



Technical Analysis of the Use of Dual Fuel HSD-Hydrogen Fuel in the UTD-20 Ranpur Bvp-2 Diesel Engine Using Ansys Forte Numerical Analysis

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ABSTRACT

This study analyzes the effect of dual fuel HSD-hydrogen on the performance, combustion, and emissions of the UTD-20 Ranpur BVP-2 engine using ANSYS Forte simulation. The simulation tested the variation of SOI (-27°C A and -13°C A BTDC), hydrogen fraction (0-50%), and engine rotation (1600-2600 rpm). The results show that the SOI -27°C A BTDC provides the most stable operation. At SOI -27°C A, the addition of hydrogen up to 50% significantly increases ITE, as well as lowers ISFC, NO_x emissions, and soot. The 50% HSD + H₂ 50% configuration at 2000 rpm resulted in the highest ITE (48.59%) and lowest ISFC (157.54 g/kWh). In contrast, the SOI of -13°C A with 50% hydrogen at 2600 rpm triggers misfire and a drastic decrease in efficiency. The SOI -27°C A BTDC strategy with a high hydrogen fraction proved to be the most prospective

INTRODUCTION

The dependence of diesel engines on fossil fuels is still a crucial issue in the transportation and defense sectors because it is directly related to energy efficiency, operational costs, and exhaust emissions (Cernat et al., 2020)(Pielecha, 2024). The use of hydrogen in transport diesel engines is proving to be one of the most strategic solutions to overcome these challenges (Cernat et al., 2020). In combat vehicles, the need for reliable, fuel-efficient, and low-emission propulsion systems is increasingly relevant as the demands of energy sustainability increase. The UTD-20 diesel engine used in the Ranpur BVP-2 is a large-capacity heavy-duty engine designed to produce high power and reliability, but until now it still relies heavily on High Speed Diesel (HSD) as the main energy source (ANSYS, 2025c) (Lostari et al., 2024).

One of the rapidly developing approaches to reduce diesel consumption is the use of hydrogen (H₂) as a companion fuel through the dual-fuel concept (Dimitriou & Javaid, 2023). In this system, diesel continues to function as a pilot fuel to trigger autoignition, while hydrogen is supplied to the intake manifold to replace a portion of the HSD energy fraction (Yip et al., 2019). A review of the spraying characteristics of hydrogen confirms that its thermophysical properties play a vital role in combustion stability (Yip et al., 2019). Hydrogen has advantages in the form of a very high Lower Heating Value of 120 MJ/kg, a fast speed of laminar flame, and does not contain carbon atoms so that it has great potential to increase thermal efficiency and reduce particulate emissions (SOOT) (Dimitriou & Javaid, 2023). This reactivity control-based combustion concept is proven to optimize thermal energy conversion effectively (Reitz & Duraisamy, 2015)

In dual-fuel diesel-hydrogen engines, the ignition fuel injection strategy plays a central role in determining the success of the transient combustion process (Ghadamkheir et al., 2025). The most decisive parameter is the starting angle of injection (Start of Injection/SOI). SOI settings affect ignition delay, fluid mixing homogeneity, key heat discharge location to the Upper Dead Point (TMA), and pressure profile and peak temperature within the cylinder (Xu et al., 2023). Previous research by Borkhetaria & Kaushik (2022) Cernat et al. (2020) and Dimitriou & Javaid (2023) confirming that the addition of hydrogen and SOI settings in the dual-fuel engine are able to control the Heat Release Rate. However, most previous studies are still limited to small to medium-scale commercial diesel engines with stationary operational ranges and relatively low hydrogen substitution ratios (Ariani et al., 2024)(Pielecha, 2024).

Based on a literature review, there is still a research gap related to the characteristics of transient combustion in large-capacity heavy-duty engines, especially UTD-20 military engines. Until now, there have not been many studies that have comprehensively examined the interaction between high hydrogen substitution fractions (up to 50%), variations in engine rotation from peak torque (1600 rpm) to rated power (2600 rpm), as well as advanced and retarded SOI strategies on combustion performance, efficiency, and emissions.

Therefore, the novelty of this study lies in a three-dimensional computational analysis using ANSYS Forte 2025 R1 with a 51.43° sector mesh

approach and a transient chemical kinetics model to evaluate the limits of technical feasibility, the shift in thermodynamic cycle characteristics towards combustion close to constant volume, as well as the misfire/extinction phenomenon in the UTD-20 Ranpur BVP-2 military diesel engine (ANSYS, 2025a)(ANSYS, 2025b)(ANSYS, 2025c).

Based on this background, this study aims to analyze the effect of the use of dual-fuel HSD-hydrogen fuel with variations in hydrogen energy fractions of 0%, 10%, 30%, and 50%, as well as SOI variations of -27° CA BTDC and -13° CA BTDC on engine performance, transient combustion characteristics, and exhaust gas emissions in UTD-20 engines with variations in rotation of 1600 rpm, 2000 rpm, and 2600 rpm using ANSYS Forte 2025 R1-based numerical simulation.

LITERATURE REVIEW

Dual-Fuel Combustion Characteristics of HSD-Hydrogen

The hydrogen-based dual-fuel system in the Compression Ignition (CI) engine utilizes diesel fuel as the pilot fuel to trigger the ignition (autoignition), while hydrogen is injected through the intake manifold as the main fuel (Cernat et al., 2020)(Yip et al., 2019). The implementation of hydrogen in transportation diesel engines shows great potential in reducing fossil fuel consumption and carbon emissions (Cernat et al., 2020). Hydrogen has superior thermophysical characteristics, including a lower heating value of around 120 MJ/kg and a much higher flame propagation speed than diesel fuel(Dimitriou & Javaid, 2023)(Yip et al., 2019). In addition, the high diffusion of hydrogen accelerates the formation of a more homogeneous air-fuel mixture in the cylinder, thereby increasing the Heat Release Rate (HRR) and shifting combustion characteristics closer to a constant volume cycle. These conditions contribute to the increase in Indicated Thermal Efficiency (ITE) (Liu & Wei, 2021)(Reitz & Duraisamy, 2015). The absence of carbon atoms in hydrogen also plays a role in lowering the formation of particulate emissions (soot) and greenhouse gases during the combustion process (Borkhetaria & Kaushik, 2022) (Cernat et al., 2020).

Role of Pilot Injection Angle (Start of Injection / SOI)

The pilot fuel spraying time strategy is one of the parameters that most determine the combustion characteristics of a dual-fuel diesel engine (Ghadamkheir et al., 2025). Advanced Start of Injection provides a longer ignition delay time so that diesel and hydrogen fuels have the opportunity to form a more homogeneous mixture before reaching the Upper Dead Point (TMA) (Reitz & Duraisamy, 2015)(Xu et al., 2023). This condition results in a more efficient combustion process, although it has the potential to increase the maximum cylinder pressure (Peak Cylinder Pressure / Pmax) and Maximum Pressure Rise Rate (MPRR) (Borkhetaria & Kaushik, 2022). On the other hand, the retarded SOI strategy shortens the fuel mixing time so that at high hydrogen fractions it can trigger delayed combustion (retarded combustion), unstable combustion, and even misfire/extinction (Dimitriou & Javaid, 2023)(Yip et al., 2019).

CFD Computational Modeling and Chemical Kinetics

A three-dimensional Computational Fluid Dynamics (CFD) approach combined with transient chemical kinetic mechanisms has been widely used to analyze the phenomena of compression, fuel spraying, combustion, and emission formation inside diesel engine cylinders (ANSYS, 2025a)(ANSYS, 2025b)(ANSYS, 2025c). ANSYS Forte software provides a solver capable of modeling spray atomization, fuel evaporation, species mixing, and multidimensional chemical reactions in heavy-duty engines (Ghadamkheir et al., 2025). The use of mesh sectors combined with the Adaptive Mesh Refinement (AMR) feature based on temperature and speed gradients allows simulations to capture the development of the flame front more accurately while maintaining computational efficiency and numerical stability (Liu & Wei, 2021)(Lostari et al., 2024).

METHODOLOGY

This study uses a three-dimensional numerical simulation approach based on Computational Fluid Dynamics (CFD) with ANSYS Forte 2025 R1 software to analyze the effect of the use of dual-fuel High Speed Diesel (HSD)–hydrogen fuel on the combustion and emission characteristics of the UTD-20 Ranpur BVP-2 diesel engine. The simulation domain is limited to the in-cylinder closed cycle phase, which starts from the Inlet Valve Closing (IVC) at -134° CA ATDC to the Exhaust Valve Opening (EVO) at 130° CA ATDC. Domain restrictions are carried out to focus analysis on the process of compression, fuel spraying, combustion, and emission formation within the combustion chamber.

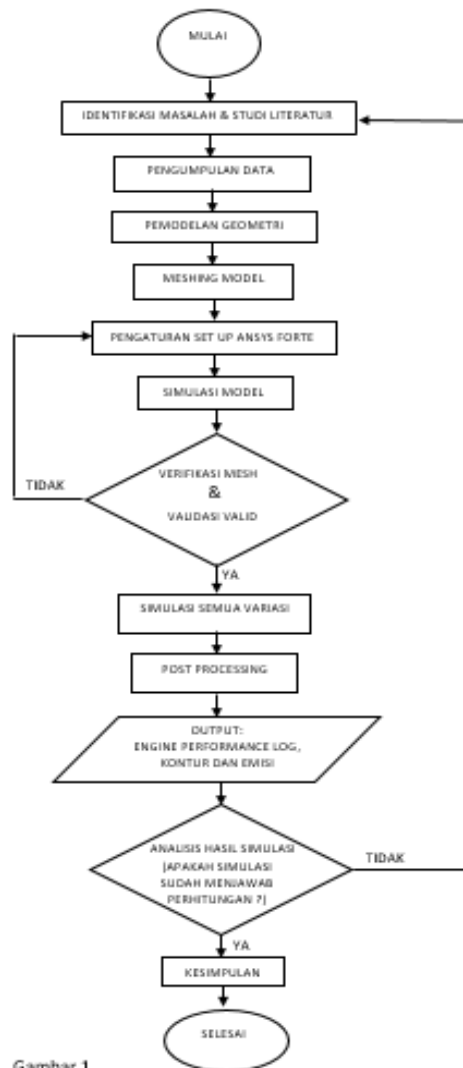
The object of the research was a heavy-duty diesel engine UTD-20 with a cylinder diameter (bore) of 150 mm, a piston stroke of 150 mm, and a compression ratio of 15.8:1. The combustion chamber geometry is built based on the actual specifications of the engine. To improve computational efficiency without compromising the accuracy of the simulation results, the computing domain is modeled using a 51.43° cylindrical sector mesh representing the symmetrical configuration of a 7-hole nozzle.

The mesh generation process uses a base mesh of 10,930 cells in the gas phase combined with the Adaptive Mesh Refinement (AMR) feature. This feature automatically smooths the mesh based on temperature and speed gradients in areas with high combustion reaction activity. In addition, Fixed Embedding is applied to the area around the injector nozzle to increase the calculation resolution, while a cell height expansion ratio of 1.15 is used on the piston wall and cylinder head. The simulation was run with an initial time-step of 5.0×10^{-7} seconds and was automatically controlled using the Courant–Friedrichs–Lewy (CFL) criteria to maintain numerical stability and convergence.

The simulation applied several physics submodels to represent the dual-fuel combustion process within the combustion chamber. The turbulence model uses the renormalization group (RNG) k - ϵ to model the characteristics of turbulent flows. The fuel atomization process is modeled using a combination of Kelvin–Helmholtz (KH) and Rayleigh–Taylor (RT) breakup models, while the evaporation process is calculated using the Frössling Evaporation Model. The interaction between droplets is modeled using the Dynamic Drag Model and the

Nordin Collision Model. The combustion kinetics were calculated using a CHEMKIN solver with the reaction mechanism of n-heptane ($n\text{-C}_7\text{H}_{16}$) as the surrogate fuel HSD and the reaction mechanism of hydrogen (H_2). Nitrogen oxide (NO_x) emissions were predicted using the Extended Zeldovich Thermal NO_x Mechanism, while soot (soot) formation was analyzed using the Hiroyasu-Nagle Soot Model.

The independent variables in this study include the Start of Injection (SOI) configuration of HSD fuel at -27° CA BTDC (advanced injection) and -13° CA BTDC (retarded injection), variations in hydrogen energy fractions of 0%, 10%, 30%, and 50%, and variations in engine rotation of 1600 rpm, 2000 rpm, and 2600 rpm. The bound variables analyzed included Maximum Cylinder Pressure (P_{max}), Maximum Temperature (T_{max}), Indicated Mean Effective Pressure (IMEP), Indicated Specific Fuel Consumption (ISFC), Indicated Thermal Efficiency (ITE), Heat Release Rate (HRR), Maximum Pressure Rise Rate (MPRR), as well as nitrogen oxide (NO_x) and soot (soot) emission concentrations.



Gambar 1

Figure 1. Research flowchart

Table 1. Operating conditions and variables of the research simulation

Parameter	Remarks
Engine	Diesel UTD-20
Software	ANSYS Forte 2025 R1
Fuel	HSD + H ₂
Hydrogen fraction	0%, 10%, 30%, 50%
SOI Variations	-27°CA BTDC -13°CA BTDC
Engine rotation	1600 rpm, 2000 rpm, 2600 rpm
Output parameters	Pmax, ITE, NOx, soot

RESEARCH RESULT

Cylinder Maximum Pressure (Pmax)

The simulation results show that the maximum pressure characteristics of the cylinders are strongly influenced by the combination of the hydrogen fraction and the pilot fuel injection time. In the SOI configuration of -27°CA BTDC, an increase in the hydrogen fraction tends to result in a more controlled peak pressure, even decreasing at high fractions, indicating that the heat release process is more stable and less aggressive. In contrast, at the SOI configuration of -13°CA BTDC, the increase in the hydrogen fraction to the intermediate level still raises the Pmax, but in the 50% HSD + H₂ 50% mixture at 2600 rpm the pressure drops drastically to 3.21 MPa. This sharp drop shows symptoms of misfire/extinction, so the SOI configuration of -13°CA at the high hydrogen fraction is considered less stable for the operation of the UTD-20 engine.

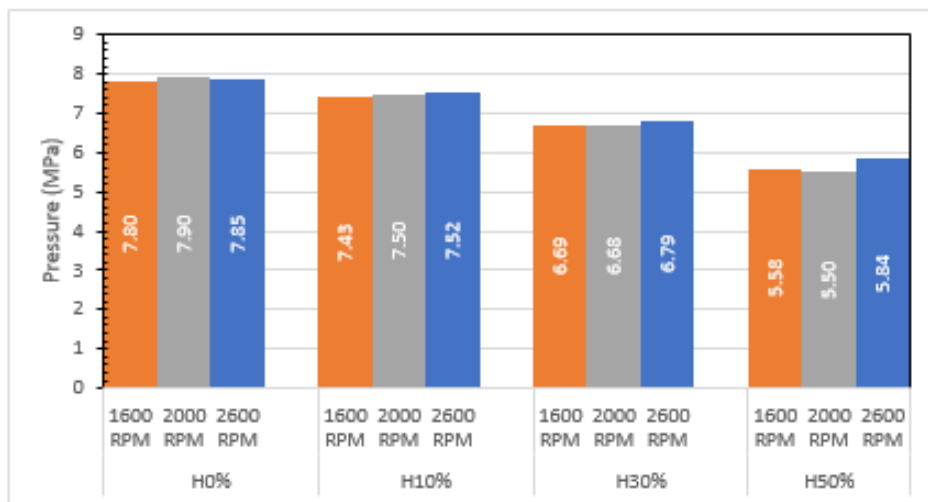


Figure 2. Maximum cylinder pressure (Pmax) of the entire SOI variation - 27°CA

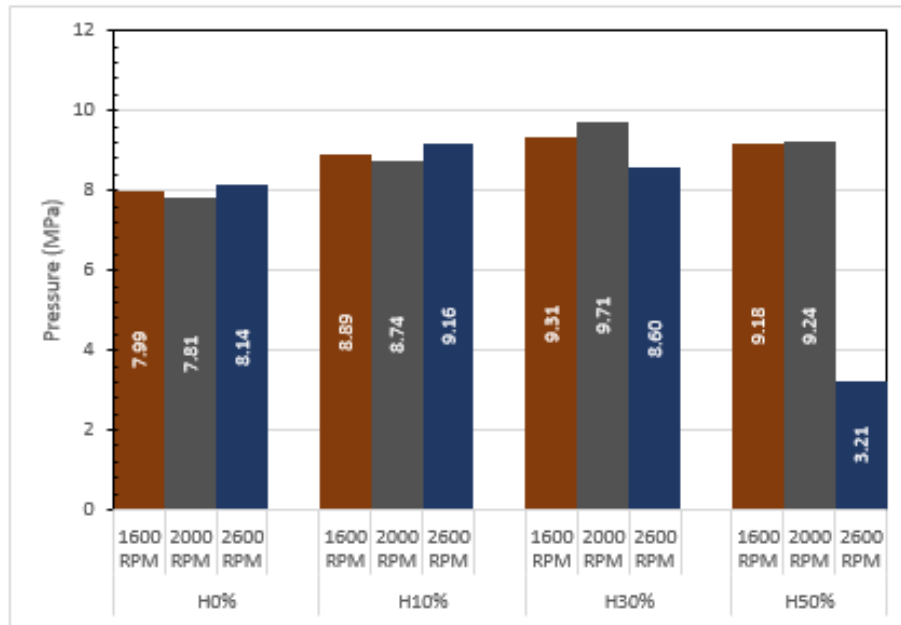


Figure 3. Maximum cylinder pressure (Pmax) of the whole SOI variation - 13°C

Indicated Thermal Efficiency (ITE)

The indicated thermal efficiency (ITE) value is used to evaluate the engine's ability to convert fuel energy into indicator work. The simulation data showed that the SOI configuration of -27°C BTDC provided the best efficiency response at the high hydrogen fraction. The optimum condition was obtained in a mixture of 50% HSD + H₂ 50% with an ITE value of 47.99% at 1600 rpm, 48.59% at 2000 rpm, and 45.23% at 2600 rpm. In contrast, at SOI -13°C BTDC, thermal efficiency drops sharply at high hydrogen fractions, even reaching only 1.93% at 2600 rpm for a 50% HSD + 50% H₂ mixture. These findings confirm that SOI -27°C is more prospective because it is able to maintain combustion efficiency at greater variations of hydrogen fractions.

Table 2. Indicated thermal efficiency value at SOI -27°C

No	Fuel Variations	Thermal Efficiency (%)		
		1600 rpm	2000 rpm	2600 rpm
1	HSD 100% + H ₂ 0%	33,96	33,96	33,28
2	HSD 90% + H ₂ 10%	33,24	34,52	35,09
3	HSD 70% + H ₂ 30%	41,18	35,91	37,13
4	HSD 50% + H ₂ 50%	47,99	48,59	45,23

Table 3. Indicated thermal efficiency value at SOI -13°C

No	Fuel Variations	Thermal Efficiency (%)		
		1600 rpm	2000 rpm	2600 rpm
1	HSD 100% + H ₂ 0%	41,23	38,95	42,61
2	HSD 100% + H ₂ 10%	37,86	39,97	41,33
3	HSD 100% + H ₂ 30%	31,38	31,71	34,03
4	HSD 100% + H ₂ 50%	21,98	24,25	1,93

Nox Emissions

The change in NO_x emissions in this study showed a close relationship with combustion temperature and the stability of the heat release process. At SOI -27°CA BTDC, an increase in the hydrogen fraction of up to 50% actually significantly reduces NO_x emissions and produces a low value of 2.50 g/kgfuel at 2000 rpm. The results show that this configuration is able to utilize hydrogen without triggering excessive NO_x formation. At SOI -13°CA BTDC, the NO_x trend is more volatile; Although in the high hydrogen fraction emissions tend to decrease, the decline must be read together with performance degradation and indications of unstable combustion.

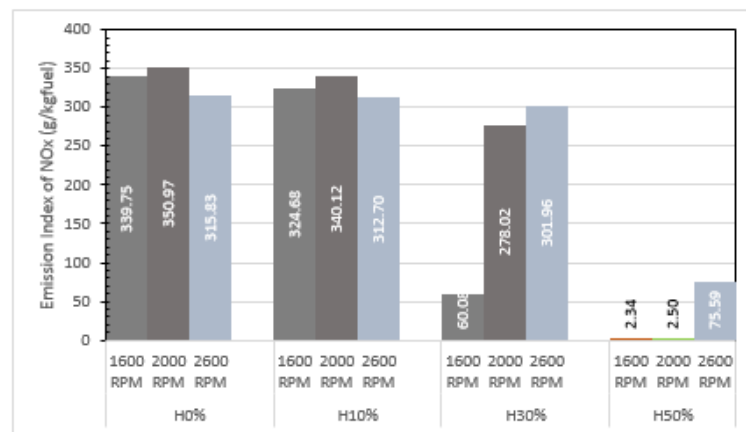


Figure 4. EINO_x comparison of all SOI variations -27°CA

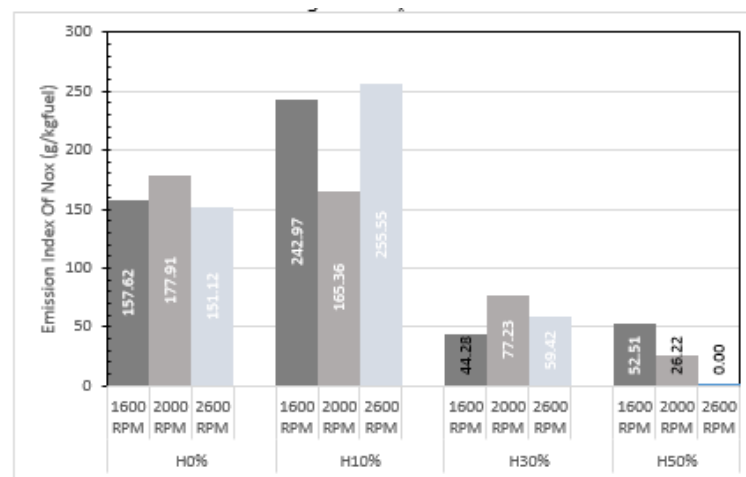


Figure 5. EINO_x comparison of all SOI variations -13°CA

Emisi Soot

Soot emissions in both SOI configurations are generally at low levels, in line with the characteristics of carbon-free hydrogen. Nevertheless, the soot distribution still shows a difference in combustion character between the two injection strategies. At SOI -27°CA BTDC, soot still appears under certain conditions, but tends to decline at high hydrogen fractions and remains in the low range. At SOI -13°CA BTDC, soot emissions are also low, but their interpretation should be attributed to the risk of misfire in high hydrogen

mixtures. Thus, the decline in soot cannot be seen as separate from the combustion stability and overall performance of the engine.

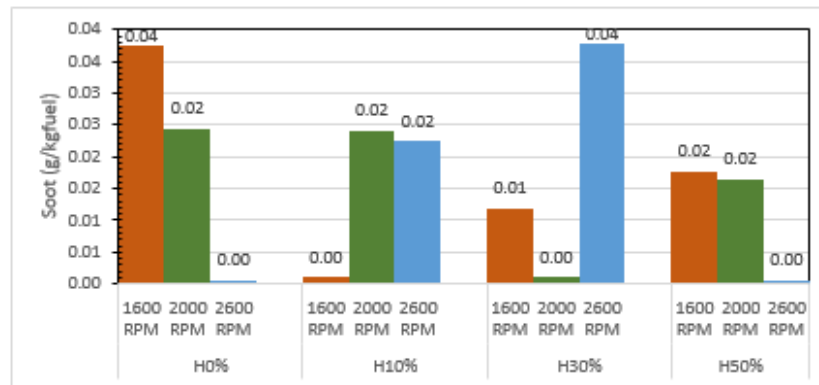


Figure 6. Soot emission graph at SOI -27°C A

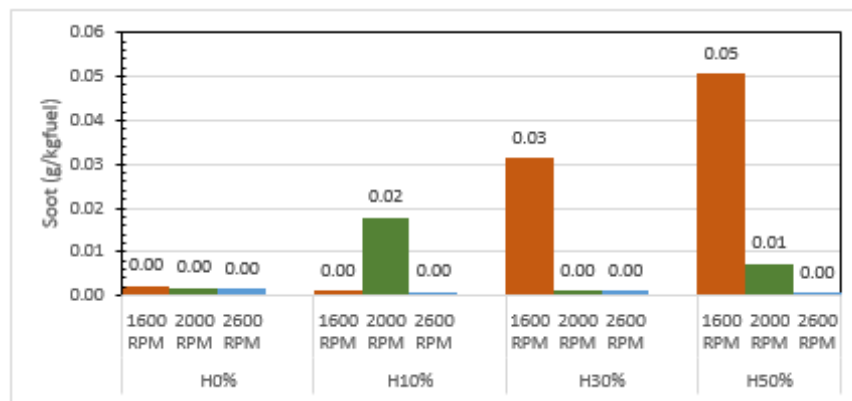


Figure 7. Soot emission graph at SOI -13°C A

DISCUSSION

Combustion Dynamics Phenomenon and Pmax Stability

The difference in the characteristics of the maximum cylinder pressure (Peak Cylinder Pressure/ P_{max}) between the two injection strategies is mainly influenced by the duration of the ignition delay and the level of homogeneity of the air-fuel mixture. In the advanced Start of Injection (SOI) -27° CA BTDC strategy, earlier pilot fuel spraying allows sufficient time for HSD droplets to undergo atomization, evaporation, and mixing with hydrogen and air before autoignition. The presence of hydrogen with a high flame propagation speed accelerates heat release (HRR), but still results in a more even combustion distribution within the combustion chamber. A decrease in the P_{max} value of 50% in the hydrogen fraction indicates that the reduction in the mass of the pilot fuel is able to reduce the local energy concentration so as to prevent pressure spikes that have the potential to cause knocking.

In contrast, the retarded SOI strategy at -13° CA BTDC shortens the ignition delay so that the time available for homogeneous mixture formation becomes more limited. At 50% hydrogen substitution and 2600 rpm engine rotation, the residence time of the mixture in the cylinder becomes shorter due to the increase

in piston speed. The reduction in the number of HSDs causes the ignition energy to no longer be sufficient to sustain flame propagation in a relatively poor hydrogen-air mixture (lean mixture), resulting in flame extinction or misfire indicated by a decrease in P_{max} to 3.21 MPa. These results are in line with research Yip et al. (2019), Xu et al. (2023) and Liu & Wei (2021), which reported that the retarded pilot injection strategy in dual-fuel diesel engines with high hydrogen substitution increases the risk of combustion instability if the pilot fuel is insufficient.

Thermodynamic Shifts and Improved Thermal Efficiency (ITE)

The increase in Indicated Thermal Efficiency (ITE) of up to 48.59% in the SOI -27° CA BTDC configuration with a mixture of 50% HSD and 50% H₂ indicates that the combination of earlier injection time and hydrogen substitution is able to improve energy conversion efficiency. The high rate of hydrogen combustion shifts the heat release process closer to the Upper Dead Point (TMA), so that the combustion characteristics are getting closer to the constant-volume combustion cycle. These conditions allow the energy from combustion to be used more effectively during the expansion step thereby increasing the thermal efficiency of the engine.

These findings support the concept of Reactivity Controlled Compression Ignition (RCCI) put forward by Reitz & Duraisamy (2015), that is, that the control of fuel reactivity through injection timing is able to improve combustion efficiency while maintaining the stability of engine operation. The results of this study are also consistent with the findings of the Dimitriou & Javaid (2023) and Pielecha (2024), which suggests that increased hydrogen substitution can improve thermal efficiency when combined with an appropriate injection strategy. In contrast, the ITE decrease of up to 1.93% at the SOI configuration -13° CA BTDC with 50% hydrogen substitution at 2600 rpm indicates that the heat release shifts towards the expansion step (retarded combustion), so that most of the energy cannot be converted into mechanical work. The phenomenon was also reported by Ghadamkheir et al. (2025) in a numerical study of the compression ignition machine with a dual injection strategy.

Mechanism for Terminating the Trade-Off of NO_x and Soot Emissions

One of the main findings of this study is the ability of the advanced SOI strategy to reduce NO_x and soot emissions simultaneously. Theoretically, NO_x formation is affected by high combustion temperatures, oxygen concentrations, and the length of gas residence at high temperatures. In the SOI -27° CA BTDC configuration, a reduction in the number of HSDs by up to 50% reduces the formation of a rich mixture zone which is generally a source of high-temperature hot spots. On the other hand, a more homogeneous hydrogen mixing results in a more even temperature distribution so that NO_x formation can be suppressed without sacrificing combustion efficiency. These results are in line with research Borkhetaria & Kaushik (2022) and Kadhim et al. (2025), which reports that the combination of hydrogen and advanced injection timing can reduce NO_x emissions when the number of pilot fuels is proportionately reduced.

The reduction in soot emissions in this study was mainly due to the reduction in carbon content due to the substitution of HSD with hydrogen. Since hydrogen does not contain carbon atoms, the formation of soot precursors during the combustion process is much lower than the use of pure HSD. In addition, the high concentration of H and OH radicals produced during hydrogen combustion accelerates the oxidation process of soot particles that are still forming in the final stages of combustion. These findings are consistent with the results of the study Cernat et al. (2020), Ariani et al. (2024) and Lostari et al. (2024), which shows that the application of hydrogen in dual-fuel diesel engines can significantly reduce particulate emissions without reducing engine performance if combustion strategies are optimized.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that the application of HSD-hydrogen dual-fuel fuel has an influence on combustion characteristics, engine performance, thermal efficiency, and exhaust gas emissions in the UTD-20 heavy-duty diesel engine. Among the injection strategies tested, the advanced Start of Injection (SOI) of -27° CA BTDC results in the most stable combustion characteristics under all operating conditions. An increase in the fraction of hydrogen energy substitution of up to 50% is able to shift the heat release process closer to the Upper Dead Point (TMA), thereby increasing Indicated Thermal Efficiency (ITE) and decreasing Indicated Specific Fuel Consumption (ISFC). The optimum condition was obtained at 2000 rpm with an HSD composition of 50%-H₂ 50%, which produced an ITE of 48.59% and an ISFC of 157.54 g/kWh. In contrast, the SOI retarded strategy of -13° CA BTDC lowers combustion stability at high hydrogen fractions and causes combustion failure at 50% hydrogen substitution conditions at 2600 rpm. In addition, the advanced SOI strategy is able to maintain the maximum cylinder pressure (Peak Cylinder Pressure/P_{max}) and Maximum Pressure Rise Rate (MPRR) within safe mechanical limits, while reducing NO_x and soot emissions through more optimal combustion phase regulation and reduced carbon content in the fuel.

The results of this study can be used as a reference in the development of a dual-fuel combustion strategy in heavy-duty diesel engines to improve energy efficiency and reduce exhaust emissions. Further research is recommended to validate the simulation results through experimental testing on the UTD-20 engine, evaluate further combustion strategies such as split injection or Reactivity Controlled Compression Ignition (RCCI), and develop open-cycle CFD simulations to analyze the characteristics of hydrogen-air mixing and the potential for backfire under more realistic operating conditions.

ADVANCED RESEARCH

This study has several limitations, namely a simulation model that only covers the in-cylinder closed cycle phase assuming a homogeneous hydrogen-air mixture, the use of n-heptane as an HSD surrogate fuel, and validation that is still based on mesh verification and historical performance data without direct experimental testing. Therefore, further research is recommended to validate using the UTD-20 test bench engine, evaluate combustion strategies such as split injection or Reactivity Controlled Compression Ignition (RCCI), and develop open-cycle CFD simulations to analyze hydrogen-air mixing and the potential for backfire under more realistic operating conditions.

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