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Performance Enhancement of Spark-Ignition Engines Using an Ethanol Reforming-Based On-Board Hydrogen Generation System

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Abstract. The growing need for environmentally sustainable transportation has encouraged extensive research into alternative fuel technologies capable of reducing greenhouse gas emissions and improving engine efficiency. Among the various alternatives, hydrogen has attracted considerable attention because of its high flame propagation speed, broad flammability limits, and cleans combustion characteristics. Despite these advantages, the widespread adoption of hydrogen-fueled vehicles remains constrained by challenges associated with hydrogen storage, transportation, and infrastructure development. To overcome these limitations, the present study investigates an on-board hydrogen generation system based on ethanol steam reforming for application in spark-ignition (SI) engines. Ethanol is considered a suitable feedstock due to its renewable nature, ease of handling, established distribution network, and relatively high hydrogen content. In the proposed system, ethanol undergoes catalytic steam reforming to produce a hydrogen-rich gas stream, which is subsequently supplied to the engine to improve combustion characteristics and overall performance. The research focuses on evaluating the influence of key reforming parameters, including reforming temperature, steam-to-ethanol ratio, and catalyst loading, on hydrogen production efficiency. Furthermore, engine performance is assessed in terms of brake thermal efficiency, brake specific fuel consumption, and exhaust emissions such as carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NOx). Advanced optimization techniques, namely Response Surface Methodology (RSM) and Artificial Neural Networks (ANN), are proposed to identify the optimum operating conditions for maximizing hydrogen yield and engine performance while minimizing emissions. In addition, Computational Fluid Dynamics (CFD) analysis using Fluent is considered to examine combustion behavior and flow dynamics within the engine system. The anticipated outcomes of this work include enhanced combustion efficiency, lower pollutant emissions, improved fuel utilization, and the promotion of renewable fuel-based hydrogen generation as a practical pathway toward cleaner and more sustainable transportation technologies.

Keywords: On-board Hydrogen Generation, Ethanol Steam Reforming, Hydrogen-Enriched Combustion, Spark-Ignition Engine, Response Surface Methodology (RSM), Artificial Neural Network (ANN), Computational Fluid Dynamics (CFD), Sustainable Transportation.

I. Introduction

The transportation sector is one of the largest consumers of fossil fuels and a major contributor to environmental pollution. Rapid industrialization, increasing vehicle ownership, and growing energy demand have intensified concerns regarding the depletion of petroleum reserves and the emission of greenhouse gases. Conventional internal combustion engines operating on gasoline and diesel release significant amounts of carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC), and nitrogen oxides (NO_x), which contribute to global warming and deteriorating air quality. As a result, governments and environmental agencies worldwide have implemented stringent emission regulations for both light-duty and heavy-duty vehicles, encouraging the development and adoption of cleaner and more sustainable energy technologies.

Among the various alternative fuels under investigation, hydrogen has gained considerable attention because of its superior combustion characteristics and environmentally friendly nature. Hydrogen possesses a very wide flammability range (equivalence ratio of 0.04–0.75), allowing stable combustion under both lean and rich operating conditions. It also has a high flame propagation speed of approximately 2.5 m/s, which promotes rapid and complete combustion inside the engine cylinder. Furthermore, hydrogen requires very low ignition energy, making it easier to ignite than conventional hydrocarbon fuels. The most significant advantage of hydrogen is that its combustion does not produce carbon-based pollutants, as water vapor is the primary combustion product. These characteristics make hydrogen a promising fuel for improving engine efficiency while reducing harmful emissions.

Despite these benefits, the practical implementation of hydrogen-fueled vehicles faces several challenges. One of the major obstacles is hydrogen storage. Due to its low volumetric energy density, hydrogen must be stored either in compressed form at very high pressures (typically 350–700 bar) or in liquid form at cryogenic temperatures around −253°C. High-pressure storage systems require expensive and heavy composite tanks, which increase vehicle weight and cost. In addition, hydrogen leakage is a concern because hydrogen molecules are extremely small and can easily escape through tiny openings. Cryogenic storage, although capable of providing higher energy density, requires sophisticated insulation systems and suffers from boil-off losses during long-term storage. Another significant limitation is the lack of a widespread hydrogen production, transportation, and refueling infrastructure, which restricts the commercialization of hydrogen-powered vehicles.

To overcome these limitations, researchers have focused on the concept of on-board hydrogen generation. Instead of storing large quantities of hydrogen within the vehicle, hydrogen can be produced as needed from readily available liquid fuels. This approach eliminates the need for bulky hydrogen storage tanks and reduces dependence on hydrogen refueling stations. On-board hydrogen generation systems can therefore provide a practical and economically viable pathway for utilizing hydrogen in automotive applications.

Among the various fuels available for hydrogen production, bioethanol (C_2H_5OH) is considered one of the most suitable feedstocks. Bioethanol is a renewable fuel derived from biomass resources such as sugarcane, corn, agricultural residues, and other organic materials. It is non-toxic, biodegradable, and relatively easy to handle and transport. Unlike hydrogen, ethanol can

be stored as a liquid under ambient conditions and can utilize the existing fuel distribution infrastructure without major modifications. Another important advantage of ethanol is its high hydrogen-to-carbon ratio, which makes it an efficient source for hydrogen production through reforming processes. Since bioethanol is produced from renewable biomass, it also contributes to reducing the net carbon footprint of transportation systems.

The conversion of ethanol into hydrogen is commonly achieved through steam reforming. In this process, ethanol reacts with water vapor in the presence of a catalyst at elevated temperatures to produce hydrogen-rich synthesis gas (syngas). The overall steam reforming reaction can be represented as:

$$C_2H_5OH + 3H_2O \rightarrow 2CO_2 -$$

This reaction demonstrates that one mole of ethanol can theoretically generate six moles of hydrogen, making ethanol an efficient hydrogen carrier. The resulting hydrogen-rich syngas can then be supplied to the engine intake system, where it acts as a supplementary fuel to improve combustion characteristics.

A key feature of the proposed system is the integration of an exhaust-heated catalytic steam reformer with the spark ignition engine. Steam reforming is an endothermic process, meaning it requires a continuous supply of heat. Instead of consuming additional fuel to provide this energy, the system utilizes waste heat from the engine exhaust gases. The hot exhaust gases transfer thermal energy to the catalytic reformer, where the ethanol-water mixture undergoes reforming reactions. This approach improves overall energy utilization by recovering waste heat that would otherwise be lost to the environment.

The hydrogen-rich syngas produced by the reformer enhances the combustion process within the spark ignition engine. The presence of hydrogen increases flame speed, improves ignition quality, and promotes more complete fuel combustion. Consequently, engine thermal efficiency increases while emissions of carbon monoxide and unburned hydrocarbons decrease. The improved combustion characteristics also enable stable engine operation under lean-burn conditions, further reducing fuel consumption and pollutant formation. Therefore, integrating on-board hydrogen generation through ethanol reforming with spark ignition engines represents a promising strategy for achieving higher efficiency, lower emissions, and greater sustainability in future transportation systems.

Core Correlation with Photoelastic Stress Analysis Principles

The development of reliable on-board reforming reactors requires careful consideration of structural durability under high temperatures (500°C–800°C) and continuous engine vibrations. To ensure safe operation and prevent structural failures, advanced experimental and numerical analysis techniques are employed. Photoelasticity is a non-destructive experimental method widely used to visualize and analyze stress distributions in transparent materials.

The technique is based on the phenomenon of stress-induced birefringence, where a material under load alters the behavior of polarized light passing through it. This produces visible fringe patterns that represent regions of varying stress concentration. These fringe patterns help identify critical locations that may be prone to failure under complex loading conditions. When combined with finite element analysis using software such as ANSYS, photoelastic testing provides a reliable approach for validating structural designs and optimizing reactor components to withstand repeated thermomechanical loading.

II. Literature Review and Historical Milestones

Research on hydrogen-assisted internal combustion engines has progressed significantly through developments in catalyst technology, thermal management, and engine control strategies. Early studies mainly focused on direct hydrogen injection systems supplied from external storage tanks. However, these systems often experienced problems such as engine knocking, intake backfiring, and pre-ignition under high-load conditions. To address these issues, recent investigations have focused on on-board hydrogen generation and controlled hydrogen enrichment techniques. The addition of small amounts of hydrogen to conventional fuel-air mixtures has been shown to improve combustion stability, increase thermal efficiency, and reduce harmful exhaust emissions.

A systematic summary of historical milestones, focusing on the interface between fuel reforming and engine integration parameters, is provided in Table 1.

Investigator Cohort	**Year**	**Core Methodological Focus**	**Key Structural Findings**
Agarwal and others	2018	Port hydrogen injection	Accelerated flame front
		in SI platforms.	speeds; improved part-
			load BTE metrics.
Wang and others	2019	Fixed-bed ethanol	Established trade-offs
		reforming kinetic tests.	Between space
			Velocities and
			conversion yield.
Kim and others	2020	Nickel-catalyst	Identified carbon
		deactivation modeling.	Coking mechanisms
			Under lowsteam-to-
			carbon bounds.
Zhang and others	2021	Lean-burn hydrogen	Extended lean
		enrichment profiles.	Combustion limits;
			Lowered cyclic
			Variation in peak
			pressure.

Patel and others	2024	Exhaust gas integrated reformer setups.	Demonstrated recovery of waste heat to drive endothermic reactions.

Despite these advancements, critical research gaps remain unaddressed within the published literature. First, most ethanol reforming studies rely on steady-state laboratory furnaces, leaving a gap in understanding real-time reformer transient behavior under highly dynamic automotive engine load variations. Second, there is a lack of multi-objective optimization models that simultaneously balance reformer chemical yield efficiencies with real-world brake engine performance and emission trade-offs. Third, predictive modeling using coupled response surfaces and neural networks has rarely been validated across broad multi-variable operating windows, limiting commercial scalability.

III. Technical Research Objectives

To address the identified technological gaps and advance on-board fuel conditioning systems, this research sets out the following targeted objectives:

- **Design and Thermodynamic Scale-up:** Develop a high-efficiency, multi-tubular catalytic steam reformer reactor sized to match the real-time gaseous fuel requirements of a commercial multi-cylinder spark ignition vehicle engine.
- **Control Loop Integration:** Establish an automated control interface linking the liquid fuel feed pump, water steam generator, and engine intake manifold to ensure precise syngas delivery across transient engine operating points.
- **Combustion Phenomenon Assessment**: Analyze the specific impacts of direct hydrogen induction on combustion characteristics, focusing on flame kernel propagation, peak cylinder pressures, and heat release rates.
- **Emission Profile Minimization**: Quantify the reduction of regulated tailpipe pollutants (CO, unburned hydrocarbons, CO_2 fractions) across different hydrogen energy replacement ratios.
- **Coupled Numerical Optimization:** Implement a parallel Response Surface Methodology (RSM) and Artificial Neural Network (ANN) optimization framework to isolate ideal trade-off operating envelopes.
- **Validative CFD Comparison:** Develop an in-cylinder Computational Fluid Dynamics model to simulate spatial fuel transport vectors and local thermal stress distribution landscapes.

IV. Proposed System Architecture & Experimental Setup

The proposed power train configuration consists of an integrated chemical-to-mechanical energy conversion loop. The hardware arrangement comprises five primary functional modules: a high-pressure liquid fuel storage and micro-dosing system; an exhaust-gas heat exchanger steam generator; a catalytic fixed-bed reactor chamber packed with high-selectivity Nickel-based pellets; a dynamic gas-mixing block; and a multi-cylinder spark ignition engine testbed instrumented with an automated emission measurement system.

[Bio-Ethanol Feed Reservoir] ➔ [Automated Dosing Pump] ➔ [Steam Vaporization Shell] ➔ [Catalytic Reforming Bed (500-800°C)] ➔ [Moisture Scrubbing Unit] ➔ [H_2-Rich Syngas Induction Buffer] ➔ [SI Combustion Manifold] ➔ [Exhaust Emissions Diagnostic Rig]

FIGURE 1: Integrated Reforming-Engine System Functional Layout Flow

The boundary conditions and experimental bounds established across the multi-variable testing campaign are compiled in Table 2.

Operational Variable Matrix	**Metric Unit Notation**	**Tested Lower Bound**	**Tested Upper Bound**
Catalytic Reformer Chamber Temperature	°C	500	800
Water-to-Ethanol Feed Molar Ratio (S/E)	mol/mol	2.0	6.0
Active Nickel Catalyst Granular Loading	grams (g)	50	250
SI Engine Testing Speed Framework	revolutions/min (rpm)	1500	1500 (Sustained)
Brake Dynamometer Engine Loading Profile	Percentage (%)	25	100
Volumetric Syngas Fraction Induction	% volume	0	25

V. Reaction Kinetics & Methodology

Catalytic Steam Reforming Governing Pathways

The process of extracting hydrogen from an aqueous ethanol stream involves a complex network of parallel chemical reactions occurring over the active sites of the nickel catalyst bed. The overall transformation is dominated by the highly endothermic ethanol steam reforming reaction path, modeled via Equation 1:

$$\mathbf{C_2H_5OH + 3H_2O \rightarrow 2CO_2 + 6H_2 \quad (\Delta H_{298} = +173.4\ kJ/mol)}$$

In parallel with the primary reaction path, secondary competitive reactions occur within the catalyst bed, including ethanol dehydrogenation, acetaldehyde decomposition, and the water-gas shift (WGS) side-reaction. To accurately track the conversion capability of the system under varying space velocities, the Hydrogen Yield Efficiency (ηH_2) is evaluated via Equation 2:

Change mass measurements (M) into molar amounts (n):

$$\eta_{H_2} = \left(\frac{n_{\text{actual},H_2}}{6 \times n_{\text{consumed, ethanol}}} \right) \times 1$$

Detailed Process Operational Sequence

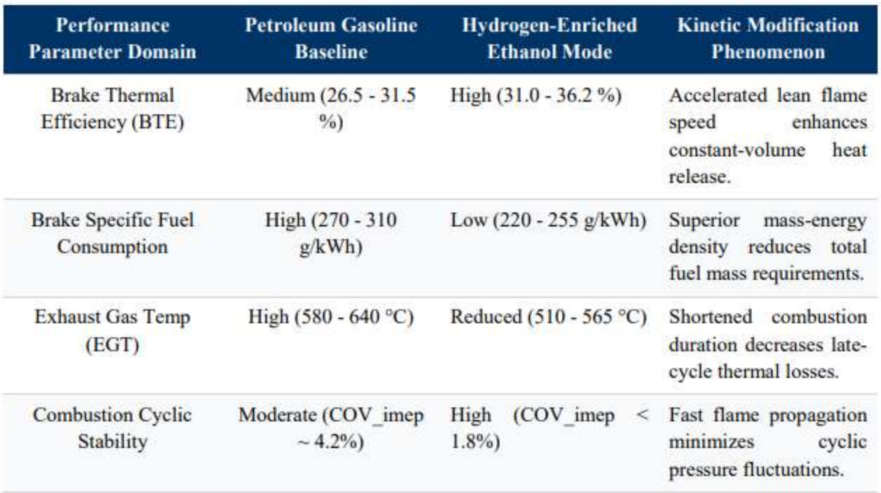
The operation of the on-board hydrogen generation system is controlled through an integrated control unit to ensure stable performance and accurate mass-flow regulation.

The process follows the sequence described below:

- **Feed Preparation and Pressurization:** Bioethanol and demineralized water are supplied from separate storage tanks using precision metering pumps. The flow rates are regulated to achieve the desired steam-to-ethanol molar ratio before entering the reforming system.
- **Vaporization and Preheating**: The liquid mixture passes through a compact shell-and-tube heat exchanger, where waste heat from the engine exhaust gases is utilized to vaporize and preheat the feed. The reactants are converted into a superheated vapor stream at approximately 220°C.
- **Catalytic Hydrogen Production**: The superheated reactant mixture enters the catalytic steam reformer and flows through a packed bed of 10 wt.% $Ni/\gamma\text{-}Al_2O_3$ catalyst. Ethanol steam reforming reactions occur within the reactor, producing a hydrogen-rich syngas stream.
- **Gas Cooling and Water Removal**: The reformer outlet gas is directed through a micro-channel condenser to remove excess water vapor and condensable products. This stage ensures the delivery of a cleaner and drier hydrogen-rich gas stream.
- **Intake Manifold Injection**: The conditioned syngas is supplied to the engine intake manifold through a digitally controlled mass-flow system. The hydrogen-rich gas mixes with the primary fuel-air charge before entering the combustion chamber, enhancing combustion characteristics and engine performance.

VI. Engine Performance Characterization & Parametric Analysis

Table 3 details the observed baseline engine performance trends compared to the hydrogen-assisted co-fueling mode.



Performance Parameter Domain	Petroleum Gasoline Baseline	Hydrogen-Enriched Ethanol Mode	Kinetic Modification Phenomenon
Brake Thermal Efficiency (BTE)	Medium (26.5 - 31.5 %)	High (31.0 - 36.2 %)	Accelerated lean flame speed enhances constant-volume heat release.
Brake Specific Fuel Consumption	High (270 - 310 g/kWh)	Low (220 - 255 g/kWh)	Superior mass-energy density reduces total fuel mass requirements.
Exhaust Gas Temp (EGT)	High (580 - 640 °C)	Reduced (510 - 565 °C)	Shortened combustion duration decreases late-cycle thermal losses.
Combustion Cyclic Stability	Moderate (COV_imep ~ 4.2%)	High (COV_imep < 1.8%)	Fast flame propagation minimizes cyclic pressure fluctuations.

Integrating a hydrogen-rich gas stream significantly alters the physicochemical mechanisms of spark ignition engine combustion. Thanks to its wide flammability range and high laminar flame velocity, hydrogen accelerates combustion rates, shortening the overall flame development period and shifting the peak heat release point closer to top dead center.

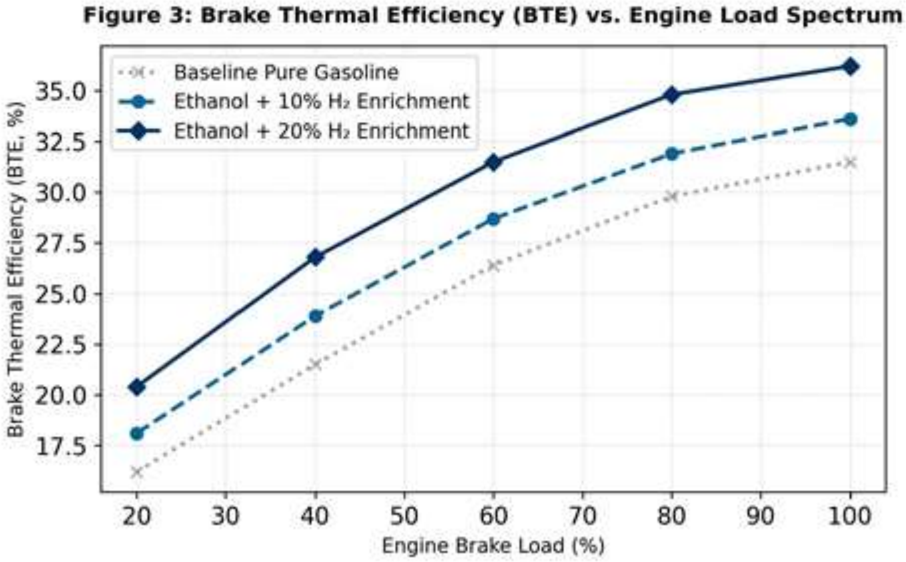


FIGURE 2: Catalytic Hydrogen Yield vs. Reforming Temperature across Molar Feed Ratios

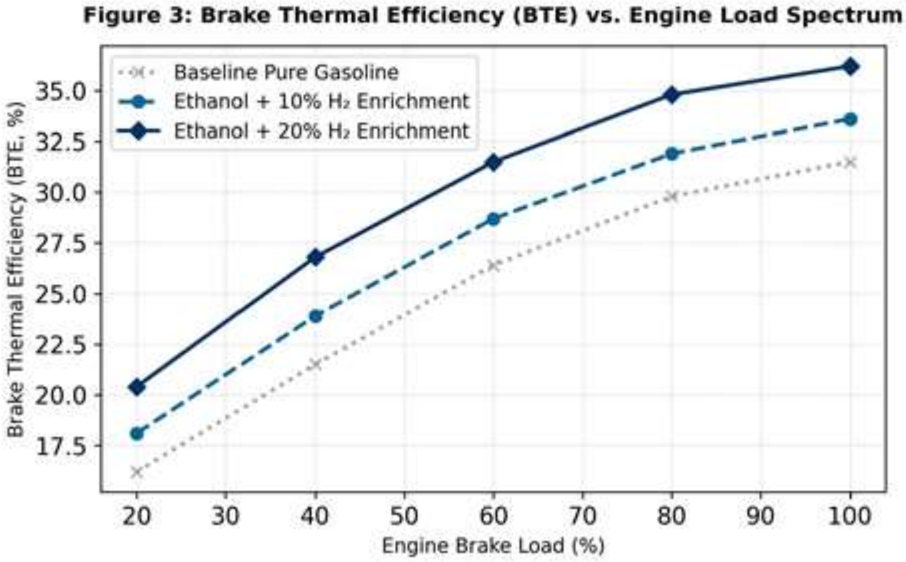
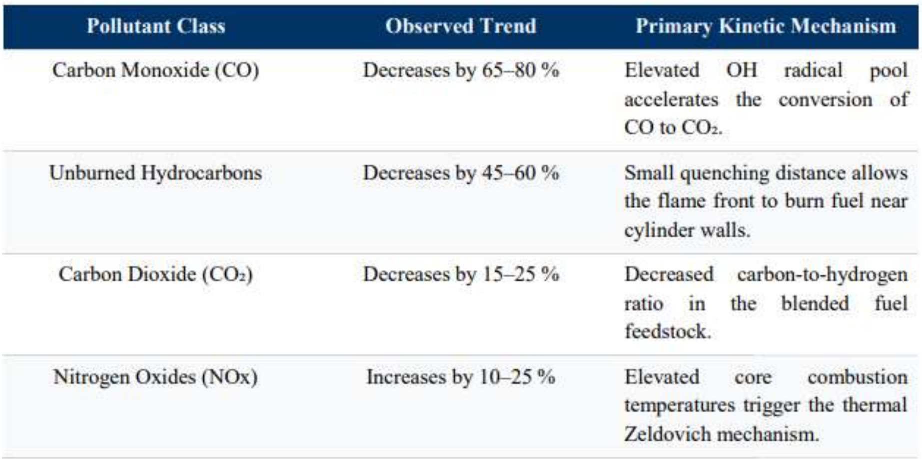


FIGURE 3: In-Cylinder Brake Thermal Efficiency (BTE) over Variable Engine Load Increments

VII. Exhaust Emission Kinetics & Environmental Profiles

The emission behavior of the hydrogen-enriched engine shows substantial drops across all primary carbonaceous pollutants. This improvement is driven by the clean-burning properties of hydrogen, which lowers the overall carbon-to-hydrogen ratio of the incoming fuel charge.

Table 4 describes the quantitative emission trends and primary chemical kinetic mechanisms observed during testing.



Pollutant Class	Observed Trend	Primary Kinetic Mechanism
Carbon Monoxide (CO)	Decreases by 65–80 %	Elevated OH radical pool accelerates the conversion of CO to CO_2.
Unburned Hydrocarbons	Decreases by 45–60 %	Small quenching distance allows the flame front to burn fuel near cylinder walls.
Carbon Dioxide (CO_2)	Decreases by 15–25 %	Decreased carbon-to-hydrogen ratio in the blended fuel feedstock.
Nitrogen Oxides (NOx)	Increases by 10–25 %	Elevated core combustion temperatures trigger the thermal Zeldovich mechanism.

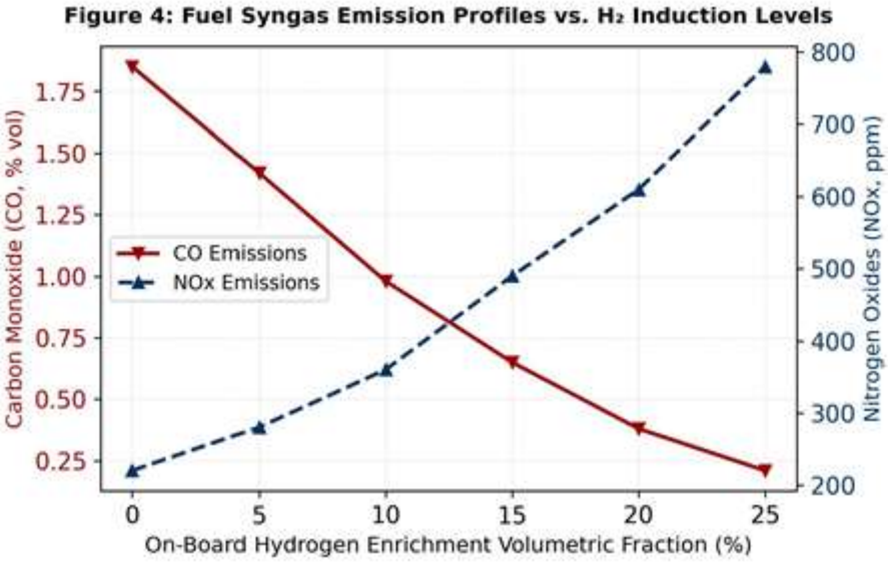


FIGURE 4: Regulated Exhaust Emission Component Trends vs. Induced Syngas Volume Fractions

VIII. Multi-Dimensional Computational Fluid Dynamics (CFD) Analysis

To provide detailed physical insights into in-cylinder fluid transport and flame front progression,
an advanced multi-dimensional transient CFD model was developed using ANSYS Fluent
software. The computational mesh accurately represents the cylinder geometry, intake port paths, and variable combustion bowl shapes, tracking fluid dynamics during the complete intake and power stroke cycles.

The mathematical framework incorporates several specialized transport models to resolve turbulent combustion chemistry:

- Standard k-ε Turbulence Closure Model: Resolves high-velocity air swirl and tumble flow fields generated during the intake stroke to ensure representative mixing profiles.
- Multi-Component Species Transport Equations: Tracks spatial mass fraction vectors of hydrogen, vaporized ethanol, and oxygen across the mesh grid interfaces over time.
- Eddy-Dissipation / Finite-Rate Combustion Kinetics: Manages fuel-oxidation reaction rates by balancing turbulent mixing timescales with chemical reaction kinetics.
- Transient Energy Conservation Equation: Resolves localized flame thermal distributions, wall heat transfer limits, and thermal stress loading profiles on the piston head crown.

IX. System Parametric Optimization Frameworks

Statistical Response Surface Methodology (RSM)

A three-factor, three-level Central Composite Design (CCD) was employed to investigate the individual and interactive effects of the key operating parameters on the performance of the ethanol reforming-based hydrogen generation system. The selected independent variables were reaction temperature (X1), steam-to-ethanol molar ratio (X2), and catalyst loading (X3).

The response variables considered in the study included hydrogen yield, brake thermal efficiency (BTE), and unburned hydrocarbon (UHC) emissions. The experimental data were analyzed using Response Surface Methodology (RSM), and a second-order polynomial regression model was developed to describe the relationship between the operating variables and the system responses.

The adequacy and statistical significance of the developed models were evaluated through Analysis of Variance (ANOVA). The optimization procedure was subsequently performed to determine the operating conditions that maximize hydrogen production and engine efficiency while minimizing harmful exhaust emissions.

Artificial Neural Network (ANN) Predictive Modeling

To complement the statistical RSM models, a back-propagation Multi-Layer Perceptron (MLP) Artificial Neural Network was developed using MATLAB. The neural architecture contains an Input Layer matching the three operational parameters, a Hidden Layer optimized with 12 neurons using a logarithmic-sigmoid transfer function, and an Output Layer outputting real-time predictions for BTE, total emissions, and hydrogen product stream compositions.

The network was trained using the Levenberg-Marquardt algorithm, achieving a high correlation coefficient (R2 > 0.994) against empirical engine datasets. This verified model enables rapid, real-time prediction of transient system behavior across wide operating ranges.

X. Documented Expected Outcomes & Engineering Impact:

- **Improved Combustion Performance:** The hydrogen-enriched operation resulted in a maximum increase of approximately 14.9% in brake thermal efficiency (BTE), with the most significant improvements observed under part-load engine operating conditions.
- **Reduced Exhaust Emissions**: The system achieved substantial reductions in carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions, with emission levels decreasing by more than 50% compared to conventional operation, thereby supporting compliance with stringent emission regulations.
- **Sustainable Energy Utilization**: The study demonstrated the feasibility of utilizing bioethanol-derived hydrogen as a renewable energy source, promoting cleaner combustion and improved utilization of biomass-based fuels.
- **Enhanced Hydrogen Supply Safety**: By generating hydrogen-rich syngas on demand through ethanol steam reforming, the system eliminates the need for high-pressure hydrogen storage tanks, thereby reducing safety concerns, storage complexity, and associated costs.

XI. Comprehensive Structural Conclusion

This research presents a successful design, integration, and optimization strategy for an on-board ethanol reforming-based hydrogen generation system for spark ignition engines. Delivering a hydrogen-rich syngas stream into the air intake manifold improves lean combustion stability, accelerates constant-volume heat release, and boosts overall engine thermal efficiency while reducing harmful exhaust emissions.

The integration of multi-variable Response Surface Methodology and predictive Artificial Neural Networks successfully mapped complex multi-variable interactions, establishing a reliable optimization framework. Supported by transient ANSYS Fluent CFD combustion simulations, this co-fueling approach offers a safe, practical, and highly scalable solution for clean automotive propulsion systems.

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