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To cite this version:

N. Seignour, J. Masurier, B. Johansson, G. Dayma, P. Dagaut, et al.. Ozone-assisted combustion of hydrogen: A comparison with isooctane. International Journal of Hydrogen Energy, 2019, 44 (26), pp.13953-13963. 10.1016/j.ijhydene.2019.03.175 . hal-02132319

HAL Id: hal-02132319

https://hal.science/hal-02132319v1

Submitted on 22 Oct 2021

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Ozone-assisted combustion of hydrogen: a comparison with isooctane

N. Seignour[*], J. Masurier[#], B. Johansson[#], G. Dayma[$], P. Dagaut[$], F. Foucher[*]

[*]Laboratoire Pluridisciplinaire de Recherche en Ingénierie des Systèmes, Mécanique, Energétique (PRISME), Université d'Orléans, 8 Rue Leonard de Vinci, 45072 Orléans Cedex, France

[#]King Abdullah University of Science and Technology (KAUST), Clean Combustion Research Center (CCRC), Thuwal, 23955-6900, Saudi Arabia

[$]Institut de Combustion Aérothermique Réactivité et Environnement (ICARE), Centre National de la Recherche Scientifique (CNRS)-Institut des Sciences de l'Ingénierie et des Systèmes (INSIS), 1C Avenue de la Recherche Scientifique, 45071 Orléans Cedex 2, France

Abstract:

Homogeneous Charge Compression Ignition (HCCI) engines have the potential to achieve low emissions of nitrogen oxides and particulate matter but the use of carbon-based fuels leads to significant emissions of carbon monoxide and unburned hydrocarbon which hinder the widespread development of HCCI. Nonetheless, HCCI engines have also the potential to use various types of fuel such as hydrogen, a carbon free fuel. The present study examined hydrogen combustion in an HCCI engine comparing hydrogen with isooctane. The sensitivities of CA05, CA50 and ringing intensity to intake pressure, intake temperature and ozone were investigated for both fuels. Results highlighted that hydrogen autoignites more easily than isooctane despite its higher-octane number. Ozone seeding was therefore used to shift the combustion region of isooctane in order to perform a viable comparison between the two fuels while starting with the same initial conditions. From this point, all of the three parameters were found to promote the HCCI combustion of both fuels but greater sensitivities were observed for hydrogen than for isooctane. Ozone was observed to have the strongest influence, making it a good strategy for a future control approach. The noise level of hydrogen was very high due its high reactivity. Finally, the use of hydrogen together with ozone should enable a very clean engine cycle to be achieved cycle with only water and nitrogen as engine-out emissions.

Keywords: HCCI combustion; Hydrogen; Isooctane; Ozone

1. Introduction

The main challenges for internal combustion engines are to drastically reduce fuel consumption and to meet ever more stringent emission standards. Low Temperature Combustion (LTC) engines, and particularly Homogeneous Charge Compression Ignition (HCCI) engines, have demonstrated their potential for achieving high efficiency while keeping low levels of NOx, soot and particulate matter emissions. However,

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several issues must be solved before a widespread implementation of such concepts. A reliable cycle-to-cycle combustion phasing control in particular is the main issue discussed in current HCCI research [1, 2].

Several studies have explored HCCI combustion control by varying intake thermodynamic parameters, especially intake temperature. All the studies showed that increasing the intake temperature reduced the ignition timing and promoted combustion. Machrafi *et al.* [3] and Dubreuil *et al.* [4] reported such a trend with Primary Reference Fuels (PRF). Mohammadi *et al.* [5] also studied the impact of intake temperature and obtained similar results with natural gas.

The implementation of Exhaust Gas Recirculation (EGR) has also been widely studied in HCCI engines in order to control the combustion phasing. Dubreuil *et al.* [4], Lü *et al.* [6, 7] and Fathi *et al.* [8] performed experiments with PRF mixtures and n-heptane/natural gas mixtures. Results showed that EGR delays ignition timing due to the dilution of air and the modification of the heat capacity which limits the rise in temperature.

Another strategy to control combustion phasing is related to the ability of HCCI engines to run with various fuels. Fuel properties can therefore be a key parameter in combustion phasing. Lü *et al.* [6], Machrafi *et al.* [3], Masurier *et al.* [9] conducted investigations with PRF mixtures and showed that the higher the Octane Number (ON), the later the ignition timing. Experiments were also performed with gaseous fuels by Aceves *et al.* [10], Ibrahim *et al.* [11], and Masurier *et al.* [12], and alcohols, by He *et al.* [13], Maurya *et al.* [14], and Masurier *et al.* [15]. As HCCI engines can operate with a wide range of alternative fuels [16,17], hydrogen looks to be the ideal fuel for HCCI engines to eliminate CO, HC and particulate matter emissions. Hydrogen combined with HCCI combustion has been one of the main topics in HCCI research over the last decade [18, 19, 20, 21]. However, hydrogen combustion unfortunately leads to NOx emissions because of the high local temperatures in the combustion chamber. Hydrogen has also been studied under conventional CI combustion [22, 23] and as an additive for a dual fuel combustion strategy [24, 25, 26]. Results showed that hydrogen HCCI combustion maintains the same level of performances as conventional fuels while eliminating HC and CO emissions. However, the main issue for hydrogen combustion remains noise, because of the fast combustion of hydrogen.

Lastly, the need to achieve a reliable control of combustion, which is mainly governed by chemical kinetics in HCCI engines, led research to focus on new approaches such as seeding the engine intake ports with oxidizing species. Masurier *et al.* [27] investigated the potential of ozone, nitric oxide, and nitrogen dioxide to control the combustion phasing. Among all these species, ozone appeared to be the most promising species by increasing the air/fuel reactivity. A few ppm of ozone was found to be enough to significantly improve the autoignition of high-octane fuel.

Hydrogen is among the high-octane fuels which could lead to clean combustion while burning under HCCI conditions. The present study investigated experimentally the impact of ozone on hydrogen combustion and compared it with the effect of varying either the intake pressure or the intake temperature. Additionally, hydrogen combustion was compared to the combustion of isooctane, a reference fuel, while varying the same parameters.

2. Experimental Setup

Experiments were performed using a PSA DW10 four-stroke Diesel engine modified to operate as a single-cylinder Homogeneous Charge Compression Ignition (HCCI) engine. The engine is directly coupled to an electric motor to maintain a constant rotation speed. The main characteristics of the engine are

listed in Table 1 and a schematic of the experimental setup is given in Figure 1.

Parameters	Unit	Value
Bore	mm	85
Stroke	mm	88
Connecting Rod	mm	145
Displaced Volume	cc	499
Geometric Compression Ratio	-	16:1
Effective Compression Ratio	-	16.13:1
Number of Valves	-	4
Intake Valve Closure	CAD	351 ATDC
Intake Valve Opening	CAD	157 BTDC
Exhaust Valve Opening	CAD	140 ATDC
Exhaust Valve Closure	CAD	366 ATDC
Coolant Temperature	°C	90
Oil Temperature	°C	90

Table 1 : Engine characteristics

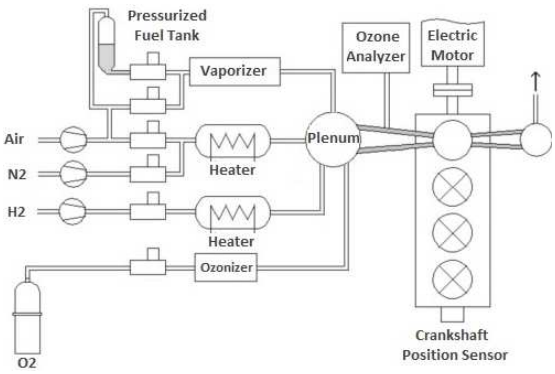

Figure 1: Schematic of the experimental setup.

The inlet manifold was modified to work under HCCI conditions. A plenum was set upstream of the intake valves of the engine and all the gases were injected in this plenum to allow a long mixing time and therefore a homogeneous mixture. Homogeneity of the mixing was validated in a previous work [6]. Gases were supplied using Brooks mass flow controllers, with an accuracy of ± 0.7% of the full scale, and liquids were supplied using Bronkhorst mass flow controllers, with an accuracy of ± 1 % of the full scale. Table 2 lists the mass flow controllers associated with the mixture component and the range. For the experiments, dry air was supplied by a compressor and pure nitrogen was supplied from the dry air with a filter. Hydrogen and pure oxygen were supplied from gas cylinders. Isooctane was stored in a pressurized tank.

Gas/Liquid	Type	range
Air	Brooks	500 (nL/min)
N_2	Brooks	200 (nL/min)
H_2	Brooks	30 (nL/min)
O_2	Brooks	5 (nL/min)
C_8H_{18}	Bronkhorst	2 (kg/h)

Table 2: Characteristics of the mass flow controllers.

Intake pressure was measured by a Kistler 4075A piezo-resistive absolute pressure sensor, with an accuracy of ± 0.3% of the full scale, and was controlled by the mass flow controllers with respect to the equivalence ratio required and the fraction of each component. The fuels used in this work are hydrogen (H_2) and isooctane (C_8H_{18}). Hydrogen was injected directly into the intake plenum after being heated. Isooctane was injected into the plenum after an initial dilution with air and a preheating allowing its evaporation.

Intake temperature was measured with two K-type thermocouples, one in each intake port, with an accuracy of ± 2K, and was controlled by a main heater warming up the main air flow and a band heater set around the plenum. In-cylinder pressure was measured by a Kistler 6043A piezo-electric sensor, with an accuracy of ± 2%. For all the experiments, intake and in-cylinder pressures were recorded with a resolution of 0.1 CAD using a Külber 8.5020.D842.3600 encoder set on the crankshaft and data were analyzed over 100 consecutive cycles.

The engine intake was seeded with ozone using an Anseros COM-AD-01 corona-discharge ozone generator operating with pure oxygen. A nitrogen flow was added to maintain an oxygen/nitrogen ratio similar to that of air. Lastly, ozone concentration was measured by an ozone analyzer (Anseros Ozomat MP6060) by collecting a sample from one of the intake ports.

3. Kinetics support

In addition to experimental results, kinetic analyses were conducted. Simulations were performed using the CHEMKIN PRO package [28]. An isooctane detailed kinetic mechanism developed by Curran et al. [29] and an ozone sub-mechanism [30,31] were selected. This mechanism has already been used and validated by Masurier et al. [27].

4. Results and discussion

In the present study, all the experiments with hydrogen and isooctane were performed at a rotation speed and an equivalence ratio of 1500 rpm and 0.3, respectively. First, a way to compare hydrogen and isooctane, under HCCI conditions was investigated. Second, three parameters - the intake pressure, the intake temperature and the ozone concentration seeded in the intake – affecting HCCI combustion were investigated with both fuels and finally, a discussion will oppose each parameter and the impact of each parameter on hydrogen and isooctane combustion was compared.

4.1. Towards a comparison of hydrogen with isooctane

Comparing the combustion of two fuels in an HCCI engine is complex because fuels do not autoignite under the same conditions. Hydrogen and isooctane are no exceptions. To conduct a suitable comparison, it is essential to find a unique experimental condition in which the intake pressure, intake temperature, rotation speed, equivalence ratio and therefore amount of energy injected will be the same. This first section therefore focuses on finding common intake conditions to enable a comparison between hydrogen and isooctane in terms of intake pressure, intake temperature and ozone concentration seeded in the intake.

The combustion of hydrogen and isooctane was investigated experimentally to find the couples of intake pressure and intake temperature leading to a suitable combustion behavior. In the present work, a suitable combustion behavior is reflected by the CA50, i.e. the crank angle degree at which 50 % of the total energy is released, when CA50 is in the range 1 to 6 crank angles (CAD). These limits correspond respectively to the maximum acceptable noise level and to misfires. Combustion regions for both hydrogen and isooctane with respect to intake pressure and intake temperature are shown in Figure 2. The lower limit of each region corresponds to a CA50 of 6 CAD and the upper limit corresponds to a CA50 of 1 CAD.

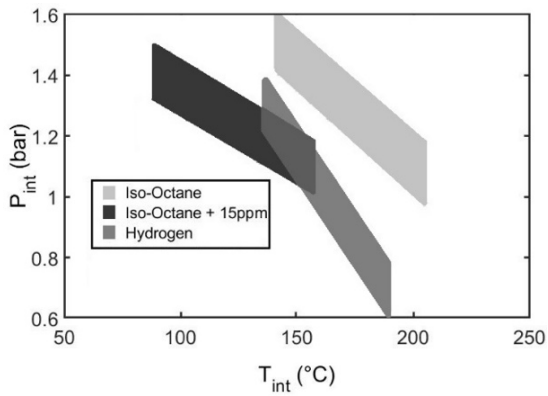

Figure 2: Fuel regions of optimal HCCI combustion as a function of the intake pressure and the intake temperature. Upper and lower limits of each region correspond to a CA50 of 1 CAD and 6 CAD, respectively.

Results show unexpectedly that hydrogen autoignites more easily than isooctane. Indeed, hydrogen has a research octane number (RON) greater than 120 and even greater than the RON of isooctane (100). In other words, hydrogen should require higher intake conditions than isooctane to autoignite but the experiments conducted show the opposite. These results suggest that RON is inappropriate for describing HCCI autoignition, especially for hydrogen fuel, and similar observations were reported by other groups with different fuels [32]. In fact, RON was initially applied to SI combustion and characterizes the autoignition of the end-gases leading to knock. This phenomenon depends on the turbulent flame propagation, the conditions in the unburnt gases (pressure, temperature and equivalence ratio) and how fast the energy of the unburnt gases is released whereas autoignition in HCCI only

depends on the conditions in the unburnt gases. The difference in the autoignition processes should make RON an unsuitable rating for HCCI. Nonetheless, the motor octane number (MON), based on a higher engine speed (900 rpm vs. 600 rpm for RON determination), was rated at 60 for hydrogen [33, 34] while isooctane, which is still the reference, is rated at 100. MON therefore indicates that under high engine speed hydrogen should autoignite more easily than isooctane. Finally, observing more carefully Figure 2, extrapolations of the respective linear trends for both hydrogen and isooctane towards high intake pressure will make the trends cross each other meaning that under very high intake pressure – low intake temperature conditions, hydrogen could autoignite more easily than isooctane, thus making RON a viable criterion. Further investigations are required to confirm this statement and an experimental setup allowing very high intake pressure should be used. Moreover, finding a similar initial point to perform our comparison cannot be achieved with the present experimental setup except by using ozone. Ozone showed in previous studies its ability to shift the combustion region of isooctane (as in Figure 2) towards a lower intake temperature without impacting too much the combustion sensitivity to both intake pressure and intake temperature [35].

To find a suitable similar point at 1 bar intake pressure to perform our comparison, ozone concentration required to get a combustion phasing (CA50) near 6 CAD, the misfire limit for HCCI combustion, with respect to the intake temperature was studied. Considering these conditions, hydrogen required an intake temperature of 150 °C meaning that the intake temperature for isooctane should be 60 °C lower to obtain a similar point. 15 ppm of ozone were found suitable to complete the requirements. New sweeps in intake pressure and temperature were therefore conducted to ensure that the sensitivities of isooctane combustion did not change. The new combustion region obtained is shown in Figure 2 where the shift can be clearly observed. The sensitivities to both intake parameters are further discussed below.

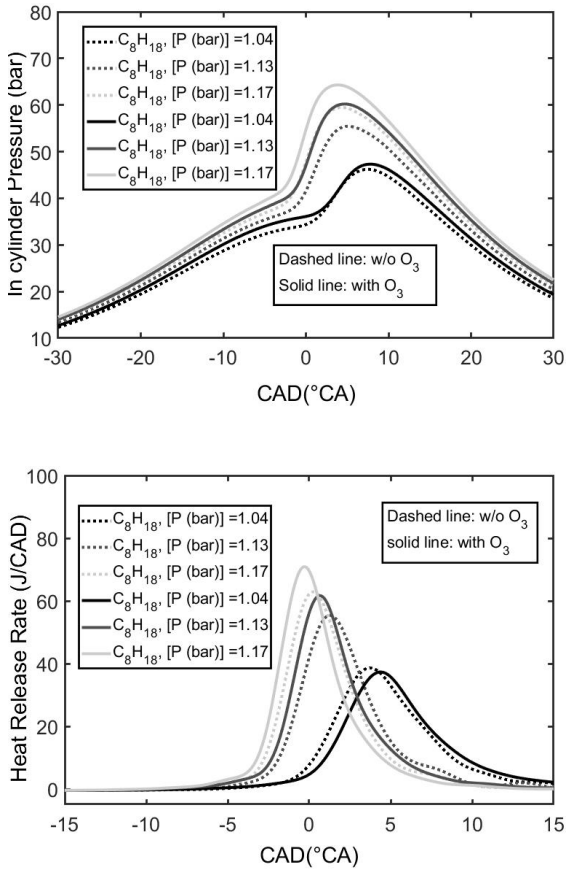

Figure 3: In-cylinder pressure (top) and heat release rate (bottom) as a function of the intake pressure for isooctane as a fuel with and without ozone.

With the similar point for our comparison between hydrogen and isooctane found at 1 bar and 150 °C, the sensitivity of isooctane to a change in both the intake pressure and the intake temperature was studied and compared to the sensitivity to the same parameters at 1 bar and 210 °C, i.e. a comparison of the cases with and without ozone seeding. The sensitivity is here expressed by observing the pressure traces, the heat release traces, as well as CA05 and CA50, representing respectively the onset of the combustion and the combustion phasing.

Figure 3 shows in-cylinder pressure and heat release rate traces for both isooctane at 210°C without ozone and isooctane at 150 °C with

ozone. A small increase in intake pressure, about 130 mbar, increases the in-cylinder pressure peak by 13 bar for isooctane at 210 °C and by 17 bar for isooctane with ozone addition at 150 °C. Meanwhile, the crank angle associated to the maximum in-cylinder pressure peak moves forward by 3 CAD for pure isooctane and by 4 CAD for isooctane with ozone. A rise in intake pressure therefore enhances the combustion of isooctane in both cases. Heat release rate traces show that the combustion enhancement is even more noticeable as the peak of heat release rate is twice higher and moves towards the top dead center while the combustion duration decreases. In both conditions, results in Figure 3 highlight a similar combustion enhancement with a slight advantage at 150 °C as the amount of energy injected in the engine is slightly higher. A similar enhancement is better observed with CA05 and CA50 in Figure 4.

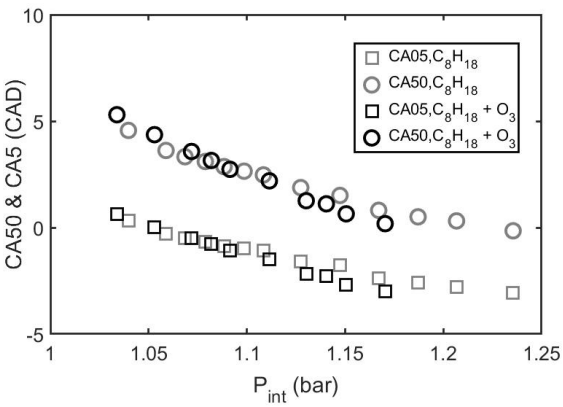

Figure 4: CA05 and CA50 as a function of the intake pressure for isooctane as fuel with and without ozone.

Figure 4 shows that both CA05 and CA50 linearly decrease with respect to the increase in intake pressure. The small difference shows that the case at 150 °C is perhaps slightly more sensitive to the intake pressure. However, these results are based on 100 consecutive cycles which generate a standard deviation of 0.25 CAD. The sensitivity of these parameters to the intake pressure can be considered as similar.

Similarly to the intake pressure, sensitivity to an increase in intake temperature was investigated. Figure 5 shows the in-cylinder pressure and heat release rate traces at 1 bar with respect to intake temperature. Traces show a similar dependence on the temperature, i.e. a combustion enhancement. Again, cases with ozone lead to higher pressure and heat release peaks than cases without ozone because of the energy injected into the combustion chamber. CA05 and CA50 are also plotted with respect to the rise in temperature, i.e. the difference with the initial temperature for each case, 150 °C with ozone and 210 °C without ozone (Figure 6). All the results evolve linearly and while a slight gap can be observed at a low temperature difference, it can be concluded from the standard deviation on CA05 and CA50 that there is a similar dependence on intake temperature.

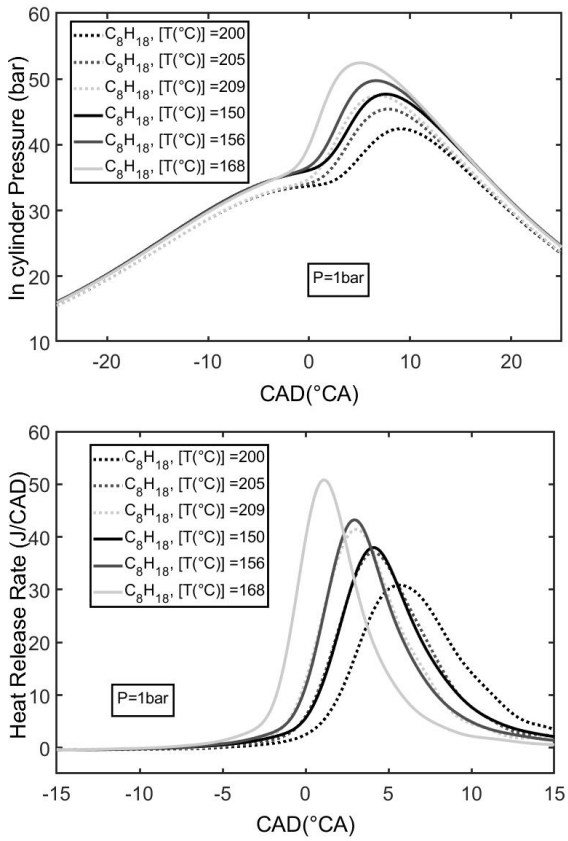

Figure 5: In-cylinder pressure (top) and heat release rate (bottom) as a function of the intake temperature for isooctane as a fuel with and without ozone.

To sum up, this preliminary study shows that the dependence of isooctane combustion on intake pressure and intake temperature is preserved for the two points investigated, i.e. at 1 bar and 210 °C and at 1 bar and 150 °C with ozone. As a result, a comparison between hydrogen and isooctane according to a change of intake pressure, intake temperature and ozone seeding in the intake can now be conducted.

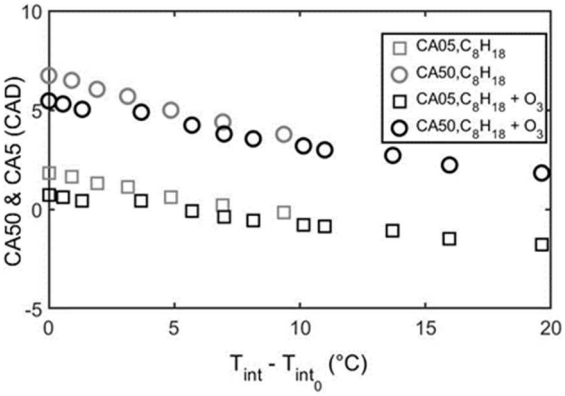

Figure 6: CA05 and CA50 as a function of the temperature difference with reference to the initial temperature for a CA50 phased at 6 CAD.

4.2. Comparison between hydrogen and isooctane

The previous section examined the sensitivities of isooctane at two different experimental points in order to enable an accurate comparison between hydrogen and isooctane. The intake pressure and the intake temperature set respectively at 1 bar and 150 °C were found suitable to compare hydrogen combustion to isooctane combustion when the intake pressure, intake temperature and ozone seeded in the intake vary. Under this intake pressure and temperature, the FuelMEP for isooctane and hydrogen are 9.14 bar and 9.28 bar respectively. The following sections discuss separately the impact of intake pressure, intake temperature, and ozone on both hydrogen and isooctane and a final discussion compares these parameters.

4.2.1. Intake pressure effect

The increase in intake pressure on the combustion of pure hydrogen and isooctane with a small amount of ozone at 1 bar and 150 °C was investigated first. Figure 7 shows in-cylinder pressure and heat release rate traces under different intake pressures. As for isooctane, increasing the intake pressure enhances the combustion of hydrogen.

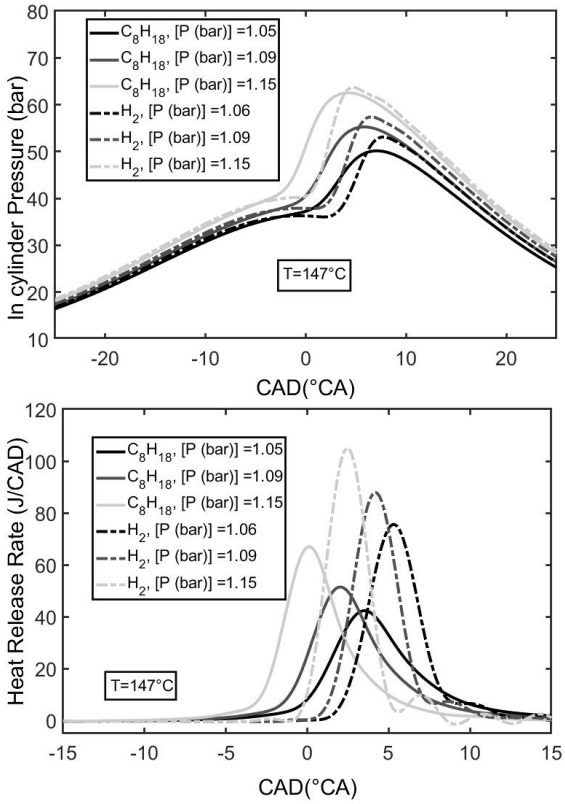

Figure 7 : In-cylinder pressure (top) and heat release rate (bottom) as a function of the intake pressure for isooctane and hydrogen.

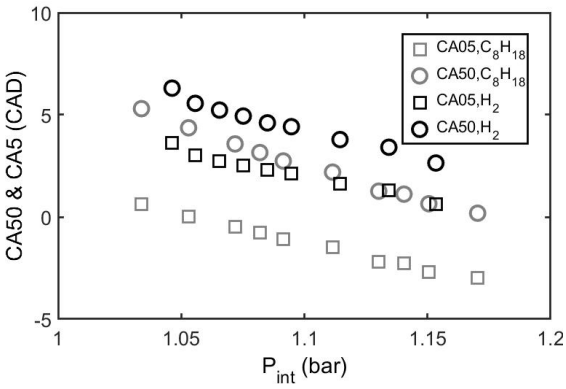

Figure 8 : Comparison of the CA05 and the CA50 for hydrogen and isooctane as a function of the intake pressure.

In-cylinder pressure traces show that hydrogen always ignites later than isooctane regardless of the intake pressure.

Nevertheless, hydrogen burns faster and more strongly as per the rapid increase in the in-cylinder pressure and the high pressure peaks. Heat release rate traces showed even better that the reactivity of hydrogen is higher than that of isooctane due to the high heat release peak and the shorter combustion duration.To better observe intake pressure dependance, CA05 and CA50 were analyzed. Figure 8 shows that both the onset of the combustion and the combustion phasing depend linearly on the intake pressure for both fuels. Moreover, the sensitivities of both CA05 and CA50 are similar regardless of the fuel. However, the noticeable difference between hydrogen and isooctane in Figure 8 is the gap between CA05 and CA50 which is fixed over the intake pressure sweep but smaller in the case of hydrogen indicating its rapid combustion. The last parameter examined to compare the dependence of hydrogen and isooctane on the intake pressure was the ringing intensity. Ringing intensity (RI) is defined by Equation 1 and used here as an indicator of the level of noise [36].

$$RI \approx \frac{1}{2\gamma} \cdot \frac{\left(\beta \cdot \left(\frac{dP}{dT}\right)_{max}\right)^2}{P_{max}} \cdot \sqrt{\gamma . R . T_{max}} \qquad (1)$$

In Equation 1, γ is the ratio of specific heats, P_{max} is the maximum in-cylinder pressure, $(dP/dt)_{max}$ represents the maximum pressure rise rate, β is the tuning parameter which correlates the pressure and the maximum pressure rise rate, R denotes the ideal gas constant, and T_{max} is the maximum in-cylinder temperature. Ringing intensities with respect to the intake pressure for both hydrogen and isooctane are plotted in Figure 9. Noise linearly increases with respect to the intake pressure but hydrogen rapidly reaches high ringing intensity values as soon as combustion occurs due to a higher reactivity than isooctane. Moreover, the maximum ringing intensity for the engine, fixed here at 20 MW/m^2, is rapidly reached with a small increase of intake pressure (roughly 100 mbar) while isooctane shows a smoother linear increase.

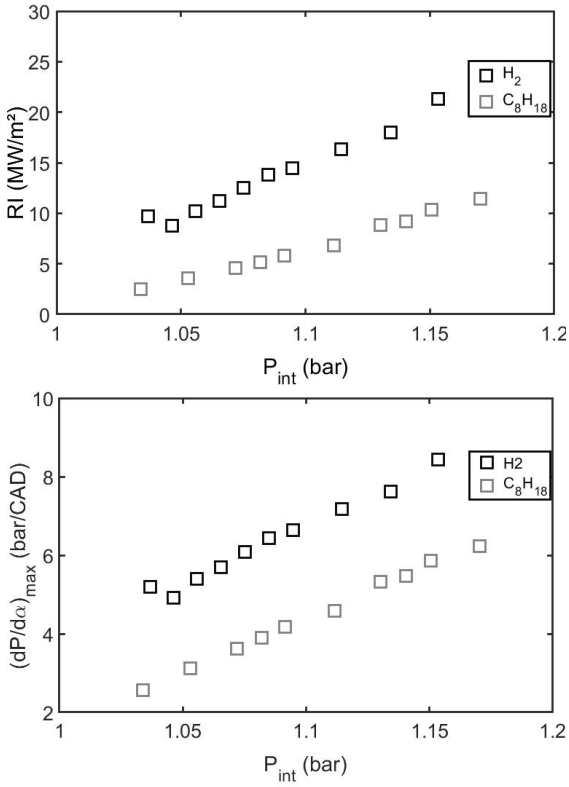

Figure 1 : Comparison of the ringing intensity (top) and maximum pressure rise rate (bottom) of hydrogen and isooctane as a function of the intake pressure.

4.2.2.Intake temperature effect

The effect of Intake temperature was also investigated starting from the same initial point, i.e. 1 bar and 150 °C for pure hydrogen and for isooctane with a small amount of ozone. Figure 10 shows in-cylinder pressure traces and the corresponding heat release rate traces for different intake temperatures. Intake

temperature promotes both combustion of hydrogen and isooctane and yet, hydrogen burns more intensively than isooctane. At the initial temperature of 150 °C, hydrogen ignites later than isooctane progressively catches up with isooctane ignition when the intake temperature increases. Even if the last temperature tested shows an ignition around the same crank angle, hydrogen ignition will likely overtake isooctane by raising the intake temperature.

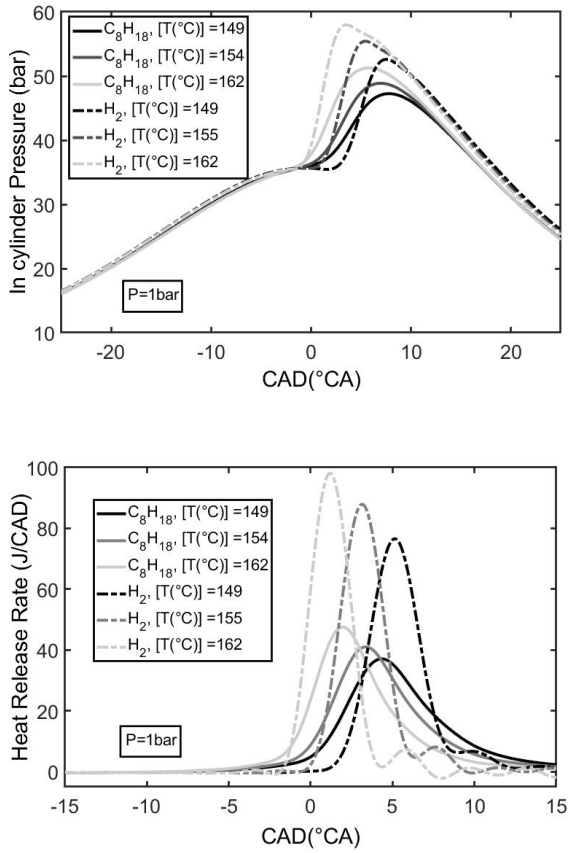

Figure 10: In-cylinder pressure and heat release rate as a function of the CAD and intake temperature for isooctane and hydrogen.

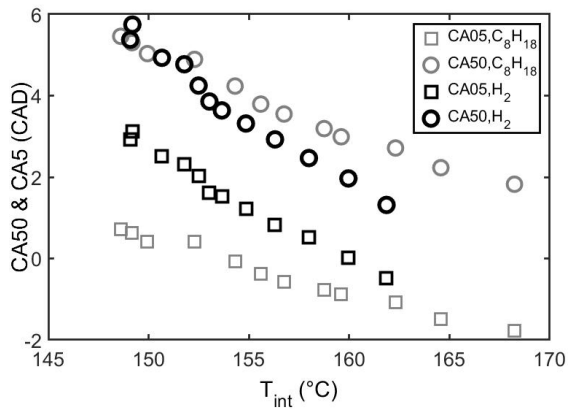

Figure 11: Comparison of the CA05 and the CA50 for hydrogen and isooctane as a function of the intake temperature

CA05 and CA50 trends show that hydrogen might ignite earlier than isooctane (Figure 11). Both parameters evolve linearly and in parallel with respect to the two fuels used. However, hydrogen combustion exhibits a higher sensitivity mainly due to its higher reactivity and the fact that a change in temperature highly impacts the chemical reactivity of fuels.

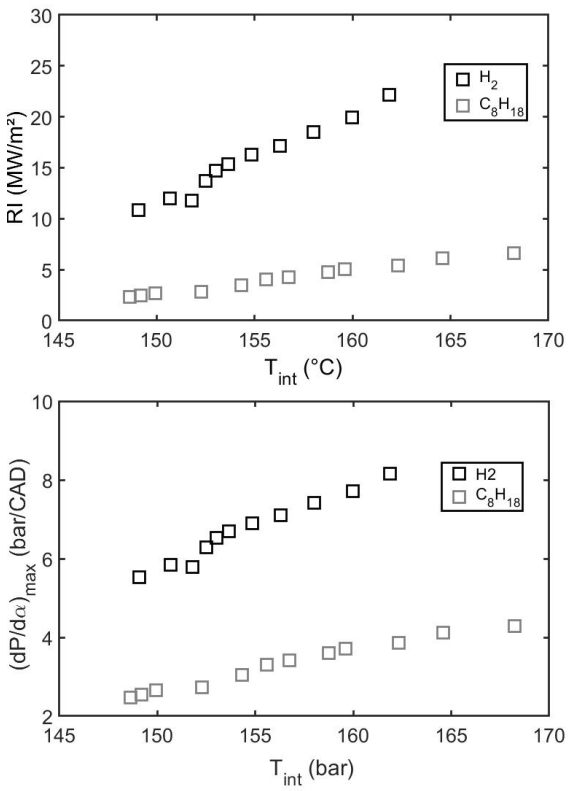

Figure 12: Comparison of the ringing intensity (top) and maximum pressure rise rate (bottom) of hydrogen and isooctane as a function of the intake temperature.

Figure 12 presents the ringing intensity for the two fuels with respect to intake temperature. As intake temperature promotes combustion of hydrogen and isooctane, a linear increase in the ringing intensity was expected. Again, the ringing intensity of hydrogen fuel is much higher than that of isooctane and the threshold of 20 MW/m^2 is rapidly reached for hydrogen without a high increase in the intake temperature. Isooctane shows an even smoother trend with intake temperature compared to intake pressure for the same variation of ringing intensity with hydrogen.

4.2.3.Ozone Effect

Lastly, the impact of ozone seeding in the intake port was investigated for both hydrogen and isooctane. In-cylinder pressure traces and heat release rate traces are presented in Figure 13 with respect to ozone seeding. It is worth noting that for isooctane experiments were performed with 15 ppm more ozone than in hydrogen experiments to

allow the same initial CA50 for both fuels at 1 bar and 150 °C. The impact of these additional 15 ppm will be discussed later in this section but as a result, the comparison of the results with ozone is discussed based on a difference in ozone concentration. In other words, the results in Figure 13 correspond to the same ozone addition with respect to the initial concentration. Initially, hydrogen ignites later than isooctane but the combustion of both fuels is rapidly promoted as soon as a small concentration of ozone seeds the intake. However, hydrogen appears to be more promoted than isooctane regarding the shift in both in-cylinder pressure and heat release rate peaks and the shift in the onset of combustion.

A better observation can be made from CA05 and CA50 with respect to the ozone concentration in Figure 14. Unlike intake pressure and intake temperature which show a linear dependency on CA05 and CA50, the first few ppm of ozone have a strong impact but then, although ozone continuously improves combustion, the impact becomes weaker. An increase of 10 ppm ozone advances hydrogen combustion phasing by 6 CAD while 10 ppm of ozone, added to the 15 required to operate at 150 °C with isooctane, advances isooctane combustion phasing by 4.5 CAD. Ozone therefore shows more impact on hydrogen combustion than on isooctane combustion for the same increase in the ozone proportion.

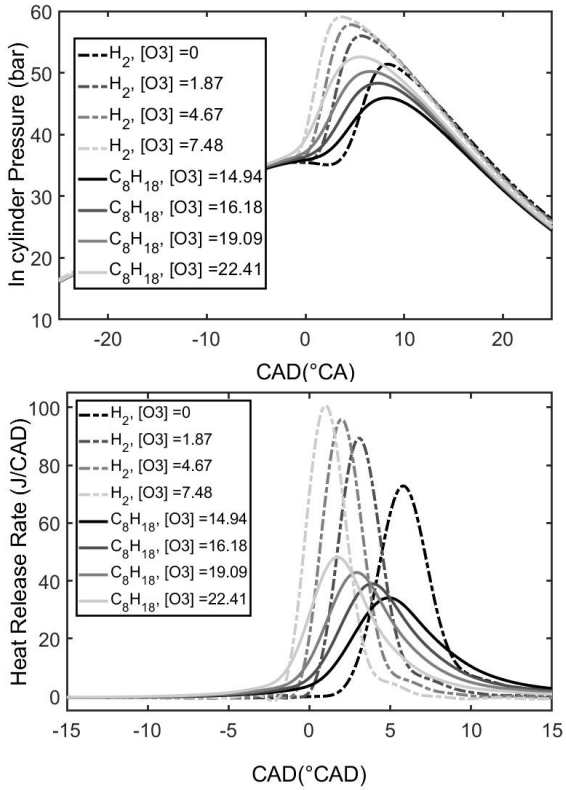

Figure 13: Comparison of In-cylinder pressure and heat release rate as a function of CAD and ozone concentration for isooctane and hydrogen.

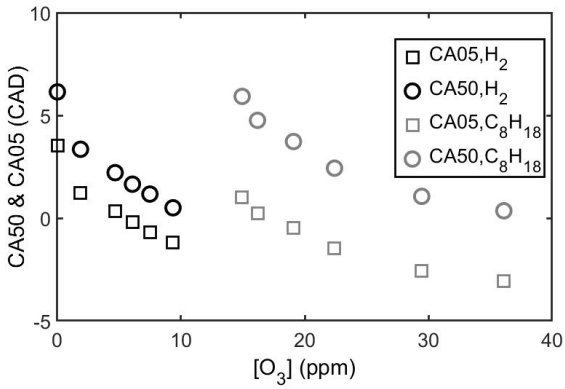

Figure 14 : Comparison of the CA05 and the CA50 of hydrogen and isooctane as a function of ozone concentration.

However, as previously stated, an initial ozone concentration is required to burn isooctane at the same pressure and temperature conditions as hydrogen. Previous studies conducted by Masurier et al. [9, 12, 15, 27] showed that a small addition of ozone has a stronger impact on the combustion phasing than a high addition of ozone. As the ozone concentration with isooctane is 15 ppm more than with hydrogen, the higher impact on

hydrogen observed in Figure 14 is questionable. In their study, Masurier et al. [9]. highlighted that 9 ppm of ozone advanced the combustion phasing of isooctane by 9 CAD by running the engine with an intake temperature set at 200 °C. Comparing those results with the present hydrogen results, ozone should have more impact on isooctane combustion because the present isooctane results use higher ozone concentrations than in the study by Masurier et al. However, intake temperature is a key parameter in this comparison. Temperature has a strong influence on ozone reactivity [37, 38] which in turn promotes combustion, meaning that the same concentration of ozone under two engine intake temperatures, such as 150 °C and 200 °C, will lead to a stronger impact with the higher of the two temperatures. Finally, it is likely that 15 ppm of ozone compensates for the lower intake temperature for isooctane ignition, and that additional ozone concentrations only enhance isooctane combustion. As a result, hydrogen combustion is much more promoted by ozone than isooctane.

Furthermore, to confirm that ozone promotes hydrogen combustion more than isooctane combustion, a set of simulations were performed at constant volume for several ozone concentratons to observe ignition delay. Initial conditions were chosen with respect to the experimental conditions, i.e. the equivalence ratio was set at 0.3 for both fuels and intial pressure and temperature were derived from the experimental traces (35 bar and 1000 K corresponding to the ignition). Computed Ignition delays are presented in Figure 15 as a function of initial ozone concentration with respect to the fuel.

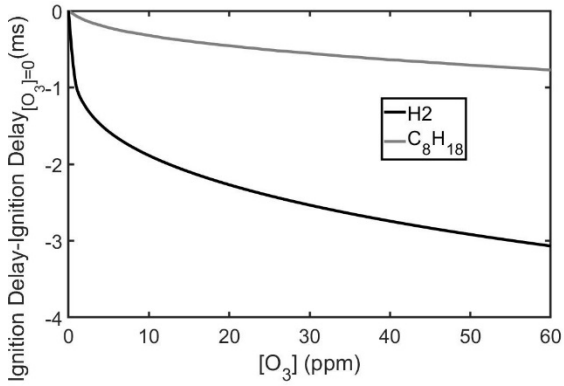

Figure 15 : Computed ignition delay in reference to the initial ignition delay without ozone and as a function of ozone concentrations.

Figure 15 shows distinctly that hydrogen is more sensitive to ozone addition than isooctane. A few ppm of ozone (~ 10 ppm) significantly advance the ignition delay of hydrogen compared to that of isooctane. High concentrations of ozone show less impact on ignition delays but hydrogen is still more impacted than isooctane.

Finally, the impact of ozone on ringing intensity was also observed. Results are

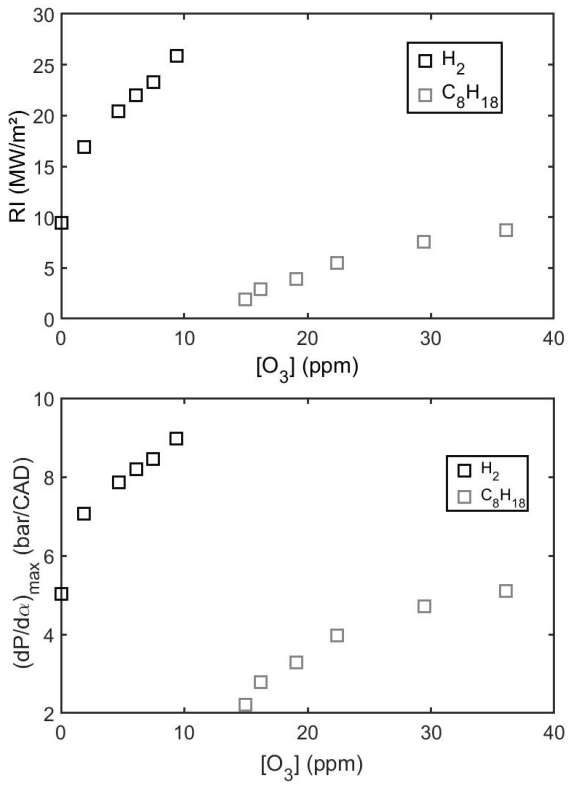

Figure 16 : Comparison of the ringing intensity (on the top) and maximum pressure rise rate (on the bottom) of hydrogen and isooctane as a function of ozone concentration.

shown in Figure 16. Similarly to the intake pressure and the intake temperature, noise is more intense and more sensitive for hydrogen when using ozone. Moreover, it is worth noting that a small ozone concentration is enough to rapidly reach the threshold of 20 MW/m^2. Nonetheless, it is highly due to hydrogen itself which ignites rapidly when seeded with ozone.

4.3. Discussion

Pressure and temperature impact the oxidation of the two fuels in a similar way. Increasing one of them promotes autoignition as per the Arrhenius equation. Ozone has the potential to change the chemical pathway via new reactions and strongly promotes combustion. As a result, in the new approach proposed here, ozone is a key parameter. Moreover, results with isooctane showed that ozone can shift the combustion region towards lower intake temperatures. Using this benefit with hydrogen could lead to lower in-cylinder temperatures, and a clean combustion cycle might be reached, i.e. reducing potential NOx emissions. In terms of control, temperature can easily be increased but with some hysteresis using heaters. However, if decreasing this parameter is required, no control could be easily made. Nonetheless, some concepts have been developed in order to rapidly handle this parameter [39]. Pressure can be handled via turbochargers/superchargers but with some lag. Perhaps the ringing intensiy limits will be reached even faster than with the other parameters. Finally, ozone can be injected directly in the intake port when needed and could give good combustion control [40]. To conclude, it is easier to control the combustion of hydrogen than that of iso-octane with ozone under HCCI conditions.

5. Conclusion

The present study assessed the combustion of hydrogen in an HCCI engine and compared it to the combustion of isooctane, a reference fuel. Three parameters -- the intake pressure, the intake temperature and the concentration of ozone seeded into the intake port -- were investigated and compared in order to control HCCI combustion of both fuels. Analyses were performed mainly based on CA05, CA50, and ringing intensity. Results showed that hydrogen autoignition required lower intake pressures and intake temperatures than isooctane despite its higher octane number. In order to perform a viable comparison between the two fuels while varying the three parameters, he combustion region of isooctane seeded with ozone was shifted, without altering the dependency on the intake thermodynamic conditions. Comparison while varying the three parameters was therefore conducted at 1 bar and 150 °C. All the parameters were identified as combustion improvers for both hydrogen and isooctane but with a noticeable effect of ozone seeding. Compared with isooctane combustion,

hydrogen was found to be more sensitive to increases in intake temperatures and ozone concentrations while it was slightly less impacted than isooctane by changes in intake pressure. In terms of noise, hydrogen was always the most impacted due to its high reactivity. Finally, in the new approach proposed here, ozone is a key parameter to control combustion.

Furthermore, with hydrogen fuel, a clean combustion cycle might be achieved.

Acknowledgments

The work performed at the University of Orléans was supported by the CICCO project from the French National Research Agency, ANR-15-CE22-0004.

The research reported in this publication was also supported by funding from King Abdullah University of Science and Technology (KAUST).

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Abbreviations

CAD Crank Angle Degree

CO Carbon Monoxide

CR Compression Ratio

EGR Exhaust Gas Recirculation

HC Unburned hydrocarbons

HCCI Homogeneous Charge Compression Ignition

IMEP Indicated Mean Effective Pressure

NOx Nitrogen Oxides

ON Octane Number

PRF Primary Reference Fuels

RI Ringing Intensity

RON Research Octane Number

MON Motor Octane Number

Contact

Jean-Baptiste Masurier
jeanbaptiste.masurier@kaust.edu.sa
King Abdullah University of Science and Technology (KAUST), Clean Combustion Research Center (CCRC)
Thuwal, 23955-6900
Saudi Arabia

Fabrice Foucher
fabrice.foucher@univ-orleans.fr
Laboratoire PRISME
Université d'Orléans
45072 Orléans
France