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ORIGINAL PAPER

The Effect of Adding Hydrogen Peroxide to an Engine Used in Unmanned Aerial Vehicles on Fuel Consumption, Energy, Exergy, and Sustainability Parameters

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Abstract

This study explores the use of hydrogen peroxide solution—a novel additive not previously used in UAV engines—to improve the energy efficiency of commercially available unmanned aerial vehicles (UAVs). Different hydrogen peroxide ratios were blended with JP-8 fuel, a common UAV fuel, to boost engine performance and optimise operating conditions. The effects of these fuel blends on engine performance and emissions were thoroughly analysed at various UAV thrust levels (5 kg, 10 kg, 15 kg, 20 kg, and 25 kg). Energy, exergy, and sustainability assessments were conducted based on the findings. It was found that increasing engine thrust with the same fuel mixture resulted in higher system disorder and entropy production. For instance, at 5 kg thrust with the P20 fuel mixture, entropy generation was 0.046 kW/K, rising to 0.112 kW/K at 25 kg thrust. The study indicates that adding hydrogen peroxide to JP-8 fuel in UAVs decreases energy and exergy efficiencies. Specifically, at 15 kg thrust, JP-8's energy and exergy efficiencies were 18.54% and 17.37%, respectively. These values dropped to 15.50% and 14.59% with the P30 fuel blend. The sustainability index ranged from 1.226 to 1.070 across all fuel types.

Keywords UAV · JP-8 · Hydrogen peroxide · Energy · Exergy · Sustainability

1 Introduction

The growing use and spread of unmanned aerial vehicles (UAVs) are driving new developments in internal combustion engine (ICE) technology. These engines, constantly refined to meet the energy needs and load capacities of modern societies, enable UAVs to perform a wide range of tasks [1]. Notably, low-speed two-stroke diesel engines offer significant benefits, such as the ability to incorporate waste heat recovery systems, which can significantly improve fuel efficiency in platforms like drones [2]. Their simple design provides essential advantages in terms of cost and ease of maintenance for UAV use [3]. However, their high exhaust emissions present environmental challenges that limit their application. Among various internal combustion engines, two-stroke engines are preferred in drone use due to their high efficiency potential [4]. A key objective is to control emissions without compromising performance, especially under strict environmental regulations. Using alternative fuels is essential to this goal. Renewable fuels, along with cleaner energy sources like natural gas and hydrogen, can lower carbon footprints and boost energy security [5, 6]. JP-8, a kerosene-based fuel used in military jet engines, is a promising option for advancing two-stroke engines and expanding their use in UAVs [7]. Research studies have examined emissions and performance in relation to JP-8 fuels. For example, Poola et al. [8] found that blending orange and eucalyptus oils with gasoline in two-stroke spark-ignition engines can improve performance due to higher octane ratings. Their experiments show these blends deliver better

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performance and lower emissions than gasoline alone, especially at higher compression ratios. Overall, the development of UAV technology supports the sustainable advancement of internal combustion engines and efforts to reduce environmental impacts.

Yu et al. [9] thoroughly investigated n-butanol as an alternative to traditional gasoline in spark-ignition piston engines, focusing on its use in aviation. They found that while emissions of carbon monoxide (CO) and nitrogen oxides (NOx) improved significantly, fuel consumption increased. The study also showed that adding kerosene to the n-butanol blend significantly boosted the fuel 's energy density, though this came with reduced knock resistance. They suggest that high-octane fuel additives could help improve knock resistance in n-butanol and kerosene blends, potentially benefiting combustion efficiency and emissions, which are crucial for environmental standards. In contrast, Fernandes et al. [10] evaluated diesel engine performance and emissions using military JP-8 fuel. They observed that JP-8's lower density and viscosity could reduce engine torque and fuel economy. However, using JP-50 with EGR technology could cut NOx and PM emissions by about 50%. Their experiments showed that JP-8's slow cetane number increased combustion delay, but engine calibration modifications could improve torque and fuel efficiency. Labeckas et al. [11] compared diesel and JP-8, finding that JP-8 saved fuel under various loads and at 1 400 rpm but increased CO and HC emissions. Adding 2 2-ethylhexyl nitrate (0.04–0.24%) to JP-8 raised the cetane number, improved engine performance, and slightly affected fuel consumption at 2200 rpm. Uyumaz et al. [12] experimented with JP-8 and sunflower methyl ester blends at different loads, noting that higher biodiesel content raised NOx emissions but lowered CO emissions. Lee et al. [13] studied EGR and multiple injections in JP-8-fueled light-duty diesel engines, finding that JP-8 increased ignition delay in single injections but not in various injections. They highlighted that combining JP-8 with EGR could reduce NOx and PM emissions by around 50%, promoting wider use. Labeckas et al. [14] also examined JP-8 and its mixtures with diesel fuel, reporting faster injection and combustion onset, up to 12. 7% reduction in ignition delay, and improvements in maximum in- cylinder pressure (6. 6.8–4. 4.0%), thermal efficiency (3. 3.3–7. 7.7%), and reduced fuel consumption (2. 2.8–7%), illustrating ongoing efforts to find better fuel options and improve engine performance and sustainability.

Analysing the performance variations of thermal systems based on thermodynamics offers a detailed understanding of both the quantity and quality of fuels used in different applications [15]. According to energy conservation principles, a part of the heat produced during fuel combustion in engines is converted into mechanical work. Still, most often the majority is released as heat into the environment, leading to inefficiencies [16]. Therefore, it is essential to monitor temperature and pressure changes carefully to evaluate internal energy variations impacting engine performance. Relying solely on the first law of thermodynamics may not be sufficient for performance analysis; hence, exergy analysis, rooted in the second law, becomes crucial for optimising energy efficiency [17, 18]. Exergy measures the maximum work a system can perform until reaching thermodynamic equilibrium with its surroundings, a state where no further work can be extracted. This highlights the importance of minimising exergy losses to make optimal use of energy resources [19, 20]. In internal combustion engines, exergy analysis helps identify irreversibilities and develop strategies to reduce these losses, revealing the engine's actual efficiency under specific conditions [21]. Additionally, evaluating the sustainability of various fuel blends using the sustainability index (SI)—which assesses environmental and economic performance based on the total exergy input and losses—is vital [22, 23]. For example, Akdeniz and Balli [24] performed an energy and exergy assessment of a turbojet running on different fuels, including biofuel, hydrogen, and JP-8. They found that exergy efficiency dropped slightly from 15.34 to 15.25% with JP-8, while hydrogen increased efficiency from 14.36 to 15.25%, indicating potential advantages of alternative fuels. Similarly, Korba et al. [25] evaluated a turbodiesel engine used in UAV take-offs, reporting an energy efficiency of 43.158% and an exergy efficiency of 40.655%, demonstrating high efficiency levels. Zhang et al. [26] studied the impact of 30% hydrogen peroxide (H_2O_2-30%) mixed with ethanol in a spark ignition engine. Results showed decreased peak pressure and temperature but increased combustion efficiency above 5% H_2O_2. Optimal ratios improved efficiency and reduced emissions such as BSHC, BSCO, and BSNOx. Chen et al. [27] explored how H_2O_2 enhances methane/air flame combustion, observing increased combustion speed, flame temperature, and efficiency, alongside variations in CO and CO_2 production. Adding H_2O_2 also increased OH radicals, boosting reaction rates but raising NO emissions. Zhang et al. [28] examined 30% H_2O_2 in an ethanol/gasoline engine, noting increased efficiency, fluctuating maximum pressure and temperature, and significant emission reductions at optimal ratios of 15% H_2O_2 and 30–40% direct injection. Özer and colleagues studied UAV engines fueled with gasoline-octanol and gasoline-hexanol, finding that 30% octanol (OC30) reduced fuel consumption, while hexanol increased it. Both additives decreased CO emissions but increased CO_2. Exergy efficiency declined with octanol but improved with HX30, varying across fuel mixtures [29]. In another study, Özer et al. evaluated JP5 + HHO fuel mixtures in UAV engines, testing at various speeds and HHO flow rates. They found HHO improved performance, lowered brake-specific fuel consumption, increased exergy efficiency, and reduced exergy loss by roughly 10%, despite a slight rise in CO_2 emissions, which was acceptable from an exergoenvironmental perspective [30].

The rising use of uncrewed aerial vehicles (UAVs) has increased attention on their engines, particularly two-stroke engines, prompting further research and development. As environmental concerns and emission standards become stricter, researching alternative fuels is necessary to minimise the ecological effects of these engines. Most studies in the literature examine hydrogen peroxide (H_2O_2) combined with ethanol, gasoline, and methane in spark-ignition (SI) and compression-ignition (CI) engines [26–28]. However, to our knowledge, no experimental research has been published on the direct use of liquid 90% H_2O_2 as an additive to military-grade JP-8 fuel in small UAV two-stroke engines. Our study is the first to analyse this particular fuel combination under different thrust levels in UAV setups. Existing research mainly targets four-stroke or turbojet air engines or focuses on thrust system simulations. In contrast, we employed a commercially available air-cooled two-stroke engine with two cylinders attached to a UAV propeller system, providing a more realistic scenario for tactical UAVS. The fields of exergy and exergy economic analysis remain underexplored in experimental thermodynamic studies of UAVs. We performed a comprehensive assessment involving energy, exergy, and sustainability across five UAV thrust levels (5–25 kg). Our analysis includes heat losses, entropy production, exergy destruction, and the sustainability index (SI) changes with different peroxide ratios. To our knowledge, no prior research has evaluated the sustainability performance (SI > 1) of H_2O_2-JP8 mixtures in UAV thrust systems within such an extensive thermodynamic framework.

Table 1 Technical specifications of the test engine

Technical specification	Value (unit)
Brand and model	Erin motor and Baykuş
Number of cylinders	2
Cooling type	Air Cooled
Bore x stroke	48 × 36.5 (mm x mm)
Total cylinder volume	0.132 (litre)
Maks. power	12 Hp (@8000 rpm)
Compression ratio	10.4:1
Idle speed	1800 (rpm)
Recommended propeller diameter	27 (Inch)

2 Material and Method

2.1 Engine Setup

The experiments took place in Erin Motor Company's R&D laboratory. The engine tested is a two-stroke, two-cylinder design developed for uncrewed aerial vehicles. Detailed technical specifications are provided in Table 1.

Engine tests at Erin Motor Company were conducted in sound-insulated cabinets to reduce noise. Propeller thrust was measured using a precise 'S' type load cell, from which engine torque was calculated. The fuel consumption of 20 ml was timed with a stopwatch for accuracy. Engine speed was recorded by a laser tachometer attached to the propeller. A high-resolution thermal camera monitored the engine casing temperature, while exhaust temperature was measured with a K-type thermocouple. Emissions were analysed using a BOSCH-BEA 060 device to ensure environmental standards and provide performance data. Details on sensor

Table 2 Sensitivity of measurement devices and their uncertainties

Parameter	Sensitivity	Tolerance	Remarks
Shaft Speed (rpm)	1 rpm	± 0.5%	Includes resolution and repeatability uncertainty
Thrust (kg)	± 0.01 kg	± 0.1%	Resolution and calibration-related uncertainty
Fuel Flow Time (s)	± 0.1 s	± 0.1 s	Chronometer precision
Surface Temperature (°C)	± 2 °C	–	Thermal camera precision
Exhaust Gas Temperature (°C)	± 0.1 °C	–	K-type thermocouple precision
CO (%vol)	0.001%vol	± 0.005%vol	Combines device sensitivity and tolerance
CO_2 (%vol)	0.01%vol	± 0.2%vol	Combines device sensitivity and tolerance
HC (ppm vol)	1 ppm vol	± 12 ppm	Combines device sensitivity and tolerance
O_2 (%vol)-	0.01%vol	± 0.4%vol	Combines device sensitivity and tolerance

Table 3 Properties of experimental fuels

Property	JP-8	Hydrogen Peroxide (90% Solution)
Viscosity (cSt at 20 °C)	4.77	1.15
Density (kg/m^3 at 15 °C)	0.810	1.39
Lower Heating Value (LHV) (MJ/kg)	42.8	–
Oxygen Content (% by weight)	%1 <	%85

measurement ranges and uncertainty analysis are available in Table 2. The following articles have been examined for the uncertainty calculations of measuring instruments [31–34].

2.2 Experimental Fuel Blends

While preparing the fuel blends, an aqueous solution of 90% hydrogen peroxide was used. A precise process was followed to determine the correct mixture ratio. The hydrogen peroxide was sourced from a reputable commercial supplier. To prevent separation during the experiment, the fuel blends were continuously stirred with a magnetic stirrer, ensuring a uniform mixture and enhancing experimental reliability. The detailed properties of the fuels are listed in Table 3.

2.3 Test Conditions

Motor performance and emissions were assessed under varying loads and speeds to replicate UAV operating scenarios: 5 kg at 3250 RPM, 10 kg at 3750 RPM, 15 kg at 4500 RPM, 20 kg at 5250 RPM, and 25 kg at 6250 RPM. An optical laser tachometer recorded the engine speed, while an S-type load cell measured the load. Exhaust gas temperature was tracked with a thermocouple, and casing temperature was monitored using a thermal camera. Fuel consumption of 20 ml was timed with a stopwatch, and an exhaust gas analyser measured the concentrations of CO, HC, NOx, CO2, O2, and lambda. Each experiment was repeated three times, and the average values were calculated. The setup schematic is shown in Fig. 1, and the study workflow is depicted in Fig. 2.

3 Thermodynamic Analysis

3.1 Energy Analysis

The First Law of Thermodynamics describes energy conservation in internal combustion engines, where heat transforms into mechanical energy and total energy remains constant. The engine's goal is to produce power efficiently, releasing significant fuel energy during combustion. Practical work is the energy converted into mechanical power, with thermal losses also occurring. Therefore, fuel energy equals practical work plus thermal losses, which is crucial for enhancing engine efficiency.

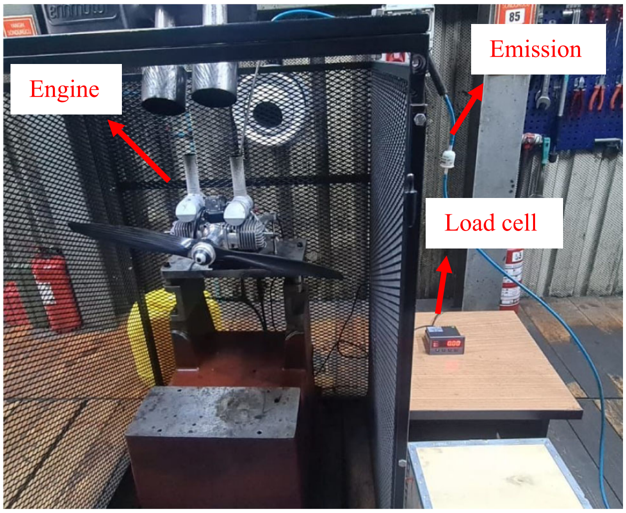

Fig. 1 Actual photograph of the experimental setup

$$\dot{E}_{in} = \dot{W} + \dot{E}_{loss} \tag{1}$$

$$\dot{E}_{fuel} + \dot{E}_{air} = \dot{E}_{in}. \tag{2}$$

The energy of the fuel ($\dot{E}_{fuel}$), in an internal combustion engine, consists of the sum of the energy of the air entering the engine ($\dot{E}_{air}$) and the thermal losses ($\dot{E}_{loss}$). This equation explains the energy balance of the engine and is crucial for understanding the energy flow within the system. The energy potential of the fuel is calculated using the fuel flow rate ($\dot{m}_{fuel}$) and its lower heating value (LHV_{fuel}), as shown in Eq. 3 [35]. This equation represents the maximum amount of energy that can be released during the combustion process. The combination of the fuel flow rate and the lower heating value clearly defines the energy contribution of the fuel, thereby highlighting an essential factor influencing engine performance.

$$\dot{E}_{fuel} = \dot{m}_{fuel} LHV_{fuel}. \tag{3}$$

The recorded air mass flow rate ($\dot{m}_{air}$), along with parameters such as inlet temperature (T_1) and ambient temperature (T_0), is critical for calculating the amount of energy carried by the engine during testing. These measurements represent the energy flow, which is expressed by the following Eq. (4) [36].

$$\dot{E}_{air} = \dot{m}_{air} C_p (T_1 - T_0). \tag{4}$$

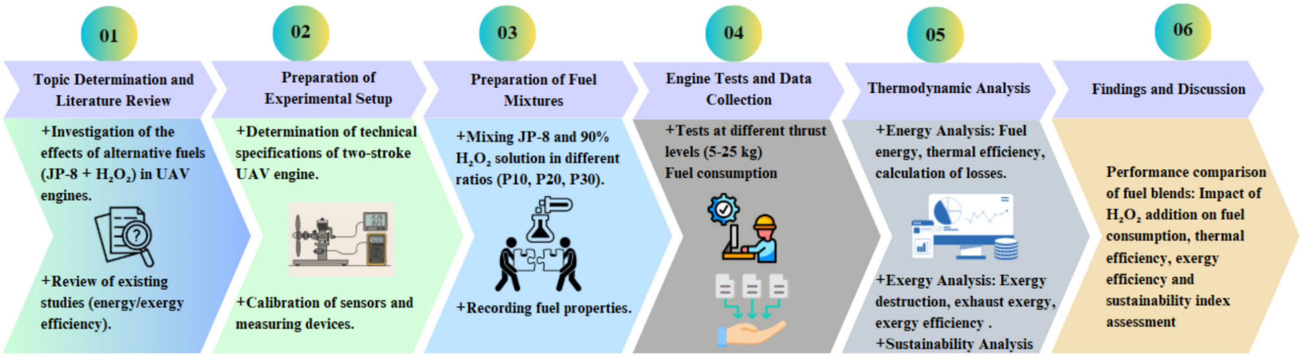

Fig. 2 Workflow diagram

Here, m_{air}, the relationship between the energy carried by the air and the air mass flow, $\dot{m}_{air}$ rate is explained using expressions that represent the specific heat, C_p at constant pressure. The inlet temperature T_1 and ambient temperature T_0 are represented by specific symbols. This equation is crucial for evaluating and improving engine performance, as it directly determines the amount of energy carried by the airflow. The total energy losses of the engine are calculated as the difference between the amount of energy delivered to the engine and the work performed by the engine. In this context, the total energy loss of the engine is expressed in terms of the total energy entering the engine and the work done by the engine [37].

$$\dot{E}_{loss} = \dot{E}_{in} - \dot{W}. \quad (5)$$

The thermal efficiency, defined as the ratio of the practical work produced by the engine to the energy of the fuel, provides valuable insights for assessing how efficiently the engine operates and identifying areas for improvement if necessary. The thermal efficiency is calculated using Eq. 6 below [18].

$$\eta_{th} = \frac{\dot{W}}{\dot{E}_{fuel}}. \quad (6)$$

3.2 Exergy Analysis

In internal combustion engines, energy conversion and heat transfer are often observed to be inefficient. Exergy plays a critical role in evaluating how much of the energy's potential can be converted into practical work. As a measure of energy quality, exergy is vital for improving energy conversion systems. The exergy balance within the control volume helps assess energy utilisation efficiency and, therefore, exergy calculations become indispensable for maximising efficiency. This is expressed in Eq. 7 [38].

$$\dot{E}x_{air} + \dot{E}x_{fuel} = \dot{E}x_{w} + \dot{E}x_{ex} + \dot{E}x_{heat} + \dot{E}x_{dest}. \quad (7)$$

Here, the exergy of the fuel ($\dot{E}x_{fuel}$), is composed of the exergy work ($\dot{E}x_{w}$), exhaust exergy ($\dot{E}x_{ex}$), the exergy of the heat transferred from the engine body ($\dot{E}x_{heat}$), and the destroyed exergy ($\dot{E}x_{dest}$).

The exergy of the air taken into the cylinder ($\dot{E}x_{air}$) is determined using the equation provided below. When the air is drawn into the cylinder under ambient conditions, its exergy is assumed to be zero [36].

$$\dot{E}x_{air} = \dot{m}\left[C_p\left[T_1 - T_0 - T_0\ln(\frac{T_1}{T_0})\right]\right] + RT_0\ln(\frac{P_1}{P_0}). \quad (8)$$

In Eq. 9, ($\dot{m}$) represents the mass flow rate, (C_p) the specific heat, (R) the specific gas constant, (T_1) the inlet air temperature, (T_0) the ambient temperature, (P_1) the inlet pressure, and (P_0) the ambient pressure. The exergetic power ($\dot{E}x_w$) produced by the internal combustion engine represents the valuable work performed by the engine. The fuel exergy is determined using Eq. 9 [39].

$$\dot{E}_{fuel} = \dot{m}_{fuel}\varphi LHV_{fuel}. \quad (9)$$

The exergy factor (φ), is determined using the chemical composition obtained from fuel analysis, as calculated by Eq. 10 [40].

$$\varphi = 1.0401 + 0.1728\frac{h}{c} + 0.0432\frac{o}{c} + 0.2169\frac{\alpha}{c}(1 - 2.0628\frac{h}{c}). \quad (10)$$

When determining the exergy of exhaust gases, the physical (ε_p) and chemical exergies (ε_c) of each gas are summed, as shown in Eq. 14. The physical and chemical exergies are calculated using Eqs. 11 and 12, respectively [40, 41].

$$\varepsilon_p = \left[(h - T_0 s) - (h_0 - T_0 s_0)\right] \quad (11)$$

$$\varepsilon_{ch} = \overline{R}T_0 ln \frac{1}{y^e} \tag{12}$$

$$\dot{E}x_{ex,i} = \sum (\varepsilon_p + \varepsilon_c)_i. \tag{13}$$

Here, the subscript zero indicates ambient conditions. The gas percentages (y^e) in the atmosphere, used in Eq. 12, were sourced from the literature [42]. During testing, we precisely measure the engine body's temperature (T_s). The exergy of heat transferred from the engine body to the surroundings is calculated using Eq. 14, where Ts represents the engine body temperature [43].

$$\dot{E}x_{heat} = \sum (1 - \frac{T_0}{T_s})\dot{Q}_{loss}. \tag{14}$$

The exergy values of the fuel and air entering the control volume, the power of exergy generation, exhaust exergy, and the exergy associated with heat transfer are evaluated, and the destroyed exergy is calculated. Subsequently, entropy production is determined using Eq. 15 [44].

$$\dot{s}_{gen} = \frac{\dot{E}x_{dest}}{T_0}. \tag{15}$$

Exergy efficiency is determined using the equation below [45].

$$\eta_{ex} = \frac{\dot{E}x_W}{\dot{E}x_{in}}. \tag{16}$$

3.3 Sustainability Analyses

The sustainability index (SI) is a tool used to measure a system's sustainability performance, assessing its environmental, economic, and social sustainability over time. High exergy efficiency indicates lower energy losses, a crucial aspect of sustainability evaluation. The SI is calculated by considering exergy flows and losses within the studied system, ultimately determining its value through a specific equation [46].

$$\mathrm{SI} = \frac{1}{1 - \eta_{ex}}. \tag{17}$$

4 Findings and Discussion

4.1 Energy Analysis

When evaluating alternative fuels, key indicators include specific fuel consumption, thermal efficiency, and operational-economic viability. Lower fuel consumption not only reduces operational costs but also lessens environmental impact, especially in drone applications where fuel weight directly affects flight time and payload capacity. The study found that adding hydrogen peroxide to JP-8 fuel increases fuel consumption across all thrust levels. This is due to H_2O_2 in the liquid phase decreasing the mixture's lower heating value. For instance, at 10 kg thrust, pure JP-8 consumes 1.450 kg/hour, while a 10% peroxide mixture (P10) raises this to 1.595 kg/hour. The P30 mixture reaches a peak of 3.865 kg/hour at 25 kg thrust. In two-stroke engines, fuel is supplied with each crank revolution, and unburned fuel during scavenging further supports higher consumption. Short residence times at high speeds hinder complete combustion, boosting fuel use. As peroxide content rises, flame instability and cooling losses also increase, causing consumption to spike disproportionately at high thrust levels. Similarly, Akdeniz and Balli [24] reported that biofuel additives raise turbojet mass flow rates from 0.160 kg/s to 0.184 kg/s, while hydrogen decreases it to 0.058 kg/s. These results suggest that oxidative additives should be optimised based on the engine's combustion characteristics [47] (Fig. 3).

Energy analyses indicate that the engine takes in more energy with increasing thrust; this situation is primarily due to the rising fuel flow rate. The addition of peroxide reduces the lower heating value of the mixture, while the increased mass flow compensates for this loss by raising the total energy entering the control volume. For example, in 10 kg thrust, peroxide-enhanced fuels (P10–P30) have provided 9–20% more energy compared to pure JP-8. However, this increase has not resulted in a proportional improvement in efficiency, thus highlighting the importance of the thermodynamic balance between energy density and chemical composition. The study emphasises the overall trend instead of interpreting each thrust level separately; it shows that peroxide-containing mixtures provide more energy, but this occurs at the cost of efficiency loss. Previous studies on four-stroke engines have also reported that the thermal value of H_2O_2 affects combustion efficiency, which is consistent with the results of this study [28] (Fig. 4).

In internal combustion engines, thermal energy losses are directly related to fuel consumption and combustion inefficiencies, which depend on the thrust level. The findings indicate that high peroxide mixtures, especially P30, produce higher thermal losses compared to pure JP-8 and peak at 38,068 kW with 25 kg of thrust. This increase is due to both high fuel flow rates and low heating value. Instead of treating all thrust levels separately, the data reveal a general trend that the addition of peroxide increases heat rejection but does not yield efficiency gains. This situation indicates that the balance between oxidative additives and thermal loss needs to be carefully managed. Similar findings exist regarding the decreasing thermal values of oxygen-rich fuels and

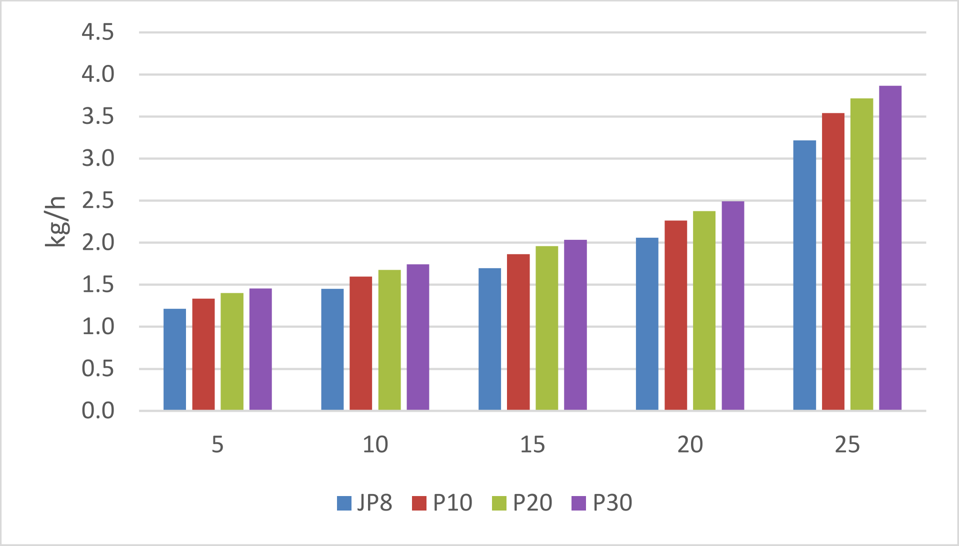

Fig. 3 Fuel consumption of fuel blends

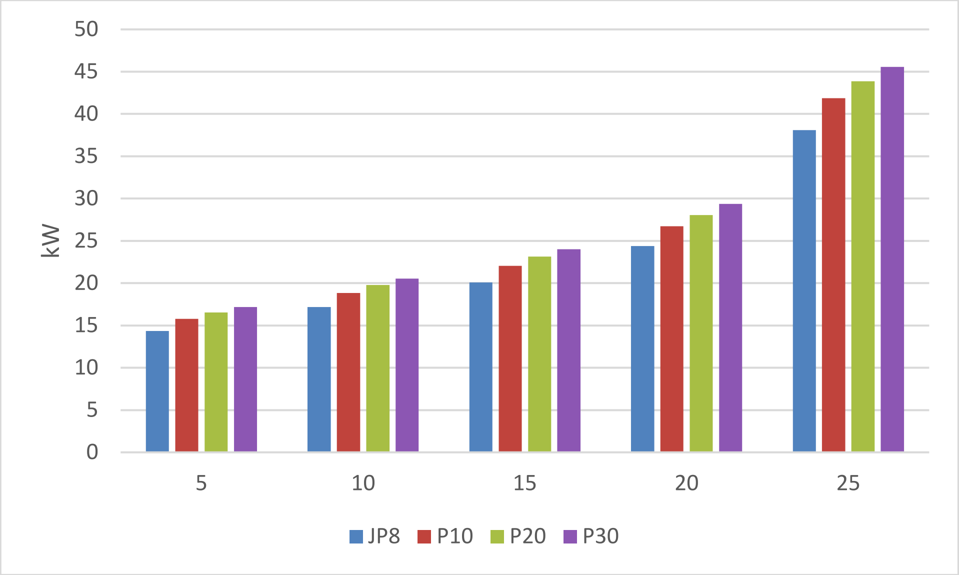

Fig. 4 Fuel energy input of fuel blends at different thrust levels

water-based additives, which lead to energy losses [48–50] (Fig. 5).

The First Law of Thermodynamics determines thermal efficiency and shows how well chemical energy from fuel is converted into practical mechanical work. In this study, peroxide-enriched mixtures consistently had lower thermal efficiencies than pure JP8, despite a higher energy input. This discrepancy is due to the reduced lower heating value and increased thermal losses caused by adding peroxide. Notably, the highest efficiency of 20.61% was achieved with JP8 at 20 kg thrust, while P30 only reached 17.12%. The efficiency trend was nonlinear, with a subsequent decline, indicating diminishing returns beyond a certain peroxide level. These results suggest that a moderate peroxide level may enhance combustion, but too high a concentration reduces overall system efficiency. The findings agree with Korba et al. [25] and Balli and Çalışkan [37], highlighting the need to balance the sustainability advantages of alternative fuels with the thermodynamic penalties. For UAV applications where load, endurance, and fuel economy are critical, fuel mixtures should be optimised for both reactivity and stable thermal efficiency across operational loads (Fig. 6).

4.2 Exergy Analysis

The incoming exergy flow measures the maximum theoretical work potential of the fuel as it enters an internal combustion engine's control volume. This includes both the chemical exergy—based on elemental composition and lower heating value (LHV)—and the physical exergy of the fuel. Figure 7 shows the incoming exergy for different fuel blends at various thrust levels. As engine load

Fig. 5 Thermal losses of fuel blends at different thrust levels

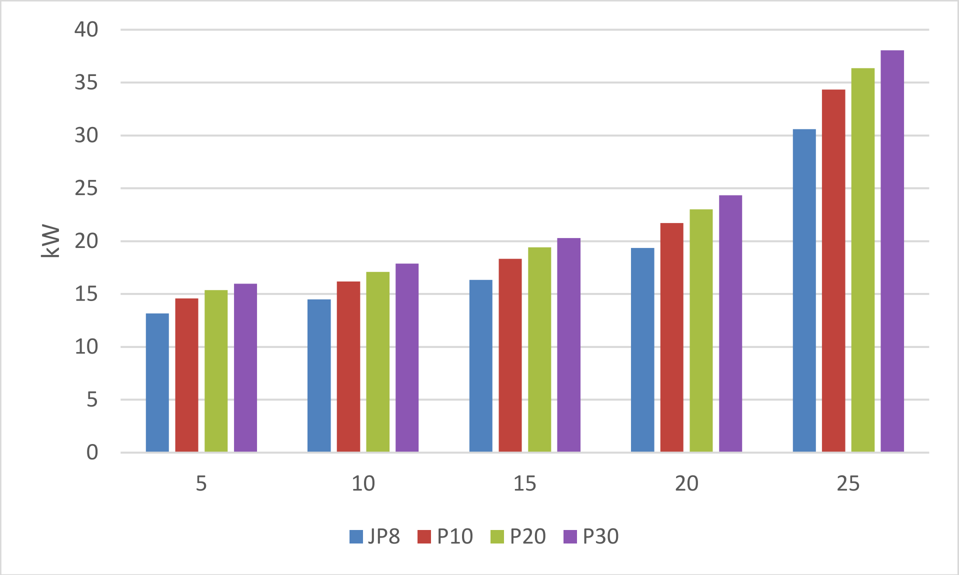

Fig. 6 Variation of thermal efficiency of fuel blends at different thrust levels

increases, so does fuel mass flow, raising the incoming exergy. For example, the P20 blend's exergy increased from 17.614 kW at 5 kg thrust to 46.673 kW at 25 kg. Similarly, all peroxide-enriched blends showed growth, with the P30 blend reaching 48.419 kW at maximum load, compared to 40.668 kW for pure JP8. This difference is due to higher fuel consumption and the altered chemical potential from hydrogen peroxide. At 10 kg thrust, exergy rose from 18.327 kW (JP8) to 21.820 kW (P30). In two-stroke UAV engines, this relationship is affected by factors like high combustion frequency, limited thermodynamic equilibration, and scavenging short-circuiting. These engines tend to operate fuel-rich and oxygen-limited, amplifying the impact of exergy inflow- especially with added oxidisers like hydrogen peroxide. While peroxide provides extra oxygen and changes combustion chemistry, it also increases inflow exergy because of its Gibbs free energy. Yet, unless combustion efficiency improves accordingly, this added exergy may not translate into practical benefits. These results support prior research by Balli et al. [51], who found that hydrogen-enriched fuels have higher exergy ratios due to superior chemical exergy coefficients despite similar energy content. The findings highlight the need to match fuel chemistry with engine cycle dynamics to optimise converting incoming exergy into practical work, particularly in fast-cycle propulsion systems such as UAVs.

Exhaust exergy indicates the portion of energy irreversibly lost to the environment via exhaust gases and is essential for assessing a system's second law efficiency. In this research, fuel mixtures enhanced with peroxide showed slightly lower

Fig. 7 Fuel exergy values of test fuels at different thrust levels

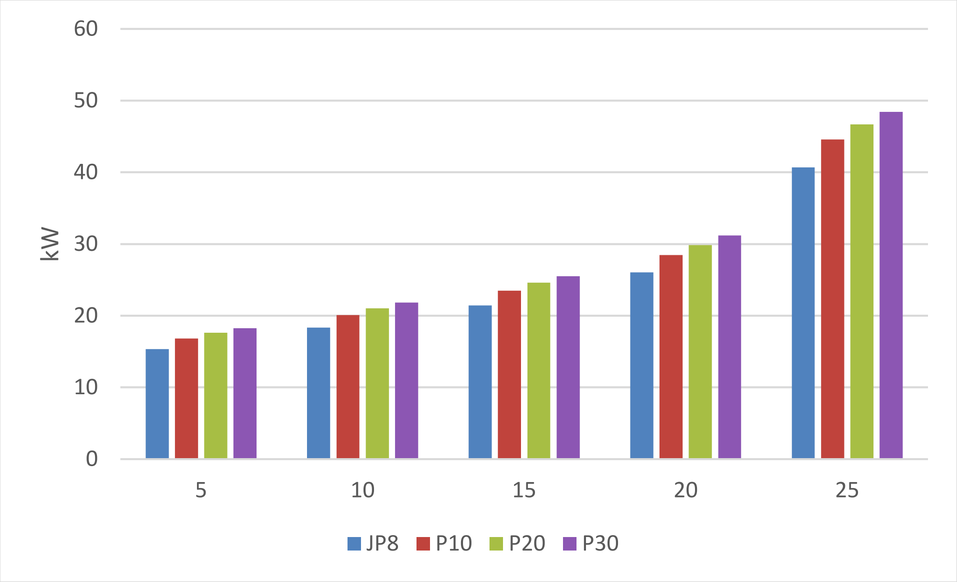

Fig. 8 Exhaust exergy values of test fuels at different thrust levels

exhaust exergy values than pure JP8 across all thrust levels. Although this slight reduction is thermodynamically advantageous, it does not fully offset the greater efficiency losses resulting from thermal redistribution from the peroxide source. Notably, JP8 exhibited the highest exhaust exergy (2.471 kW at 25 kg thrust), implying a greater residual energy potential in unreacted or partially burned gases. However, this also indicates that the conversion of chemical energy into work is incomplete. The slight differences in exhaust exergy among the mixtures imply that adding peroxide slightly shifts energy losses toward other reservoirs, like heat transfer or internal irreversibilities. This impact is more evident in two-stroke engines, which typically experience leakage and short-circuit losses due to the absence of dedicated exhaust and intake strokes. These factors inherently hinder complete combustion and leave residual chemical energy in the exhaust. Additionally, limited air–fuel mixture durations during high-speed operation and in two-stroke engines reduce combustion efficiency and raise exhaust exergy. To improve UAV engine performance, especially in two-stroke designs, it is crucial not only to minimise exhaust losses but also to implement combustion strategies that enhance fuel–air mixing and reduce leakage-related irreversibilities. Overall, optimising UAV engines requires a system-level approach that minimises exhaust losses while ensuring efficient combustion and managing other entropy-producing mechanisms. The insights from this study are thus highly valuable for the field (Fig. 8).

Fig. 9 Thermal exergy values of test fuels at different thrust levels

The exergy of thermal losses indicates the potential usable energy lost during thermodynamic processes without being converted back to heat. These losses diminish the system's capacity to do practical work and are especially important for lightweight, high-speed UAV engines. Figure 9 displays the exergy losses for different fuel mixtures, with the highest value reaching 3.637 kW for the P30 mixture at 25 kg thrust. In peroxide-rich mixtures, thermal exergy losses increase with engine power, showing that peroxide has a larger impact under higher load conditions. For instance, in the P10 mixture, losses grew from 1.191 kW at 5 kg thrust to 3.167 kW at 25 kg thrust. At 10 kg thrust, P10's losses were 1.329 kW, while P30's were 1.501 kW. These losses are worsened by two-stroke engine design constraints, such as the lack of separate exhaust strokes, rapid heat transfer, and higher wall surface-to-volume ratios, which hinder effective heat recovery and raise entropy production. Moreover, insufficient exhaust gas discharge and faster cycle times in two-stroke engines lead to increased thermal irreversibilities by limiting residence time for combustion and heat exchange. As a result, the trend of rising thermal exergy losses with peroxide content and thrust is more evident in two-stroke UAV engines than in four-stroke engines documented in previous research.

Exergy destruction is a key measure of thermodynamic irreversibility in internal combustion engines, indicating the portion of energy lost to entropy that cannot be converted into practical work. It generally results from combustion inefficiencies, incomplete chemical reactions, mechanical friction, heat transfer at finite temperatures, and turbulence dissipation. As shown in Fig. 10, exergy destruction increases notably with engine thrust. For example, in the P20 fuel blend, it rose from 13.571 kW at 5 kg thrust to 33.293 kW at 25 kg thrust. The lowest was for JP8 at 5 kg (11.462 kW), while peroxide-enriched blends consistently showed higher exergy destruction across all thrusts. At 20 kg thrust, JP8's exergy destruction was 17.077 kW, increasing to 21.803 kW for the P30 blend. In two-stroke UAV engines, high exergy destruction is intensified by design features like overlapping intake and exhaust phases, rapid pressure variations, and limited combustion chamber residence time. These conditions lead to incomplete combustion and short-circuiting of unburned fuel–air mixtures, wasting chemical energy and increasing entropy. Additionally, peroxide addition—despite its oxidising potential—can destabilise combustion due to its high reactivity and cooling effect, worsening thermal gradients and internal irreversibilities. Therefore, the rise in exergy destruction with peroxide content reflects a thermodynamic penalty that offsets potential benefits in combustion performance. These results emphasise the importance of fuel-additive compatibility with two-stroke combustion dynamics and support using exergy-based metrics to optimise energy conversion efficiency.

Exergy destruction is a vital concept indicating the irreversible loss or degradation of usable energy within thermodynamic systems. It typically results from intrinsic irreversibilities such as combustion inefficiencies, mechanical friction, heat transfer across finite temperature gradients, and fluid dynamic losses. High rates of exergy destruction signal inefficient energy conversion and reduce second law efficiencies. Data in Fig. 10 shows that exergy destruction increases significantly with engine thrust. For instance, in the P20 fuel mixture, exergy destruction rose from 13,571 kW at 5 kg thrust to 33,293 kW at 25 kg. Adding hydrogen peroxide to JP8 further raises this loss; at 20 kg thrust, exergy destruction went from 17,077 kW (JP8) to 21,803 kW (P30). In two-stroke UAV engines, this pattern is more pronounced due

Fig. 10 Exergy destruction values of test fuels at different thrust levels

Fig. 11 Exergy loss values of test fuels at different thrust levels

to limitations like incomplete exhaust, short residence times, and limited combustion control. These engines often run with richer air–fuel ratios and experience rapid thermal cycles, increasing entropy production and worsening chemical and mechanical irreversibilities. Additionally, phenomena such as backflow and load short-circuiting, common in two-stroke designs, hinder combustion completion and raise exergy destruction. Therefore, peroxide-related increases in exergy destruction should be viewed not only as chemical instability but also in light of the operational dynamics of two-stroke UAV engines. These insights are key for assessing overall engine performance and identifying optimisation strategies focused on combustion stability, exhaust efficiency, and entropy reduction (Fig. 11).

Exergy efficiency is a vital measure of a system 's thermodynamic performance, reflecting the quality and usability of energy. Unlike thermal efficiency, which only considers the amount of energy converted into work, exergy efficiency accounts for irreversibilities and entropy generation, offering a more thorough performance assessment based on the Second Law of Thermodynamics. As shown in Fig. 12, exergy efficiency varied considerably with thrust and peroxide content. The lowest efficiency is 6. 533%—was observed with the P 30 blend at 5 kg thrust, whereas the JP 8 baseline achieved 17—17.373% at 15 kg thrust. A clear trend was evident: increasing peroxide concentration led to decreased exergy efficiency, mainly due to higher thermal losses and exergy destruction. For example, at 15 kg thrust, the P 10, P 20, and P 30 blends showed efficiencies of 15. 15.845%,

Fig. 12 Exergy efficiency

15. 15.123%, and 14. 14.592%, respectively. This decline is especially significant in two-stroke UAV engines, where rapid combustion, poor in-cylinder mixing, and the absence of distinct intake and exhaust strokes generate more entropy. Additionally, operating at high RPMs with limited control over combustion timing further intensifies irreversibilities, reducing energy conversion efficiency. The addition of peroxide accelerates exothermic decomposition, which can destabilise combustion timing in two-stroke engines, increasing irreversibilities and lowering exergetic performance. Although higher thrust levels can slightly improve exergy efficiency—due to increased combustion temperatures and better volumetric efficiency—these advantages are often offset by inefficiencies caused by peroxide. Literature supports these findings: Akdeniz and Balli [24] found a slight decrease in exergy efficiency when using JP-8 compared to hydrogen, and Balli et al. [52, 53] observed marginal reductions with alternative fuels like methyl oleate and hydrogen, especially in aviation turbojet engines. These parallels highlight that, despite their energetic potential, peroxide-enriched fuel blends can compromise the thermodynamic stability of two-stroke propulsion systems, thus limiting their efficiency improvements.

4.3 Sustainability

Sustainability analysis is a comprehensive method to evaluate the long-term viability of energy systems from environmental, economic, and thermodynamic viewpoints. In internal combustion engines, this assessment is often performed using the Sustainability Index (SI), which combines exergy efficiency and entropy generation to measure how sustainably the energy input is used. A higher SI value (typically above 1) indicates more efficient and environmentally friendly operation. As shown in Table 4, JP8 fuel consistently achieved the highest SI values across all thrust levels, with a value of 1.170 at 10 kg thrust. Peroxide-blended fuels also maintained SI values above 1, although slightly lower—P10: 1.153, P20: 1.145, P30: 1.139—indicating a modest decrease in sustainability with increasing peroxide content. The best SI values for all fuels were observed at 20 kg thrust, likely due to favourable combustion conditions and lower entropy production at moderate loads. In two-stroke UAV engines, factors like scavenging losses, incomplete combustion, and increased cyclic heat rejection further influence the sustainability index, raising entropy production. These can offset the sustainability advantages of additives like hydrogen peroxide, which promote oxidation but may also cause thermodynamic instability and heat transfer losses. Literature supports these findings; Akdeniz and Balli [24] reported increased exergetic sustainability with hydrogen in turbojet engines, while Yucer and Nacakli [53] found that diesel-JP8 blends had slightly lower SI values in UAV jet engines. Overall, these results highlight the importance of a systems-level sustainability approach, considering fuel reactivity, engine design, and operating conditions when choosing additives.

5 Conclusions

This study thoroughly examines how adding hydrogen peroxide to JP8 fuel influences the energy, exergy, and sustainability aspects of internal combustion engines. The experimental analysis yielded the following key findings:

Table 4 Sustainability index at different engine thrust levels

Thrust (kg)	JP8	P10	P20	P30
5	1.084	1.076	1.073	1.070
10	1.170	1.153	1.145	1.139
15	1.210	1.188	1.178	1.171
20	1.239	1.214	1.202	1.192
25	1.226	1.202	1.192	1.183

- Adding peroxide to JP8 fuel led to increased fuel consumption across all thrust levels. For example, at 10 kg thrust, the fuel consumption for the P10 blend rose from 1.450 kg/h to 1.595 kg/h. Although these peroxide blends consumed more fuel, they also delivered more energy because of higher combustion rates. Nevertheless, their energy efficiency was lower than that of pure JP8.
- Adding peroxide markedly raised thermal losses, reaching a maximum of 38.068 kW in the P30 blend at 25 kg thrust. Thermal efficiency was highest at 20.607% with JP8 fuel at 20 kg thrust but decreased as peroxide levels went up, indicating the trade-off between fuel formulation and system efficiency.
- The exergy flow grew with increased thrust power and peroxide addition, driven by higher fuel consumption and chemical potential. For instance, at 10 kg thrust, the incoming exergy flow increased from 18.327 kW with JP8 to 21.820 kW with the P30 blend.
- Exergy destruction and thermal exergy losses were greater in peroxide-containing blends, which reduced exergy efficiency. At 15 kg thrust, the exergy efficiency dropped from 17.373% with JP8 to 14.592% with the P30 blend.
- The sustainability index (SI) declined with higher peroxide content but stayed above one across all tested blends, indicating acceptable long-term performance. JP8 fuel had the highest SI at every thrust level, although the differences between the fuel blends were minor. This suggests that peroxide blends could be viable alternative fuels in certain situations.

The data show that mixing hydrogen peroxide with JP8 fuel decreases energy efficiency but offers a practical trade-off by increasing thrust and energy input. Although peroxide addition results in higher fuel consumption, thermal losses, and exergy destruction—reducing both thermal and exergy efficiencies—the sustainability index stays within acceptable limits. This suggests that blends containing peroxide could serve as suitable alternative fuels for aviation or UAV applications where higher energy input and thrust are more critical.

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Declarations

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

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