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Ignition and combustion characteristics of hydrogen-diesel dual-fuel direct injection

Visualizations

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ABSTRACT

The transportation sector, contributing significantly to global CO2 emissions, is a critical target for decarbonization. Hydrogen, as a zero-emission energy carrier, offers a promising solution but faces challenges in reliable ignition and stable combustion in internal combustion engines. This study investigates the ignition and combustion characteristics of hydrogen-diesel dual-fuel combustion using a constant-volume combustion chamber (CVCC) with high-speed shadowgraphy imaging. Two injection strategies were examined: pilot-main (diesel before hydrogen) and main-pilot (hydrogen before diesel). The results show that the pilot-main strategy leads to shorter hydrogen ignition delays and more stable combustion, while the main-pilot strategy delays hydrogen ignition due to diesel evaporation cooling. The simultaneous injection of diesel and hydrogen leads to the shortest ignition delay and the most rapid heat release, indicating that the diffusion flame generated by the diesel spray is effective in reducing the hydrogen ignition delay. Ambient temperature significantly affects combustion, with lower temperatures delaying diesel ignition and enhancing initial heat release. The study provides insights into optimizing hydrogen-diesel dual-fuel combustion, suggesting that controlled injection timing and ambient conditions can improve efficiency and reduce emissions, supporting the development of practical dual-fuel engine systems.

1 INTRODUCTION

The global energy landscape is undergoing a dramatic transformation driven by the urgent need to address climate change and reduce greenhouse gas emissions [1, 2]. The transportation sector, which contributes 20% of global CO_2 emissions, ranks as the second-largest carbon-polluting sector worldwide and is responsible for nearly 40% of emissions from end-use sectors [3]. This makes it a critical target for decarbonization efforts. Hydrogen has emerged as a particularly promising energy carrier due to its unique characteristics: it produces zero direct CO_2 emissions during combustion, has high energy density by mass, and can be produced using renewable energy sources [4]. The potential of hydrogen as a sustainable fuel is evidenced by major investments in hydrogen infrastructure and technology development across Europe, Asia, and North America. However, the transition to hydrogen-based transportation systems presents substantial technical challenges that must be addressed.

While dedicated hydrogen engines and fuel cells represent long-term solutions, the immediate need for carbon reduction has sparked interest in retrofit solutions that can leverage existing engine infrastructure [5, 6]. Modifying conventional engines to run on hydrogen provides a practical near-term solution for reducing emissions while preserving the reliability and performance that industries rely on [7, 8]. Despite the promising potential of hydrogen as a clean fuel, its application in internal combustion engines faces significant challenges, particularly in achieving reliable ignition and stable combustion. The low ignition energy and wide flammability range of hydrogen can lead to issues such as pre-ignition and backfire, which compromise engine performance and safety [9].

Dual-fuel combustion represents a well-established approach to utilizing gaseous fuels in compression ignition engines [10]. The fundamental principle involves using a small quantity of diesel fuel, typically 10-20% of the total energy input, as an ignition source for the primary gaseous fuel. This pilot ignition strategy overcomes the inherent limitations of gaseous fuels in compression ignition engines, particularly their high auto-ignition temperatures under conventional diesel engine conditions [11]. Diesel fuel serves as an ideal pilot ignition source due to several advantageous characteristics. Its low auto-ignition temperature and well-understood spray behavior provide reliable ignition under various operating conditions [12]. The physical and chemical processes of diesel spray formation, atomization, and combustion create multiple ignition sites within the combustion chamber, facilitating rapid and stable combustion of the premixed gaseous fuel. Furthermore, the existing high-pressure fuel injection systems in conventional diesel engines can be retained, minimizing modification costs and maintaining operational flexibility. Previous research [13-15] on dual-fuel systems has predominantly focused on natural gas applications, establishing a robust understanding of the fundamental mechanisms governing pilot-ignited combustion. Studies have demonstrated that parameters such as pilot quantity, injection timing, and gas-air mixture properties significantly influence combustion stability, efficiency, and emissions formation [16]. However, the unique properties of hydrogen, including its high flame speed, wide flammability limits, and low ignition energy requirements, necessitate a specific investigation of hydrogen-diesel dual-fuel operation.

In the field of diesel-hydrogen dual-fuel engines, recent representative studies are summarized as follows. Tsujimura and Suzuki [17] focus on the utilization of hydrogen in a hydrogen/diesel dual fuel (HDDF) engine to enhance thermal efficiency and reduce emissions compared to conventional diesel engines. They employed a single-cylinder diesel engine modified for HDDF operations, where hydrogen is injected into the intake pipe to create a uniform mixture with air and diesel fuel, with specific test conditions including varying hydrogen fractions, engine speeds, and loads. The experimental results indicate that the hydrogen HDDF operation can achieve higher thermal efficiency at relatively high engine loads, although issues such as pre-ignition were observed when a significant amount of hydrogen was injected before diesel fuel ignition. Dimitriou et al. [18] investigated the combustion and emission characteristics of a hydrogen-diesel dual-fuel engine, focusing on the implementation of hydrogen as a fuel source to enhance performance and reduce emissions. A heavy-duty four-cylinder compression-ignition (CI) engine was employed to conduct experiments at a constant speed of 1,500 rpm under low and medium load conditions of 20 kW and 40 kW, respectively. The experimental setup includes a hydrogen supply system with injectors delivering hydrogen into the engine's intake manifold, while exhaust gas recirculation (EGR) is utilized to control NOx emissions. The results indicate that at low loads, the engine can operate with up to 98% hydrogen energy share, achieving over 90% reduction in carbon and NOx emissions, and an 85% decrease in soot emissions compared to conventional diesel operation. However, at medium loads, the increased energy content of hydrogen leads to higher NOx emissions, presenting a challenge for dual-fuel operation. Castro et al. [19] studied the performance and emissions of a hydrogen-diesel dual fuel compression ignition internal combustion engine, focusing on the maximum substitution of diesel fuel with hydrogen. The research employed a marine, four-cylinder light-duty diesel engine operating in dual fuel mode. Engine tests were conducted under various conditions, including four engine speeds (2000, 2400, 2800, and 3000 rpm) and three load levels (30%, 60%, and 100%). The results indicated that hydrogen substitution was feasible without backfire at 80%, 60%, and 40% for engine loads of 30%, 60%, and 100%, respectively, although backfire limited substitution at higher loads. The study also suggested that the autoignition intensity shows a linear relationship with the hydrogen molar concentration in air, which is crucial for optimizing engine performance. Gültekin et al. [20] studied the effects of hydrogen energy ratio and valve lift amount on the performance and emissions of a hydrogen-diesel dual-fuel compression ignition engine. This study was conducted using a single-cylinder CI engine equipped with a programmable electronic control unit (ECU) to manage the hydrogen and diesel fuel system. Experiments were performed at a constant speed of 1850 rpm, with varying loads (3 to 9 Nm) and valve lift amounts (4.0, 4.46, and 4.9 mm). The results indicated that increasing the hydrogen energy ratio up to 14% improved engine performance and reduced emissions, except for NO emissions, while higher valve lift amounts enhanced volumetric efficiency.

Apart from engine analysis, the complex interactions between the pilot diesel spray and the premixed hydrogen-air mixture require detailed examination to optimize system performance and ensure reliable operation across the entire engine operating range. Rorimpandey et al. [21] studied the ignition and combustion characteristics of hydrogen and diesel-pilot fuel in a dual-fuel direct-injection system under compression-ignition engine conditions. Two converging single-hole injectors were utilized to inject hydrogen and pilot diesel into an optically accessible constant-volume combustion chamber to analyze their interactions. Various test conditions are established, including different fuel injection sequences, timing between injections, and evaporating ambient temperatures ranging from 780 K to 890 K. The results reveal that when the diesel-pilot is injected before hydrogen, an increase in time separation leads to a cooling effect on burnt diesel products, which necessitates longer jet-jet interaction times for hydrogen ignition. Conversely, if hydrogen is injected first, the amount of hydrogen-air mixing prior to pilot-fuel ignition significantly influences combustion spread. The research also suggests that if hydrogen ignition occurs after the end of injection, the mixture becomes excessively lean for combustion, especially at lower ambient temperatures. This phenomenon enhances combustion variability due to diesel-pilot lean-out. Subsequently, they further studied the ignition and combustion characteristics of hydrogen and diesel surrogate (n-heptane) jets in a dual-fuel direct injection engine setup [22]. Experiments were conducted based on two converging single-hole injectors, with the pilot fuel (n-heptane) contributing 12% of the total injected fuel energy. The tests were performed under varying jet interaction angles (12° to 19°) and ambient oxygen concentrations (10% to 21% vol.) to simulate engine-relevant conditions. The results indicate that the interaction between the hydrogen and n-heptane jets significantly influences the ignition timing, with the presence of hydrogen either advancing or delaying pilot ignition based on the sequence of jet interactions. Specifically, a smaller jet interaction angle leads to a longer ignition transition period, while lower ambient O_2 concentrations prolong the transition under constant angles. The formation of upstream flame kernels is observed, attributed to the entrainment of residual n-heptane into the hydrogen jet, which affects heat and flame stabilization characteristics. Rajasegar et al. [23] investigates the impact of hydrogen on the ignition and combustion behavior of diesel sprays in a dual-fuel, diesel-piloted, premixed hydrogen engine. Optical diagnostics, including high-speed cool-flame and OH* chemiluminescence imaging, were used to study the spatial and temporal evolution of the two-stage autoignition of a diesel-fuel surrogate, n-heptane, injected into a hydrogen-air premixed charge. The results reveal a complex interplay of physical and chemical processes, including jet entrainment and enhanced mixing, which govern the ignition process in the presence of hydrogen. Cui et al. [24] investigated the ignition and combustion characteristics of methane blended with hydrogen when ignited by diesel, focusing on the effects of hydrogen volume fractions of 10% and 20% on combustion performance. Rapid compression and expansion machine (RCEM) was used to conduct visualization experiments, allowing for a detailed observation of the ignition and flame propagation processes under controlled conditions. The results indicate that while blending hydrogen has minimal impact on the diesel ignition stage, it significantly enhances the premixed combustion stage, leading to improved flame propagation and reduced combustion duration, particularly at lower equivalence ratios.

Despite significant advances in dual-fuel combustion research, several critical knowledge gaps persist in understanding hydrogen-diesel pilot injection systems. The local mixing processes between the diesel pilot spray and the hydrogen-air mixture remain inadequately characterized. While conventional optical diagnostic techniques have provided insights into diesel spray behavior and flame propagation, the rapid diffusion of hydrogen and its interaction with the pilot spray presents unique challenges for visualization and measurement. Therefore, this research aims to investigate the fundamental ignition and combustion characteristics in hydrogen-diesel dual-fuel combustion concept.

2 EXPERIMENTAL DETAILS

2.1 Constant-volume combustion chamber

Figure 1 illustrates the schematic of the experimental setup based on a constant-volume combustion chamber (CVCC). This optically accessible CVCC operates on the pre-burn principle. Detailed information on the CVCC's operation for non-evaporating, evaporating, and burning sprays can be found in our previous publication [25]. Here, only a brief description is provided. The CVCC is equipped with four mutually perpendicular quartz windows and two metal plugs. One plug houses the injectors, while the other is used for the premixture inlet and exhaust. The combustion chamber has a 2L capacity and is designed to withstand pressures up to 450 bar. The visible window diameter is 100 mm. To prevent water vapor condensation on the windows, sixteen heating rods and an insulation jacket are attached to the CVCC body. These elements are controlled by a PID controller to maintain the chamber wall temperature at 360 K across all scenarios. Additionally, a circulating flow of cooling silicone oil, established by a circulation cooler, is used to cool the injector side to approximately 320 K.

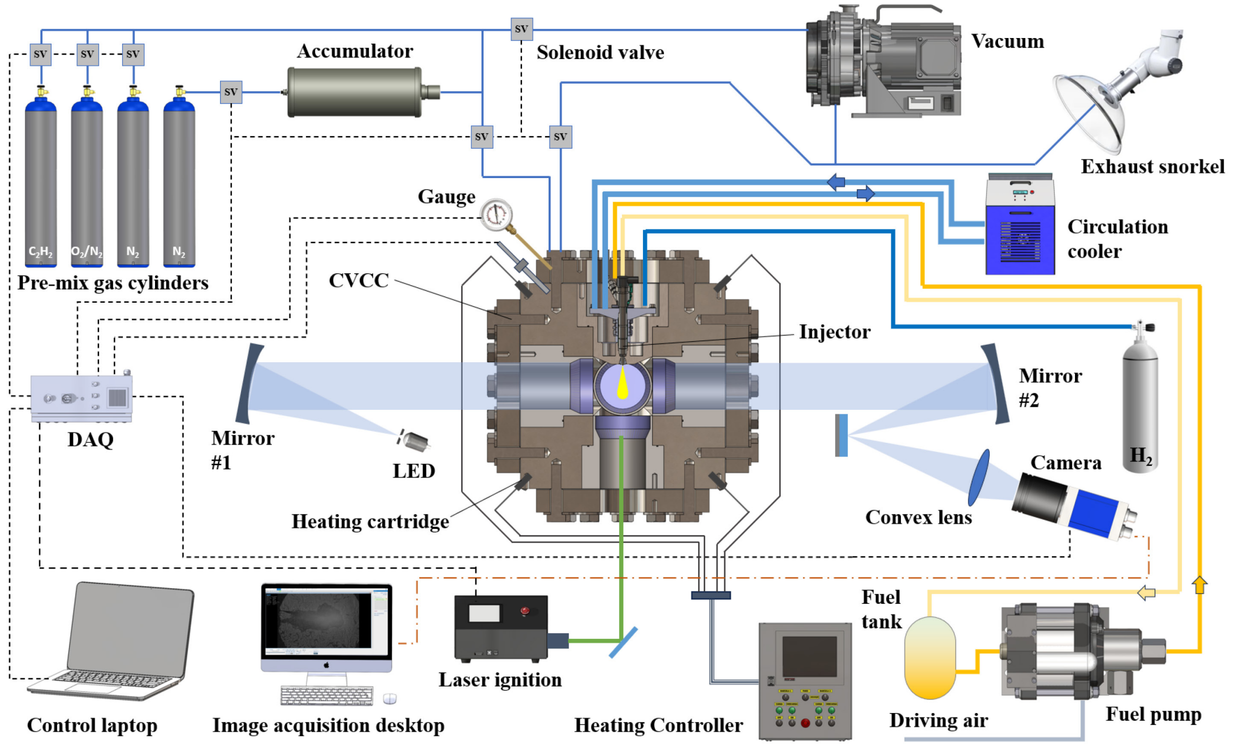

Figure 1. Experimental setup of the constant-volume combustion chamber and optical arrangement

The methodology for achieving quiescent, steady high-pressure and high-temperature conditions within the CVCC through the pre-burn process has been extensively described in prior research [21, 22, 25]. To summarize, acetylene (C_2H_2, 3.7%), oxygen (O_2, 29.86%), and nitrogen (N_2, 66.43%) were initially charged into the pre-mixing accumulator in pre-calculated proportions to generate a homogeneous combustible mixture. This mixture was then introduced into the CVCC and ignited by a high-energy laser (Quantel Q-smart100, 60 mJ/pulse) to create the target pressure and temperature environment, similar to the top dead center (TDC) conditions of diesel engines. Figure 2 shows the pressure and temperature history during a typical experiment run. Following the ignition of the premixture, the combustion byproducts gradually cooled over a relatively long period due to heat transfer to the chamber walls, causing the inner pressure to slowly decrease. A dynamic pressure transducer (Kistler 6041B) with a charge amplifier (Kistler 5018) was used to record the pressure and temperature history at a sampling rate of 50 kHz. The fuel injection event was initiated once a predetermined target in-chamber temperature condition was reached during the cool-down phase. Analysis of the pressure profile was also employed to calculate the apparent heat release rate (AHRR), based on the equation below:

$$\frac{dQ}{dt} = \frac{\gamma}{\gamma-1} P \frac{dV}{dt} + \frac{1}{\gamma-1} V \frac{dP}{dt} \quad (1)$$

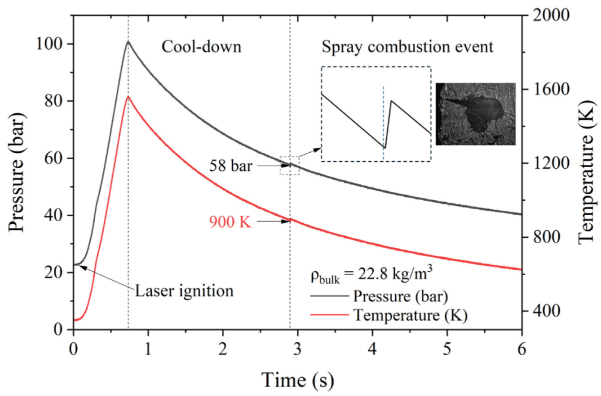

Figure 2. Recorded CVCC inner pressure and temperature history during one single experiment run, highlighting three distinct events: premixed gas combustion by laser ignition, combustion cool-down, and spray combustion.

In this study, the composition measured by the partial pressure meter was adjusted to attain a 21 vol% O_2 concentration post premixed gas combustion, while maintaining an ambient density set at 22.8 kg/m^3. A summary of experimental conditions is provided in Table 1.

Table 1. Summary of the test conditions

Parameters (unit)	Value
Wall temperature (K)	360
Reactants (mole fraction, %)	3.7% C_2H_2, 29.86% O_2, 66.43% N_2
Ambient gas density (kg/m3)	22.8
Ambient gas pressure (MPa)	45, 52, **58**
Ambient gas temperature (K)	700, 800, **900**
Ambient O_2 concentration (vol.%)	21

2.2 Injection system

The hydrogen-diesel dual-fuel direct injection and combustion were conducted using two independent single-hole injectors, as illustrated in Figure 3.

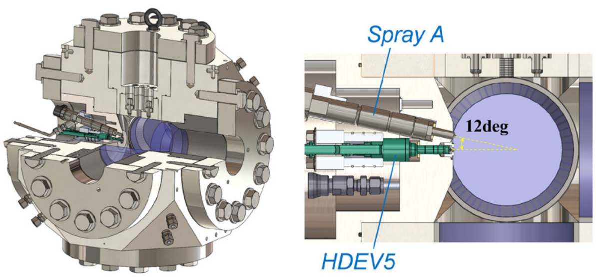

Figure 3. Cross-section view of CVCC and layout of injectors

The Spray A injector from the Engine Combustion Network (ECN) was used for diesel injection. This injector features a single hole with a diameter of 0.09 mm and a K factor of 1.5. The injection pressure was fixed at 1500 bar, and the injection duration was set at 0.4 ms. For hydrogen injection, a customized single-hole HDEV5 GDI injector (Bosch, PN0261500109) was used. The HDEV5 injector was positioned horizontally, with its axis aligned through the center of the window. The Spray A injector was set at a 12-degree crossing angle relative to the HDEV5 injector.

The original HDEV5 GDI injector features six identical holes with a diameter of approximately 0.16 mm, which is insufficient for providing the necessary hydrogen flow rate for practical engine applications. To address this, we increased the flow area of the orifice in the nozzle tip. The solid part between the six holes was precisely machined using CNC to form a single coaxial hole with a diameter of 1.2 mm. Before machining, the original injector tip was scanned using X-ray computer tomography to determine the exact depth and maximum diameter of material removal. This ensured that the modification did not damage the original ball needle and sealing surface. A nozzle gap was placed between the injector tip and nozzle attachment to minimize the effective sac volume and ensure a tight seal. In this study, the customized nozzle diameter and length are 1.0 mm and 3.25 mm, respectively. The utilization of single-hole injectors, as opposed to multi-hole injectors, was intended to streamline result analysis by circumventing the intricacies linked with interactions from multiple jets originating from a single injector [22]. These two solenoid injectors were controlled using a direct injection driver system (National Instruments DIDS-2003). Injection conditions are summarized in Table 2.

Table 2. Summary of the injection conditions

Parameters (unit)	Diesel	Hydrogen
Nozzle diameter (mm)	0.09	1.0
Fuel reservoir pressure (bar)	1500	100
Injection duration (ms)	0.4	2.0
Injected mass (mg)	0.90	5.55
Low heat. value (MJ/kg)	43.5	120.1
Energy share (%)	5.5	94.5

2.3 Shadowgraphy imaging

The high-speed shadowgraphy imaging method was employed to visualize the jet interaction and combustion. This technique is crucial in combustion research as it enables the visualization and analysis of density gradients within reacting flows and flame dynamics. It exploits the principle that variations in refractive index, caused by density changes in the flow field, deflect light rays, creating shadow patterns that can be captured by high-speed cameras to reveal intricate details of combustion processes. A high-power LED light was used to generate a monochromatic blue light beam with a wavelength of 450-460 nm. The diverging light beam passed through a 1 mm aperture and was subsequently collimated by the parabolic schlieren mirror #1, manufactured by Luftvis Science (Model: Luftvis-160). This mirror has a diameter of 160 mm and a focal length of 1300 mm. The resulting parallel light was directed through one side of the CVCC window to illuminate the hydrogen jet and diesel spray. The collimated light from the opposite side of the window was then refocused by parabolic mirror #2. For shadowgraphy, there is no need to use a knife-edge to partially obstruct the refracted light beams before reaching the focusing lens (300 mm). The transmitted beam was then imaged by a high-speed CMOS camera (Fastcam SA-X2) with a high-transmission band-pass filter (F25-450). The shooting frequency was 30,000 frames per second, and the exposure was set to 2.5 μs. The resulting image dimension was 1024×400 pixels, yielding an approximate physical image resolution of 0.082 mm per pixel.

2.4 Experimental matrix and notations

The hydrogen-diesel dual-fuel direct injection and combustion were investigated using two different injection strategies: the pilot-main strategy and the main-pilot strategy, as described in Ref [21]. Figure 4 illustrates the pilot-main injection strategy, where pilot diesel is injected before the main fuel (hydrogen). The dwell time denotes the trigger delay between the pilot fuel and the main fuel. In the main-pilot strategy, the main fuel is injected before the pilot diesel. A *pre-trigger* of 1 ms was used for early camera triggering, referenced to the first injector's triggering. The *inj_delay* represents the delay time of the first injector's triggering when the ambient temperature reaches the target value, with laser ignition as the reference.

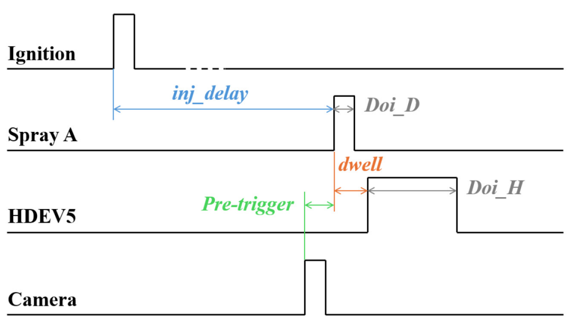

Figure 4. Trigger signal timing for pilot-main strategy. For main-pilot strategy, the trigger signal of HDEV5 precedes the trigger signal of Spray A

Nine cases with different fuel injection sequences, timing between injections, and ambient temperatures are listed in Table 3. In this study, the case notation represents the dwell time between the two fuels and the ambient temperature condition. The abbreviations for pilot diesel (D) and hydrogen main fuel (H) are arranged in the order of the injection sequence. For example, a pilot-main case with a dwell time of 0.5 ms and an ambient temperature of 900 K is denoted as “D05H-900,” while a main-pilot case with a dwell time of 0 ms and an ambient temperature of 700 K is denoted as “D0H-700.” “D-900” and “H-900” indicate cases with only diesel injection and only hydrogen injection, respectively.

Table 3. Case name and notation

Case	Notation	Dwell (ms)	T_{amb} (K)
Case 0	**D0H-900**	**0**	**900**
Case 1	D-900	-	900
Case 2	D05H-900	0.5	900
Case 3	D10H-900	1.0	900
Case 4	H-900	-	900
Case 5	H05D-900	0.5	900
Case 6	H10D-900	1.0	900
Case 7	D0H-700	0	700
Case 8	D0H-800	0	800

3 RESULTS AND DISCUSSION

3.1 Pilot-main injection strategy

Figure 5 displays the selected high-speed shadowgraphy images under pilot-main injection strategies. The first column serves as a reference, showcasing the case with only diesel injection, exhibiting typical diffusion combustion behavior. Upon injection, the diesel fuel vaporizes in the hot ambient environment. Following a brief ignition delay, auto-ignition of the vaporized diesel occurs. At 0.70 ms, a luminous region, characterized by a high soot concentration, emerges at the spray flame's tip [26]. This luminous zone persists until the soot is gradually consumed after t=1.37 ms. In scenarios where diesel and hydrogen are simultaneously injected, hydrogen ignition takes place where the diesel flame intersects the hydrogen jet plume at approximately 0.70 ms. Subsequently, the hydrogen flame progressively spreads throughout the jet area, igniting all injected hydrogen. The flame region notably expands compared to instances with only diesel injection. Furthermore, it is evident that the hydrogen jet and flame alter the trajectory of the diesel flame by lifting it. When hydrogen is injected 0.5 ms after diesel, hydrogen ignition occurs at 1.20 ms as the injected hydrogen contacts the diesel spray flame.

The hydrogen flame then extends to the entire jet area, reaching close to the nozzle outlet. With a hydrogen injection delay of 1.0 ms, hydrogen flame ignition is similarly delayed to ~1.70 ms. By this time, the diesel spray and combustion are mostly concluded, with high-brightness soot fully burned to create a local high-temperature zone along the spray path. As the injected hydrogen reaches this elevated temperature region, jet auto-ignition is initiated.

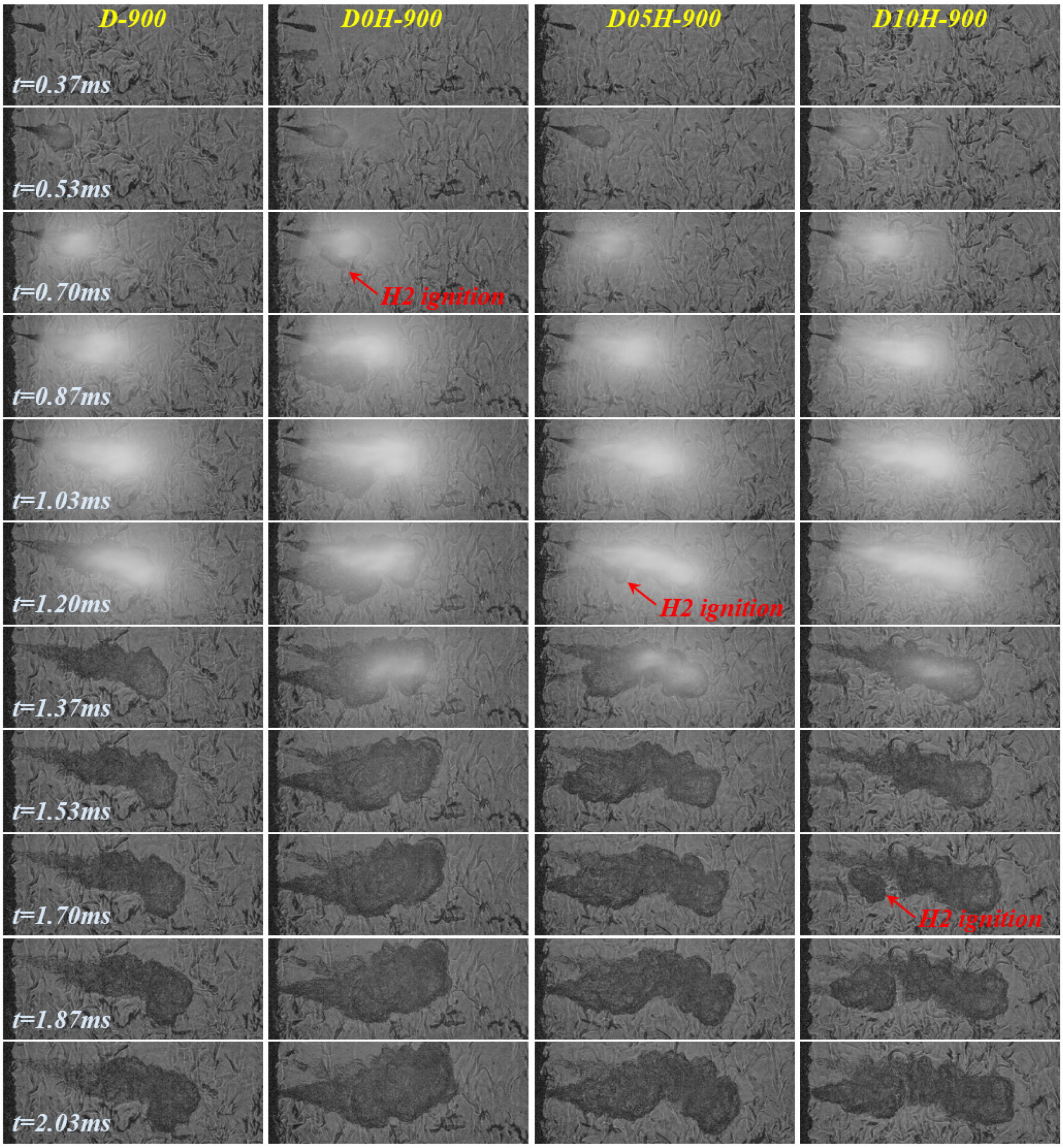

Figure 5. High-speed shadowgraphy images showcasing the pilot-main injection strategies. The cases from left to right are: solely diesel injection, simultaneous diesel and hydrogen injection without delay, diesel injection followed by hydrogen injection with a delay of 0.5 ms, diesel injection followed by hydrogen injection with a delay of 1.0 ms. The ambient temperature is maintained at 900 K. Note that the time referenced here is based on the trigger signal from the pilot-fuel injection as the starting point.

Figure 6 illustrates the AHRR profiles after start of first injector trigger (aSFIT) in pilot-main injection strategies. The grey area represents the delay time (~0.27 ms) from the injector trigger signal to the emergence of the diesel spray. In cases where only diesel is injected, the ignition timing and combustion phases are assessed based on AHRR [21]. Following a brief ignition delay of around 0.17

ms, auto-ignition of the vaporized diesel occurs, leading to an extended low-temperature heat release event (cool flame). The majority of heat release stems from reactions after complete soot oxidation. When hydrogen and diesel are concurrently injected without delay, a hydrogen ignition delay of roughly 0.63 ms is observed. The primary heat release from hydrogen combustion occurs earlier compared to diesel spray combustion alone. As the injection delay between hydrogen and diesel increases to 0.5 ms and 1.0 ms, the hydrogen ignition delays increase to 1.10 ms aSFIT and 1.63 ms aSFIT, respectively. Consequently, the main heat release is notably postponed in accordance with these delays.

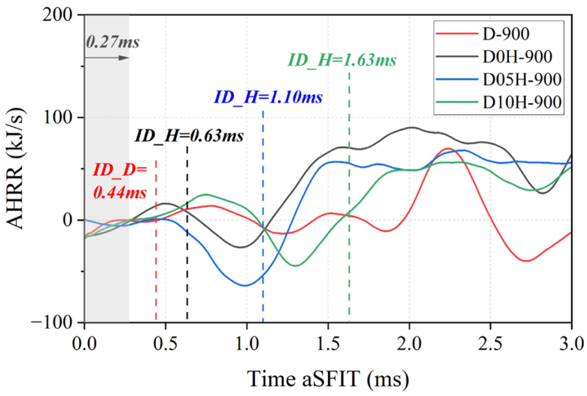

Figure 6. AHRR profiles under pilot-main injection strategies (the grey area represents the delay from injector trigger signal to the appearance of the spray/jet)

3.2 Main-pilot injection strategy

The high-speed shadowgraphy images depicting main-pilot injection strategies are presented in Figure 8. In the scenario where solely hydrogen is injected, auto-ignition occurs before 1.03 ms aSFIT. Notably, the auto-ignition of hydrogen originates at the midpoint of the jet, spreading subsequently to both the near-nozzle region and the downstream sector of the jet. An important observation is that the ignition delay period for hydrogen-only injection surpasses that of hydrogen-diesel simultaneous injection. When diesel injection follows 0.5 ms after hydrogen, the ignition of the hydrogen jet is delayed to approximately 1.2 ms. This delay could be attributed to the decrease in temperature within the jet interaction zone caused by diesel evaporation, which may hinder the self-ignition of hydrogen. Furthermore, the combustion dynamics of the diesel spray are influenced by the burning hydrogen flame, evident in a trajectory deviation in the diesel spray and the presence of a high-brightness soot region suspended above the hydrogen flame. Upon further increasing the diesel injection delay in relation to hydrogen to 1.0 ms, the diesel spray exhibits no significant impact on the ignition of hydrogen, as the ignition timing of hydrogen aligns closely with the condition of hydrogen-only injection.

Figure 7 displays the AHRR profiles within main-pilot injection strategies. For the case where solely hydrogen is injected, the ignition delay time is recorded at 0.97 ms, a value closely resembling the scenario where diesel is injected 1.0 ms after hydrogen injection. Nevertheless, the ignition delay for hydrogen in both cases is shorter than when hydrogen and diesel are injected concurrently. Thus, the diffusion flame generated by the simultaneous injection of diesel spray appears to be the most effective in reducing the hydrogen ignition delay. Within the H05D-900 scenario, the hydrogen ignition delay is notably extended, reaching approximately 1.13 ms. Analyzing the AHRR, it becomes evident that the simultaneous injection of hydrogen and diesel leads to the swiftest heat release, followed by the case involving solely hydrogen injection. Conversely, when diesel is injected later in conjunction with hydrogen, a notable delay in combustion heat release emerges.

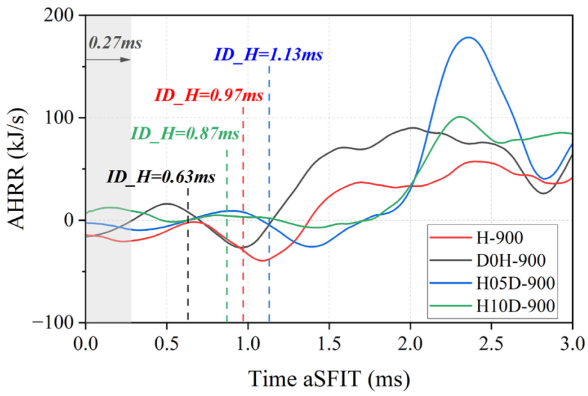

Figure 7. AHRR profiles under main-pilot injection strategy (the grey area represents the delay from injector trigger signal to the appearance of the spray/jet)

3.3 Effects of ambient temperature

Figure 9 illustrates the impacts of ambient temperature on the ignition and combustion behaviors of hydrogen-diesel dual-fuel injection. At an ambient temperature of 700 K, the diesel spray undergoes several significant changes in its ignition and combustion behavior. The lower temperature leads to reduced fuel evaporation rates and slower vapor-air mixing, which extends the physical ignition delay period. This prolonged delay allows more fuel to accumulate in the combustion chamber before ignition occurs. Consequently, the initial premixed combustion phase becomes more intense when ignition finally takes place at around

1.53 ms aSFIT, resulting in enhanced initial heat release as seen in Figure 10.

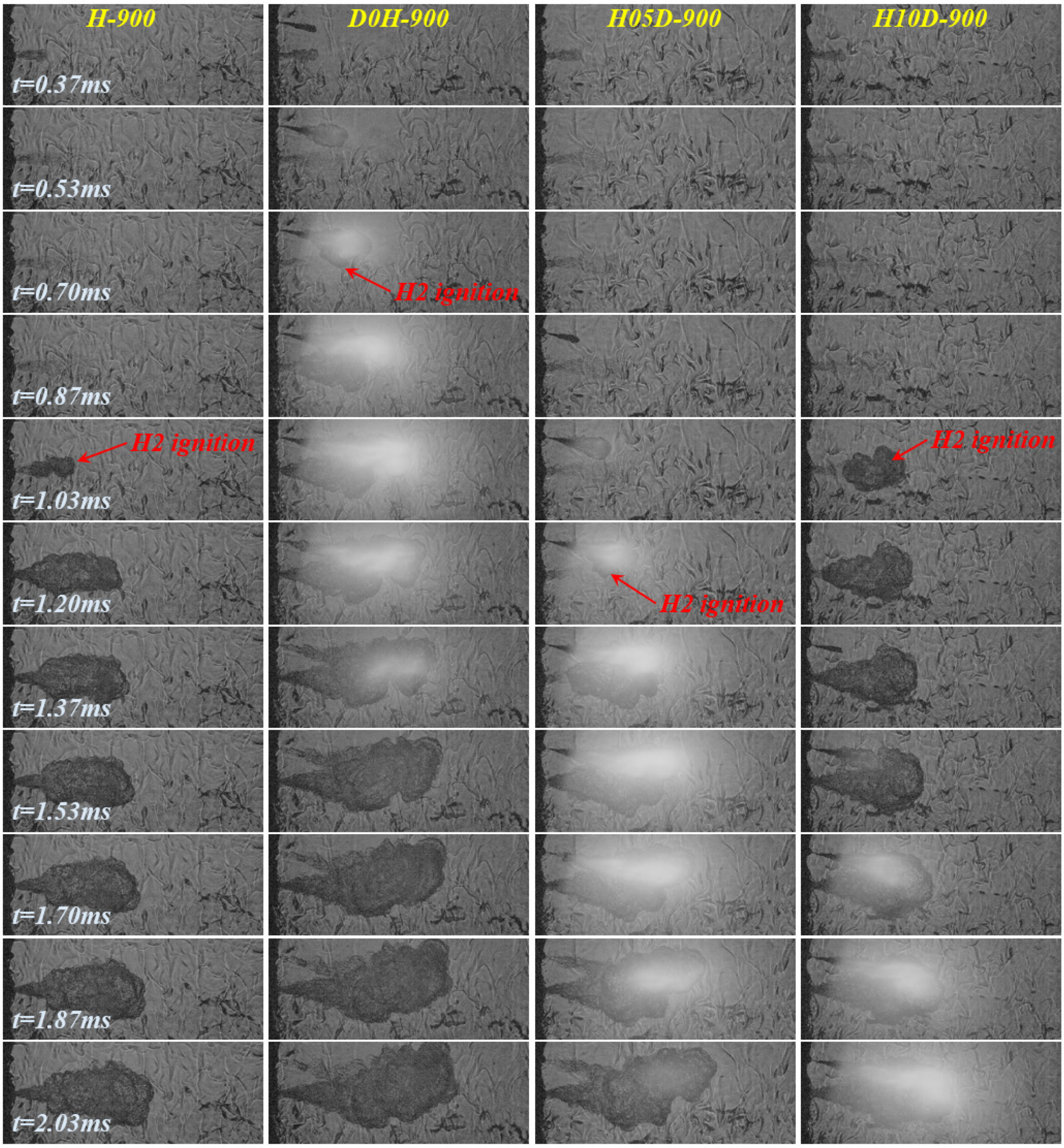

Figure 8. High-speed shadowgraphy images showcasing main-pilot injection strategies. The cases from left to right are: only hydrogen injection, simultaneous diesel and hydrogen injection without delay, hydrogen injection followed by diesel injection with a delay of 0.5 ms, hydrogen injection followed by diesel injection with a delay of 1.0 ms. The ambient temperature is maintained at 900 K. Note that the time referenced here is based on the trigger signal from the main-fuel injection as the starting point

Upon the elevation of the ambient temperature to 800 K, the ignition behavior of the hydrogen jet closely mirrors that observed at 900 K. This alignment is attributed to the substantial reduction in the spray ignition delay of diesel at this temperature, a contrast to the conditions at 700 K, with minimal deviation from the environment at 900 K. Furthermore, the initial position of the hydrogen jet flame kernel remains nearly consistent between T_{amb}=800 K and T_{amb}=900 K. As depicted in Figure 10, the ignition delay stands at 0.63 ms for both ambient temperatures of 800 K and 900 K. Furthermore, their AHRR profiles exhibit remarkable similarity, signifying an almost identical combustion process between the two temperature settings.

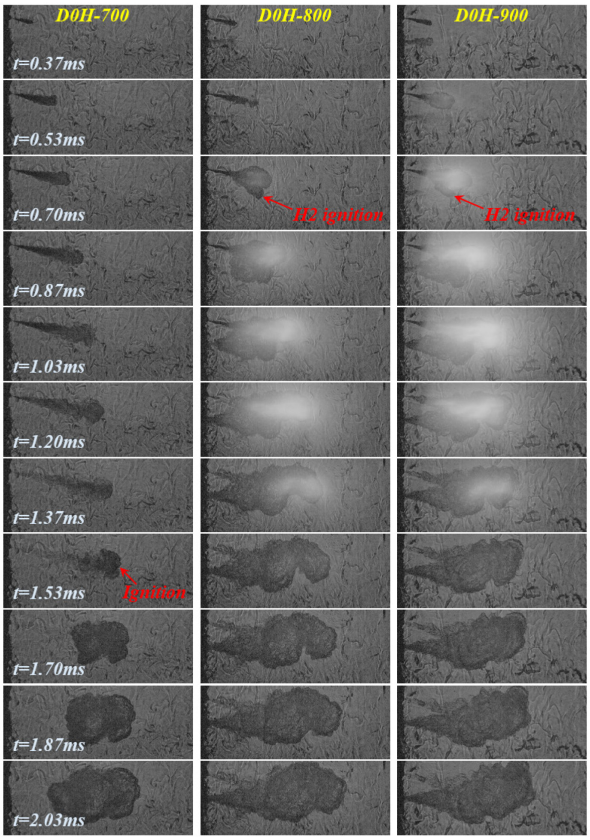

Figure 9. High-speed shadowgraphy images depicting diesel-hydrogen dual-fuel simultaneous injection without delay. The ambient temperatures, presented from left to right, are 700 K, 800 K, and 900 K

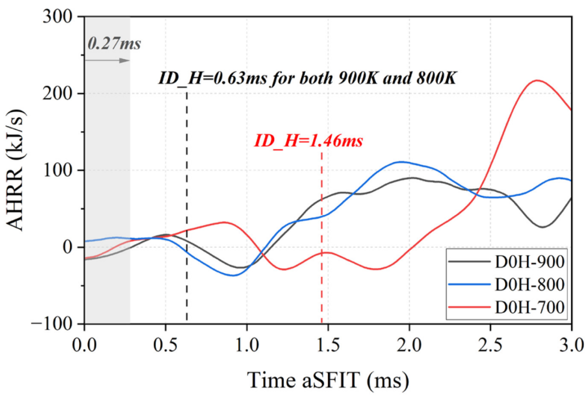

Figure 10. AHRR profiles under different ambient temperature conditions

4 CONCLUSIONS

This study investigates the ignition and combustion characteristics of hydrogen-diesel dual-fuel combustion under various injection strategies and ambient conditions. The key findings and conclusions are summarized as follows:

When diesel is injected before hydrogen, the hydrogen ignition is significantly influenced by the interaction with the diesel flame. The ignition delay of hydrogen increases with the delay in its injection relative to diesel. The combustion process is characterized by an initial diffusion flame of diesel followed by the ignition and spread of the hydrogen flame, which alters the trajectory of the diesel flame. When hydrogen is injected before diesel, the ignition of hydrogen is delayed due to the cooling effect of diesel evaporation. The combustion dynamics of the diesel spray are influenced by the burning hydrogen flame, leading to deviations in the spray trajectory and the presence of high-brightness soot regions. At lower ambient temperatures (700 K), the ignition and combustion of the diesel spray are significantly delayed due to reduced fuel evaporation rates and slower vapor-air mixing. At higher ambient temperatures (800 K and 900 K), the ignition behavior of the hydrogen jet is consistent, with minimal differences in ignition delay and combustion characteristics.

The simultaneous injection of diesel and hydrogen leads to the shortest ignition delay and the most rapid heat release, indicating that the diffusion flame generated by the diesel spray is effective in reducing the hydrogen ignition delay. Additionally, the combustion process is highly dependent on the interaction between the diesel spray and the hydrogen-air mixture. The presence of hydrogen significantly enhances the premixed combustion stage, leading to improved flame propagation and reduced combustion duration.

5 ABBREVIATIONS

AHRR: Apparent heat release rate

aSFIT: Afet start of first injector trigger

CI: Compression-ignition

CVCC: Constant-volume combustion chamber

ECU: Electronic control unit

EGR: Exhaust gas recirculation

HDDF: Hydrogen/diesel dual fuel

RCEM: Rapid compression and expansion machine

TDC: Top dead center

6 ACKNOWLEDGMENTS

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