Experimental study on tri-fuel combustion using premixed methane-hydrogen mixtures ignited by a diesel pilot

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HIGHLIGHTS
- A comprehensive study on diesel pilot tri-fuel combustion has been conducted in a compression ignition engine.
- The H₂ concentration and charge-air temperature were parametrically applied to study their effects on engine performance.
- A short-time Fourier transfer method was employed to estimate the combustion stability.
- A continuous wavelet transfer method was adopted to assess the cycle-to-cycle variations.

ABSTRACT
A comprehensive investigation on diesel pilot spray ignited methane-hydrogen (CH₄–H₂) combustion, tri-fuel combustion (TF), is performed in a single-cylinder compression ignition (CI) engine. The experiments provide a detailed analysis of the effect of H₂ concentration (based on mole fraction, M_{H₂}) and charge-air temperature (T_{air}) on the ignition behavior, combustion stability, cycle-to-cycle (CCV) and engine performance. The results indicate that adding H₂ from 0 to 60% shortens the ignition delay time (IDT) and combustion duration (based on CA90) up to 33% and 45%, respectively. Thereby, H₂ helps to increase the indicated thermal efficiency (ITE) by as much as 10%. Furthermore, to gain an insight into the combustion stability and CCV, the short-time Fourier transform (STFT) and continuous wavelet transform (CWT) methodologies are applied to estimate the combustion stability and CCV of the TF combustion process. The results reveal that the pressure oscillation can be reduced up to 4 dB/Hz and the CCV by 50% when M_{H₂} < 60% and T_{air} < 55 °C. However, when M_{H₂} > 60% and T_{air} > 40 °C, abnormal combustion and knocking are observed.

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Introduction
To meet the climate and air quality goals, the governments are signaling to the world to move to zero-emission vehicles. The conventional internal combustion engines (ICEs) are facing a huge challenge from electrification due to their emission issues. Many countries and a dozen cities or states have announced the phase-out of fossil fuel-driven vehicles by 2040...
during the last few years [1,2]. However, there are still no real alternatives that can compete with the ICE over the entire range of applications that they cover, even today, ICEs are undergoing continuous improvements [3–5]. Both natural gas and hydrogen have long been considered alternative fuels for the transportation sector and have fueled vehicles for decades [6]. Particularly, H2 has been attracted the attention of researchers because of its carbon-free nature and excellent combustion properties. Additionally, it can be produced by using renewable energies. However, using H2 as a sole fuel in ICEs faces many challenges, including lower volumetric efficiency, pre-ignition, backfire and knocking [6,7]. Therefore, a multi-fuel combustion technology in ICE using H2 and CH4 mixtures with pilot diesel, namely TF combustion has been investigated as a promising method for future ICEs [6].

The excellent combustion properties of H2, such as broader flammable limits, lower ignition energy, higher diffusion rate, faster laminar flame speed, and stronger lean-burn capability, has the potential to effectively improve the combustion efficiency and reduce exhaust emissions [7–10]. Furthermore, the concept has several attractive properties from the research point of view: 1) H2 addition may shorten the ignition delay, 2) it could reduce the combustion duration, 3) it can improve the combustion stability and reduce the CCV, and hence 4) it may increase the engine efficiency and reduce the emissions.

H2 as an additive for various fuels has been studied extensively in ICEs (SI and CI engines). For instance, Liu et al. [11] studied the effect of H2 addition on combustion characteristics and ignition behavior with H2/CH4 mixture and single-pilot diesel. The experimental results indicated that adding H2 shortens the IDT and combustion duration due to its excellent combustion properties. Zhou et al. [12] compared the engine performance and emissions fueled with DF and TF in a diesel engine. They found that the H2/CH4 ratio equal to 30%:70% shows the optimized ratio in reducing particulate and NOx emissions at 70% and 90% loads. Alrazen et al. [13] investigated TF combustion fueled with diesel-CNG-H2 and compared TF combustion with diesel-CNG and diesel-H2 DF operations at various air/fuel ratios using numerical simulations. Lower CO/CO2 and NO emissions performance were observed in the TF engine when compared to DF operation. Mansor et al. [14] investigated the influence of diesel enrichment with H2 and CH4 in a direct injection compression ignition (CI) engine at various H2/CH4 ratios with CFD simulation. The result showed that the high H2/CH4 ratio is useful for improving the engine performance with reduced CO emission, conversely, the low H2/CH4 ratio lowers NO emission. Abu-Jrai et al. [15] examined TF (H2, CNG, conventional diesel) engine on the combustion characteristics, engine emissions, and selective catalytic reduction at low, medium, and high engine loads. Results showed that the H2 and CNG reduce in-cylinder pressure and heat release rate (HRR) at low load, and considerably increase in the premixed combustion phase at high engine load.

From the above literature [7–15], it can be noted that several studies have examined the positive features of CH4 enriched with H2 in DF engines and the outcomes on performance and pollutant emissions. However, there are very few studies that report the combustion stability and CCV in TF engines. Single-cycle combustion stability or CCV in a continuous operation is known to pose a critical role in H2 enriched TF combustion. Cyclic variations are typically observed in spark ignition (SI) engines due to the changes in the burn rate for each successive cycle [12]. These variations may have numerous root causes, including cyclic variation in the cylinder gas motion and fuel mass flow rate, unscavenged exhaust gases composition, or cyclic variation of the mixture composition near the spark plug, leading to differences in combustion speed or local end-gas autoignition [16–18]. These effects have been studied extensively in the past using experimental [19–21] and numerical tools [18,22–25]. Similarly, in pilot-diesel ignited DF or TF combustion, high cyclic...
variations are expected due to the high influence of small perturbations in small-scale combustion engines. These variations are due to the nature of the combustion properties of CH₄, which has a relatively low flame speed and high octane number, resulting in stable combustion and less CCV [28]. However, at lean conditions (e.g., λ > 1.6), the CCV dramatically increases due to the low diffusivity, reactivity, flame propagation speed and burning velocity, and narrow flammability range [29]. The addition of H₂ allows the engine to operate at lean conditions with high combustion stability [30]. Wu et al. [31] investigated the addition of H₂ on engine performance and CCV at various engine loads (0–60%) and EGR coefficient (0–40%), adjusting the share of H₂ energy in the range from 0 to 20%. The combustion CCV was analyzed based on the coefficient of variance in the indicated mean effective pressure (COV of IMEP). The results showed that adding H₂ increases the COV of IMEP from 0.9% to 2.8%. Talibi et al. [32] found that by increasing the H₂ concentration up to 20%, H₂ auto-ignition may lead to abnormal combustion and increased CCV. Tsujimura et al. [33] recorded similar pre-ignition characteristics in a TF engine with 50% of the H₂ energy share. Allenby et al. [34] revealed that the H₂ addition to NG with EGR utilization can greatly extend combustion stability. The existence of H₂ produces a significant reduction in the percentage of COV of IMEP.

Combustion stability and CCV are known to pose a critical role in H₂ enriched TF combustion, however, comprehensive studies on CCV in DF or TF engines have been limited in number. The CCV information derived from cylinder pressure variations can be used to estimate the engine performance and control the combustion [34]. Recent efforts have focused on considering the cycle-to-cycle variability in the realm of nonlinear dynamics and applying chaos-theoretic methods to unravel the nonlinear aspects of these variations. It has also been shown that the variability may be due to a stochastic component [12], and attempts have been made to estimate the noise level [16]. The short-time Fourier transform (STFT) has attracted much attention in recent years because it can be applied to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time. Compared to the conventional method based on COV of IMEP, the new methods can provide a wealth of information and valuable content of the thermodynamic processes for TF combustion [35]. These methods have been applied in conventional diesel engines for CCV estimation. Stankovic et al. [36] present a time-frequency analysis of multiple resonances with STFT in combustion chamber pressure signals and investigate a procedure to estimate the instantaneous frequencies. Payiri et al. [37] analyzed the frequency components of the in-cylinder pressure signal to decompose the in-cylinder pressure evolution according to three phenomena taking place during diesel engine operation: pseudo-motored, combustion and resonance excitation.

However, for the TF combustion, since the combustion process is completely different from the conventional diesel combustion, the size and shape of the window for STFT needs to be selected properly. Owing to the achievable time-frequency resolution of STFT, it is limited by the Heisenberg uncertainty principle and thus, this method cannot be used for CCV estimation. On the contrary, CWT is introduced to overcome the disadvantages of STFT [38]. Wavelet-based techniques are increasingly used for time series analysis in a wide variety of applications. The CWT maps the spectral characteristics of a time series onto a time-frequency plane from which the various periodicities and their temporal variations can be discerned [39–41]. Using a variable-size window in the time-frequency (time-period) plane, the CWT adjusts the time and frequency resolutions adaptively. It uses a window that narrows when focusing on high-frequency components of the time series and widens on low-frequency features, analogous to a zoom lens [42]. Recently, CWT has been applied to the analysis of CCV in gasoline, diesel, and natural gas engines [43,44].

The present study provides a systematic framework for performing TF combustion in a heavy-duty CI engine to clarify the effect of H₂ concentration and charge-air temperature on the combustion stability and cycle-to-cycle variations at a wide range of operating conditions. The present study aims to:

1) Characterize the ignition behavior and engine performance of TF combustion by varying the H₂ concentration (M₁₂ = 10%, 20%, 40%, 60%) and the charge-air temperature (Tₐ = 25 °C, 40 °C, 55 °C),
2) Analyze the combustion stability with short-time Fourier transform (STFT) to assess the knock intensity and the resonant frequency evolution,
3) Apply continuous wavelet transform (CWT) to examine the effect of the pilot fuel properties on the engine CCV.

### Experimental setup and operating conditions

#### Full-metal single cylinder engine

Fig. 1 shows the schematic of the test-engine setup. A single-cylinder CI engine is operated under multiple-fuel modes (e.g., DF or TF). A 45 kW ABB low voltage motor coupled with a frequency convertor (ACS800-11) are adopted to provide the load and control the engine speed. The engine allows monitoring and flexible control of engine operating parameters related to necessary parallel systems, such as electro-hydraulic valve actuation (EHVA), charge-air conditioning, and fuel injection systems. An electrohydraulic valve actuator (EHVA) system is employed to provide a fully flexible variable valve lift and timing for the air-exchange system. The engine is equipped with RHM-08 Coriolis mass flow meters (Rheonik Messtechnik GmbH), for measuring charge-air (ṁₘₐₓ) and two EL-FLOW® mass flow meters/controllers, for measuring port-injected CH₄ and H₂ mass flow rates (ṁ₀CH₄ and ṃ₀H₂), respectively. In this study, the charge-air mass flow rate is 80 kg/h and maintained as the temperature is increased. To get the same air mass flow rate, a PID controller was adopted to adjust the charge air mass flow accordingly. The charge air mass flow measured by a Coriolis mass flow meter and the thermocouple is located at manifold where close to the intake valve. A
Bosch CRI3 piezo injector (3-hole) is adopted to provide pilot diesel injection with high stability and low delay [45]. Two Bosch natural gas injectors (NGI2) are employed for gaseous fuel injection. The cylinder pressure is measured by a piezo-electric sensor (type 6125C, Kistler Co., Inc.) with a charge amplifier (type 5011B, Kistler Co., Inc.) at a resolution of 0.2 CAD. The crank-angle signal is acquired at a resolution of 0.2° CA with a crank-angle encoder. An external water-cooling system is employed to warm the engine. An engine control unit (ECU) based on the National Instrument field-programmable gate-array (NI-FPGA) is adopted to control and monitor the charge-air mass flow and temperature. More detailed specifications of the test engine is shown in Table 1.

Fuel properties

The properties of the EN590, CH4, and H2 are listed in Table 2. The EN590 is utilized as a pilot fuel, which has higher reactivity and lower auto-ignition temperature compared to gaseous fuels, thereby can be easily ignited by compression. CH4 and H2 as gaseous fuels premixed with charge air, which can be ignited by the pilot ignition source. The CH4 and H2 are provided by AGA Industrial Gases (Finland) with a purity of 99.95% and 99.9%, respectively.

Engine operating conditions and experimental matrix

This investigation aims to assess the effect of H2 concentration (MH2) and charge-air temperature (Tair) on ignition behavior, combustion stability and engine performance in a TF combustion engine. Fig. 2 outlines the matrix for investigating the effect of MH2 and Tair on TF combustion. It should be noted that the test matrix is limited by the knocking, and increasing in MH2 or Tair beyond the certain limit may produce heavy knocking (based on peak HRR value), enough to cause permanent damage to the engine.

The engine operating conditions are shown in Table 3. In this study, a full metal single-cylinder engine is operated at 1200 rpm with an equivalence ratio of 0.5 (\(\phi = 0.5\)) to estimate the effect of H2 addition on ultra-lean TF combustion. The total energy input into the cylinder is ~130 MJ/h depending on the MH2, which corresponds to the IMEP of 13 bar. The charge-air mass flow is controlled by an air mass flow controller, which is set to 80 kg/h. The pilot injection pressure is 1000 bar, and the pilot diesel energy share ratio is ~10% (P ratio = ~10%) with a constant injection duration. The pilot injection time is 7 CAD BTDC. A total of 200 continuous cycles for each test point are recorded for data analysis.

Operating parameter and data analysis

Before starting the data analysis, the motored cylinder pressure profiles under different MH2 conditions are calibrated with a detailed GT-Power model. Fig. 3 illustrates the modeled bulk in-cylinder temperature (T_{bulk}) and specific heat ratio (\(\gamma\)) with different MH2 at 298 K. The purpose of this calibration is to estimate the T_{bulk} and \(\gamma\), which cannot be measured directly. The result indicates that pure charge-air shows a higher \(\gamma\) value than the H2–CH4-air mixture, and there is a
huge change of $\gamma$ during the compression and expansion stroke. The variety of $\gamma$ may lead to different motored pressures and temperatures at the SOI. For the conventional diesel engine, $\gamma = 1.35$ is usually selected for heat release rate calculation. However, to gain an accurate HRR, a variable $\gamma$ vs crank angle should be used in DF and TF combustion due to the large gap between the pure charge-air and H2–CH4-air mixture in $\gamma$. In this study, the $\gamma$ for different charge mixtures is varied according to the verified GT-Power results.

**Table 2** – Specification of diesel fuel, CH4 and H2 [46–48].

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>ENS90</th>
<th>Hydrogen</th>
<th>Methane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular formula</td>
<td>CnH1.8n</td>
<td>H2</td>
<td>CH4</td>
<td></td>
</tr>
<tr>
<td>Lower heating value</td>
<td>MJ/kg</td>
<td>43.1</td>
<td>120</td>
<td>50</td>
</tr>
<tr>
<td>Cetane number</td>
<td>52.6</td>
<td>—</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Stoichiometric air-fuel ratio</td>
<td>14.5</td>
<td>34.48</td>
<td>17.19</td>
<td></td>
</tr>
<tr>
<td>Density at 15 °C, 1 atm</td>
<td>kg/m³</td>
<td>820–845</td>
<td>0.09</td>
<td>0.725</td>
</tr>
<tr>
<td>H/C ratio</td>
<td>mole/mole</td>
<td>1.91</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>Viscosity at 40 °C</td>
<td>mm²/s</td>
<td>2.0–4.5</td>
<td>—</td>
<td>18.72</td>
</tr>
<tr>
<td>Autoignition temperature</td>
<td>°C</td>
<td>250</td>
<td>585</td>
<td>540</td>
</tr>
<tr>
<td>Minimum ignition energy</td>
<td>mJ</td>
<td>—</td>
<td>0.02</td>
<td>0.3</td>
</tr>
<tr>
<td>Flammability limits (volume% in Air)</td>
<td>%</td>
<td>0.6–5.5</td>
<td>4–75</td>
<td>5–15</td>
</tr>
<tr>
<td>Burning velocity in NTP</td>
<td>cm/s</td>
<td>37–43</td>
<td>37–45</td>
<td>265–325</td>
</tr>
<tr>
<td>Quenching gap in NTP air</td>
<td>cm</td>
<td>—</td>
<td>0.064</td>
<td>0.203</td>
</tr>
<tr>
<td>Diffusivity in air</td>
<td>cm²/s</td>
<td>—</td>
<td>0.63</td>
<td>0.16</td>
</tr>
<tr>
<td>Research octane number</td>
<td></td>
<td>30</td>
<td>130</td>
<td>&gt;122</td>
</tr>
<tr>
<td>Specific heat Cp</td>
<td>kJ/kgK@300k</td>
<td>2.05</td>
<td>14.89 (gas)</td>
<td>2.226</td>
</tr>
</tbody>
</table>

**Fig. 2** – Experimental matrix of the effect of $M_{\text{H2}}$ and $T_{\text{air}}$ on TF combustion.

**Table 3** – Overview of the engine operating conditions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed</td>
<td>rpm</td>
<td>1200</td>
</tr>
<tr>
<td>SOI</td>
<td>CAD BTDC</td>
<td>7</td>
</tr>
<tr>
<td>Pilot injection duration</td>
<td>ms</td>
<td>0.256</td>
</tr>
<tr>
<td>$m_{\text{air}}$</td>
<td>kg/h</td>
<td>80</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>H2 mole fraction</td>
<td>mole %</td>
<td>0, 10, 20, 40, 60</td>
</tr>
<tr>
<td>Charge-air temperature</td>
<td>°C</td>
<td>17, 25, 40, 55, 70</td>
</tr>
<tr>
<td>Pilot energy ratio</td>
<td>%</td>
<td>10</td>
</tr>
<tr>
<td>CH4 energy ratio</td>
<td>%</td>
<td>90, 87.1, 83.7, 74.9, 61.9</td>
</tr>
<tr>
<td>H2 energy ratio</td>
<td>%</td>
<td>0, 2.9, 6.3, 15.1, 28.1</td>
</tr>
<tr>
<td>Total energy</td>
<td>MJ/h</td>
<td>123, 127, 131, 133, 136</td>
</tr>
</tbody>
</table>

The estimation of IDT plays a crucial role in TF combustion. The IDT in the current study is defined as the time interval between the start of pilot injection and the start of combustion.

$$\text{IDT} = \theta_{\text{IDT}} - \theta_{\text{SOI}} \quad (1)$$

Normally, the crank angle at 5% or 2% of cumulative heat release, namely CA5 or CA2 is defined as IDT in the conventional diesel engine [49]. However, these IDT definitions are not suitable to the DF and TF combustion due to the combustion rate is not determined by the pilot fuel but by pre-mixed flame propagation. In this study, the pressure rise delay (PRD) is defined as the IDT. **Fig. 4** shows ITDs with different definitions. It indicates that PRD shows more reproducible and reliable IDT compared with CA5 and CA2. The coefficient of
However, an increase in $M_{H2}$ or $T_{air}$ promotes auto-ignition in CHR, and different definitions for IDTs. $\frac{dP}{dq}$-based IDT cannot represent real IDT properly compared to $\frac{dP}{dq}$-IDT. CA2 and CA5 based start of combustion. CA2 and CA5 are defined as 2% and 5% of the total cumulative heat release. $CA2$ and $CA5$ are defines as 2% and 5% defined as the pressure rise delay which represents the carbon oxygen variation (COV) of IDT is derived to characterize the variation of ignition as below,

$$\text{IDT}_{STD} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{200} (\text{IDT}_i - \text{IDT}_{AVG})^2}$$  

(2)

$$\text{IDT}_{COV} = \frac{\text{IDT}_{STD}}{\text{IDT}_i}$$  

(3)

where $\text{IDT}_i$, $\text{IDT}_{AVG}$ are the individual IDT and averaged IDT, respectively. $\text{IDT}_{STD}$ is the standard deviation of the IDT. $\text{IDT}_{COV}$ is the coefficient of variation of the IDT.

Definition of the combustion states

To estimate the combustion states at different $M_{H2}$ and $T_{air}$ conditions, the pressure rise rate (PRR) is applied to evaluate the pressure oscillations and define the abnormal combustion such as PREMIER combustion and knocking, as shown in Fig. 5. It can be observed that, in normal combustion, the PRR after the main combustion (CA50) is gradually declining. In PREMIER combustion, the PRR shows a small rebounding and apparent peak after CA50. Here, the peak value is comparable to the PRR during the premixed or main combustion. However, in the knocking, the peak of the PRR after CA50 is abrupt and much higher than that of the PRR during the main combustion.

In normal combustion, the declining PRR after CA50 is due to low $M_{H2}$ or $T_{air}$, which results in a low flame propagation or even quenching at the end of the main combustion [20]. However, an increase in $M_{H2}$ or $T_{air}$ promotes auto-ignition in the end-gas region. This end-gas auto-ignition in a favorable range is called PREMIER combustion mode. When end-gas auto-ignition exceeds a favorable range due to an increased $M_{H2}$ or $T_{air}$ beyond a specific level, this creates multiple flame fronts and generates an extremely high PRR [26,27], which leads to engine knocking.

Short-time fourier transform -STFT

In recent years, the short-time Fourier transformation (STFT) has attracted much attention because it can be applied to determine the sinusoidal frequency and phase content of local sections of a signal as it changes over time. Here, in this study, STFT time-frequency method is implemented to determine single-cycle combustion stability. It extracts the frequency content of an in-cylinder pressure signal while preserving the time signal events. The STFT algorithm windows a small segment of the time series waveform and applies a Discrete Fourier Transform (DFT) on the data contained in the window [50]. The result is a set of data representing the signal’s energy signature in frequency and time. Windows represent weighting functions, which aim to reduce the order of discontinuity at the boundary of the finite observation interval, are applied to data to reduce the effect of the spectral leakage when dividing the signal $s(\Theta) = s(\Theta) \omega(\Theta - \alpha)$. In this study, the STFT method is applied to estimate the combustion stability in an individual cycle. The STFT applies a window function at various locations and performing a Fourier transform to analyze its frequency content, such as:

$$P_{STFT}(\alpha, f) = |S_{f}(f)| = \sum_{\Theta \in \Theta} s(\Theta) \omega(\Theta - \alpha) e^{i2\pi f(\Theta)} \Delta t(\Theta)$$  

(4)

where $\omega(\Theta)$ is the window function, here, the Blackman-Harris window is designed to reduce spectral leakage. $s(\Theta)$ is the bandpass pressure (the signal to be transformed). $P_{STFT}(\alpha, f)$ is essentially the Fourier transform of $s(\Theta) \omega(\Theta - \alpha)$, a complex function representing the phase and magnitude of the signal over time and frequency. Often phase unwrapping
is employed along with either or both the time axis, $\alpha$, and frequency axis, $f$, to suppress any jump discontinuity of the phase result of the STFT. The time index $\alpha$ is normally considered to be “slow” time and is usually not expressed in as high resolution as time $t$. The length of the window is always a trade-off between frequency and time resolution.

Continuous wavelet transform – CWT

Since TF combustion processes are completely different from conventional diesel combustion, the size and shape of the STFT window function require a precise implementation. Moreover, the time-frequency resolution generated by STFT is limited by the Heisenberg uncertainty principle, which prevents the correct estimation of CCV in a continuous operation. Therefore, continuous wavelet transform (CWT) is introduced here to overcome the disadvantages of STFT. CWT maps the spectral characteristics of a time series onto a time-frequency (time-period) plane from which the various periodicities and their temporal variations can be discerned by visual inspection [39–41]. It uses a variable-size window in the time-frequency (time-period) plane, which adjusts the time and frequency resolutions adaptively. Additionally, an adaptive window function has applied that narrows when focusing on high-frequency components of the time series and widens on low-frequency features, analogous to a zoom lens [42].

In this study, the CWT method is adopted to create the WPS and global power spectrum (GPS) from the time series of IMEP. CWT can construct a time-frequency representation of a time series that offers convincing time and frequency localization, so it can analyze localized intermittent periodicities of the CCV in the engine. In practice, CWT is estimated by applying the frequency-domain fast algorithm to IMEP time-series in Matlab. In time series IMEP, due to the similar resolution in both time and frequency, a complex Morlet wavelet consists of a plane wave modulated by a Gaussian function and is described by Ref. [43]:

$$\psi_0(t) = e^{ \frac{-1}{8} \omega_0^2 t^2 } \cos(\omega_0 + \omega_0 t) \frac{\omega_0}{\pi}$$

where $\omega_0$ is the one-dimensional frequency taken as $\omega_0 = 2500$ Hz throughout this paper for the Morlet wavelet. Let $f$ be a continuous time series. Then the wavelet transform of $f$ is defined as

![Image of Figure 6 showing the effect of $M_{H_2}$ on the TF combustion at different $T_{air}$: (a) 25 °C, (b) 40 °C, (c) 55 °C, (d) 70 °C. The normal combustion gradually transits to abnormal combustion such as PREMIER combustion and knocking with the increase of the H$_2$ concentration or/and charge-air temperature due to the end-gas auto-ignition.](image-url)
where the overbar denotes a complex conjugate. We call \( \bar{W}_{f}(a,b) \) the wavelet power spectrum of \( f \). For the discrete-time series \( \{x_n\}^{N-1} \) of time step \( \Delta t \), its wavelet transform is defined as

\[
W_n(s) = \sqrt{\frac{\Delta t}{s}} \sum_{n=0}^{N-1} x_n \bar{\psi}_{n} \left( \frac{n-n_0}{s} \right) d(n-n_0)
\]

where \( |W_{n}(s)|^2 \) the wavelet power spectrum of \( \{x_n\}^{N-1} \). The wavelet transform is very useful for time series analysis where smooth, continuous variations in wavelet amplitude are expected.

**Results and discussion**

This section is divided into three subsections. Section Effect of \( H_2 \) on ignition characteristics and engine performance characterizes the effect of \( H_2 \) concentration and charge-air temperature on the characteristics of aHRR, IDT, IMEP, COVs and ITE. Section Combustion stability based on STFT quantifies the effect of \( M_{H2} \) and \( T_{air} \) on the combustion stability in an individual cycle based on the STFT. Section Cycle-to-cycle variations based on CWT estimates the effect of \( M_{H2} \) and \( T_{air} \) on the CCV based on the CWT.

**Effect of \( H_2 \) on ignition characteristics and engine performance**

Fig. 6 (a)–(d) illustrates the effect of \( M_{H2} \) on the in-cylinder pressure and aHRR under different \( T_{air} \) (17 °C–70 °C) conditions. It should be noted that the results under cold conditions (\( T_{air} = 17 \) °C) are not shown for brevity. The results indicate that the addition of the \( H_2 \) increases the in-cylinder pressure and aHRR. This can be explained, on the one hand, increasing \( M_{H2} \) leads to a slight increase in the total energy because of the high LHV of the \( H_2 \) when keeping the equivalence ratio constant (\( \phi = 0.5 \)), as shown seen in Table 3. On the other hand, the addition of the \( H_2 \) also increases the combustion efficiency due to its excellent combustion properties, such as broader flammable limit, lower ignition energy, higher diffusion rate, faster laminar flame speed, and stronger lean-burn capability [8–11].

At low \( T_{air} \) conditions as shown in Fig. 6(a), the addition of the \( H_2 \) shortens the IDT, CA50 and combustion durations. The abnormal combustion starts at \( M_{H2} = 60\% \) and \( T_{air} = 25 \) °C where an abnormal aHRR peak after the main combustion can be defined as PREMIER combustion due to the end-gas auto-ignition [26,27]. The PREMIER combustion occurs with auto-ignition in the end-gas region when the main combustion...
flame propagation is nearly finished. Auto-ignition is triggered by the increase of the in-cylinder pressure and temperature when MH2 is high. Fig. 6(b) shows the TF combustion at Tair = 40°C with varying the H2 concentration. The addition of the H2 exhibits a similar effect on IDT, CA50 and combustion durations with a lower charge-air temperature. However, an extremely strong abnormal aHRR peak can be observed right after CA50. Similarly, this strong pressure rise caused by end-gas auto-ignition is defined as knocking. In knocking mode, heat is released in two stages when the engine undergoes this type of combustion.

With further increasing the Tair to 55°C as shown in Fig. 6(c), the PREMIER combustion can be observed when MH2 = 40% and the higher H2 concentration case cannot proceed due to heavy knocking. Fig. 6(d) depicts the effect of the MH2 at high Tair condition (Tair = 70°C). The high charge-air temperature dramatically promotes the combustion process, resulting in a shorter IDT, CA50, and combustion duration compared to the lower Tair conditions. Additionally, the increase of the charge-air temperature reduces the tolerance of the H2 addition in normal combustion, which exhibits the PREMIER combustion at MH2 = 20% and knocking at MH2 = 40% conditions.

Overall, the increase of the charge-air temperature and H2 concentration, resulting in a combustion transition. With increasing the Tair and/or MH2, the normal combustion gradually transits to PREMIER combustion, then transits to knocking due to the faster flame speed and wider flammability of the gaseous mixture with increasing Tair or MH2, which creates a faster auto-ignition burning rate and induces a sudden pressure rise between the premixed flame and end-gas flame. Subsequently, inducing strong pressure oscillations during main combustion. This process also dramatically reduces the IDT, CA50 and combustion duration.

The effect of MH2 on the IDT, CA50, and combustion duration are shown in Figs. 6 and 7. Increasing MH2 leads to a shorter IDT, CA50, and combustion duration at all Tair. On the one hand, increasing MH2 results in a faster burning rate due to its excellent combustion properties (e.g., fast flame speed and board flammability limits), thereby shortening the CA50 and combustion duration. On the other hand, the addition of the H2 leads to a higher in-cylinder temperature, subsequently induces the end-gas auto-ignition, which results in abnormal combustion (e.g., PREMIER and knocking).

The abnormal combustion can shorten the combustion duration dramatically due to the main combustion and end-gas burning take place simultaneously. Fig. 7 shows that the addition of the H2 significantly reduces the combustion duration, especially in knocking mode (e.g., MH2 = 60% and Tair = 40°C), the combustion duration is less than half of the normal combustion (e.g., MH2 = 0% and Tair = 40°C). However, the Tair shows an insignificant effect on the combustion duration at low MH2. With increasing H2 concentration, the charge mixture shows more sensitivity to the Tair due to the combinative effect of the increase of the H2 concentration and charge-air temperature on the in-cylinder temperature, which may enhance the end-gas auto-ignition. It is noted that the increase of the Tair shows a marginal effect on the combustion duration in normal combustion (e.g., MH2 ≤ 20%).
the increase of the $T_{\text{air}}$ significantly reduces the combustion duration in abnormal combustion (e.g., $M_{\text{H}_2}/C_{21} > 40\%$). It is worth noting that, when $T_{\text{air}} < 55^\circ C$, the maximum $H_2$ addition can achieve 60%. However, when $T_{\text{air}} \geq 55^\circ C$, the maximum $H_2$ addition is 40% due to the appearance of the heavy knocking which may lead to serious damage to the engine.

It is well known that the $H_2$ addition can accelerate the combustion rate. However, the effect of $M_{\text{H}_2}$ on IDT is still unclear. Fig. 8 demonstrates the comparison of the effect of $M_{\text{H}_2}$ on IDTs at different $T_{\text{air}}$. Interestingly, the increase of the $M_{\text{H}_2}$ shortens IDT, which represents an opposite trend with the previous simulation results in Refs. [51, 52]. It is worth noting that this phenomenon appears in a wide charge-air temperature range ($17^\circ C$ to $70^\circ C$), which hints that these opposite trends in IDTs are not caused by the change of the $T_{\text{air}}$. The hypothesis of this opposite phenomenon between the real engine and chemical kinetics simulation is related to the difference of the bulk in-cylinder temperature. In real engines (operating continuously), increasing the $M_{\text{H}_2}$ leads to a higher accumulative bulk in-cylinder temperature at SOI due to the higher combustion temperature with $H_2$ addition, which may shorten the IDT. However, in simulation, the temperature at SOI is defined by the users rather than determined by accumulative combustion temperature. Fig. 8(a) shows the effect of $M_{\text{H}_2}$ on the COV of IDT. At lower $M_{\text{H}_2}$ and $T_{\text{air}}$ ($M_{\text{H}_2} \leq 20\%$ and $T_{\text{air}} < 70^\circ C$), increasing $M_{\text{H}_2}$ leads to a lower ignition variation. However, further increasing $M_{\text{H}_2}$ ($M_{\text{H}_2} > 20\%$), a dramatic increase in ignition variation (COV of IDT) can be observed. This is because the addition of $H_2$ increases the bulk in-cylinder temperature due to the fast combustion rate compared with $CH_4$. The high temperature at the SOI greatly improves the reactivity of the pilot diesel, which leads to high ignition variations (COV of IDT) as shown in Fig. 8(b).

Fig. 9 (a)–(c) shows the effect of $M_{\text{H}_2}$ on IMEP, COV of IMEP and ITE at different $T_{\text{air}}$. Fig. 9 (a) and (b) depict that adding $H_2$ leads to a higher IMEP and lower COV of IMEP. As the above explanation, increasing $M_{\text{H}_2}$ results in higher total energy, combustion efficiency and shorter combustion duration, leading to higher thermal efficiency and less CCV due to its excellent combustion properties. It can be observed in Fig. 9 (c) that the ITE increases ~10% from $M_{\text{H}_2} = 0$ to 60%. It should be noted that, in DF mode ($M_{\text{H}_2} = 0$), the low ITE can be attributed to the ultra-lean ($\phi = 0.5$) condition which leads to incomplete combustion. Increasing the $M_{\text{H}_2}$ extends the lean-burn limit and accelerates the combustion rate, which leads to higher combustion efficiency compared to lower $H_2$ content. Additionally, the addition of $H_2$ also contributes to

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**Fig. 11** — The resonant frequency and intensity at different combustion states, (a) normal, (b) PREMIER, (c) knocking, (d) averaged PSD comparison. It is noted that PREMIER combustion exhibits the lowest pressure oscillation intensity which represents the highest combustion stability compared to normal combustion and knocking.
combustion stability, which shows a lower COV of IMEP (see in Fig. 9(b)). This is because the addition of H₂ extends the stretch extinction limit, and thus may improve the lean premixed flame stability [34]. However, when \( M_{H2} > 20\% \), further increasing the \( M_{H2} \) exhibits less sensitivity to the COV of IMEP.

The comprehensive comparison of the effect of \( M_{H2} \) and \( T_{air} \) on the TF combustion are summarized in Fig. 10(a). It shows that either increasing the \( M_{H2} \) or \( T_{air} \) leads to a shorter IDT. This is because increasing the \( T_{air} \) leads to a higher bulk in-cylinder temperature at SOI, thereby shortening the IDT. Similarly, increasing the \( M_{H2} \) leads to a higher combustion temperature and an accumulative bulk in-cylinder temperature, which also creates a higher temperature at SOI and shortens the IDTs. Additionally, the addition of the H₂ improves the heat capacity of the charge mixture, which also slightly increases the bulk in-cylinder temperature as shown in Fig. 3. Fig. 10(b) depicts the effect of \( M_{H2} \) and \( T_{air} \) on engine performance. It is observed that increasing \( M_{H2} \) leads to a higher ITE due to the addition of the H₂ extending the flammability limits of the H₂–CH₄ mixtures and improving combustion efficiency. Additionally, the addition of the H₂ shortens the combustion duration, which can also improve the thermal efficiency. It should be noted that increasing \( T_{air} \) shows an insignificant or negative effect on TF combustion. This is because increasing \( T_{air} \) exhibits an insignificant effect on combustion efficiency but reduces combustion stability (when keep the charge-air mass flow and equivalence ratio constant). Furthermore, if the \( T_{air} \) or \( M_{H2} \) exceeds a specific level (e.g., \( T_{air} > 70\degree C \) or/and \( M_{H2} > 60\% \)) it may lead to heavy knocking.

**Combustion stability based on STFT**

Next, the STFT method is applied to estimate the combustion stability in an individual cycle. Fig. 11(a)–(c) illustrates the resonance phenomenon of a single cycle (cycle No. 50) at different combustion states (normal, PREMIER and knocking). In each figure (e.g. Fig. 11(a)), the top plot presents the filtered cylinder pressure (green color) and the unfiltered cylinder pressure (red color). The blue line represents bandpass pressure defined as the difference between unfiltered and filtered pressure. The higher resonant frequency but lower intensity can be observed with increasing the \( M_{H2} \) or \( T_{air} \) in normal and PREMIER combustion modes, which represents that the addition of the H₂ or the increase of the charge-air temperature improves the combustion stability in normal and PREMIER combustion modes. However, when PREMIER combustion transits to knocking, a wide resonant frequency band and extremely strong pressure oscillation intensity can be observed due to the violate end-gas auto-ignition.

![Fig. 12 – Effect of the \( M_{H2} \) on combustion stability at different \( T_{air} \)](image-url)
cylinder pressure. The contour plot (lower-left) illustrates resonant frequency and intensity based on the bandpass pressure using STFT. The plot is laid out for a crank angle, while the color shades represent the varying magnitude of the frequency component. The power spectral density (PSD) is a summarized fluctuation power at each frequency and it is presented in the plot at the lower-right corner. The cyclic (transparent curves) and averaged (solid curves) PSD of all combustion states are illustrated in Fig. 11(d).

Fig. 11(a) demonstrates resonance phenomenon in normal combustion mode ($M_{H2} = 10\%$ and $T_{air} = 25^\circ C$). In this case, the combustion shows higher bandpass pressure oscillations after 370 CAD (tail combustion), which represents more unstable combustion at the end of the main combustion due to the depletion of the $H_2/CH_4$ mixture. In PREMIER combustion mode, the appearance of the end-gas auto-ignition leads to a small pressure rise at the end of the main combustion, as shown in Fig. 11(b). Nevertheless, a very smooth bandpass pressure can be found after premixed combustion (364–374 CAD) due to the addition of the $H_2$ that accelerates the flame propagation and broadens the flammability limits. In knocking mode (see Fig. 11(c)), a high PRR during the main combustion exhibits an extremely strong pressure oscillation.

Fig. 11(d) depicts the individual and averaged distribution of the resonant frequency and the oscillation intensity at different combustion states. In normal combustion mode, two peaks in PSD at a frequency of 4.89 kHz and 8.46 kHz can be observed, which represents the low-frequency oscillation at tail combustion and high-frequency oscillation at premixed and main combustion. The former shows higher oscillation intensity (5.9 dB/Hz) due to lean mixture with low $H_2$ addition, which leads to flame quenching. The PREMIER combustion shows lower oscillation intensity, but higher resonant frequency compared to normal combustion. This is related to the faster and smoother combustion with $H_2$ addition, which accelerates the flame propagation and extends the flammability limits. In knocking mode, a broadband resonant frequency (5.66 kHz) with high oscillation intensity (7.125 dB/kHz) can be observed right after premixed combustion. The aforementioned phenomenon has been proposed to originate from the combined effects of the increased $H_2$ addition and charge-air temperature, which accelerates the flame propagation, shortens the end-gas auto-ignition timing, and creates multiple flame fronts, which results in a strong pressure oscillation [26,27].

Fig. 12(a)–(d) depicts the effect of $M_{H2}$ and $T_{air}$ on combustion stability based on STFT analysis. In normal and PREMIER combustion, adding $H_2$ leads to a larger resonant frequency but lower oscillation intensity, which implies that the addition of $H_2$ accelerates the combustion rate and leads to smoother combustion. However, in knocking mode (see Fig. 12(b)–(d)), the high $H_2$ content and $T_{air}$ promotes the end-gas auto-ignition and induces a broader resonant frequency (2 kHz–7 kHz), as well as a very strong pressure oscillation (6–7 dB/Hz).

To provide a quantitative assessment for combustion stability, Fig. 13 and Fig. 14 summarize the quantitative effect of $M_{H2}$ and $T_{air}$ on peak pressure oscillation frequency and intensity based on the STFT analysis. As the aforementioned explanation, either increasing the $H_2$ concentration or charge-air temperature leads to a higher pressure oscillation frequency as shown in Fig. 13, in particular, the addition of the $H_2$ exhibits more sensitivity to the pressure oscillation frequency. This can be explained by the addition of the $H_2$ improves the combustion properties of the charge mixtures, which results in a faster flame speed, thereby creating a higher pressure oscillation frequency. Fig. 14 summarizes the effect of $M_{H2}$ and $T_{air}$ on pressure oscillation intensity, which corresponds to combustion stability. The results reveal that increasing $H_2$ concentration or charge-air temperature leads to a lower...
pressure oscillation intensity, which represents higher combustion stability. The interpretation is related to the higher reactivity of the charge mixture with increasing the H2 concentration or charge-air temperature. However, it is noted that when the H2 concentration or charge-air temperature exceeds a specific level (e.g., M_{H2} > 40% and T_{air} > 55 °C), the occurrence of the knocking may lead to a higher pressure oscillation intensity.

Cycle-to-cycle variations based on CWT

Here, we aim to estimate the global CCV in TF combustion engines. The time series IMEP and CCV based on CWT at different T_{air} at varying M_{H2} (0%, 10%, 20%, 40%, 60%) are shown in Fig. 15(a)–(d). In each figure, the IMEPs at different M_{H2} conditions are combined from low to high (top). The contour plot shows the distribution of the wavelet power spectrum (WPS) (bottom left). A color bar represents the variation level. In WPS, it is assumed that the IMEP time series has a mean spectrum. If a peak of WPS is significantly above this background spectrum, then it can be considered a true feature of the time series [27]. The integrated WPS value at each cycle period is applied to estimate the global CCV (bottom right).

Fig. 15 illustrates the CCV features at T_{air} = 25 °C. It indicates that increasing H2 concentration lowers the CCV level. Even adding 10% H2, the wavelet spectrum power is distinctly lower than that in the DF mode. However, when M_{H2} > 20%, further increasing the H2 content shows an insignificant effect on CCV. Similar trends also can be observed at a higher T_{air}. As explained in Section Combustion stability based on STFT, this can be explained by the addition of the H2 improves the combustion stability and extends the flammability limits when the charge mixture with low H2 content, which results in dramatic improvements in CCV. However, when M_{H2} exceeding a specific level (e.g. M_{H2} ≥ 20%) depending on the
charge-air temperature, the addition of the H2 exhibits less contribution to the combustion efficiency. The lowest CCV features can be observed at $T_{\text{air}} = 40^\circ \text{C}$, as shown in Fig. 15(b). Especially, when $M_{\text{H2}} \geq 20\%$, the intermittent low power wavelet spectrum can be observed in the low-frequency band of around the 10-cycle period. However, these periodicities do not persist long enough to be considered true oscillations. Further increasing the $T_{\text{air}}$ to 55 °C and 70 °C exhibit a high-level of CCV compared to $T_{\text{air}} = 25^\circ \text{C}$ when $M_{\text{H2}} \geq 20\%$. This result can be explained by the abnormal combustion induced by the end-gas auto-ignition such as PREMIER combustion and knocking. Although the PREMIER combustion can improve combustion stability in an individual cycle, the cyclic variations caused by uncontrollable end-gas auto-ignition may increase the CCV level.

To assess the effect of $M_{\text{H2}}$ and $T_{\text{air}}$ on CCV level, the effective wavelet power spectrum based on IMEP is summarized and cataloged to estimate the CCV level from 1 to 10, corresponding to the CCV level from low (blue) to high (red). It is shown that increasing the MH2 or Tair decreases the CCV level. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(1) Increasing the H2 content and the intake temperature leads to a shorter IDT. The results indicate that increasing the H2 content from 0% to 60% decreases the IDT by 33% depending on the charge-air temperature. Increasing the intake temperature from 17 °C to 70 °C decreases the IDT by 30%.

(2) Increasing the H2 content leads to a shorter combustion duration. When increasing the H2 content from 0% to 60%, the combustion duration is decreasing by 30–50% depending on the intake temperature.

(3) The addition of the H2 leads to a higher in-cylinder pressure and aHRR, thereby resulting in a higher IMEP and ITE. The increase of the IMEP up to 3 bar (~30% improvement) and the increase of ITE is ~10% when increasing the H2 content from 0% to 60%, which is independent of the charge-air temperature.

(4) The addition of the H2 may lead to abnormal combustion such as PREMIER combustion and knocking when H2 concentration exceeding a specific level ($M_{\text{H2}} \geq 40\%$) depending on the charge-air temperature. The PREMIER combustion improves the combustion stability and combustion efficiency. However, heavy knocking lowers the combustion stability and thermal efficiency.

(5) The addition of the H2 improves the combustion stability based on STFT analysis, which shows a higher pressure oscillation frequency but lower pressure oscillation intensity. However, the appearance of the knocking (e.g., $M_{\text{H2}} \geq 40\%$ depending on $T_{\text{air}}$) dramatically reduces the combustion stability, which exhibits a larger pressure oscillation frequency and intensity simultaneously.

(6) The addition of the H2 reduces cycle-to-cycle variations when $M_{\text{H2}} < 20\%$ based on CWT analysis. However, when $M_{\text{H2}} \geq 20\%$, no significant effect can be observed with a further increase of $M_{\text{H2}}$. Increasing the charge-air temperature may lead to high CCV due to the appearance of knocking.

Overall, there are many benefits from enriching CH4 with H2, for instance, the extension of the flammability limits of the mixtures, enhancing the ignition and combustion stability, improvement of the thermal efficiency and potential reduction of the CO2, UHC and CO emissions. However, it is worth noting that the increase of $M_{\text{H2}}$ enhances the knocking tendency. As such, the higher $M_{\text{H2}}$ in the H2–CH4 mixture at cold conditions is more beneficial for TF combustion.

**Conclusions**

This study aimed at characterizing the effect of $M_{\text{H2}}$ and $T_{\text{air}}$ on ignition behavior, combustion stability and CCV in a TF combustion engine. The combustion states (e.g., normal, PREMIER and knocking) are well defined under certain conditions (e.g., $\phi = 0.5$, charge-air mass flow = 80 kg/h). The main findings of this work are:

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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