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Advancements in Gel Propellant Technology: Synthesis, Characterization, and Sustainable Solutions for Versatile Space Exploration

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Abstract:

This study presents the synthesis and characterization of gel propellants engineered for a range of space applications. Addressing the demand for efficient and adaptable propulsion systems, the research focuses on formulations combining hydroxypropyl methylcellulose (HPMC) and ethanol in varying ratios. HPMC was selected as the gelling agent due to its environmentally friendly properties and proven performance. The primary goal is to develop tailored propellant solutions that meet the specific demands of diverse space missions, highlighting the importance of innovation in propellant technology. Formulations were carefully optimized by adjusting HPMC and ethanol concentrations to enhance key performance parameters such as viscosity, stability, and combustion efficiency. A suite of analytical techniques was employed to evaluate the gel propellants, including Fourier Transform Infrared Spectroscopy (FTIR) for molecular structure validation, Differential Scanning Calorimetry (DSC) and bomb calorimetry for thermal performance assessment, Thermogravimetric Analysis (TGA) for decomposition behavior, and rheological measurements to characterize flow properties under varying shear rates. These comprehensive evaluations confirm the potential of the developed gel propellants to support a wide spectrum of space applications, contributing meaningfully to the advancement of next-generation propulsion technologies.

Keywords: Propellant, Propulsion, Space Exploration, HPMC.

1. Introduction

In the realm of advanced propulsion systems, gel propellants have emerged as a fascinating intersection of solid and liquid characteristics. Originally stemming from research on slurry fuels in the 1940s, these non-Newtonian fluids have undergone a resurgence in recent years, driven by advancements in preparation and formulation techniques (Padwal et al., 2021). Unlike conventional solid or liquid propellants, gel fuels present a unique blend of safety features, combining spill-resistant qualities with controllable combustion. This has positioned them as a promising alternative for applications ranging from rocket motors and ramjets to furnace combustion and afterburners in jet engines. Recent breakthroughs have rekindled interest in gel propellants, emphasizing the demand for a safer and high-performance substitute in propulsion technology. The advantages of gel propellants include reduced leakage risk, adjustable thrust, multi-time ignition capability, and ease of handling. However, challenges persist—most notably in achieving optimal combustion efficiency. Ongoing research endeavors are directed toward overcoming these complexities and unlocking the full potential of gel propellants. Rheological studies play a pivotal role in quality control, offering insights into viscosity variations at different shear rates and aiding in understanding gel deformation during shearing. Despite these advancements, the incorporation of gelling agents, while enhancing viscosity, poses challenges to atomization in gel propulsion technology. In this context, current

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research focuses on an ethanol-based gel, chosen for its ready availability, cost-effectiveness, low toxicity, and eco-friendly attributes as a biofuel. Methylcellulose, an organic gellant, is employed for its molecular structure, which fosters a robust web-like framework that maintains gel compactness. Distilled water serves as the solvent, leveraging methylcellulose's hydrophobic unit cross-linking for gelation. This study specifically delves into assessing the rheological characteristics of ethanol-based gel fuels, exploring the impact of varying gellant concentrations (Padwal et al., 2021).

2. Methodology

2.1. Selection of Base Fuel

In the current study, the choice of gellant was a strategic decision, favoring hydroxypropyl methylcellulose (HPMC) over low-substituted methylcellulose (LSMC). This preference was based on the solubility properties of HPMC, which is soluble in water but insoluble in ethanol. In contrast, LSMC is insoluble in both water and ethanol. As a result, using LSMC in an ethanol–distilled water mixture would prevent gel formation until the water reaches a temperature of 55°C (Rahimi et al., 2004). The molecular structure of HPMC, depicted in Figure 1, was a key factor in its selection. HPMC is known to form a more intricate web-like structure at the molecular level, contributing to the compactness and stability of the gel. This arrangement enhances the overall effectiveness of HPMC as a gellant in the formulation studied. Methylcellulose, chosen as the organic gellant, also aligns with eco-friendly practices. Distilled water, selected as the solvent, complements the gelation mechanism of methylcellulose by promoting the cross-linking of its hydrophobic units. This specific combination of gellant and solvent was designed to optimize gel formation, ensuring the production of stable and well-structured gel.

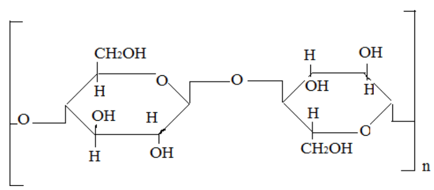

Figure 1: Hydroxy Propyl Methyl Cellulose

3. Preparation of Ethanol Gel Propellant

3.1 Non-Metalized Ethanol Gel

The preparation of pure ethanol gel without metallization followed a sequential process. Initially, 99.8% pure ethanol was mixed with distilled water and stirred briefly. Methylcellulose was then added to the solution, and the mixture was stirred at 800 rpm for 10 minutes using a mechanical stirrer to ensure thorough mixing. After stirring, the mixture was left undisturbed at room temperature for 10 minutes to allow for consistent gelation (Jyoti et al., 2014). This resting period facilitated the formation of internal bonds among ethanol, distilled water, and HPMC, resulting in a uniform and homogeneous gel.

3.2 Standardization of Non-Metalized Ethanol Gel

The gel formulation was further refined based on the target viscosity, aiming for a lower-viscosity gel with improved atomization characteristics. Accordingly, the concentration of hydroxypropyl methylcellulose (HPMC) was adjusted within the range of 15% to 18%. The various ethanol gel compositions prepared to determine the optimal base gel are presented in Table 1.

Table 1: Different Compositions of Non- Metalized Ethanol Gels

S.No.	Ethanol	Methylcellulose	Distilled water	Observation
Gel 1	80%	10%	10%	Soft gel with no separation, flowing smoothly when kept still.
Gel 2	80%	12%	8%	No separation and not flowing when kept steady
Gel 3	80%	15%	5%	Hard gel, no separation

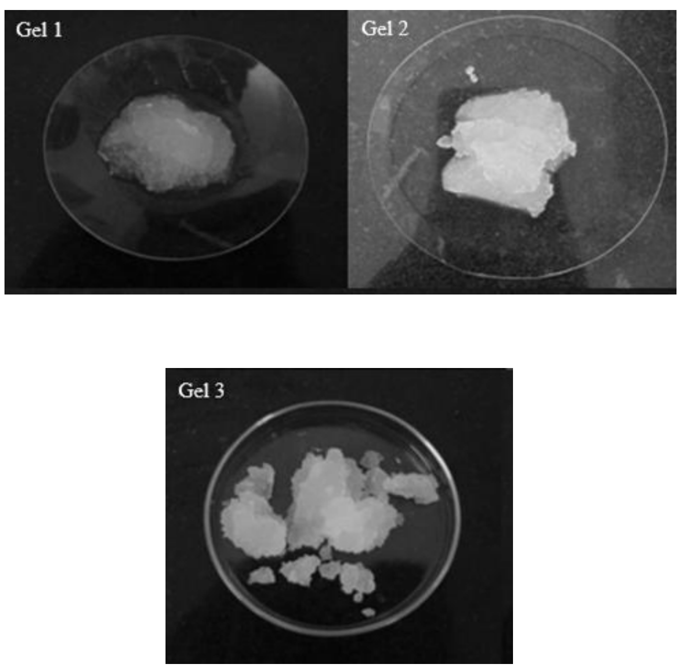

Figure 2: Different Compositions of Gel Propellants

Figure 3: Test Tube Test For 15% Gellant Non- Metalized Gel

3.3 Metalized Ethanol Gel

The preparation of metalized ethanol gel follows a process similar to that of the non-metalized variant, with the key distinction being the addition of micro-sized aluminum particles. The gel is formulated using ethanol, methylcellulose, distilled water, and aluminum. After the initial mixing, the aluminum is introduced into the non-metalized gel mixture. The resulting solution is then stirred at 600 rpm for 5 minutes using a mechanical stirrer. Following this, the mixture is allowed to rest undisturbed at room temperature for 10 minutes to ensure uniform gelation.

3.4 Standardization of Metalized Ethanol Gel

To enhance the gel's atomization characteristics, adjustments were made to its formulation, focusing on achieving lower viscosity. This involved modifying the concentration of hydroxypropyl methylcellulose (HPMC) within the range of 10% to 15%. Various ethanol gel compositions were prepared within this range to establish the optimal base gel, as detailed in Table 2.

Table 2: Different Compositions of Metalized Ethanol Gels

S.No.	Ethanol	Methylcellulose	Distilled water	Aluminum	Observation
Gel 1	80%	10%	5%	5%	Soft gel with no separation, flowing smoothly when kept still
Gel 2	80%	12%	4%	4%	No separation and no flowing when kept steady
Gel 3	80%	15%	2.5%	2.5%	Hard gel, no separation

4. Testing and Validation

4.1 Characterization of Base Material with XRD

To obtain high-quality X-ray Diffraction (XRD) data for hydroxypropyl methylcellulose (HPMC), a meticulously prepared 0.5-gram sample was used. The HPMC powder, measured within the recommended range for XRD analysis, was evenly spread onto a suitable sample holder. Gentle pressure was applied to achieve a flat, uniform surface, minimizing any irregularities that could affect diffraction patterns. Particular attention was paid to maintaining surface cleanliness to avoid contamination or interference. During the XRD procedure, X-rays were directed at the prepared HPMC sample. As the X-rays interacted with the electrons in the atoms, diffraction occurred. The diffracted X-rays, captured at various angles, produced a diffraction pattern crucial for determining the spacing between atomic planes within the HPMC crystal lattice (Roy et al., 2010). This diffraction pattern provided crystallographic information about the atomic arrangement in the HPMC structure, essential for understanding the material's properties. The data analysis involved correlating the obtained diffraction pattern with known crystallographic references to identify the crystalline phases present in the sample. This systematic approach ensured accurate and reliable insights into the crystal structure of hydroxypropyl methylcellulose, as shown in **Figure 4**, facilitating further interpretation within the context of this research.

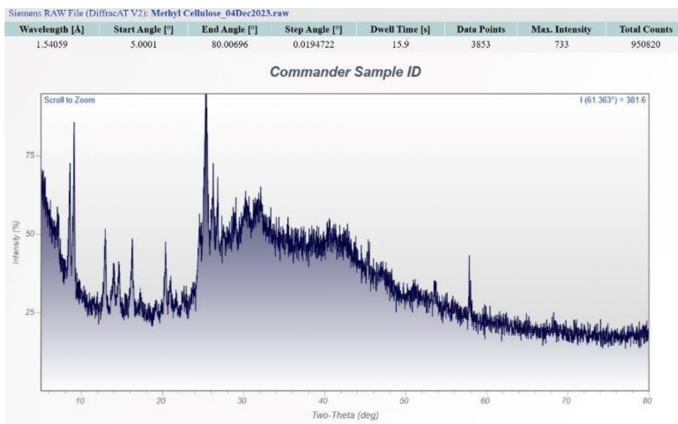

Figure 4: XRD Results

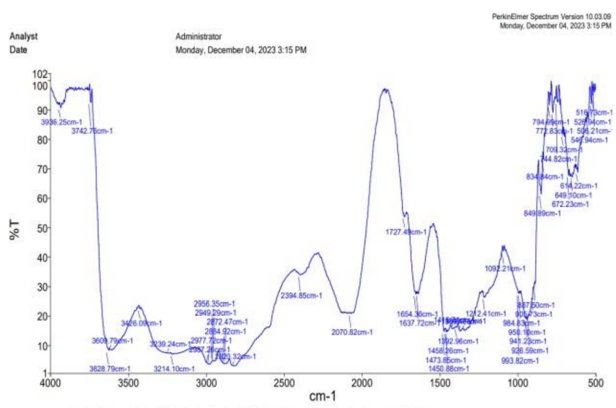

Figure 5: FTIR Test Results

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Table 3: Functional Groups and Their Bonds Found in the HPMC

S.No.	Groups	BANDS
1	C=C	1680-1640
2	C-C	3100-3000
3	O-H	3500-3200
4	C-O	1260-1050
5	H-C=O	1260-1050
6	C=O	1740-1685

4.3 Differential Scanning Calorimetry (DSC)

The insights gained from the analysis of the glass transition temperature (Tg) of ethanol–hydroxypropyl methylcellulose (HPMC) gels via Differential Scanning Calorimetry (DSC) are of particular importance in rocket propulsion and propellant development. The precise thermal characterization provided by DSC plays a critical role in tailoring the thermal properties of these gels for specific aerospace applications. In the context of rocket propulsion, the Tg range of 70 °C to 100 °C, obtained from our research and shown in **Figure 6**, is especially significant. This temperature range marks the transition from a glassy to a rubbery state—a key transformation in the physical behavior of the gel. Understanding this transition is essential when formulating propellants, as it can influence both combustion efficiency and overall performance during propulsion. The flexibility and stability imparted by the Tg range in ethanol–HPMC gels offer advantages in propellant formulation. The gel's transformation from a rigid to a more pliable state aligns well with the dynamic demands of rocket propulsion systems. The comprehensive thermal analysis through DSC ensures that the gel-based propellant can maintain optimal performance under the varying temperature conditions experienced during rocket launches (Xue et al., 2022). As we explore the implications of this Tg range within the context of propulsion, it becomes clear that such foundational knowledge supports not only propellant development but also broader advancements in aerospace technology. The findings demonstrate the potential for enhanced gel formulations to contribute meaningfully to innovations in rocket propulsion systems (Padwal et al., 2021).

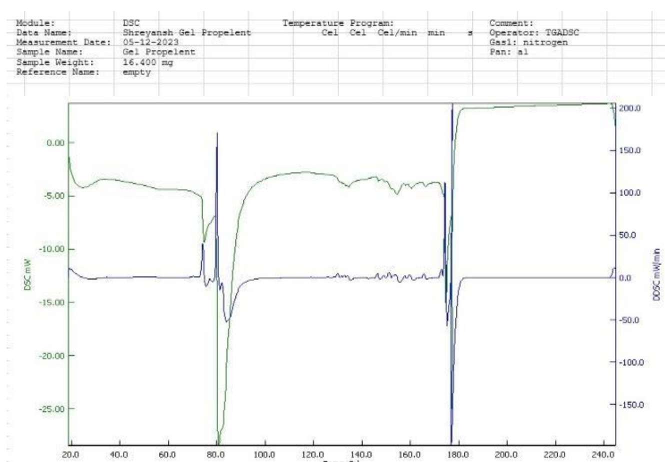

Figure 6: Glass Transition Temperature of Prepared Gel

4.4 Bomb Calorimeter Test

As part of evaluating the gel's potential as a propellant, a key focus of this study involved measuring the **calorific value** of the prepared gel samples. The calorific value, which represents the heat or energy released during complete combustion, is a crucial metric for assessing the efficiency and performance of fuels intended for propulsion. The experimental procedure was carried out with precision to ensure accurate and reliable results. One gram of each gel sample was carefully measured and placed into designated sample cups (Botchu et al., 2013). A nichrome fuse wire, connected to the ignition system, was inserted into the gel sample, with an additional cotton thread immersed in the gel to aid ignition. The bomb calorimeter was then charged with oxygen gas at a pressure of 25 psi. The assembled bomb was placed inside the inner bucket of the calorimeter, where the water temperature was maintained between 20°C and 21°C. The combustion process was initiated by firing the fuse wire, marking the start of the reaction. After the experiment concluded, the calorific value of the gel sample was recorded digitally in Cal/gram, as presented in **Table 4**. This highly controlled process ensured accurate measurement of the energy released during combustion. Determining the calorific value is especially vital when considering the gel's application as a propellant. The resulting data provide valuable insights into the gel's combustion efficiency and heat release characteristics (Palaszewski et al., n.d.). These findings, derived through a rigorous experimental protocol, lay a strong foundation for further optimization and potential application of the gel in practical propulsion systems, thereby contributing to the ongoing evolution of propulsion technologies (Nachmoni et al., 2000).

Table 4: Calorific Value of Prepared Gel Samples

Sno.	Ethanol	HPMC	Distilled Water	Observations
1	80% - 40 ml	15% - 7.5 g	5% - 2.5 ml	Highest calorific value 32501.31 kj/kg
2	80% - 40 ml	18% - 9 g	2% - 1 ml	Calorific value 25731.6 kj/kg
3	75% - 37.5 ml	18% - 9 g	7% - 3.5 ml	Least Calorific value 24233.73 kj/kg

4.5 Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is a widely used technique for analyzing the thermal stability and decomposition behavior of materials, including gel propellants. In this study, a small amount of the prepared gel propellant was placed in a crucible or pan and loaded into the TGA instrument. The instrument heated the sample at a controlled rate, typically from ambient temperature to a specified maximum temperature. Throughout the heating process, the TGA continuously measured the weight change of the sample. As the temperature increased, several thermal events occurred, such as the evaporation of volatile components, decomposition of organic materials, and oxidation reactions. The resulting data were plotted as a thermogravimetric curve, shown in Figure 7, which illustrates the change in sample weight as a function of temperature. A two-step degradation process was observed:

- Ethanol degraded completely at around 130 °C
- HPMC degraded at approximately 350 °C

These results confirm that the gellant behavior of HPMC was effectively demonstrated in the prepared gel formulation. The TGA analysis thus validates the thermal resilience and decomposition profile of the gel propellant, providing crucial insights for its application in propulsion systems.

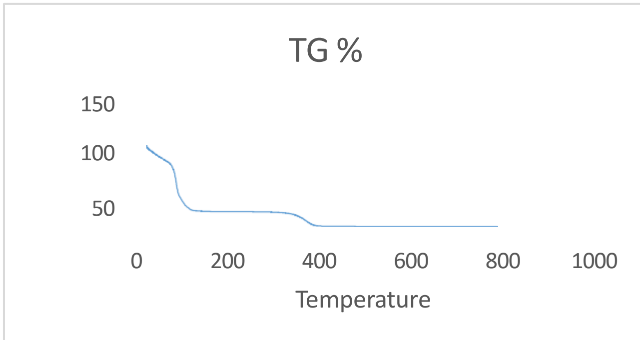

Figure 7: Thermogravimetric Curve of Prepared Gel

5.1 Non-Metalized Gel Propellant

To evaluate the characteristics of the ethanol-based gels, apparent viscosity was measured across a range of shear rates. The rheological analysis was carried out using a Rheolab QC rheometer, specifically designed for measuring the behavior of highly viscous fluids. The CC17 measuring bob was employed in this experimental setup to determine both viscosity and shear stress for various gel compositions.

It is important to note that shear stress is calculated as the product of viscosity and shear rate. In the case of non-Newtonian fluids, such as gel propellants, viscosity typically decreases with increasing shear rate (γ)—a behavior known as shear thinning.

The results of the rheological tests are presented in Figures 8 and 9, which display viscosity as a function of shear rate. In the graphs:

- The blue line represents the results for gel sample 1
- The orange line corresponds to gel sample 2
- The grey line indicates the results for gel sample 3

The compositions of all three samples are detailed in Tables 1 and 2.

Each of the three gel samples was tested at two different temperatures:

- 25 °C
- 35 °C

This comparative analysis highlights the influence of temperature and composition on the rheological behavior of the non-metalized gel propellants, providing critical insight into their flow properties under varying operational conditions.

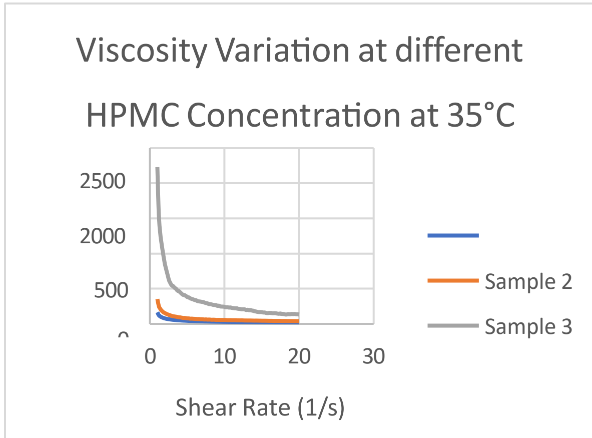

Figure 8: Rheometer Results at 25°C

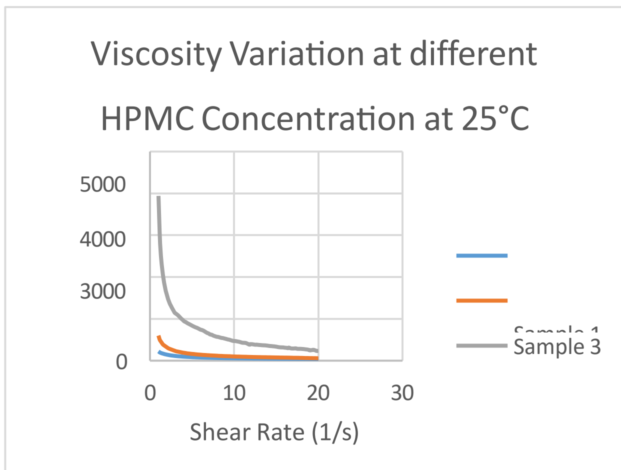

Figure 9: Rheometer Results at 35°C

5.2 Metalized Gel Propellant

To evaluate the characteristics of ethanol-based gels containing metal additives, a rheological analysis—similar to that conducted for the non-metalized gels—was performed to measure apparent viscosity across varying shear rates. A Rheolab QC rheometer, optimized for highly viscous fluids, was used in conjunction with the CC17 measuring bob to determine the viscosity and shear stress of the metalized gel compositions.

As with non-Newtonian fluids, viscosity in these metalized gels generally decreases with increasing shear rate (γ), exhibiting shear-thinning behavior. Since shear stress is the product of viscosity and shear rate, these relationships are key to understanding flow behavior.

The results are presented in Figure 10, showing the variation in viscosity with respect to shear rate for gel sample 2, as outlined in Table 2. This sample was selected based on visual inspection, having exhibited non-flowing behavior and optimal gel-like characteristics. In the figure:

- The orange line represents the viscosity of the sample at 35 °C
- The blue line indicates viscosity at 25 °C

A noticeable reduction in viscosity was observed following the addition of metal particles, demonstrating the significant impact of metallization on the gel's rheological properties.

In terms of performance, metallized propellants—such as those incorporating aluminum particles—offer higher energy density and enhanced combustion efficiency. However, they also pose certain challenges:

- Increased viscosity, which may hinder atomization and combustion efficiency
- Residue formation, potentially affecting injector performance and combustion chamber stability

On the other hand, non-metalized ethanol gels typically exhibit lower viscosity, allowing for improved atomization, more efficient combustion, and minimal residue formation (Teipel et al., 2004). This highlights a critical trade-off between energy density and operational simplicity, which must be carefully considered when selecting propellant formulations for specific aerospace applications.

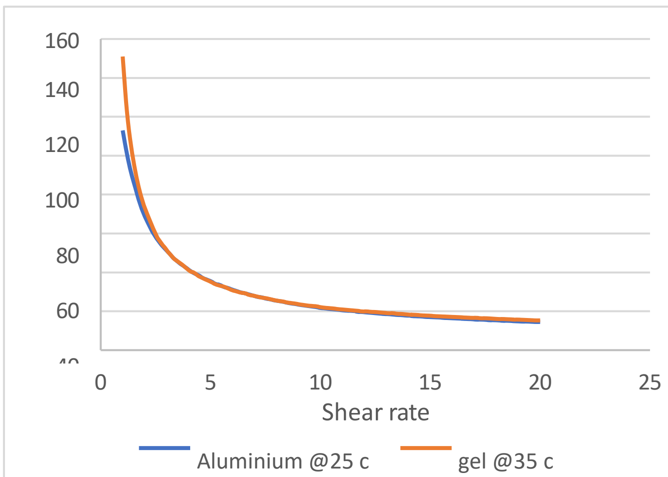

Figure 10: Aluminum -Ethanol Gel Results At 25°C And 35°C

5.3 Atomization of Gel Propellant

The relationship between viscosity, atomization, and combustion efficiency is critical in the context of gel-based propellants. Generally, lower viscosity enhances atomization at the injector, which can significantly improve combustion efficiency. However, this relationship is not strictly linear—it is influenced by factors such as injection pressure, nozzle geometry, and the combustion environment. A practical strategy for improving atomization involves pre-heating the propellant during transfer from the tank to the injector, thereby lowering its viscosity. This approach could also be integrated into a regenerative cooling scheme, offering dual benefits: improved thermal management of engine components and better injector performance due to lower viscosity.

Atomization studies of cellulose-based ethanol gels revealed that as the concentration of gellant increased, the number of atomized particles decreased, and the droplet size increased. Additionally, it was observed that increasing the impingement angle and orifice diameter resulted in a larger mean droplet area and diameter, but a reduction in droplet count (Padwal et al., 2021). In summary, non-metallized ethanol gels offer clear advantages in terms of ease of handling, efficient atomization, and consistent combustion. Future work could explore metallized gels, weighing the higher energy densities they provide against the challenges of increased viscosity and potential residue formation.

5.4 Combustion Properties

To contextualize the energy content of our developed gel propellant, its calorific value was compared with that of widely used aerospace fuels. This comparison helps assess its potential applications based on energy density and practical benefits.

Table 5: Calorific Value Comparison of Different Fuels

Fuel Type	Calorific Value (MJ/kg)
Our Propellant	32.5
JP-10	39.0
Kerosene	43.1
RP-1	44.1

As shown in Table 5, our gel propellant has a lower calorific value than traditional hydrocarbon fuels such as JP-10, kerosene, and RP-1. However, it offers advantages in terms of cost-efficiency, ease of synthesis, and suitability for low-temperature operations. These trade-offs must be carefully considered when selecting a fuel for specific mission requirements.

5.4.1 Specific Gravity and Energy Density

The specific gravity of the propellant, a key factor in determining volumetric energy density, was measured using a pycnometer and found to be 0.95. Using this, the energy per unit volume was calculated as:

Energy Density = 32.5 MJ/kg × 0.95 = 30.88 MJ/L

While lower than JP-10 (37.05 MJ/L) and RP-1 (41.87 MJ/L) (Palaszewski et al., n.d.), this energy density remains adequate for systems where volume is not a primary constraint and where other features (e.g., thermal stability, cost, or safety) are more critical.

5.4.2 Combustion with Other Oxidizers

Although initial combustion testing used oxygen as the oxidizer, it's important to evaluate performance with alternative oxidizers commonly used in space propulsion, such as nitrogen tetroxide (N_2O_4) and hydrogen peroxide (H_2O_2):

- **Nitrogen Tetroxide (N_2O_4):** As a hypergolic oxidizer, N_2O_4 can ignite spontaneously with many fuels. Its reaction with our gel propellant is expected to yield a slightly lower specific impulse than with oxygen, due to its lower enthalpy of formation. Nonetheless, its hypergolic nature and storability make it highly advantageous for spacecraft maneuvering and deep-space missions (Padwal et al., 2021).

- **Hydrogen Peroxide (H_2O_2):** H_2O_2 is particularly appealing due to its clean decomposition into water and oxygen. It offers the potential for simpler system designs, especially in monopropellant or bipropellant systems. Although it may deliver slightly lower specific impulse than oxygen, it compensates with safer handling and operational simplicity (Botchu et al., 2013).

Further experimental studies are planned to evaluate combustion performance with these oxidizers, aiming to assess the versatility and mission adaptability of our gel propellant.

5.4.3 Stoichiometric Ratio and Oxidizer Requirement

The stoichiometric oxidizer-to-fuel (O/F) ratio was calculated from the balanced chemical reaction of the propellant:

$$\mathbf{O/F\ Ratio = 3.5}$$

This implies that 3.5 kg of oxidizer are required for every 1 kg of fuel to achieve complete combustion. This ratio is critical for determining the oxidizer load, influencing both vehicle mass and propulsion system design.

Table 6: Oxidizer Requirement for Complete Combustion

Propellant Mass (kg)	Oxidizer Mass (kg)
1.0	3.5
5.0	17.5
10.0	35.0

Accurate knowledge of this ratio is vital for propellant optimization, mission planning, and mass budget assessments.

5.4.4 Ignition Energy and Delay

Two key ignition parameters were considered:

- **Ignition Energy:** The minimum energy input required to initiate combustion.
- **Ignition Delay:** The time lag between oxidizer injection and the onset of sustained combustion.

Experimental measurements of these properties are ongoing. Initial estimates indicate a low ignition energy requirement, suggesting fast start-up capabilities—desirable in scenarios demanding rapid thrust generation. Future testing under varied operating conditions will provide insights into reliability and response times, helping assess suitability for launch systems and in-space propulsion

6. Conclusion

This research has provided valuable insights into the use of hydroxypropyl methylcellulose (HPMC) as a gelling agent for ethanol-based gel propellants. Among cellulose derivatives, HPMC demonstrated superior solubility, making it a strong candidate for gel formulations. This was confirmed through FTIR analysis, which verified the presence of all critical functional groups necessary for effective gel formation. The glass transition temperature (Tg), identified in the range of 70°C to 100°C, is a crucial thermal parameter that marks the transition of the gel from a glassy to a rubbery state. This characteristic is vital for assessing the thermal behavior and operational stability of the gel in practical applications. Comprehensive rheological studies revealed that increasing the concentration of the gelling agent led to a corresponding rise in viscosity. This behavior illustrates the ability to tune the flow characteristics of the gel—transitioning from a thick, semi-solid state at low shear to a more fluid-like behavior under higher shear. This tunability is essential for diverse applications where controlled flow and consistency are needed.

The research also established that temperature significantly affects viscosity, with higher temperatures resulting in reduced viscosity. This temperature-dependent behavior has important implications for systems subjected to thermal fluctuations, guiding material selection and design parameters. Notably, it was observed that increasing the concentration of the gelling agent can negatively impact the calorific value, indicating a trade-off between mechanical properties and energy content. This underscores the need for careful optimization when designing gels for energy-sensitive applications. In terms of combustion properties, the developed propellant exhibited a calorific value of 32.5 MJ/kg and a volumetric energy density of 30.88 MJ/L, which, while lower than traditional aerospace fuels like JP-10, kerosene, and RP-1, offers distinct advantages in terms of cost-effectiveness, ease of production, and suitability for low-temperature environments. These characteristics position the propellant as a viable option for specialized applications where volume and energy density are less critical. The study also explored the combustion compatibility of the propellant with alternative oxidizers, including nitrogen tetroxide (N_2O_4) and hydrogen peroxide (H_2O_2). These findings underscore the versatility and adaptability of the formulation in various propulsion configurations. The stoichiometric O/F ratio of 3.5, derived from combustion calculations, further supports efficient oxidizer management and propulsion system design. Finally, preliminary work on ignition energy and delay suggests that the propellant could support rapid ignition, a desirable trait in aerospace propulsion. Future research will aim to experimentally validate these parameters, alongside estimating specific impulse through exhaust analysis. In summary, this study lays the groundwork for the targeted design and optimization of ethanol-based gel propellants using HPMC. The findings support their potential application in reaction control systems, cold gas thrusters, and energy-related sectors, offering a balance between performance, practicality, and cost in aerospace and defense technologies.

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8.Conflict of Interest

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