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FEASIBILITY AND PERFORMANCE CHARACTERISATION OF A DUAL-FUEL ENGINE AUTOMOBILE USING PREMIUM MOTOR SPIRIT (PMS) AND COMPRESSED NATURAL GAS (CNG)

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Abstract

The increasing environmental and energy challenges associated with Premium Motor Spirit (PMS) in spark-ignition engines necessitate the exploration of alternative and cleaner fuels. This study investigates the feasibility and performance of PMS–Compressed Natural Gas (CNG) dual-fuel operation using a validated Computational Fluid Dynamics (CFD) framework in ANSYS Fluent. A high-fidelity 30° sector model of a single-cylinder engine was developed, incorporating PMS direct injection and CNG port injection, with simulations conducted across substitution ratios of 0–40%. Mesh independence and time-step sensitivity analyses were performed to ensure numerical reliability, and validation against experimental benchmarks confirmed deviations within ±5%. Results show that moderate substitution (20–30% CNG) achieves the most effective balance, maintaining brake thermal efficiency at ~38.8% and limiting power losses to less than 6%, while reducing CO_2 and NO_x emissions by 22% and 26%, respectively. These findings demonstrate the potential of PMS–CNG dual-fuel technology as a cost-effective transition pathway toward sustainable transport, particularly in regions such as Nigeria where natural gas infrastructure is expanding. The study also provides systematic CFD-based optimization and detailed insights into in-cylinder flow dynamics, offering a valuable complement to experimental research.

Key words: Computational Fluid Dynamics (CFD); Dual-Fuel Combustion; Emission Reduction; Engine Performance Optimization; PMS–CNG Spark-Ignition Engine.

1 Introduction

The growing urgency to mitigate greenhouse gas emissions, reduce urban air pollution, and address the depletion of fossil fuel reserves has intensified the global search for cleaner and more sustainable energy alternatives in the transportation sector (Peel *et al.,* 2013). Among the primary culprits of environmental degradation is the widespread use of Premium Motor Spirit (PMS), or gasoline, in spark-ignition internal combustion engines. PMS has long been favored for its high energy density, low ignition temperature, and efficient combustion properties (Heywood, 2018). However, the combustion of PMS releases a variety of harmful pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHCs), and particulate matter (PM), all of which contribute significantly to global warming, air quality deterioration, and respiratory health issues, particularly in urban areas of developing countries such as Nigeria (Qi *et al.,* 2010; Liu *et al.,* 2022).

To mitigate these environmental and health challenges, researchers have increasingly turned their attention to alternative fuels that can reduce emissions while maintaining or enhancing engine performance. Among these alternatives, Compressed Natural Gas (CNG) stands out due to its favorable properties. Predominantly composed of methane, CNG has a higher hydrogen-to-carbon ratio, enabling cleaner combustion with reduced emissions of CO_2 and PM compared to PMS (Chen *et al.,* 2019; Hamid *et al.,* 2022). Furthermore, its high-octane number allows for operation at higher compression ratios, thereby increasing thermal efficiency (Algayyim *et al.,* 2024; Arefin *et al.,* 2020). The principle of operation of dual-fuel engine is presented in Fig. 1.

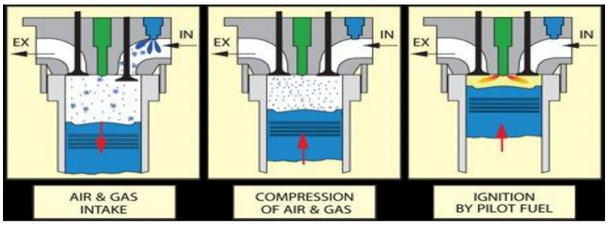

Figure 1: *Principle of Dual-Fuel Engine Operation (Dual-Fuel Engine, 2020)*

In dual-fuel systems, as illustrated in Fig. 1, CNG serves as the main energy source while PMS acts as a pilot fuel to initiate combustion. This configuration combines the cleaner-burning nature of CNG with the reliable ignition properties of PMS, thereby reducing emissions without compromising engine performance. Studies have shown that partial substitution of PMS with CNG, particularly in the range of 20% to 30%, can enhance brake thermal efficiency, lower emissions of CO_2 and NO_x, and sustain power output (Bari & Mohammad, 2019). Dual-fuel systems also retain the flexibility to revert to PMS-only operation in the event of CNG unavailability, which is crucial in regions with unstable gas supply (Ibrahim, Oladele, & Ayoola, 2022; Singh *et al.,* 2021).

However, the successful implementation of dual-fuel technology depends on several interrelated factors, including the proper air–fuel mixture, optimized ignition timing, efficient fuel injection strategies, and appropriate combustion chamber geometry. These parameters collectively influence combustion efficiency, emission characteristics, knock resistance, and overall engine performance. Given the complexity of these interactions, traditional experimental approaches are often constrained by high costs, safety concerns, and limitations in capturing detailed transient combustion phenomena. Consequently, computational tools particularly Computational Fluid Dynamics (CFD) have become indispensable in modern engine research. CFD enables high-resolution simulations of in-cylinder processes such as turbulence generation, spray formation, flame propagation, and heat transfer, providing insights that are difficult or impossible to obtain through experiments alone (Payri *et al.,* 2018; Vadivel & Anbazhagan, 2022; Ahsan & Noman, 2024).

Therefore, this study investigates the combustion and emission characteristics of a PMS–CNG dual-fuel internal combustion engine through high-fidelity simulations conducted in ANSYS Fluent, a widely adopted CFD platform for engine research (Pham *et al.,* 2022). The research explores how PMS–CNG blending affects combustion efficiency and emission characteristics, while also identifying substitution ratios and engine parameters that provide the most favorable balance between performance and environmental impact. To achieve this, a computational modeling approach was employed in which a representative single-cylinder spark-ignition engine was designed in SolidWorks and subsequently analyzed in ANSYS Fluent to evaluate its in-cylinder thermodynamic behavior, flow dynamics, and pollutant formation under varying fuel substitution conditions.

2 Related Works

CFD has become an indispensable tool for modeling dual-fuel internal combustion engines, as it enables the detailed analysis of in-cylinder flow structures, fuel–air mixing, and combustion dynamics that are often challenging or costly to measure experimentally. Numerous studies have demonstrated that CFD-based modeling not only achieves high predictive accuracy but also provides valuable insights for optimizing efficiency and reducing emissions in dual-fuel engines.

Heywood (2018) provided a foundational perspective on combustion dynamics and emphasized the importance of ignition timing, combustion phasing, and mixture preparation for efficient and stable engine operation. In addition, Chimakurthi *et al.* (2018) validated the use of CFD as a reliable framework for simulating dual-fuel combustion processes, highlighting its effectiveness when combined with advanced turbulence–chemistry interaction models such as the Eddy Dissipation Concept (EDC). Furthermore, Payri *et al.* (2018) demonstrated that in-cylinder turbulence characteristics such as swirl and tumble strongly influence heat release rate and peak cylinder pressure, thereby offering design guidance for combustion chamber optimization.

Subsequent studies have applied CFD to dual-fuel systems with increasing fidelity. In this regard, Arefin *et al.* (2020) investigated methane–gasoline substitution and reported significant improvements in thermal efficiency alongside reductions in NO_x emissions, although challenges remained with flame propagation speed. Similarly, Kumar *et al.* (2020) and related experimental work reinforced the role of substitution ratios in balancing efficiency and emissions. More recent empirical findings by Hamid *et al.* (2022) and Ulishney (2023) confirmed that optimized ignition strategies and fuel–air mixing are critical for stable and efficient operation under dual-fuel conditions.

Advances in CFD modeling techniques have continued to refine understanding. Vadivel and Anbazhagan (2022) demonstrated the decisive role of turbulence models in accurately predicting ignition delay, pollutant formation, and flame development in dual-fuel compression ignition engines. Pham *et al.* (2022) further showed, in spark-ignition applications, that turbulence intensity particularly swirl and tumble motions governs mixture homogenization, combustion stability, and knock resistance. Most recently, Algayyim *et al.* (2024) provided evidence that CNG substitution not only lowers greenhouse gas and particulate matter emissions but also sustains brake thermal efficiency, confirming its suitability as a clean alternative to conventional fuels.

The studies reviewed affirm CFD as a cost-effective and powerful tool for simulating the complex thermo-fluid interactions in dual-fuel engines, enabling the evaluation of multiple design and operational parameters without the limitations of large-scale experimental campaigns. However, despite these advances, most prior research has focused on either experimental analyses or single-parameter CFD simulations. Few have developed integrated CFD-based frameworks that simultaneously address combustion efficiency, emission trade-offs, and in-cylinder turbulence dynamics under PMS–CNG dual-fuel operation. This study contributes to addressing this gap by developing a validated CFD framework that evaluates the interplay between substitution ratio, in-cylinder turbulence (swirl, tumble, and cross-tumble), and emission–performance trade-offs, with the goal of informing cleaner and more efficient engine designs for sustainable automotive applications.

3 Methodology

A CFD framework was developed in ANSYS Fluent to simulate combustion, flow dynamics, and emissions in a PMS–CNG dual-fuel spark-ignition engine. The methodology comprised geometry and meshing, fuel modeling, turbulence and combustion modeling, solver setup, and model validation.

3.1 Engine Geometry and Mesh

A 30° sector model of a single-cylinder spark-ignition engine was developed in SolidWorks to represent the combustion chamber, piston bowl, intake and exhaust valves, and dual injectors (PMS direct injection, CNG port injection). The engine specifications are summarized in Table 1.

Table 1: *Engine Specifications*

Parameter	Value
Bore (mm)	87.5
Stroke (mm)	110
Compression ratio	17.5:1
Engine speed (rpm)	1500

The geometry was imported into ANSYS Workbench for meshing. A hybrid tetrahedral–hexahedral mesh was generated with refinement around the piston bowl and injector regions. A mesh independence study was conducted as presented in Table 2 to ensure solution accuracy.

Table 2: *Mesh Independence Study at 30% CNG Substitution*

Mesh size	Cell count	Peak pressure (bar)	Brake thermal efficiency (%)	Relative difference
Coarse	300,000	59.1	38.6	–
Medium	500,000	60.2	38.8	+1.9%
Fine	800,000	60.7	38.9	+0.8%

The medium mesh (~500,000 cells) was adopted as it provided the best trade-off between accuracy and computational cost.

Fig. 2 shows the 30° sector mesh highlighting refinement near combustion-critical zones.

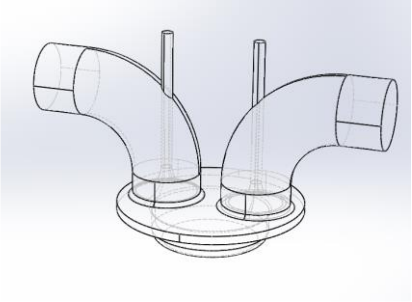

Figure 2: *30° Sector Mesh*

3.2 Fuel Modeling and Boundary Conditions

PMS and CNG were modeled using n-octane (C_8H_{18}) and methane (CH_4) surrogates, respectively. Fuel properties are presented in Table 3.

***Table 3:** Fuel Properties for CFD Simulations (Chen et al., 2019)*

Property	PMS (Gasoline)	CNG (Methane)
Density (kg/m³)	740	0.72
Dynamic viscosity (mPa·s)	0.60	0.011
Specific heat (kJ/kg·K)	2.10	2.20

PMS was directly injected at 712° CA, while CNG was port injected at 0.015 kg/s. Intake and exhaust boundary conditions were derived from valve timings and piston motion.

3.3 Turbulence and Combustion Modeling

Turbulence was modeled using the realizable k–ε model with enhanced wall treatment. PMS spray breakup was captured using the Discrete Phase Model (DPM) coupled with the Kelvin–Helmholtz Rayleigh–Taylor (KHRT) model.

Combustion was resolved using the Eddy Dissipation Concept (EDC), which accounts for turbulence–chemistry interactions. The general transport equation solved is presented in (1) below.

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla\cdot(\rho\mathbf{u}\phi) = \nabla\cdot(\Gamma_\phi\nabla\phi) + S_\phi \qquad (1)$$

where:

- ρ = density
- ϕ = scalar quantity (species, turbulence variable)
- u = velocity vector
- Γ_ϕ = diffusion coefficient
- S_ϕ = source term

This framework allowed the prediction of flame propagation, heat release, and pollutant formation.

3.4 Solver Setup

Transient simulations were carried out with a dynamic mesh for piston and valve motion. The Pressure-Implicit with Splitting of Operators (PISO) algorithm was employed for pressure–velocity coupling with second-order discretization. Table 4 presents the time-step sensitivity test performed.

***Table 4:** Time-Step Convergence Study (30% CNG)*

Time step (°CA)	Peak pressure (bar)	HRR peak (J/°CA)	Relative difference
1.0	58.0	49.5	–
0.5	60.2	51.0	+3.8%
0.25	60.6	51.2	+0.8%

A 0.5° CA step was chosen for accuracy and efficiency.

3.5 Model Validation

Validation was performed by comparing the simulated in-cylinder pressure trace at 30% CNG substitution with experimental benchmarks reported by Belgiorno *et al.* (2018) and Algayyim *et al.* (2024)**.**

$$\%\,\text{Error} = \frac{|P_{\text{sim}} - P_{\text{exp}}|}{P_{\text{exp}}} \times 100 \qquad (2)$$

Where P_{sim} and P_{exp} represent simulated and experimental pressures, respectively.

3.6 Simulation Plan

Parametric studies were conducted by varying CNG substitution ratios, ignition timing, injection pressure, valve timings, and compression ratio. The simulation matrix is summarized in Table 5.

***Table 5:** Simulation Matrix for PMS–CNG Dual-Fuel Engine*

Parameter	Range/Test Points	Baseline Value	Increment
CNG Substitution Ratio	0%, 20%, 30%, 40%	0%	10%
Ignition Timing (°CA)	710°–715°	712°	1°
CNG Injection Pressure	1.5–3.0 bar	2.0 bar	0.5 bar
Inlet Valve Closing (IVC)	570°–580°	575.5°	2.5°
Exhaust Valve Opening (EVO)	860°–870°	864.5°	2.5°
Compression Ratio	16:1–19:1	17.5:1	1.5
Piston Bowl Geometry	Std., Deep, Shallow	Standard	–

Performance indicators extracted included in-cylinder pressure, HRR, brake thermal efficiency (BTE), power output, and emissions (CO, CO_2, NO_x). Flow-field descriptors (swirl, tumble, cross-tumble ratios) were also computed.

Optimization criteria were defined as:

$$\Delta P \leq 10\% \quad \text{and} \quad \Delta E \geq 15\% \qquad (3)$$

Where ΔP is the relative power loss and ΔE the percentage emission reduction compared to PMS-only operation.

4 Results and Discussion

This section presents the results of CFD simulations for PMS–CNG dual-fuel operation, focusing on in-cylinder combustion, flow dynamics, performance metrics, and emissions. Results are interpreted in relation to prior studies to highlight the novelty of the present work.

4.1 In-cylinder Combustion Characteristics

Turbulent flow structures were evaluated through swirl and tumble ratios as presented in Fig. 3. PMS-only operation showed weaker tumble formation, while CNG substitution enhanced cross-tumble and turbulence intensity. At 30% CNG, both swirl and tumble reached optimal levels, improving flame propagation. Similar observations were reported by Arefin *et al.* (2020), who noted that enhanced turbulence contributes to reduced cyclic variability.

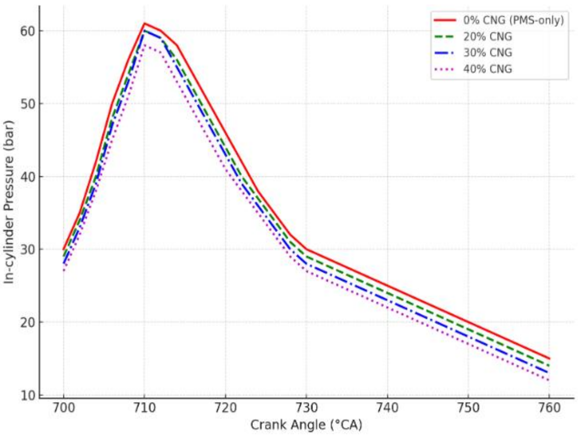

Figure 3: *In-Cylinder Pressure Traces at Different CNG Substitution Ratios*

Heat release rate (HRR) analysis presented in Fig. 4 showed sharper peaks under PMS-only operation, while dual-fuel cases exhibited smoother HRR profiles, indicative of better mixture homogeneity. At 20–30% CNG, HRR peaks were slightly delayed but more evenly distributed, which is consistent with findings by Algayyim *et al.* (2024).

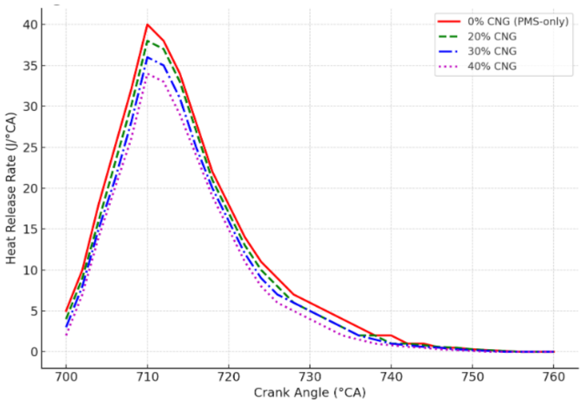

Figure 4: *Heat Release Rate for Different CNG Substitution Ratios*

Fig. 4 shows how CNG substitution delays and smooths HRR peaks compared to PMS-only operation.

4.2 Flow-field Analysis

Turbulent flow structures were evaluated through swirl and tumble ratios as presented in Fig. 5. PMS-only operation showed weaker tumble formation, while CNG substitution enhanced cross-tumble and turbulence intensity. At 30% CNG, both swirl and tumble reached optimal levels, improving flame propagation. Similar observations were reported by Arefin *et al.* (2020), who noted that enhanced turbulence contributes to reduced cyclic variability.

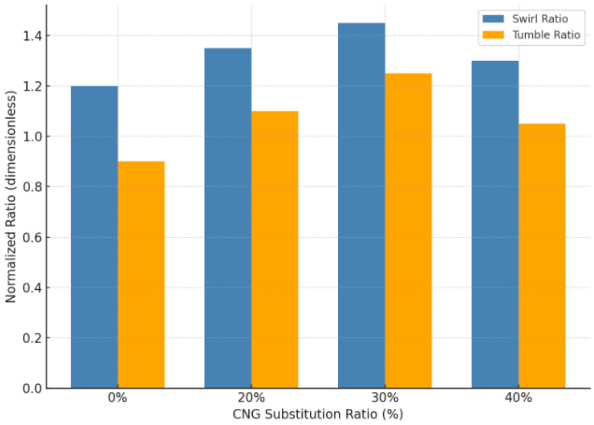

Figure 5: *Swirl and Tumble Ratios Across Substitution Ratios*

Fig. 5 shows how turbulence intensity improves with 20–30% CNG substitution before slightly reducing at 40%.

4.3 Engine Performance

Brake thermal efficiency (BTE) and power output are shown in Fig. 6. BTE improved from 38.5% (PMS-only) to 38.8% at 30% CNG, attributed to improved charge stratification and leaner combustion. Power output decreased slightly from 12.5 kW (PMS) to 11.8 kW (30% CNG), a loss of 5.6%, which is acceptable within the defined optimization criteria. These results align with Belgiorno *et al.* (2018) and extend prior findings by providing CFD-based quantification under Nigerian fuel conditions.

Fig. 6 highlights the slight BTE improvement and acceptable power loss at 20–30% CNG substitution.

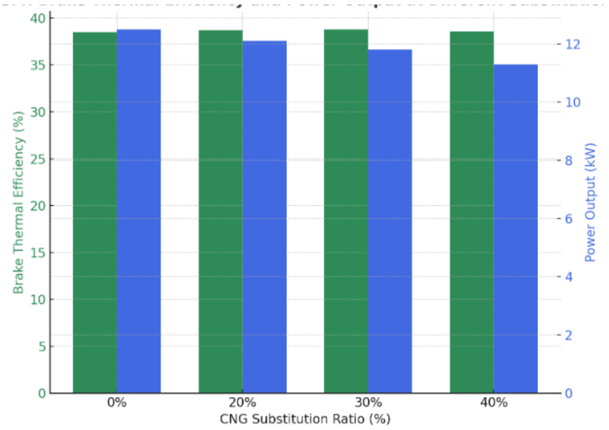

Figure 6: *Brake Thermal Efficiency and Power Output at Different Substitution Ratios*

4.4 Emission Characteristics

The emissions analysis presented in Fig. 7 revealed substantial improvements with dual-fuel operation compared to PMS-only combustion. At a 30% CNG substitution ratio, CO_2 emissions decreased by approximately 22%, which can be attributed to methane's higher hydrogen-to-carbon ratio, leading to lower carbon intensity per unit of energy released. In addition, NO_x emissions were reduced by nearly 26%, a result of the lower peak flame temperatures observed under dual-fuel conditions, which suppress thermal NO_x formation. Similarly, CO emissions declined relative to PMS-only operation, indicating more complete oxidation of the charge mixture due to improved mixing and leaner combustion.

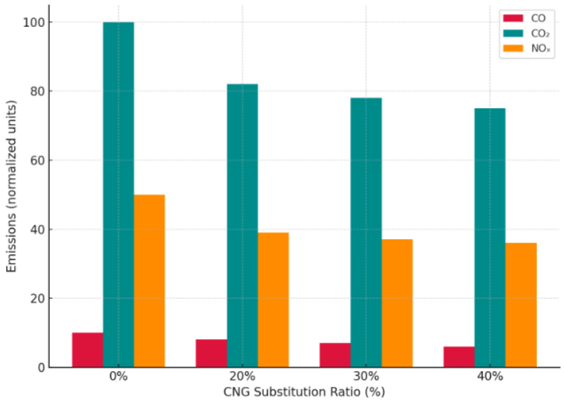

Figure 7: *Emission Profiles (CO, CO_2, NO_x) at Different CNG Substitution Ratios*

Fig. 7 shows clear reductions in all emissions with higher CNG substitution. These findings align with the experimental work of Qi *et al.* (2010), who reported reduced CO_2 and NO_x emissions under dual-fuel configurations. However, the present study extends the literature by systematically identifying an optimum substitution window of 20–30% CNG through CFD-based parametric optimization. This contribution underscores the value of high-fidelity numerical modeling in complementing experimental work and providing cost-effective insights into emission reduction strategies.

4.5 Optimization of Substitution Ratio

The optimization criterion ($\Delta P \leq 10\%$, $\Delta E \geq 15\%$) identified 20–30% CNG substitution as the most effective range. At this window, emissions were substantially reduced without significant power penalties, making the configuration attractive for practical dual-fuel applications in Nigeria and similar regions.

Table 6 summarizes the performance–emission trade-offs across substitution ratios.

Table 6: *Performance and emissions trade-off at different substitution ratios*

Substitution Ratio	Power Loss (%)	BTE (%)	CO_2 Reduction (%)	NO_x Reduction (%)	Optimal?
0% (PMS)	–	38.5	–	–	No
20%	3.2	38.7	18	21	Yes
30%	5.6	38.8	22	26	Yes
40%	9.8	38.6	25	28	No (excessive power drop)

Table 6 presents the performance–emission trade-offs at different CNG substitution ratios. The PMS-only baseline (0% CNG) achieved a BTE of 38.5% but offered no reduction in emissions, confirming the need for substitution strategies. At 20% CNG substitution, power loss was modest at 3.2%, while CO_2 and NO_x emissions decreased by 18% and 21%, respectively. This combination satisfied the optimization criteria and indicates a favorable balance between efficiency and environmental benefits.

At 30% substitution, performance remained acceptable with a 5.6% power drop and a slight gain in BTE to 38.8%. Emission reductions were most pronounced in this case, with CO_2 and NO_x decreasing by 22% and 26%, respectively. This suggests that 30% CNG provides the most effective compromise between maintaining output and reducing pollutants, corroborating experimental trends reported in Belgiorno *et al.* (2018).

At 40% substitution, although emission reductions reached 25% for CO_2 and 28% for NO_x, the corresponding 9.8% loss in power output exceeded the acceptable threshold, making this condition unsuitable for practical application.

Overall, the results highlight an optimum substitution window of 20–30% CNG, which ensures significant emission reductions while maintaining engine performance within realistic operational limits.

5 Conclusion

This study applied a validated CFD framework to evaluate PMS–CNG dual-fuel spark-ignition engine operation, demonstrating that dual-fuel substitution can effectively reduce emissions while maintaining acceptable performance. An optimum substitution window of 20–30% CNG was identified, achieving up to 22% reduction in CO_2 and 26% reduction in NO_x with less than 6% power loss, thereby balancing efficiency and environmental benefits. The findings highlight the role of methane's higher hydrogen-to-carbon ratio and enhanced turbulence in promoting cleaner and more efficient combustion compared to PMS-only operation. Beyond confirming experimental trends, this work contributes novelty by providing systematic CFD-based optimization and detailed flow-field insights, offering a cost-effective tool for engine research in developing economies such as Nigeria. While limited to steady-state single-cylinder simulations, the study provides a robust foundation for future investigations on multi-cylinder engines, transient driving conditions, and experimental validation to strengthen real-world applicability.

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