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Numerical Study on the Combustion Characteristics of Dual Fuel Engine Using Natural Gas-Diesel Fuel Blended with Hydrogen at Low Load

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수소를 혼합한 천연가스-디젤 이중연료 엔진의 저부하 연소특성에 대한 수치적 연구

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Abstract The combustion performance and emissions of internal combustion engines under low-load conditions can be significantly improved by blending hydrogen with natural gas-diesel dual fuel. This study is based on experimental data obtained from a natural gas-diesel dual-fuel engine, for which a numerical model of the dual-fuel internal combustion engine was established. This numerical model effectively validates the combustion characteristics of diesel/natural gas dual-fuel operation under low load conditions. Using numerical simulation methods, this study replaced natural gas with hydrogen maintaining a consistent diesel energy and investigated the combustion performance and emission characteristics of dual-fuel combustion with varying energy ratios of blended hydrogen. In this study, the highest thermal efficiency of the internal combustion engine is observed at SOI 22°BTDC with a hydrogen energy ratio of 10%.With the increase in the hydrogen energy ratio, combustion within the cylinder becomes more complete, resulting in a reduction of unburned fuel and hydrocarbon emissions. Therefore, the emissions of UHC, CO, CO_2, and soot are significantly reduced after combustion in the internal combustion engine. On the other hand, with the increase in the hydrogen energy ratio, the cylinder is more prone to generating localized high temperatures, leading to the production of NOx. In this study, a hydrogen energy ratio of 10% and SOI of 22°BTDC can maintain a higher thermal efficiency in the internal combustion engine while experiencing a relatively modest increase in NOx.

요 약 수소를 천연가스-디젤 이중 연료에 혼합하면 저부하 조건에서 내연기관의 연소 성능과 배출가스를 크게 개선할 수 있다. 본 연구에서는 먼저 천연가스-디젤 이중 연료 엔진의 실험 데이터를 기반으로 저부하 조건에서 수치 모델의 결과를 검증하였다. 천연가스-디젤의 이중 연료에서 디젤 에너지는 일정하게 유지하고, 천연가스의 일부를 수소로 대체함으로써 수소 에너지 비율을 변경시켰을 때 연소 성능과 배출가스 특성에 미치는 영향을 조사하였다. 본 연구에서 내연기관의 열효율은 수소 에너지 비율이 10%, 연료분사시기가 22° BTDC에서 가장 높았으며, 수소 에너지 비율이 높아질수록 실린더 내 연소가 더욱 완전해져 미연소 연료와 탄화수소 배출량이 감소하는 것으로 나타났으며 일산화탄소, 이산화탄소, 매연 등의 배출량이 현저히 감소하였다. 반면, 수소 에너지 비율이 증가함에 따라 실린더는 국부적으로 고온이 발생하기 쉬워 질소산화물(NOx)이 발생하기 쉽다. 본 연구에서는 수소 에너지 비율이 10%, 연료분사시기가 22° BTDC 일 때 높은 열효율을 유지하면서도 질소산화물(NOx)의 증가는 상대적으로 크지 않은 것으로 나타났다.

Keywords : Diesel Engine, Dual Fuel Combustion. Emission, Hydrogen Energy Ratio, Natural gas. Thermal Efficiency

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Nomenclature	
ATDC	After Top Dead Center
BTDC	Before Top Dead Center
CAD	Crank Angle Degree
CFD	Computational Fluid Dynamic
CI	Compression Ignition
HRR	Heat Release Rate
IMEP	Indicated Mean Effective Pressure
ISFC	Indicated Specific Fuel Consumption
NG	Natural Gas
NOx	Nitrogen Oxides
RCCI	Reactivity Controlled Compression Ignition
TDC	Top Dead Center
UHC	Unburned Hydrocarbon
CA50	crank angle degree at which 50% of the accumulated heat release is reached
MPRR	Max Pressure Rise Rate

1. Introduction

Against the backdrop of the increasingly prominent global environmental issues, reducing air pollutant emissions and lowering carbon emissions have become crucial focal points in the field of scientific research. Diesel engines are widely favored for their higher fuel efficiency, durability, and high torque, making them extensively used in transportation (land, sea and air), stationary power generation units, and various industrial applications. However, the combustion process of diesel engines produces significant byproducts categorized as air pollutants, including nitrogen oxides (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC), and particulate matter (PM). To address these issues, a new combustion strategy known as Premixed Low-Temperature Combustion (PLTC) has been introduced to reduce pollutant and carbon emissions from traditional diesel combustion[1].

Dual Fuel (DF) systems, similar to RCCI (Reactivity Controlled Compression Ignition)combustion strategy, are designed for engines to operate using two fuels. In addition to adding a second fuel injection system in the intake manifold, the fundamental design of a diesel compression ignition (CI) engine remains unchanged. The primary advantage of the DF concept lies in its ability to use sustainable low-carbon fuels while maintaining the high efficiency of diesel engines[2]. Therefore, natural gas, due to its abundant resources, relatively low cost, ease of storage and transportation, has emerged as an attractive and feasible alternative fuel replacement in the combustion chamber within the DF strategy. However, a major drawback of natural gas as an alternative fuel is the potential presence of significant unburned hydrocarbons (UHC) in the exhaust [3-5], making the reduction of its carbon emissions a key focus of research.

On the other hand, the basic combustion reaction between hydrogen and oxygen produces water vapor with no carbon dioxide emissions. Compared to all other hydrocarbon (HC) fuels, hydrogen boasts a wide flammable range, a smaller quenching distance, a relatively high autoignition temperature , extremely high diffusivity, and a high combustion speed[6].

Due to hydrogen's higher autoignition temperature, internal combustion engines require external sources, such as spark plugs or glow plugs, to initiate combustion. In Compression Ignition (CI) engines, the air-hydrogen mixture, with its higher autoignition temperature, cannot serve as the sole fuel during the compression stroke because the compression pressure and temperature attained are insufficient for ignition. Therefore, hydrogen cannot be used as the exclusive fuel in CI engines; instead, a small amount of easily auto-ignitable diesel fuel is injected as the source to initiate hydrogen consumption[7].

Hydrogen's laminar combustion speed is significantly higher than all other fuels burned in a premixed manner[8,9], resulting in faster and more complete combustion, ensuring higher power output and lower emissions of UHC, CO, and particulate matter. For example, when hydrogen is mixed with carbon fuels (such as diesel in DF combustion), it produces lower amounts of CO, UHC, and PM[10,11]. However, on the other hand, the rapid combustion also leads to higher cylinder temperatures and increased nitrogen oxides (NOx). Suzuki and Tsujimura[12] conducted experimental and numerical studies on hydrogen dual-fuel combustion in diesel engines, and overall, hydrogen dual-fuel combustion significantly improved CO, CO_2, and UHC emissions while increasing NOx emissions.

Adding hydrogen to natural gas fuel can enhance the chemically controlled combustion phase of diesel with gaseous fuel, as well as the combustion phase of the gas mixture and air mixture. W. Tutak et al. [13] conducted experiments to investigate the effects of hydrogen-enriched natural gas on the performance and emissions of natural gas-diesel dual-fuel engines under conditions of IMEP = 0.7 MPa and hydrogen energy ratios ranging from 0% to 21%. The test results indicated that blending hydrogen with natural gas reduced the combustion duration by 30% compared to the case without hydrogen addition, but led to an increase in NOx emissions. H. Mabadi Rahimi [14] conducted numerical analysis using diesel and hydrogen-enriched natural gas as fuels on an internal combustion engine set to an indicated mean effective pressure (IMEP) of 9.4 bar (medium load). The simulation results showed that, without engine knock occurring in the diesel engine, the hydrogen energy ratio could be increased to 40.43% by adding hydrogen to natural gas. Despite this increase, the engine power output decreased by only about 1% compared to combustion using only natural gas and diesel as fuels. This demonstrates the potential for significantly reducing engine emissions. These studies indicate that blending hydrogen with diesel-natural gas dual-fuel combustion introduces complexities in both performance and emission control. However, there are relatively few cases that extensively investigate the combustion and emission performance under low-load conditions using experimental modeling. Additionally, research tends to focus on factors related to the hydrogen energy ratio, with limited studies simultaneously analyzing the timing of diesel injection and the hydrogen energy ratio.

This study relies on the results of experimental research as references[15,16]. Yousefi injected natural gas into the intake manifold through the fuel injection manifold and used a prototype common rail fuel injection system to inject diesel directly into the cylinder. The combustion and emission performance of the dual-fuel internal combustion engine was studied under low-load conditions with different diesel SOI (Start Of Injection Timing) settings. A numerical model of the diesel engine was established using Computational Fluid Dynamics (CFD) software. The model was validated by comparing numerical results with experimental findings. Numerical investigations were carried out on dual-fuel combustion using hydrogen-methane gas mixtures with varying energy ratios under partial load. Two key factors were considered: the dual-fuel combustion with hydrogen-methane gas mixtures at different energy ratios under partial load, and variations in diesel injection timings. The objective is to investigate enhanced combustion and emission performance within the dual-fuel approach involving diesel-natural gas with added hydrogen blending.

2. Numerical model

2.1 Experiment Test conditions

This study focuses on examining the combustion and emission performance of a dual-fuel internal combustion engine with blended hydrogen, using a numerically modeled experiment, especially under low load conditions. A schematic view of the dual-fuel engine combustion chamber . As shown in the Fig. 1, natural gas and hydrogen are blended and injected into the intake manifold via the fuel injection manifold. Diesel is directly injected into the cylinder using a prototype common rail fuel injection system. And a detailed description of the experimental setup and methodology is available elsewhere[15-17].

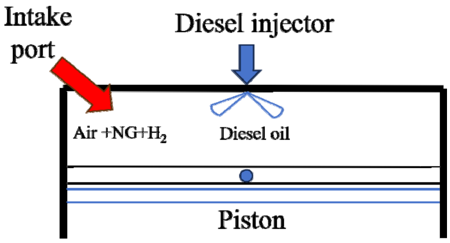

Fig. 1. A schematic view of the dual-fuel engine combustion chamber

Table 1. Engine specifications

Single cylinder-caterpillar 3400 heavy duty engine	
Displacement[L]	2.44
Bore×Stroke[mm]	137.2×165.1
Connecting Rod Length[mm]	261.6
Compression Ratio	16.2:1
IVO[deg ATDC]	-358.3°ATDC
IVC[deg ATDC]	-169.7°ATDC
EVO[deg ATDC]	145.3°ATDC
EVC[deg ATDC]	348.3°ATDC
Common Rail Diesel Fuel Injector	
Number of Holes	6
Hole Diameter[μm]	230
Included Spray Angle	130°
Diesel oil injection pressure[bar]	525

Table 2. Experimental test conditions

	Test case
BMEP (bar)	4.05
Speed (rpm)	910
Intake temperature (°C)	40
Intake pressure (bar)	1.05
%NG (energy fraction)	75
Diesel Injection Time (°BTDC)	14°
Injector Pressure (bar)	525
Natural Gas (kg/h)	1.39
Diesel (kg/h)	0.49
Air (kg/h)	67.21

Test cases involved operating the dual-fuel at a fixed engine speed (910 rpm) under partial load (25% load-4.05 bar BMEP). In this configuration, 75% of the energy was derived from natural gas, with the remaining 25% sourced from diesel fuel. The parameters of the internal combustion engine used in the experiment and the specific experimental conditions are shown in Tables 1 and Table 2.

2.2 Model set up and validation

The numerical model was developed using the ANSYS Forte CFD program to simulate the in-cylinder combustion process from intake valve closing to exhaust valve opening. Heptane (n-C7H16) served as a substitute for diesel, and to better emulate real-world conditions, the physical properties of n-heptane were adjusted to those of n-tetradecane (n-C14H30)[19]. Methane (CH_4) was utilized to represent natural gas fuel. Reduced mechanisms obtained through skeletal dynamic mechanisms were applied for heptane and methane, comprising 137 species and 1022 reactions[18,19]. A sector mesh is employed due to the symmetrical arrangement of the injector cylinder center and nozzle holes. Considering the geometric configuration, a 60° section of the combustion chamber is considered, corresponding to the six injector nozzle holes. The elements of the sector mesh are depicted in the Fig. 2. Table 3 present the initial conditions and boundary conditions. It can be observed from Fig. 3 that the simulated cylinder pressure curve closely matches with the experimentally obtained curve. Variations in the predicted heat release rate may arise from differences in fuel substitution and chemical kinetic mechanisms used in the simulation.

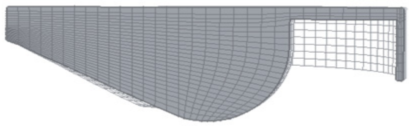

Fig. 2. 60° sector meshes for numerical model.

In summary, the numerical model effectively captures the combustion characteristics of diesel/ natural gas dual fuel under low load, making it suitable for simulation and analysis of this process.

Table 3. Initial conditions and Boundary conditions for numerical model

Initial conditions.	
Intake Pressure (bar)	1.02
Intake Temperature (K)	360
Turbulent Kinetic Energy (m^2/s^2)	10
Turbulent Length Scale (m)	0.003
Turbulent Model	Rans RNG k-epsilon
Swirl Ratio	0.5
Spray Cone Angle	15^o
Boundary conditions	
Cylinder Head	425K
Piston	450K
Liner	400K

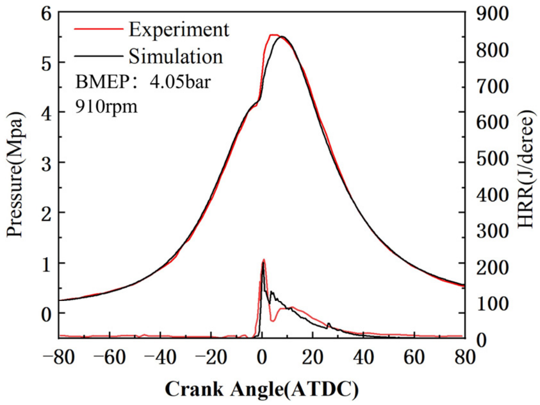

Fig. 3. Comparison of cylinder pressure and heat release rate between numerical model and experimental data

2.3 Parametric study

The numerical simulation in this paper primarily targets the combustion characteristics of diesel-natural gas dual-fuel with blended hydrogen.

For the numerical simulation research, it is assumed that the injected diesel fuel remains constant (25% energy fraction), while the remaining 75% of the energy is shared between hydrogen and natural gas fuels. Energy balance can be achieved based on Equation (1), where methane is considered as natural gas, and n-heptane is considered as diesel.

$$CH_4 = \frac{m_{ch_4} \times LHV_{ch_4}}{m_{diesel} \times LHV_{diesel} + m_{ch_4} \times LHV_{ch_4} + m_{h_2} \times LHV_{h_2}} \quad (1)$$

$$H_2 = \frac{m_{h_2} \times LHV_{h_2}}{m_{diesel} \times LHV_{diesel} + m_{ch_4} \times LHV_{ch_4} + m_{h_2} \times LHV_{h_2}}$$

The abbreviations in the simulated cases represent the energy proportions for diesel, natural gas, and hydrogen fuels. For example, D25NG65H10 indicates that 25% of the energy comes from diesel fuel, 65% from natural gas fuel, and the remaining 10% from hydrogen fuel. Energy sharing only occurs between natural gas and hydrogen while maintaining a constant total energy of 100%. The LHV values for each fuel in the simulated cases are presented in Table 4. The parametric operation conditions are as shown in Table 5.

Table 4. Fuel properties

Fuel type	Natural gas	Diesel	H_2
LHV (MJ/kg)	48.4	44.64	111.96

Table 5. Parametric operation conditions

Different H2 energy ratio	D25NG 75H00	D25NG 65H10	D25NG 50H25	D25NG 25H50	D25NG 10H65	D25NG 00H75
Different Diesel SOI (BTDC)	14	18	22	26	30	34

3. Results and discussion

3.1 Effect of hydrogen energy ratio on combustion performance and characteristics under various diesel injection timing

In this study, hydrogen energy ratios of 10%, 25%, 50%, 65%, and 75% were used to replace natural gas, exploring the impact and characteristics of H_2 on the combustion performance of diesel/natural gas dual-fuel at different energy ratios for SOI ranging from 30° BTDC to 14° BTDC. Fig. 4 shows the cylinder pressure and HRR curves, respectively.

In the case of SOI at 14° BTDC, as the blended hydrogen energy ratio increases, the peak cylinder pressure becomes larger, the peak point gets closer to TDC, and the peak curve becomes steeper, indicating that the combustion speed inside the cylinder is increasing. This is because the combustion rate of hydrogen is much faster than that of natural gas. From the HRR curve, the first peak mainly corresponds to the ignition phase of diesel combustion, and the primary combustion in the second phase is attributed to hydrogen combustion. A well-timed diesel injection plays a role similar to hydrogen, accelerating the combustion rate.

Fig. 5 shows the CA50 which represents the crank angle at which 50% of the cumulative heat release occurs. It can be observed that, at the same diesel injection timing, with the increase in the hydrogen, CA50 is advanced significantly. This further demonstrates the positive impact of hydrogen's rapid combustion on the overall combustion performance of the dual-fuel system. It also indicates that hydrogen has an influence on the entire combustion process after the auto-ignition of the fuel. When SOI is advanced, complete fuel pre-mixing in the cylinder favors combustion, and CA50 advances accordingly. When the hydrogen energy ratio exceeds 50%, the influence of advancing the start of injection (SOI) on CA50 becomes relatively minor.

The ISFC(Indicated Specific Fuel Consumption) decreases with an increasing hydrogen energy ratio in all cases presented in Fig. 6. This reduction in ISFC values is attributed to the high-energy characteristics of hydrogen, reaching its minimum value when the hydrogen energy ratio is 75%. Similarly, the high-energy characteristics of hydrogen as a fuel and its fast combustion rate also indicate its tendency towards knock. In Fig. 7, as the hydrogen energy ratio

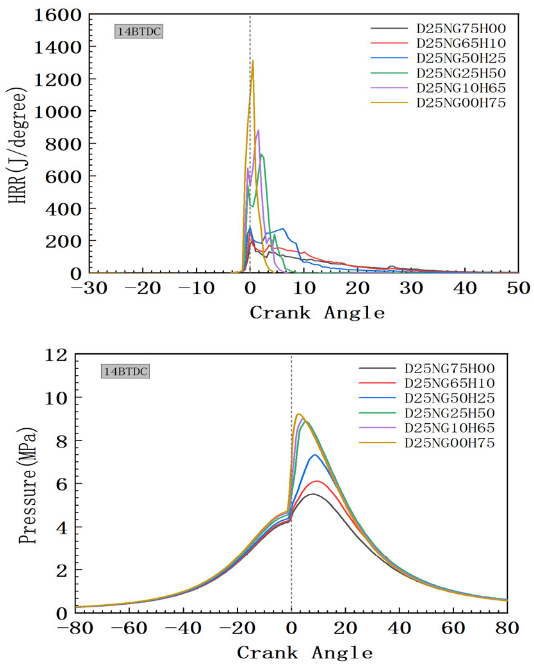

Fig. 4. Effect of H2 ratio on cylinder pressure and HRR at 14°BTDC with the change of hydrogen energy ratio

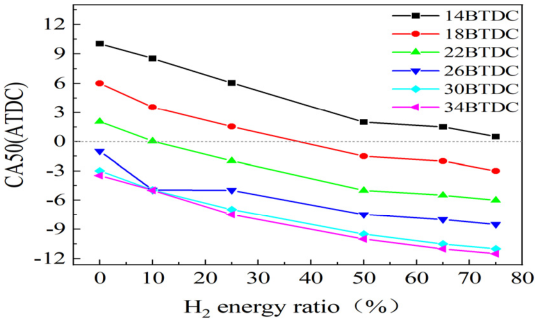

Fig. 5. Variation of CA50 with the hydrogen energy ratio change

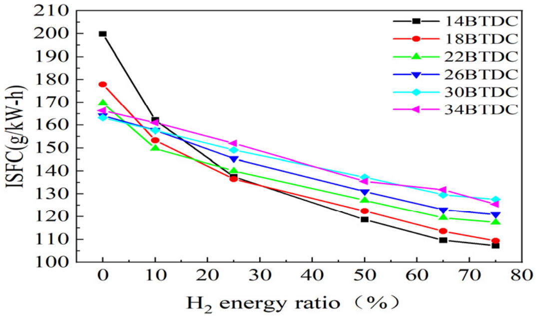

Fig. 6. Variation of ISFC with hydrogen energy ratio change

increases, the MPPR(Maximum Pressure Rise Rate) values in the cases also increase. When the hydrogen energy ratio is large, the impact of adding the same amount of energy from hydrogen on in-cylinder combustion becomes more significant. With higher hydrogen energy, the in-cylinder pressure becomes more sensitive due to the fast combustion characteristics of hydrogen. Particularly, at SOI of 30° BTDC, the MPRR shows the most significant variation with the hydrogen energy ratio. Under this injection timing, the fuel pre-mixing is more thorough, with more autoignition cores accelerating the combustion rate. The oxidation reaction of the fuel in the cylinder rapidly releases a large amount of heat. In addition to the effect of hydrogen with a faster combustion rate, when the hydrogen energy ratio is 75%, the maximum MPRR reaches 3.06 MPa/degree.However, in the practical application of diesel engines, to avoid engine damage and mitigate the impact of knock, the maximum allowable pressure rise rate is kept below 1.3Mpa/CAD [11]. Fig. 8 illustrates the variation in thermal efficiency. The rapid combustion of hydrogen may imply rapid energy loss, but fast combustion can help achieve more complete combustion of fuel in the cylinder, reducing unburned fuel in the exhaust gases and promoting more complete combustion reactions. When the gaseous fuel is exclusively hydrogen, as in the case of D25NG0H70, thermal efficiency is consistently the lowest across all SOI.

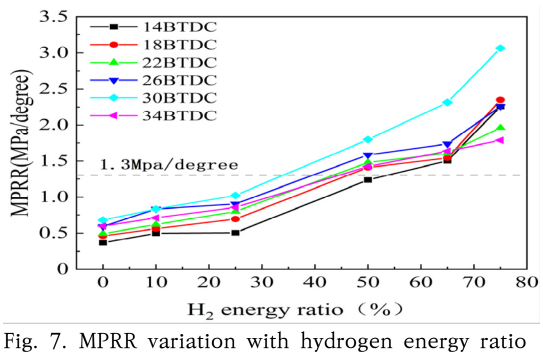

Fig. 7. MPRR variation with hydrogen energy ratio change

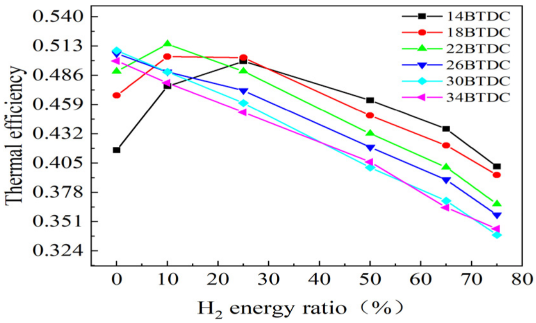

Fig. 8. Thermal efficiency variation with hydrogen energy ratio change

In this study, the highest thermal efficiency occurs at a 10% hydrogen energy ratio. When SOI is advanced, fuel pre-mixing becomes more complete, leading to a more uniform distribution of fuel within the cylinder. This effectively accelerates the combustion rate. Overall, in this study, the combustion reaches its highest thermal efficiency when the SOI is 22° BTDC, and the hydrogen energy ratio is 10% in the diesel-natural gas dual-fuel. This condition represents a good balance point, where the rapid combustion characteristics of hydrogen and appropriate fuel pre-mixing ensure more thorough combustion in the cylinder, thereby improving combustion efficiency at low loads. Simultaneously, this process ensures a more uniform distribution of fuel combustion within the cylinder, preventing the reduction in combustion efficiency due to localized rapid combustion and minimizing heat loss.

3.2 Effect of hydrogen energy ratio on combustion emissions under various diesel injection timing

In diesel engine research, emission characteristics have consistently been a closely examined focal point.

CO_2, being a greenhouse gas, stands as a pivotal indicator for carbon emissions in environmental studies. As shown in Fig. 9, CO_2 emissions decrease with the increase in the hydrogen energy ratio, and the declining curve exhibits a linear trend. CO_2 emissions are influenced by two factors: on one hand, the fast combustion characteristics of hydrogen facilitate the more complete combustion of diesel/natural gas dual fuel, leading to increased CO_2 generation from natural gas combustion. On the other hand, with the increase in the hydrogen energy ratio, the proportion of natural gas in the cylinder's fuel mix decreases, resulting in reduced CO_2 generation. Overall, the substitution of hydrogen for an equal amount of natural gas has a greater impact on CO_2 emissions. Advancing SOI promotes more thorough fuel pre-mixing in the cylinder, leading to increased combustion of natural gas and, consequently, higher CO_2 emissions.

The introduction of hydrogen in the dual-fuel diesel-natural gas system, particularly under low-load conditions, effectively enhances combustion efficiency, promoting more complete combustion. As shown in Fig. 10, with an increase in the hydrogen energy ratio, there is a noticeable reduction in unburned hydrocarbons (UHC) emitted by the internal combustion engine. In the early stages of hydrogen blending, when the hydrogen energy ratio is low, the positive impact of hydrogen on UHC reduction is most prominent compared to the original dual-fuel diesel-natural gas configuration. The slope of the UHC curve with respect to the change in the hydrogen energy ratio is steeper initially, and the improvement in UHC becomes limited beyond 50% of the hydrogen energy ratio.

The similar trend is observed for CO emissions, as illustrated in Fig. 11. With an increasing hydrogen energy ratio, there is a significant decrease in CO emissions. At lower hydrogen energy ratios, the prominent effect is attributed to the positive influence of hydrogen on combustion. As the hydrogen energy ratio increases, the energy contribution of natural gas in the fuel mixture gradually decreases, leading to a weakening of CO and UHC content in emissions from the fuel source. In Fig. 12, the improvement in soot emissions is also evident with an increasing hydrogen energy ratio, especially in the initial stages of hydrogen energy ratio increment from 0%.

The combustion of diesel-natural gas dual fuel with hydrogen blending effectively increases the cylinder temperature, ensuring complete fuel combustion. However, the elevated cylinder temperature also significantly influences NOx emissions in internal combustion engine exhaust. As shown in Fig. 13, NOx varies with the hydrogen energy ratio in all cases. With the increase of the hydrogen energy ratio, NOx also increases, showing an overall linear growth trend. By comparing the distribution maps of cylinder temperature and NOx, the correlation between high temperature and NOx can be observed. Fig. 14 shows the contour maps of cylinder temperature and NOx emissions for different hydrogen energy fractions at 5° ATDC crank angle, indicating that regions with NOx typically

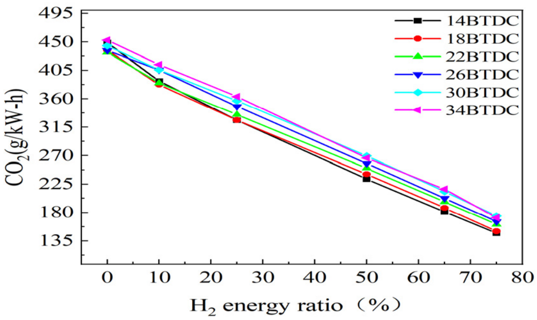

Fig. 9. Variation of CO_2 emissions with hydrogen energy ratio change

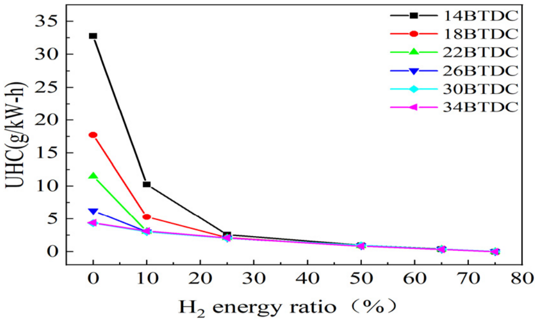

Fig. 10. Variation of Unburned Hydrocarbons (UHC) with hydrogen energy ratio change

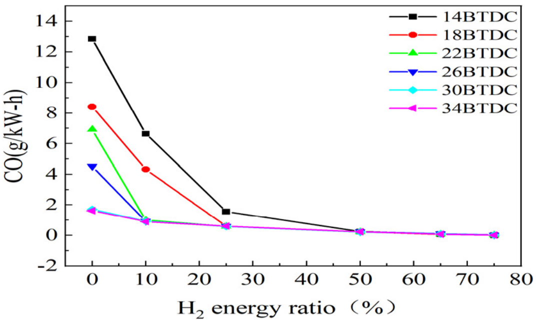

Fig. 11. Variation of CO emissions with hydrogen energy ratio change

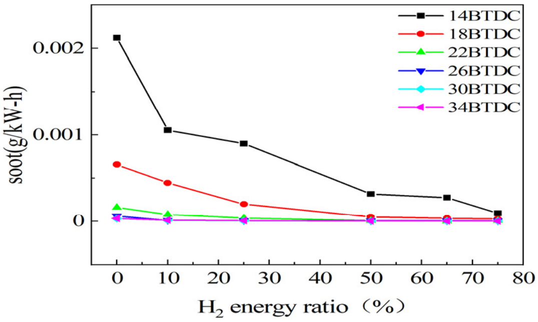

Fig. 12. Variationin of soot emissions with hydrogen energy ratio change

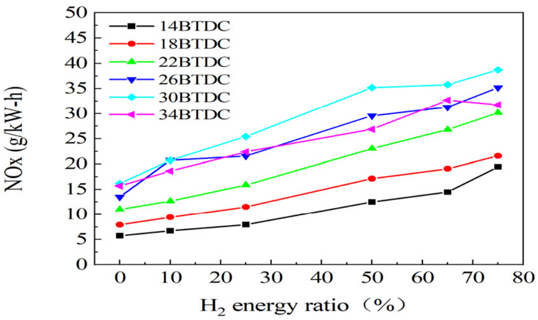

Fig. 13. Variation of NOx emissions with hydrogen energy ratio change

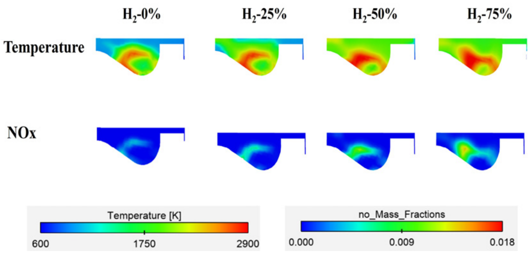

Fig. 14. Combustion chamber temperature (K) and NO cloud map at 5°ATDC (SOI 14°BTDC)

coincide with local high temperatures. Compared to the initial case of D25NG75H00 with diesel SOI at 14BTDC, an increase in the hydrogen energy ratio, as well as the advance of SOI causing fuel pre-mixing effects, both accelerate the oxidation reaction of fuel in the cylinder, leading to faster temperature rise and consequently higher NOx emissions. Therefore, it is essential to avoid situations where there is localized intense combustion of fuel in the cylinder, releasing a large amount of heat rapidly, while considering the combustion performance of the internal combustion engine.

Overall, for the dual-fuel internal combustion engine studied in this paper, to ensure the safe operation of the engine, it is found from Fig. 6 that a hydrogen energy ratio below 25% is more appropriate. Prioritizing the thermal efficiency of the internal combustion engine, followed by minimizing CO_2 and NOx emissions, serves as the basis for selecting suitable operating conditions. The involvement of hydrogen reduces CO_2 emissions while ensuring more complete combustion of fuel at low loads. When the hydrogen energy ratio is below 25%, Fig. 12 indicates relatively lower NOx emissions in the 14BTDC~22BTDC range of SOI. Therefore, considering all factors, an SOI of 22°BTDC and a hydrogen energy ratio of 10% can ensure higher thermal efficiency and relatively lower NOx emissions from the internal combustion engine.

4. Conclusions

This study involves the development and validation of a numerical model, grounded in experimental data [11,12], to simulate the entire combustion process in a dual-fuel engine using natural gas-diesel fuel blended with hydrogen at low load. The investigation maintains a consistent diesel energy input for ignition, systematically substituting hydrogen for natural gas at varying hydrogen energy ratios and distinct diesel injection timings. The summarized conclusions are as follows:

1) Appropriate advancement of SOI can enhance the pre-mixing of fuel in the internal combustion engine cylinder, exhibiting an accelerated combustion rate. In this study, an appropriate SOI is around 30° BTDC. Considering the impact of the hydrogen energy ratio, the highest MPPR occurs at SOI 30° BTDC with a hydrogen energy ratio of 75%.
2) The rapid combustion characteristics of hydrogen, coupled with an appropriate SOI, result in a faster and more thorough combustion. Consequently, the heat released from fuel oxidation is greater. However, rapid heat release also leads to increased heat losses. In this study, the highest thermal efficiency of the internal combustion engine is observed at SOI 22° BTDC with a hydrogen energy ratio of 10%.
3) After blending hydrogen with diesel-natural gas dual fuel, emissions of UHC, CO_2, CO, and soot in the internal combustion engine are significantly reduced at low loads. With the increase in the hydrogen energy ratio replacing natural gas, it enhances both the thorough combustion of fuel in the cylinder, reducing unburned fuel, and the reduction of carbon content in the fuel from the source.
4) There is a correlation between NOx emissions and localized high temperatures in the cylinder. Therefore, it is crucial to balance the appropriate hydrogen and natural gas energy ratios to control combustion. Considering both combustion performance and emissions, at SOI of 22° BTDC with a hydrogen energy ratio of 10%, higher thermal efficiency and relatively lower NOx emissions in the internal combustion engine can be ensured.

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