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Exergy Analysis of Different Propane-Hydrogen Blends in an Internal Combustion Engine

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Abstract: In this article, an exergy analysis was performed for different propane-hydrogen mixtures in an internal combustion engine (ICE), considering an air excess ratio of $\lambda = 1$ and real combustion conditions. In the exergy analysis, the pressure and temperature of the exhaust gases from the combustion reaction were set to 1 atm and 420°C, respectively. The reference conditions were set to 1 atm and 25°C. Combustion reactions were formulated for fuel cases of 100% Propane (C_3H_8), 60% Propane + 40% Hydrogen, 30% Propane + 70% Hydrogen, and 100% Hydrogen (H_2), with a total fuel amount of 1 kmol. For each reaction, both physical and chemical energies were calculated separately for the fuel and exhaust gases. The analysis revealed that increasing the hydrogen content reduces total fuel exergy but improves exergetic efficiency and lowers exergy destruction. The study highlights the thermodynamic advantages of hydrogen-enriched fuel mixtures in ICEs and supports the use of hydrogen as a cleaner alternative fuel.

Keywords: physical exergy, chemical exergy, propane, hydrogen, molar mixtures of propane and hydrogen, combustion reaction

1. Introduction

In the face of rising global energy demand, the depletion of fossil fuel reserves, escalating costs, and growing environmental concerns, there has been a significant, urgent global movement towards renewable and sustainable energy sources. This paradigm shift is driven not only by the need for environmental preservation but also by the limitations of traditional energy systems in meeting long-term economic and operational efficiency goals. In this context, internal combustion engines (ICEs)—which have historically relied on fossil fuels—are increasingly being investigated for optimization through thermodynamic performance metrics and integration with alternative fuels.

Exergy analysis, grounded in the second law of thermodynamics, has emerged as a critical methodology for evaluating the actual performance of energy systems beyond the conventional energy balance approaches. Unlike first-law efficiency calculations, which may overestimate system performance by neglecting entropy generation, exergy analysis provides deeper insights into the quality and usability of energy, the location and magnitude of irreversibilities, and potential optimization strategies (Kotas, 1985; Tsatsaronis & Lazzaretto, 1999).

Numerous studies have emphasized that combustion is the principal source of exergy destruction in ICEs. Norouzi et al. (2021) analyzed exergy losses in engines running on gasoline, methane, and hydrogen, concluding that while the work exergy output was nearly identical across fuels, hydrogen exhibited the lowest irreversibility under stoichiometric conditions. Jafarmadar (2012) numerically investigated hydrogen-air combustion and demonstrated that higher air–fuel ratios and initial temperatures enhance exergy performance. Gupta (2025) corroborated these findings, showing that higher combustion temperatures reduce fuel exergy destruction for ethanol, methanol, propane, and octane-air mixtures.

Exergoeconomic and environmental assessments further reveal nuanced trade-offs. Gürbüz et al. (2019) found that CO_2 emissions and environmental costs scale with engine power in LPG-fueled engines, suggesting that operating at lower speeds is more sustainable. Gürbüz and Gülcan (2025) compared hydrogen, LPG, and gasoline in an air-cooled engine under stoichiometric conditions and found that hydrogen, despite lower energy and exergy performance, was more environmentally and economically favorable due to its zero carbon emissions. Şöhret et al. (2019) examined the effects of ignition timing and compression ratio on hydrogen-fueled ICEs, highlighting optimization opportunities.

Experimental work by Akçay & Gürbüz (2024) using HHO-assisted flame-jet ignition in propane-fueled engines reported improved engine performance and emission characteristics. Likewise, Beccari & Pipitone (2022, 2023) modeled combustion dynamics in hydrogen-fueled and supercharged SI engines, contributing simplified yet accurate combustion models. Depcik et al. (2023) provided open-source entropy–exergy tools, thereby enhancing accessibility for engine heat-release simulations.

Fuel injection strategies and combustion control also play vital roles. Pan et al. (2022) and Shang et al. (2023) studied hydrogen injection under lean-burn conditions and its effect on emissions. Wei et al. (2022) explored different combustion modes for hydrogen ICEs at low loads. Dual-fuel strategies were examined by Makaryan et al. (2022) and Scrignoli et al. (2022), who reported on the thermodynamic and operational characteristics of hydrogen–methane blends. Rahmani et al. (2023) applied a multiphysics approach to hydrogen-fueled ICEs, while Rovai & Mady (2022) conducted exergetic evaluations on ethanol-based blends.

Alternative fuels like ammonia–hydrogen blends (Salahi et al., 2023) and hydrogen-rich syngas (Shang et al., 2023) have been recognized for their potential to support carbon-neutral transitions. The feasibility of hydrogen adoption in pre-chamber designs has also been reviewed (Matla, 2022; Aljabri et al., 2022), reinforcing its role in sustainable propulsion technologies.

Pozzato et al. (2022) and Galloni et al. (2022) explored hydrogen's sensitivity in engine models and downsized ICE performance, respectively, confirming its promise despite integration challenges. Studies by Falfari et al. (2023), Serbin et al. (2023), and Pielecha & Szwajca (2023) expanded the combustion landscape to turbine systems and multi-stage natural gas combustion, contributing to the diversification of future propulsion systems.

Foundational works such as those by Sayyaadi (2021) and Shukuya & Hammache (2002) provide theoretical and practical frameworks for the design and optimization of low- and high-temperature systems. Meanwhile, Chríbik et al. (2022) and Becerra-Núñez et al. (2022) examined the impacts of synthesis gas and blended fuel on engine operation. Koyun (2018) analyzed exergy across hydrogen–octane blends, and Manavalla et al. (2022) extended this to biodiesel.

In broader sustainable system design, Akbulut et al. (2025) conducted regression-based economic evaluations of photovoltaic investments. Akbulut, Coşgun et al. (2025) proposed a solar-powered biomass system for pet food and compost under a campus-scale circular economy framework. Kochanek et al. (2025) reviewed hydrogen integration in transport systems, while Akbulut, Taşdelen & Coşgun (2025) assessed metaheuristic optimization algorithms in demand-side energy management. Akbulut, Tezcan & Coşgun (2019, 2020) implemented MILP and genetic algorithms for cost-optimized voltage configuration in electrical distribution networks.

Additional modeling studies, such as Agrebi et al. (2022), focused on exergy losses in adiabatic systems, accounting for exhaust gas contributions—particularly relevant for highly insulated ICE environments. Wikipedia (2025) ensures conceptual clarity on combustion thermochemistry, and Çengel & Boles (2011) remain authoritative on applied thermodynamic principles.

Collectively, these 41 studies constitute a comprehensive, interdisciplinary body of knowledge on energy efficiency, thermodynamic optimization, alternative fuels, and sustainability in internal combustion engines and broader energy systems. This literature provides the scientific foundation for the current study, which conducts a detailed exergy and exergetic efficiency analysis of complete combustion in an adiabatic internal combustion engine using propane–hydrogen mixtures at various volumetric ratios. The combustion temperature is assumed to be 2000°C, with exhaust conditions at 1 atm and 420°C, and ambient conditions at 25°C and 1 atm. This thermodynamic approach offers valuable insights into fuel-blending strategies to improve exergy performance in future energy systems. However, it should be noted that the current analysis is based on values obtained under actual internal combustion engine operating conditions in our university laboratory (product and exhaust gas composition) and that these values are used to determine the chemical reaction required for the physical and chemical exergy calculations. It should also be noted that during the analysis, exergy was calculated under idealized steady-state, adiabatic assumptions. Real internal combustion engines are subject to heat losses, mechanical friction, incomplete combustion, and transient operating conditions, which can affect the actual exergy distribution and irreversibility levels. Therefore, the findings of this study should be interpreted as a theoretical thermodynamic assessment that provides an upper limit evaluation of the exergy behavior of propane-hydrogen mixtures.

2. Models and Methods

In this study, real complete combustion conditions for pure propane, hydrogen, and their mixtures at different volumetric ratios were examined in an internal combustion engine. First, combustion reactions for real, complete combustion conditions were established. While creating these reactions, experimentally obtained exhaust gas components and their percentage values for Air-Fuel Equivalence Ratio $\lambda = 1$ were taken into account. The air entering the combustion chamber was assumed to be at 25°C and 1 atm pressure. The temperature and pressure values for the reaction products were assumed to be 420°C and 1 atm, respectively. The control volume for the adiabatic internal combustion engine is schematically shown in Figure 1. As seen in Figure 1, the control volume is considered a steady-flow open system.

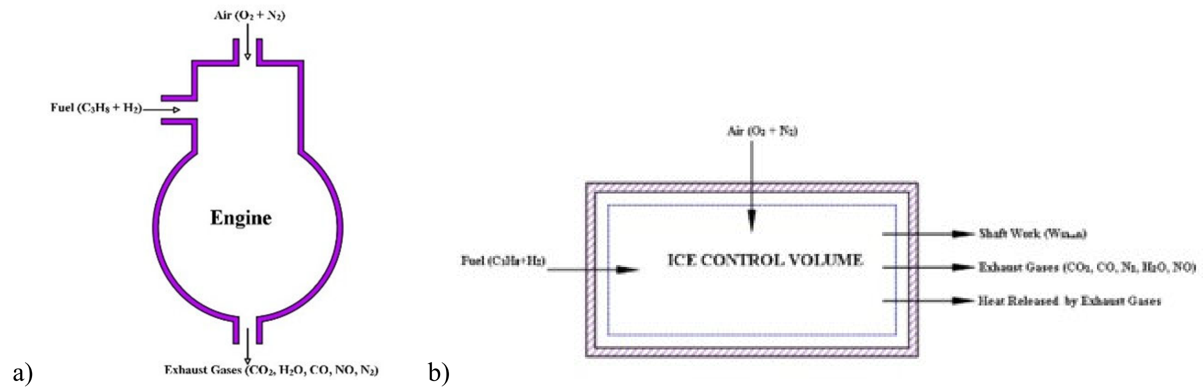

Fig. 1. (a) Schematic representation of an internal combustion engine, (b) Control volume for a steady-flow open system

Accordingly, if we write the First Law of Thermodynamics for a steady-flow open system, we get:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{d\dot{E}}{dt} \tag{1}$$

Where, $\dot{E}_{in}$ represents the energy entering the control volume, and E˙out represents the energy leaving it. Since the system is considered steady, $\frac{d\dot{E}}{dt} = 0$, thus $\dot{E}_{in} = \dot{E}_{out}$

For the case of real complete combustion of 100% propane as fuel, equation (2) was formulated based on experimentally obtained products.

$$\begin{aligned}&[(1-x)\text{kmol}C_3H_8 + x\ \text{kmol}H_2] + y\ \text{kmol}\ (O_2 + 3.76\ N_2) \Rightarrow\\&\Rightarrow a\ \text{kmol}CO_2 + b\ \text{kmol}H_2 + c\ \text{kmol}N_2 + \text{heat}\end{aligned} \tag{2}$$

In the reaction described by equation (2), while HC and NO_x values were measured in ppm for the products obtained at λ = 1, other products were measured in liters per minute (L/min). When the HC and NO_x values measured in ppm were converted to volumetric percentages, the HC value was neglected because it was very small. Nitrogen oxides are emitted from combustion systems in both NO and NO_2 forms. However, while NO_x is in the NO form in high-temperature regions, it transforms into the NO_2 form by cooling and oxidizing in the atmosphere. Since our reaction product conditions are at high temperature, NO_x was taken as NO. Accordingly, the propane combustion reaction in equation (2) was rewritten as:

$$\begin{aligned}&[(1-x)\text{kmol}C_3H_8 + x\ \text{kmol}\ H_2] + y\ \text{kmol}\ (O_2 + 3.76\ N_2) \Rightarrow\\&\Rightarrow a\ \text{kmol}CO_2 + b\ \text{kmol}H_2O + c\ \text{kmol}N_2 + d\ \text{kmol}\ CO + e\ \text{kmol}\ O_2 + \ \text{heat}\end{aligned} \tag{3}$$

When the combustion reaction in equation (3) was balanced according to the conservation of mass, the values of x, y, a, b, c, e, and f in the reaction were calculated as x = 1.67; y = 8.2; a = 4.65; b = 6.68; c = 0.37; e = 0.0572, and f = 30.832.

For the case of 100% hydrogen as fuel, the reaction was written as:

$$x\ \text{kmol}\ H_2 + y\ \text{kmol}\ (O_2 + 3{,}76N_2) \Rightarrow a\ \text{kmol}\ H_2O + b\ \text{kmol}\ N_2 + \text{heat} \tag{4}$$

where: x = 1, y = 0.5, a = 1, b = 1.88.

The volumetric percentages of propane and hydrogen in the combustion chamber were considered as 100% C_3H_8 + 0% H_2, 60% C_3H_8 + 40% H_2, 30% C_3H_8 + 70% H_2, and 0% C_3H_8 + 100% H_2. It was stated that the values of x, y, a, b, c, e, and f in the reactions would differ for different fuel mixture ratios. The mole percentages of the components in the reaction were calculated according to equation (5)[9].

Mole percentage of reaction:

$$x = \frac{n_i}{\sum_i n_i} \tag{5}$$

Where n represents the number of moles of the components, and i represents the components. Thermodynamic characteristics of the fuels and products used in the study are given in Table 1.

Table 1. Thermodynamic characteristics of the fuels and products used[10]

Chemical Component	Mole Mass (kg/kmol)	Lower Thermal Value (MJ/Kg)
C_3H_8	44	46.350
H_2	2	119.930
CO	28	10.112
NO	30	-
H_2O	18	-
CO_2	44	-
N_2	28	-
O_2	16	-

Exergy is defined as the maximum useful work that can be obtained when a system is in equilibrium with the selected reference environment (thermal, mechanical, or chemical). Exergy is not conserved like energy; it is destroyed within the system. The most common characteristic of a system is that it depends on both the system's state and the environment's properties. The state of the environment, also called the dead state, is defined by the ambient temperature and pressure. The exergy analysis of thermal systems is divided into Physical (Thermo-mechanical) exergy and chemical exergy. Physical exergy represents the maximum useful work that can be obtained when the system reaches thermal and mechanical equilibrium with the surrounding atmosphere, and in this case, the system does not undergo any chemical reaction with the environment. When the temperature and pressure of the system become equal to the temperature and pressure of the environment, thermal and mechanical equilibrium are achieved. Chemical exergy is the maximum work obtained in a state of chemical equilibrium established as a result of a chemical reaction.

In this study, firstly four different combustion reactions were formulated for fuel mixtures of 100% propane, 100% hydrogen, and various molar percentage ratios of propane + hydrogen for an internal combustion engine. Subsequently, an exergy-based performance analysis was conducted for these reactions. In the calculations, a reference pressure of 1 atm (P_0) and a temperature of 25°C (T0) were used, while the pressure and temperature of the reaction products were set to 1 atm and 420°C, respectively. For the four different reactions considered in the internal combustion engine, the physical and chemical exergy values were calculated separately for the incoming fuel(s) and the outgoing reaction products. The calculation of chemical exergy for the air required for combustion was neglected in the reactions. The only input exergy is the fuel's chemical exergy. Since propane is a hydrocarbon fuel in the gas phase, its chemical exergy was calculated according to equation (6).

$$\beta = 1.0406 + 0.0144\ \frac{h}{c} \tag{6}$$

Where the h/c ratio represents the atomic ratio for the hydrogen (h) and carbon (c) elements in propane. The total exergy for the reaction products was calculated according to equation (7):

$$\bar{e}^{pr}_{x,out} = \bar{e}^{ph}_{pr} + \bar{e}^{ch}_{pr} \tag{7}$$

Where, $\bar{e}^{ph}_{pr}$ represents the physical exergy, and $\bar{e}^{ch}_{pr}$ represents the chemical exergy. The physical exergy of the reaction products herein was calculated using equation (8).

$$\bar{e}^{ph}_{pr} = \left[\left(\sum_i \bar{s}(T, P_{=1atm})_i + \sum_i \bar{h}_0(T_0, P_0)_i\right) - \left(\sum_i \bar{s}(T, P_{=1atm})_i + \bar{s}_0(T_0, P_0)_i\right)\right] \tag{8}$$

For the calculation of the physical exergy of the reaction products, all necessary values were either read from tables or calculated using equation (8) based on the reference pressure and temperature (P0 = 1 atm, T0 = 25°C) and the exhaust gas pressure and temperature (P = 1 atm, T = 420°C). Thus, the physical exergy of the combustion products was calculated. The chemical exergy of the products was calculated according to equation (9).

$$\bar{e}^{ch}_{pr} = \sum_i x_i \bar{e}^{ch}_i + \bar{R}T_0 \sum_i x_i \ln x_i \tag{9}$$

Where, $\bar{e}^{ch}_i$ is the standard chemical exergy for each component (kJ/kmol), and $\bar{R}$ is the universal gas constant (8.315 kJ/kmolK). According to equation (9), the chemical exergy of the reaction products was calculated separately, and the total chemical exergy was found.

The exergy of the heat released during combustion is calculated according to equation (10):

$$\bar{e}_{x,in}^{Q} = Q\left(1 - \frac{T_0}{T_{combustion}}\right) \quad (10)$$

Where Q is the heat released during combustion, and $T_{combustion}$ is the combustion temperature.

Considering that approximately 1/3 of the heat energy generated from combustion in the engine is lost with the exhaust gases, the total exergy for the reaction products can be written according to equation (11):

$$\bar{e}_{x,out} = \frac{\bar{e}_{x,out}^{Q}}{3} + \bar{e}_{x,out}^{pr} + \bar{e}_{x,W} \quad (11)$$

Exergy loss, or irreversibility, is a measure of process inefficiency. Unlike traditional performance criteria, the concept of irreversibility is based on the second law of thermodynamics. The exergy balance for a considered steady-flow control volume was derived by combining the steady-flow energy equation (1st Law) and the entropy generation rate (2nd Law). The exergy balance for a control volume (system) is rewritten according to equation (12) (kJ).

$$\dot{E}_{x,in} - \dot{E}_{x,out} - \dot{E}_{dest.} = \frac{d\dot{E}}{dt} \quad (12)$$

Where, $\dot{E}_{x,in}$ is the exergy entering the system (kJ), $\dot{E}_{x,out}$ is the exergy leaving the system (kJ), and $\dot{E}_{dest.}$ is the exergy destruction (kJ). If the equation is rewritten per unit kmol for a steady-flow open system, equation (13) is obtained.

$$\bar{e}_{x,in}^{Q} - \bar{e}_{x,out}^{Q} + \bar{e}_{x,in}^{fuel} - \bar{e}_{x,out}^{pr} - \bar{e}_{x,dest.} - \bar{e}_{x,W} = 0 \quad (13)$$

Where, $\bar{e}_{x,in}^{Q}$ is the specific heat exergy input (kJ/kmol), $\bar{e}_{x,out}^{Q}$ is the specific heat exergy output(exhaust) (kJ/kmol), $\bar{e}_{x,in}^{fuel}$ is the specific fuel exergy input (kJ/kmol), $\bar{e}_{x,out}^{pr}$ is the specific product exergy output, $\bar{e}_{x,W}$ is work exergy per kmol and $\bar{e}_{x,dest.}$ is the specific exergy destruction (kJ/kmol). All exergy calculations for the real complete combustion in the adiabatically assumed internal combustion engine are shown in Table 2.

Table 2. Engine exergy calculation results for True Complete Combustion in an internal combustion engine, assumed to be adiabatic

Fuel (%)		$\bar{e}_{x,propane}$ (kJ/kmol) Fuel exergy (C_3H_8)	$\bar{e}_{x,hydrogen}$ (kJ/kmol) Fuel exergy (H_2)
C_3H_8 (Propane)	H_2 (Hydrogen)	C_3H_8	H_2
100	0	2161464.0	-
60	40	1296878.4	96051.2
30	70	648439.2	168089.6
0	100	-	240128.0

Table 2. Continued

$\bar{e}_{x,propane}+\bar{e}_{x,hydrogen}$ (kJ/kmol) Total fuel exergy ($C_3H_8+H_2$)	$\bar{e}_{x,products}^{physical}$ (kJ/kmol) Exhaust gas (CO_2, H_2O, CO, NO, N_2) physical exergy	$\bar{e}_{x,products}^{chemical}$ (kJ/kmol) Exhaust gas (CO_2, H_2O, CO, NO, N_2) chemical exergy
C_3H_8+ H_2		
2161464.0	-87843.482	-85627.411
1392929.6	-87824.878	-85640.792
816528.8	-88222.873	-86065.621
240128.0	-109568.324	107401.301

Table 2. Continued

Fuel (%)		$\bar{e}^{Q}_{x,propane}$ (kJ/kmol) Fuel heat exergy	$\bar{e}^{Q}_{x,hydrogen}$ (kJ/kmol) Fuel heat exergy
C_3H_8	H_2	C_3H_8	H_2
100	0	1726819.744	-
60	40	1036091.777	83458.477
30	70	518045.923	146052.336
0	100	-	208646.194

Table 2. Continued

$\bar{e}^{Q}_{x,propane} + \bar{e}^{Q}_{x,hydrogen}$ (kJ/kmol) Total fuel heat exergy	$\bar{e}^{Q}_{x,out}$ (kJ/kmol) Heat exergy released from the combustion chamber with the exhaust gas	W_{shaft} (kJ/kmol) Shaft work
C_3H_8+ H_2	C_3H_8+H_2	
1726819.744	1132802.496	695580.48
1119550.324	734430.681	450966.20
664098.259	435651.820	267505.50
208646.194	136872.960	84044.80

Table 2. Continued

$\bar{e}^{total}_{x,out}$ $\bar{e}^{total}_{x,products}+\bar{e}^{Q}_{x,out}+\bar{e}_{x,W}$ (kJ/kmol)	$\bar{e}_{x,dest.}$ (kJ/kmol) Exergy destruction
1742755.565	333081.20
1099756.089	207532.80
617091.699	113371.48
113516.459	19210.24

Based on the calculated values for different fuel ratios in the table, diagrams were drawn, and the results were interpreted.

The exergetic efficiency, which reflects the system's performance, was also calculated. Exergetic efficiency is an important parameter that indicates the thermal evaluation of energy systems.

The performance evaluation and design optimization of thermal systems require a clear definition of exergetic efficiency and a consistent costing approach for each system component.

The literature contains three definitions of exergetic efficiency for continuous processes. These may be listed as conventional or simple exergetic efficiency, rational exergetic efficiency, and utilizable exergy coefficient. Conventional exergetic efficiency is the simplest form (conventional)of exergetic efficiency as Eq.14,

$$\eta_{ex} = \frac{\dot{E}_{x,out}}{\dot{E}_{x,in}} \tag{14}$$

The terms, $\dot{E}_{in}$ and $\dot{E}_{out}$ herein have been previously defined. Furthermore, for power-producing systems, conventional exergetic efficiency can be expressed by equation (15).

$$\eta_{ex} = \frac{\dot{W}_{sh}}{\dot{E}_{x,fuel}} \tag{15}$$

Where, $\dot{W}_{sh}$ is the shaft work(=$\dot{E}_{x,W}$), and $\dot{E}_{fuel}$ is the exergy of the fuel entering the engine. The variation in the exergetic efficiency obtained from the calculations as a function of the fuel quantity is shown in a Table and a diagram. As seen in Table 3, the exergetic efficiency increases as the mole percentage of hydrogen in the fuel mixture increases. However, as seen from the calculations, as the hydrogen mole percentage increases, the total fuel energy, total fuel exergy, shaft work, and shaft exergy decrease.

Table 3. Variation of exergetic efficiency based on exergy of input and output for different volumetric blends of propane and hydrogen

Propane (%)	Hydrogen (%)	Total incoming fuel energy (kJ/kmol)	Total incoming fuel exergy (kJ/kmol)
100	0	1987372.80	2161464.0
60	40	1288474.88	1392929.6
30	70	764301.44	816528.8
0	100	240128.00	240128.0

3. Results and Discussion

The exergy results for the combustion reactions analyzed in this study are presented in Table 2. For internal combustion engines using propane and hydrogen in various ratios, an exergy balance must be established. To formulate this balance, the exergies entering and leaving the engine must be calculated separately. The inlet exergies were considered to be the fuel exergy and the heat exergy released from combustion. The outlet exergies were taken as the physical and chemical exergies of the combustion products, along with the exergy of the heat lost with the exhaust.

Following these calculations, the exergy destruction was determined by applying the exergy balance equation to the system under investigation. The calculations showed that as the propane percentage decreased and the hydrogen percentage increased, the fuel exergy decreased. Conversely, the total physical and chemical exergy of the products increased under these same conditions.

The exergy of the heat generated by the combustion of the propane-hydrogen fuel in the engine was calculated, with approximately one-third of this exergy lost through the exhaust. The heat exergy released from combustion decreased with a decrease in propane percentage and an increase in hydrogen percentage. Finally, it was found that increasing the hydrogen content of the fuel decreased the calculated exergy destruction from the exergy balance equation.

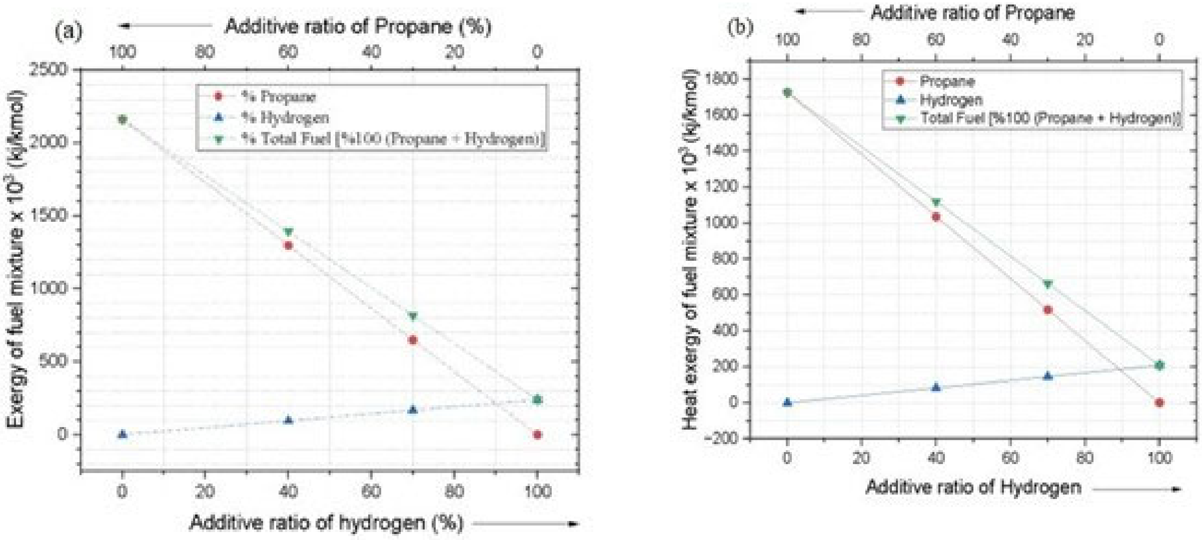

Fig. 2. Variation of (a) fuel exergy and (b) heat exergy as a function of percentage blends of propane and hydrogen as mole rate

For an internal combustion engine, graphs were plotted (Figures 2-8) using the exergy analysis values from Tables 1 and 2, based on the combustion reaction for a propane-hydrogen mixture. Figure 2 illustrates the variation of fuel exergy and heat exergy as a function of the percentage composition of propane and hydrogen.

As depicted in Figure 2(a), as the mole percentage of hydrogen in the fuel mixture decreases (i.e., the proportion of propane increases), the total exergy increases. It is evident from the graph that the contribution of hydrogen to the total fuel exergy remains low; propane provides higher exergy.

Figure 2(b) presents the variation in the total fuel heat exergy with hydrogen mole percentage. As shown in the figure, as the mole fraction of hydrogen in the fuel mixture increases, the total fuel heat exergy decreases. The graph also makes it clear that hydrogen's contribution to the total fuel heat exergy is similarly low.

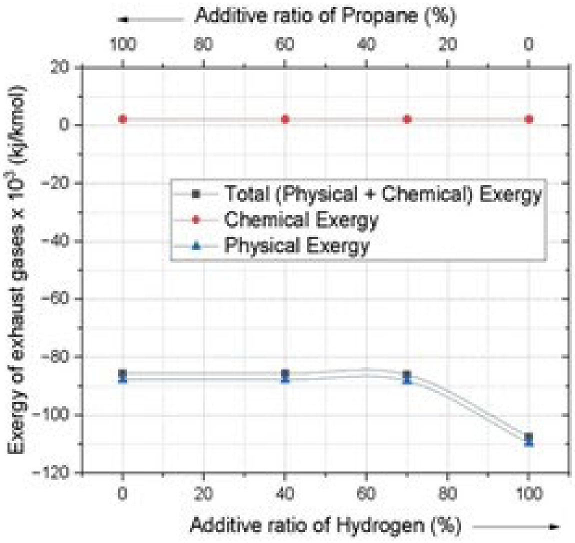

Fig. 3. Variation of the physical and chemical exergy of combustion products as a function of the molar percentage of propane and hydrogen in the fuel blend

Figure 3 illustrates the changes in the physical, chemical, and total exergy of the combustion products for various propane and hydrogen blend ratios. As shown in the graph, the chemical exergy of the combustion products remains virtually unchanged across blend ratios. Consequently, it is evident that the physical exergy of the products primarily determines the total exergy of the exhaust gases. It is also observed that as the hydrogen enrichment ratio increases, the physical exergy becomes more negative. This decrease accelerates, particularly after the hydrogen content in the mixture exceeds 80%.

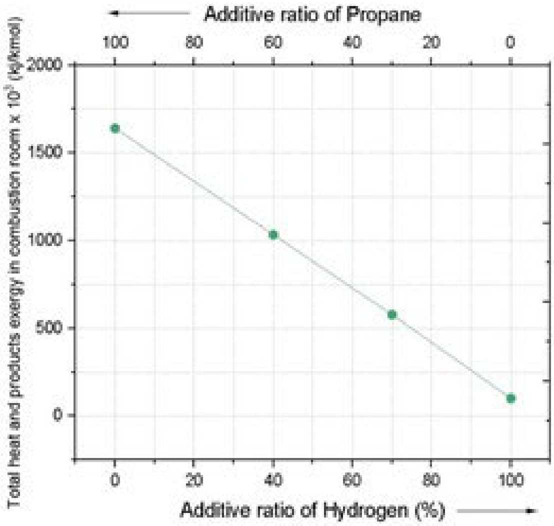

Fig. 4. Total heat and exhaust exergy in the combustion chamber for propane-hydrogen mixtures with various molar ratios

As shown in Figure 4, the sum of the heat released by the combustion reaction and the product exergy in the combustion chamber decreases as the molar percentage of hydrogen increases.

As shown in Figure 5, the exergy destruction for the considered system decreases as the mole percentage of hydrogen in the fuel mixture increases. This result indicates that hydrogen's exergetic efficiency as a fuel is superior to that of propane. Nevertheless, in practical engine applications, additional irreversibilities such as wall heat transfer, friction losses, pumping work, and mixture inhomogeneities may alter the absolute values of exergy destruction and efficiency. Although the numerical magnitudes may vary under real operating conditions, the observed trend of decreasing exergy destruction with increasing hydrogen content is expected to remain valid.

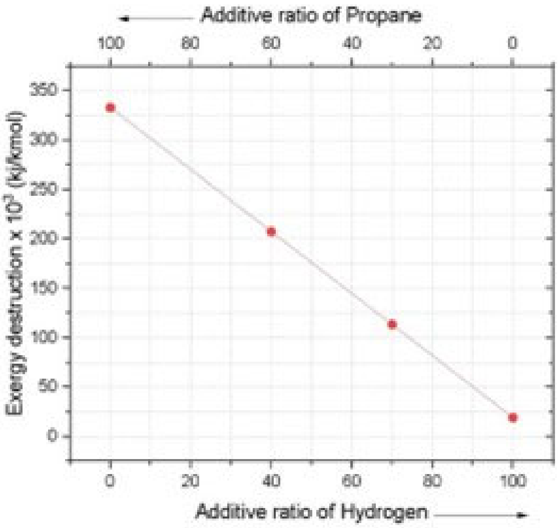

Fig. 5. Variation of exergy destruction for the system with propane-hydrogen mixtures at various molar ratios

Figure 6 presents the variation in shaft work exergy and exergetic efficiency with increasing propane-hydrogen blend percentage. As shown in Figure 6, the exergetic efficiency increases with increasing hydrogen content in the fuel mixture. This increase becomes more pronounced at hydrogen concentrations of 40% and higher.

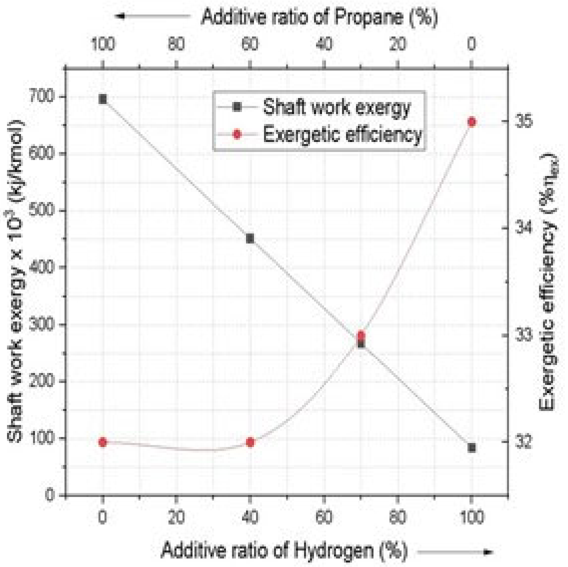

Fig. 6. Variation of shaft work exergy and exergetic efficiency in the system as a function of percentage blends of propane and hydrogen as mole rate

4. Conclusions

In this study, the combustion behavior of various volumetric mixtures of propane and hydrogen was modeled under real complete combustion conditions within an adiabatically assumed internal combustion engine. A detailed exergy analysis was carried out using the second law of thermodynamics, based on a steady-flow open control-volume approach, which appropriately represents the thermodynamic behavior of the engine system. Both mass and energy interactions across the control boundaries were accounted for, ensuring accurate representation of the energy conversion and loss mechanisms.

The exergy analysis focused on evaluating physical and chemical exergies of both the incoming fuel and the outgoing combustion products. Additionally, the heat exergy released from combustion and the shaft work were analyzed. Through this methodology, a complete exergetic balance was established for each fuel blend, enabling the quantification of exergy destruction (irreversibility) and exergetic efficiency.

The results, summarized in Tables and Figures, demonstrate that increasing the hydrogen content of the fuel mixture consistently improves exergetic efficiency. This enhancement is primarily due to hydrogen's lower irreversibility and cleaner combustion characteristics. However, it was also observed that as the hydrogen mole fraction increases, the total input energy, the fuel's chemical exergy, and the resulting shaft work decrease. This trade-off suggests that although hydrogen increases efficiency from an exergy standpoint, it may yield lower power output unless compensated by system design changes (e.g., higher compression ratios or injection strategies).

Furthermore, the physical exergy of the exhaust products was found to become more negative with higher hydrogen ratios, while the chemical exergy of the products remained relatively constant. This indicates that the exergy performance is strongly influenced by the thermomechanical properties of the exhaust gases rather than their chemical composition in the studied scenarios.

In conclusion, integrating hydrogen into propane-based fuel mixtures offers a promising pathway to enhance the exergetic performance of internal combustion engines, particularly under adiabatic, stoichiometric operating conditions. Nonetheless, the observed reduction in shaft work and total input energy at higher hydrogen levels must be carefully considered in practical engine applications. Future research should explore advanced combustion strategies and engine designs that leverage hydrogen's high exergy efficiency without compromising overall power output. Additionally, experimental validation and detailed numerical simulations (e.g., CFD-based combustion modeling) are recommended to verify the practical applicability of the theoretical results derived from the assumptions made during the analysis for the selected control volume and to quantify deviations from actual engine operating conditions.

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