DOI: 10.13009/EUCASS2023-314
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Mass Transfer due to Liquid Film of Paraffin-Based Fuels for Hybrid Rocket Engines

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Abstract

Paraffin-based fuels are considered promising propellants for hybrid rockets due to their fast-burning rates. These fuels produce a thin liquid layer on the surface of the solid fuel, which promotes the entrainment of droplets and consequently enhances regression rates. In this study, we introduce a new mechanism for mass transfer and investigate the regression rate resulting from the presence of a liquid film on the solid fuel surface. To achieve this, we utilized a two-dimensional slab hybrid motor and three different types of paraffin-based fuel with varying viscosity of the liquid film. The results demonstrated that mass transfer caused by the liquid film played a significant role, making a substantial contribution to the overall regression rate.

1. Introduction

The conventional solid fuels in hybrid rockets which are the pyrolysis process, such as Polyethylene, Polymethylmethacrylate, etc., have a low regression rate intrinsically, and therefore they are not suitable for use in launch rockets. Over the years, researchers have developed and investigated numerous ways to improve the low regression rate of the hybrid systems [1]. Among others, paraffin-based hybrid fuels have fast-burning rates, and they are excellent candidates for hybrid rocket systems. The droplet entrainment theory for the liquefying paraffin-based fuels in hybrid rockets was proposed by Karabeyoglue et al. [2]. It was described that a thin liquid layer with low melt-layer viscosity and surface tension is produced on the surface of high-regression-rate fuels when burning, and entrainment of liquid droplets occurs on the unstable liquid layer surface under the shear forces associated with the oxidizer gas. Therefore, the entrainment mechanism greatly increases the mass transfer rate of solid fuels in addition to the evaporation regression rate that is generated by the vaporization of the liquid on the surface, and he suggested that the total regression rate can be expressed as a sum of the vaporization regression rate and the entrainment regression rate that is related to the mass transfer mechanically extracted from the liquid surface. Visualization tests were conducted to confirm the droplet entrainment phenomenon by several researchers, and the results support the entrainment theory [3, 4, 5, 6].
Our research has focused on investigating the mass transfer mechanism and characteristics of paraffin-based fuels. After conducting combustion tests with these fuels on a horizontal hybrid test bench, we have observed significant liquid fuel stagnation at the bottom of the post-combustion chamber on multiple occasions. This observation has also been reported in tests conducted in other studies [7, 8]. We propose the existence of a previously unrecognized fuel mass transfer mechanism for the liquefying fuels in addition to the vaporization and entrainment of liquid droplet. In this study, we investigate a new mechanism for the mass transfer of liquefying fuels. Specifically, we suggest that a liquid film flowing on a solid fuel surface can lead to a substantial increase in the fuel regression rate. The regression rate is a crucial parameter in predicting rocket performance and designing hybrid motors, and accurate prediction of this quantity is invaluable. Therefore, understanding the mass transfer mechanism of paraffin-based fuels with precision is of great significance.

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2. Experimental Conditions

Horizontal firing tests were conducted by passing gaseous oxygen over a liquid film formed on the fuel surface under various experimental conditions, with the aid of a slab motor in Korea Aerospace University. The slab hybrid motor allows for the visual observation of liquid film motion and fuel droplet entrainment inside the motor, which can be used to analyze the properties of fluid flow, such as velocity, pressure, and temperature. The schematic of the slab hybrid motor is presented in Fig. 1. The motor consists of five main parts: the honeycomb section, the injector section, the contraction section, the combustion chamber section, and the collection duct section.

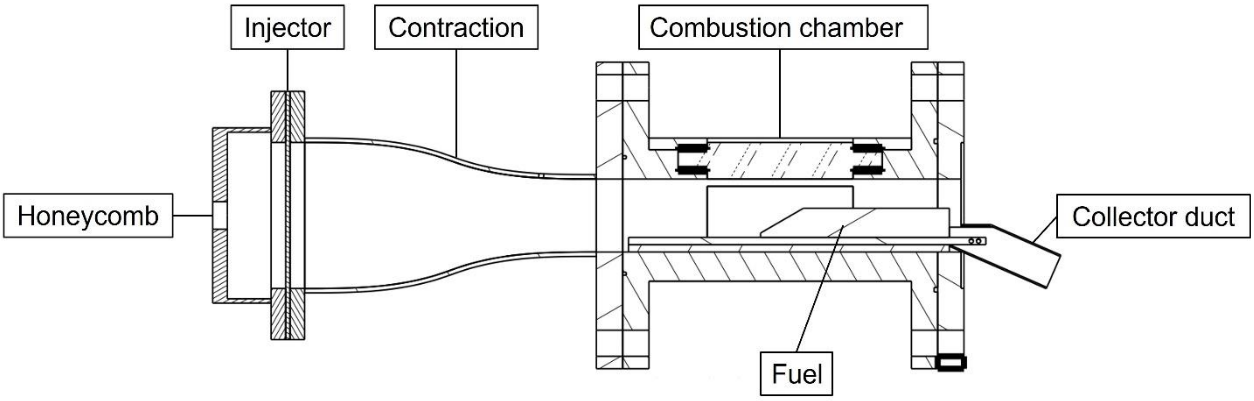

Figure 1: Configuration of slab hybrid motor

The honeycomb is a device used to create uniform oxidizer flow before entering the combustion chamber. It consists of a fine structure with small holes arranged in a same size. A showerhead-type injector with a hole diameter of 2 mm and 36 holes is installed at the front end. The contraction section is designed to achieve flow uniformity and reduce frictional losses, and a commonly used three-dimensional equation in wind tunnel design was utilized for its shape design [9].
The combustion chamber is a zone where the paraffin-based fuel and oxidizer (GOx) are mixed and undergo a chemical reaction. Figure 2 illustrates the slab fuel configuration of the paraffin-based fuel employed in the experiments, with dimensions of 50 mm (width) x 20 mm (height) x 100 mm (length), and Fig. 3 shows a typical paraffin grain that was utilized during the test campaign, prior to being burned. The fuel was placed only at the bottom of the combustion chamber, and the initial port height, which refers to the distance between the surface of the fuel and the ceiling of the combustion chamber, was 20 mm. The leading edge of the fuel is tapered to ensure a streamlined flow of the incoming oxidizer. No nozzle was installed in the test setup because these experiments were conducted with the purpose of measuring the mass transfer rate of liquid film flowing on the solid fuel surface at the rear of the fuel, and therefore, the experiments were carried out under atmospheric pressure and restricted velocity conditions. A 0.5 mm thick nichrome wire was affixed to the front of the fuel, with a groove for the wire located at the bottom of the fuel. The paraffin fuel was ignited by heating it for 3 seconds using the nichrome wire to melt the surface, after which gaseous oxygen for the ignition was introduced. The fuel consumption weight resulting from ignition was negligible enough to be disregarded, and it has been confirmed that it has no significant effect on the total regression rate of the fuel. The combustion chamber has a rectangular transparent test section on the side to observe the flow and flame, however, no observations were captured in this research, and the quartz window section for visualization was covered with stainless steel.

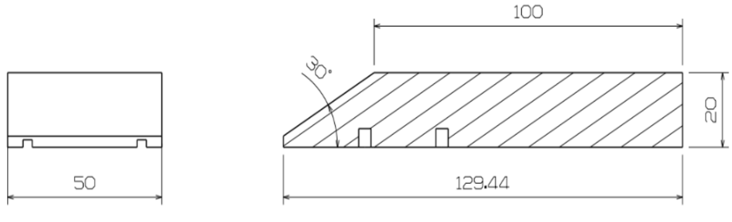

Figure 2: Geometry of slab motor fuel

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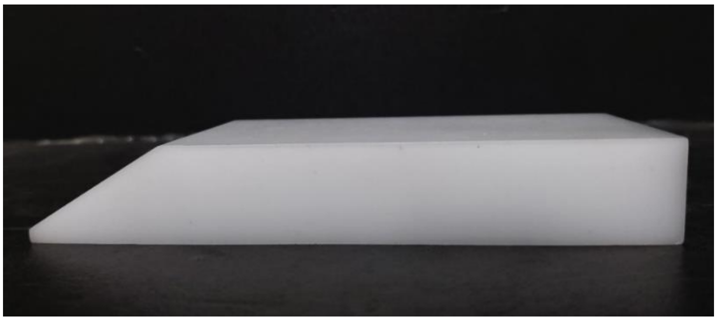

Figure 3: Photo of paraffin-based fuel

The liquid film fuel collector duct is located at the rear of the paraffin-based fuel, where it passes the fuel mass due to a liquid film formed on the surface of the solid fuel. Figure 4 shows the paraffin-based fuel placed on the support base before combustion and the collector duct located behind it. In order to facilitate the collection of liquid film fuel, the collector was assembled at an angle and the upper portion of the duct was obstructed to prevent splashing paraffin droplets from entering the collector during combustion. It utilized a square duct made of aluminium. The liquid fuel melted on the fuel surface flows along the collector duct and is collected in a small container located underneath the plate. The regression rate due to the liquid film can be calculated using the collected mass. The total fuel regression rate is determined by calculating the difference in total weight of the fuel before and after a burning test.

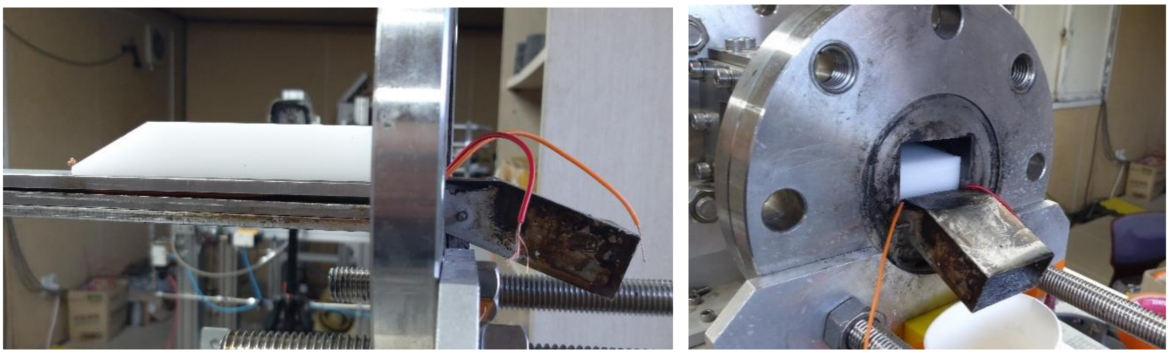

Figure 4: Collector duct mounted on slab motor

Paraffin-based fuels which are consisting of paraffin wax and Low-Density Polyethylene (LDPE) with varying LDPE ratios and gaseous oxygen (GOx) were employed as the fuel and oxidizer in this experiment, respectively. The liquid film viscosity for paraffin-based fuel plays a critical role in determining the mass transfer rate of liquefying fuels. To investigate this effect, three types of paraffin-based fuels with varying viscosities were utilized in this study: PR100 (100 wt% pure paraffin), PR95PE05 (95 wt% pure paraffin and 5 wt% LDPE), and PR90PE10 (90 wt% pure paraffin and 10 wt% LDPE). The pure paraffin wax used in this study, PR100, was supplied by Sasol 0907, which is fully refined soft paraffin wax with a melting point between about 88 °C and 102 °C. The density of PR100 is 922 kg/m^3 at 25 °C, and its molecular weight is 352.7 g/mol. And pellet-type low-density polyethylene supplied by Hanwha Chemical Co., Ltd. was used as an additive (5301 model, melting point 110 °C, density 921 kg/m^3 at 25 °C, molecular weight 3.0×10^5 g/mol). Since both paraffin wax of alkane and LDPE of alkene are homologous materials, the proposed blended fuel can be considered a homogeneous material when mixed properly.

Table 1 shows the properties of the three fuels. The liquid film viscosities for the blended fuels were measured at the temperature of 150 °C using a rotational rheometer. As the LDPE content in the fuel is increased, the melt viscosity is significantly increased. The densities for solid phase fuels were measured using samples for the fuels. For the blended fuels containing a homologous LDPE of up to 10% in pure paraffin, there is no significant difference in surface tension due to the small difference in average liquid film temperature and molecular weight [10], and therefore, the surface tension value for all three fuels was determined by referencing the value for paraffin wax in Ref. [2].

Table 1: Material properties of paraffin-based fuels

Parameter	PR100	PR95PE05	PR90PE10

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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[2]	654.4[2]	654.4[2]
Surface tension (mN/m)	7.1[2]	7.1[2]	7.1[2]

The oxidizer mass flow rate was regulated using various hole diameters of the sonic orifice in the oxidizer feeding line and measured using a turbine flow meter. The sonic orifice controls the oxidizer mass flow rate (6–35 g/s), and it is supplied independently of the downstream pressure under sonic flow condition. The burning time was 10 s for all tests. The experiments were controlled by a programmable logic controller, and data from each sensor was acquired through a data acquisition board.
Figure 5 shows photos taken during the firing test with PR100, revealing the occurrence of flame at the rear of the fuel and the spattering of liquid fuel droplets separated from the solid fuel surface in the combustion chamber. And, across all experiments, it was confirmed that a significant amount of liquid fuel was flowing through the collector duct, as shown in Fig. 5, regardless of the fuel type.

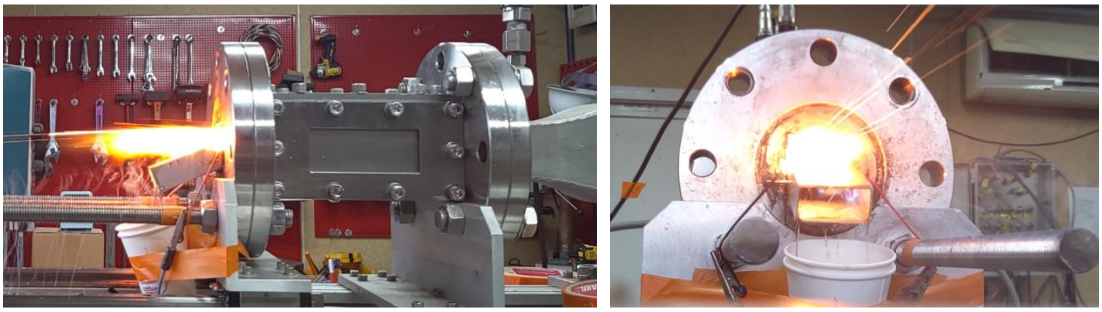

Figure 5: Images of slab motor combustion test

3. Experimental Results

The regression rate is defined as the burning rate of the solid fuel grain in the motor and is one of the most important parameters for designing a hybrid motor, and it is well known that there is a strong correlation between the regression rate and the mass flux of the fluid flowing through the fuel port. After conducting combustion tests, the total regression rate, liquid film regression rate, and regression rates due to vaporization and droplet entrainment were measured for each fuel at various propellant mass fluxes, and the combustion characteristics of three fuels with different viscosities were analyzed.

3.1 Regression Rates

Figure 6 shows the regression rates with respect to the total propellant flow mass flux (gas oxidizer, fuel vaporization, and fuel entrainment) through the fuel port over the liquid film, G_{tot}, for three different paraffin-based fuels, namely, PR100, PR95PE05, and PR90PE10. The total regression rate ($\dot{r}_{tot}$) and the liquid film regression rate ($\dot{r}_{l.f}$) were measured after completing a firing test, and the regression rate of the vaporization and entrainment ($\dot{r}_{v+e}$) was calculated as the difference between $\dot{r}_{tot}$ and $\dot{r}_{l.f}$. All types of regression rates ($\dot{r}_{tot}$, $\dot{r}_{l.f}$, and $\dot{r}_{v+e}$) increase as G_{tot} increases regardless of the fuel types. The rate of mass transfer due to the liquid film decreases as the proportion of LDPE in the solid fuel (or the liquid film viscosity) increases at a constant total mass flux since the shear stress between the liquid film and solid fuel surface increase with increasing the viscosity. Of particular significance is the fact that the ratio of regression rate due to liquid film to the total regression rate is significantly large. Figure 7 shows the ratio of the liquid film mass flow rate to the total fuel mass flow rate for the three different fuels with respect to the total propellant mass flux. The proportions for PR100, PR95PE05, and PR90PE10 are considerable as around 0.8, 0.65, and 0.45 respectively. As the viscosity of the liquid fuel increases, the mass ratio decreases. The regression rate of the

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liquid film has a significant impact on the performance of a paraffin-based hybrid rocket motor and should, therefore, be taken into account during the motor design process.

Although paraffin-based fuels exhibit high burning rates, the combustion efficiency of these fuels in combustion chambers with non-optimized designs is believed to be lower than that of classical fuels that do not form a liquid film. This is due to a significant amount of the flowing liquid film not participating in the combustion process within the chamber. In various studies, it has been demonstrated that combustion efficiency for paraffin-based fuels in lab-scale motors can range from 60% to 80%, and, overall, these efficiencies were found to be lower than those of High-density polyethylene fuel [11].

Note that these experiments were performed on the motor without a nozzle, resulting in low gas velocity conditions. And it is inferred that a significant portion of the fuel mass rate in the liquid film is entrained and undergoes combustion inside the nozzle in the rocket motor that has a high-velocity gas stream. In cases where a thin liquid film is exposed to a hot and high-velocity gas stream, it has been reported that entrainment mass transfer significantly contributes to the overall mass transfer [12]. Therefore, it is expected that the mass transfer rate due to the entrainment of liquid paraffin will play a significant role in a rocket nozzle with high flow velocity. The amount of entrainment may depend strongly on geometry of the nozzle, the flow velocity, etc. It is crucial to consider the mass transfer that occurs in the liquid film when designing hybrid rocket motors that use the liquifying fuels.

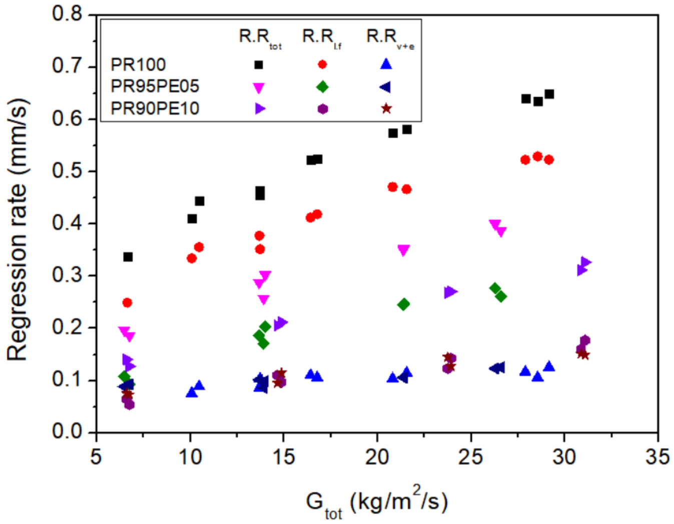

Figure 6: Regression rates for paraffin-based fuels

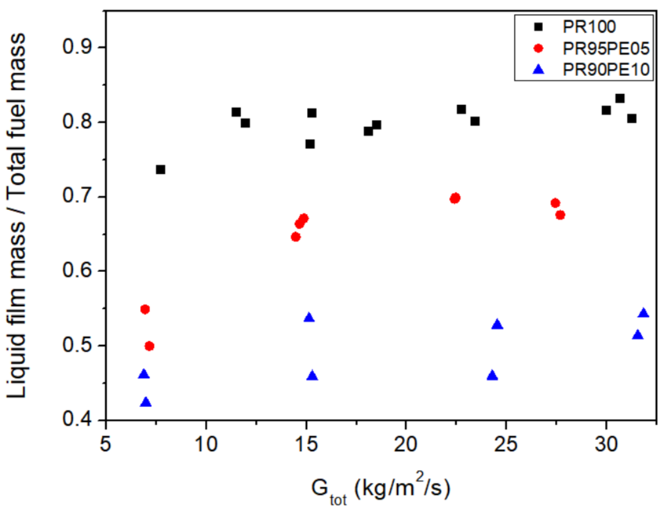

Figure 7: Ratio of liquid film mass flow rate to total mass flow rate

It can be confirmed that the difference of the total regression rate due to the change of viscosity is solely attributed to the liquid film regression rate because the regression rates due to vaporization and entrainment for the three fuels are almost constant at a value of G_{tot}, as shown in Fig. 6. It can be inferred that the liquid film viscosity has no significant effect on the regression rate of droplet entrainment plus vaporization. The classical regression rate model for

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vaporization fuel mass transfer, based on Marxman's theory, is expressed in terms of the propellant mass flux, the gas viscosity, the solid fuel density, and the mass transfer number [13]. Since the three fuels (PR100, PR95PE05, and PR90PE10) are homologous materials, there are no significant differences in the thermochemical properties of these materials, implying that the fuel mass transfer by vaporization would be similar for all the fuels at a constant propellant mass flux. And therefore, the entrainment regression rates for the fuels do not exhibit significant differences at a constant G_{tot}. It is emphasized that the effect of liquid film viscosity on the occurrence of droplet entrainment is quite small. Some references referring the same tendency for the entrainment phenomenon have been reported. Gater et al. in Ref. [12] conducted an experimental investigation with a flat film to determine the rate of mass transfer of vaporization and entrainment from a thin liquid film to a proximate gas stream using various fluids under a wide range of test conditions, and they observed that the liquid viscosity was not found to influence the rate of entrainment. Pravin Sawant et al. measured the entrainment fraction in the Ref. [14], using the liquid film extraction technique. They stated that the entrainment fraction was strongly influenced by the two non-dimensional numbers; a modified Weber number ($We = \frac{\rho_g {j_g}^2 D}{\sigma}\left(\frac{\Delta\rho}{\rho_g}\right)^{1/3}$) and a liquid phase Reynolds number ($Re_f = \frac{\rho_f j_f D}{\mu_f}$). And they confirmed that the entrainment fraction was not dependent on Re_f in a low We region. Miller and Coy [15] also concluded from the analysis of literatures that mass transfer due to droplet entrainment is more strongly dependent on surface tension and gas momentum flux at low gas momentum fluxes, however, at higher gas momentum fluxes, the entrainment is dependent more on the liquid film viscosity and liquid film flow rate than on surface tension. As mentioned earlier, these experiments were conducted with low levels of mass flux (5 to 35 kg/s-m^2) and pressure (1 atm), and therefore, it is inferred that the liquid film viscosity has no appreciable influence on the rate of droplet entrainment mass transfer from a liquid film to a gas stream.

In the future, it will be necessary to conduct analyses of fluid flows under high mass flux conditions or supercritical pressures, and to confirm differences in mass transfer mechanisms using visualization devices.

4. Conclusions

This research investigates the mass transfer mechanisms in paraffin-based fuels for hybrid rockets, focusing on the regression rate of the fuels. The study confirms the droplet entrainment phenomenon previously proposed and observed by other researchers. Additionally, it proposes the existence of a previously unrecognized fuel mass transfer mechanism involving a liquid film flowing over the solid fuel surface, which leads to a substantial increase in the regression rate. The experiments conducted on the hybrid slab motor yield a meaningful result, highlighting the significant role of the liquid film in enhancing the regression rate of the solid fuel. The influence of liquid film viscosity on the regression rate of the liquid film is evident, however, it had no significant effect on the regression rate of liquid droplet entrainment. The results underscore the importance of considering the liquid film as a key factor in fuel regression rate enhancement. However, further investigation of the mass transfer mechanism of paraffin-based fuels under high mass fluxes or supercritical conditions is necessary, as these experiments were conducted at low mass fluxes and ambient pressure. Understanding these mass transfer mechanisms is crucial for accurately predicting the regression rate and designing efficient paraffin-based hybrid rocket motors. The findings of this study contribute to the advancement of hybrid rocket technology and provide valuable insights for motor design and performance optimization.

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