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Yeganeh, Maryam; Rönn, Kristian; Karimkashi, Shervin; Cheng, Qiang; Hlaing, Ponnya; Hyvönen, Jari; Vuorinen, Ville; Kaario, Ossi; Larmi, Martti

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Published in: Proceedings of the Combustion Institute

DOI: 10.1016/j.proci.2024.105715

Published: 01/01/2024

Document Version Publisher's PDF, also known as Version of record

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Please cite the original version: Yeganeh, M., Rönn, K., Karimkashi, S., Cheng, Q., Hlaing, P., Hyvönen, J., Vuorinen, V., Kaario, O., & Larmi, M. (2024). Experimental investigations of hydrogen pre-ignition phenomenon induced by two different lubricating oils in a rapid compression expansion machine. *Proceedings of the Combustion Institute*, *40*(1-4), Article 105715. https://doi.org/10.1016/j.proci.2024.105715

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Contents lists available at ScienceDirect



Proceedings of the Combustion Institute

journal homepage: www.elsevier.com/locate/proci



Experimental investigations of hydrogen pre-ignition phenomenon induced by two different lubricating oils in a rapid compression expansion machine



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ARTICLE INFO

Keywords: H₂ pre-ignition Lubricating oil RCEM Air-to-fuel ratio Compression ratio

ABSTRACT

The growing interest in utilizing hydrogen (H_2) as a zero-carbon fuel has ignited extensive research on its potential application within internal combustion engines (ICEs). However, a major challenge regarding H₂ ICEs is the pre-ignition phenomenon. Various factors, including hot spots, oil droplets/deposits, and the ignition system, contribute to pre-ignition. This study focuses on pre-ignition caused by engine lubricating oil droplets/deposits. A Rapid Compression Expansion Machine (RCEM), equipped with optical access is employed to conduct a comparative analysis of the pre-ignition characteristics of two distinct engine lubricating oils called oil A and oil B. Oil A is an API (American Petroleum Institute) Group II lubricating oil with Ca (calcium) detergents, while oil B is of API Group V with a combination of Mg (magnesium) and Ca (calcium) components. The study identifies pre-ignition limits for both oils across various air-to-fuel ratios ($\lambda = 2, 2.5, 3$) and compression ratios ($\epsilon = 11$ -14.5). Comparative assessments are also performed through a chemical analysis (homogenous constant volume ignition delay time (IDT) simulations) as well as investigating the cylinder pressure and heat release rate (HRR) curves for the tested lubricating oils. This study represents the first exploration of the H_2 pre-ignition phenomenon in response to different engine lubricating oils within the context of an RCEM. The findings reveal that oil A is more susceptible to pre-ignition. In contrast, oil B exhibits pre-ignition at higher ε while maintaining constant λ . Simultaneously, oil B displays an accelerated flame propagation and more robust combustion due to the incidence of pre-ignition at higher ϵ . Hence, in the context of H₂ ICEs, the Group V oil sample (oil B) presents itself as a more advantageous choice compared to the Group II oil sample (oil A) for alleviating undesirable pre-ignition.

1. Introduction

In response to the escalating energy demand, the call for an efficient and robust hydrogen (H₂) economy has become more pronounced. The appeal of H₂ as a fuel varies significantly depending on the production method, with distinct categories such as "green H₂" emerging as a compelling energy storage solution. During times of surplus renewable energy generation, excess electricity can be utilized for electrolysis, generating green H₂ as a practical energy storage solution. The stored H₂ proves its efficacy by being employed in either fuel cells (FCs) or internal combustion engines (ICEs), thereby, actively contributing to addressing peak energy demands.

H₂ emerges as a highly promising fuel for ICEs, as it can effectively address the need for suitable range, enhanced performance, and overall

resilience [1,2]. However, H₂ ICEs pose challenges primarily because of the unique characteristics of H₂, including a low minimum ignition energy, a wide flammability range, and a combination of high flame speed and low quenching distance [2,3]. Abnormal combustion phenomena associated with H₂ ICEs can be classified into various types including backfire, spark knock, knocking surface ignition, non-knocking surface ignition or pre-ignition, phantom spark, and misfire [2]. Consequently, it is imperative to initially address the complexities associated with combustion abnormalities in H₂ ICEs [4–6].

Given the current study's primary focus on pre-ignition, this phenomenon is defined as a self-triggered onset of combustion before the intended ignition timing, leading to increased in-cylinder pressure or knocking [7]. In the context of H_2 ICEs, the thermal diffusivity of the mixture emerges as a significant factor contributing to pre-ignition,

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https://doi.org/10.1016/j.proci.2024.105715

Received 1 December 2023; Accepted 15 July 2024 Available online 19 August 2024

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especially under lower pressures and increased ignition delay times [8]. Various potential triggers for pre-ignition are presented in the literature such as auto-igniting oil droplets and heated particles or deposits on engine walls [9], hot-spots e.g., spark plug or exhaust valves [10], and residual heat from the prior cycle [11]. Nonetheless, there is still a fundamental gap in comprehending individual pre-ignition triggers due to the wide range of engine designs.

In the light of the provided literature review, this study aims to enhance the understanding of a potential pre-ignition mechanism in H_2 ICEs, specifically related to pre-ignition induced by engine lubricating oil droplets/deposits. The investigation involves comparing pre-ignition phenomenon using two different engine lubricating oils from API (American Petroleum Institute) Groups II and V, in a rapid compression expansion machine (RCEM) equipped with optical access. These two lubricating oils have different detergent additive formulations which can affect ignitability, e.g., c.f. [12]. High-speed imaging techniques are employed to detect the timing of pre-ignition and monitor the natural luminosity of the flame. The detailed objectives of this study are as follows:

- 1. Determining the pre-ignition limits and the different combustion modes arising from using each of the two lubricating oils across various air-to-fuel ratios ($\lambda = 2, 2.5, 3$) and compression ratios ($\epsilon = 11-14.5$) relevant to H₂ ICEs.
- 2. Conducting a detailed comparative analysis of the pre-ignition phenomenon induced by the two different engine lubricating oils (oil A, an API Group II lubricating oil with Ca (calcium) detergents and oil B from API Group V with mixed Mg (magnesium)/Ca components targeting pre-ignition mitigation). This involves i) a chemical kinetics analysis (homogenous constant volume ignition delay time (IDT) simulations using CHEMKIN and Cantera), ii) investigation of the cylinder pressure and heat release rate (HRR) curves, and iii) flame propagation speed (flame front velocity) measurements using a method different but consistent with the thermodynamic model of the same RCEM for estimating the flame speed of H₂/air mixtures developed by De Bellis et al [13].

In accordance with the outlined objectives, this research constitutes a groundbreaking initiative, serving as the first investigation of H_2 preignition phenomenon concerning various engine lubricating oils within the framework of an RCEM.

2. Methodology

This section provides an overview of the experimental setup, optical system, test matrix, data post-processing techniques, and error analysis in the current study.

2.1. RCEM set up description

Fig. 1 shows a schematic view of the RCEM system which is designed for a single compression stroke and an expansion stroke. As it can be observed, the setup is connected to gas bottles in ventilated cabinets and a PC operating/control system outside the test cell. Here is the detailed step-by-step procedure of setting up the experiments:

- 1. System warm-up: Setting the operating temperature (piston, cylinder head and liner tempreture) to the maximum allowable level for this device, which is 85 $^\circ$ C.
- 2. Adjustment of λ : Setting λ for the H₂/air mixture (not for oil) using the partial pressure method (by adjusting the fuel energy based on the C_p value at 1.96 bar charge pressure).
- 3. Gas filling: Filling the cylinder with the gas mixture by supplying air in two steps with fuel supply in between. It is also important to highlight the use of scavenging, repeated three times, to remove residual gases and prepare the system for the next cycle.
- 4. Lubricating oil injection: Injecting the lubricating oil on the cylinder liner (wall) using a typical automotive diesel injector (Bosch Solenoid 0445110259) during the gas filling phase well before starting the cycle. This allows for controlling the injection pressure and duration to ensure a consistent injected oil mass. While the conventional method for assessing lubricating oil pre-ignition characteristics involves suspending an oil droplet within the combustion chamber [14-18], the industrial context of the current application and limitations of the setup prompt us to try alternative methods. To replicate real engine scenarios and achieve results consistent with previous studies, this study examines the concept of injecting lubricating oils onto the cylinder liner well before starting the cycle, considering that lubricating oil often leaks to the combustion chamber from this area. By injecting the lubricating oils well before starting the cycle, we ensure the presence of oil droplets on the liner and minimize the effects of spray atomization and evaporation on pre-ignition. The injection serves solely for applying the oil onto the cylinder liner while controlling its quantity. There was no evidence of evaporating particles, nor oil mist in the recorded videos, which



Fig. 1. A schematic picture of the RCEM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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further confirms the minimal effect of spray atomization and evaporation.

- 5. Cycle operation: Initially, the driving pressure generated by compressed air is moving the counterweights backward. This action, in turn, is compelling the piston tube to move forward, facilitated by the incompressible hydraulic oil in the oil volume. Thus, the hydraulic oil is efficiently transferring the driving pressure to induce piston movement. During this phase, a high-speed magnetic sensor measures the piston's position precisely, and the spark is activated just before TDC (Top Dead Center) to facilitate the observation of pre-ignition induced by the lubricating oil. Simultaneously, the control system is automatically measuring the cylinder pressure. It should be also noted that the driving pressure is adjusted to achieve the target ε through a trial-and-error process, ensuring the desired compression ratio is attained.
- 6. Cleaning: Following each test point, the setup is opened, and a clean cloth and oil solvent are used to clean any oil droplets/deposits left on cylinder surfaces. This ensures the system is properly prepared for the next cycle, maintaining consistency in test conditions and subsequently, test data. Further specifications of the system are outlined in Table 1.

2.2. Optical system

Within the optical setup, the optical piston and transparent side windows enable direct visual observation of the combustion process using two high-speed cameras (Phantom V2012). One camera is positioned in front of the mirror to provide the cylinder head view from the optical piston, while the other is placed in front of the side windows are relatively small and the field-of-view is limited to the center of the combustion process and flame propagation within the cylinder. Recording begins around 3 ms before the piston reaches TDC. Natural chemiluminescence of the flame is captured using a continuous LED light, which enhances the background for proper detection of flame propagation. Table 2 provides further specifications of the optical system.

2.3. Test matrix

Table 3 outlines the test matrix designed for investigating preignition phenomenon induced by two distinct engine lubricating oils, namely oil A from API Group II and oil B from API Group V, both including additives. The assessment spans various λ and ε values. The choice of comparing these oils is based on a study by Haas et al. [19], on base oils/gasoline blends. This study reveals that API Groups I–IV base oil samples demonstrate an increasing paraffinic CH₂/CH₃ ratio as the group number increases, whereas the Group V base oil sample exhibits a lower CH₂/CH₃ ratio. This ratio is critical, signifying the level of paraffinic branching and impacting ignition propensity. Consequently,

Table 1

Description (units)	Value
Bore (mm)	84
Maximum Stroke (mm)	180
Maximum Pressure (bar)	250
Driving Pressure Range (bar)	10-40
Cylinder Displacement Volume (mm ³)	998
Intake and Exhaust Pipe Diameter(mm)	1.4
Volume of Piston land (mm ³)	1529
Volume of Adduction line (mm ³)	34,840
Volume of Scavenging line (mm ³)	34,840
Spark Timing (mm before TDC)	1-2
Oil Injection Pressure (bar)	600
Oil Injection Duration (ms)	600-700

Table 2

Optical system specifications.

Description (units)	Value
Piston optical access diameter (mm)	45.7
Frame Rate (fps)	67000
Exposure Time (µs)	12.77
Resolution	512*512
LED light	12700lm/120W

Table 3	
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I COL CAOCO INALIA	Test	cases	matrix
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Engine Lubricating Oil	Air-to-fuel ratio (λ)	Compression ratio (e)
A-API Group II	2, 2.5, 3	11-14
B-API Group V	2, 2.5, 3	11-14.5

the bulk hydrocarbon functional group composition plays a pivotal role in determining how lubricating oils influence pre-ignition.

2.4. Data post-processing

The post-processing of experimental data involves several steps. First, the recorded videos are converted to images. Second, the preignition location and limit with respect to λ and ε are pinpointed. Third, a MATLAB code is developed to showcase the average cylinder pressure and HRR of multiple repetitions of each test point. The cylinder pressure is recorded using a Kistler sensor and then filtered to eliminate fluctuations. After that, the filtered data is averaged across all repetitions of each test point, with max-min error bars displayed to show the range of variations. HRR is also considered as net or "apparent" heat release rate (1) with ideal gas assumptions:

$$Q_{ch} = (1/\gamma(T) - 1)Vdp/dt + (\gamma(T)/\gamma(T) - 1)pdV/dt$$
(1)

where \dot{Q}_{ch} , $\gamma(T)$, V, p, and t indicate HRR, specific heat ratio as a function of temperature, cylinder volume, cylinder pressure, and time, respectively. Further details on deriving this formula can be found in supplementary materials (S1.pdf).

Additionally, a separate code is formulated to measure flame propagation speed (flame front velocity) to compare the speed of the preignition flame with that of the spark. For the flame front velocity calculation, the flame is considered spherical and tracked from both the cylinder head and side view, providing a 3D perspective. Fig. 2



Fig. 2. Flame propagation speed calculation method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

illustrates the flame propagation like a circle from both the cylinder head and side view. As it is shown, the flame front location (dashed white arc) is tracked over several time steps (small arrows in succession) on different lines (solid white lines) drawn from the pre-ignition/spark point to the flame boundaries in as many directions as possible. The same process is performed for the side view. Finally, the speeds along different lines are averaged for each time interval and presented in a bar chart, with each bar representing the average speed for the corresponding time interval.

2.5. Error analysis

In the current experiments, several factors introduce potential sources of error. First, the precision of the pressure sensors, which measure gauge pressures, is within ± 0.5 % of the full-scale output. Second, the resolution of the high-speed magnetic sensor responsible for measuring the piston position is 0.01 mm. Another layer of complexity arises during the detection of the pre-ignition starting point and following the relevant flame front. The error in following the flame front location possesses the range of 2–3 pixels on the images. Lastly, addressing the potential error stemming from cycle-to-cycle variation is imperative. A minimum of 3 repetitions are conducted for each test point to ensure data accuracy and error bars are incorporated into the plots to illustrate the maximum and minimum measured values for the cylinder pressure. HRR is also calculated based on the average cylinder pressure.

3. Results

In this section, the outcomes of the experimental campaign are presented. First, an overview of the general observed phenomena in the experiments is provided. Following that, the behavior of both lubricating oils is analyzed across various λ and ε values, and a comprehensive comparison is conducted using cylinder pressure, HRR, and chemical analysis through ignition delay time (IDT) simulations. Finally,

flame speed measurements are conducted to compare the propagation speed of the pre-ignition point with that of the normal spark flame.

3.1. Overview of the observed phenomena

Fig. 3 presents an overview of the different modes of combustion observed during the measurements through a combination of visualizations (a-d) and analysis of the cylinder pressure curve (e). The visual representation illustrates instances of both normal and abnormal combustion. Normal combustion (a) serves as the baseline condition initiated by the spark. However, three other different modes are observed in the abnormal category: oil-spot pre-ignition (b), multi-spot ignition (c), and knocking (d). First, oil-spot pre-ignition is characterized by oil droplets/deposits ignition in a limited number of spots before or around the same time as the spark-induced ignition. This mode exhibits a slightly higher peak in the cylinder pressure curve compared to normal combustion. Second, multi-spot ignition is identified by the occurrence of multiple flames apart from the normal spark-induced flame, where the origins of ignition for these flames could be either oil droplets/deposits or locally high-temperature spots of the fuel. The cylinder pressure curve for multi-spot ignition displays a higher peak than that of oilspot pre-ignition, but without significant oscillations or observable system vibrations. Third, knocking involves multiple flames beside the normal spark-induced flame, leading to a turbulent combustion process that induces pronounced oscillations in the cylinder pressure curve. System vibrations are also observable in knocking, which can result in severe damages, including the potential for optical piston breakage. It is important to highlight that the transition from normal combustion to knocking, as illustrated in Fig. 3, is a result of increasing ε at identical λ for the same oil (oil B). Furthermore, the differences between the cylinder pressure curves for the same categories, observed in panel (e) of the figure, are attributed to cycle-to-cycle variations.



Fig. 3. Different combustion modes observed in the experiments: normal combustion (a), oil-spot pre-ignition (b), multi-spot ignition (c), and knocking (d) for oil B at $\lambda = 2.5$ and $\varepsilon = 13$, 14, 15, 15.7, respectively. The cylinder pressure curves for the different modes are displayed in panel (e) and here t = 0 is equivalent to TDC (~spark timing). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Comparative analysis of the pre-ignition behavior of the tested lubricating oils

The combustion modes for both lubricating oils at the tested λ and ε values are detailed in Table 4, which is of high importance in the design of H₂ ICEs. It is worth noting that the leanest condition, $\lambda = 3$, represents the most unstable case. Additionally, for safety reasons, the driving pressure increase is limited to avoid knocking, which could lead to the optical piston breakage. As it is shown in Table 4, across all tested λ values, the oil-spot pre-ignition for oil B occurs at ε values 0.8-1 higher compared to oil A. Likewise, the transition from oil-spot pre-ignition to multi-spot ignition requires 0.5-1 higher values of ε for oil B.

The observed results are supported by the findings of the previous literature, concluding that either the base oil or the additive composition of oil A is the reason for its increased reactivity. First, regarding the base oil effect, according to Haas et al. [19], Lubricants from API Groups I-IV are characterized by a high CH_2/CH_3 ratio, signifying a substantial presence of linear alkanes. These linear alkanes exhibit high reactivity at temperatures relevant to engine operation [20]. The same study by Haas et al. [19] also discovered that API Group V lubricants can possess reduced reactivity and CH_2/CH_3 ratio, further emphasizing the higher reactivity of oil A.

Here, a detailed chemical analysis (homogenous constant volume reactor ignition delay time (IDT) simulations using CHEMKIN and Cantera) is conducted to compare the IDT of a possible formulation of the base stock of tested lubricating oils.

A mechanism by Sarathy et al. [21] is utilized to simulate n-Hexadecane as a surrogate for oil A base stock, with validation provided in the supplementary materials (S1.pdf). The effect of n-Hexadecane on the reactivity of the mixture can be observed by comparing H₂/air and H_2 /air+n-Hexadecane mixtures under the same condition of $\lambda = 2.5$ and T = 900 K, which are relevant to the tested cases. As it is shown in the top subfigure of Fig. 4, 100 % H_2 case ignites at 46 ms while the 99 % H_2 + 1 % n-Hexadecane case ignites at 10 ms. The effect of n-Hexadecane on the reactivity of the mixture can be also investigated by tracking key species and related reactions. For instance, the formation of OH radical can be analyzed until the timestep of 5 % of cumulative heat release (9.38 ms for the 1 % n-Hexadecane case) just before final ignition at 10 ms on the top subfigure of Fig. 4 at the same $\lambda = 2.5$ and T = 900 K. Until this timestep, for 1 % n-Hexadecane case, the decomposition of H₂O₂ is the main contributor for OH production which is also consistent with [25]. This reaction is also the most prominent one for OH production in 100 % H₂ case. However, H₂O₂ decomposition produces over 500 times

Table 4

Comparison of oil-spot pre-ignition and multi-spot ignition limits for the tested lubricating oils.

Oil	λ	ε	Combustion Mode
A-API Group II	2	11	Normal
		12	Normal
		12.5	oil-spot pre-ignition
		13	Multi-spot ignition
	2.5	11	Normal
		13	oil-spot pre-ignition
		14	Multi-spot ignition
	3	11	Normal
		12	oil-spot pre-ignition
		13.5	Multi-spot ignition
B-API Group V	2	11	Normal
		13	Normal
		13.3	oil-spot pre-ignition
		14	Multi-spot ignition
	2.5	13	Normal
		14	oil-spot pre-ignition
		14.5	Multi-spot ignition
	3	12	Normal
		13	oil-spot pre-ignition
		14	Multi-spot ignition



 H_2 molar fraction in H_2 +methyl decanoate mixture (%)

Fig. 4. IDT of n-Hexadecane as a surrogate for oil A base (top) versus IDT of methyl decanoate, a surrogate for oil B base (middle and bottom) under identical conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

more OH radicals until 9.38 ms in 1 % n-Hexadecane case. The lower OH production in the 100 % H₂ case, can be attributed to less H₂O₂ being formed from reactions of two HO₂ radicals or HO₂ radicals abstracting an H atom from H₂. Overall, the increase in the radical pool from initial consumption of n-Hexadecane speeds up the reactivity of the entire mixture.

For oil B from API Group V, the base stock can comprise various compositions, including esters or glycols [22]. Therefore, a mechanism for an ester or glycol should be used to do IDT simulatations for oil B base stock. In this study, two different mechanisms (Herbinet et al. [23] and POLIMI [24]) are utilized to simulate oil B base stock as methyl decanoate (an ester). As it is shown in Fig. 4, both mechanisms demonstrate that methyl decanoate has lower reactivity compared to n-Hexadecane (representative of API Group II oils, i.e., oil A) at similar

temperature and molar fraction. However, it is important to note that if a different ester, particularly one with a longer saturated carbon chain containing many secondary carbons, is used, the reactivity may exceed that of n-hexadecane. Another possible formulation for a Group V base oil (oil B) could be a polyalkylene glycol, for which no chemical mechanism is available at low and intermediate temperature ranges. However, a similar structure has been considered and analyzed in the supplementary materials (S1.pdf).

Regarding the effect of additives, steady-state experiments in gasoline engines have discovered that increased Ca content promotes preignition while a partial replacement of the Ca content with Mg, which is the case for oil B, can mitigate pre-ignition [26]. The distinctive pre-ignition responses of lubricant detergent metals have been also investigated by Burger [12]. Burger's molecular dynamics analysis indicates that n-alkane is consumed more rapidly even at low temperatures (600 K) due to H atoms binding with the CaO in the detergent. This leads to an H atom abstraction reaction, resulting in n-Hexadecane becoming an alkyl radical (C16H33). As it is shown in Fig. 5, a small fraction of this radical can significantly reduce IDT compared to n-Hexadecane explaining how oil A (containing only Ca in the detergent additive) can promote pre-ignition. Additionally, Burger's findings reveal that if Ca is replaced by Mg (like in oil B), MgO does not bind with H atoms from n-alkane, meaning that the alkyl radical would not form as rapidly as with a Ca detergent additive.

In the remainder of this work, we shift our focus to the detailed analysis of the oil-spot pre-ignition mode, called pre-ignition hereafter. Pre-ignition can be categorized as early pre-ignition, when it starts well before the spark ignition, and late pre-ignition, where ignition at point (s) other than the spark occurs closely around the spark timing [2]. This is because the pre-ignition phenomenon is of a stochastic nature. In the tested cases, oil A exhibits early pre-ignition at $\lambda = 2$ and 2.5, transitioning to late pre-ignition at $\lambda = 3$. On the other hand, oil B displays early pre-ignition at $\lambda = 2$ and late pre-ignition at $\lambda = 2.5$ and 3. This is also in line with the higher reactivity of the oil A. Fig. 6 illustrates the progression of early pre-ignition and spark-induced flame propagation over time for both tested lubricating oils at $\lambda = 2$. Pre-ignition and spark-induced flame propagation at $\lambda = 2.5$ and 3 are also shown in Fig. S3 of the supplementary materials (S1.pdf) for both lubricating oils.

Another aspect resulting from the random nature of pre-ignition is its diverse behavior, which can vary significantly from one case to another. For instance, in the scenario depicted in Fig. 6, oil A exhibits pre-ignition originating from a single point near the 2 o'clock position, while oil B displays pre-ignition originating from two oil droplets around the 11 o'clock position. Although alternative testing methods, such as





suspending an oil droplet [14–17], might mitigate this variability, the inherent unpredictability of pre-ignition in real engine conditions underscores the importance and relevance of the current experiments.

It is also important to highlight that, in most of the cases, pre-ignition begins from a point on the top half of the liner (as shown in 6 videos in supplementary materials S2-S7). This is linked to the injection process, utilizing a symmetrical 6-hole nozzle in a horizontal setup positioned closer to the top half of the liner (c.f. Fig. 1). Moreover, oil droplets injected on the top half are more likely to detach from the wall and suspend in the cylinder. Conversely, for oil droplets injected on the bottom half of the liner, there is a greater tendency for slipping on the wall and accumulating near the 6 o'clock position. This clarifies why pre-ignition typically originates from a point on the top half of the liner in the current experiments. The combined insights into the chemical composition of the tested lubricating oils and the observation of preignition initiation mostly on the top half of the liner suggest that the oil pre-ignition phenomenon is influenced not only by chemical factors but also by transport phenomena.

For a better comparison of the tested lubricating oils' pre-ignition limits, cylinder pressure and HRR curves are shown in Fig. 7. As it can be observed, oil A and B show pre-ignition at different λ and ε values due to their different characteristics. However, the experiments have been conducted at the same conditions and cylinder pressure and HRR curves at identical conditions are provided in Fig. S4 of the supplementary materials (S1.pdf). According to Fig. 7, although oil B is more resistant to pre-ignition, it shows greater peak of the cylinder pressure and HRR due to pre-ignition at higher ε values. The observed behavior of the cylinder pressure curve also aligns with the distinctions between early and late pre-ignitions.

The final evaluation of pre-ignition characteristics of the two tested lubricating oils is based on flame propagation speed (flame front velocity) measurements, as described in Fig. 2. In Fig. 8, pre-ignition (red bars) and spark-induced flame propagation speeds (blue bars) are compared at $\lambda = 2$. A similar comparison for $\lambda = 2.5$ and 3 is also presented in Fig. S5 of the supplementary materials (S1.pdf). According to this bar chart, the pre-ignition flame initially accelerates due to compression, followed by a deceleration marking the onset of the expansion phase. In contrast, the spark-induced flame mainly decelerates since the spark timing occurs just before TDC, primarily experiencing the expansion phase. Fig. 8 also shows a generally lower pre-ignition flame propagation speed compared to the spark flame for both oil A and B. This not only confirms the oil-driven nature of preignition but also aligns with the fact that H₂ flame speed is higher than a hydrocarbon (lubricating oil) flame speed under the same conditions. Fig. 6 further supports this by showing higher luminosity of the pre-ignition flame compared to spark induced flame due to the presence of hydrocarbons in the lubricating oils. As a final note, despite inherent uncertainties related to flame front position detection, the range of the calculated flame propagation speeds aligns with those reported in [13] at lower ε values.

4. Conclusions

This paper presents the first exploration of the H_2 pre-ignition phenomenon in the context of an RCEM, focusing on its response to different engine lubricating oils (oil A from API Group II and oil B from API Group V, the latter with a higher Mg/Ca ratio). The main outcomes can be listed as follows:

- 1. The pre-ignition limits and combustion modes have been determined across varying air-to-fuel ratios ($\lambda = 2, 2.5, 3$) and compression ratios ($\varepsilon = 11-14.5$) for both lubricating oils. Notably, at identical λ values, oil B shows higher pre-ignition resistance at higher ε compared to oil A due to its lower reactivity.
- 2. Chemical analysis (homogenous constant volume ignition delay time (IDT) simulations) of the mixtures of H_2/air and H_2/air + oil



Fig. 6. Temporal evolution of pre-ignition and spark- induced flame propagation. Left column is pre-spark, middle is around spark timing, and right is after-spark. Here, t is real time with t=0 at the start of recording, and t* is a reference time set to 0 at the spark. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



Fig. 7. Cylinder pressure and HRR curves at the pre-ignition limit of the tested lubricating oils. Here t=0 is equivalent to TDC (~spark timing) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

surrogates shows that only a small molar fraction of lubricating oil at the tested conditions, can promote reactivity of the mixture significantly.

- 3. The observation of the flame luminosity, together with the analysis of cylinder pressure and HRR curves, reveal instances of both early and late pre-ignition.
- 4. The pre-ignition phenomenon induced by lubricating oils has been found to be driven by both chemical composition and transport phenomena.
- 5. Flame speed measurements have validated that lubricating oils are the main contributors to pre-ignition. For all the cases, the spark flame demonstrates a higher propagation speed compared to pre-ignition, aligning with faster speed of a pure H_2 flame compared to a hydrocarbon flame under the same conditions.

Novelty and significance statement

This research employs a novel approach to investigate the impact of



Fig. 8. Pre-ignition and spark induced flame propagation speed of both lubricating oils at λ =2. Here, t=0 is the start of recording. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

lubricating oil on mitigating the pre-ignition phenomenon in hydrogen internal combustion engines. The significance of this problem lies in the inevitability of using hydrogen as a fuel in future engines, where preignition poses a substantial challenge. Addressing this issue is critical for a smooth transition to hydrogen-powered engines, necessitating innovative solutions. The study is novel since it focuses on comparing lubricating oils from distinct API Groups (II and V) with different additive formulations for the first time. This work concludes that the Group V oil sample significantly diminishes pre-ignition propensity, enhancing combustion robustness. Notably, the research faces challenges as the experiments are resource-intensive, and the characteristics of lubricating oils remain confidential, demonstrating the novel features of the work.

CRediT authorship contribution statement

Maryam Yeganeh: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. Kristian Rönn: Conceptualization, Methodology, Resources, Software, Writing – review & editing. Shervin Karimkashi: Supervision, Writing – review & editing. Qiang Cheng: Supervision, Writing – review & editing. Ponnya Hlaing: Conceptualization, Writing – review & editing. Jari Hyvönen: Conceptualization, Writing – review & editing. Ville Vuorinen: Conceptualization, Funding acquisition, Supervision, Writing – review & editing. **Ossi Kaario:** Supervision, Writing – review & editing. **Martti Larmi:** Conceptualization, Supervision, Writing – review & editing.

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.

Acknowledgements

This work was conducted as a part of the HENNES project (no. 7578/ 31/2022), supported by Business Finland, and in collaboration with Wärtsilä Finland Oy. The receipt of the financial support from the Academy of Finland (grant no. 141921202) and Fortum-Neste Foundation (grant no.20230111) is also acknowledged. Our sincere gratitude extends to Per Löfholm, Juha Leino, Isak Rodas, Antonino Di Miceli and Viljam Grahn for their exceptional technical assistance and to Dr. Heikki Kahila and MSc. Saber Hosseinzade for their support in data analysis.

Supplementary materials

This article is accompanied by 7 supplementary files. S1.pdf provides additional explanations and figures that support the manuscript. S2-S7 are videos that complement the text. Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.proci.2024.105715.

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