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Original article

Ignition thresholds of HTP-ethanol bipropellants with an electrothermal mesh igniter

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ABSTRACT

Reliable low-power ignition is essential for replacing toxic hypergolic propellants with green bipropellant systems in spacecraft propulsion. This work experimentally evaluates a Nickel–Chromium (NiCr) thermal wire mesh igniter for high-test peroxide (HTP) with ethanol and Jet A in two laboratory configurations: open premixed surface ignition and confined spray-through hot-mesh ignition. Each power condition was repeated five times, and thresholds were defined as the minimum power producing at least 80% self-sustained ignition success ($\geq 4/5$). In the open configuration, ethanol–HTP and Jet A–HTP reached self-sustained ignition at 12.5 W and 10.0 W, respectively, corresponding to an estimated pre-contact mesh temperature of approximately 420 °C and 380 °C, respectively. In the confined configuration, thresholds decreased to 10 W for ethanol–HTP and 7.5 W for Jet A–HTP, corresponding to approximately 380 °C and 320 °C, respectively. Ignition delay time, estimated from 240 fps video, decreased from approximately 500–700 ms near threshold to 50–75 ms at the highest tested powers. The results indicate that NiCr mesh ignition can provide repeatable, low-power ignition of HTP-based green bipropellants, while confinement improves ignition by increasing heat retention and reactant residence near the heated mesh.

1. Introduction

Bipropellant rocket propulsion systems are widely used in spaceflight because they combine high performance with storability and proven reliability. Nevertheless, conventional combinations, including nitrogen tetroxide (NTO) with unsymmetrical dimethylhydrazine (UDMH) or monomethylhydrazine (MMH), pose substantial safety and environmental hazards due to their toxicity, carcinogenicity, and harmful decomposition products [1,2]. In response to the growing emphasis on sustainable space technologies, considerable effort has been directed toward “green” propellants that reduce environmental impact while preserving competitive propulsion performance [3–6].

For bipropellant applications, the central difficulty is not only identifying less toxic propellant combinations, but also achieving reliable, repeatable ignition under spacecraft-relevant constraints. Spacecraft attitude-control and orbit-maneuvering thrusters may require many

start events over mission life, while operating with limited bus power, strict mass and volume budgets, and variable thermal boundary conditions. Therefore, ignition concepts for green bipropellants must be evaluated not only for single-event feasibility, but also for ignition threshold, ignition delay time (IDT), repeatability, and compatibility with pulse-mode operation.

A particularly attractive green bipropellant pairing is high test peroxide (HTP) with ethanol [7]. High-concentration HTP (> 80%) is a storable oxidizer that decomposes to oxygen and steam when heated or exposed to catalytic surfaces, making it relevant for both monopropellant and bipropellant propulsion applications [8]. Unlike cryogenic oxidizers such as liquid oxygen (LOX), HTP can be stored at near-ambient temperature, reducing storage and handling complexity for extended missions. Ethanol offers low toxicity, straightforward handling, broad availability, low cost, and compatibility with existing fueling infrastructure [9]. From a spacecraft-integration perspective, the ability to avoid

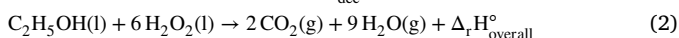
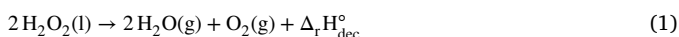
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toxic handling constraints and cryogenic storage can simplify operations for small spacecraft, rideshare missions, and rapid-turnaround propulsion systems.

When HTP decomposes, the released heat and oxygen can promote ignition of an injected fuel, creating a decomposition-assisted ignition pathway that avoids the need for additional reactive ignition fluids. For spacecraft use, this pathway is attractive because it can, in principle, be implemented in compact hardware with direct electrical control and without introducing separate hypergolic ignition fluids.

The HTP decomposition reaction and the overall combustion reaction between ethanol and HTP are given in Eqs. (1) and (2), respectively. The corresponding reaction enthalpies at 298.15 K were calculated using Hess's law and the tabulated standard molar enthalpies of formation reported in the NIST Chemistry WebBook and the NIST-JANAF Thermochemical Tables [10,11]. The reaction enthalpy of HTP decomposition, $\Delta_r H_{\text{dec}}^\circ$, is -1589 kJ kg^{-1} , whereas that of the overall ethanol-HTP reaction, $\Delta_r H_{\text{overall}}^\circ$, is -6234 kJ kg^{-1} .



Although HTP/fuel systems are promising, ignition remains a key scientific and engineering challenge. Hypergolic propellants ignite on contact, whereas most green bipropellant combinations require an external ignition source to initiate peroxide decomposition and fuel combustion. Existing approaches include spark plugs, glow plugs, catalyst beds, plasma ignition, and other electrothermal devices, but their maturity, lifetime, power demand, and integration complexity vary substantially [12,13]. For spacecraft propulsion, the ignition system must also tolerate repeated starts, minimize electrical power draw, avoid excessive mass and volume, and remain compatible with valve timing, feed-system stability, and small-thruster thermal constraints.

For HTP-based propulsion specifically, catalytic decomposition is well established, and catalyst beds using materials such as platinum-group metals or other active surfaces are commonly used to decompose peroxide. However, catalyst performance and lifetime can be sensitive to peroxide concentration, contamination, thermal cycling, and operating conditions [14]. Electrothermal ignition approaches are therefore attractive because they offer compact packaging, direct control of ignition timing, and potential compatibility with repeated pulse-mode operation [15,16]. Electrically heated elements have also been shown to promote hydrogen peroxide decomposition in flow-through configurations, highlighting the coupling between localized heating, surface properties, and peroxide decomposition [17].

Within this context, thermal wire igniters provide a simple and reusable means of delivering localized heat to the propellant. Prior work has demonstrated the applicability of thermal-wire concepts to monopropellant and bipropellant ignition, where either the oxidizer or the fuel is thermally activated before reaction [18]. However, single-wire geometries may limit the contact area available for heat transfer and peroxide decomposition. A mesh geometry may improve coupling between the heated igniter and the liquid oxidizer by increasing the active surface area exposed to impingement, film formation, and local decomposition. This raises an important scientific question: can a resistively heated mesh reduce the electrical power required for reliable ignition while maintaining short IDT and repeatable operation?

This work investigates a Nickel Chromium (NiCr) thermal wire mesh igniter for HTP/fuel bipropellant ignition. NiCr was selected because of its high-temperature robustness, oxidation resistance, and corrosion resistance relative to several common thermal-wire materials, including FeCrAl alloys, CuNi alloys, and ceramic- or silica-based alternatives. Although NiCr can be more costly than some wire materials, its thermal durability and compatibility with repeated resistive heating make it suitable for a reusable laboratory igniter. From a propulsion-hardware standpoint, the mesh concept is also attractive because it can be packaged as a compact insert near an injector or prechamber region, where

it may couple strongly to sprayed peroxide while remaining compatible with modular thruster architectures.

The scientific objective of this work is to determine how a NiCr thermal wire mesh influences ignition thresholds and ignition dynamics for HTP/fuel bipropellants under laboratory conditions. The study is guided by three specific questions. First, what electrical power is required to obtain repeatable ignition of 90 wt.% HTP with ethanol and Jet A using a reusable NiCr mesh igniter? Second, how do fuel identity, confinement, and oxidizer/igniter contact mode affect ignition probability and IDT? Third, can the observed threshold behavior be interpreted in terms of decomposition-assisted ignition, heat retention, and spacecraft-relevant electrical energy input?

To answer these questions, ethanol is used as the primary green fuel, while Jet A is included as a comparison fuel with different volatility and autoignition characteristics. Two ignition configurations are examined: an open premixed surface-ignition case and a closed spray-through hot-mesh case. The open configuration provides a simple baseline for premixed propellant loading, whereas the closed configuration provides a confinement and heat-retention surrogate relevant to compact thruster environments. The closed setup is not intended to reproduce a flight combustor; rather, it isolates how confinement, residence time, and spray/mesh interaction can shift ignition thresholds and IDT.

The main contributions of this work are as follows:

- 1) Ignition thresholds and IDT trends are experimentally quantified for 90 wt.% HTP combined with ethanol and Jet A using a reusable NiCr wire mesh igniter, with an explicit distinction between combustion and self-sustained ignition.
- 2) Ignition outcomes are reported using repeat-count statistics and a threshold criterion based on $\geq 80\%$ ignition probability.
- 3) The influence of ignition environment is assessed by comparing open premixed surface ignition with closed spray-through hot-mesh ignition.
- 4) The measured power levels and IDTs are interpreted using electrical input energy to ignition, providing a spacecraft-facing metric relevant to limited-power propulsion systems.
- 5) Compact mesh-geometry metrics, including exposed area, resistance, power density, and thermal mass, are introduced to support comparison with single-wire igniters and future scaling to thruster-relevant designs.

The scope of the present work is intentionally limited to laboratory ignition-threshold characterization. Direct chamber pressure measurements and spatially resolved transient mesh-temperature measurements during propellant contact were not obtained; therefore, mechanistic interpretations are presented as physically supported explanations rather than fully validated combustion models. Within this scope, the results provide an experimental basis for assessing whether NiCr mesh ignition can reduce power demand and IDT for HTP-based green bipropellant systems.

The structure of the paper is organized as follows. Section 2 details the experimental methodology, including propellant selection, mesh igniter design, open- and closed-environment test configurations, and the classification procedure used to describe ignition behavior and IDT. Section 3 presents and discusses the effects of electrical power, fuel properties, confinement, and mixing/impingement regime on ignition thresholds and ignition dynamics, followed by a scaling discussion linking the measurements to spacecraft-relevant operating constraints.

2. Experimental methods

2.1. Propellants and materials

The experimental campaign employed high-test peroxide (HTP) and ethanol as the oxidizer and fuel, respectively. Specifically, HTP at 90 wt.% concentration (concentrated in-house from a procured 30 wt.%

solution; HTP CAT No. BP2633-500; NC 1592410, ThermoFisher Scientific Corp., the Netherlands) and 95 wt.% lab-grade ethanol (manufacturer/supplier article No. S25309, Fisher Science Education Corp., the Netherlands) were used. For propulsion relevance, the selected propellant pairs (HTP–ethanol and HTP–Jet A) represent non-hypergolic, storable combinations for spacecraft chemical propulsion, for which ignition must be initiated electrically and repeated reliably over multiple start events.

The 90% HTP was produced from the 30 wt.% solution using a gas-phase dehydration method, based on a patented concentration approach described in Patents US17775065 [19] and NL2024229B1 [20]. In this process, regulated inert nitrogen gas was injected over the surface of the 30 wt.% hydrogen peroxide solution to promote the removal of water molecules and thereby increase the peroxide concentration. A magnetic stirrer and plate were employed to maintain solution homogeneity, which in turn accelerated the concentration process. Concentrating the hydrogen peroxide to 90 wt.% required approximately 60–70 hours.

To ensure chemical stability and compositional consistency, solution concentrations were measured using a calibrated digital refractometer immediately prior to the experimental campaign and rechecked weekly during storage. A strict acceptance criterion of ± 0.25 wt.% was applied; any solution exceeding this deviation was discarded and freshly prepared. All HTP solutions were stored in vented, high-density polyethylene–capped borosilicate glass containers and refrigerated at 2 °C in a dark environment to maintain stability. In all tests, propellants were handled and dispensed at ambient laboratory temperature; while temperature was not actively controlled, the experimental intent was to keep the initial thermal state consistent across power sweeps within a given configuration.

In addition to the baseline ethanol–HTP combination, Jet A fuel (CAS No. 91770-15-9, Sigma-Aldrich, the Netherlands) was also tested with the same HTP for comparison.

For the thermal wire mesh igniter, a Nickel–Chromium Alloy (NiCr) wire (80% Nickel / 20% Chromium, diameter 0.25 mm, 30 AWG, Omega Corp., UK) was used. A 45-mesh NiCr wire mesh with a wire diameter of 0.25 mm and an opening size of approximately 0.31 mm was employed, corresponding to a porosity of 0.31 and a specific surface area of approximately $1.1 \times 10^4 \text{ m}^2 \text{ m}^{-3}$. A new mesh specimen was used for each individual test to minimize the influence of surface condition and thermal history on ignition behavior. This “new specimen per test” protocol isolates ignition-threshold trends from cumulative oxidation, fouling, or resistance drift of a single element, but it also implies that the present results characterize per-test performance rather than lifetime or multi-start durability of a single mesh element; repeat-start endurance testing is identified as an important next step for flight-relevant maturation.

To inject the liquid oxidizer as an atomized mist, a piezoelectric actuator disc (PZT) with a flow rate of 0.025 mL/s was used. At the vibration frequency applied in the experiment (113 kHz), the theoretical mean droplet diameter is estimated at approximately 8.7 μm based on Lang capillary wave theory [21]. Atomization to this small droplet size is beneficial because it substantially increases the surface-area-to-volume ratio, thereby promoting more efficient combustion. The injector-to-mesh spacing and the spray incidence angle were held constant within each configuration to preserve repeatability of droplet impingement and wetting dynamics near the mesh.

2.2. Mixture ratio and reactant loading

Ignition thresholds in bipropellant systems are strongly dependent on mixture ratio (oxidizer-to-fuel, O/F) and on the total mass loading (total amount of reactants available near the igniter during a given test). To enable interpretation and reproducibility, the present work explicitly defines the mixture ratio reporting convention and provides a per-test reactant loading conditions and mixture-ratio characterization table for both experimental configurations. For spacecraft propulsion interpretation, reporting O/F and total loading is also important because ignition

delay and repeatability can shift with propellant residence time, two-phase heat-sink effects, and oxidizer decomposition completeness under different thruster feed and injection conditions.

2.2.1. Definition of mixture ratio (mass basis) and reporting convention

In this paper, the mixture ratio is reported on a mass basis as

$$\left(\frac{O}{F}\right)_m \equiv \frac{m_{\text{HTP}}}{m_{\text{fuel}}}, \quad (3)$$

where m_{HTP} is the total mass of 90 wt.% HTP loaded (open premixed case) or delivered to the vial/mesh region (closed spray-through case) for a given test, and m_{fuel} is the corresponding total mass of ethanol or Jet A involved in that test. For clarity, the term “fuel/HTP ratio” is used when reporting $m_{\text{fuel}}/m_{\text{HTP}}$; otherwise, “O/F” implies Eq. (3).

2.2.2. Per-test volume/mass accounting

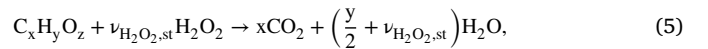
Volumes were metered using laboratory pipettes/syringes for liquid loading and delivery. Masses (m) can be obtained from measured volumes (V) using the corresponding liquid densities (ρ) at laboratory temperature using the well-known Eq. (4):

$$m = \rho V. \quad (4)$$

When density variations with temperature are non-negligible, densities should be evaluated at the measured liquid temperature. Because the present experiments were conducted at ambient laboratory conditions and the focus is on relative ignition-threshold trends, the volume-based metering is the primary control variable; however, O/F is reported on a mass basis to align with propulsion convention. In future thruster-representative testing, closed-loop control of mass flow rates and real-time O/F measurement would further reduce uncertainty and enable mapping of ignition behavior to commanded valve timing sequences.

2.2.3. Stoichiometric mixture ratio and global equivalence ratio

To compare the measured loading ratio with the chemically stoichiometric condition, a stoichiometric oxidizer-to-fuel ratio was calculated on the same total-HTP-solution mass basis as Eq. (3). For a fuel represented by $\text{C}_x\text{H}_y\text{O}_z$, complete combustion with hydrogen peroxide may be written as



where the stoichiometric peroxide requirement is

$$\nu_{\text{H}_2\text{O}_2, \text{st}} = 2x + \frac{y}{2} - z. \quad (6)$$

Because the oxidizer was 90 wt.% HTP, the stoichiometric mixture ratio was reported using the total mass of the HTP solution:

$$\left(\frac{O}{F}\right)_{\text{st}} = \frac{w_{\text{fuel}} \nu_{\text{H}_2\text{O}_2, \text{st}} M_{\text{H}_2\text{O}_2}}{w_{\text{HTP}} M_{\text{fuel}}}, \quad (7)$$

where $w_{\text{HTP}} = 0.90$, M_{fuel} is the molar mass of the fuel surrogate, and w_{fuel} is the mass fraction of active fuel in the loaded fuel liquid. The ethanol was 95 wt.% $\text{C}_2\text{H}_5\text{OH}$ with the remaining mass treated as diluent, while the surrogate formula of $\text{C}_{12}\text{H}_{23}$ was used for the Jet A fuel.

The global equivalence ratio was then defined as

$$\phi_g = \frac{(F/O)_m}{(F/O)_{\text{st}}} = \frac{(O/F)_{\text{st}}}{(O/F)_m}. \quad (8)$$

Thus, $\phi_g = 1$ corresponds to the stoichiometric condition, $\phi_g > 1$ indicates globally fuel-rich loading, and $\phi_g < 1$ indicates globally oxidizer-rich loading. The term “global” is used because the value is based on the total loaded or delivered reactant masses and does not imply that the local vapor-phase mixture at the ignition site is spatially uniform.

Table 1

Open and closed environment: per-test reactant loading conditions and mixture-ratio characterization.

Propellant pair	V_{fuel} [mL]	V_{HTP} [mL]	$(O/F)_m$ [-]	$(O/F)_{st}$ [-]	ϕ_g [-]	m_{tot} [g]
Ethanol-HTP	0.30	0.70	4.11	4.67	1.14	1.210
Jet A-HTP	0.30	0.70	4.05	8.02	1.98	1.213

2.2.4. Mixture ratio usage across different tests

For a given propellant pair and configuration, ignition-threshold sweeps ideally keep O/F and total loading fixed while varying only the electrical power to the mesh. In the present work, the experimental intent was to keep the mixture ratio and reactant loading consistent within each dataset (ethanol-HTP open, Jet A-HTP open, ethanol-HTP closed, Jet A-HTP closed) while power was stepped. Any deviations from the nominal loading (e.g., due to handling losses, wetting/retention on surfaces, or atomizer delivery variability) constitute an additional uncertainty source. Therefore, per-test loading should be recorded and is reported in the table format provided below. Because droplet impingement and liquid retention on the mesh can alter the effective local O/F during the ignition transient, the reported global O/F should be interpreted as a nominal per-test loading metric rather than an instantaneous near-mesh mixture ratio.

2.2.5. O/F ratio of the propellants

Table 1 provides information on the (i) fuel volume/mass, (ii) HTP volume/mass, (iii) O/F mass basis and stoichiometric mixture ratio, (iv) equivalence ratio, and (v) total reactant loading per test.

2.2.6. Sensitivity of ignition threshold to mixture ratio and loading

Because (i) oxidizer decomposition can be inhibited by rapid cooling and dilution and (ii) fuel-rich conditions can increase soot formation and reduce effective oxygen availability near the mesh, both mixture ratio and total loading are expected to shift ignition thresholds. Qualitatively, for a fixed mesh power, increasing delivered HTP fraction (higher O/F) can increase local oxygen generation and exothermic decomposition heat release, potentially reducing ignition delay time and lowering the apparent threshold (until excessive liquid cooling or flooding reduces T_{mesh} transiently). Conversely, increasing total mass loading at fixed O/F generally increases the thermal sink and can raise the threshold unless confinement and residence time compensate. In the present manuscript, the primary reported sweep variable is mesh electrical power. For spacecraft propulsion design, this sensitivity motivates reporting ignition thresholds alongside nominal O/F and loading so that future thruster-scale tests can map ignition behavior across feed-system operating points.

2.3. Open configuration: premixed surface ignition

Two experimental configurations were developed. The first apparatus was designed to investigate the ignition behavior of premixed ethanol-HTP and Jet A-HTP propellant combinations in an open environment, using the electrically heated NiCr wire mesh as the igniter. In this configuration, the ignition mode is premixed surface ignition: the fuel and HTP are premixed prior to contacting the heated mesh, and ignition outcomes therefore reflect both the thermal interaction with the mesh and the pre-established local mixture in the liquid phase. This configuration provides a baseline case with strong convective losses and minimal confinement, which is useful for isolating the minimum heating requirement for initiating decomposition-assisted ignition under near-ambient conditions.

Although a flight-ready rocket combustion chamber operates as a closed environment with substantial pressure and temperature rise, it is also useful to document reaction and ignition characteristics under ambient conditions to establish baseline behavior. For this open-environment experiment, premixed propellant combinations of HTP and

fuel (either ethanol or Jet A) were placed on a round glass plate. The plate geometry was selected to promote collection of the propellant mixture at the center, thereby maximizing and standardizing contact with the thermal wire mesh and improving repeatability.

While ethanol was the primary fuel of interest, Jet A was included as a reference hydrocarbon fuel with comparatively higher ignitability under many conditions. This comparison enabled evaluation of differences in the minimum electrical power required to achieve combustion and self-sustained ignition.

During testing, the NiCr mesh was heated by applying a prescribed current and voltage using a DC power supply. Electrical power was delivered through two wires attached to the mesh and the supply; the attachment points were spaced sufficiently to preserve a large contact area between the thermal wire mesh and the propellant mixture. The mesh was brought into contact with the premixed propellant at a consistent location on the plate, and the minimum applied power leading to combustion and to self-sustained ignition was determined. Electrical power at each set point was computed from the measured current and voltage ($P = IV$) and is reported with the supply output uncertainty (estimated at ± 0.1 W). This electrical-power definition is directly relevant to spacecraft integration because it corresponds to the commanded electrical input that would be drawn from the spacecraft bus during an ignition pulse.

For safety, the entire setup was placed inside a fume hood equipped with a glass shutter while experiments were conducted. A detailed schematic of the open-environment apparatus is provided in Fig. 1.

2.4. Closed configuration: spray-through hot mesh (sequential contact)

The second apparatus investigated the ignition behavior of the same propellant combinations in a closed environment using the heated NiCr mesh igniter. In this configuration, the ignition mode is spray-through hot mesh (sequential contact): HTP is injected as a spray through the heated mesh and then interacts with the fuel contained in the vial. Decomposition of the HTP is expected to occur during passage through the hot mesh and in the near-mesh region; upon subsequent contact with the fuel (either Ethanol or Jet A fuel), ignition behavior is examined. Because the propellants are not premixed prior to heating, the local mixing state and reactant residence time near the heated surface can differ substantially from the open premixed configuration. This mode is conceptually closer to practical thruster implementation than premixed ignition because it preserves sequential oxidizer-fuel contact and emphasizes near-igniter residence time and impingement, which are important determinants of ignition delay and repeatability in pulsed spacecraft thrusters.

A representative rocket engine combustion chamber is inherently a closed environment, and confinement can promote combustion by increasing heat retention and reactant residence time in the reacting volume. In a sealed container, some pressure rise is also expected during vigorous decomposition/combustion; however, pressure was not measured in the present setup and therefore the closed-environment condition is treated primarily as a confinement/heat-retention case rather than as a quantified elevated-pressure reactor. The Arrhenius equation is provided in Eq. (9), where k is the reaction rate, A is the pre-exponential factor, and E_a is the activation energy, as a general reminder that reaction rates are temperature dependent; in the present work, the dominant experimentally supported effect of the closed configuration is improved

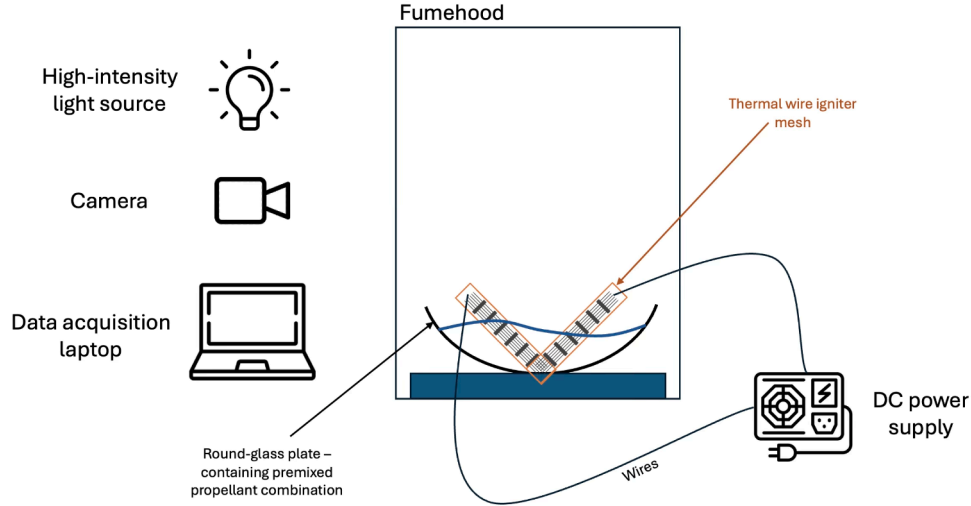


Fig. 1. Schematic of the open-environment thermal wire-mesh ignition setup for premixed propellant tests conducted inside a fume hood.

thermal confinement near the heated mesh.

$$k = A \exp\left(-\frac{E_a}{RT}\right) \quad (9)$$

Because the closed configuration is not a flowing combustor and does not replicate thruster chamber pressure histories, the results are interpreted as comparative trends with respect to heat retention, wall preheating, and near-mesh mixing/impingement, rather than as direct prediction of ignition thresholds in a flight thruster.

To approximate a confined environment (simulating a constant-volume reactor), the fuel was placed in a 50 mL borosilicate glass vial that served as the reaction chamber and was positioned inside a fume hood for safety. Through drilled holes in the vial side walls, a heated NiCr mesh was installed and electrically heated using the same approach as in the open-environment experiment. HTP was injected using the PZT mounted on a 3D printed injector; the spray entered the vial and passed through the heated mesh, which was positioned 3 cm from the entrance of the vial. As in the first experiment, the minimum power applied to the mesh that resulted in combustion and self-sustained ignition was determined. A consistent “preheat-and-fire” procedure was used across closed-configuration tests so that the timing between energizing the mesh, initiating spray, and recording video was comparable across power levels.

For this closed-environment case, additional heating of the glass chamber was provided by NiCr wires (30 cm) wound around the external walls of the vial, with an applied power of 6 W. The additional 6 W heating was used as a laboratory preheating condition to establish a repeatable initial thermal state of the igniter/closed-vial region before oxidizer injection. This value was selected empirically because it provided stable preheating without premature ignition, visible HTP decomposition, or excessive thermal loading of the apparatus; it is not intended to represent an optimized or required thruster operating condition.

Each experimental batch was conducted approximately 30 seconds after energizing the wound wire to allow sufficient time for the vial to warm. This auxiliary heating is a potential confounding factor relative to the open configuration because it reduces heat loss to the chamber walls and may increase initial wall and reactant temperatures; therefore, the closed-configuration results are interpreted as the combined effect of confinement and chamber preheating rather than confinement alone. A detailed schematic of the closed-environment apparatus is shown in Fig. 2. From a spacecraft perspective, such preheating can be viewed as an analog to elevated initial wall temperatures that may occur after prior pulses in a pulse-mode firing sequence; however, the present work does

not attempt to model thermal soak-back explicitly and instead treats the auxiliary heating as a controlled boundary-condition modification.

2.5. Igniter geometry and electro-thermal characteristics

This section summarizes compact metrics such as exposed area, electrical resistance, power density, and thermal mass, that support quantitative comparison between mesh-based and single-wire electrothermal igniters and aid interpretation of ignition thresholds in terms of energy coupling to HTP. In addition to supporting novelty claims, these metrics are intended to facilitate engineering scaling by enabling comparison of ignition behavior across different mesh sizes, wire diameters, and commanded power levels using normalized quantities (e.g., areal power density).

2.5.1. Geometric parameters, exposed surface area, and thermal mass

Let the active mesh have in-plane dimensions $L \times W$ (m). For a woven mesh with N_L and N_W wires per unit length in the two orthogonal directions (approximately equal for a square mesh), the total wire length can be approximated as

$$\ell_{\text{tot}} \approx (N_L W) L + (N_W L) W, \quad (10)$$

where $N_L W$ is the number of wires spanning length L and $N_W L$ is the number of wires spanning width W . For a nominal “45-mesh” screen, the wire count is commonly specified per inch; converting to SI yields

$$N \approx 45 \text{ in}^{-1} \approx \frac{45}{0.0254} \text{ m}^{-1} \approx 1772 \text{ m}^{-1}, \quad (11)$$

and $N_L \approx N_W \approx N$ may be used as a first-order estimate when the weave is approximately symmetric.

With wire diameter d_w , the external surface area of a cylindrical wire is $\pi d_w \ell$. Thus, the total exposed wire surface area is approximated as

$$A_{\text{mesh}} \approx \pi d_w \ell_{\text{tot}}. \quad (12)$$

The same geometric approximation gives the active mesh volume and thermal mass:

$$V_{\text{wire}} = A_c \ell_{\text{tot}}, \quad m_{\text{mesh}} = \rho_{\text{NiCr}} V_{\text{wire}} = \rho_{\text{NiCr}} A_c \ell_{\text{tot}}, \quad (13)$$

where $A_c = \pi(d_w/2)^2$ is the wire cross-sectional area. The lumped thermal inertia of the mesh is then $m_{\text{mesh}} c_p$, which affects the heating time scale for a given applied electrical power.

This A_{mesh} represents the maximum geometric area available for convective heat transfer to surrounding gas/liquid and for interfacial contact with droplets/films, recognizing that some fraction may be occluded at wire crossings and at clamps/contacts.

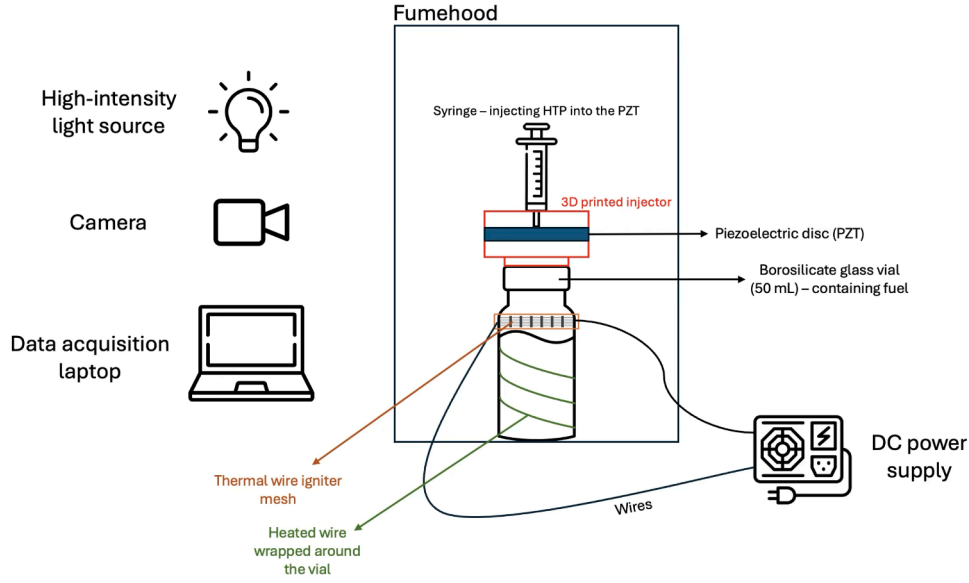


Fig. 2. Schematic of the closed-environment spray-through ignition setup with a heated wire mesh positioned near the vial entrance.

2.5.2. Electrical resistance and volumetric/area power density

Let ρ_e denote the electrical resistivity of NiCr at the operating temperature (or an effective value over the temperature range), and let $A_c = \pi(d_w/2)^2$ be the wire cross-sectional area. Neglecting contact-resistance contributions for the moment, the mesh electrical resistance can be approximated by an effective network resistance. A conservative bounding approach is:

- **Upper-bound (series path):** assume current travels along an effective length $\ell_{\text{eff}} \sim \ell_{\text{tot}}$:

$$R_{\text{mesh,series}} \approx \frac{\rho_e \ell_{\text{tot}}}{A_c}. \quad (14)$$

- **Lower-bound (parallel paths):** assume n_p parallel current paths of characteristic length ℓ_p :

$$R_{\text{mesh,parallel}} \approx \frac{1}{n_p} \frac{\rho_e \ell_p}{A_c}. \quad (15)$$

In practice, the resistance lies between these bounds and is measured directly at room temperature (with optional inference at temperature via resistance thermometry).

For a given applied electrical power P , two useful intensity metrics are:

$$q''_{\text{mesh}} \equiv \frac{P}{A_{\text{mesh}}} \quad [\text{W/m}^2], \quad (16)$$

$$q'''_{\text{mesh}} \equiv \frac{P}{V_{\text{act}}} \quad [\text{W/m}^3], \quad (17)$$

where V_{act} is an effective active volume around the mesh participating in heating and decomposition (e.g., a near-mesh control volume). The areal power density q''_{mesh} is particularly useful for comparing mesh of different sizes and for comparing mesh versus single-wire igniters at equal power.

2.5.3. Single-wire reference comparison

For a single straight wire igniter of the same material and diameter d_w , with heated length ℓ_{sw} , the exposed surface area and mass are

$$A_{\text{sw}} = \pi d_w \ell_{\text{sw}}, \quad m_{\text{sw}} = \rho_{\text{NiCr}} A_c \ell_{\text{sw}}. \quad (18)$$

Therefore, a mesh-to-single-wire geometric advantage factor may be expressed as

$$\Gamma_A \equiv \frac{A_{\text{mesh}}}{A_{\text{sw}}} \approx \frac{\ell_{\text{tot}}}{\ell_{\text{sw}}}, \quad \Gamma_m \equiv \frac{m_{\text{mesh}}}{m_{\text{sw}}} \approx \frac{\ell_{\text{tot}}}{\ell_{\text{sw}}}, \quad (19)$$

Table 2

Mesh geometry/electrical/thermal parameterization to quantify mesh-based ignition advantages relative to a single-wire reference.

Quantity	Value
Mesh surface area exposed to propellant, A_{mesh}	2.83 cm ²
Electrical resistance of mesh (cold), R_0	1.5 Ω
Power density, $q''_{\text{mesh}} = P/A_{\text{mesh}}$	3.54 W/cm ² at $P = 10$ W
Thermal mass ratio vs. single-wire reference, $\Gamma_{mc} = \frac{m_{\text{mesh}} c_p}{m_{\text{sw}} c_p}$	2.0

which clarifies that increased area is accompanied by increased thermal mass, and that the net ignition benefit depends on the coupled electrical heating, heat transfer, and decomposition kinetics.

2.5.4. Mesh parameters

Table 2 provides information on the mesh geometry effects, including exposed area, resistance, power density, and thermal mass. These quantities support mechanistic interpretation and provide a quantitative basis for the novelty claim of mesh-based ignition.

2.6. Mesh temperature estimation

Although the experimental results are reported as a function of applied electrical power, the ignition physics is governed more directly by the mesh surface temperature T_{mesh} (and its transient evolution) because both HTP decomposition and fuel ignition kinetics depend primarily on local temperature. To strengthen interpretation of “HTP decomposition vs. fuel auto-ignition” mechanisms, an electro-thermal framework is introduced here to map power input P to an estimated mesh temperature, including an uncertainty estimate.

2.6.1. Lumped energy balance linking

A first-order electro-thermal model is constructed by treating the heated mesh as a lumped thermal mass with effective heat capacity mc_p and effective heat-loss area A_{eff} . The electrical heating power P is balanced by convective and radiative losses, with an optional transient term:

$$mc_p \frac{dT_{\text{mesh}}}{dt} = P - h A_{\text{eff}} (T_{\text{mesh}} - T_{\infty}) - \epsilon \sigma A_{\text{eff}} (T_{\text{mesh}}^4 - T_{\infty}^4), \quad (20)$$

where T_{∞} is ambient temperature, h is an effective convection coefficient, ϵ is an effective emissivity, and σ is the Stefan-Boltzmann constant. Under steady operation prior to contact ($dT_{\text{mesh}}/dt \approx 0$), Eq. (20)

Table 3

Estimated pre-contact mesh temperature versus applied electrical power. Uncertainty bounds reflect variability in convective/radiative losses and are intended as conservative interpretation limits.

Power [W]	Estimated T_{mesh} [°C]
5.0	270 ± 40
7.5	320 ± 40
10.0	380 ± 40
12.5	420 ± 40
15.0	472 ± 40
17.5	500 ± 70
20.0	530 ± 70

reduces to an implicit relationship between P and T_{mesh} :

$$P \approx hA_{\text{eff}}(T_{\text{mesh}} - T_{\infty}) + \epsilon\sigma A_{\text{eff}}(T_{\text{mesh}}^4 - T_{\infty}^4). \quad (21)$$

2.6.2. Model calibration and validation

The parameters (hA_{eff} , ϵA_{eff} , mc_p) can be identified by independent temperature measurement of the mesh. The validation procedure involves applying a sequence of power levels, recording the quasi-steady $T_{\text{mesh}}(P)$, and fitting the model parameters in Eq. (21).

2.6.3. Estimated $T_{\text{mesh}}(P)$ curve and uncertainty (present work)

In the present dataset, the active mesh region reached approximately 380 °C at 10 W, as measured experimentally with a thermocouple placed in contact with the active mesh region under ambient laboratory conditions. This value is used only as a representative temperature for interpreting the applied-power condition. To relate applied power to mesh temperature in a compact way, an effective $P \rightarrow T_{\text{mesh}}$ mapping is introduced. Over the limited range considered here, the heat loss is represented by a lumped linear coefficient K_{loss} :

$$P \approx K_{\text{loss}}(T_{\text{mesh}} - T_{\infty}). \quad (22)$$

Eq. (22) should be interpreted as a first-order approximation to the fuller steady heat-loss balance in Eq. (21), which includes both convective and radiative heat losses. The radiative term is therefore not retained explicitly in Eq. (22); this simplification is intentional and is used only to provide an approximate power–temperature scaling for the ignition-threshold discussion. Because radiation may become important at elevated mesh temperatures, the linear model is not used as a predictive thermal model outside this representative operating condition.

Using $T_{\infty} = 20$ °C and anchoring the curve at $T_{\text{mesh}} \approx 380$ °C for $P = 10$ W yields $K_{\text{loss}} \approx 0.0278$ W/K. This produces the approximate relationship

$$T_{\text{mesh}}(^{\circ}\text{C}) \approx 20 + 36 P(\text{W}), \quad (23)$$

which provides an order-of-magnitude context for interpreting ignition regimes. A conservative uncertainty of ± 40 °C is adopted in the 5.0–15 W range and ± 70 °C above 15 W to reflect increasing radiative contributions at higher temperature.

Table 3 summarizes the resulting estimated temperature versus power curve used for interpretation in Section 3.

This representative temperature measurement provides qualitative context for discussing possible HTP-decomposition-assisted ignition pathways, but it should not be interpreted as a validated transient thermal characterization of the mesh. Spatially and temporally resolved temperature measurements, combined with a heat-transfer model including convective, radiative, and contact losses, would be required to quantify the mesh temperature evolution during propellant contact.

2.7. Test matrix, outcome classification, threshold definition, and IDT measurement

To quantify repeatability and enable a probability-based threshold definition, each applied power level was tested in $N = 5$ repeat trials for

each propellant pair and for both open- and closed-environment configurations. Electrical power supplied to the thermal wire mesh was varied primarily in increments of 2.5 W to provide adequate resolution across the tested operating range while maintaining experimental repeatability. In addition to these regularly spaced power levels, a measurement at 12 W was intentionally included because preliminary experiments suggested it lies within a transition region where behavior shifts from non-sustained reactions to sustained combustion.

At each power level, outcomes were classified according to experimentally defined reaction and ignition criteria. A *reaction* was identified when clear evidence of chemical interaction between the propellants was observed (e.g., formation of white fumes consistent with HTP decomposition into oxygen and water vapor). *Combustion* was defined by the appearance of a flame, confirmed by visible chemiluminescence. When combustion occurred, ignition was further classified as *self-sustained* if the flame remained stable after the external DC power supply was switched off and the thermal wire mesh was no longer actively heated. For each trial, the outcome was therefore categorized as: (i) no combustion, (ii) combustion but not self-sustained, or (iii) self-sustained ignition.

To summarize repeatability at each power, ignition probability was reported as

$$p(P) \equiv \frac{n(P)}{N}, \quad (24)$$

where $n(P)$ is the number of trials (out of $N = 5$) that satisfy the criterion of interest (combustion or self-sustained ignition) at applied power P . Thus, p is naturally expressed as 0/5, 1/5, 2/5, 3/5, 4/5, or 5/5.

To avoid defining a threshold from a single trial or a single observed point, the threshold power for a given criterion was defined using an 80% probability requirement:

$$P_{\text{thresh}} \equiv \min\{P : p(P) \geq 0.8\}. \quad (25)$$

With $N = 5$ repeats, this corresponds to at least 4/5 successful trials at that applied power. The same probability criterion was applied when reporting both combustion and self-sustained ignition thresholds.

Ignition delay time (IDT) was estimated from recorded video at 240 fps. Time zero was defined as the instant when the heated thermal wire mesh first came into contact with the oxidizer and/or fuel (depending on configuration), and IDT was measured as the elapsed time from this instant to the onset of visible chemiluminescence (first sustained flame appearance). IDT was obtained by counting frames between these two events and converting the frame count using the known frame rate. In the present dataset, IDT values are reported as representative values at each power level (rather than mean $\pm$ standard deviation), because per-trial IDT values were not retained in the summary dataset.

2.7.1. IDT measurement criterion, temporal resolution, and uncertainty bounds

Ignition delay time (IDT) was estimated from recorded video at 240 fps, corresponding to a frame period of

$$\Delta t_{\text{frame}} = \frac{1}{240} \text{ s} \approx 4.17 \text{ ms}. \quad (26)$$

While the frame rate provides millisecond-level temporal quantization, the dominant uncertainty in IDT is generally not the frame period itself, but rather (i) the timing uncertainty in identifying the instant of mesh-propellant contact (time zero) and (ii) the subjectivity of identifying the first appearance of chemiluminescence in the presence of reflections, exposure variations, and evolving flame shape.

To reduce subjectivity and to make the IDT definition reproducible, an operational optical criterion is defined as follows. For each test video, a fixed region-of-interest (ROI) is selected around the mesh/near-mesh zone where ignition first becomes visible. Let $I(t)$ denote the mean grayscale pixel intensity within this ROI at time t , and let I_0 and σ_0 denote the mean and standard deviation of $I(t)$ over a pre-contact baseline

Table 4

Estimated uncertainty contributors for IDT derived from 240 fps video. Values are conservative bounds intended to reflect contact-time and ignition-onset identification uncertainty in addition to frame quantization.

Uncertainty source	Bound (typical)
Frame quantization (240 fps)	$\pm 0.5 \Delta t_{\text{frame}} \approx \pm 2.1 \text{ ms}$
Contact-time identification (time zero)	$\pm 2 \Delta t_{\text{frame}} \approx \pm 8.3 \text{ ms}$
Ignition-onset identification (threshold/persistence)	$\pm 3 \Delta t_{\text{frame}} \approx \pm 12.5 \text{ ms}$
Conservative combined bound (sum of bounds)	$\pm 23 \text{ ms}$

window (several frames immediately before the mesh–propellant contact). The ignition-onset frame is defined as the first frame for which the ROI intensity satisfies

$$I(t) \geq I_0 + k \sigma_0 \quad (27)$$

and remains above this threshold for at least M consecutive frames. In the present work, the criterion parameters are taken as $k = 5$ and $M = 3$ as a conservative choice to reject single-frame spikes due to glare or noise while capturing the first sustained luminous event associated with combustion. If a visible flame grows outside the initial ROI (e.g., due to plume motion), the ROI is expanded to include the luminous area while maintaining a consistent background reference region.

Time zero is defined as the first frame in which the heated thermal wire mesh is observed to make physical contact with the oxidizer and/or fuel. Because contact can occur between frames (and because the contact moment can be partially obscured by droplets or reflections), the time-zero selection is also subject to uncertainty. Operationally, time zero is chosen as the earliest frame in which (i) the mesh position overlaps the liquid/spray region and (ii) a discernible change in the local interface occurs (meniscus deformation, wetting onset, or droplet impingement signature) consistent with physical contact.

Based on these considerations, an IDT uncertainty bound is estimated using three contributors: (a) frame quantization, (b) contact-time identification uncertainty, and (c) ignition-onset (chemiluminescence) identification uncertainty. A conservative bound is summarized in Table 4. In practice, the contact-time and ignition-onset uncertainties dominate the frame quantization term.

Accordingly, IDT values inferred from the present procedure are interpreted with an approximate uncertainty of order ± 20 – 25 ms . This level of uncertainty is small relative to the bin widths used to classify IDT behavior (150 ms and 350 ms boundaries), but it is explicitly noted here to prevent over-interpretation of small differences near bin boundaries. For bin-based reporting, this implies that a measurement within $\sim 25 \text{ ms}$ of a boundary (150 ms or 350 ms) may be classified differently under a slightly different but still reasonable contact/ignition identification choice.

To incorporate uncertainty bounds directly into the qualitative IDT categories, the category boundaries are interpreted with a tolerance band of approximately $\pm 25 \text{ ms}$. Thus, the effective interpretation is:

- **Short:** IDT < 150 ms (interpretation robust when IDT $\lesssim 125 \text{ ms}$),
- **Intermediate:** 150 ms < IDT < 350 ms (robust when 175–325 ms),
- **Long:** IDT > 350 ms (robust when IDT $\gtrsim 375 \text{ ms}$).

The terms "short", "intermediate", and "long" are used as qualitative categories for comparing IDT behavior within the present electrothermal mesh-ignition dataset. They are not intended to imply hypergolic-timescale ignition, for which substantially higher-speed diagnostics would be required. In the present work, "short" denotes IDT below 150 ms, which is short relative to the longer near-threshold delays of approximately 500–700 ms observed in the same dataset. Table 5 summarizes the IDT category definitions used in this work.

This approach enabled consistent comparison across experimental conditions and emphasized relative trends in ignition behavior, particularly in cases where regime transitions were more significant than pre-

Table 5

Qualitative IDT category definitions used for scatter plot classification.

Category	IDT range
Long	IDT > 350 ms
Intermediate	150 ms < IDT < 350 ms
Short	IDT < 150 ms

cise ignition timing. In addition, reporting ignition probability (repeat counts) at each power level provides a direct measure of repeatability and enables threshold definition without relying on a single observation.

In the scatter plots, the horizontal axis represents the applied electrical power, while the vertical axis denotes the observed reaction or IDT behavior category. Each experimental condition is represented by a marker, with marker type and color indicating whether combustion occurred and whether ignition was self-sustained. This visualization enables clear identification of power-dependent transitions between non-reactive, reactive, combusting, and self-sustained ignition regimes, and provides a compact framework for comparing ignition behavior across the tested power range.

3. Results and discussion

3.1. Overview and reporting conventions

This section reports ignition outcomes for two propellant pairs (ethanol-HTP and Jet A-HTP) in two configurations: (i) an open, premixed surface-ignition configuration and (ii) a confined spray-through hot-mesh configuration with sequential oxidizer–fuel contact. At each electrical power level, five trials were performed, and outcomes are reported as (a) combustion occurrence and (b) self-sustained ignition (continued burning after external power removal). Representative ignition delay time (IDT) is extracted from 240 fps video and reported in the tables and figures for comparison across cases. Fig. 3 illustrates the ignition phenomenon (intermediate IDT, according to Table 5, for ethanol-HTP, input power 17.5 W) and method of extracting IDT from the videos. The contact frame between the heated mesh and the propellant region was defined as t_0 . Ignition onset was then identified as the first frame showing sustained visible flame/chemiluminescence. The IDT was calculated as the time difference between these two frames using the video frame rate. Because the recording rate was 240 fps, the nominal frame spacing was 4.17 ms. The same procedure of extracting IDT data from the videos applies to all other experiments as well.

For propulsion-system relevance, the reported results are presented as mesh temperature, electrical input power thresholds and delay times, which corresponds directly to required igniter mesh temperature, commanded igniter power and ignition timing constraints in spacecraft pulse-mode firing and multi-start thruster operation.

Across all cases, increasing applied power increases ignition probability and reduces IDT. The key result is that confinement reduces the self-sustained ignition threshold power relative to the open configuration and yields shorter IDTs at a given power, consistent with improved energy coupling between the mesh and the propellants. In addition to threshold power, the combination of repeat-count statistics (0/5–5/5) and IDT trends provides an engineering measure of ignition margin: operation just above threshold minimizes power draw but can incur long delays, whereas operation with margin improves timing robustness and reduces energized time per pulse.

3.2. Open configuration

3.2.1. Ethanol-HTP

Fig. 4 and Table 6 show the ethanol-HTP response in the open configuration. No combustion occurred for 5–12 W (0/5 self-sustained).

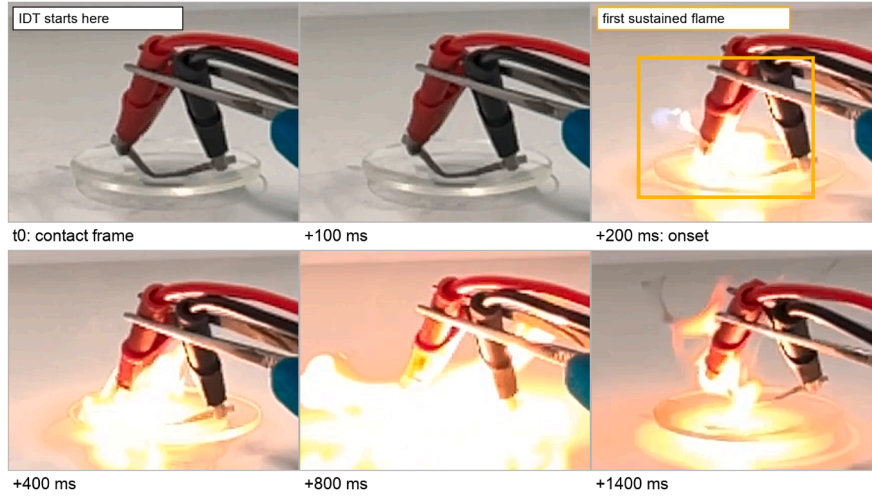


Fig. 3. Figure illustrating the ignition phenomenon and method of extracting IDT from the 240 fps videos.

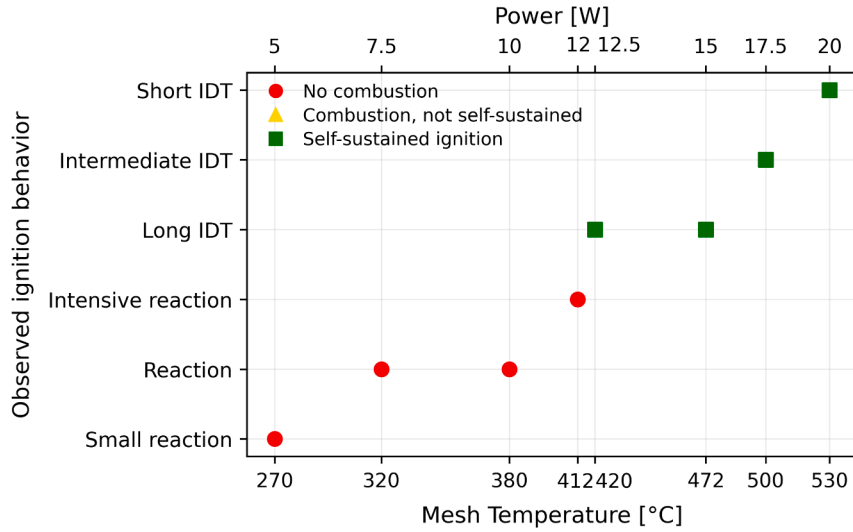


Fig. 4. Scatter plot showing the observed reaction and IDT behavior of the ethanol-HTP propellant in an open environment as a function of mesh temperature and applied electrical power. Marker type and color indicate combustion occurrence and whether ignition is self-sustained.

A clear transition occurs at 12.5 W, where both combustion and self-sustained ignition are first observed in 4/5 trials, establishing the open-configuration threshold at 12.5 W using the $\geq 80\%$ criterion. Above threshold, ignition becomes fully repeatable (5/5) from 15 W onward.

Representative IDT decreases systematically with increasing power: 500 ms at 12.5 W, 400 ms at 15 W, 200 ms at 17.5 W, and 75 ms at 20 W. Thus, while 12.5 W is sufficient for self-sustained ignition, higher power substantially improves ignition rapidity and reduces energized time per firing event. For spacecraft electrical budgeting, these power levels correspond to modest bus power draw; for example, at a 12 V bus, 10–12.5 W corresponds to ~ 0.8 –1.0 A, while at a 28 V bus the corresponding current is ~ 0.36 –0.45 A (neglecting conversion losses).

In temperature terms, the 12.5 W threshold corresponds to an estimated pre-contact mesh temperature of $T_{\text{mesh}} \approx 420^\circ\text{C}$ (Table 3). While this estimate carries uncertainty and the mesh cools upon contact, the mapping provides temperature context for the observed onset of self-sustained ignition.

A practical spacecraft-facing metric is the *electrical input energy to ignition*, defined as an upper bound

$$E_{\text{elec}} \equiv \int_0^{t_{\text{IDT}}} P(t) dt \approx P t_{\text{IDT}}, \quad (28)$$

Table 6

Open environment (ethanol-HTP): ignition probability and representative IDT versus applied electrical power ($N = 5$ per power level).

Power [W]	Combustion	Self-sustained	IDT [ms]
5.0	–	–	–
7.5	–	–	–
10.0	–	–	–
12.0	–	–	–
12.5	4/5	4/5	500 ± 25
15.0	5/5	5/5	400 ± 25
17.5	5/5	5/5	200 ± 25
20.0	5/5	5/5	75 ± 25

where the approximation holds for approximately constant applied power during the delay. Using representative IDTs, E_{elec} decreases from ~ 6.3 J at 12.5 W and 500 ms to ~ 1.5 J at 20 W and 75 ms. This quantity should be interpreted as a spacecraft electrical-budget metric and an upper bound on the energy actually coupled into the propellants prior to ignition, because a portion of the input power heats the mesh and is lost to the surroundings. It should be emphasized that the present power range does not establish a minimum electrical ignition energy or an

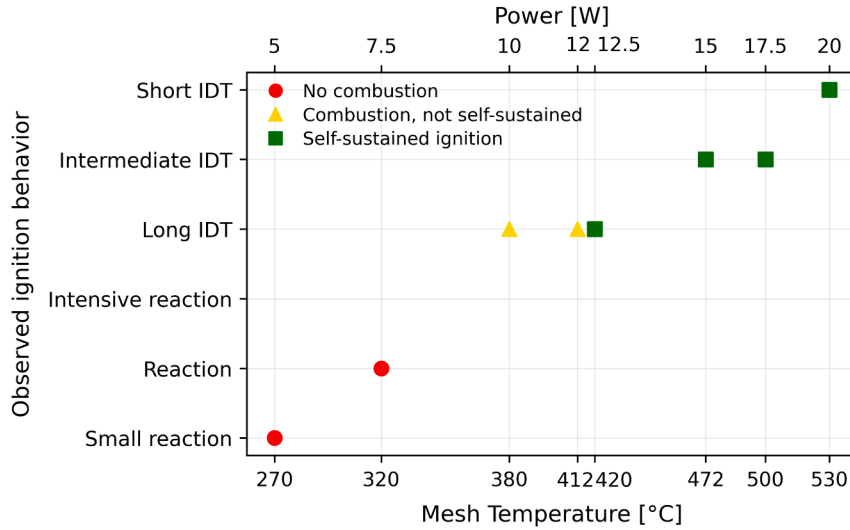


Fig. 5. Scatter plot showing the observed reaction and IDT behavior of the Jet A-HTP propellant in an open environment as a function of mesh temperature and applied electrical power. Increasing power leads to combustion with decreasing IDT and eventual self-sustained ignition.

Table 7

Open environment (Jet A-HTP): ignition probability and representative IDT versus applied electrical power ($N = 5$ per power level).

Power [W]	Combustion	Self-sustained	IDT [ms]
5.0	–	–	–
7.5	–	–	–
10.0	4/5	4/5	700 ± 25
12.0	5/5	4/5	500 ± 25
12.5	5/5	4/5	200 ± 25
15.0	5/5	5/5	100 ± 25
17.5	5/5	5/5	75 ± 25
20.0	5/5	5/5	50 ± 25

Table 8

Closed environment (ethanol-HTP): ignition probability and representative IDT versus applied electrical power ($N = 5$ per power level).

Power [W]	Combustion	Self-sustained	IDT [ms]
5.0	–	–	–
7.5	–	–	–
10.0	4/5	4/5	700 ± 25
12.0	5/5	4/5	500 ± 25
12.5	5/5	4/5	200 ± 25
15.0	5/5	5/5	100 ± 25
17.5	5/5	5/5	75 ± 25
20.0	5/5	5/5	50 ± 25

asymptotic high-power ignition-delay limit. Within the tested range, E_{elec} is therefore used only as a system-level electrical-input metric for comparing the present tests, not as the thermal or chemical energy absorbed by the propellants. Extending the test matrix to higher mesh powers until the IDT approaches a power-independent plateau, together with transient mesh-temperature measurements, would be required to determine the limiting ignition delay and reduce the influence of heat losses accumulated during longer pre-ignition heating periods.

3.2.2. Jet A-HTP

Fig. 5 and Table 7 show the Jet A-HTP response in the open configuration. Using the $\geq 80\%$ criterion, self-sustained ignition is first achieved at 10 W (4/5) and becomes fully repeatable (5/5) from 15 W onward. As in the ethanol case, ignition delay decreases systematically with increasing power, reaching 50 ms at 20 W. Interpreted as electrical input energy, $E_{\text{elec}} \approx P t_{\text{IDT}}$ yields ~ 7 J at 10 W and 700 ms near threshold, decreasing to ~ 1 J at 20 W and 50 ms at the highest tested power.

Using the $\geq 80\%$ criterion, the open-configuration Jet A-HTP self-sustained ignition threshold is 10 W (4/5). Robust ignition (5/5 self-sustained) is achieved from 15 W onward. The representative IDT decreases with increasing power, reaching 50 ms at 20 W.

Using the estimated mapping in Table 3, the onset of combustion in open Jet A-HTP at 10 W corresponds to $T_{\text{mesh}} \approx 380^\circ\text{C}$ (pre-contact). Because auto-ignition temperatures depend strongly on pressure, oxygen availability, residence time, and geometry, this comparison is used only as qualitative context. The observed ignition behavior is consistent with an HTP-decomposition-assisted pathway in which oxygen and heat release promote subsequent fuel ignition, rather than ignition controlled solely by thermal auto-ignition of the fuel in air. For spacecraft pulse-

mode operation, the 50–100 ms IDT range observed at higher powers (15–20 W) indicates that ignition timing is compatible with short commanded ignition pulses, while the ~ 500 –700 ms IDTs near threshold imply that operating too close to the minimum power can impose long preheat durations and increased sensitivity to boundary conditions.

3.3. Closed configuration

3.3.1. Ethanol-HTP

Fig. 6 and Table 8 show the ethanol-HTP response in the confined spray-through configuration. Using the $\geq 80\%$ criterion, the self-sustained ignition threshold is 10 W (4/5), which is lower than the 12.5 W threshold in the open configuration.

Representative IDT decreases strongly with increasing power: 700 ms at 10 W, 500 ms at 12 W, 200 ms at 12.5 W, 100 ms at 15 W, and 50 ms at 20 W. Ignition becomes fully repeatable (5/5 self-sustained) from 15 W upward. The combined reduction in threshold and IDT indicates more effective coupling in the confined geometry, where heat losses are reduced and reactants remain in the near-mesh region longer. In electrical-input-energy terms, $E_{\text{elec}} \approx P t_{\text{IDT}}$ yields ~ 7 J at 10 W and 700 ms near threshold, decreasing to ~ 1 J at 20 W and 50 ms. The lower threshold in the confined configuration therefore corresponds not only to reduced power but also to reduced total energized time needed to trigger ignition.

In temperature terms, the 10 W threshold corresponds to an estimated pre-contact $T_{\text{mesh}} \approx 380^\circ\text{C}$ (Table 3). Because the confined configuration also employed auxiliary vial heating (6 W) and pressure was not measured, the reduced threshold should be interpreted as the combined effect of confinement, preheating, and near-mesh mixing/impingement

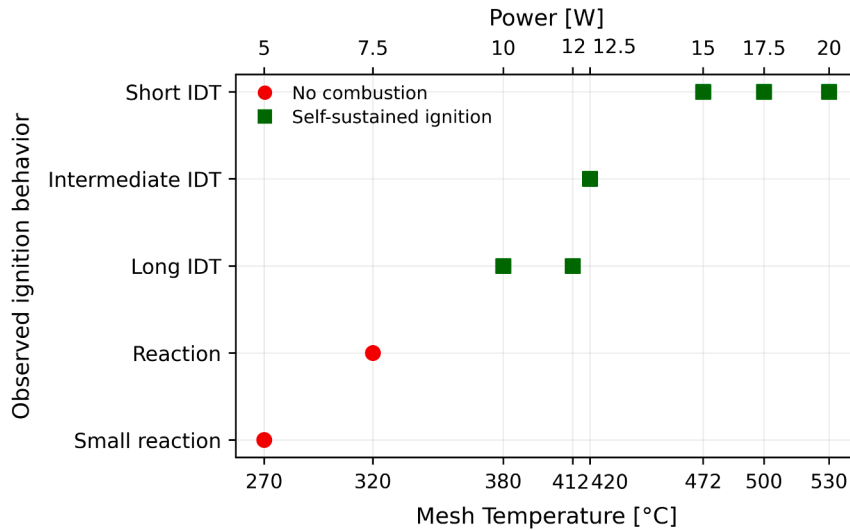


Fig. 6. Scatter plot showing the observed reaction and IDT behavior of the ethanol-HTP propellant in a closed environment as a function of mesh temperature and applied electrical power. Confinement lowers the power threshold for self-sustained ignition and reduces IDT.

conditions. From a spacecraft perspective, this result is qualitatively consistent with the expectation that reduced heat losses (e.g., due to proximity of chamber walls or elevated initial wall temperature after prior pulses) can lower the commanded igniter power needed for repeatable starts.

3.3.2. Jet A-HTP

Fig. 7 and Table 9 show the Jet A-HTP response in the confined configuration. Self-sustained ignition is achieved at the lowest power among all tested cases: 7.5 W (4/5), and becomes robust from 12.5 W (5/5 self-sustained). Representative IDT decreases with increasing power, reaching 60 ms at 20 W. In electrical-input-energy terms, $E_{\text{elec}} \approx P t_{\text{IDT}}$ yields ~ 4.5 J at 7.5 W and 600 ms near threshold, decreasing to ~ 1.2 J at 20 W and 60 ms.

The shorter IDTs observed for Jet A are consistent with its lower reported auto-ignition temperature relative to ethanol, but auto-ignition temperature should be interpreted only as supporting context rather than as the sole controlling parameter in the present HTP/thermal-mesh configuration. Reported auto-ignition temperatures are approximately 225–232 °C for Jet A [22] and approximately 365–368.8 °C for 95 wt.% ethanol, as mentioned in the Section 1, while hydrogen peroxide decomposition is thermally promoted at elevated temperatures, near 280 °C and above, and is strongly affected by surface/material effects [23]. However, these literature auto-ignition temperatures are measured in air and are sensitive to pressure, oxygen availability, residence time, and test method; they are therefore not directly equivalent to the present liquid fuel-HTP contact condition. In this work, the estimated pre-contact mesh temperature is used as a quantitative parameter to characterize the observed ignition transition. Increasing mesh temperature promotes HTP decomposition and accelerates the associated chemical reaction rates, thereby increasing the likelihood of ignition and reducing ignition delay. The observed ignition behavior is therefore interpreted as decomposition-assisted: heating of the HTP near the mesh promotes peroxide decomposition, producing heat and oxygen that subsequently support fuel vaporization, ignition, and combustion.

With further increases in power to approximately 12–15 W, the IDT decreased into the intermediate regime while maintaining stable self-sustained combustion. At the highest tested power levels (17.5–20 W), short IDTs were consistently observed, indicating rapid and robust ignition. Overall, these results demonstrate that both fuel properties and confinement critically influence ignition thresholds and stability, with Jet A exhibiting enhanced ignitability relative to ethanol under closed-environment conditions.

Table 9

Closed environment (Jet A-HTP): ignition probability and representative IDT versus applied electrical power ($N = 5$ per power level).

Power [W]	Combustion	Self-sustained	IDT [ms]
5.0	–	–	–
7.5	4/5	4/5	600 ± 25
10.0	4/5	4/5	500 ± 25
12.0	5/5	4/5	400 ± 25
12.5	5/5	5/5	250 ± 25
15.0	5/5	5/5	200 ± 25
17.5	5/5	5/5	100 ± 25
20.0	5/5	5/5	60 ± 25

The reduced thresholds in the confined configuration are most directly attributable to enhanced heat retention, reduced convective losses, and increased reactant residence time and impingement/mixing near the heated mesh. While a pressure rise may occur in a sealed vial during vigorous decomposition/combustion, pressure was not measured and is therefore not used as a primary explanatory variable.

Using the $\geq 80\%$ criterion, the closed-environment Jet A-HTP self-sustained ignition threshold is 7.5 W (4/5). The probability trend shows robust ignition (5/5) from 12.5 W onward, and the representative IDT decreases as power increases, reaching the tens-of-milliseconds scale at 20 W. For spacecraft applications, the combination of low threshold power and short IDT at moderate power suggests that ignition margin can be achieved without excessive electrical draw, which is particularly relevant for CubeSat-to-smallsat-class propulsion modules with limited peak power availability.

In temperature terms, the 7.5 W Jet A-HTP closed-environment threshold corresponds to an estimated pre-contact mesh temperature of approximately 320 °C. This value lies in an elevated-temperature regime where HTP decomposition is expected to be promoted, with decomposition rates depending strongly on temperature and surface/material effects [23]. Therefore, the closed spray-through ignition behavior is interpreted as a coupled decomposition-assisted process: HTP impingement near the heated mesh can produce heat and an oxygen-rich water-vapor environment, which then promotes fuel vaporization and subsequent fuel ignition/combustion [24]. Because spatially and temporally resolved temperatures were not measured directly inside the closed vial during propellant contact, this pathway is presented as a physically plausible interpretation rather than a directly validated reaction sequence.

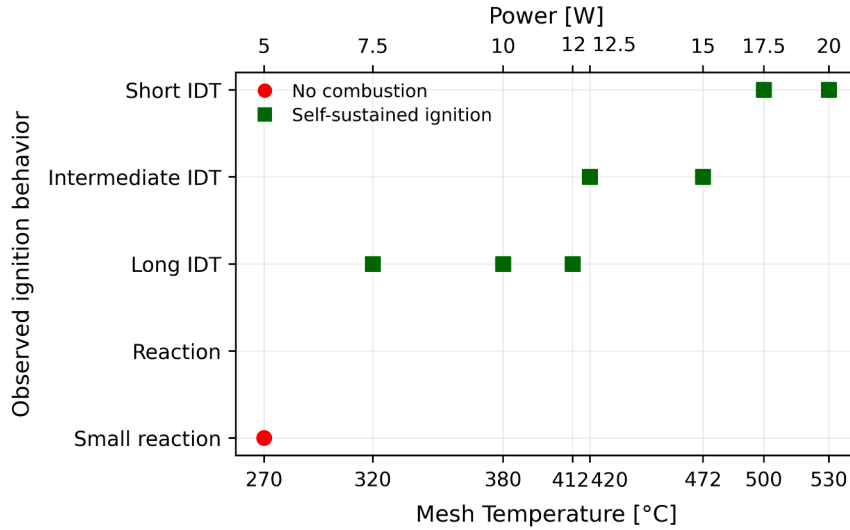


Fig. 7. Scatter plot showing the observed reaction and IDT behavior of the Jet A-HTP propellant in a closed environment as a function of mesh temperature and applied electrical power. Stable self-sustained ignition occurs at lower power levels compared to open-environment conditions.

Table 10

Summary of self-sustained ignition thresholds using the $\geq 80\%$ success criterion ($\geq 4/5$).

Case	Self-sustained threshold [W]	Equivalent mesh temperature [°C]
Open, ethanol-HTP	12.5	420 $\pm$ 40
Open, Jet A-HTP	10.0	380 $\pm$ 40
Closed, ethanol-HTP	10.0	380 $\pm$ 40
Closed, Jet A-HTP	7.5	320 $\pm$ 40

It is noted that, while a pressure rise may occur in a sealed vial during vigorous decomposition/combustion, pressure was not measured in the present experiments. Therefore, the reduced thresholds observed in the closed configuration are most directly supported as being likely due to confinement-driven heat retention, reduced convective losses, and increased reactant residence time and mixing/impingement effects near the heated mesh, rather than being attributed solely to pressure-driven kinetics.

3.4. Cross-case comparison and key trends

Table 10 summarizes the self-sustained ignition thresholds extracted from the four datasets. Confinement reduces the threshold for both fuels (ethanol: 12.5 W $\rightarrow$ 10 W; Jet A: 10 W $\rightarrow$ 7.5 W), and Jet A exhibits the lowest threshold in the confined configuration.

Beyond threshold power, ignition rapidity improves strongly with increasing power. For ethanol-HTP in the open configuration, representative IDT decreases from 500 ms at threshold (12.5 W) to 75 ms at 20 W. For Jet A-HTP in the confined configuration, representative IDT reaches 60 ms at 20 W while requiring only 7.5 W for first self-sustained ignition. These trends highlight a practical design trade: operating closer to threshold minimizes power but increases delay and variability, whereas operating with margin reduces IDT and improves repeatability. Expressed as electrical input energy, the highest-power cases yield E_{elec} on the order of $\sim 1\text{--}2$ J, while near-threshold cases yield several joules due primarily to longer energized time. This underscores that ignition “cost” for spacecraft systems can be governed as much by delay-time sensitivity as by the steady electrical power level itself.

3.5. Implications for spacecraft ignition systems

While the present experiments are laboratory-scale, the measured thresholds and IDTs can be mapped to first-order spacecraft integration considerations. For a commanded ignition pulse, the relevant electrical budget is the input energy E_{elec} (Eq. (28)) and the timing con-

straint is the IDT relative to the desired valve/sequence timeline. In this dataset, near-threshold operation yields long IDTs ($\sim 0.5\text{--}0.7$ s) and therefore larger E_{elec} despite modest power, whereas operation with margin (15–20 W) yields short IDTs (50–100 ms) and E_{elec} of order 1–2 J. For pulse-mode firing, the short-IDT regime reduces sensitivity to boundary-condition variability (wall temperature, droplet cooling, and convective losses) and can improve synchronization with commanded propellant delivery. Conversely, threshold-adjacent operation may be acceptable for limited-start systems but can impose longer energized times and greater variability, which may be undesirable for repeated ACS pulsing. Finally, because the “closed” configuration includes both confinement and intentional chamber preheating, its reduced thresholds should be interpreted as a qualitative indication that reduced heat loss (e.g., in a compact thruster cavity or after thermal soak-back from prior pulses) can lower required commanded igniter power; direct extrapolation to flight thrusters requires future testing with controlled mass flow, measured pressure, and repeated starts on the same igniter element.

4. Conclusion

This work experimentally characterized ignition of two green bipropellant pairs—ethanol-HTP and Jet A-HTP—using a reusable NiCr thermal wire mesh igniter operated at low electrical power. Two ignition modes were examined: (i) an open-environment premixed surface-ignition configuration and (ii) a confined spray-through hot-mesh configuration with sequential oxidizer–fuel contact. At each power level, five repeats were conducted and outcomes were reported as ignition probability for combustion and for self-sustained ignition; ignition thresholds were defined at an 80% success level ($\geq 4/5$). From an astronautics perspective, the key outcome is that repeatable, electrically commanded ignition of non-hypergolic HTP-based bipropellants is achievable at single-digit-to-low-teens watt-level input power, which supports the feasibility of compact ignition subsystems for multi-start spacecraft chemical propulsion.

In the open premixed configuration, self-sustained ignition first occurred at 12.5 W and 10.0 W for both ethanol-HTP and JetA-HTP pairs, respectively (4/5 for ethanol-HTP and 4/5 for Jet A-HTP), with fully repeatable self-sustained ignition (5/5) achieved by 15 W for both propellant pairs. In the confined spray-through configuration, thresholds were reduced: ethanol-HTP reached self-sustained ignition at 10 W (4/5), while Jet A-HTP reached self-sustained ignition at 7.5 W (4/5), with robust behavior (5/5) from 12.5 W onward. Across both configurations, representative ignition delay time (IDT) decreased with increasing power, ranging from long delays on the order of ~500–700 ms near threshold to short delays on the order of ~50–75 ms at the highest tested powers. Interpreted as a spacecraft electrical-budget metric, these IDTs imply that the *electrical input energy to ignition* (upper bound) is on the order of a few joules near threshold and decreases to order-unity joules at the highest tested powers, emphasizing that ignition “cost” depends strongly on energized time as well as on steady power level.

To interpret these power-based trends mechanistically, the study introduced an electro-thermal framework to relate applied power to an estimated pre-contact mesh temperature. Although direct temperature measurements during ignition were not performed, the observed onset behavior and the estimated $T_{\text{mesh}}(P)$ context are consistent with an ignition pathway initiated by thermal decomposition of HTP (oxygen and heat release) followed by fuel ignition, rather than ignition controlled solely by fuel auto-ignition in air. The lower thresholds in the confined spray-through mode are attributed primarily to confinement-driven heat retention and increased reactant residence and mixing/impingement near the heated mesh; possible pressure rise in the sealed vial was not measured and is therefore not used as a primary explanatory variable. Accordingly, the closed-configuration results should be interpreted as comparative trends under modified thermal boundary conditions (confinement and preheating) rather than as direct prediction of flight-thruster ignition thresholds; nonetheless, they provide practical evidence that reduced heat losses can lower commanded igniter power and shorten ignition delay.

Overall, the measured thresholds (7.5–12.5 W for first self-sustained ignition depending on configuration and propellant) and the observed IDT reductions with increasing power indicate that wire-mesh electrothermal ignition can provide repeatable ignition for HTP-based green bipropellants at power levels compatible with CubeSat-to-smallsat-class electrical budgets for pulsed operation. Future work should implement thruster-representative propellant flow and mixture-ratio control, directly measure transient mesh temperature and chamber/vial pressure, and report per-trial IDT distributions to more rigorously quantify repeatability and enable scaling of the present laboratory results to flight-relevant operating envelopes. To further mature the concept toward spacecraft implementation, additional flight-relevant steps include: (i) multi-start endurance testing on the same mesh element (resistance drift, oxidation/fouling, and ignition repeatability over many pulses), (ii) testing under reduced-pressure or vacuum-relevant boundary conditions to capture changes in convective losses and plume behavior, (iii) assessment of material compatibility/contamination risks for HTP and hydrocarbon fuels (including potential deposits on the mesh and nearby injector hardware), and (iv) coupled tests with thruster-like valve timing and propellant delivery transients to quantify ignition robustness under commanded pulse sequences.

CRedit authorship contribution statement

Kyoungeun Lee: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Prakhar Jindal:** Writing – review & editing, Supervision; **Sebastien Reichstadt:** Supervision, Project administration, Funding acquisition, Conceptualization; **B.V.S. Jyoti:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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