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Nytrox-based Hybrid Propellants Characterization

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Abstract

Hybrid rocket propellants have arised as alternatives to conventional propellants by combining the low cost and simplicity of solid propellants with the safety, performance, and throtability of liquid propellants. These systems typically pair a solid fuel matrix with a gaseous or liquid oxidizer. Liquid Oxygen (LOX) is a popular oxidizer owing to its high specific impulse and efficiency at low oxidizer-to-fuel ratios (O/F). However, its deep cryogenic nature makes it difficult to store and handle. On the other hand, nitrous oxide (N_2O) is widely used for its self-pressurizing and storable characteristics and ease of handling, although it delivers a lower specific impulse than LOX. Nytrox is a blend of oxygen and N_2O that emerged as a promising alternative oxidizer, offering intermediate properties that combine the high performance of LOX with safer handling and operational simplicity compared to that of N_2O. Nytrox achieves a specific impulse comparable to LOX while maintaining less stringent cryogenic requirements owing to its higher saturation temperature, making it a versatile and safer option for hybrid propulsion systems. This study investigates the combustion and propulsion performance of Nytrox as an oxidizer, focusing on its behavior across varying oxygen concentrations when combined with solid fuels such as HTPB, HDPE, PMMA, ABS, PLA, and paraffin. The analysis uses CEA software and an in-house Python algorithm to evaluate the performance benefits of Nytrox-based hybrid propellants relative to conventional systems based solely on oxygen or N_2O. The results aim to provide valuable insights into the practical applications and potential advantages of Nytrox for advancing hybrid rocket technologies.

1. Introduction

The aerospace industry is undergoing a transformation in its development model. Government monopoly involvement in space technologies is declining due to the state-driven nature of these programs, which are often characterized by a focus on public opinion, national prestige, excessive bureaucracy, economically unsustainable approaches, and slow technological advancement.

In contrast, the New Space model addresses several of these issues by promoting the development of space technologies through alternative approaches. This paradigm emphasizes innovation driven by private investment and commercial applications focused on entrepreneurship, including mass-produced satellites, space tourism, worldwide internet access, and other space-related endeavors. These applications depend on simpler, more affordable, and reusable systems. Consequently, there are now more options for alternative propulsion technologies, such as hybrid rocket propulsion, which combines the simplicity of solid propellants with the controllability of liquid systems.

Solid propellants are widely used in the aerospace industry as boosters and military assets, consisting of a pre-mixed blend of fuel and oxidizer in a solid phase. They are simple, stable, and also provide high density, and storability. They typically have a low throttling capability, though and, once ignited, they cannot be extinguished. Furthermore, when compared to liquid propellants, solid propellants offer a lower specific impulse.[13]

Liquid propellants use separate fuel and oxidizer stored in individual tanks, which are injected, atomized and mixed into the combustion chamber, and then ignited to produce thrust. They are well-established and provide high specific impulse, when compared with solid ad hybrid propulsion along with the ability to throttle, shut down and restart the engine. However, they require complex turbopumps, valve controls mechanisms and usually cryogenic handling systems.[2]

The development of hybrid rocket propellants dates back to the early 20th century, when Sergei Korolev and Mikhail Tikhonravov, as part of the Soviet GRID program, conducted the first hybrid rocket flight using gasoline, colophonium, and liquid oxygen as propellants.[11] This technology has emerged as an alternative solution for the

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traditional propellants, due to the combination of both conventional propellants characteristics, it combines the fuel and oxidizer in different phases, aiming to bring the trade-offs.

Recently, the hybrid propulsion has shown increasing interest in alternative oxidizers that balance performance with operational simplicity. Among these, Nytrox has emerged as a promising candidate, offering self-pressurizing behavior and improved thermochemical performance compared to nitrous oxide, while avoiding the cryogenic requirements of liquid oxygen. Although Nytrox thermodynamic properties and viability in propulsion systems have been assessed in earlier research (Karabeyoglu 2009), some comprehensive performance analyses involving various solid fuels remains limited. This study aims to evaluate the combustion performance of six polymer-based fuels with Nytrox at different compositions, contributing to a deeper understanding of hybrid propulsion optimization through oxidizer-fuel synergy.

2. Methods

This study aims to provide performance parameters of propellant mixtures that use nytrox as oxidizer. For this purpose, it is divided into four main sections. The first section describes the CEA (Chemical Equilibrium with Applications) and how the problem is modeled, the second section is the description and work-flow of the in-house Python algorithm, the third section is the theoretical background, presenting a review of each fuel in the literature and the evaluating the nytrox since its has been recently evaluated in the literature.

The last section is the thermochemical and performance parameters analysis of some propellant mixtures using the in-house Python algorithm to sequentially create the input parameter's file in function of the percentage of oxygen in nytrox composition and mainly the CEA software, presenting the results of the simulation and comparing those parameters between the pair of studies.

2.1 CEA thermochemical parameters

The CEA software is a computational tool designed to evaluate the chemical equilibrium of multi-component reactive systems. In this study, the rocket performance module is employed to compute the equilibrium composition, temperature of combustion gases within the adiabatic rocket chamber and the characteristic velocity. This is achieved using the Newton-Raphson method, which solves for the minimization of Gibbs and Helmholtz free energies, the conservation of species, and the first law of thermodynamics. The calculation assumes adiabatic conditions and complete combustion of the reactants, based on initial guesses of species concentrations, gas mole fractions, and temperature. The solver also considers the one-dimensional frictionless flow of ideal gases along the nozzle, with specific heats varying with temperature.[4] For CEA thermochemical simulations, the problem is modeled using the following parameters:

For the thermochemical simulations performed in this study, CEA software was configured using the predefined rocket problem type, which models propulsion systems based on specified chamber conditions. Both equilibrium and frozen expansions were evaluated to account for chemical recombination effects along the nozzle. Additionally, infinite-area chamber (IAC) is a mandatory condition, since the calculation with "Finite-area chamber" is not available with "Frozen" condition. These and other conditions and other are explained in CEA Manual.[4]

An in-house Python algorithm is employed to generate the input files, with its routine described later in this work. For proper functionality, the algorithm requires predefined input parameters to be used in the model:

Table 1: Fixed input parameters for combustion modeling

Simulation Parameter	**Value**
Combustion chamber pressure	7 bar
Fuel mass fraction	1
Fuel initial temperature	298 K
Oxidizer initial temperature[5]	193 K

The fuel mass fractions are always equal to 1 because it is considered a pure component. Therefore, in this work, the fuels are not mixed with other fuels or additives. For the oxidizer mass fraction, the sum of liquid oxygen and nitrous oxide is equal to 1. The nytrox is modeled as a mixture of oxygen and nitrous oxide inside the input file using as parameters the values of $0 < wt_{ox} < 1$ and $0 < wt_{nox} < 1$, which is further explained on this present work.

Moreover, the initial temperature of fuel is considered as the ambient temperature, approximately 298 K as it is stored and handled at ambient temperature. For nytrox, the initial temperature is set according to the optimum, as stated by Karabeyoglu, 2009,[5] equivalent to 193 K.

Furthermore, for this analysis, the oxidizer-fuel ratio (O/F) is a variable parameter. The range of O/F is given by 1 to 8 in steps of 0.25.

DOI: 10.13009/EUCASS2025-078

2.2 In-house Python algorithm

The in-house Python algorithm is used to structure the input iteration of the propellant mixture, the data storage and graphics production. The routine of the main algorithm is to create an input file for CEA solver and calls it, then the CEA solver creates an output file that thoroughly describes all iterations with several valuable information about the reactions and a resumed spreadsheet file with thermochemical and performance data in chamber and throat, including pressure, temperature, density, internal energy, enthalpy, entropy, characteristic velocity, and specific impulse.

The second algorithm contains a routine that calls the main algorithm and iterates the mass fractions of the two oxidizers that compose nytrox. For example, in the first iteration, the mass fraction of liquid oxygen is 0.1 and that of nitrous oxide is 0.9; in the second iteration, the mass fraction of liquid oxygen is 0.2 and that of nitrous oxide is 0.8, and so on sequentially. Therefore, producing a total of 9 iterations of each propellant mixture, those data bank is used in a third algorithm to produce the graphics that are shown in results chapter.

For this study, the performance analysis focuses on the characteristic velocity, which is used to compare the performance of propellant mixture. These parameters are used to evaluate the potential of the rocket engine and can be applied to the analysis of hybrid propulsion, as it only depends on the properties of combustion products.

2.3 Fuels

This study investigates six thermoplastic and thermosetting fuels commonly considered in hybrid propulsion research: HTPB, HDPE, ABS, paraffin wax, PLA, and PMMA. These are solid fuels and were selected based upon their usability in solid propulsion, as some of then are binders and others are low-cost solution, also there are the mechanical processability and structural features, which enables a broad comparison of performance outcomes when combined with Nytrox oxidizer blends.

Acrylonitrile Butadiene Styrene (ABS) is a thermoplastic polymer synthesized from three monomers: acrylonitrile, butadiene, and styrene. Because of its mechanical properties, structural stability, and melting point, it is utilized in additive manufacturing. ABS is frequently used as the structural matrix in fuel grain for rocket propulsion.[14] In this study, however, it is evaluated as an independent fuel.

High-Density Polyethylene (HDPE) is a pyrolizing polymer consisting of long chains of ethylene monomers C_nH_{2n}. It is known for its low cost, ease of processing, and low values of regression rate.[3] However, HDPE exhibits good structural stability and is frequently used as a reference fuel in hybrid motor testing. As the enthalpy of formation of CH_2 is equivalent to −29.07 kJ/mol per monomer unit.

Hydroxyl-Terminated Polybutadiene (HTPB) is a thermosetting polymer derived from alkenes, such as 1,3-butadiene (C_4H_6). It has historically been used as a binder in composite solid propellants, combining metal powders and oxidizers to guarantee even combustion. However, because of its high combustion enthalpy and compatibility with a variety of oxidizers, HTPB also shows great promise as a stand-alone hybrid rocket fuel. Its adaptability and versatility make it even more appealing for hybrid propulsion.[7]

Paraffin Wax is a very common hydrocarbon polymer that is employed as a fuel in hybrid rocket propulsion systems due to its high regression rate and high combustion performance. One of its most attractive features lies on its rapid surface regression, which significantly enhances the fuel mass flow rate during operation. This behavior, primarily driven by a melt layer that forms and is entrained into the oxidizer stream, allows higher thrust levels without requiring complex fuel grain geometries. Structurally, its general chemical formula of C_nH_{2n+2}.

Polylactic Acid (PLA) is a polyester derived from lactic acid, with the empirical formula $C_3H_4O_2$, it is extensively used in additive manufacturing processes (same as ABS), as filament material for additive manufacturing. Its use in hybrid propulsion as structural reinforcement, also offering low regression rates[9] and a more sustainable, low-toxicity combustion profile.[10] Its enthalpy of combustion varies by the polymer chain but is approximately 18 MJ/kg[18] for the monomer unit.

However, the standard enthalpy of formation of PLA varies depending on the length of the polymer chain and the synthesis method employed. For this reason, it can be theoretically estimated using the following relation:

$$\Delta H_f^\circ = \sum \Delta H_f^\circ(\text{products}) - \sum \Delta H_f^\circ(\text{combustion}) \quad (1)$$

The enthalpy of combustion can be calculated from the heat of combustion and the molecular mass of the fuel, as shown in Equation 2, where M_{fuel} is the molecular weight in kg/mol, and q_{comb} is the heat of combustion in MJ/kg:

$$\Delta H_{\text{comb}} = q_{\text{comb}} \cdot M_{\text{fuel}} \quad (2)$$

Assuming a complete combustion, the reaction for a generic compound $C_xH_yO_z$ can be represented as:

DOI: 10.13009/EUCASS2025-078

$$C_xH_yO_z + \left(x + \frac{y}{4} - \frac{z}{2}\right)O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O \quad (3)$$

Since the standard enthalpies of formation of the combustion products are well established, $\Delta H_f^\circ(H_2O) = -285.8$ kJ/mol and $\Delta H_f^\circ(CO_2) = -393.5$ kJ/mol.

Considering the molecular mass of PLA as $M_{PLA} = 0.072$ kg/mol, the enthalpy of combustion is approximately −1296 kJ/mol. Consequently, applying Equation 1, the standard enthalpy of formation is estimated to be around −456.1 kJ/mol.

Polymethyl Methacrylate (PMMA) is a transparent thermoplastic derived from the polymerization of methyl methacrylate monomers ($C_5H_8O_2$). It features relatively low regression rates and good energy output, making it a viable fuel candidate in hybrid rocket systems. PMMA also offers good machinability, as it is a material used in general industry, and with low thermal conductivity,[1] which can improve combustion stability. The enthalpy of formation is −348.70 kJ/mol.

The Table 2 summarized the main properties used as input in CEA software.

Table 2: Main properties of each fuel and oxidizer to be used in CEA.

Fuel	**Molecular Formula**	**Enthalpy of Formation** [kJ/mol]
ABS[17]	$C_{3.85}H_{4.85}N_{0.43}$	+62.63
HDPE[12]	C_2H_4	−58.14
HTPB[6]	$C_{7.075}H_{10.65}O_{0.223}N_{0.063}$	−58.00
Paraffin Wax[15]	$C_{20}H_{42}$	−594.57
PLA	$C_3H_4O_2$	−456.10
PMMA[8]	$C_5H_8O_2$	−348.70

2.4 Nytrox

LOX is a highly reactive oxidizer that delivers high specific impulse at favorable O/F ratios in both liquid and hybrid rocket engines. However, since LOX is deep cryogenic, with the boiling point at 90 K, it poses challenges in terms of storage, handling, and system design. It is also not self-pressurizing due to its density at high pressures, often requiring complex pressurization and thermal management systems.[5]

Nitrous Oxide (N_2O) is a widely used oxidizer in hybrid propulsion systems, valued for its self-pressurizing behavior, which simplifies system design by removing the need for external pressurization mechanisms. Despite the advantages, it has some downsides, including lower specific impulse and impulse density. Its enthalpy of formation is 81.6 kJ/mol.[16]

Nytrox is an oxidizer mixture composed of liquid oxygen and nitrous oxide, which combines the advantages of both components. This mixture is gaining attention due to its enhanced thermodynamic properties and facilitated operational.

When both oxidizers are mixed, the resulting phase equilibrium leads to a saturation temperature that falls between those of the pure components. At around 193 K and 20 atm, Nytrox exhibits a higher density than either of its individual constituents, ensuring self-pressurization at near-cryogenic (but not deeply cryogenic) conditions. This temperature of 193 K is considered for all Nytrox compositions, as a simplified formulation. The performance characteristics of the mixture include specific impulse and characteristic velocity approach those of pure liquid oxygen and exceed those of pure nitrous oxide.[5]

Furthermore, the oxidizer performance is strongly influenced by its oxygen mass fraction. An increase of O_2 in the mixture leads to a higher fuel regression rate, improving overall performance.[5] For thermochemical simulations using CEA software, the enthalpy of formation is treated as the individual contributions of oxygen and nitrous oxide (81.6 kJ/mol).

2.5 Thermochemical Parameters

The characteristic velocity (c^*) is a key parameter in propulsion analysis, defined as the ratio of the product of chamber pressure and throat area to the mass flow rate of the exhaust gases. It represents the efficiency of energy conversion in the combustion chamber and the ideal exhaust velocity, independent from nozzle geometry, making it useful for evaluating combustion performance alone.

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Therefore, c^* is widely used as a performance comparative parameter for different propellants, making it especially valuable when analyzing hybrid propellants with many blend compositions. Higher values of c^* indicate more efficient conversion of chemical energy into thermal energy.

3. Results

The results obtained from the thermochemical simulations provide insights into the performance trends of various hybrid rocket fuels in combination with oxidizer blends of Nytrox.

The simulations results are consistent with hybrid rocket literature and experimental findings.[15] Moreover, they reveal the thermochemical relations between c^* and fuel composition with its enthalpy of combustion and formation for different Nytrox oxidizer variations.

Among all fuels tested, HDPE and paraffin wax demonstrated the highest c^* values throughout the simulated O/F range, as shown in Figure 2 and 1.

When paraffin-wax combines with Nytrox blends at higher O/F ratios, such as Nytrox90 (lime-green dashed line in Figure 1), it yields the highest peak of c^* values, approximately 1782.86 m/s at O/F of 2.25, it is a relatively low O/F ratio at optimal conditions, which is an important factor for system mass optimization.

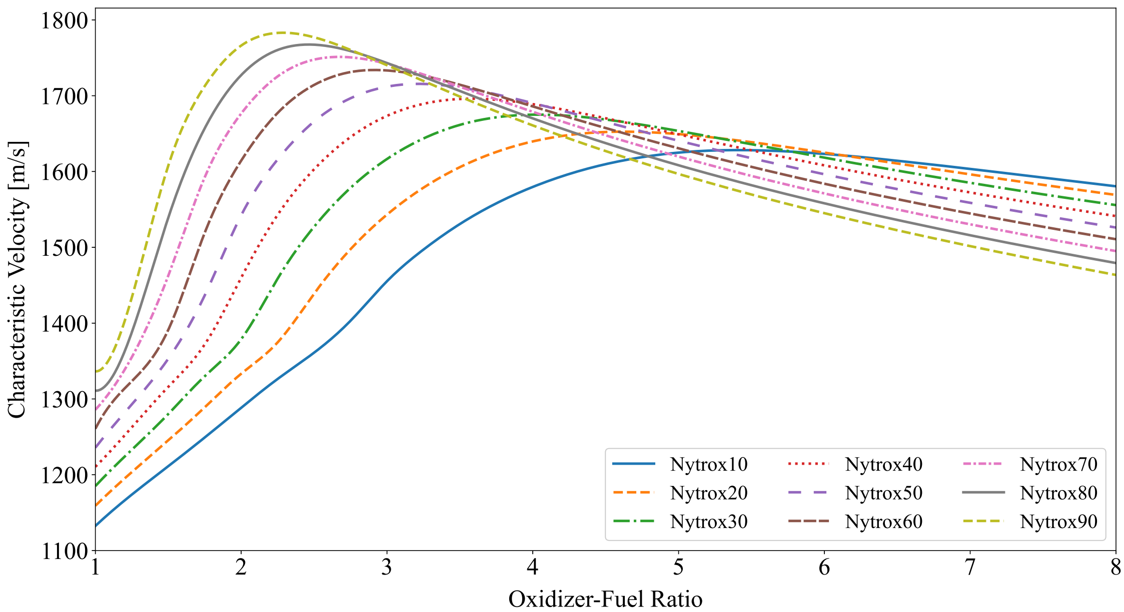

Figure 1: Characteristic velocity, as a function of O/F for paraffin with range of oxygen in Nytrox oxidizer.

Additionally, the breakeven, in which the lower oxygen Nytrox blends outperform the higher ones, shifts towards higher O/F, suggesting a nuanced interaction between chemical equilibrium and oxidizer composition. These results highlight the versatility of paraffin and strong potential as a fuel for hybrid propulsion systems, especially in missions requiring high thrust-to-weight ratios, modular engine design, and simplified operational control.

Among the tested fuels, HDPE preseted itself with the widest amplitude range of characteristic velocity across varying mixture ratios, as shown in Figure 2. This means that, while HDPE reaches on of the highest peak c^* equivalent to 1774.84 m/s, at O/F of 2.25 ranking behind and paraffin, it shows a strong sensitivity to changes in the O/F ratio, with c^* values ranging from modest levels at low O/F to relatively high performance at optimized conditions.

This data suggests that HDPE combustion performance is highly dependent on the oxidizer environment, and that careful adjustment of mixture ratio can significantly improve its performance characteristics. In practical scenario, this may imply that HDPE-based systems offer greater flexibility in hybrid rocket missions, but they require precise oxidizer refinement and combustion control. Besides that, it may also imply that this fuel can be combined with other high energy density fuel.

Furthermore, HDPE's widespread availability, low cost, and ease of manufacturing make it an appealing option for educational and low-cost flight applications, especially when paired with oxidizer delivery systems capable of maintaining optimal O/F conditions throughout the burn.

ABS and HTPB followed closely, achieving c^* values of 1761.16 m/s (O/F = 1.75) and 1760.13 m/s (O/F = 2.00), respectively. Their performance still support relatively efficient combustion. Since HTPB is a thermosetting

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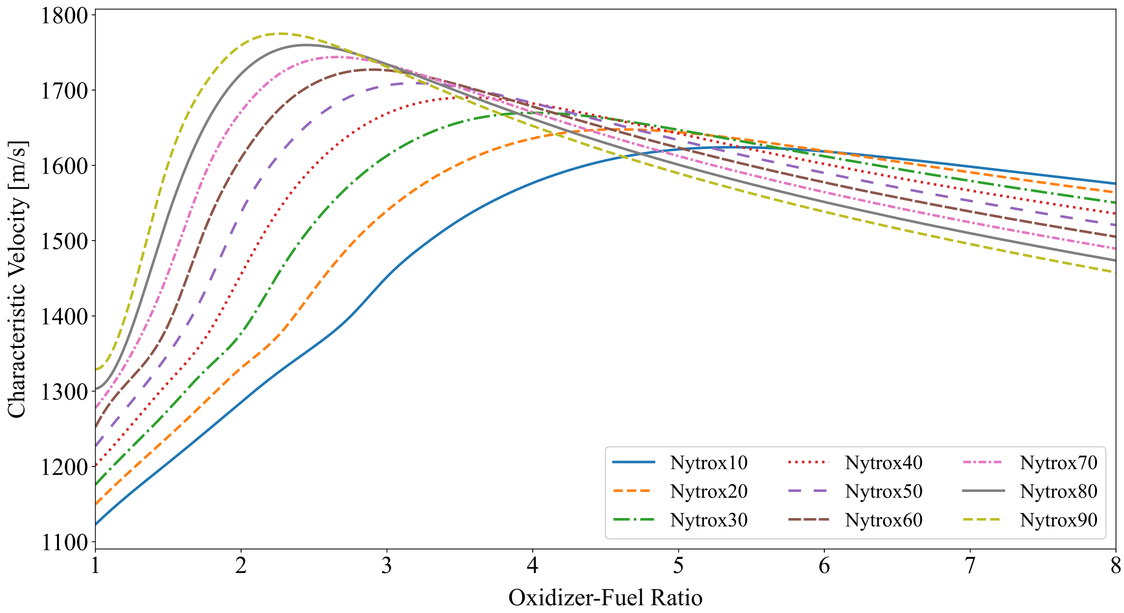

Figure 2: Characteristic velocity, as a function of O/F for HDPE with range of oxygen in Nytrox oxidizer.

binder with energetic properties, it offers strong exothermic potential and consistent performance across different oxidizer types. The fuel present a high performance, reaching 1760.13 m/s at O/F of 2.00 with 90% of oxygen in Nytrox, as seen in Figure 3.

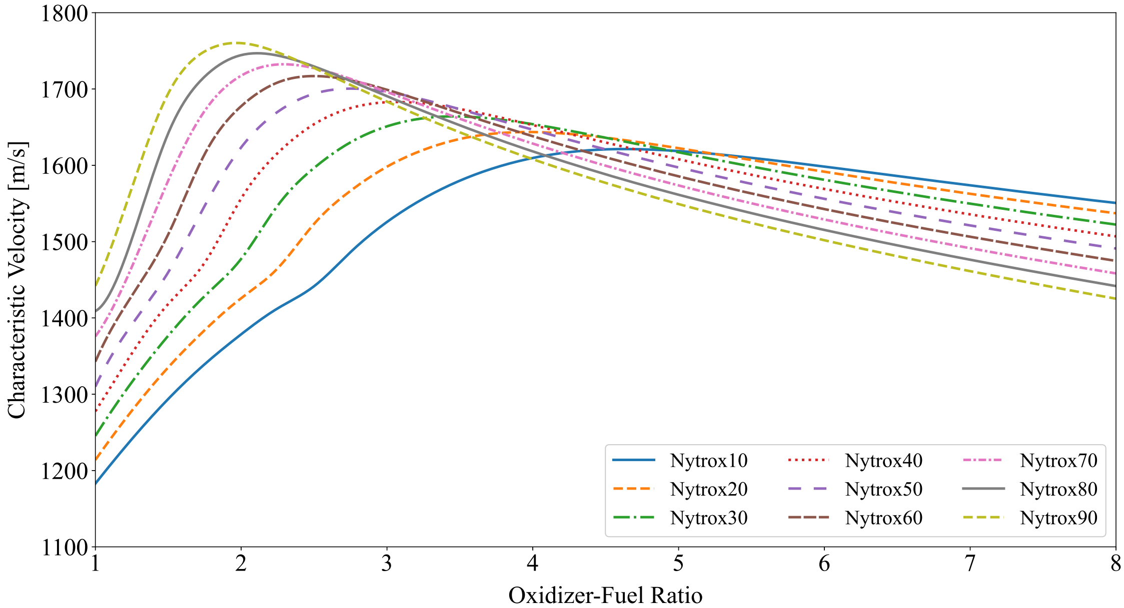

Figure 3: Characteristic velocity, as a function of O/F for HTPB with range of oxygen in Nytrox oxidizer.

ABS emerged as the third-best performer in terms of c^*, as shown in Figure 4 and Table 3. Although it is not a traditional option in propulsion applications, ABS presents a favorable balance between combustion performance, mechanical processability and machinability.

It was indicated as the best option when the fuel grain has a complex geometry. The enthalpy of formation makes it a viable candidate for specific mission profiles requiring manufacturability and structural integrity. Also, it is a good candidate to blend with other high performance solid fuels.

The PLA and PMMA displayed the lowest values of characteristic velocities across all fuels. Despite their ease of processing and environmental appeal, both materials are limited by their relatively low combustion energy.

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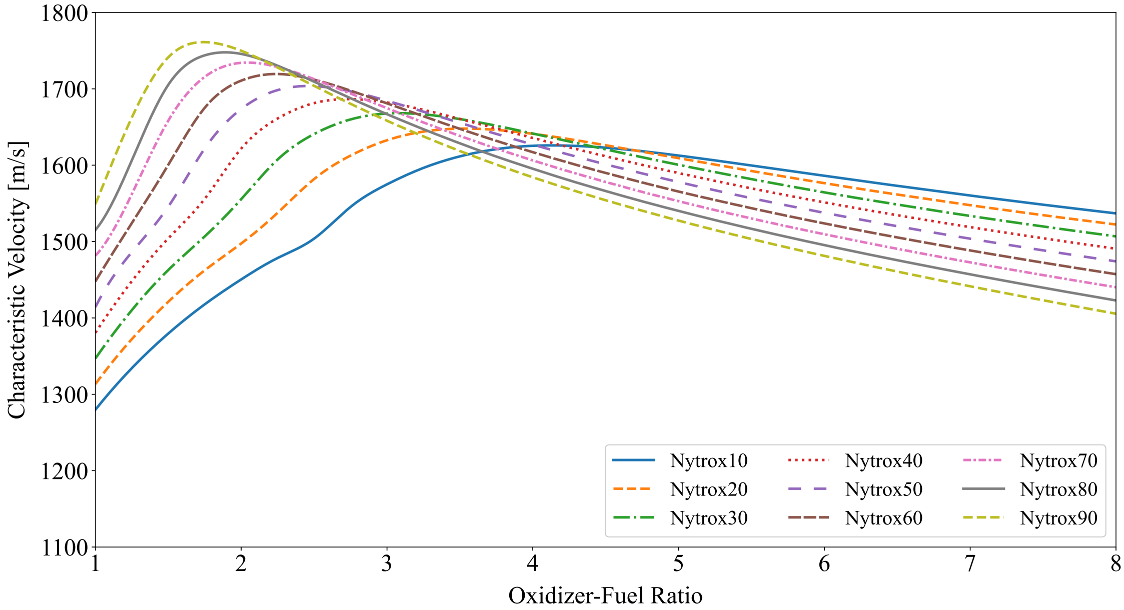

Figure 4: Characteristic velocity, as a function of O/F for ABS with range of oxygen in Nytrox oxidizer.

Noteworthy, both PLA and PMMA exhibited peak c^* at significantly lower O/F ratios, specifically below 2 when compared to other fuels. This behavior suggests a reduced oxygen demand, likely due to the inherent oxygen content in their molecular structures, which decreases the amount of external oxidizer required to reach stoichiometric or near-stoichiometric conditions.

However, despite this lower O/F requirement, the results may also reflect suboptimal thermal decomposition characteristics or limited compatibility with gas-phase oxidizer diffusion, potentially leading to inefficient combustion at higher oxidizer concentrations. Particularly, reached a maximum c^* of only 1514.83 m/s at an O/F of 1.00, the lowest value among all propellant mixtures tested, presented in Figure 6. PMMA performed marginally better, with a peak of 1670.42 m/s at O/F of 1.25, as shown in Figure 5.

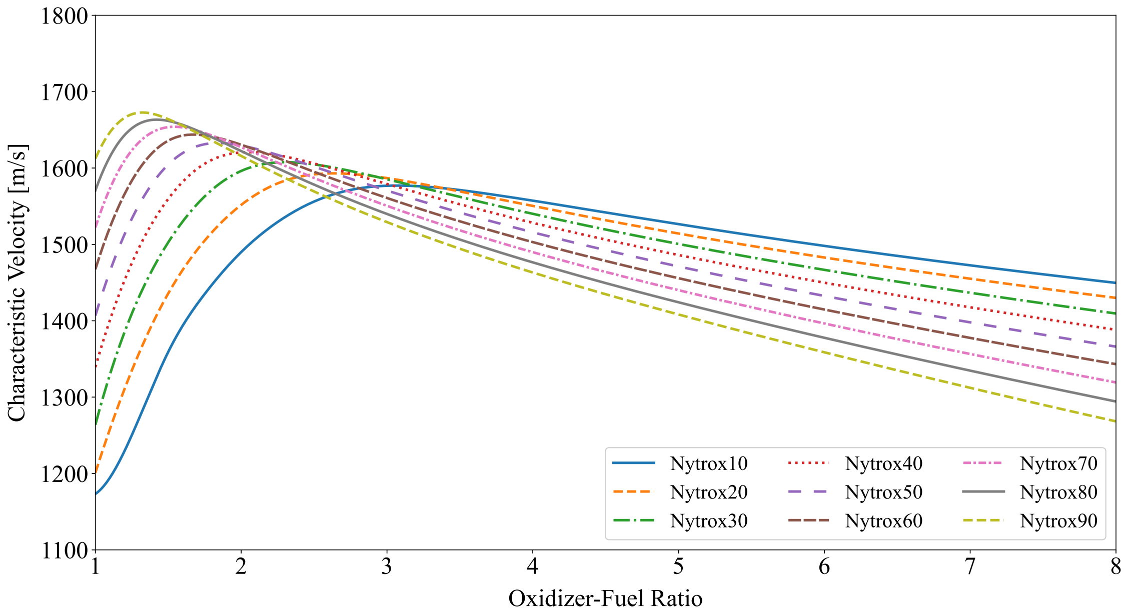

Figure 5: Characteristic velocity, as a function of O/F for PMMA with range of oxygen in Nytrox oxidizer.

Consistently, all fuel combinations produced their maximum c^* values with Nytrox90, attributed to its higher oxygen content and correspondingly lower optimal O/F ratios. This reinforces the benefit of oxidizer-rich blends in

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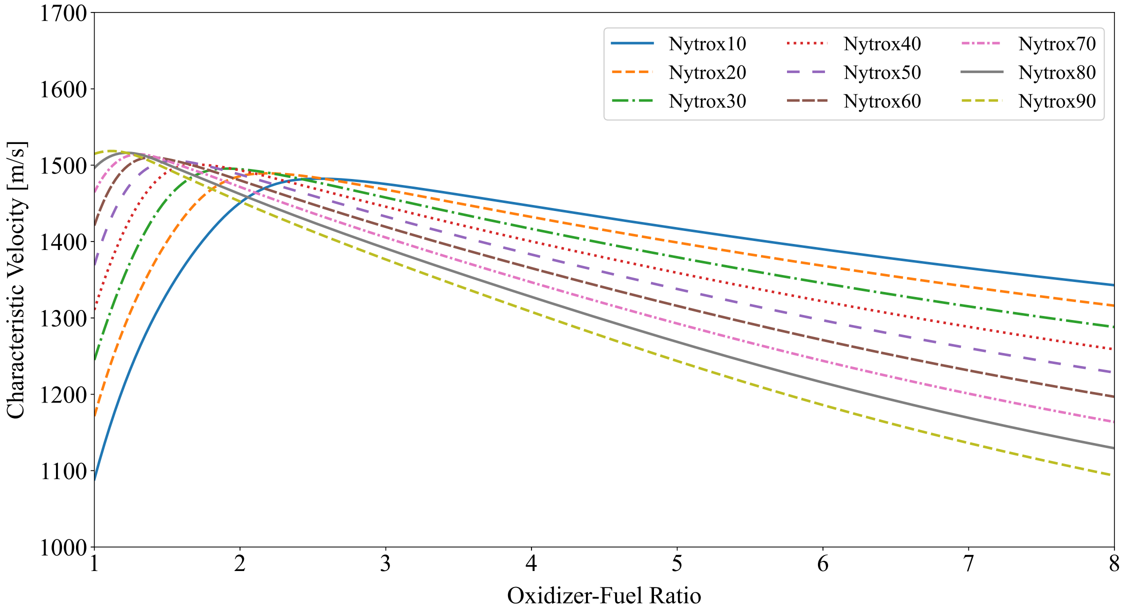

Figure 6: Characteristic velocity, as a function of O/F for PLA with range of oxygen in Nytrox oxidizer.

enhancing combustion efficiency.

Another notable trend was observed in the analysis, at higher O/F ratios blends with lower oxygen content began to outperform those with higher oxygen content. For instance, using paraffin + Nytrox propellant blend, at an O/F of 2.75, the c^* for paraffin + Nytrox90 was 1760.45 m/s, slightly lower than the 1758.90 m/s observed with Nytrox80.

This inversion continued at an O/F of 3.00, where paraffin + Nytrox90 yielded 1740.18 m/s, compared to 1743.15 m/s for the Nytrox80 blend. In lower-oxygen blends like Nytrox80 may offer localized reaction zones where the effective O/F is higher than the global average due to the complex behavior in the boundary layer. These zones can benefit from the characteristics of Nytrox80, particularly in regions with reduced oxygen availability, which enhances the combustion process.

The analysis reveals clear performance distinctions among the six thermoplastic fuels when used in combination with varying Nytrox oxidizer blends. The performance metric of interest, c^*, serves as an indirect measure of combustion efficiency and energy release in hybrid propulsion systems.

The Table 3 summarizes the maximum c^* values at optimal O/F ratios for each fuel when used with Nytrox90.

Table 3: Peak c^* values and optimal O/F ratios for each fuel with Nytrox90

Fuel	**Peak c^* [m/s]**	**O/F Ratio**
Paraffin	1782.86	2.25
HDPE	1774.84	2.25
ABS	1761.16	1.75
HTPB	1760.13	2.00
PMMA	1670.42	1.25
PLA	1514.83	1.00

4. Conclusion

Hybrid rocket propulsion continues to gain relevance as a safer and cost-effective alternative to traditional liquid and solid propulsion systems, particularly in the context of New Space initiatives. Its performance depends on the choice of O/F combinations according to the mass and size of such systems. In this context, the present work focused on evaluating the combustion characteristics and thermochemical efficiency of hybrid propellants formed by Nytrox oxidizer blends and six different solid fuels. Through simulations based on chemical equilibrium analysis, a comparative assessment was conducted to understand how oxidizer composition and fuel properties influence propulsion performance metrics such as c^*.

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Overall, it was possible to evaluate and compare the performance using chemical equilibrium of six solid fuels: HTPB, HDPE, ABS, paraffin wax, PMMA, and PLA. When paired with varying compositions of the Nytrox oxidizer blend.

Through the fuels analyzed, the paraffin wax and HDPE demonstrated their suitability for missions demanding high thrust-to-weight ratios and efficient oxidizer utilization, due to the higher c^* values. Particularly, the HDPE exhibited strong sensitivity to oxidizer composition, since it has the widest range of c^* variation across O/F ratios.

HTPB and ABS achieved high c^* values at low O/F ratios, reinforcing their viability as high-energy and structurally fuel options. However, PLA and PMMA presented limited combustion performance, despite the lower oxidizer fractions, which could be an advantage for systems constrained by oxidizer storage but are unsuitable for high-performance applications due to their low energy output.

The use of Nytrox, especially at higher oxygen fractions, consistently resulted in superior performance across all fuels, confirming previous findings on its thermochemical advantages and operational simplicity compared to pure LOX or N_2O. However, the behavior at high O/F ratios, in which lower-oxygen Nytrox blends outperformed the higher ones, suggests a potential shift in combustion dynamics and pointing toward the importance of adaptive oxidizer strategies depending on mission phases and thrust demands.

This study reinforces the value of polymer fuels as promising candidates for hybrid rocket propulsion, particularly when used with oxygen-rich Nytrox blends, enhancing the growing understanding of hybrid propellant behavior. Future work should further investigate the characterization of the regression rate of Nytrox-based propellants and also the addition of additives in propellant mixture.

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