavior of both the liquid layer and entrained droplets, it is expected to play a pivotal role in influencing the combustion characteristics of paraffin-based fuels under varying oxidizer flow conditions.

This study aims to investigate the influence of liquid film viscosity on the regression rate and overall combustion characteristics of paraffin-based hybrid fuels. To systematically vary viscosity, paraffin was blended with different ratios of low-density polyethylene (LDPE). Combustion experiments were carried out using a two-dimensional slab burner, and a specially designed chamber was employed to isolate and quantify the contribution of liquid film flow to the regression process.

In addition to the experimental findings, this work proposes a new regression rate model that explicitly incorporates the effect of liquid film viscosity. The total regression rate is formulated as the sum of three components: vaporization-

driven regression, droplet entrainment, and liquid film flow. Among these, the newly modeled liquid film contribution is shown to correlate strongly with total propellant mass flux and liquid viscosity. By relying only on physically measurable parameters—mass flux and viscosity—the proposed model offers a simple yet practical tool for predicting liquid film regression behavior, thereby supporting the accurate design and performance estimation of next-generation hybrid rocket motors.

2. Experimental Setup and Methodology

To investigate the influence of liquid film viscosity on the combustion behavior of paraffin-based hybrid rocket fuels, a series of horizontal firing tests were conducted at Korea Aerospace University using a slab-type hybrid motor of Fig. 1 [6]. The slab motor was designed to separately measure the liquid film regression rate and droplet-induced regression rate of paraffin-based fuels. These tests focused on how varying liquid fuel viscosities affect the transport of the liquid layer and droplet entrainment on the fuel surface, both of which are known to impact the overall regression behavior.

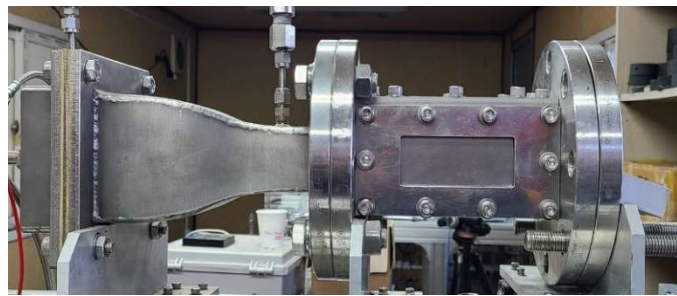


Fig. 1 Slab hybrid motor

The motor assembly consists of five main sections: a honeycomb-type flow straightener, a showerhead injector, a contraction section for flow uniformity, a combustion chamber, and a downstream collector duct designed to accumulate the liquid film. Slab-shaped paraffin-based fuel samples with dimensions of 50 mm (width) $\times$ 20 mm (height) $\times$ 100 mm (length) were prepared, as shown in Fig. 2. The initial port height—the vertical distance from the fuel surface to the chamber ceiling—was fixed at 20 mm. The leading edge of each fuel sample was tapered to reduce flow separation at the fuel inlet. The tests were conducted at atmospheric pressure, with no nozzle installed.

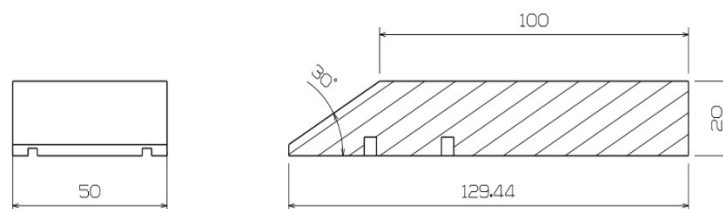


Fig. 2 Geometry of slab motor fuel

To quantify the contribution of the liquid film to fuel regression, an angled aluminum collector duct (Fig. 3) was installed downstream of the fuel block. This duct channeled the flowing molten paraffin into a collection container below the chamber. The mass of the collected fuel was used to estimate the liquid film regression rate, while the total regression rate was determined from the difference in pre- and post-burn fuel weight. Oxidizer mass flow rates (ranging from 6 to 35 g/s) were precisely controlled using interchangeable sonic orifices and measured via a turbine flow meter. All tests were operated for 10 seconds under consistent control by a programmable logic controller, with data acquisition handled by an external DAQ system.

To assess the influence of melt viscosity on liquid film behavior, three paraffin-based fuel compositions were prepared by varying the content of low-density polyethylene (LDPE): PR100 (100 wt% paraffin), PR95PE05 (95 wt% paraffin + 5 wt% LDPE), and PR90PE10 (90 wt% paraffin + 10 wt% LDPE). The pure paraffin (Sasol 0907) and LDPE (Hanwha 5301) are chemically homologous, ensuring a homogenous mixture when melted. Key material properties, including melt viscosity measured, are presented in Table 1. The dynamic viscosity of paraffin-based fuel samples was measured using a rotational rheometer. All measurements were conducted at a controlled temperature of 150 °C to simulate the thermal conditions under which the liquid fuel film typically exists during combustion. The viscosity was evaluated over a shear rate range of 0.01 to 500 s⁻¹, with representative data reported at selected shear rates (10 and

100 s⁻¹) for comparison. This method enabled reliable characterization of the shear-thinning behavior of the molten paraffin-LDPE mixtures under combustion-relevant conditions. As anticipated, the melt viscosity increased markedly with higher LDPE content. The solid-phase densities of the fuels were determined experimentally using representative fuel samples.

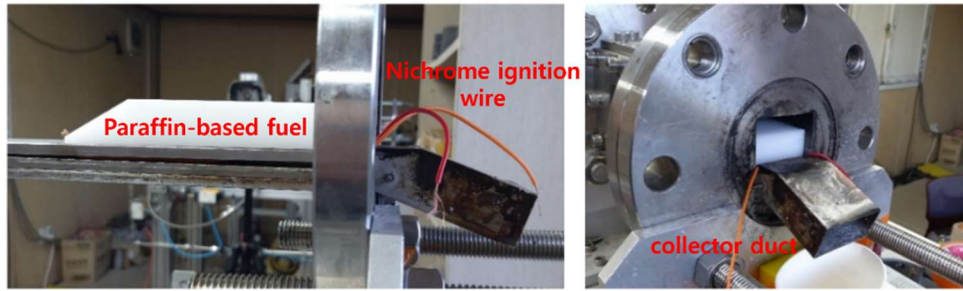


Fig. 3 Collector duct mounted on slab motor

Table 1: Material properties of paraffin-based fuels

Parameter	PR100	PR95PE05	PR90PE10
Liquid film viscosity (mPa·s)	3	20	109
Density-solid phase (kg/m ³)	922	924	924
Density-liquid phase, kg/m ³	654.4 ^[1]	654.4 ^[1]	654.4 ^[1]

Figure 4 presents images captured during the firing test using PR100 fuel, illustrating the combustion of vaporized paraffin-based fuel and oxidizer inside the slab motor and the ejection of liquid fuel droplets separated from the solid fuel surface. Additionally, a noticeable amount of liquid film was observed flowing through the collector duct in all tests, regardless of the fuel type.

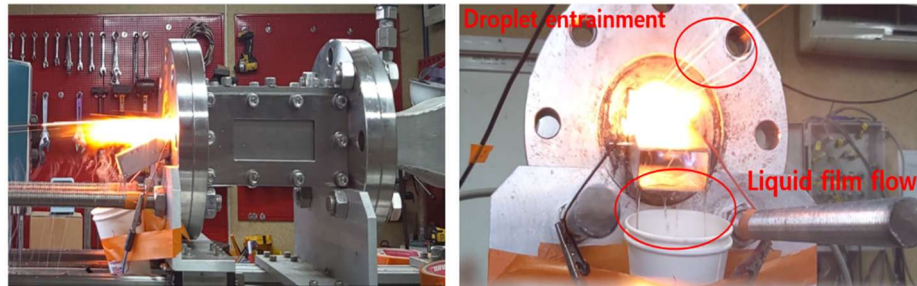


Fig. 4 Combustion test images of slab motor

3. Experimental Results

3.1 Regression Rates

The regression behavior of paraffin-based fuels with varying viscosities was investigated by evaluating the total regression rate, the liquid film regression rate, and the combined contribution of vaporization and droplet entrainment under different propellant mass flux conditions. The total and liquid film regression rates were directly measured from the experiments, while the vaporization plus droplet-induced regression rate was obtained by subtracting the liquid film contribution from the total regression rate. Figure 5 showed that all regression rates increased with the total mass flux (G_{tot}), while viscosity primarily affected the liquid film regression. Although the experiments were conducted under low-mass flux conditions, liquid film regression contributed significantly to the total regression rate. For PR100, PR95PE05, and PR90PE10 fuels, the contribution of the liquid film to the total fuel mass flow was approximately 80%, 65%, and 45%, respectively. This confirms that liquid film dynamics play a dominant role in determining the overall fuel consumption rate in paraffin-based hybrid motors, particularly under low mass flux conditions [6].

It was observed that the proportion of regression attributable to the liquid film decreased with increasing LDPE content—and thus higher viscosity—suggesting increased shear resistance at the fuel surface. Conversely, the regression due to vaporization and droplet entrainment remained relatively unaffected by viscosity across all fuels at the same G_{tot} , indicating that the liquid viscosity does not significantly affect entrainment under the tested low-velocity, atmospheric-pressure combustion chamber conditions.

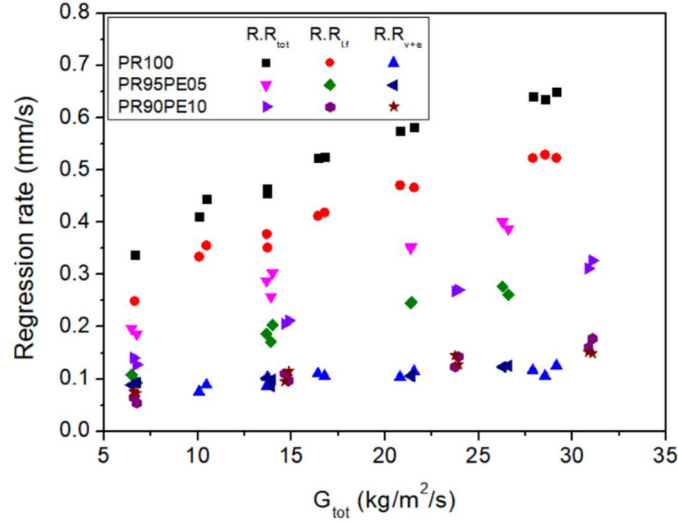


Fig. 5 Regression rates for paraffin-based fuels

3.2 Regression Rate Model

The regression rate is a key parameter in hybrid rocket design and performance prediction. While various models have been proposed, most do not explicitly consider the influence of the liquid film. This study introduces a new regression rate model that incorporates liquid film viscosities. The total regression rate of paraffin-based fuels is defined as the sum of three components: vaporization ($\dot{r}_v$), droplet entrainment ($\dot{r}_e$), and liquid film flow ($\dot{r}_{l,f}$), each contributing to the overall fuel mass transfer within the combustion chamber, as presented in Eq. (1). The regression rate due to vaporization is generally modeled using the classical theory for turbulent diffusion flames proposed by Marxman et al. [7-9]. This theory focuses on convective heat transfer to the fuel surface, and Eq. (2) is a commonly used expression for the local regression rate in flat-plate configurations. The droplet generation model proposed by Karabeyoglu, presented in Eq. (3), is commonly used for this purpose although further research is needed for droplet-induced regression [1].

$$\dot{r}_{tot} = \dot{r}_v + \dot{r}_{l,f} + \dot{r}_e \quad (1)$$

$$\rho_f \dot{r}_v = 0.0295 G_{tot}^{0.8} \left(\frac{\mu}{\chi} \right)^{0.2} \frac{C_H}{C_{H0}} \frac{u_e}{u_b} \left(\frac{h_b - h_w}{h_v} \right) \quad (2)$$

$$\dot{r}_e \propto \frac{P_d^\alpha h^\beta}{\sigma^\gamma \mu^\delta} \quad (3)$$

Under the low mass flux conditions investigated in this study, the liquid film regression rate was found to be well represented as a function of the total mass flux, G_{tot} , and the liquid film viscosity, μ_l , as shown in Eq. (4). The correlation reveals an exponent of 0.56 for G_{tot} and -0.366 for μ_l , indicating that the regression rate increases with greater mass flux and decreases with higher viscosity. As shown in Fig. 6, this model accurately predicted the regression behavior of paraffin-based fuels with three different viscosity levels. Notably, the model relies solely on two key parameters—propellant mass flux and liquid film viscosity—that are readily available during the design phase, making it highly practical and suitable for implementation in hybrid rocket motor development within the aerospace industry.

$$\dot{r}_{l,f} = 0.0104 G_{tot}^{0.56} \mu_l^{-0.366} \quad (4)$$

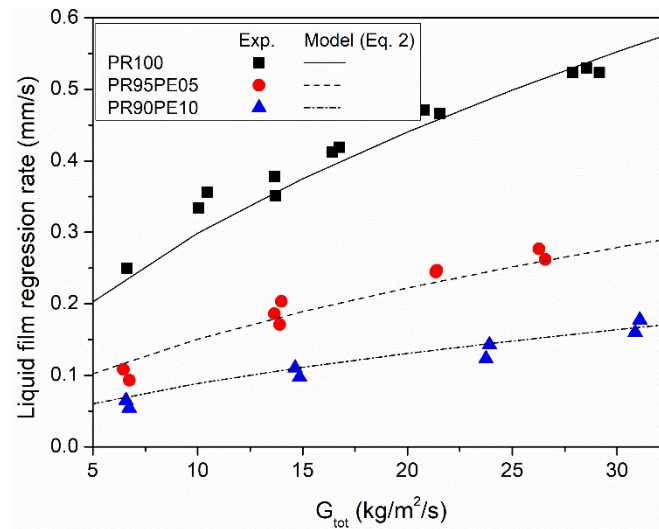


Fig. 6 Comparison of experimental and modeled liquid film regression rates for paraffin-based fuels with varying viscosities

4. Conclusions

This study investigated the influence of liquid film viscosity on the regression behavior of paraffin-based hybrid rocket fuels through a series of combustion experiments using a two-dimensional slab burner. By blending paraffin wax with varying amounts of low-density polyethylene (LDPE), fuel samples with three distinct viscosities were prepared and tested under a range of propellant mass flux conditions, particularly in the low propellant mass flux regime. Experimental results demonstrated that the liquid film plays a dominant role in fuel consumption, contributing significantly to the total regression rate. It was found that increasing the LDPE content—and thus the liquid viscosity—substantially reduced the proportion of fuel consumed via liquid film flow, while the combined vaporization and droplet entrainment components remained relatively unaffected. These findings highlight the critical importance of accurately modeling the behavior of the liquid film to improve combustion performance prediction in paraffin-based hybrid systems. To address this, a new regression rate model was proposed that explicitly incorporates the effect of liquid film viscosity. The model expresses the liquid film regression rate as a function of total mass flux and viscosity, with fitted exponents of 0.56 and -0.366 , respectively. This correlation successfully predicted the experimental regression rates across all tested fuels, demonstrating its reliability and applicability. By relying solely on measurable design parameters—propellant mass flux and liquid film viscosity—the proposed model offers a practical and effective tool for hybrid rocket motor design. Future work should explore the behavior of liquid film dynamics under high-chamber pressure or high mass flux conditions, including nozzle effects, to further refine the predictive capabilities of regression models for real-flight hybrid propulsion systems.

References

- [1] Karabeyoglu, M. A., Altman, D., and Cantwell, B. J., “Combustion of Liquefying Hybrid Propellants: Part 1, General Theory,” *Journal of Propulsion and Power*, Vol. 18, No. 3, 2002.
<https://doi.org/10.2514/2.5975>
- [2] Chandler, A., Jens, E., Cantwell, B. J., and Hubbard, G. S., “Visualization of the Liquid Layer Combustion of Paraffin Fuel for Hybrid Rocket Applications,” 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA Paper 2012-3961, July 2012.
<https://doi.org/10.2514/6.2012-3961>
- [3] Nakagawa, I. and Hikone, S., “Study on the Regression Rate of Paraffin-Based Hybrid Rocket Fuels,” *Journal of Propulsion and Power*, Vol. 27, No. 6, 2011, pp. 1276–1279.
<https://doi.org/10.2514/1.B34206>
- [4] Kobald, M., Schmierer, C., Ciezki, H. K., and Schlechtriem, S., “Viscosity and Regression Rate of Liquefying Hybrid Rocket Fuels,” *Journal of Propulsion and Power*, Vol. 33, No. 5, 2017.

- <https://doi.org/10.2514/1.B36207>
- [5] Jens, E. T., Karp, A. C., Miller, V. A., Hubbard, G. S., and Cantwell, B. J., “Experimental Visualization of Hybrid Combustion: Results at Elevated Pressures,” *Journal of Propulsion and Power*, Vol. 36, No. 1, 2020.
<https://doi.org/10.2514/1.B37416>
- [6] Lee, J., Ko, S., Kim, S., Jeon, H., Lee, I., Moon, H. J., Ryu, S., and Shynkarenko, O., “Mass Transfer due to Liquid Film of Paraffin-Based Fuels for Hybrid Rocket Engines,” *Aerospace Europe Conference 2023 – 10th EUCASS – 9th CEAS*, 2023-314, 2023
<https://10.13009/EUCASS2023-314>
- [7] Marxman, G. A., Wooldridge, C. E., and Muzzy, R. J., *Fundamentals of Hybrid Boundary Layer Combustion*, Vol. 15, *Progress in Astronautics and Aeronautics*, AIAA, New York, 1964, pp. 485–522.
- [8] Marxman, G. A., and Gilbert, M., “Turbulent Boundary Layer Combustion in the Hybrid Rocket,” *9th International Symposium on Combustion*, Vol. 9, No. 1, 1963, pp. 371–383.
[https://doi:10.1016/S0082-0784\(63\)80046-6](https://doi:10.1016/S0082-0784(63)80046-6)
- [9] Marxman, G. A., “Combustion in the Turbulent Boundary Layer on a Vaporizing Surface,” *Proceedings of the 10th International Symposium on Combustion*, Vol. 10, No. 1, 1965, pp. 1337–1349.
[https://doi:10.1016/S0082-0784\(65\)80268-5](https://doi:10.1016/S0082-0784(65)80268-5)