# Combustion Behavior of Gel Fuels for Sounding Rocket Applications

## M.Tech. Thesis

By

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**DEPARTMENT OF MECHANICAL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY INDORE**

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# Combustion Behavior of Gel Fuels for Sounding Rocket Applications

**A THESIS**

*Submitted in partial fulfilment of the*
*requirements for the award of the degree*
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*by*
**Anshul Kashyap**

**DEPARTMENT OF MECHANICAL ENGINEERING**
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# INDIAN INSTITUTE OF TECHNOLOGY INDORE

## CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Combustion Behavior of Gel Fuels for Sounding Rocket applications** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF MECHANICAL ENGINEERING Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2023 to May 2025 under the supervision of **Dr. Ankur Miglani**, **Associate Professor, Department of Mechanical Engineering**.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Anshul Kashyap
02/06/25

Signature of the student with date
**(Anshul Kashyap)**

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

05-06-2025
Signature of the Supervisor of
M.Tech. thesis with date
**(Dr. Ankur Miglani)**

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**Anshul Kashyap** has successfully given his M.Tech. Oral Examination held on **26 May 2025**.

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Signature of Supervisor of M.Tech. thesis
Date:

Convener, DPGC
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With Regards,

Anshul Kashyap

**Anshul Kashyap**

# Dedication

With deepest gratitude, I dedicate this thesis to my parents, **Mr. Subhash Chandra Kashyap** and **Mrs. Mamta Kashyap**, whose unwavering love, encouragement, and sacrifices have been the foundation of all my achievements.

Their constant support and belief in my potential have inspired me throughout this journey. Without their blessings and guidance, this work would not have been possible.

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# ABSTRACT

Gelled propellants have now become an attractive alternative to traditional liquid and solid fuels for space propulsion because they can take advantage of the best of both fuels—providing better safety, storage stability, and throttling. Among various gel formulations, inorganic gel fuels using kerosene and silica have drawn interest for their clean burning nature and structural integrity. In this work, the combustion of inorganic gel fuels prepared by suspending fumed silica in kerosene is studied. The study is concerned with the thermal and physical processes involved in single droplet burning under normal conditions. Experimental research was performed to monitor and examine distinct phases of combustion, such as initial heat-up, gellant shell development, and internal vapor pressure-induced exfoliation. Thermal diagnostics and high-speed imaging were used to describe the flame structure, burning rate, and droplet regression behavior. The impact of silica concentration on combustion performance was also assessed with particular focus on shell behavior and bubble formation. The findings show that inorganic gel fuels can have more controlled and stable combustion than organic gels, despite the creation of non-combustible silica residue. This steady burning rate makes these fuels a good choice for sounding rocket missions, where rapid response and stability of combustion is important. The research adds to the understanding of inorganic gel combustion and offers insights for their possible use in future aerospace propulsion systems.

**Keywords:** Inorganic gel, sounding rocket, fumed silica, combustion, shell formation, exfoliation.

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# NOMENCLATURE & ABBREVIATIONS

| Symbol | Description | Unit |
|---|---|---|
| $\tau$ | Shear stress | Pa |
| $\dot{\gamma}$ | Shear rate | $s^{-1}$ |
| T | Temperature | °C |
| t | Time | s |
| m | Mass of the sample | g or mg |
| d | Droplet diameter | mm |
| $\Delta m$ | Change in mass | g or mg |
| $\rho$ | Density | $g/cm^3$ |
| v | Jet velocity | mm/s |
| $\varphi$ | Angular location of jet in Schlieren imaging | Degrees (°) |

| **Abbreviation** | **Full Form** |
|---|---|
| TGA | Thermogravimetric Analysis |
| DTG | Differential Thermogravimetric Analysis |
| DSC | Differential Scanning Calorimetry |
| KS-x | Kerosene-Silica gel fuel with x wt.% silica |
| HPMC | Hydroxypropyl Methylcellulose |
| HEC | Hydroxyethyl Cellulose |
| MC | Methylcellulose |
| fps | Frames Per Second (used in high-speed imaging) |
| μL | Microliters |
| °C | Degrees Celsius |
| $SiO_2$ | Silicon Dioxide (Fumed Silica) |
| ρ (rho) | Density |
| $d^2$-law | Classical droplet combustion law: burning rate ∝ square of droplet size |
| wt.% | Weight percent |

# Chapter 1

# Introduction

## 1.1 Background

Propulsion systems form the backbone of aerospace and rocketry technology, where fuel performance, safety, and reliability dictate mission success. Conventional propellants fall into two primary categories: solid and liquid fuels. Each comes with its distinct set of advantages and limitations. Solid propellants offer ease of storage and simplicity in engine design, but they lack flexibility in terms of throttling, shutdown, and re-ignition. Once ignited, the burn rate of a solid fuel cannot be controlled in-flight. On the other hand, liquid propellants provide high specific impulse, and their flow can be modulated in real-time, making them suitable for a wide range of missions. However, they come with handling risks, sloshing issues, and complexity in feed systems, especially when using cryogenic or hypergolic fluids.

To bridge this gap, gelled fuels have gained attention in recent years as a hybrid class of propellants. A gel fuel is typically a liquid fuel thickened by a gelling agent, resulting in a non-Newtonian fluid that exhibits solid-like behavior at rest and liquid-like flow under shear. This transformation drastically reduces the risk of leakage, enhances storage safety, and prevents fuel sloshing [1]. At the same time, gel fuels retain the capability to be pumped, atomized, and combusted similarly to liquid fuels, thereby combining the operational flexibility of liquids with the safety features of solids.

The scientific and engineering interest in gel fuels stems from their potential use in rocket engines, sounding rockets, ramjets, hybrid propulsion systems, and even tactical missiles. Gel fuels are capable of carrying energetic additives such as aluminium, boron, or magnesium particles, which can be suspended uniformly due to the gel's high viscosity. This allows further enhancement of the energy content and specific impulse, a feature difficult to achieve in liquid or solid propellants alone.

Depending on the type of thickening agent used, gel fuels are broadly classified into organic gels and inorganic gels. Organic gels make use of polymeric gellants, such as hydroxypropyl methylcellulose (HPMC), hydroxyethyl cellulose (HEC), and other cellulose derivatives. These gellants participate in the combustion process, often leading to complex flame structures, micro-explosions, and carbonaceous residue. In contrast, inorganic gels use non-combustible gellants like fumed silica ($SiO_2$), which remain inert during combustion. This makes them appealing for applications requiring cleaner combustion and minimal residue, along with better structural stability of the fuel matrix.

This thesis focuses on the combustion behavior of inorganic gel fuels, specifically those composed of kerosene as the base fuel and fumed silica as the gelling agent. The study aims to uncover the thermal and physical processes involved in droplet combustion and to assess their applicability in sounding rocket propulsion.

## 1.2 Gel Fuels in Aerospace Propulsion

The versatility of gel propellants has led to experimental and practical use in a variety of aerospace systems. Several national and private space agencies have explored gel-based propulsion, especially for throttleable and restartable engines, where flow control is critical. The shear-thinning behavior of gels makes them easily pumpable through injectors while maintaining high viscosity in storage, which is advantageous for launch vehicle stages, upper-stage propulsion, and attitude control systems [4-6].

Sounding rockets, which are suborbital launch vehicles used for scientific payload delivery, atmospheric studies, and re-entry experiments, require propellants that are safe to handle, quick to ignite, and reliable during flight. Liquid fuels offer good performance but pose risks due to leakage and vapor pressure. Solid fuels are safer but rigid in operation. Gel fuels provide an optimal compromise by allowing in-flight throttle control, short ignition delays, and lower sensitivity to mechanical shock [2].

Furthermore, gel fuels allow suspension of metal particles and oxidizers, which enhances combustion characteristics, such as burning rate and specific impulse. The stable matrix of the gel prevents settling and allows consistent energy output over time. Although much of the recent research has focused on organic gel fuels, inorganic gels are now gaining attention due to their stable combustion profile and reduced environmental impact.

## 1.3 Inorganic Gel Fuels: Characteristics and Advantages

Inorganic gels, such as kerosene gelled with fumed silica, represent a relatively new and under-explored area of gel fuel research. Fumed silica particles, typically nanoscale in size, have a very high surface area and form a thixotropic network when dispersed in hydrocarbons. This network traps the liquid fuel molecules within its structure, significantly increasing viscosity.

Key advantages of inorganic gel fuels include:

- Non-combustible gellant: Fumed silica does not react during combustion, which leads to minimal soot and clean residues.
- Controlled regression: Shell formation and exfoliation mechanisms allow a more predictable combustion process.
- Short ignition delay: The high thermal conductivity of silica enhances heat transfer to the fuel core, reducing ignition time.
- Shear-thinning and reversible flow: Allows gel to behave like a liquid under injector conditions but remain static in tanks.
- Enhanced thermal stability: Inorganic gels can withstand higher storage temperatures without degradation.

However, these gels also present challenges. For instance, the rigid silica shell formed during combustion can inhibit vapor release, leading to exfoliation events where the shell ruptures due to internal pressure. Understanding such combustion dynamics is essential for implementing these fuels in aerospace systems [7].

### 1.4 Combustion Behavior of Gel Droplets

Single-droplet combustion is a widely used experimental technique to investigate the fundamental combustion characteristics of gel fuels. Unlike liquid droplets that burn uniformly, gel droplets show multi-stage combustion behavior:

1. Transient Heat-Up Phase: The droplet is exposed to a heat source, causing internal temperature rise and evaporation of the base fuel.

2. Shell Formation Phase: Due to phase separation, the gellant accumulates on the outer surface, forming a rigid or elastic shell.
3. Disruptive Events (Jetting or Exfoliation): In organic gels, internal vapor leads to jetting or micro-explosions; in inorganic gels, the shell cracks or exfoliates.
4. Steady Regression or Carbonization: Combustion continues until the fuel is depleted, often leaving behind gellant residue.

The burning rate, regression behavior, and ignition delay are influenced by factors such as gellant concentration, ambient pressure, droplet size, and oxidizer presence. For inorganic gels, the formation and exfoliation of the silica shell is a key feature, significantly affecting heat and mass transfer mechanisms.

### 1.5 Motivation for the Present Study

While extensive research has been conducted on organic gel fuels, especially regarding jetting, bursting, and combustion instability, inorganic gel fuels remain relatively under-investigated. Their combustion is characterized by unique features such as:

- Rigid shell dynamics, not observed in organic gels.
- Lower flame distortion due to reduced internal jetting.
- Distinct deviation from the $d^2$-law due to silica residue accumulation.
- Clean combustion with minimal environmental emissions.

These features suggest that inorganic gel fuels could be ideal candidates for sounding rocket applications, where safety, reliability, and combustion control are critical. However, detailed experimental data on droplet combustion, particularly involving different silica concentrations, are scarce.

The motivation for this research stems from this knowledge gap. By studying the combustion behavior of kerosene-silica gel droplets, we aim to provide insights that can help optimize gel fuel formulations and inform future engine design strategies.

### 1.6 Research Objectives

The major goal of this thesis is to understand and characterize the combustion behavior of inorganic gel fuels, with emphasis on droplet-scale phenomena. The specific objectives are as follows:

- To prepare inorganic gel fuels using kerosene and varying concentrations of fumed silica.
- To analyse their rheological behavior, particularly viscosity and stability.
- To conduct single-droplet combustion experiments under controlled conditions.
- To observe combustion stages including shell formation, bubble activity, and exfoliation.
- To measure key parameters such as ignition, burning rate, and flame structure.
- To compare the observed combustion behavior with that of organic gels and pure kerosene from literature.
- To evaluate the potential of these fuels for use in sounding rocket propulsion systems.

### 1.7 Scope and Limitations

This study is conducted in a laboratory environment using single suspended droplets. While such experiments provide high-resolution insights into the combustion process, they do not replicate the full complexity of actual engine conditions, such as oxidizer injection, chamber pressure, and multiphase flow effects.

The research focuses exclusively on:

- Non-metalized, inorganic gel fuels
- Kerosene as the base fuel
- Fumed silica as the gellant
- Ambient pressure, static air conditions

Limitations include:

- Absence of forced convection or oxidizer flow
- No simulation of full-scale injector or spray dynamics
- Focus on isolated droplets rather than continuous combustion

Despite these constraints, the findings from this study serve as a foundation for scaling up, integrating the fuels into realistic combustion systems, and guiding future numerical modelling efforts.

### 1.8 Organization of the Thesis

The thesis is divided into the following chapters:

- **Chapter 2. Literature Review:** A critical review of previous research on organic and inorganic gel fuels, including combustion models, experiments, and key findings.

- **Chapter 3. Fuel Formulation and Rheological Analysis**: Details the preparation of inorganic gel fuels and their characterization in terms of viscosity, flow behavior, and stability.
- **Chapter 4. Experimental Setup and Methodology:** Describes the experimental apparatus, droplet suspension method, heating system, and high-speed imaging techniques.
- **Chapter 5. Results and Discussion:** Presents the combustion behavior of various gel formulations, analysis of combustion stages, and effects of silica concentration on performance.
- **Chapter 6. Conclusions and Future Scope:** Summarizes the major findings of the study and highlights the advantages of inorganic gel fuels for propulsion. It outlines possible directions for future research, including spray combustion, numerical modeling, and engine-level testing.

# Chapter 2

# Literature Review

## 2.1 Overview of Inorganic Gel Fuel Research

R. Arnold and W. E. Anderson [8] studies the combustion characteristics of gelled JP-8 turbine fuel with fumed silica as a gelling agent. The primary focus was to assist in the design of gel-operated injectors by understanding the vaporization and combustion processes of single droplets. The research confirmed that gelled fuels exhibit different combustion characteristics than liquid fuels, following the $d^2$-law but with reduced burning rates due to the presence of the gelling agent. The study also highlighted the impact of gel consistency on droplet size and combustion temperature, which are crucial for optimizing propulsion system performance.

R. Arnold et al. [9] compares the rheological and combustion properties of monomethyl hydrazine (MMH) gelled with hydroxypropyl cellulose (HPC) and hydrocarbon-based gels (JP-8 and RP-1) with silica gelling agents. The study demonstrated significant differences in viscosity and yield stress due to the choice of gelling agent. MMH/HPC gels showed a swelling process during combustion, forming a flexible surface, whereas hydrocarbon/silica gels developed a rigid silica structure that remained unburned. The burning rates were analysed using the $d^2$-law, showing the influence of gellant concentration on combustion dynamics.

Y. Solomon et al. [10] explores the vaporization and combustion of gelled monomethyl hydrazine (MMH) droplets in a nitrogen dioxide

(NTO) environment. It investigates two types of MMH gels—one using hydroxypropyl cellulose (HPC) and the other using fumed silica. The study found that MMH/HPC gels exhibited swelling and jetting due to the flexible nature of the organic gellant, whereas MMH/Silica gels formed rigid structures that underwent micro-explosions before breaking down. The burning rate was found to depend on droplet diameter but not on pressure within the investigated range. The study provides insights into the combustion mechanisms of hypergolic gelled fuels, which are relevant for future space propulsion systems.

Dali Yang et al. [11] investigates the evaporation behavior of single kerosene gel droplets under different temperature conditions. The experiments were conducted by suspending gel droplets on a thermocouple wire and exposing them to elevated temperatures ranging from 100°C to 500°C. The results revealed that the evaporation process could be divided into three distinct stages: (i) evaporation of kerosene, (ii) formation of a gellant layer, and (iii) swelling of the gellant layer followed by microexplosions. The study highlighted several unique phenomena, including bubble nucleation, vapor cloud formation, and periodic microexplosions, which are absent in pure kerosene droplets. It was observed that at temperatures above the boiling point of kerosene, the gellant layer prevented fuel vapor diffusion, leading to a buildup of internal pressure and eventual rupture. The findings contribute to understanding the phase separation mechanism in gel propellants, which is crucial for their application in propulsion systems.

Qinliu Cao et al. [12] in their study examines the combustion properties of inorganic kerosene gelled with fumed silica. Unlike organic gels, these inorganic gels form a rigid shell that shrinks and exfoliates during combustion. The burning rate follows the $d^2$-law in the early stage but deviates in the later stages due to the presence of solid residues. The study also found that inorganic gels have shorter ignition delay times and survival times than pure kerosene, making them suitable for high-performance propulsion systems. Enhanced heat transfer due to silica's thermal conductivity contributes to increased combustion rates in the later stages.

Sharma et al. (2023) [15] conducted a detailed investigation into the combustion behavior of ethanol-based organic gel fuels using high-speed and Schlieren imaging, focusing on fuels formulated with 3% Hydroxypropyl Methylcellulose (HPMC) and 9% Methylcellulose (MC). The study identified three distinct combustion stages: transient heat-up with initial shell formation, disruptive burning marked by vapor bubble generation and jetting, and a final carbonization stage. HPMC-based gels exhibited oscillatory bursting due to their flexible shells, while MC-based gels showed high-pressure transient ruptures because of their rigid structure. Flame disruptions, such as flame distortion, pin ejections, and fireballs, were more intense in MC gels and directly linked to jetting behavior. Burn rates peaked during disruptive burning due to vapor release, and SEM analysis revealed morphological differences in the combustion residue—striated for HPMC and blistered or cracked for MC—highlighting the critical influence of gellant properties on combustion dynamics.

## 2.2 Research Gaps and Scope for Further Study

Over the past two decades, considerable progress has been made in the field of gelled propellants, particularly in the development and combustion of organic gel fuels. Extensive work has been reported on the formulation, rheological characterization, and combustion behavior of organic gels such as hydroxypropyl methylcellulose (HPMC) and hydroxyethyl cellulose (HEC)-based systems [2]. These fuels have been widely studied under both droplet-scale and full-scale combustion conditions, often with suspended energetic additives like aluminium or boron [17].

However, in contrast to organic gels, inorganic gel fuels remain significantly underexplored, especially in the context of combustion behavior and applicability to aerospace propulsion systems such as sounding rockets. Inorganic gels, typically formulated using fumed silica as the gelling agent, are fundamentally different in combustion dynamics. The silica matrix does not participate in combustion but forms a rigid shell around the burning droplet, leading to distinctive phenomena such as shell shrinkage, cracking, and exfoliation [7].

While some researchers have documented these phenomena qualitatively, detailed quantitative investigations into the effects of gellant concentration, shell behavior, and heat transfer mechanisms are still limited. Specifically:

- There is a lack of comprehensive data on burning rates, ignition delays, and droplet regression behavior for varying silica concentrations.
- The role of shell formation and exfoliation on combustion stability and efficiency is not fully understood.
- Most previous studies were carried out under ambient and quiescent conditions; very few address forced convection or pressurized environments, which are more representative of practical applications.

- The deviation from the classical $d^2$-law in later combustion stages due to unburned silica residue has not been thoroughly modelled or predicted [7].
- Limited rheological data is available linking yield stress and shear-thinning behavior with combustion characteristics, especially under dynamic flow and injector-relevant shear conditions.

As a result, there exists a clear research gap in the experimental, theoretical, and application-oriented understanding of inorganic gel fuels. Bridging this gap is essential for the future integration of such fuels into practical propulsion systems.

# Chapter 3

## Formulation and Characterization of Inorganic Gel Fuels

### 3.1 Materials and Methods

In this study, kerosene-based gel fuels were formulated using fumed silica (Aerosil 200) as the gelling agent. The objective was to investigate the influence of gellant concentration on combustion behavior. A total of six compositions were selected for detailed experimental analysis, although gels were prepared over a wider range of silica concentrations (from 0 to 10 wt.%). The selected compositions are KS-0, KS-2, KS-4, KS-6, KS-8, and KS-10 as they exhibited distinct rheological and combustion characteristics, making them suitable for comparative study.

Table 3.1. Composition of Gel Fuel Samples

| **Sample** | **Concentration (Weight%)** | |
|---|---|---|
| | **Kerosene** | **Silica** |
| KS-0 | 100 | 0 |
| KS-1 | 99 | 1 |
| KS-2 | 98 | 2 |
| KS-3 | 97 | 3 |
| KS-4 | 96 | 4 |
| KS-5 | 95 | 5 |
| KS-6 | 94 | 6 |
| KS-7 | 93 | 7 |
| KS-8 | 92 | 8 |
| KS-9 | 91 | 9 |
| KS-10 | 90 | 10 |

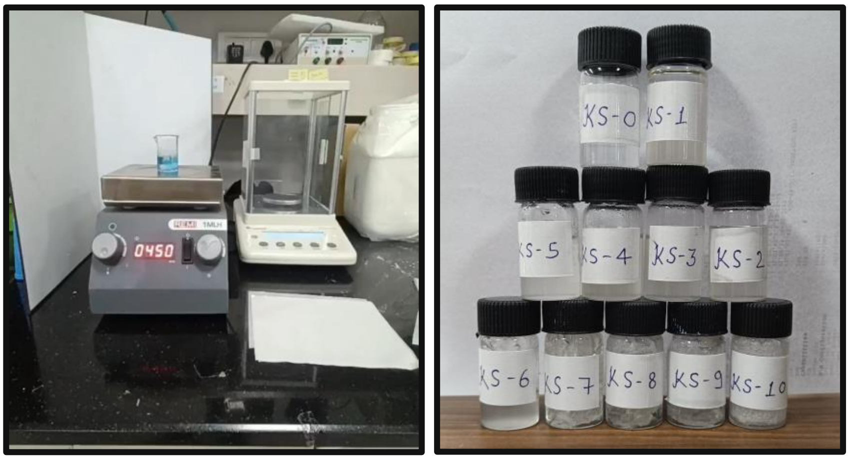


Figure 3.1 (Left) Experimental setup for gel formulation, including a hot plate magnetic stirrer and precision balance used during sample preparation. (Right) Prepared gel fuel samples labelled KS-0 to KS-10, representing increasing silica concentrations from 0 to 10 wt.%.

Table 3.1 presents the composition of the prepared fuel samples, where each is labelled based on its silica concentration. KS-0 represents pure kerosene with no gellant and serves as the control sample. KS-2 through KS-10 represent increasing silica concentrations from 2 to 10 wt.%.

Although all samples were successfully prepared, only KS-0, KS-2, KS-4, and KS-6 were selected for combustion experiments, as they demonstrated significant and progressive changes in combustion stages such as shell formation, bubble growth, and exfoliation.

The gellant used was Aerosil 200, a high-purity fumed silica known for its high surface area and thixotropic gelation capability. Its physical properties are provided in Table 3.2. The base fuel used was kerosene, selected for its widespread use in aerospace applications due to its high energy content and well-characterized combustion behavior. The properties of the kerosene used in this study are shown in Table 3.3.

Table 3.2. Properties of Aerosil 200

| **Property** | **Value** |
|---|---|
| Melting Point (°C) | ~1700 |
| Specific Surface Area (m²/g) | ~200 |
| Primary Particle Size (nm) | ~7 |
| Bulk Density (g/cm³) | 0.03684 |

Table 3.3. Properties of Kerosene

| **Property** | **Value** |
|---|---|
| Boiling Point (°C) | 150–300 |
| Flash Point (°C) | 37–65 |
| Autoignition Temperature (°C) | ~220 |
| Density (g/cm³) | 0.76–0.79 |

The gel fuels were prepared under ambient laboratory conditions. A precise weight of fumed silica was gradually added to kerosene while stirring continuously using a magnetic stirrer. The mixing was performed at a constant speed of 450 revolutions per minute (rpm) for 15 minutes to ensure uniform dispersion of silica throughout the fuel.

After mixing, the resulting gel was transferred to sealed glass containers and left undisturbed for 48 hours at room temperature to evaluate short-term stability. Samples were visually inspected for signs of phase separation, sedimentation, or syneresis (expulsion of trapped liquid). No significant phase instability was observed in the selected compositions, confirming that the silica network formed a stable three-dimensional structure within the fuel matrix.

### 3.2 Rheological Characterization

Rheology is the study of flow and deformation behavior of materials under applied forces. In the context of gel fuels, rheology plays a pivotal role in defining fuel behavior during storage, pumping, atomization, and combustion. Unlike Newtonian fluids such as water or pure kerosene, gel fuels are non-Newtonian and exhibit complex flow characteristics, including shear-thinning, yield stress, viscoelasticity, and thixotropy [2]. These behaviours arise due to the formation of a three-dimensional microstructure formed by the interaction between the fuel and the gelling agent, in this case, fumed silica.

Table 3.4. Yield Stress Range for Kerosene–Silica Inorganic Gels

| **Fumed Silica Content (wt.%)** | **Approximate Yield Stress** |
|---|---|
| 1–2 wt.% | 5–30 Pa |
| 3–4 wt.% | 30–80 Pa |
| 5–6 wt.% | 80–200 Pa |
| >6 wt.% (dense gel) | >200 Pa (may exceed 300 Pa) |

Inorganic gel fuels, such as kerosene–silica systems, display non-Newtonian flow characteristics that significantly influence their handling, injection, and combustion performance. A primary feature is shear-thinning behavior, where the apparent viscosity decreases with increasing shear rate, aiding in ease of flow during injection while ensuring high viscosity at rest to prevent sloshing and leakage. This behavior can be modelled using the power-law equation, where a lower flow behavior index ($n<1$) indicates stronger shear-thinning, typically observed at higher silica concentrations due to denser gel networks [4].

Yield stress is the minimum stress required to initiate flow in the gel. Below this threshold, the material behaves like a solid; above it, it flows like a fluid. Yield stress ensures mechanical stability of the fuel in tanks, preventing unintended movement or separation. The presence of yield stress in silica-based gels arises due to the formation of interconnected silica particle networks, stabilized by hydrogen bonding and van der Waals forces. Increasing silica content leads to: Higher yield stress, Increased gel rigidity, Improved sedimentation resistance for suspended additives [5]. Table 3.4 shows typical Yield Stress Range for different Kerosene–Silica Inorganic Gels.

Viscoelasticity is another critical property, indicating that the fuel behaves partly like a solid and partly like a liquid under stress. [6].

Thixotropy is a time-dependent shear-thinning behavior where viscosity decreases under constant shear and recovers when the shear is removed. It is particularly useful in gel fuels for maintaining structural integrity during storage and ensuring flow recovery post-injection. Thixotropic behavior in silica gels arises due to reversible breaking and reformation of the silica network. This behavior is typically evaluated using a hysteresis loop test, where shear is increased and then decreased to plot a flow curve [4-6].

# Chapter 4

# Experimental Setup and Methodology

## 4.1 Overview

The combustion behavior of gel fuels is influenced by various factors such as rheology, droplet structure, and heat transfer dynamics. To accurately characterize the burning process of inorganic gel fuels, droplet-scale experiments were carried out under controlled laboratory conditions. This chapter outlines the experimental approach, apparatus, diagnostic techniques, and testing methodology used to investigate the combustion characteristics of kerosene–silica gel fuels, including shell formation, bubbling, and exfoliation behavior.

Two distinct experimental setups were utilized: a pendant droplet combustion system for high-speed video imaging, and a dual-mirror Schlieren optical system for visualizing thermal and density gradients in the flame zone. Both setups operated under ambient atmospheric conditions, and the results were recorded using high-speed imaging to capture rapid combustion phenomena.

## 4.2 Pendant Droplet Combustion Setup

### 4.2.1 Description of Setup

The pendant droplet setup was designed to suspend and ignite individual gel fuel droplets while capturing combustion events using high-speed videography. The schematic of the setup is shown in Figure 4.1.

Key components of the setup include: Variable intensity light source (LA150D by LITEMONS), Diffuser sheet and diffuser plate to ensure uniform backlighting, Vertical traverse stand for positioning adjustment, Suspended gelled fuel droplet mounted on a nichrome wire (0.18 mm diameter), 4.5× Navitar microscopic zoom lens for high-resolution optical magnification, Chronos 2.1 HD high-speed camera, Labjack platform for adjusting the focal plane.

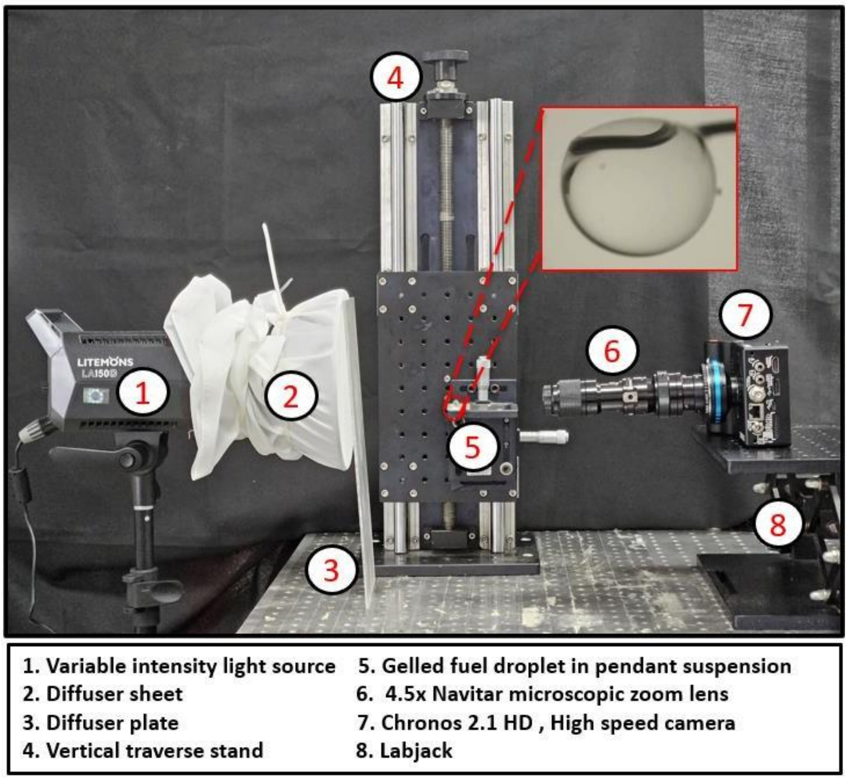


Figure 4.1. A schematic diagram illustrating the experimental setup and its key components used to study the droplet-scale combustion dynamics of gel fuels.

### 4.2.2 Droplet Preparation and Suspension

Prior to combustion testing, the gel fuels were aged for 48 hours to ensure full development of the silica network and to rule out phase separation. A calibrated micro-syringe was used to extract and dispense consistent 5 µL droplets onto a horizontally mounted nichrome wire. The wire provided a stable platform that minimized droplet deformation and allowed flame observation from the side.

Droplet diameters were maintained within a narrow range (typically 1.7–1.9 mm) to ensure experimental repeatability. More than 50 gel droplets with varying silica concentrations (from 0 to 10 wt.%) were prepared and tested throughout this study.

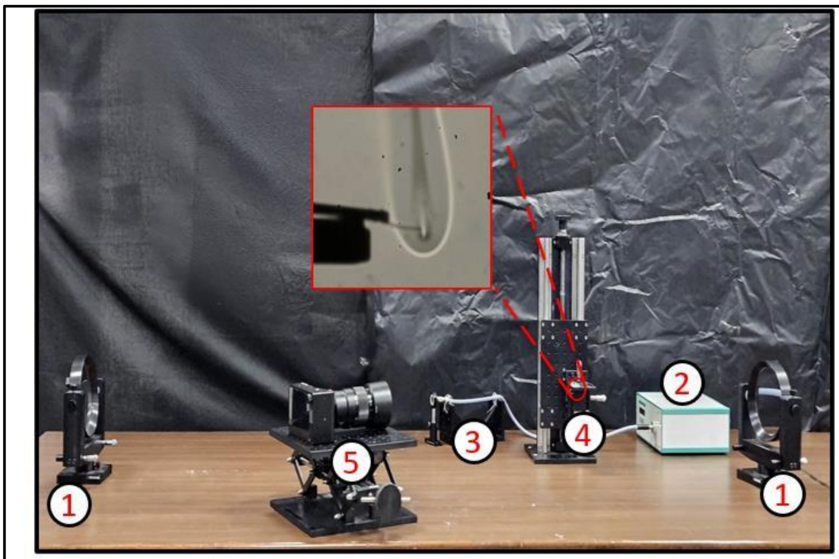
### 4.3 High-Speed Imaging and Data Collection

To analyse transient combustion events such as bubble formation, shell development, flame growth, and exfoliation, high-speed video was recorded using a Chronos 2.1 HD camera. The camera was equipped with a 4.5× Navitar zoom lens and operated at: Frame rate of 5775 frames per second (fps), Exposure time of 60 µs, Spatial resolution of ~5 µm/pixel.

This configuration enabled the visualization of fine-scale events that occur within milliseconds. The high temporal and spatial resolution helped analyse the onset of ignition, shell cracking, flame propagation, and vapor jetting, which are critical to understanding gel fuel combustion.

### 4.4 Schlieren Imaging System

To observe flame structure and density variations around the burning gel droplets, a dual-mirror Z-type Schlieren system was employed. This technique captures the refractive index gradients created by temperature and pressure variations in the combustion zone, allowing visualization of otherwise invisible flow structures [12]. As shown in Figure 4.2, the Schlieren setup consisted of the following: Two parabolic mirrors mounted on gimble stands to align the optical path, Xenon variable intensity light source, Precision pinhole (30 µm) for point light formation, Gelled fuel droplet in pendant suspension, High-speed camera with Canon EF 100 mm f/2.8 L macro lens.



1. **Parabolic mirrors**
2. **Xenon variable intensity light source**
3. **Pin hole (30 micron)**
4. **Gelled fuel droplet in pendant suspension**
5. **High speed camera with canon EF 100mm 2.8 L macro lens**

Figure 4.2. A schematic diagram of the experimental setup illustrating the dual-mirror Z-type Schlieren system used for flame visualization.

The parabolic mirrors (focal length: ~120 cm) were used to collimate and focus the light beam. A knife-edge (not shown in figure) was placed at the focal point to enhance contrast. The system was aligned to minimize beam shift and optimize sensitivity. The gimble mounts helped maintain precise mirror alignment during adjustments.

## 4.5 Operating Conditions and Procedure

All experiments were conducted under ambient laboratory conditions: Ambient temperature: ~25 °C, Atmospheric pressure: ~1 atm, still air environment (no external flow), Dark background to enhance flame visibility.

Procedure:

- A gel droplet was dispensed onto the nichrome wire.
- The camera and light source were aligned to focus on the droplet centre.
- Ignition was achieved using a micro-torch or hot wire placed near the droplet.
- Simultaneous video and Schlieren recordings were initiated upon ignition.
- Each experiment lasted until complete burnout or exfoliation.

## 4.6 Parameters Recorded

The following parameters were observed and recorded:

- Combustion duration (total burning time)
- Shell formation and exfoliation events
- Flame shape and movement (via Schlieren visualization)
- Bubble dynamics within the droplet (via high-speed video)
- Droplet regression rate (measured from diameter change over time)

Post-processing was performed using software like Photron Fastcam viewer (PFV4) with calibration using pixel-to-length conversion based on known droplet size. To ensure the reproducibility of results, each test was repeated at least five times per sample.

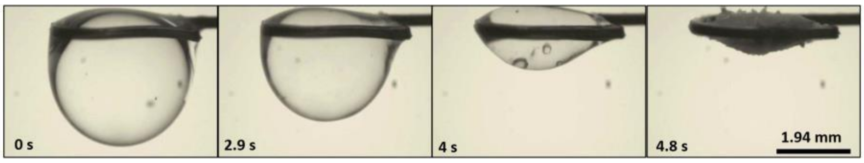
This chapter described the experimental techniques used to evaluate the combustion characteristics of inorganic gel fuel droplets. The pendant droplet system enabled precise control and high-speed recording of flame dynamics, while the Schlieren system provided valuable insights into flow structures and temperature gradients. Together, these techniques support a comprehensive understanding of gel fuel behavior during ignition and combustion.

# Chapter 5

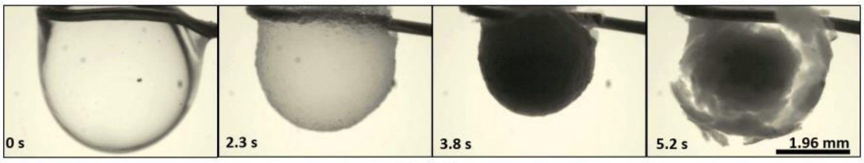
# Results and Discussion

## 5.1 Characterization of Combustion Stages

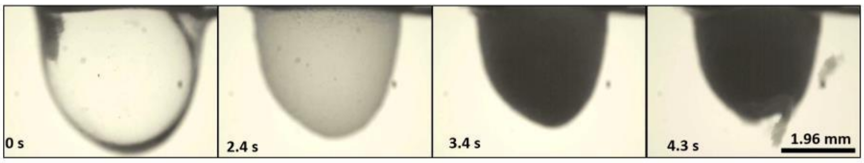
The combustion behavior of kerosene-based inorganic gel fuels was analysed through high-speed video imaging of single droplets under ambient conditions. Based on visual evidence, the combustion process is categorized into three distinct stages: (I) Transient Heat-Up, (II) Gellant Shell Formation, and (III) Shell Exfoliation. Each stage is defined by specific thermal and structural transformations of the droplet, influenced by the gellant (silica) content.



a. KS-2



b. KS-4



c. KS-6

Figure 5.1. Combustion of inorganic kerosene gel droplets. (a) 2% silica content, (b) 4% silica content, (c) 6% silica content in kerosene respectively.

### 5.1.1 Stage I: Transient Heat-Up

The initial phase of combustion begins with ignition, during which heat is first absorbed by the droplet's outer surface in proximity to the ignition source. A visible flame envelope forms and gradually wraps around the droplet, resulting in increasing heat absorption. This stage is characterized by droplet shrinkage due to evaporation of kerosene from the droplet surface.

In this transient stage, no significant structural change in the gellant matrix is observed. As heat transfer intensifies, it starts to affect the internal temperature distribution within the droplet, initiating the conditions necessary for the subsequent phase separation. The duration of this phase is relatively short and strongly depends on the droplet size, ambient temperature, and silica concentration.

Similar initial heating behavior has been reported in prior gel fuel studies, confirming that evaporation dominates this early stage before structural transformations commence [2,7].

### 5.1.2 Stage II: Gellant Shell Formation

As heating progresses, a phase separation initiates in the outer layers of the droplet, resulting in the accumulation of silica particles near the surface. This leads to the formation of a rigid, while the droplet core remains unchanged. The shell formation process propagates radially inward, driven by continued kerosene evaporation and thermal energy absorption as shown in Figure 5.2.

During this stage, the droplet's surface texture begins to change, becoming rough and irregular. For intermediate silica concentrations (e.g., KS-4), the shell becomes visibly more pronounced, transitioning from a semi-soft membrane to a hardened silica shell.

A color transition from grey to black is often observed, potentially due to soot deposition and localized thermal stress.

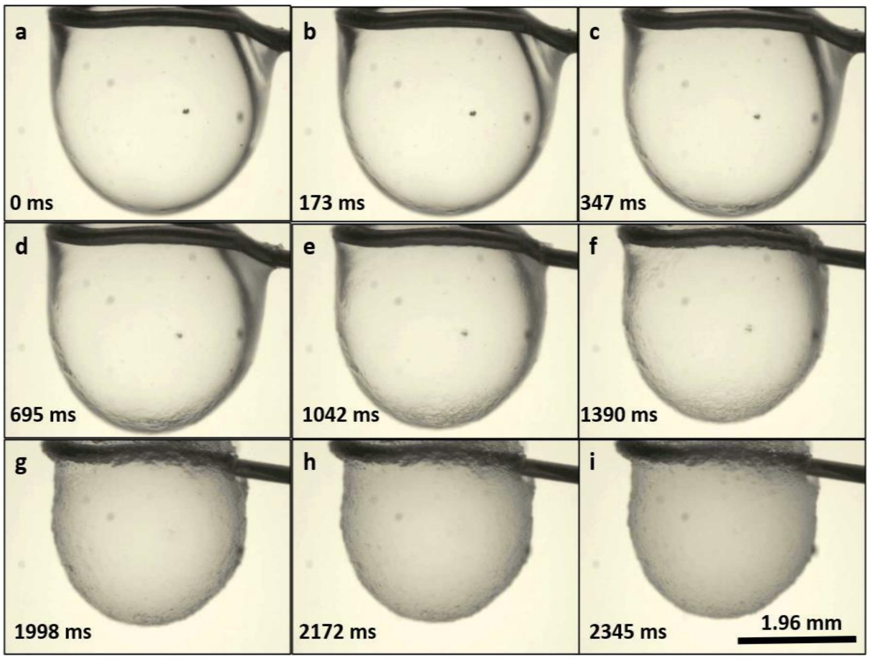


Figure 5.2. Shell formation and propagation of KS-4 gel droplet.

In droplets with lower silica content (e.g., KS-2), this stage is also marked by the formation of internal vapor bubbles, typically near the droplet support wire. As these bubbles grow and migrate toward the surface, they exert pressure on the inner shell wall. Upon reaching a critical pressure threshold, the shell ruptures, resulting in a bursting event, represented in figure 5.3. These ruptures may create transient flame oscillations and high-velocity vapor jets.

This behavior aligns with combustion models that describe bubble nucleation and shell rupture in gel fuels as part of disruptive burning modes, especially when the shell lacks sufficient strength to contain internal vapor pressure [17].

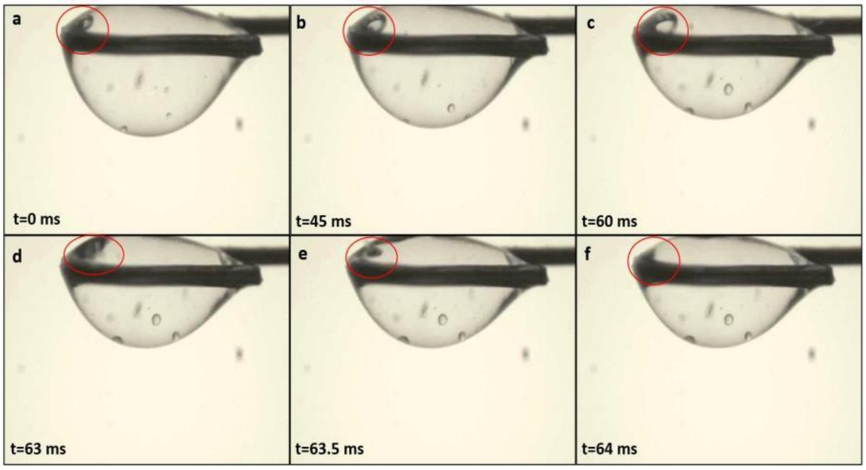


Figure 5.3. Burst event for KS-2 gelled droplet, (a to c) bubble growth, (c to d) sudden rupture of gellant shell due to bubble bursting, (d to f) shell retraction.

### 5.1.3 Stage III: Shell Exfoliation

In the final stage of combustion, continued heating causes the internal vapor pressure to rise significantly, leading to the development of micro-cracks in the rigid silica shell. As combustion progresses, the trapped kerosene vapor creates localized stress zones within the shell. These stresses, combined with thermal gradients, initiate flaking and peeling of the shell material—a process referred to as exfoliation. Figure 5.4 illustrates this process for KS-4.

Exfoliation manifests as the detachment of small silica fragments or layers from the droplet surface. These flakes are often lifted and carried away by the convective gas flow surrounding the flame. The removal of shell material exposes new fuel-rich regions, allowing fresh vaporization and sustaining combustion. This cyclic exposure of internal fuel due to exfoliation contributes to non-uniform flame dynamics and irregular droplet shapes in the final stages.

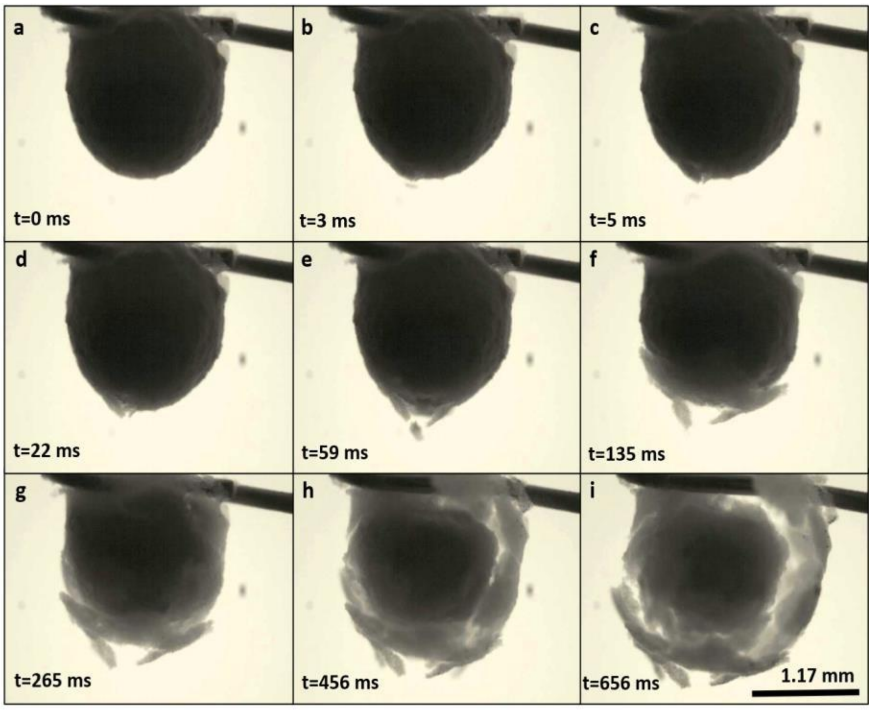


Figure 5.4. Exfoliation of silica shell during combustion for KS-4 (Kerosene 96% and Silica 4%).

The intensity and frequency of exfoliation events are observed to increase with silica concentration. At higher gellant contents (e.g., KS-6 and above), the thicker and more brittle shell tends to undergo more frequent cracking and flake ejection, possibly due to higher internal stress accumulation and less elastic accommodation.

The final residue typically consists of porous, white or grey silica ash, as the gellant does not undergo combustion. This residue plays a role in post-combustion heat transfer by acting as a thermal barrier around the core in the final moments of burning.

Exfoliation has been reported in other studies on inorganic gels, particularly those using silica as the gelling agent, where the non-combustible shell acts as a mechanical barrier until it fails under thermal loading [7].

### 5.2 Thermogravimetric analysis

Thermogravimetric analysis was done for the sets of fuels under study. These experiments aimed to investigate the phase transitions occurring during the combustion of gel fuel samples. TGA measures the change in mass of a material as a function of temperature or time under controlled temperature. A sample of 30 mg is placed on a highly sensitive microbalance in a furnace. The furnace heats the sample at 10°C/min, the microbalance continuously measures the weight of sample during heating in an inert atmosphere of nitrogen.

Figure 5.5 presents the thermogravimetric (TG) and differential thermogravimetric (DTG) thermograms, which depict the mass loss behaviour and thermal decomposition characteristics of the gels. It is observed that the gel fuel samples go through a single step thermal decomposition. In case of KS-4, during initial phase 30 °C to 45 °C, there is no significant weight loss, the mixture remains thermally stable. In the range of 50 °C to 200 °C, a mass loss of ~95% is observed, indicating the evaporation of kerosene, as kerosene consists of volatile hydrocarbons that evaporate or decompose in this temperature range. Beyond 200°C, the weight stabilizes which corresponds to silica content. Silica is thermally stable and does not undergo significant mass loss within this temperature range. In both the fuels, a peak at approximately 130 °C is seen which corresponds to the boiling of kerosene.

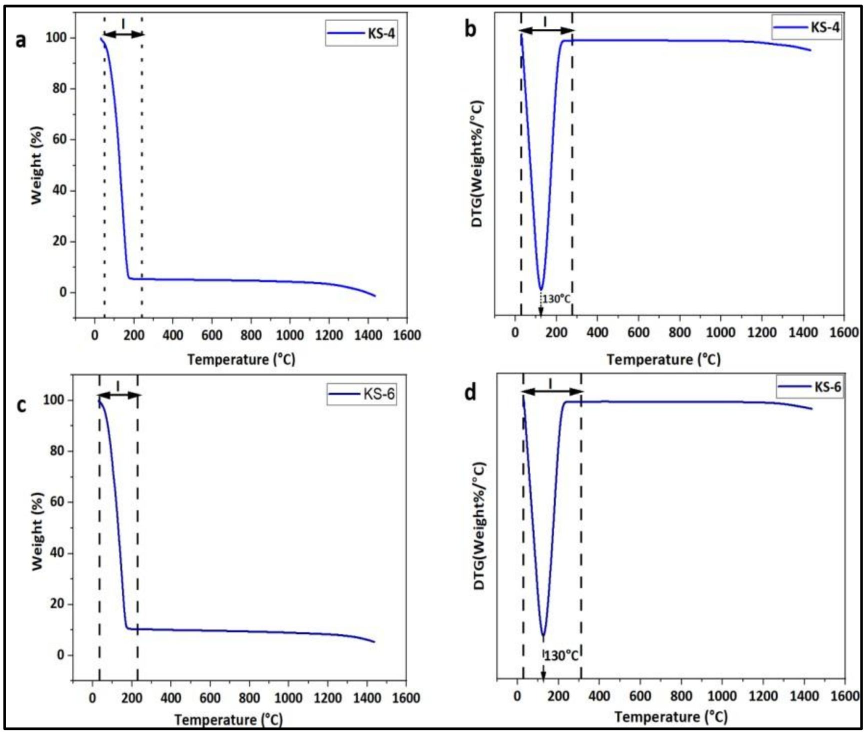


Figure 5.5. (a) TGA and (b) DTG thermograms for KS-4 gel fuel; (c) TGA and (d) DTG thermograms for KS-6 gel fuel. Both samples were analyzed at a heating rate of 10 °C/min under an inert nitrogen atmosphere.

Figure 5.6 shows the thermograms of the fuel samples obtained from the differential scanning calorimetry. The endothermic peak of each individual fuel sample appears as a broad peak in the range of 100–200 °C. Specifically, the endotherm peak occurs at 150 °C, and 140 °C for KS-4 and KS-6 fuel samples respectively. In this range kerosene molecules undergo endothermic reactions. This is followed by a gradual increase in heat flow 200–800°C due to the thermal decomposition of kerosene in the absence of oxygen. For higher silica content i.e., KS-6 a distinct endothermic peak near 1180 °C was observed which shows the glass transition of silica. Glass transition temperature refers to the temperature at which the silica network in the kerosene-silica gel transitions from a rigid, brittle state to a flexible, rubbery state.

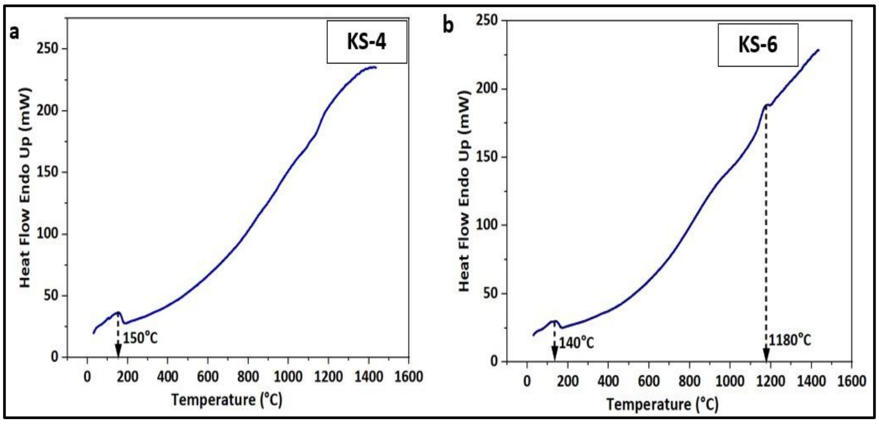


Figure 5.6. DSC thermograms for (a) KS-4 and (b) KS-6 gel fuel samples, recorded at a heating rate of 10 °C/min under an inert nitrogen atmosphere.

### 5.3 Flame scale visualization

The classification of combustion stages was further analysed by studying the influence of jetting phenomena on flame disruption events. This section focuses on the flame-scale disturbances observed during the combustion of inorganic gel fuels. During combustion, the internal pressure buildup within the gel droplet is released through jetting of unreacted kerosene vapours. These high-velocity jets interact with the surrounding flame, repeatedly disrupting the flame envelope throughout the droplet's combustion lifetime. The pressure energy stored inside the droplet is converted into kinetic energy, which manifests as flame-scale disturbances caused by the vapor jets impinging on the flame. At the droplet level, rupture occurs due to the pressure buildup, while at the flame level, the subsequent jetting of unreacted vapours results in noticeable flame-scale disruptions. These disruptions are classified into the following events: Insipid jets, flame distortion, pin ejection and particle ejection [13-14].

Figure 5.7 and Figure 5.9 shows multiple jetting events (insipid jets, flame distortion, pin ejection and particle ejection) occurring at a time for KS-2 and KS-4 gel fuel droplet respectively. In figure 5.8 and 5.10, the graphs are plotted for combined 5 runs of a single composition. During the initial stage of combustion, no jetting is observed at the droplet scale hence no flame disruptions are observed. In the later stages of combustion, multiple jetting events are observed. In the case of inorganic gel fuels mostly insipid jets are observed as shown in figure 5.8(b) and 5.10(b). Insipid jets are the one that doesn’t disrupt the flame, they got disappear without reaching to the flame periphery. For higher silica content like KS-4 and KS-6, particle ejections are also observed in the last stage of the combustion process which can be referred to the exfoliation of silica gellant shell.

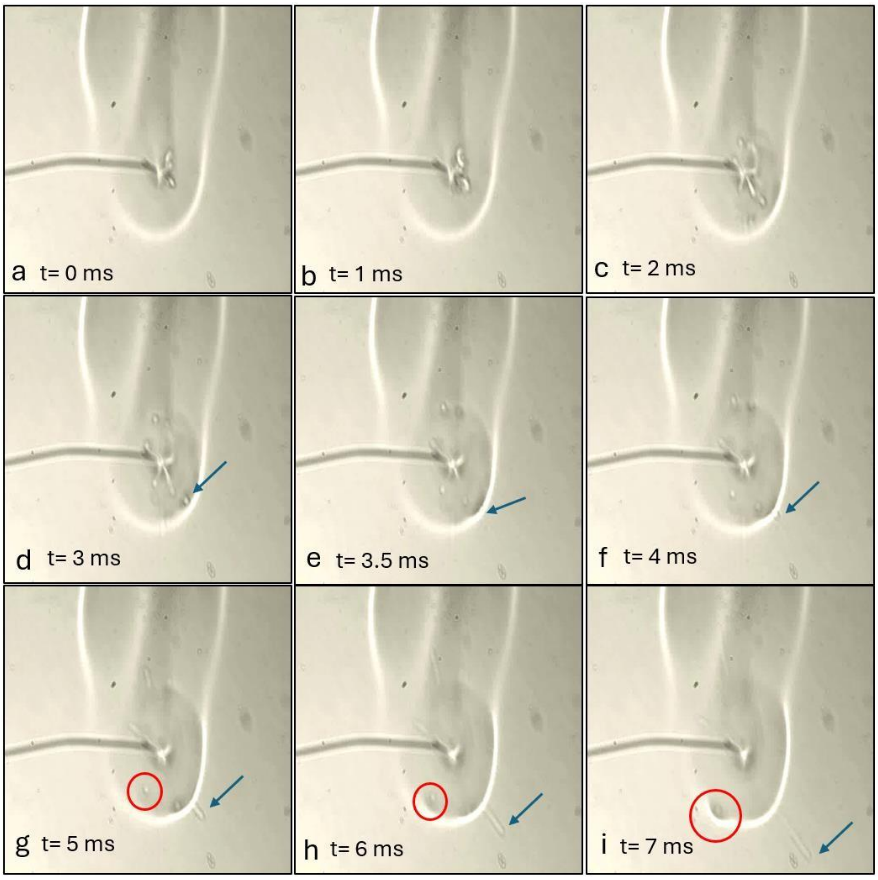


Figure 5.7. Time-frozen snapshots capturing multiple jetting events during combustion of KS-2 gel fuel, including a flame distortion event (highlighted in red), a pin ejection event (indicated by a blue arrow), and several insipid jets emerging from different angular locations.

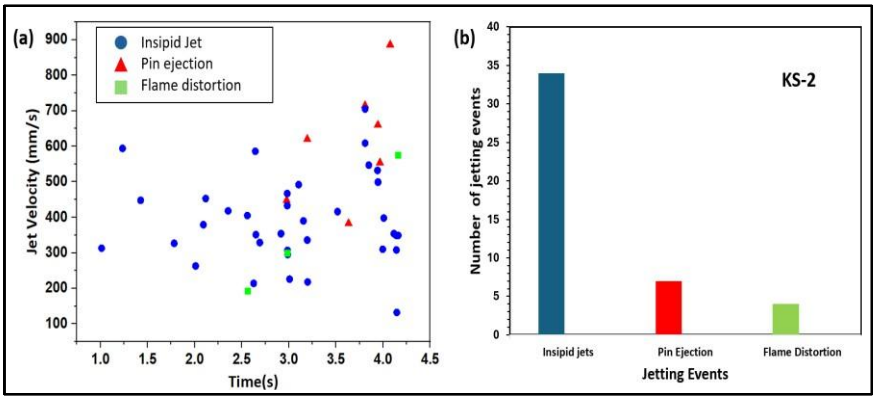


Figure 5.8. (a) Jet velocity variation over time during the combustion of a KS-2 gel fuel droplet. (b) Histogram illustrating the frequency of different jetting events insipid jets, pinhole ejections, and flame distortions for the KS-2 sample.

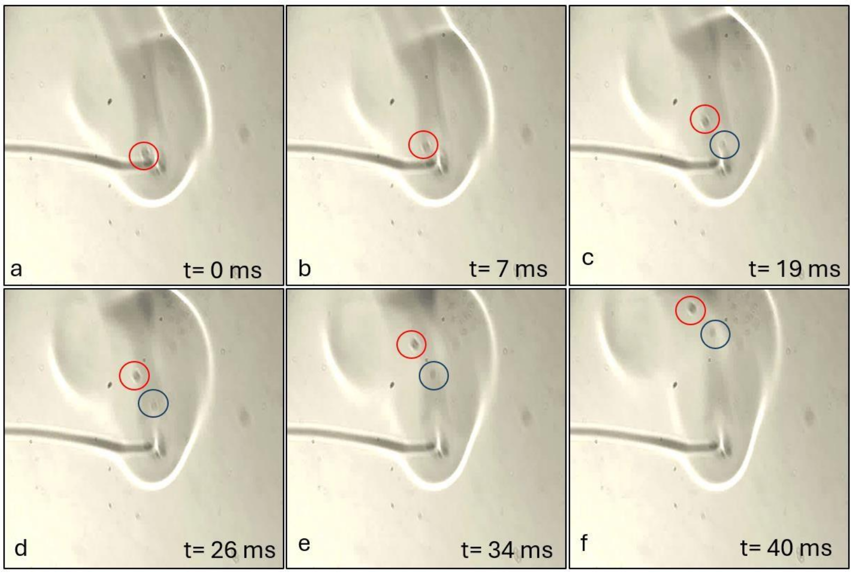


Figure 5.9. Time-frozen snapshots showing particle ejection events during combustion of a KS-4 gel fuel droplet, with ejected particles highlighted in red and blue circles.

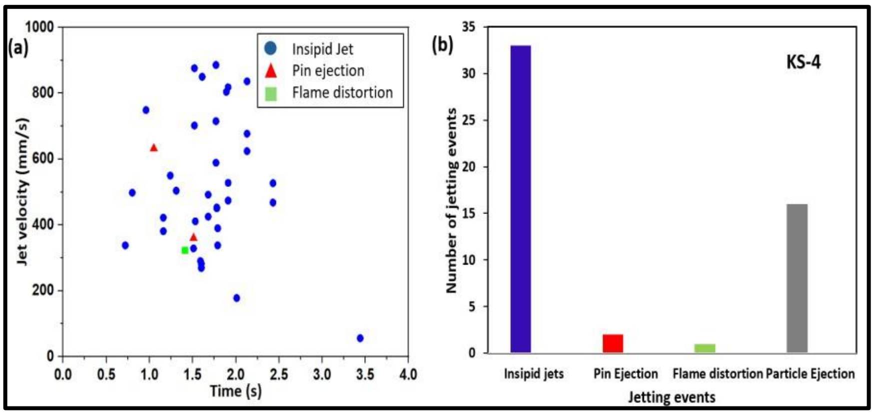


Figure 5.10. (a) Jet velocity variation with time during the combustion of a KS-4 gel fuel droplet. (b) Histogram showing the frequency of each jetting event type insipid jets, pinhole ejections, flame distortions, and particle ejections for the KS-4 sample.

## 5.4 Comparison Between Organic and Inorganic Gel Fuels

The combustion characteristics of gel fuels are heavily influenced by the nature of the gellant used. Broadly, gel fuels are categorized into organic and inorganic gels, depending on whether the gelling agent is combustible or inert. While both types aim to enhance storage stability, safety, and controllability compared to conventional liquid propellants, their combustion behavior reveals fundamental differences that affect flame dynamics, disruption modes, and overall performance.

One of the most prominent differences between organic and inorganic gel fuels lies in the role of the gellant during combustion. Organic gels, typically formulated with hydroxypropyl methylcellulose (HPMC), hydroxyethyl cellulose (HEC), or methylcellulose (MC), feature gellants that decompose and combust along with the base fuel. This dual participation results in energetic burning, often accompanied by violent micro-explosions or jetting due to uneven heating and phase transitions within the elastic gellant matrix [9]. In contrast, inorganic gel fuels, such as kerosene–silica systems, contain non-combustible gellants like fumed silica. The silica forms a rigid and thermally stable matrix that does not burn. Instead, it contributes to physical effects like shell formation, exfoliation, and thermal insulation, which shape the combustion stages but do not directly add to the energy release [7-11].

Organic gels often show unstable combustion due to the elastic nature of the gellant shell. During combustion, vapor pressure buildup inside the droplet leads to shell deformation and bursting events. These events are typically highly disruptive, producing high-velocity jets and multiple flame distortions. The resultant flame structure is often oscillatory, turbulent, and asymmetrical, particularly in gel droplets with high polymer content [15]. In contrast, inorganic gels burn with greater structural integrity. The silica shell that forms during combustion retains its rigidity longer, allowing for more stable flame propagation. Jetting events in inorganic gels occur primarily through crack formation and exfoliation, which are less violent compared to the elastic ruptures in organic systems. As a result, the flame shape remains relatively smooth and axisymmetric, with gradual changes in intensity over time.

Combustion experiments reveal that organic gels tend to burn faster, particularly when disruptive events enhance vapor release and mixing. Jetting events in organic gels momentarily increase surface area and heat transfer, leading to temporary spikes in regression rate. However, these events can also cause combustion instability and inefficient fuel utilization if not controlled. In contrast, inorganic gels exhibit slower and steadier regression, often deviating from the classical $d^2$-law due to shell insulation and delayed vapor escape. Although burning rates are lower, the controlled exposure of fuel surfaces through exfoliation contributes to consistent combustion, which is advantageous for propulsion systems requiring predictable thrust profiles [2,7].

Organic gel fuels typically leave behind carbonaceous residues, resulting from the incomplete combustion of polymeric gellants. These residues can affect post-combustion heat transfer and may clog injector components in repeated operations. On the other hand, inorganic gel fuels form non-reactive silica residues that are chemically stable and environmentally inert, making them more attractive for clean combustion applications.

## Chapter 6

# Conclusions and Future Scope

### 6.1 Conclusions

The present study focused on the formulation, characterization, and combustion analysis of kerosene-based inorganic gel fuels using fumed silica as the gellant. A range of silica concentrations (0–10 wt.%) was explored to understand how gellant content influences physical properties, thermal stability, and combustion dynamics. Key conclusions drawn from this work are outlined below:

Stable gel fuels were successfully prepared using fumed silica. The rheological analysis confirmed non-Newtonian shear-thinning behavior, with increasing yield stress and viscosity observed at higher silica concentrations. These properties ensure good storage stability while allowing ease of flow under shear, critical for fuel handling and injection systems. TGA and DSC analysis revealed that the gel fuels undergo single-stage thermal decomposition, with ~95% mass loss due to kerosene evaporation. The remaining mass corresponded to non-combustible silica, which formed a solid residue. The glass transition temperature (~1180 °C) observed in high-silica gels confirms the thermal stability of the inorganic matrix.

High-speed imaging enabled detailed observation of combustion in three distinct stages: Stage 1: Transient Heat-Up – Initial shrinkage due to evaporation, Stage 2: Shell Formation – Rigid silica shell develops, accompanied by bubble formation and occasional rupture, Stage 3: Exfoliation – Microcracking and peeling of the silica shell expose fresh fuel layers, sustaining combustion. Schlieren imaging effectively captured jetting events, flame envelope distortion, and particle ejection. The flame scale behavior varied with silica concentration, with higher gellant content resulting in more frequent exfoliation and droplet shape irregularities. Compared to organic gels, inorganic gel fuels demonstrated more stable and controlled combustion, with fewer violent disruptions. The inert nature of the silica matrix contributed to clean, symmetrical flame behavior and predictable burnout. These findings suggest that kerosene–silica inorganic gels possess several advantages for controlled propulsion applications, including clean combustion, structural stability, and predictable burn behavior—making them promising candidates for sounding rockets and other small-scale aerospace systems.

## 6.2 Future Scope

While the current study provides foundational insights, several important areas remain for further investigation, all experiments in this study were conducted under ambient pressure and still-air conditions. Follow-up studies should explore combustion in pressurized chambers and under forced convection to simulate actual rocket engine environments. Real-world propulsion systems involve fuel injection as sprays rather than single droplets. Future work should focus on understanding spray breakup, atomization, and interaction effects in silica gel fuels under realistic engine conditions. Future work could explore the incorporation of metal additives (e.g., aluminium, boron) into silica gel matrices to enhance energy density while retaining the mechanical stability of inorganic gels. Investigating the long-term stability, aging effects, and performance degradation of gel fuels under varying environmental conditions will be essential for practical implementation and mission planning. Finally, scaling up to engine-level testing is necessary to validate the performance of inorganic gels in real-world aerospace application.

# References

1. H.K. Ciezki, M. Negri, J. Hürttlen, V. Weiser, K.W. Naumann, J. Ramsel, Overview of the German Gel Propulsion Technology Program, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, 2014.
2. Manisha B. Padwal, Benveniste Natan, D.P. Mishra, Gel propellants Progress in Energy and Combustion Science 83, March 2021,100885.
3. Dennis JD, Yoon C, Santos PH, Mallory JA, Fineman CN, Pourpoint TL, Son SF, Heister SD, Sojka PE, Campanella OH. Characterization of gelling systems for development of hypergolic gels. In: 4th European Conference for Aerospace Sciences, Saint Petersburg, Russia; July 2011
4. Tarpley WB. Thixotropic oxidizer propellant mixtures. US 3,449,178. June 10, 1969.
5. Tarpley WB. Thixotropic organic liquid propellant compositions with solid storage characteristics. US 3,471,344. October 7, 1969.
6. Tarpley WB. Thixotropic gel fuels. US 4,156,594. May 29, 1979
7. Qinliu Cao, Wenhe Liao, Wei-Tao Wu, Feng Feng. Combustion characteristics of inorganic kerosene gel droplet with fumed silica as gellant. Experimental Thermal and Fluid Science,2019.

8. R. Arnold, W. E. Anderson, Droplet Burning of JP-8/Silica Gels, Department of Aeronautical and Astronautical Engineering, Purdue University, West Lafayette, IN 47907, USA,2010.
9. Comparison of Monomethyl hydrazine/ Hydroxypropyl cellulose and Hydrocarbon/ Silica Gels R. Arnold, P.H.S. Santos, M. deRidder, O.H. Campanella, and W.E. Anderson, Purdue University, West Lafayette, IN47907, USA,2010.
10. Gelled MMH Hypergolic Droplet Investigation Y. Solomon, Sarah Jo DeFini, Timothée L. Pourpoint and W. E. Anderson Maurice J. Zu crow Laboratories, Purdue University, West Lafayette, IN 47907, 2011.
11. Experimental study on the evaporation characteristics of the kerosene gel droplet Dali Yang, Zhixun Xia, Liya Huang, Likun Ma, Yunchao Feng, Yunlei, Xiao Science and Technology on Scramjet Laboratory, National University of Defense Technology, Changsha 410073, China,2018.
12. Settles, G.S. Schlieren and Shadowgraph Techniques: Visualizing Phenomena in Transparent Media; Springer Science & Business Media: Berlin, Germany, 2001.
13. Solomon, y., & Natan, b. (2006). Experimental investigation of the combustion of organic-gellant-based gel fuel droplets. *Combustion science and technology*, *178*(6), 1185–1199.
14. K.Y. Cho, T.L. Pourpoint, S.F. Son, R.P. Lucht, Micro explosion investigation of monomethyl hydrazine gelled droplet with OH planar laser-induced fluorescence, J. Propul. Power 29 (2013) 1303–1310.

15. J. Sharma, A. Miglani, J. John, P. Nandagopalan, J. Shaikh, P.K. Kankar, Jetting dynamics of burning gel fuel droplets, Gels 8 (2022) 781.
16. Janmejai Sharma, Purushothaman Nandagopalan, Jerin John, Ankur Miglani, The characterization of disruptive combustion of organic gellant-laden ethanol fuel droplets, combustion and Flame 257 (2023) 113018.
17. Mishra, D.P., et al. (2017). Combustion characteristics of gel propellants for rocket propulsion applications. Journal of Propulsion and Power.