Analysis of the Effect of HHO Supplementation Produced by a Wet Cell HHO Generator on the Combustion Characteristics of a 125 cc Four-Stroke Otto Engine Using ANSYS Forte Simulation

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Abstract— *This study aims to analyze the effect of oxyhydrogen (HHO) gas supplementation on the combustion characteristics and engine performance of a 125 cc four-stroke Otto engine using ANSYS Forte simulation. HHO gas was produced through water electrolysis using a wet cell generator with a production rate of 43.88 mL/min. The simulation was conducted at 5,000 RPM with two conditions: without HHO (baseline) and with HHO supplementation. The analyzed parameters include pressure, temperature, Heat Release Rate (HRR), flame speed, Indicated Work, Indicated Mean Effective Pressure (IMEP), Indicated Power (IP), and Brake Mean Effective Pressure (BMEP). The simulation results show improvements in all combustion parameters at 15° ATDC crank angle. Pressure increased from 2.39 MPa to 2.82 MPa (18.0%), temperature from 827.09 K to 968.10 K (17.0%), HRR from 4.68 J/°CA to 6.50 J/°CA (38.9%), and flame speed from 449.75 cm/s to 552.13 cm/s (22.8%). These improvements contributed to enhanced engine performance: Indicated Work increased by 10.97% (135.41 J → 150.27 J), IMEP by 10.88% (1.085 MPa → 1.203 MPa), IP by 10.98% (5.64 kW → 6.26 kW), and BMEP by 19.92% (0.492 MPa → 0.590 MPa). This study proves that HHO gas supplementation positively affects the combustion characteristics and performance of a 125 cc four-stroke Otto engine, and demonstrates that ANSYS Forte numerical simulation is effective for analyzing in-cylinder combustion phenomena.*

Keywords— *ANSYS Forte, BMEP, combustion characteristics, flame speed, HHO, IMEP, numerical simulation, Otto engine*

I. INTRODUCTION

Rapid development in the transportation sector has led to a growing demand for highly efficient engines. Four-stroke Otto engines remain the most widely used type, but incomplete combustion results in wasted fuel energy. Therefore, various efforts continue to be made to improve combustion quality, one of which is through the use of oxyhydrogen (HHO) gas as a supplemental fuel.

HHO gas is a mixture of hydrogen and oxygen produced through the electrolysis of water. Hydrogen's characteristics—including high flame propagation speed, low ignition energy, and a wide flammability range—make it an ideal candidate for improving combustion quality in Otto engines (Shchepakina et al., 2023). Research by Karasu et al. (2025) shows that adding HHO can significantly improve combustion efficiency, while Kunaraj & Mathavan (2025) report an increase in thermal efficiency in an 89-cc engine with the addition of HHO. Research by Siriwardena et al. (2025) shows that wet-cell-type HHO generators can operate efficiently at voltages of 2.4–4.2 V with currents of 0–6.8 A, making them a potential source of supplemental gas for Otto engines.

Although various studies have demonstrated the benefits of HHO gas supplementation in improving combustion quality, most still focus on experimental testing that emphasizes engine performance parameters, such as power, torque, fuel consumption, and emissions. A bibliometric study by Ampah et al. (2024) indicates that research trends on hydrogen in internal combustion engines are beginning to shift toward a deeper understanding of combustion mechanisms. However, research that integrates the analysis of in-cylinder combustion characteristics with the evaluation of thermodynamic performance parameters through numerical simulation remains relatively limited. In fact, parameters such as pressure distribution, temperature distribution, Heat Release Rate (HRR), flame speed, Indicated Work, Indicated Mean Effective Pressure (IMEP), Indicated Power, and Brake Mean Effective Pressure (BMEP) are crucial for explaining the relationship between improved combustion quality and overall engine performance. Therefore, this study was conducted to analyze the effect of HHO gas supplementation on the combustion characteristics and thermodynamic performance of a 125 cc four-stroke Otto engine using ANSYS Forte simulation, thereby providing a more comprehensive understanding of the combustion mechanism and the improvement in engine performance resulting from the addition of HHO gas.

International Journal of Scientific Engineering and Science
Volume 10, Issue 8, pp. 8-14, August 2026
ISSN (Online):

II. Research Methodolog

A. Research Procedure

The research flowchart was developed to systematically illustrate the sequence of the research process, beginning with problem identification and ending with the formulation of conclusions. The complete research procedure is presented in Figure 1.

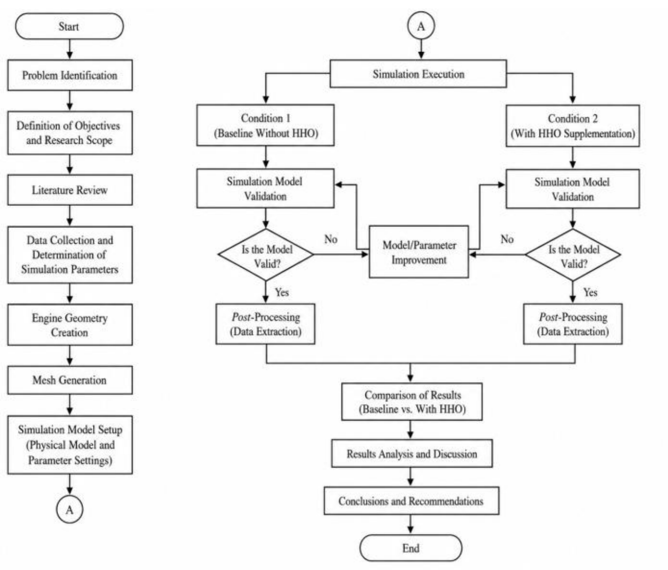

Fig. 1. Research Flowchart

B. Engine and HHO Generator Specifications

A 125 cc four-stroke Otto engine was used as the simulation object in this study. The engine geometry, including the cylinder bore, piston stroke, swept volume, and compression ratio, was used to develop the combustion chamber model in ANSYS Forte. The simulations were performed at an engine speed of 5,000 rpm. HHO gas produced by a wet cell HHO generator with a production rate of 43.88 mL/min was supplied as a supplementary fuel. The engine specifications and HHO generator parameters used in this study are presented in Table I.

TABLE I. Engine and HHO Generator Specifications

Parameter	Specification
Engine Type	125 cc Four-Stroke Otto Engine
Swept Volume	124.8 cc
Bore × Stroke	52.4 mm × 57.9 mm
Compression Ratio	11.0 : 1
Engine Speed	5,000 rpm
Fuel	Iso-octane
HHO Generator Type	Wet Cell
HHO Production Rate	43.88 mL/min

C. Numerical Simulation Setup

Numerical simulations were performed using ANSYS Forte 2021 R2 based on the Computational Fluid Dynamics (CFD) approach. The combustion chamber model was generated using the Sector Mesh Generator, while the simulation parameters were configured according to the engine specifications and operating conditions. Two simulation cases were evaluated, namely the baseline condition and HHO supplementation at an engine speed of 5,000 rpm. Before execution, all simulation settings were verified using the Validate feature in ANSYS Forte. The simulation results were then post-processed to obtain the cylinder pressure, temperature distribution, Heat Release Rate (HRR), and flame speed.

TABLE II. Numerical Simulation Parameters

Parameter	Value
Software	ANSYS Forte 2021 R2
Engine model	Spark Ignition (SI)
Geometry	Sector model (45°)
Mesh topology	Topology 6
Mesh size	1 mm
Fuel	Iso-octane (iC_8H_{18})
Reaction mechanism	Gasoline_1comp_49sp.cks
Combustion model	G-Equation Flame Speed Model
Turbulence model	RANS RNG k–ε
Ignition system	Spark ignition
Air–fuel ratio	Stoichiometric (AFR 14.7:1)
Engine speed	5,000 rpm
Simulation cases	Baseline and HHO supplementation (43.88 mL/min)

D. Data Processing and Performance Evaluation

The simulation results obtained from ANSYS Forte were post-processed to evaluate both the combustion characteristics and engine performance. The combustion characteristics were analyzed using the in-cylinder pressure, temperature, Heat Release Rate (HRR), and flame speed obtained from the simulation. Comparisons between the baseline and HHO supplementation conditions were performed at a crank angle of 15° ATDC, where both operating conditions were in the same combustion phase.

The pressure and cylinder volume data generated by ANSYS Forte were exported to determine the Indicated Work (Wi) from the pressure–volume (P–V) diagram. The indicated work for one engine cycle is defined as:

$$W_i = \oint P \, dV \qquad (1)$$

where W_i is the indicated work (J), P is the in-cylinder pressure (Pa), and V is the cylinder volume (m³).

Since the simulation data consist of discrete pressure and volume values, the integral was evaluated numerically using the Composite Trapezoidal Rule:

$$W_i = \sum_{i=1}^{n-1} \frac{P_i + P_{i+1}}{2} (V_{i+1} - V_i) \qquad (2)$$

where P_i and P_{i+1} are the in-cylinder pressures at two consecutive data points (Pa), while V_i and V_{i+1} are the corresponding cylinder volumes (m³).

The Indicated Mean Effective Pressure (IMEP) was then calculated using:

$$IMEP = \frac{W_i}{V_d} \qquad (3)$$

where V_d is the engine displacement volume (m³).

The Indicated Power (IP) was calculated as:

$$IP = \frac{W_i N}{120} \qquad (4)$$

International Journal of Scientific Engineering and Science
Volume 10, Issue 8, pp. 8-14, August 2026
ISSN (Online):

where N is the engine speed (rpm). The constant 120 is used because the engine operates on a four-stroke cycle.
Since brake power cannot be obtained directly from the closed-cycle combustion simulation in ANSYS Forte, the Brake Mean Effective Pressure (BMEP) was determined using experimental brake power data reported by Moh. Ali Sidik (2026) under the same engine configuration. The BMEP was calculated as:

$$BMEP = \frac{120\,BP}{V_d N} \qquad (5)$$

where BP is the brake power (W), V_d is the engine displacement volume (m³), and N is the engine speed (rpm). The calculated values of Wi, IMEP, IP, and BMEP were then compared between the baseline and HHO supplementation conditions to evaluate the influence of HHO gas supplementation on engine thermodynamic performance.

III. Result and Discussion

A. Model Verification

The combustion chamber model was verified using the Compression Ratio Calculator in ANSYS Forte. The verification compared the simulated compression ratio and swept volume with the engine specifications. As summarized in Table III, the simulated compression ratio was 10.96:1, which is very close to the specified value of 11.00:1, resulting in an error of only 0.39%. In addition, the simulated swept volume was 124.83 cm³, closely matching the engine displacement of 124.80 cm³. These results indicate that the developed numerical model accurately represents the engine geometry and is suitable for combustion analysis.

TABLE III. Model Verification Results

Parameter	Simulation	Specification
Swept volume (cm³)	124.83	124.80
Compression ratio	10.96 : 1	11.00 : 1
Error (%)	0.39	–

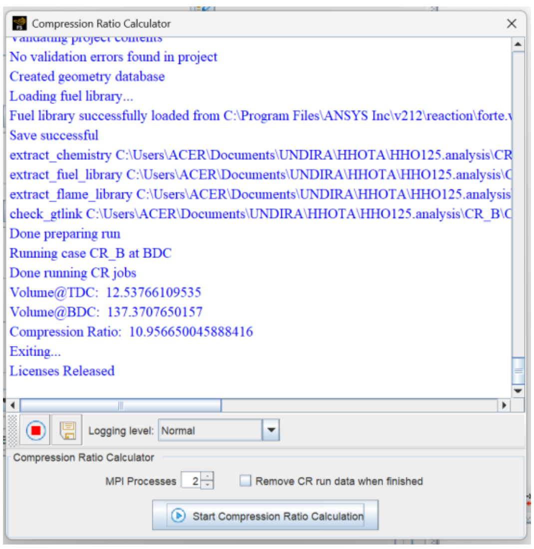

Fig. 2. Compression Ratio Calculator result

B. In-Cylinder Pressure Analysis

Figure 2 compares the in-cylinder pressure under the baseline and HHO supplementation conditions at an engine speed of 5,000 rpm. To ensure an objective comparison, the analysis was conducted at a crank angle of 15° ATDC, where both operating conditions have the same piston position and combustion phase.

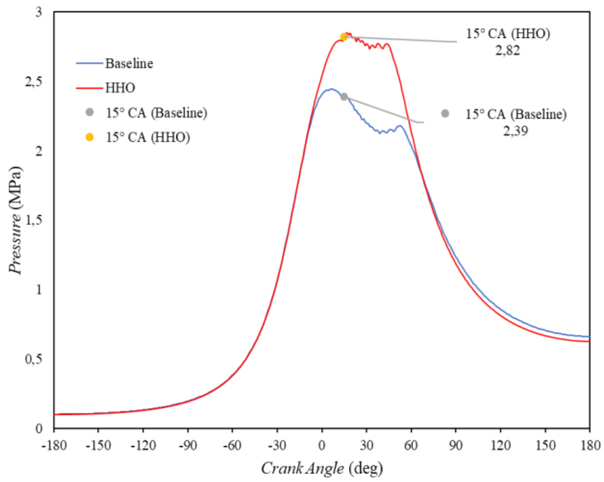

Fig. 2. Comparison of in-cylinder pressure versus crank angle under baseline and HHO supplementation conditions.

As shown in Figure 2, HHO supplementation increased the peak in-cylinder pressure from 2.39 MPa under the baseline condition to 2.82 MPa, representing an increase of 18.0%. This improvement indicates that the addition of HHO promoted a more effective combustion process, allowing a greater portion of the released combustion energy to be converted into pressure within the combustion chamber.

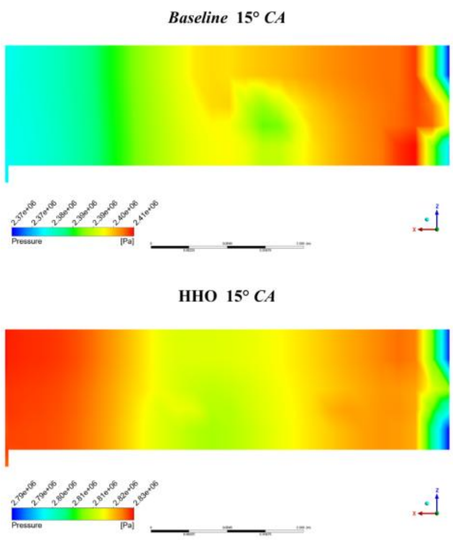

Fig. 3. In-cylinder pressure distribution at 15° ATDC under baseline and HHO supplementation conditions.

The pressure distribution inside the combustion chamber at 15° ATDC is presented in Figure 3. Compared with the baseline condition, HHO supplementation produced a larger high-pressure region within the combustion chamber. This observation indicates that combustion occurred more rapidly and uniformly, resulting in earlier energy release during the combustion process. Consequently, the increase in in-cylinder pressure demonstrates that HHO supplementation enhances the combustion characteristics and has the potential to improve the thermodynamic performance of the engine.

C. In-Cylinder Temperature Analysis

Figure 4 compares the in-cylinder temperature under the baseline and HHO supplementation conditions at an engine speed of 5,000 rpm. To ensure an objective comparison, the analysis was performed at a crank angle of 15° ATDC, where both operating conditions have the same piston position and cylinder volume.

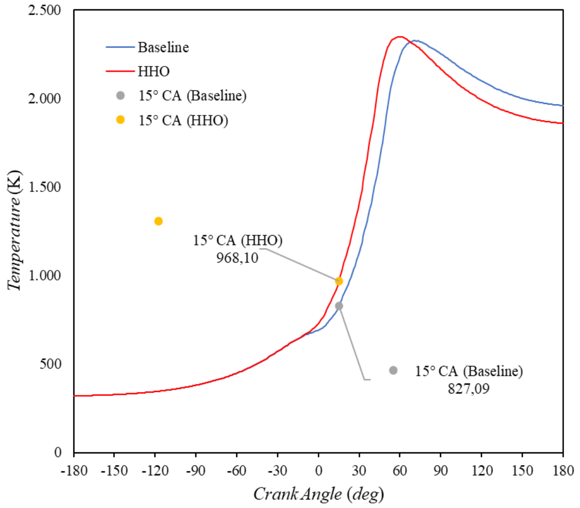

Fig. 4. Comparison of in-cylinder temperature versus crank angle under baseline and HHO supplementation conditions.

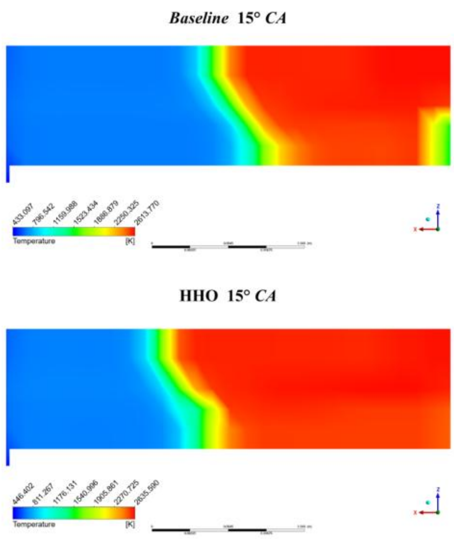

Fig. 5. Temperature distribution inside the combustion chamber at 15° ATDC under baseline and HHO supplementation conditions.

At this crank angle, the in-cylinder temperature under the baseline condition was 827.09 K, while HHO supplementation increased the temperature to 968.10 K. This represents an increase of 141.01 K, or 17.05%, compared with the baseline condition. The higher combustion temperature indicates that HHO supplementation accelerated the combustion process, resulting in faster energy release during the early stage of the expansion stroke.

Figure 5 presents the temperature distribution inside the combustion chamber at 15° ATDC. Compared with the baseline condition, HHO supplementation produced a larger high-temperature region within the combustion chamber. This observation is consistent with the temperature profile shown in Figure 4, where the HHO supplementation case exhibits a higher in-cylinder temperature at the same crank angle. The wider distribution of high-temperature regions indicates a more intensive combustion process, allowing combustion energy to be released more rapidly than under the baseline condition.

D. Heat Release Rate Analysis

Figure 6 compares the Heat Release Rate (HRR) versus crank angle under the baseline and HHO supplementation conditions at an engine speed of 5,000 rpm. To obtain an objective comparison, the analysis was focused on a crank angle of 15° ATDC, where both operating conditions were in the same combustion phase. At this crank angle, the HRR under the baseline condition was 4.68 J/°CA, whereas the HRR increased to 6.50 J/°CA with HHO supplementation. This represents an increase of 1.82 J/°CA, or approximately 38.88%, compared with the baseline condition.

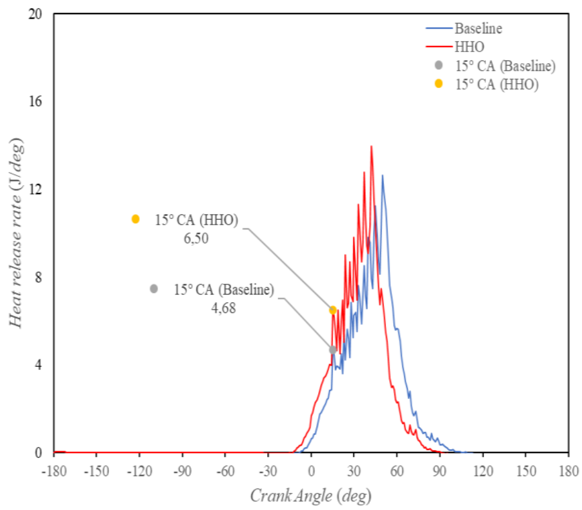

Fig. 6. Comparison of heat release rate versus crank angle under baseline and HHO supplementation conditions.

The increase in HRR indicates that HHO supplementation accelerates energy release during the combustion process. The characteristics of hydrogen, including its low ignition energy and high reaction rate, allow the air–fuel mixture to burn more rapidly, causing the chemical energy of the fuel to be released within a shorter period. This result is consistent with the increases in in-cylinder pressure and temperature discussed in the previous sections, indicating that HHO supplementation produces a more intensive combustion process during the early stage of the expansion stroke.

E. Flame Speed Analysis

Figure 7 compares the flame speed versus crank angle under the baseline and HHO supplementation conditions at an engine speed of 5,000 rpm. To obtain an objective comparison, the analysis was performed at a crank angle of 15° ATDC, where both operating conditions were in the same combustion phase. At this crank angle, the flame speed under the baseline condition was 449.75 cm/s, whereas it increased to 552.13 cm/s with HHO supplementation. This represents an increase of 102.38 cm/s, or approximately 22.76%, compared with the baseline condition. This increase indicates that HHO supplementation accelerates flame propagation, resulting in a faster combustion process.

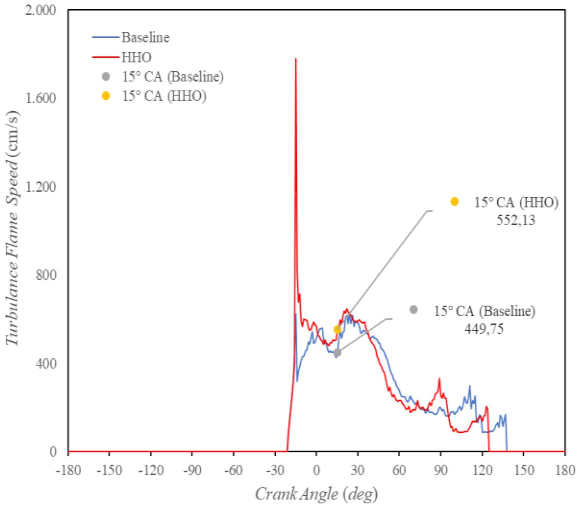

Fig. 7. Comparison of flame speed versus crank angle under baseline and HHO supplementation conditions.

Figure 8 shows the flame speed distribution inside the combustion chamber at 15° ATDC. Compared with the baseline condition, HHO supplementation produces regions with higher flame propagation speed and a wider flame front distribution. This visualization is consistent with the graph shown in Figure 7, which indicates a higher flame speed under HHO supplementation at the same crank angle. The higher flame propagation speed accelerates the spread of combustion throughout the air–fuel mixture, allowing the energy release process to occur more rapidly and more uniformly inside the combustion chamber.

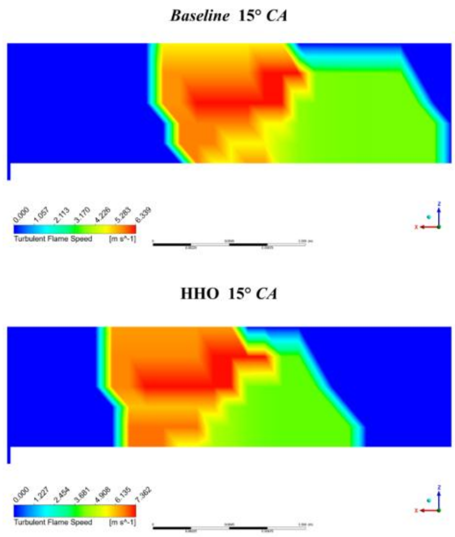

Fig. 8. Flame speed distribution inside the combustion chamber at 15° ATDC under baseline and HHO supplementation conditions.

F. Engine Performance Analysis

Engine performance was evaluated using Indicated Work (Wi), Indicated Mean Effective Pressure (IMEP), Indicated Power (IP), and Brake Mean Effective Pressure (BMEP). The comparison between the baseline and HHO supplementation conditions is presented in Table IV.

As shown in Table IV, HHO supplementation improved all evaluated performance parameters. The indicated work increased from 135.41 J to 150.27 J (10.97%), followed by increases in IMEP from 1.085 MPa to 1.203 MPa (10.88%) and indicated power from 5.64 kW to 6.26 kW (10.98%). The largest improvement was observed in BMEP, which increased from 0.492 MPa to 0.590 MPa (19.92%).

These improvements indicate that HHO supplementation enhanced the combustion process, allowing more of the released energy to be converted into useful work. The increase in engine performance is consistent with the higher in-cylinder pressure, temperature, heat release rate, and flame speed discussed in the previous sections, demonstrating the positive effect of HHO supplementation on engine thermodynamic performance.

TABLE IV. Comparison of engine performance parameters under baseline and HHO supplementation conditions.

Parameter	Baseline	HHO	Increase (%)
Indicated Work, Wi (J)	135.41	150.27	10.97
Indicated Mean Effective Pressure, IMEP (MPa)	1.085	1.203	10.88
Indicated Power, IP (kW)	5.64	6.26	10.98
Brake Mean Effective Pressure, BMEP (MPa)	0.492	0.590	19.92

IV. CONCLUSION

Based on the results of numerical simulations using ANSYS Forte regarding the effect of HHO gas supplementation on the combustion characteristics of a 125 cc four-stroke Otto engine, the following conclusions can be drawn.

1. HHO gas supplementation increases the pressure inside the cylinder at a crankshaft angle of 15° ATDC from 2.39 MPa to 2.82 MPa, representing an increase of approximately 18.0%. This increase indicates that the addition of HHO gas results in a more intense combustion process during the early phase of the expansion stroke.
2. The temperature inside the cylinder at a crankshaft angle of 15° ATDC increased from 827.09 K to 968.10 K, representing an increase of approximately 17.0%. This rise in combustion temperature indicates that energy

release occurs more rapidly due to hydrogen's high flame propagation speed.

3. The Heat Release Rate (HRR) at a crankshaft angle of 15° ATDC increased from 4.68 J/°CA to 6.50 J/°CA, or by approximately 38.9%. This indicates that the rate of energy release from combustion increased significantly with the addition of HHO gas.
4. The flame speed at a crankshaft angle of 15° ATDC increased from 449.75 cm/s to 552.13 cm/s, or by approximately 22.8%. This increase indicates that the flame front spreads more rapidly throughout the combustion chamber, causing the combustion process to occur in a shorter amount of time.
5. HHO gas supplementation enhances the engine's ability to produce work, as evidenced by an increase in Indicated Work from 135.41 J to 150.27 J (a 10.97% increase), Indicated Mean Effective Pressure (IMEP) from 1.085 MPa to 1.203 MPa (an increase of 10.88%), and Indicated Power (IP) from 5.64 kW to 6.26 kW (an increase of 10.98%). These improvements are also reflected in an increase in Brake Mean Effective Pressure (BMEP) from 0.492 MPa to 0.590 MPa (a 19.92% increase) based on experimental test data.
6. Overall, simulations using ANSYS Forte show that HHO gas supplementation has a positive effect on the combustion characteristics of a 125 cc four-stroke Otto engine by increasing cylinder pressure, combustion temperature, heat release rate, and flame propagation speed, as well as improving the engine's ability to produce indicated work and shaft power compared to conditions without HHO supplementation.

V. RECOMMENDATIONS

Based on the results of this study, several recommendations are offered: future research should vary the HHO gas flow rate so that the effect of supplementation levels on combustion characteristics can be analyzed more comprehensively. Furthermore, simulation results should be validated using experimental test data under the same operating conditions so that the accuracy of the simulation model can be quantitatively evaluated. Furthermore, future research could expand the scope of analysis by evaluating the formation of exhaust emissions, such as CO, HC, and NOx, so that the effect of HHO gas supplementation on combustion characteristics and emissions can be studied more thoroughly. Additionally, the effect of HHO supplementation could be analyzed at various engine speeds and under different operating loads to obtain combustion characteristics that are more representative of actual engine operating conditions

ACKNOWLEDGMENTS

The authors would like to express their sincere gratitude to the supervisors for their invaluable guidance, constructive comments, and continuous encouragement throughout this research. The authors also acknowledge the Department of Mechanical Engineering, Universitas Dian Nusantara, for providing academic support and research facilities. Appreciation is further extended to the research team whose experimental data served as the basis for the simulation and analysis presented in this study.

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