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# Comparative Analysis of Liquid Fuels and Oxidizers for Internal Combustion Engines Using a Composite Scoring Approach

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**Abstract:** *In this study, oxidizers like oxygen, atmospheric air, nitrous oxide, and fluorine are compared with liquid fuels like hydrogen, ethanol, jet fuel, and methane. A composite scoring framework that weighs efficiency (65%), temperature (25%), and cost (10%) was created using empirical validation, second-degree polynomial regression, and Python-based numerical simulations. Although its high cost restricts its economic viability, the analysis revealed that hydrogen with fluorine had the highest composite score, exhibiting exceptional thermal performance and combustion efficiency. Methane with nitrous oxide and fluorine also scored highly, providing stability and high efficiency at a more balanced price. Even though jet fuel was marginally less effective, it was more affordable when combined with fluorine or nitrous oxide. Air and oxygen, on the other hand, produced significantly lower scores, indicating limited combustion intensity despite their affordability and accessibility. Sensitivity analysis showed that top and bottom rankings stayed constant, but mid-tier rankings might change depending on parameter changes. With implications for propulsion, aerospace, and power generation systems, these findings offer a useful framework for choosing fuel-oxidizer pairs under performance and cost constraints.*

***Keywords:*** *Combustion Efficiency, Liquid Fuels, Oxidizers, Hydrogen, Methane, Ethanol, Composite Scoring Model*

## 1. Introduction

Any substance that may be produced to interact with other substances to release energy such as thermal radiation or that can be utilized for work is referred to as a fuel. A fuel is a substance that, when burned with oxygen, produces a significant amount of heat. It is composed of carbon and hydrogen and is known for its ability to release chemical energy in the form of heat during combustion (Singh & Pati, 2018). Fuels are essential to the world's energy system, with fossil fuels and biofuels being two of the main sources. These include petroleum, coal, and natural gas (Shaik, 2022). Additionally, a wide range of conventional liquid fuels, including petrol, kerosene, biodiesel, and natural gas, are utilized in numerous applications (Inam et al., 2019; Inam, Khan, et al., 2025; Khan et al., 2025; Ur Rahim et al., 2021)(Speight, 2011) and have considerable effect on the human health (Inam, Iqbal, et al., 2024; Rahujo et al., 2025). Liquid fuels are composed of flammable or energy-producing molecules that can be used to produce mechanical energy, frequently kinetic energy, and they must adhere to the geometry of their container. Although some other substances, such as ethanol, biodiesel, and hydrogen fuel, can also be categorized as liquid fuels, the majority of liquid fuels used in everyday life originate from fossil fuels. The fuels, which are derived from petroleum or natural gas, are easily ignited and have a high energy density while staying liquid at room temperature. Fuel injection systems are used to feed them into engines while they are stored in tanks. Heat and pressure are created when they burn inside the engine, and this is then transformed into mechanical energy for propulsion. Because of their accessibility, high energy density, and ease of use, liquid fuels are used extensively. Liquid fuels are essential to internal combustion engines because they are powerful energy sources for a range of applications, but they also come with certain maintenance, emissions, and performance considerations (Inam, Zaidi, et al., 2025)(Moore H. , 1920). The International Energy Agency defines liquid fuels as a combination of conventional and unconventional liquid products. The projected increase in liquid fuel consumption is anticipated to reach 91 million barrels of oil equivalent per day by 2015 and further climb to 107 million by 2030, compared to the 85 million recorded in 2006. Approximately half of this increase is expected to be attributed to the transportation sector.

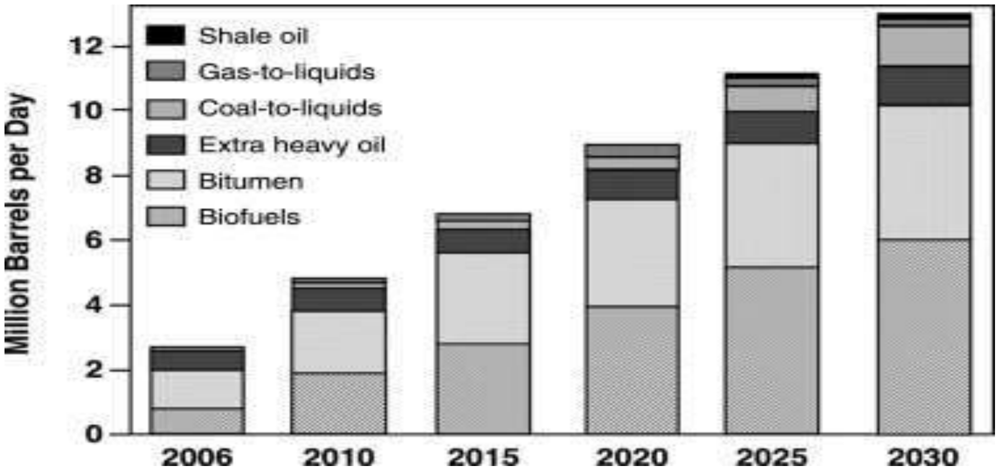

**Figure 1.** Usage of Liquid Fuel Per Day (Annual Energy Review, 2009)

As there are few alternatives that can effectively compete with liquid fuels, liquids continue to be the most significant fuel for transportation. Worldwide, the usage of liquids is expected to rise by 79 percent between 2005 and 2030 (Xiao & Beach, 2015).

Oxidizers are substances in the form of solids, liquids, or gases that readily react with organic material or reducing agents without requiring any external energy input. Oxidizers have a significant risk of causing fires. Commonly utilized oxidizers include oxygen ($O_2$), ozone ($O_3$), chlorine ($Cl_2$), hydrogen peroxide ($H_2O_2$), potassium permanganate ($KMnO_4$), and sodium chlorate ($NaClO_3$). These compounds are often used in many manufacturing and research applications. An oxidizer is a chemical substance that oxidizes other substances that is a chemical that begins or enhances combustion in another material that is neither a blasting agent nor explosive (Qi-Long Yan, 2019). Liquid oxygen (LOX) is extensively utilized in rocket engines as an oxidizer for liquid fuels. Nitrous oxide ($N_2O$) is a colorless, non-flammable gas that is extensively used in amateur rocketry and some hybrid rocket engines as an oxidizer for liquid fuels. Fluorine ($F_2$) is a highly reactive and caustic gas that may be used to oxidize liquid fuels like hydrogen or methane. Atmospheric oxygen, is the primary oxidizer utilized in internal combustion engines (Som & Datta, 2008). Overall four elements are necessary for combustion to occur: a combustible material; an ignition source; oxygen; and an ongoing reaction that produces free radicals. If any one of these elements is absent, the combustion process will not occur (Oxidizers Chemical Hazardss & Risk Minimization, 2013). According to another study basically three elements are needed for combustion to take place: a fuel that burns, an oxygen source, and a heat source. The requirements for combustion, popularly known as the "fire triangle," there must be a material that can burn, such as a gas, liquid, or solid called fuel. Enough oxygen is required to support combustion. An ignition source, such as a spark, flame, or heat, is required to start the combustion process. Combustion cannot occur in the absence of any of these three ingredients (Som & Datta, 2008). Liquid-fuel combustion is always diffusion-controlled. The combustion rate is discovered to be inversely proportional to the density of the liquid (Zhou, 2018). In general, the combustion of liquid fuel proceeds in stages: atomization, vaporization, vapor-air mixture, ignition, and combustion maintenance (Pisupadti, 2003). In the study of (Grab-Rogalinski & Szwaja, 2016), the results offered insightful information about the evaluated fuels' combustion characteristics. *The study of* (Tao, Huang, Tang, & Bell, 2009) *provides valuable insights into the current state of research on the fuel efficiency of internal combustion engines*. They offer a practical and effective energy source that permits the combustion of fuel to release energy in a controlled manner (Moore H. , 2018). The general categories can be used to classify internal combustion engines as spark-ignited motors, engines using compression ignition and HCCI engines, or homogeneous charge compression ignition.

Diesel engines employ a high compression ratio to elevate the air temperature significantly, rather than relying on a spark plug to ignite the diesel fuel. Diesel engines sometimes referred to as compression-ignition engines possess a high thermal efficiency due to their notable compression ratio and absence of intake throttle loss (Xin & Pinzon, 2014). Spark ignition (SI) gasoline engines and compression ignition (CI) diesel engines are examples of internal combustion (IC) engines. Fossil fuels have historically been the main fuel for internal combustion (IC) engines. Because internal combustion engines are so reliable and easy to drive, over 250 million highway transportation vehicles in the US are powered by them. They can run on petrol or diesel as well as alternative or renewable fuels like ethanol, natural gas, propane, or biodiesel. Combustion is the basic chemical process that releases energy from a mixture of fuel and air (Bae & Kim, 2017). According to the study of (Tao, Huang, Tang, & Bell, 2009) the choice of combustion mode, such as spark ignition or compression ignition with engine parameters, such as compression ratio, valve timing, and fuel injection timing, can be optimized along with the properties of the fuel used in an internal combustion engine and design of the vehicle, including its weight, aerodynamics, and drivetrain with the operating conditions of the engine, such as its speed and load, can also affect its fuel efficiency.

Spark-ignition engines, usually referred to as gasoline engines, commonly employ a spark plug to initiate combustion of a blend of fuel and air within the engine's combustion chamber. These engines are frequently employed in small vehicles and possess a rather low compression ratio. Conversely, compression-ignition engines, or diesel engines, utilize high pressure and temperature to compress air in the combustion chamber, resulting in the spontaneous igniting of fuel. These engines are employed in heavy-duty vehicles, such as trucks and buses, and possess a greater compression ratio compared to spark-ignition engines.

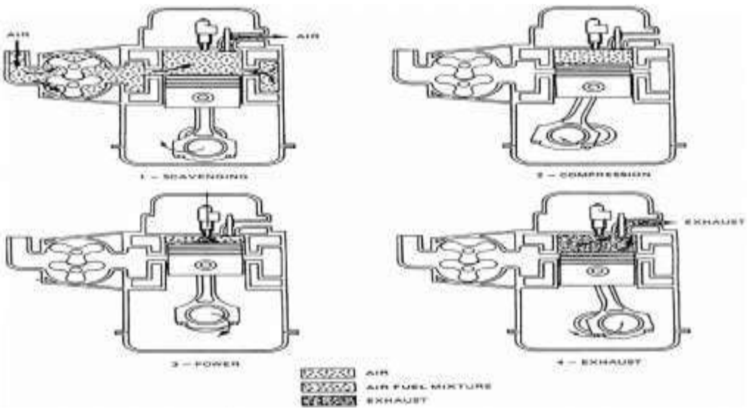

**Figure 2.** Working Process of Spark Ignition Engine (Breeze, 2018)

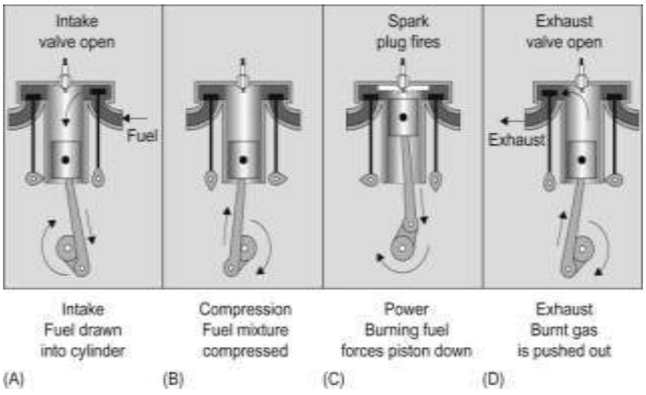

**Figure 3.** Process of Exhaust in Compression Ignition Engine (Ciatti, 2015)

For low-flammability fuels like hydrogen, LPG, LNG, methanol, and gasoline mixtures, the spark-ignition engine is adaptable (Meyers, 2001).

Methane, with the molecular formula $CH_4$, is a chemical molecule made up of one carbon atom joined to four hydrogen atoms. Natural gas's primary ingredient, methane, is widely distributed both below ground and beneath the ocean's surface. Due to its relative abundance on earth, methane is a fuel that has strong economic appeal. Methane is normally a gas, but when it is exposed to low temperatures or high pressures, it changes into a colorless, odorless liquid (Hensher & Button;, 2003). Liquid methane is frequently transported and stored for industrial and commercial purposes. Methane has a very high energy density in liquid form and may be transformed into energy with very little emission (Liquid methane as energy product - ERT Refrigeration Technology, 2020) and potential to reduce environmental pollution when compared to other hydrocarbon fuels (Grishin, Zakharov, & Aref'ev, 2022). Due to its high energy content, liquid methane, an odorless, colorless material, is frequently employed as a fuel source (Hensher & Button;, 2003). It was discovered by (Blarigan, et al., 2014), in comparison to methane-in-air operation, the fuel-conversion efficiency under oxy-combustion circumstances was much lower (Tahir, Ali, Baloch, & Jamil, 2019). The methane-air combustion have shown that it lead to an improvement in the temperature distribution inside the combustion cylinder and an increase in the fuel combustion rate (Salih & Ayaal, 2022). The combustion process may be optimized to obtain greater energy efficiency and lower emissions by employing oxygen as an oxidizer (Shi, Hu, Ishizuka, Li, & Wang, 2016). Higher flame temperatures and increased combustion efficiency can result from the usage of oxygen in combustion (Leonov & Gurov, 2020). Raising the amount of oxygen present in the fuel-air combination boosts the fuel's temperature distribution and rate of combustion (Fauzy, Chen, & Lin, Numerical Analysis of Hydrogen Peroxide Addition and Oxygen-Enriched Methane Combustion, 2023). $N_2O$ may also accelerate the reaction process overall by converting less reactive molecules into more reactive equivalents, which is particularly effective in fuel-rich environments (Hartwell & Ahn, 2022). The thermodynamic properties of reactions comprising fluorinated hydrocarbons show major heat effects and high adiabatic temperatures (Shi, Hu, Ishizuka, Li, & Wang, 2016).

Ethanol is a type of alcohol that can be made from crops and agricultural residues, and it is an excellent fuel and is less volatile than gasoline, making it less likely to ignite at low temperatures and is more corrosive than gasoline, so vehicles designed for ethanol use special lubricants (The Freedom CAR & Vehicle Technologies Program, 2003). In one study, evaporative emissions that contribute to the creation of smog are lower for pure ethanol than for gasoline, ethanol has relatively low toxicity and easily biodegrades in water and soils, which reduces the penetration of leak clouds and the effects of spills (Wyman, 2004). (Agarwal, Valera, Pexa, & Čedík, 2021) revealed that the incorporation of ethanol can enhance the engine's combustion process and efficiently regulate the emissions of NOx and smoke. (Prasetiyo, 2022) indicated that ethanol enhances the combustion rate, but reduces the flame height. According to (Ge, Kim, Yoo, & Song, 2023), it has been found that the addition of air to ethanol flames can lead to an increase in flame diameter and encourage collective effects of two-phase combustion (Noreña & Gutheil, 2020). It has been discovered that adding oxygen, improves combustion properties and processes. It makes the process more capable, speeds up combustion, raises the process's peak pressure, and accelerates the burning of the fuel (Xu, et al., 2021), (Sahu, Sahu, & Chandra, 2023). Higher reaction selectivity and the capacity to inhibit further oxidation processes are two benefits nitrous oxide has over other oxidants like $O_2$ (Carlos & Karel, 2017). Adding $NO_2$, a byproduct of $N_2O$ breakdown, reduces the ignition delay time and increases the reactivity of ethanol (Jin, et al., Experimental and Kinetic Study of the Effect of Nitrogen Dioxide on Ethanol Autoignition, 2023). According to the results of (Jianli, Xianbo, & Qi, Method for reinforcing molecular oxygen oxidation alcohol reaction method by means of fluorine surfactant, 2017), fluorine may help facilitate oxidation during ethanol fuel burning.

Commercial airlines and military facilities, mostly in the US and other NATO countries, use jet fuel, a kind of aviation fuel. High energy content and a low freezing point are two characteristics specifically engineered into jet fuels to make them appropriate for use in jet engines. Usually, they are colorless liquids with an odor like kerosene. The energy source for jet engines, which provide the thrust required for aircraft propulsion, is jet fuel (Wexler, 2014). It normally come from petroleum and are used to fuel jet engines, which provide the thrust required for flight (Apte, 2014). To provide a push for flight, jet fuel is burned in internal combustion aircraft engines. It was selected due to its best qualities in terms of operability, energy density, and performance (Grimme, 2023). Small amounts of additives, such as corrosion inhibitors and antioxidants, may also be added to jet fuel to improve its performance and safeguard the fuel system of the aircraft (Mickeviciute, 2023). Enhancing the oxidation process and lowering soot emissions can be achieved by injecting air into the exhaust of enclosed spray combustion of jet fuel (Kelesidis, Trivanovic, & Pratsinis, 2023). The combustion of jet fuel uses oxygen as an oxidant (Wang, et al., 2023). With an increase in oxygen content, the reaction system's activity also increases (Chengfei & Hao, 2022). In chemical propulsion applications, $N_2O$ is also used as an oxidizer because of its benefits in self-pressurization, high density, non-cryogenic operating temperatures, and improved safety (Venkatesh, Meyer, Bane, & Grubelich, 2019). It has been discovered that adding $N_2O$ to jet fuel can accelerate the production of poly aromatic hydrocarbons (PAHs), raise its volume fraction and number density (Razus, Nitrous Oxide: Oxidizer and Promoter of Hydrogen and Hydrocarbon Combustion, 2022). It has been found that using fluorine as an oxidizer in jet fuel combustion may improve combustion efficiency and encourage the exothermic reaction of fuels (Reuter, 2018). Fluorine atoms in the oxidizer can increase combustion (Wu, et al., Tuning the Reactivity of Perfluoropolyether-Functionalized Aluminum Nanoparticles by the Reaction Interface Fuel-Oxidizer Ratio, 2022).

According to the study of (Yip, et al., 2019), because of its quick flame speeds, wide flammability limitations, and carbon-free composition, hydrogen is emphasized as a viable choice for spark-ignited internal combustion engines. One clean energy source that is emphasized is hydrogen, which is also environmentally good and has the ability to lower prices, boost output, and be portable. It is shown how crucial hydrogen is to a number of industries as a sustainable, storable, and portable energy source (Akal, Öztuna, & Büyükakın, 2020). Possible renewable energy sources that can be utilized for the production of hydrogen include solar and wind energy. One significant energy for a sustainable future is hydrogen. The possible use of hydrogen as fuel in current internal combustion engines is covered in (Falfari, Cazzoli, Mariani, & Bianchi;, 2023). The potential for lower nitrogen oxide emissions, high engine efficiency, and zero carbon emissions are some advantages of using hydrogen as fuel (Falfari, Cazzoli, Mariani, & Bianchi;, 2023). Its low ignition energy and wide range of flammability make it a popular fuel for internal combustion engines. The hydrogen fuel mixture's air-fuel ratio and the kind of ignition system being employed have an impact on the combustion process (Module 3: Hydrogen Use in Internal Combustion Engines). It has been discovered that using oxygen in place of air increases process capacity, enhances reaction speeds, and lowers emissions in operations like oxidation and combustion (Mastrodonato & Borm, 2015), (Hendershot, Lebrecht, & Easterbrook, 2010). Air is added to the combustion process to assist in supplying the oxygen required for the reaction, which enables hydrogen to react and produce energy (Mayrhofer, et al., 2022). According to experimental findings, hydrogen and oxygen may successfully minimize NOx emissions and eliminate $CO_2$ emissions (Paunescu & Surugiu, 2022). Nitrous oxide provides oxygen and releases energy, acting as an oxidant in the process. It can start the hydrogen's ignition and advance the combustion process (Razus, Nitrous Oxide: Oxidizer and Promoter of Hydrogen and Hydrocarbon Combustion, 2022). Nitrous oxide contributes more oxygen to the hydrogen combustion process, promoting a more thorough and efficient burn of the hydrogen (Hosseini, 2023). The findings show complicated chain reactions and the existence of excited species are involved in the utilization of fluorine as an oxidizer in the burning of hydrogen fuel (Matsugi, Shiina, Tsuchiya, & Miyoshi, 2013). Hydrogen along with fluorine could be used, which will greatly enhance hydrogen energy utilization (Zhang & Zhang, 2023).

Although prior research has examined individual fuel-oxidizer pairs, few have employed a composite scoring model to systematically compare multiple combinations. By providing a multi-dimensional optimization framework with a practical foundation that balances thrust performance, thermal safety, and cost-efficiency, this study helps address challenges in propulsion systems. By doing this, it tackles the triple challenge of economic viability, durability, and efficiency while pointing to workable, sustainable fuel strategies for next-generation energy and aerospace systems. The priorities of propulsion systems in the real world maximizing energy conversion (efficiency), maintaining thermal safety (temperature), and remaining economically viable (cost) are reflected in this weighting scheme. It methodically addresses the engineering trade-offs that determine whether a fuel-oxidizer combination is both theoretically and practically optimal, in contrast to earlier single metric or evenly distributed approaches. By combining cost, efficiency, and thermal safety into a single performance score, the composite model avoids the oversimplifications of partial multi-criteria approaches and the vision of single-criteria approaches. This ensures that the method provides a comprehensive, practical perspective on combustion system optimization. By incorporating non-linear efficiency–temperature dynamics into the performance index, the polynomial regression for temperature prediction becomes part of the composite score. This method uncovers stability zones, tipping points, and risk thresholds that affect practicality in the real world, in place of linear or simplistic correlations. Consequently, the composite score transforms from a descriptive ranking to a forward-looking tool, allowing for safer and more dependable combustion system optimization.

The objective of the study is to analyze the comparison of liquid fuels and oxidizers in the combustion system. Currently, it is necessary to assign considerable resources towards identifying affordable alternative fuels for industrial and public applications. The study also want to analyze that which fuel-oxidizer combination maximizes combustion efficiency while minimizing cost and  temperature. The demand for these fuels will rise if we dedicate ourselves to exploring cost-effective energy sources suitable for urban and commercial use. Our goal is to optimize energy utilization while minimizing expenses on energy-dependent establishments. By examining and implementing these alternative fuels, we aim to achieve our objectives and improve operational efficiency. Efficient energy use in facilities, particularly those involved in combustion processes, is critical to attaining cost-effective energy management. At this point in time, we must quickly find affordable, alternative fuels that can be used for automobiles and in both industrial and localized contexts. Finding such substitutes is critical for both immediate implementation and the development of a robust and ecologically responsible energy model that satisfies with current environmental, technological, and economic requirements.

## 2. Literature Review

The identification of the best possible combination of fuel and oxidizers are of utmost importance as they can producte harmful particles in the atmosphere that can cause sever health constraints along with certain economical shortcomings (Inam, Hashim, et al., 2025; Inam, Khan, et al., 2024). (Bromberg & Cohn, 2006) investigated the advantages of employing methanol and ethanol in direct injection engines. The findings suggested that methanol potentially resulting in a 30-35% increase in efficiency. The integration of these benefits has the potential to achieve a total efficiency improvement of 40-45% for direct injection methanol engines. *A* thorough analysis of the combustion of methane, oxygen, and air revealed several findings, especially on the behavior of the flames in different situations. After the oxygen concentration reached fifty percent, it have effect on emissions control, system efficiency, and design. That result highlighted how sensitive methane, oxygen, and air combustion is to changes in oxygen content (Merlo, et al., 2014). The study examined how nitrogen dioxide ($NO_2$) and nitric oxide (NO) encouraged methane oxidation. The results demonstrated that NO started oxidation at lower temperatures than $NO_2$, which become more effective at higher temperatures (Razus, Nitrous Oxide: Oxidizer and Promoter of Hydrogen and Hydrocarbon Combustion, 2022). The study emphasized on the combustion properties of inverse tri-coflow diffusion flames of methane and nitrous oxide, it is crucial to investigate the effects in the context of methane and nitrous oxide mixtures since studies have demonstrated that various diluents can result in changes in flame stability and pollutant production (Li, Chen, & Ilbas, 2020). Another study demonstrated that the introduction of ethanol and water alters the properties of combustion, and the consequences for NOx emissions with ethanol addition are complex (Wang,, Chen, Ni, Liu, & Zhou, 2015). *Another study found that ethanol can improve engine performance and reduce emissions compared to conventional diesel fuel, but also have some drawbacks such as lower thermal efficiency and higher NOx emissions* (Aziz, et al., 2017). Previous study outlined a procedure for utilizing a fluorine to accelerate alcohol oxidation. With water acting as the solvent and air acting as the oxidant, the reaction may be conducted at surrounding. The technique produced low reaction temperatures, low environmental impact, quick reaction times, and great efficiency. It used fluorine to provide an energy-efficient and clean method of oxidizing alcohol (Jianli, Xianbo, & Qi, Method for reinforcing molecular oxygen oxidation alcohol reaction method by means of fluorine surfactant, 2017). According to the published study methanol and ethanol can decrease harmful engine exhaust emissions, but at the cost of reduced engine performance characteristics (Yusri, et al., 2017). In another study nitrous oxide ($NO_2$) improves ethanol combustion. It enhances the system's reactivity. $NO_2$ resulting in more efficient combustion and enhanced ignition characteristics (Jin, et al., Experimental and Kinetic Study of the Effect of Nitrogen Dioxide on Ethanol Autoignition, 2023). Because of its high energy density, nitrous oxide ($N_2O$) works well as an oxidant when mixed with liquid ethanol. According to the study, steady combustion environment is produced when ethanol and nitrous oxide are combined. Nitrous oxide efficiently promotes ethanol's quick burning, improving engine performance. The high efficiency of more than 85% demonstrated how well nitrous oxide functions as an oxidant, enabling the best possible energy release during combustion (Sato, et al., 2024). One more study presented that fluorine can improve combustion. The presence of fluorine may cause the development of chemicals that enhance the ignition and combustion processes (Wu, et al., µAl-based reactive materials with improved energy efficiency by using the fluorine-containing oxidizer perfluoropolyether as an interfacial layer, 2023). In additional study the efficiency increased showed that the presence of fluorine lowering the time needed for complete combustion (Jianli, Xianbo, & Qi, Method for reinforcing molecular oxygen oxidation alcohol reaction method by means of fluorine surfactant, 2017). The study has found that increasing the oxygen content enhanced combustion efficiency and flame stability (Zhen, Li, Wang, Liu, & Tian, 2020). *In particular, spare study investigated using hydrogen as a fuel for heating which has the potential to cut greenhouse gas emissions* (Iplik, Adendorff, & Muren, 2022). The study investigated the use of methane and ethanol in internal combustion engines that used oxygen and air as oxidizers. The temperature distribution and fuel combustion rate significantly improved when the oxygen ratio was raised which led to a more regulated and effective combustion process, which is important for improving the thermal efficiency, emission characteristics, and overall system performance and raised fuel combustion rates at the same time, indicating a quicker and fuller use of fuel, which lead to improved system performance (Fauzy, Chen, & Lin, Numerical Analysis of Hydrogen Peroxide Addition and Oxygen-Enriched Methane Combustion, 2023). In a different study oxidizers are used during the combustion of jet fuel, and they are essential to the process. Nitric oxide (NO) and nitrous oxide ($N_2O$) are two popular examples of the particular oxidizers utilized in jet fuel combustion (Aldarrai, Alsuwaidi, Khan, Xu, & Tolouei, 2023). In a further study nitrogen oxide (NOx) emissions during combustion can be considerably reduced by using oxygen-enriched air (Maspanov, Bogov, & Sukhanov, 2024). Another study demonstrated that atmospheric air as an oxidizer greatly effect jet fuel combustion properties, particularly under increased pressures, impacting ignition delay durations and reactivity for gas turbine combustors (Oehlschlaeger, Experimental Study of the Oxidation, Ignition, and Soot Formation Characteristics of Jet Fuel, 2010). In one more study, the molecular makeup of jet fuels has an important influence in their reactivity, with hydrocarbons exhibiting varied igniting characteristics when combined with air

(Oehlschlaeger, The Oxidation and Ignition of Jet Fuels, 2017). By providing more oxygen, raising combustion temperatures, increasing thrust, and ensuring safety and stability in propulsion systems, nitrous oxide ($N_2O$) is a great oxidizer when it comes to jet fuel combustion, according to a published study (Heydari & Massoom, 2017). Additional research revealed that adding fluorine to jet fuels could increase their rate of oxidation, lower emissions, and change the fuel's thermal characteristics (Guzman & Brezinsky, 2021). Recent advancements in the field have revealed that Methane may be completely and efficiently oxidized in the presence of oxygen, generating significant heat energy (Aktary, et al., 2024). Combustion processes, including the burning of hydrogen fuel, require oxygen, which is found in atmospheric air. Because adding air to the combustion process allows for higher temperatures and more efficient energy release, oxygen is an effective oxidizer (Zhai & Hu, 2021). The oxygen needed to burn hydrogen fuel is provided by atmospheric air (Jallais, et al., 2017). The shape of the flame and the length of the combustion zone change as a result of the decrease in hydrogen and air mixing at high temperatures (Zabaykin, 2017). The combustion characteristics of hydrogen mixtures are significantly influenced by the oxygen content of the surrounding air. The maximum explosion pressure and the rate of pressure rise are affected by changes in oxygen concentrations (Azatyan, Shebeko, Shebeko, Navzenya, & Tomilin, 2007). By providing more oxygen for the reaction, nitrous oxide enhances the combustion of hydrogen fuel (Jallais, et al., 2017). Nitrous oxide can increase hydrogen fuel's efficiency. It promotes combustion, which results in a more efficient release of energy during combustion and is crucial for improving engine performance and lowering emissions. It can be added to hydrogen-fueled engines to improve their overall performance and reduce emissions, and it may lead to a decrease in toxic emissions (Nguyen & Turner, 2023). As a strong oxidant that increases the production of active radicals and alters the dynamics of combustion, fluorine, a strongly electronegative element, enhanced hydrogen combustion (Zhang, Gao, Chen, & Li, 2024). Fluorine is an extremely reactive oxidant that facilitates the burning of hydrogen, which efficiently releases energy. It contributes to the hydrogen combustion process's stability and dependability (Liping, et al., 2017).

## 3. Methodology

The secondary data provide the foundation for a detailed analysis of the relationship between two variables including combustion efficiency and maximum temperature. The objective of the study is to clarify the relationship between maximum temperature and combustion efficiency. Using data, secondary analysis is carried out for a variety of purposes, such as evaluating alternative statistical techniques. The main concerns in secondary analysis are data ownership, confidentiality, availability, and access (Cordray, 2001). Data is analyzed using Python (version 3.10, Intel(R) Core(TM) i7-4600U CPU @ 2.10GHz 2.70GHz, RAM 4GB) software. Given that Python libraries provide a wide range of options and functionalities for effectively visualizing non-linear data and exposing correlations and patterns that may not be readily apparent from the raw data (Yada,, 2022). Many Python libraries, including Matplotlib, Seaborn, Bokeh, and Plotly, provide methods and resources for producing non-linear data visualizations. Researchers can successfully interpret and explain intricate patterns in the data by using these libraries (Cao, YunhanZeng,, Yang, & Cao, 2021). Because it provides a versatile platform for visualizing and analyzing non-linear data, Excel is a helpful tool for academics across many fields (Ze-ben, 2010). Excel can also be used to generate mathematical models and display data correlations. Regression analysis is a technique used to identify the relationships between a dependent variable and one or more independent variables. It is commonly employed to ascertain the strength of the existing relationship between the variables and to forecast the future relationship between the variables (Yang, Lu, Zhang, & Wang, 2014), (Seber, 2015). Excel was employed as a supplementary tool for basic computations, preliminary data organization, and preliminary graphical representations, while Python was mainly used for advanced data visualization, advanced numerical simulations, and non-linear regression analysis.

The graph in the results section not only expresses the non-linear relationship identified during the study, but it also provides an actual and clear visual aid for a thorough understanding of the relationship between the maximum temperature and combustion efficiency of four fuels with four oxidizers. The Excel application is also used to determine the relationship between the maximum temperature of various fuels and oxidizers and combustion efficiency. To find any trends or correlations, we plot the graph of the Combustion Efficiency (%) against the Maximum Temperature (°C) for every combination. Utilizing data that has previously been collected for a different purpose is known as secondary data analysis. Secondary data analysis is a systematic process that includes evaluative processes. It is an approach that has been used in various contexts, including social well-being, higher education, library and information science, and clinical research (lorio, Palmieri, & Roberti, 2022), (Johnston, 2017), (Carter, 2013), (Rosenberg, Greenfield, & Dimick, 2006). In order to establish a relationship between the maximum temperature of fuels and their combustion efficiency, non-linear regression analysis was used in the study (Bilgili, 2010). It provide reliable parameter estimates and statistical conclusions (Knafl & Ding, 2016). Nonlinear regression offers a greater variety of potential correlations than linear regression. Because of this, it is more practical for simulating a wide range of real-world occurrences (Chen & Chen, 2021). Even in situations when a linear approximation should be sufficient, nonlinear regression models can successfully include theoretical concerns and non-linear behavior (Huang & He, 2023). Non-linear regression model provide a means of capturing complicated correlations between variables that linear models are unable to effectively express (Ahrens & Traub, 2023). . Formulas such as $N \geq 50+8m$, where m is the number of predictors, aid in estimating minimum sizes for regression analyses with multiple predictors (McNeish & Wolf , 2020).

**Table 1.** MSE of the Experimented Models

| **Model** | **Methane** | **Ethanol** | **Jet fuel** | **Hydrogen** |
|---|---|---|---|---|
| Quadratic | 0.002 | $1.54\times10^{-6}$ | $3.60\times10^{-4}$ | 127 |
| Exponential | $1.13\times10^{52}$ | $1.20\times10^{55}$ | $4.86\times10^{55}$ | $4.03\times10^{55}$ |
| Logarithmic | 34494 | 21984 | 48517 | 22575 |
| Power law | 17690 | 31475 | 42043 | 21221 |

A thorough analysis of the various mathematical models used to forecast temperature and combustion efficiency for hydrogen, ethanol, jet fuel, and methane. The predictive accuracy of several models, such as power law, logarithmic, exponential, and quadratic, was assessed against actual values. The quadratic model continuously performed better due to its lower MSE values and smaller deviations from the data. With the quadratic model being the most dependable option among the fuels studied, the analysis emphasizes the significance of choosing the right models for precise predictions in combustion-related studies. This study uses multi-criteria decision analysis to optimize fuel-oxidizer combinations.

The ratio of useful energy output to the total chemical energy of the fuel-oxidizer mixture is the combustion efficiency while maximum temperature is the peak adiabatic flame temperature to account for non-linear behavior. Efficiency, temperature, and cost are used to evaluate each fuel oxidizer pair. Normalized efficiency is the ratio of a fuel-oxidizer combination's efficiency to the maximum efficiency in the dataset, scaling it between 0 and 1 (Carlotti & Maggi, 2022). Normalized temperature which scales combustion temperature between 0 and 1 to allow meaningful comparison and composite score. It reflects the optimal balance between high efficiency and lower temperature (Nguyen, et al., 2024). The robustness of the composite scoring model is strengthened by these definitions, which guarantee that both metrics are handled as comparable variables.

## 4. Results

We studied the comparative analysis of various liquid fuels along with oxidizers in a combustion system. The fuels on which the study was done were methane, ethanol, jet fuel and hydrogen while the oxidizers are oxygen, air, nitrous oxide and fluorine. The research found the relation of each fuel with every oxidizer to find the maximum temperature required for combustion efficiency.

The relation of methane gas with every oxidizer is found to be non-linear according to the data. The data was modeled using a non-linear regression model. The mathematical model derived for the relation of methane gas with oxidizers is found to be as

$$\mathbf{y = 0.0824x^2 + 3.8252x + 859.95}$$

Where ‘Y’ represents the predicted temperature in Celsius and ‘x’ represent the combustion efficiency in percentage. The graph of the data along with actual values and error is shown in Figure 4.

**Table 2.** Combustion Efficiency and Predicted Values of Maximum Temperature of Methane

| Combustion Efficiency (%) | Predicted Value (°C) |
|---|---|
| 10 | 906.44 |
| 20 | 969.41 |
| 30 | 1048.86 |
| 40 | 1144.79 |
| 50 | 1257.21 |
| 60 | 1386.1 |
| 70 | 1531.47 |
| 80 | 1693.33 |
| 90 | 1871.66 |
| 100 | 2066.47 |

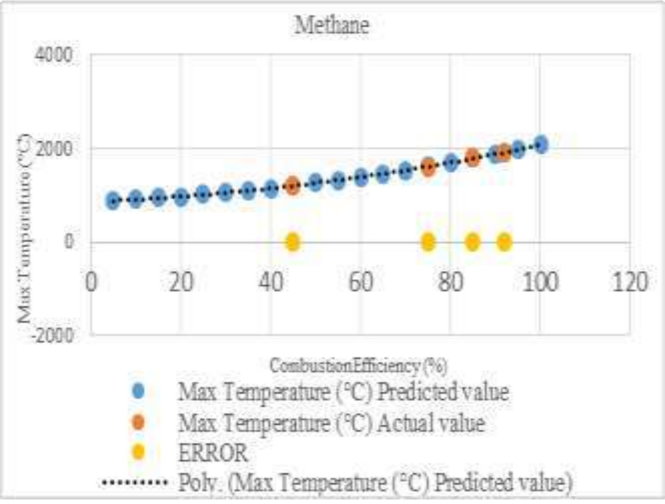

**Figure 4.** Graph of Combustion Efficiency and Maximum Temperature of Methan

The predicted value and the error in the predicted value are as under:

**Table 3.** Combustion Efficiency and Maximum Temperature and Predictive Value ($^{o}$C) and Error

| Combustion Efficiency (%) | Max Temperature (°C) | Predicted Value (°C) | Error |
|---|---|---|---|
| 85 | 1800 | 1780.42 | 1.09 |
| 75 | 1600 | 1610.33 | -0.65 |
| 92 | 1900 | 1909.28 | -0.49 |
| 45 | 1200 | 1198.94 | 0.09 |

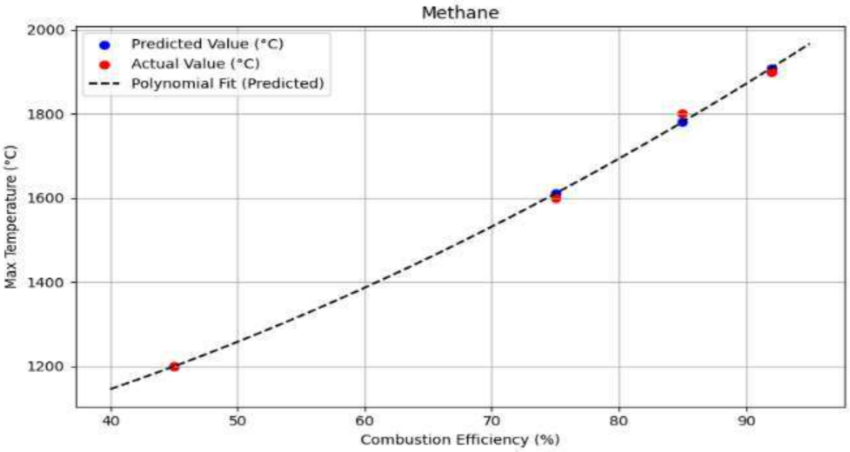

**Figure 5.** Error Graph for Polynomials

According to the study, the model exhibits a respectable degree of accuracy, as seen by the relatively small differences between the expected and actual results. The relation of combustion of ethanol with every oxidizer is found to be non-linear according to the data.

**Table 4.** Combustion Efficiency and Predicted Values of Maximum Temperature of Ethanol

| Combustion Efficiency (%) | Predicted Value (°C) |
|---|---|
| 10 | 622.17 |
| 20 | 783.12 |
| 30 | 941.63 |
| 40 | 1097.7 |
| 50 | 1251.33 |
| 60 | 1402.52 |
| 70 | 1551.27 |
| 80 | 1697.58 |
| 90 | 1841.45 |
| 100 | 1982.88 |

The mathematical model derived for the relation of ethanol with oxidizers is found to be as

$$Y = -0.0122x^2 + 16.461x + 458.78$$

Where 'Y' represents the predicted temperature in Celsius and 'x' represent the combustion efficiency in percentage. The graph of the data along with actual values and error is shown in Figure 6.

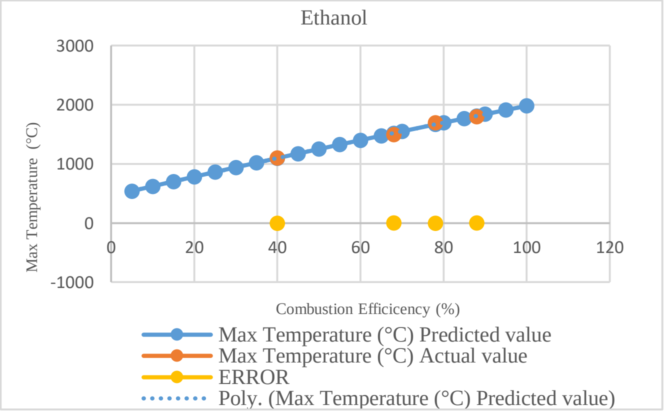

**Figure 6.** Combustion Efficiency and Maximum Temperature of Ethanol

The relation between ethanol's maximum temperature and combustion efficiency is seen in the Figure 7. The error markers show where the model's predictions diverge from actual data.

**Table 5.** Combustion Efficiency and Maximum Temperature and Predicted Value (°C) and Errors of Ethanol

| Combustion Efficiency (%) | Max Temperature (°C) | Predicted Value (°C) | Error |
|---|---|---|---|
| 78 | 1700 | 1668.51 | 1.85 |
| 68 | 1500 | 1521.72 | -1.45 |
| 88 | 1800 | 1812.87 | -0.71 |
| 40 | 1100 | 1097.7 | 0.21 |

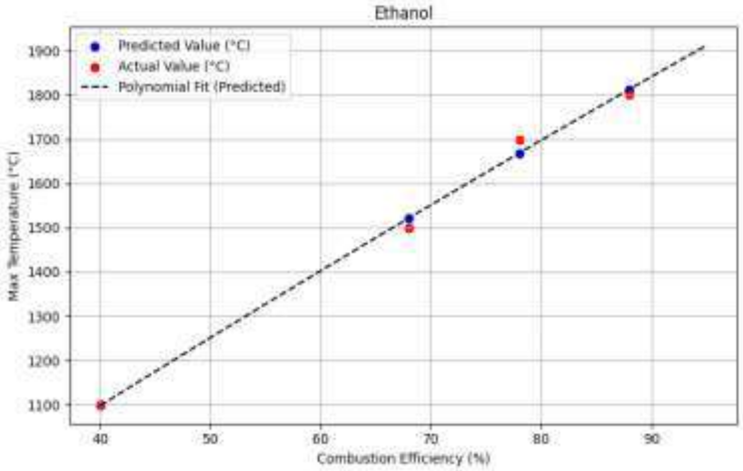

**Figure 7.** Polynomial with Errors

After examination, it is obvious the model predicts values that are typically rather close to the actual values, indicating a respectable degree of accuracy. In particular, it seems that the model performs better when dealing with lower combustion efficiencies in terms of forecast accuracy.

The relation of combustion of jet fuel with every oxidizer is found to be non-linear according to the data.

**Table 6.** Combustion Efficiency and Predicted Values of Maximum Temperature for Jet Fuel

| Combustion Efficiency (%) | Predicted Value (°C) |
|---|---|
| 10 | 1267.51 |
| 20 | 1204.64 |
| 30 | 1181.79 |
| 40 | 1198.96 |
| 50 | 1256.15 |
| 60 | 1353.36 |
| 70 | 1490.59 |
| 80 | 1667.84 |
| 90 | 1885.11 |
| 100 | 2142.4 |

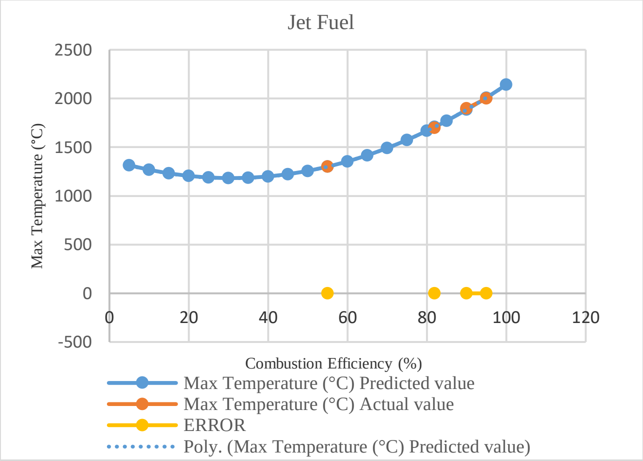

**Figure 8.** Combustion Efficiency and Maximum Temperature for Jet Fuel

The mathematical model derived for the relation of jet fuel with oxidizers is found to be as

$$Y = 0.2001x^2 - 12.29x + 1370.4$$

The graph of the data along with actual values and error is given in Figure 9.

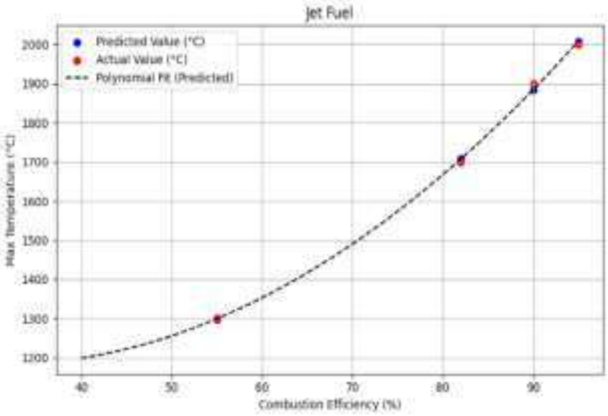

**Figure 9.** Combustion Efficiency and Maximum Temperature for Jet Fuel

The information is displayed in a table that compares the actual and predicted temperatures at different combustion efficiency levels in Table 7. The actual values and predicted values of maximum temperature required to get to achieve the combustion efficiency of jet fuel along with errors is given in the following table.

**Table 7.** Combustion Efficiency and Predicted Values of Maximum Temperature for Jet Fuel

| Combustion Efficiency (%) | Max Temperature (°C) | Predicted Value (°C) | Error |
|---|---|---|---|
| 90 | 1900 | 1884.57 | 0.81 |
| 82 | 1700 | 1707.6 | -0.45 |
| 95 | 2000 | 2008.18 | -0.41 |
| 55 | 1300 | 1299.42 | 0.04 |

The analysis reveals that an increase in combustion efficiency is correlated with a rise in both the maximum temperature and the expected values simultaneously. This positive association implies that the expected maximum temperature increases in line with improvements in combustion efficiency. The existence of prediction errors highlights the difference between actual and predicting values.

**Table 8.** Combustion Efficiency and Maximum Temperature and Predicted Value (°C) and Errors of Hydrogen

| Combustion Efficiency (%) | Predicted Value (°C) |
|---|---|
| 10 | 5407.73 |
| 20 | 4201.92 |
| 30 | 3210.37 |
| 40 | 2433.08 |
| 50 | 1870.05 |
| 60 | 1521.28 |
| 70 | 1386.77 |
| 80 | 1466.54 |
| 90 | 1760.53 |
| 100 | 2268.8 |

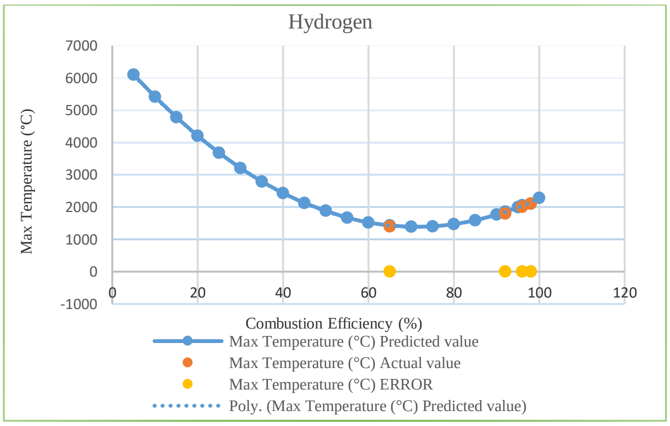

**Figure 10.** Graph of Polynomial with Errors

The relation of combustion of hydrogen with every oxidizer is found to be non-linear according to the data. The mathematical model derived for the relation of hydrogen gas with oxidizers is found to be in equation below.

$$Y = 1.0713x^2 - 152.72x + 6827.8$$

**Table 9.** Combustion Efficiency and Maximum Temperature and Predictive Values along with Error

| Combustion Efficiency (%) | Maximum Temperature (°C) | Predicted Value (°C) | Error |
|---|---|---|---|
| 96 | 2000 | 1994.31 | 0.28 |
| 92 | 1800 | 1801.98 | -0.11 |
| 98 | 2100 | 2103.32 | -0.16 |
| 65 | 1400 | 1399.84 | 0.01 |

The graph displays the relation between hydrogen's maximum temperature and combustion efficiency. This shows a clear negative relation between the highest temperature and combustion efficiency. The maximum temperature typically drops as combustion efficiency rises, with the rate of decline becoming less steep as efficiency rises and more noticeable at lower efficiencies. Interestingly, the graph reveals a modest increase in maximum temperature at extremely high combustion efficiencies above 90%, pointing towards a connection between efficiency and temperature at these extremes.

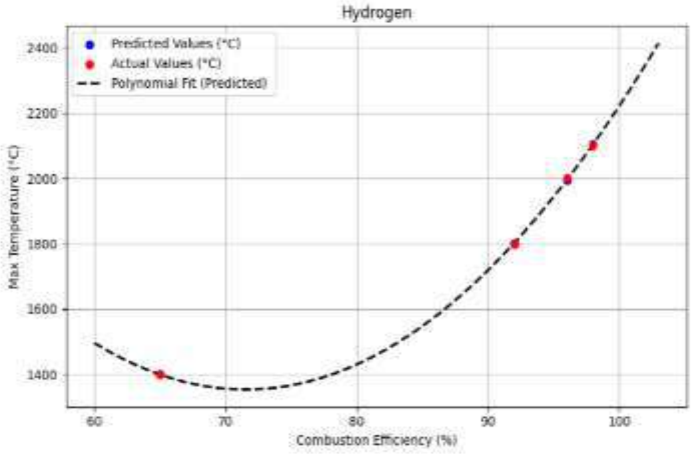

**Figure 11.** Graph of Polynomial with Errors

The analysis shows a clear trend indicating that the maximum temperature rises in line with increased combustion efficiency. It is important to point out that, even though the model is a useful tool for calculating maximum temperatures, complete accuracy cannot be guaranteed. The numerical equations of the fuels by which the predicted values of maximum temperature is found to be shown in Table 10.

**Table 10.** Equations of Fuels Used in the Present Study

| Fuels | Mathematical Equations |
|---|---|
| Methane | $y = 0.0824x^2 + 3.8252x + 859.95$ |
| Ethanol | $y = -0.0122x^2 + 16.461x + 458.78$ |
| Jet fuel | $y = 0.2001x^2 - 12.29x + 1370.4$ |
| Hydrogen | $y = 1.0713x^2 - 152.72x + 6827.8$ |

## 4.1 Prices of Fuels and Oxidizers:

**Table 11.** Prices of Fuels and Oxidizer per Liter ($)

| | **Fuels** | | | | **Oxidizers** | | | |
|---|---|---|---|---|---|---|---|---|
| **Months** | **Methane** | **Ethanol** | **Jet Fuel** | **Hydrogen** | **Atmospheric Air** | **Oxygen** | **Nitrous Oxide** | **Fluorine** |
| Jan 2024 | 0.84 | 0.45 | 0.81 | 3.18 | 17.06 | 0.34 | 0.78 | 1.12 |
| Feb 2024 | 0.46 | 0.43 | 0.79 | 1.72 | 17.06 | 0.33 | 0.76 | 1.10 |
| Mar 2024 | 0.40 | 0.42 | 0.76 | 1.49 | 17.06 | 0.32 | 0.74 | 1.08 |
| Apr 2024 | 0.42 | 0.44 | 0.78 | 1.60 | 17.06 | 0.33 | 0.75 | 1.09 |
| May 2024 | 0.52 | 0.46 | 0.80 | 2.12 | 17.06 | 0.34 | 0.77 | 1.11 |
| Jun 2024 | 0.61 | 0.48 | 0.82 | 2.54 | 17.06 | 0.35 | 0.79 | 1.13 |
| Jul 2024 | 0.50 | 0.49 | 0.83 | 2.07 | 17.06 | 0.36 | 0.80 | 1.14 |
| Aug 2024 | 0.48 | 0.50 | 0.84 | 1.99 | 17.06 | 0.36 | 0.81 | 1.15 |
| Sep 2024 | 0.55 | 0.51 | 0.85 | 2.28 | 17.06 | 0.37 | 0.82 | 1.16 |
| Oct 2024 | 0.53 | 0.52 | 0.86 | 2.20 | 17.06 | 0.37 | 0.83 | 1.17 |
| Nov 2024 | 0.51 | 0.53 | 0.87 | 2.12 | 17.06 | 0.38 | 0.84 | 1.18 |
| Dec 2024 | 0.72 | 0.54 | 0.88 | 3.01 | 17.06 | 0.39 | 0.85 | 1.19 |
| Jan 2025 | 1.10 | 0.46 | 0.85 | 4.13 | 17.06 | 0.36 | 0.80 | 1.15 |
| Feb 2025 | 1.12 | 0.47 | 0.87 | 4.19 | 17.06 | 0.37 | 0.82 | 1.17 |
| Mar 2025 | 1.10 | 0.48 | 0.88 | 4.12 | 17.06 | 0.38 | 0.84 | 1.18 |
| Apr 2025 | 0.92 | 0.47 | 0.86 | 3.42 | 17.06 | 0.37 | 0.83 | 1.16 |
| May 2025 | 0.84 | 0.46 | 0.84 | 3.12 | 17.06 | 0.36 | 0.81 | 1.14 |
| Jun 2025 | 0.82 | 0.45 | 0.83 | 3.02 | 17.06 | 0.35 | 0.80 | 1.13 |

The prices of fuels and oxidizers are from January 2024 to June 2025 in the Table 11 and full list of raw combined prices for each fuel–oxidizer pair, along with their normalized cost values using min-max scaling are shown in table 12.

## 4.2 Analysis of Fuel-Oxidizer Performance:

The efficiency of combustion determines how much of the fuel's chemical energy is converted into useful work. Efficiency was normalized to provide a scale-invariant comparison across combinations. It contributed 65% weight in the composite score due to its central importance in propulsion systems. Lower normalized temperature was weighted 25% and normalized cost was weighted 10%, satisfying thermally stable reactions (Mariani, Pulga, Bianchi, Falfari, & Forte, 2021), (Kuzhagaliyeva, Horváth, Williams, Nicolle, & Sarathy , 2022), (Comesanaa, Chen, Niemeyer, & Rapp, 2024). In order to provide a practically grounded composite score definition that outperforms previous random or evenly distributed schemes, these weighting values were chosen to mirror propulsion priorities, where maximizing usable energy conversion is important (efficiency), thermal management directly constrains material durability and safety (temperature), and economic feasibility (cost), though secondary, remains essential for large-scale deployment.

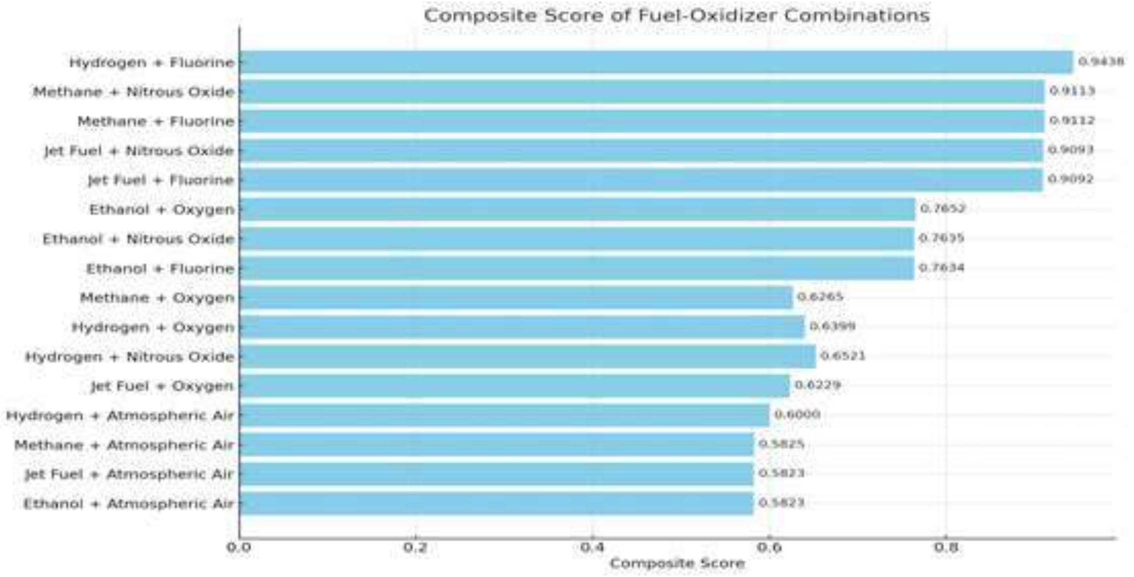

**Figure 12.** Composite Score of Various Combinations of Fuels and Oxidizers

The bar chart illustrates the comparative performance of fifteen fuel-oxidizer combinations based on their composite scores, which integrate normalized efficiency, temperature, and cost (Carlotti & Maggi, 2022), (Barato, 2023), (Ghedjatti, Yuan, & Wang, 2020). Excel is useful for effectively creating bar graphs (König, Richter, Ströhle, & Epple, Stability and Flame Structure Analysis of a Semi-Industrial Swirl-Stabilized Oxy-Fuel Combustion Chamber System for Biomass, 2025). The normalized efficiency, temperature, and cost for each fuel-oxidizer combination are multiplied by their respective weights and then added to create the weighted composite score (Nae, Andrei, Stroe, & Berbente, 2020). Lower-ranking combinations, particularly those involving Oxygen or Atmospheric Air, indicate reduced suitability due to either diminished thermal efficiency or higher normalized cost impact (Carlotti & Maggi, 2022), (Binotti, Invernizzi, Iora, & Manzolini, 2018), (Nogueira, Popi, Moore, & Kulay, 2019).

**Table 12.** The Normalized Efficiency, Normalized Temperature, Normalized Cost and Composite Score of the combination of Fuels and Oxidizers

| Rank | Fuel | Oxidizer | Normalized Cost (NC) | Normalized Efficiency (NE) | Normalized Temp. (NT) | Composite score (CS) |
|---|---|---|---|---|---|---|
| 1 | Hydrogen | Fluorine | 0.0208 | 1.0000 | 0.7500 | 0.9438 |
| 2 | Methane | Nitrous oxide | 0.0090 | 0.9481 | 0.7500 | 0.9113 |
| 3 | Methane | Fluorine | 0.0089 | 0.9481 | 0.7500 | 0.9112 |
| 4 | Jet fuel | Nitrous oxide | 0.0309 | 0.9437 | 0.7500 | 0.9093 |
| 5 | Jet fuel | Fluorine | 0.0307 | 0.9437 | 0.7500 | 0.9092 |
| 6 | Ethanol | Oxygen | 0.0470 | 0.9444 | 0.4217 | 0.7652 |
| 7 | Ethanol | Nitrous oxide | 0.0279 | 0.9444 | 0.4217 | 0.7635 |
| 8 | Ethanol | Fluorine | 0.0277 | 0.9444 | 0.4217 | 0.7634 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 9 | Ethanol | Atmospheric air | 1.0000 | 0.9481 | 0.4217 | 0.5823 |
| 10 | Hydrogen | Nitrous oxide | 0.0209 | 1.0000 | 0.0000 | 0.6521 |
| 11 | Hydrogen | Atmospheric air | 0.9994 | 1.0000 | 0.0000 | 0.6000 |
| 12 | Hydrogen | Oxygen | 0.0399 | 1.0000 | 0.0000 | 0.6399 |
| 13 | Methane | Atmospheric air | 0.9980 | 0.9481 | 0.0000 | 0.5825 |
| 14 | Methane | Oxygen | 0.0283 | 0.9481 | 0.0000 | 0.6265 |
| 15 | Jet fuel | Atmospheric air | 1.0000 | 0.9481 | 0.0000 | 0.5823 |
| 16 | Jet fuel | Oxygen | 0.0501 | 0.9437 | 0.0000 | 0.6229 |

Table 12 above offers a thorough examination of several fuel-oxidizer combinations, assessed using a Composite Score that incorporates combustion temperature, efficiency, and cost. This method allows for a more thorough assessment of propellant performance, especially in propulsion and energy systems where cost, efficiency, and thermal control are critical (Canepari, Sarritzu, & Pasini, 2024), (Türker, 2023). The composite score table is easily created using Excel and is sorted from highest to lowest composite score values (Dorokhov, Kuznetsov, Vershinina, & Strizhak, 2021). Table 12 summarizes a thorough analysis of liquid fuel and oxidizer combinations in a combustion system using a weighted composite scoring system. For the purpose of optimizing combustion systems, this analytical framework incorporates three crucial performance metrics: normalized efficiency, normalized temperature, and normalized price. These metrics are assigned weights of 0.65, 0.25, and 0.10, respectively (Carlotti & Maggi, 2022), (Pires, Han, Kramlich, & Perez, 2018), (Goldmann, et al., 2018). With 16 distinct fuel-oxidizer combinations, the dataset makes it easier to compare and find the best combinations using a comprehensive performance index. Table 13 provides the sources of fuel and oxidizer prices.

**Table 13.** Sources of the Prices of Fuels and Oxidizers

| Fuel | Source | Oxidizer | Source |
|---|---|---|---|
| Methane | Based on Henry Hub spot rates (Energy Prices, 2025). | Oxygen | Bulk industrial-grade rates (Gas Market Report) |
| Ethanol | U.S. futures market averages (GlobalPetrolPrices). | Nitrous Oxide | Estimated from medical and industrial-grade averages (Global Petrol Prices) |
| Jet Fuel | Gulf Coast kerosene-type spot prices (Monthly Oil Price Statistics, 2025). | Fluorine | Derived from chemical supplier data and industrial estimates, approximated at ~$1.10/L for modeling purposes (bulk-chemical-prices) |
| Hydrogen | Bulk chemical pricing in (North America). | Atmospheric Air | Modeled as a value for comparative analysis fixed at $17.063/L (Presman & Gany, 2024), (König, Richter, Ströhle, & Epple, Stability and Flame Structure Analysis of a Semi-Industrial Swirl-Stabilized Oxy-Fuel Combustion Chamber System for Biomass, 2025) |

This approach enables a more comprehensive analysis of the data, facilitating the informed selection of fuel-oxidizer combinations based on discernible performance differences.

In conclusion, analysis offers a useful framework for organizing fuel-oxidizer designs, especially in systems where combustion efficiency and heat output are crucial (Zuo, et al., 2020). These results can guide the creation of fuel strategies that are most appropriate for renewable energy, industrial combustion, and aerospace (König, Richter, Ströhle, & Epple, These findings can direct the development of fuel strategies that are best suited for industrial combustion, aerospace, and renewable energy, 2025). These combinations offer the best options in terms of efficiency and temperature, making them the most sensible choices. As these combinations have the highest composite scores**,** which balance high combustion efficiency and low normalized temperature indicating importance in the context of system performance (Amani, Rahdan, & Pourvosoughi, 2019). The best fuel and oxidizer combination is one that achieves high combustion efficiency, operates at a lower normalized temperature (Carrasco, Grathwohl, Maier, Ruppert, & Scheffknecht, 2019). In propulsion and energy systems, where high performance and temperature control are crucial, this analytical approach is crucial for choosing the best propellant pairings (Presman & Gany, 2024).

The performance of different fuel-oxidizer pairs is highlighted in the ranked table according to composite scores that are derived from temperature, cost, and efficiency (Presman & Gany, 2024), (Canepari, Sarritzu, & Pasini, 2024), (Singh, et al., 2021). In terms of cost-effectiveness and performance, hydrogen with fluorine ranks highest, closely followed by methane with nitrous oxide and methane with fluorine (Presman & Gany, 2024), (Alam, Depcik, Burugupally, Hobeck, & McDaniel, 2022). Combinations of jet fuel, especially those containing fluorine and nitrous oxide, also perform well (Barato, 2023), (Alam, Depcik, Burugupally, Hobeck, & McDaniel, 2022), (Cameretti, Robbio, Ferrara, & Tuccillo, 2025). Because of their low temperature and high normalized cost, combinations involving atmospheric air consistently rank lowest, while those involving ethanol occupy the mid-range scores (Alam, Depcik, Burugupally, Hobeck, & McDaniel, 2022), (Presman & Gany, 2024). With the highest score, hydrogen with fluorine performs exceptionally well in every category (Franco, 2025), (Uddin & Wang, 2024). Methane exhibits strong combustion properties when combined with nitrous oxide and fluorine (Alam, Depcik, Burugupally, Hobeck, & McDaniel, 2022), (Han, 2015). Additionally, jet fuel containing fluorine and nitrous oxide ranks highly due to its thermal behavior and competitive efficiency (Barato, 2023), (Orlin, 2020). These findings imply that methane and hydrogen provide the best performance in combustion systems when combined with oxidizers (Abbass, 2025), (Presman & Gany, 2024) (Xiao, et al., 2024). The benefits of hydrogen-based fuels with reactive oxidizers are highlighted in the study, which also demonstrates how maximizing all three parameters can maximize overall performance (Abbass, 2025), (Fauzy, Chen, & Lin, Numerical Analysis of Hydrogen Peroxide Addition and Oxygen-Enriched Methane Combustion, 2023), (Grishin, Zakharov, & Aref'ev, 2022). Additional research should validate this conclusion under dynamic operational settings and environmental constraints to ensure ecological and practical application. Additional research should validate this conclusion under dynamic operational settings and environmental constraints to ensure ecological and practical application.

**Table 14.** Sensitivity Analysis of the Composite Scores of the Combination of Fuels and Oxidizers

| **Adjacent Ranks** | **Combinations (Fuel/Oxidizer)** | | | **CS Difference** | **$^{\Delta}$NE** | **$^{\Delta}$NT** | **$^{\Delta}$NP** |
|---|---|---|---|---|---|---|---|
| | | | | **d** | **(d/0.65)** | **(d/0.25)** | **(d/0.10)** |
| 1-2 | Hydrogen with Fluorine | vs | Methane with Nitrous Oxide | 0.0325 | 0.0500 | 0.1300 | 0.3250 |
| 2-3 | Methane with Nitrous Oxide | vs | Methane with Fluorine | 0.0001 | 0.0002 | 0.0004 | 0.0010 |
| 3-4 | Methane with Fluorine | vs | Jet Fuel with Nitrous Oxide | 0.0019 | 0.0029 | 0.0076 | 0.0190 |
| 4-5 | Jet Fuel with Nitrous Oxide | vs | Jet Fuel with Fluorine | 0.0001 | 0.0002 | 0.0004 | 0.0010 |
| 5-6 | Jet Fuel with Fluorine | vs | Ethanol with Oxygen | 0.1440 | 0.2215 | 0.5760 | 1.4400 |
| 6-7 | Ethanol with Oxygen | vs | Ethanol with Nitrous Oxide | 0.0017 | 0.0026 | 0.0068 | 0.0170 |
| 7-8 | Ethanol with Nitrous Oxide | vs | Ethanol with Fluorine | 0.0001 | 0.0002 | 0.0004 | 0.0010 |
| 8-9 | Ethanol with Fluorine | vs | Hydrogen with Nitrous Oxide | 0.1113 | 0.1712 | 0.4452 | 1.1130 |
| 9-10 | Hydrogen with Nitrous Oxide | vs | Hydrogen with Oxygen | 0.0122 | 0.0188 | 0.0488 | 0.1220 |
| 10-11 | Hydrogen with Oxygen | vs | Methane with Oxygen | 0.0134 | 0.0206 | 0.0536 | 0.1340 |
| 11-12 | Methane with Oxygen | vs | Jet Fuel with Oxygen | 0.0036 | 0.0055 | 0.0144 | 0.0360 |
| 12-13 | Jet Fuel with Oxygen | vs | Hydrogen with Atmospheric Air | 0.0229 | 0.0352 | 0.0916 | 0.2290 |
| 13-14 | Hydrogen with Atmospheric Air | vs | Methane with Atmospheric Air | 0.0175 | 0.0269 | 0.0700 | 0.1750 |
| 14-15 | Methane with Atmospheric Air | vs | Ethanol with Atmospheric Air (or Jet Fuel with Atmospheric Air) | 0.0002 | 0.0003 | 0.0008 | 0.0020 |
| 15-15 | Ethanol with Atmospheric Air | vs | Jet Fuel with Atmospheric Air | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

In Table 14 small measurement or normalization errors can alter rankings; higher sensitivity is associated with smaller deltas. Sensitive pairs, such as ranks 2-3 and 14-15, are readily reversible by small efficiency changes because of their minute differences. Pairs with moderate sensitivity have differences between 0.0017 and 0.0036, making them susceptible to minor uncertainties. Pairs with low sensitivity exhibit greater differences, which stabilizes their rankings. Normalized efficiency is the primary determinant of rankings, so giving it more weight increases sensitivity. On the other hand, placing more emphasis on more stable factors, such as price or temperature, can stabilize rankings. While the top and bottom rankings remain constant, many mid-tier rankings are still subject to change with minor adjustments to parameters or weights.

## 5. Discussion

The performance of hydrogen, ethanol, jet fuel, and methane with oxidizers such as oxygen, air, nitrous oxide, and fluorine was methodically assessed in this study (Barato, 2023), (Kapitonova & Bullock, 2023), (Nae, Andrei, Stroe, & Berbente, 2020). Using a composite scoring model that takes into account cost, temperature, and normalized efficiency (Ghedjatti, Yuan, & Wang, 2020), (Kapitonova & Bullock, 2023), Because of its superior combustion efficiency and flame characteristics, hydrogen–fluorine proved to be the most effective combination; however, its high cost makes it less feasible in practice (Fauzy, Chen, & Lin, Numerical Analysis of Hydrogen Peroxide Addition and Oxygen-Enriched Methane Combustion, 2023), (Presman & Gany, 2024), (Da, Fei, & Xiangyang, 2021). When combined with fluorine and nitrous oxide, methane performed remarkably well, providing a more balanced economic profile along with strong thermal stability and efficiency (Orlin, 2020), (Cavalcanti, et al., 2024), (Da, Fei, & Xiangyang, 2021). Jet fuel is appealing for applications with a tight budget because, despite being marginally less efficient than hydrogen, it proved to be an affordable alternative when paired with fluorine or nitrous oxide (Cameretti, Robbio, Ferrara, & Tuccillo, 2025), (Kapitonova & Bullock, 2023), (Balli, 2019). However, despite their abundance and low cost, oxygen and atmospheric air consistently produced low composite scores, highlighting their limited suitability for high-performance combustion systems (Barato, 2023), (Bo, Said, Erdiwansyah, Mamat, & Xiaoxia, 2025). These results emphasize how crucial it is to balance cost, thermal output, and efficiency in a single framework to guarantee both viability and performance (Nae, Andrei, Stroe, & Berbente, 2020), (Srivastava, et al., 2025), (Dorokhov, Kuznetsov, Vershinina, & Strizhak, 2021). The approach facilitates decision-making in energy-intensive industries like power generation, aerospace, and defense (Nayebossadri, Walsh, & Smailes), (Boretti, 2024), (Sdanghi, Maranzana, Celzard, & Fierro, 2019), while encouraging further integration of environmental and operational variables in future research.

Applications in power generation, aerospace, and defense where heat management and system efficiency are crucial will benefit from this knowledge (Nayebossadri, Walsh, & Smailes), (Boretti, 2024), (Sdanghi, Maranzana, Celzard, & Fierro, 2019). These results stimulate more research into hybrid systems that can optimize design to manage cost and environmental constraints while taking advantage of high-performance fuel-oxidizer combinations (Presman

& Gany, 2024), (Hinov, Madzharov, & Grozdanov, 2020), (Hidouri, Omrane , Khalil, & Cherif, 2025).

This study acts as a valuable resource for decision-making, allowing for the prioritization of combinations based on system requirements, such as efficiency for energy-intensive applications or cost-effectiveness for budget-constrained contexts. The methodology's dependence on normalized data guarantees statistical accuracy (Richter, Braun-Unkhoff, & Naumann, 2022), (Srivastava, et al., 2025), (Mota, Fei, Liu, Jiang, & Tang, 2024). However, future investigations should integrate dynamic operational variables and environmental influences to improve ecological validity.

## 6. Conclusion

This study has looked at a range of liquid fuel and oxidizer combinations to identify which ones maximize combustion efficiency while minimizing cost and temperature in order to meet the original goal of optimizing energy utilization for industrial and commercial applications. The primary findings indicate that jet fuel and fluorine, methane and nitrous oxide, and hydrogen and fluorine are the most promising combinations. These combinations effectively balance thermal performance, efficiency, and economic viability, making them perfect for high-demand combustion systems.

By introducing a weighted composite scoring method that takes into account normalized efficiency, temperature, and cost, the study provides a comprehensive evaluation framework that surpasses traditional single-criterion evaluations. This approach ensures that the chosen fuel-oxidizer combinations are not only optimal thermodynamically but also practically and commercially viable. Even though fuels like hydrogen have high rates of combustion, they work best when combined with oxidizers like nitrous oxide or fluorine, which emphasizes the importance of considering the entire fuel-oxidizer system.

The use of non-linear regression models to predict combustion temperatures from efficiency further enhances the study's practical value by enabling better forecasting and engineering design. Together, these insights significantly contribute to the development of more energy-dense, safer, and cleaner combustion technologies that satisfy modern economic and environmental demands. Despite some limitations, including the reliance on secondary sources and the lack of dynamic operational data, the structured methodology provided is a helpful tool for guiding future research. It identifies promising avenues for the development of sustainable and effective energy solutions through the use of machine learning techniques, hybrid combustion systems, and novel biofuels.

In conclusion, the study not only finds the optimal liquid fuel-oxidizer combinations, but it also lays the groundwork for future efforts to increase the energy efficiency and cost-effectiveness of combustion-driven industries. The work emphasizes the need for future studies aimed at lowering combustion temperatures, expanding sample sizes, and improving data collection under varied circumstances in order to increase statistical validity. It suggests using machine learning techniques and incorporating real-time engine testing to improve combustion prediction models. Additional research on alternative fuels, pollutant emissions, and engine parameters (like pressure and humidity) is recommended to enhance environmental impact assessments. It also highlights the value of CFD modelling and lifecycle analysis and encourages collaboration with the aerospace and automotive industries to translate findings into workable propulsion systems.

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