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On the influence of hydrogen on the low-temperature reactivity of *n*-pentane, 1-pentene and 3-pentanone: an experimental and modeling study

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Abstract

Hydrogen can be blended with other surrogate fuels to avoid its hazard as a highly flammable and explosive gas. The effect of hydrogen addition on the ignition delay times of *n*-pentane, 3-pentanone, and 1-pentene was investigated by measuring the ignition delay times in a rapid compression machine. The experiments were performed at pressures of 10, 15, and 20 bar, equivalence ratios 0.5 and 1 and for temperatures ranging from 650 to 970 K. The molar ratios of hydrogen in the fuel mixtures were 0, 25 and 50%. The experimental data were simulated using recent models from literature, yielding good agreement. The overall observations conclude to a minor effect of hydrogen addition in the case of *n*-pentane and 3-pentanone, resulting in a decrease of the reactivity when the mole fraction of hydrogen increases. Hydrogen does however not impact the ignition delay times of 1-pentene significantly. Kinetic analysis is performed to shed light into the processes responsible for this phenomenon.

Keywords: Rapid compression machine; Ignition delay time; Hydrogen; *n*-pentane; 1-pentene; 3-pentanone

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1. Introduction

Transportation is a major contributor to air pollution, which motivates research towards finding alternative fuels with less emissions into the atmosphere. Hydrogen is a good example of a fuel that is capable of reducing carbon dioxide, knowing that it is the most abundant greenhouse gas [1], and methane which has a far greater global warming potential than carbon dioxide [2]. This carbon-free fuel does not form any unburnt methane nor CO₂ upon combustion. However, hydrogen is characterized by its extremely wide flammability domain and flame speed [3,4], which makes it ideally used as a blend with other fuels and thereby improving their combustion properties. Real life examples of vehicles fueled by hydrogen already exist, however, more studies are required to develop a hydrogen infrastructure when it comes to engines that run on both hydrogen and conventional fuels [5]. The characterization of an engine should be designed by estimating different parameters; the autoignition of the fuel is one of the important ones. The chemical auto-ignition of a fuel depends on its oxidation kinetics which are used to develop reliable models. These kinetics models are later used to design and optimize suitable control strategies ensuring low emissions of pollutants and proper engine performance [6]. Even though blending hydrogen with the fuel won't stop the emissions entirely, however, the fact that hydrogen is replacing part of the fuel means the emissions at the end will decrease as such.

We present in this paper a work on the autoignition of hydrogen blends with surrogate fuels to gasoline and diesel, to investigate how hydrogen is affecting the behavior of the fuel, and what is going to be the result. Extensive studies have been made on the combustion kinetics of hydrogen in the high-temperature domain, demonstrating that the addition of hydrogen to a fuel leads to an increase in the laminar burning velocity and of the reactivity towards ignition.

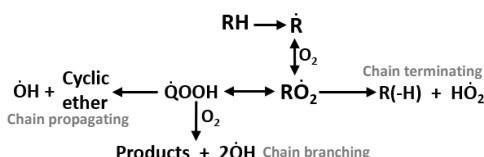


Fig. 1- Simplified mechanism for low-temperature oxidation of a hydrocarbon radical R.

However, this is not the case in the low temperature regime, where the main reaction pathways originate from the addition of the primary fuel radicals to oxygen. This reactivity is dictated by the balance between the three different probable pathways; chain propagating, branching or terminating [7] as described in Fig. 1. This regime is described as the low-temperature combustion (LTC) where $T < 1000$ K.

What makes the study of this regime crucial is its influence on important phenomena such as knock in spark ignition engines, or ignition in compression ignition engines, in addition to recent promising combustion technologies for the reduction of NO_x and soot formation at low temperatures [8].

S. Lee and S. Song studied the effect of hydrogen on the ignition delay times of *n*-butane at low-to-intermediate temperatures, the results have shown an increase in the ignition delay times upon the addition of hydrogen [9]. They also studied the effect of hydrogen on the ignition delay times of methyl butanoate in a rapid compression machine and discovered that the ignition delay increased at low temperatures but decreased at high temperatures [10]. Comandini *et al.* discussed the combustion properties of *n*-heptane/hydrogen mixtures in the low temperature regime where longer ignition delay times were obtained with higher proportions of hydrogen [11].

In this work the ignition delay times of different proportions of hydrogen/fuel with three different fuels; *n*-pentane, 3-pentanone, and 1-pentene, at different equivalence ratios ($\Phi = 1$ and $\Phi = 0.5$), pressures ($p = 1, 1.5$ and 2 MPa), and temperatures (ranging between 650 K and 970 K) have been measured in the U-Lille rapid compression machine. C₅ chain molecules are chosen to be studied for several important reasons:

- In the RCM facility, the studied fuel/air mixtures must be gaseous. As a consequence, the selected fuels should have a vapor pressure sufficient to prepare samples and avoid any condensation. The boiling temperature increases with the carbon chain length and varies with the chemical function.
- The range of temperature of this study is between 650 and 970 K. Thus, the selected fuels should be reactive enough in the low-temperature range of the combustion. Overall, the longer the carbon-chain is, the more reactive the species are.

Considering these requirements, the choice of C₅ straight-chain hydrocarbons is an optimal balance which allow a direct comparison between fuels at fixed experimental conditions.

2. Experiments

In this study, ignition delay times (IDTs) have been measured using the U-Lille RCM which has been described elsewhere [12–14]. Mixtures were prepared either in a room temperature vessel when the fuels were volatile enough at room temperature, like *n*-

pentane and 1-pentene, or in a heated vessel for 3-pentanone where the temperature was chosen to be 65°C, therefore sufficient to ensure a total volatilization of the fuel. The lines leading from the vessels to the RCM were heated to 70 °C to ensure the absence of condensation. The mixtures were composed of the surrogate fuel, hydrogen (when needed), oxygen (for reactive mixtures), and inert gases. The geometry of the combustion chamber at top dead center was kept constant, the compression ratio set to 9.65, and the initial temperature to 70 °C. In order to vary the compression temperature different compositions of the inert gases (CO₂-N₂-Ar) were used, resulting in the temperature range 650 K–970 K. Because of the difference in reactivity of the three hereby investigated fuels, this can result in limited sets of conditions where a direct comparison of IDTs is achievable. The compressed gas temperature (T_c) is calculated under the assumption of an isentropic compression as described in [15,16] and validated experimentally by Das *et al.* [17].

A Kistler type 601CA pressure transducer was used to determine the end of compression pressure and the ignition, then ignition delay times are determined from the experimental pressure profiles, and defined as the time difference between the top dead center (TDC) and the total ignition as shown in Fig. 2. In the case where two stage ignition takes place the first stage ignition delay (FSIDT) is defined as the time interval from the end of compression to the first maximum pressure rise rate during ignition. The second stage ignition delay is defined as the time interval from the first to the second maximum pressure rise rate during ignition.

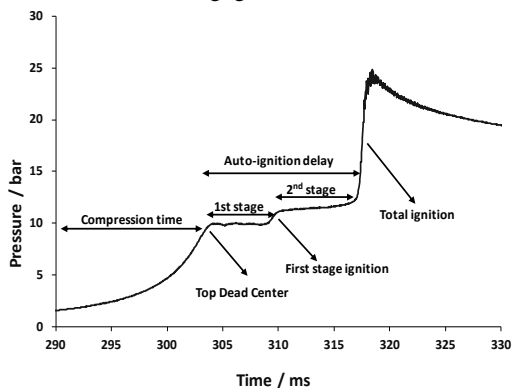


Fig. 2- Representative pressure history during a two-stage ignition delay experiment with a mixture of *n*-pentane/O₂/N₂, $\Phi = 0.5$, $T_c = 734$ K, $p = 1$ MPa.

The compression time is c.a. 45 ms and a creviced piston was used to prevent piston corner vortex. Unreactive mixtures were prepared in order to perform experiments that allow variable volume modeling of the compression phase and heat losses. To do so, oxygen was replaced by nitrogen in order to prevent oxidation and therefore any heat release while

approximately preserving the mixture's heat capacity. The non-reactive pressure histories are provided in the supplementary material. Each experiment has been replicated at least two times in order to check the reproducibility.

The ignition delay times reported are between 2 and 200 ms, in accordance with the typical validity range of the adiabatic core approximation [18]. However, the ignition delay times for 3-pentanone at the lowest investigated pressures are superior in cases to the commonly accepted limit for RCM IDT reporting of 200 ms. They are reported here for comparison purposes, but kinetic modeling of these very long ignition delay times should not be expected to reach full agreement. The typical experimental scattering of the IDT reported is ± 20 %.

3. Kinetic modeling

The RCM simulations were performed using the Cantera solver [19] at variable volume conditions using the core gas volume compression-expansion method. In this case, the RCM is considered as a variable volume isentropic reactor, to account for the compression phase and heat losses after top dead center. However, sensitivity and reaction pathway analyses are done using constant volume simulations since the same outcome is expected while reducing the necessary CPU time. In the simulations, the total ignition time was defined using the maximum of the pressure derivative with time, and the first-stage ignition time was defined as the maximum of a selected aldehydoperoxide species (C3KET21 namely 2-hydroperoxypropanal) common to the three models.

The models used in our study are:

- Bugler *et al.* model (2015) for pentane isomers [20]
- Fenard *et al.* model (2020) for 2- and 3-pentanone (2020) [21]
- Dong *et al.* model (2021) for pentene isomers [22]

These models share similar H₂ sub-mechanisms and are chosen as they are validated for fuel/oxygen/inert IDTs in our T, P and Φ conditions.

4. Results and Discussion

The influence of the fuel structure on ignition delay times was studied at pressure 1.5 MPa and at equivalence ratio 1. The results are shown in Fig. 3 at identical top dead center conditions.

It is visible that, in the investigated temperature range, 1-pentene is less reactive than *n*-pentane in the low-temperature range. It can rapidly undergo a H-atom abstraction reaction to form an allylic resonance stabilized radical as depicted in Fig. 4.

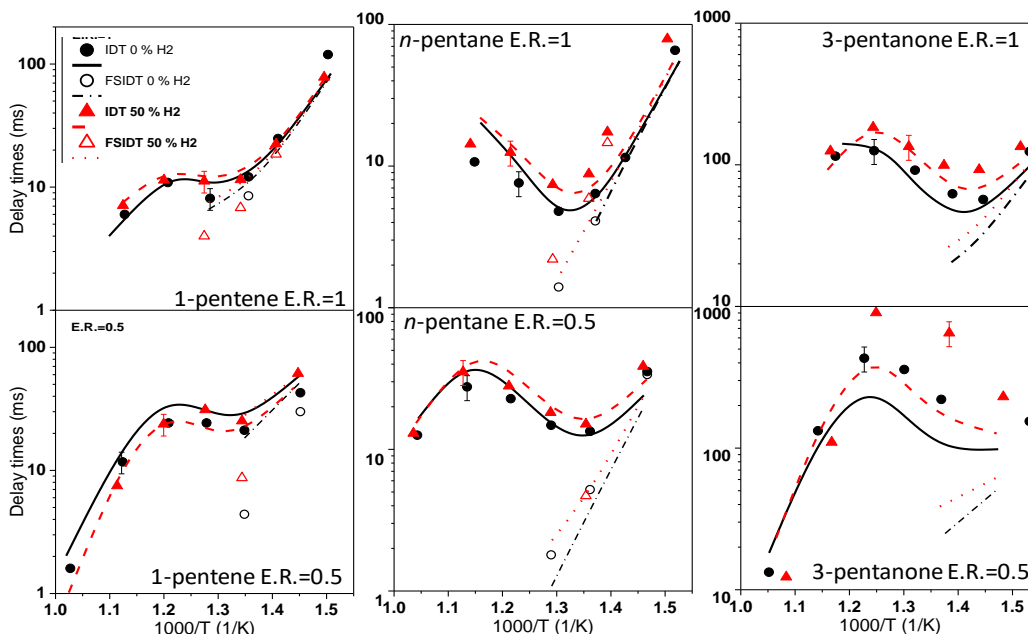


Fig. 3- Influence of the equivalence ratio and the effect of hydrogen addition on reactivity: Experimental (symbols) and simulated (lines) first stage of ignition (FSIDT) and total ignition (IDT) delay times. *n*-Pentane: $p = 1$ MPa, 1-pentene: $p = 1.5$ MPa, 3-pentanone: $p = 2$ MPa.

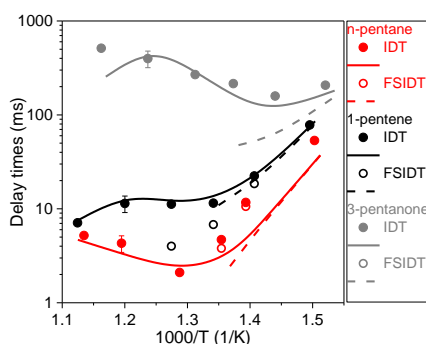


Fig. 4- Experimental (symbols) and simulated (lines) first stage of ignition (FSIDT) and total ignition (IDT) delay times of stoichiometric 50%fuel/50%H2 / 'air' at 1.5 MPa.

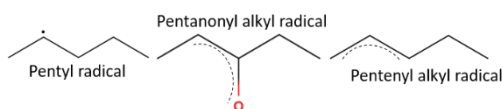


Fig. 4- Significant primary radicals for the investigated fuels

The addition of this allylic radical to molecular oxygen is unfavored, as it is thermodynamically hindered as the variation of enthalpy of reaction is low by comparison with an alkyl radical. It leads to a decrease of the overall reactivity in comparison to *n*-pentane as the low temperature chain branching reactions are inhibited. This behavior is even more visible in the case of pentanone where two allylic radical sites are available, inhibiting further the low-temperature chain branching reaction pathways. At higher temperatures (900 K and above), and at lower temperatures (650 K and below) the IDTs of 1-pentene and *n*-pentane are comparable. On the other hand, 3-pentanone displays the longest IDTs. The

simulated FSIDT and IDT of the three fuels are in a good agreement with our experimental data.

The effect of pressure at top dead center P_{TDC} on ignition delay times was studied at both equivalence ratios $\Phi=1$ and $\Phi=0.5$ for the three fuels with and without hydrogen, and are illustrated for stoichiometric 1-pentene/'air' in Fig. 5. Complementary results are provided in the Supplementary Materials. Shorter ignition delay times were measured at higher pressures in all cases and at both equivalence ratios.

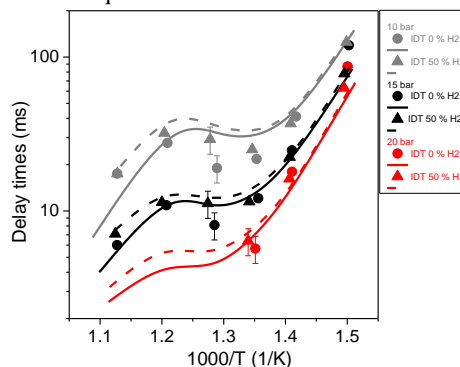


Fig. 5- Influence of the pressure and the effect of hydrogen addition on reactivity of 1-pentene: Experimental (symbols) and simulated (lines) total ignition (IDT) delay times.

The IDTs below 2 ms are not reported in figures. The agreement between the experimental and modeling results for 1-pentene is very good with a very slight over-estimation as the temperature increases. The evolution of the ignition delay times with temperature for Fuel/Hydrogen blends with different molar compositions is presented in Fig. 5. For *n*-pentane, a very good agreement is observed between the experimental results and the simulations at both equivalence ratios with and without hydrogen.

This is also true for the 1-pentene results, at both equivalence ratios and hydrogen fractions.

The model of 3-pentanone also shows good agreement with the experimental results in stoichiometric conditions with a slight under-estimation at lower temperatures, and a slight over-estimation at higher temperatures. However, in the fuel-lean case, where ignition delay times are normally higher, the discrepancy between the experimental and modeling values is higher since the ignition delay times are far beyond the limit of the adiabatic core assumption (i.e. 200 ms). One can notice that 3-pentanone's model is not validated for fuel-lean conditions. The results are however reproducible and reported here for comparison purposes.

Given their overall satisfactory agreement over the range of experimental conditions studied in this work, the selected models can be trusted for the kinetic analysis of the observed results.

The three fuels display negative temperature coefficient (NTC) behavior accompanied with a first stage ignition delay time, except for 3-pentanone for which first-stage ignition was not observed experimentally, but predicted in the simulations. Both experimental and simulation results indicate that the IDTs decrease when the equivalence ratio increases from 0.5 to 1, as already reported by Westbrook *et al.* [23] for the ignition of *n*-pentane. Most importantly, the models are able to predict the effect of hydrogen addition observed experimentally. The ignition delay times were found to increase with an increase of the hydrogen concentration, either in lean or stoichiometric cases for *n*-pentane and 3-pentanone. This is consistent with the results of Lee *et al.* [9] who studied *n*-butane/hydrogen mixtures at low to intermediate temperatures. This result is beneficial to spark ignition engines, where longer ignition delay times could span better knock resistance. The effect on the ignition delay is greatest in the NTC temperature range, which slightly shifts towards lower temperatures as the hydrogen fraction increases. However, for 1-pentene no significant effect of hydrogen was observed on the ignition delay times. Further analysis using the kinetic models was performed to help clarify the reasons for this behavior.

4.1 Reaction pathway analysis (rate of production analysis)

Flux analysis for the *n*-pentane case was carried out at $\phi = 1$, $p = 1$ MPa and $T_c = 765$ K, i.e. the temperature at which the NTC domain begins, and at 10% fuel conversion. The results are shown in Fig. 7. Any reaction pathway representing less than 5% reaction flux has been excluded. The fuel is mainly converted through hydrogen abstraction reactions by radicals, the $\dot{O}H$ radical being the major one.

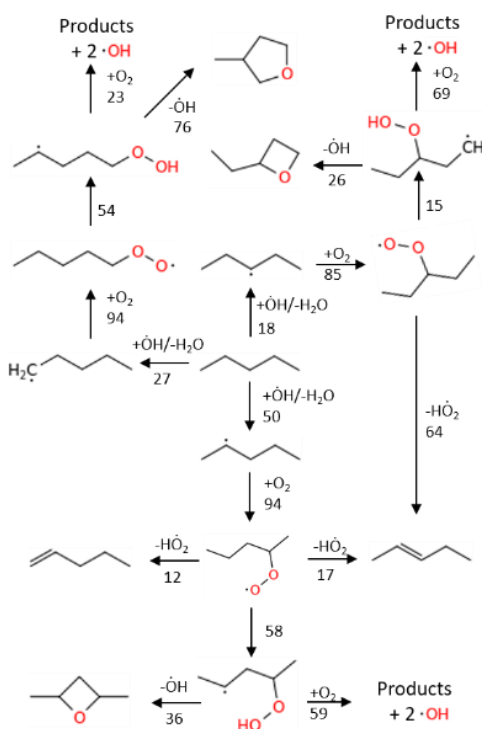


Fig. 6- Flux analysis carried out for *n*-pentane oxidation at $\phi=1$, 1 MPa, $T_c = 765$ K and 10% fuel consumption.

The main reaction pathway for the resulting fuel radicals is addition to O_2 . At this point, alkyl-peroxy radicals ($R\dot{O}_2$) are formed. These radicals either undergo isomerization to form hydroperoxyalkyl radicals ($\dot{Q}OOH$), or concerted elimination reactions forming an alkene and a hydroperoxyl radical ($H\dot{O}_2$).

This competition plays an important role in low-temperature oxidation. The produced $\dot{Q}OOH$ will lead to low temperature chain branching reactions, which increases the reactivity by forming hydroxyl radicals ($\dot{O}H$). However, concerted elimination reaction will lead finally to the production of less reactive hydroperoxyalkyl radicals ($H\dot{O}_2$). Fig. 7 shows that H-abstraction from two of three sites on *n*-pentane results mainly in the formation of a $\dot{Q}OOH$ radical (1-pentyl radical and 2-pentyl radical), with the abstraction from the third site (3-pentyl radical) leading mostly to the formation of an alkene and a hydro-peroxyl radical.

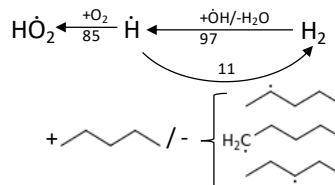


Fig. 7- Flux analysis carried out for *n*-pentane 50% / hydrogen 50% oxidation at $\phi=1$, 1 MPa, $T_c = 765$ K and 10% fuel consumption.

Fig. 8 shows that when hydrogen is added, it reacts mostly through an H-atom abstraction reaction by $\dot{\text{O}}\text{H}$ radical to give hydrogen atoms. These mostly react with oxygen to yield $\text{H}\dot{\text{O}}_2$ radicals that are far less reactive than hydroxyl radicals. This explains the increase of the ignition delay times observed when hydrogen is added to the blend.

Fig. 9 shows the main reactions of the oxidation of 3-pentanone during ignition at $p = 2$ MPa, $T_C = 700$ K, and 10% fuel consumption. The exact same scenario happens where the fuel undergoes H-abstraction by $\dot{\text{O}}\text{H}$ radicals, to give two possible radicals (pentan-3-on-1-yl and pentan-3-on-2-yl). Then these radicals add to O_2 to give alkyl-peroxy radicals ($\text{R}\dot{\text{O}}_2$). The first radical undergoes intramolecular migration of H-atom, and then forms a cyclic ether along with a hydroxyl radical. In the case of the second of these radicals, 57% of the $\text{R}\dot{\text{O}}_2$ gives a $\dot{\text{Q}}\text{OOH}$ radical, the formation of 1-penten-3-one being also significant. Further addition of the $\dot{\text{Q}}\text{OOH}$ to O_2 followed by an intramolecular H-atom migration yields a ketohydroperoxide + $\dot{\text{O}}\text{H}$. The decomposition of this ketohydroperoxide produces a second $\dot{\text{O}}\text{H}$ radical, which is responsible for the overall increase in reactivity in the low temperature region. This type of analysis was studied by Fenard *et al.* [21] and very similar results are given at 750 K, and a fuel conversion of 20%.

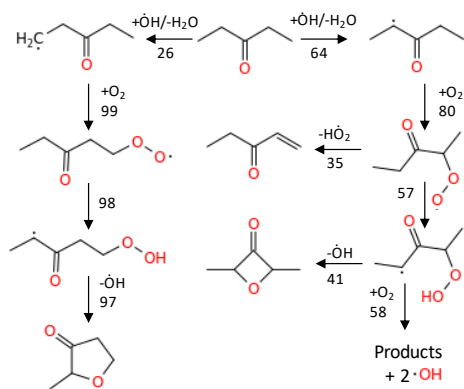


Fig. 8- Flux analysis carried out for 3-pentanone oxidation at $\phi=1$, $p = 2$ MPa, $T_C = 700$ K and 10% fuel consumption.

The flux analysis for the oxidation of 1-pentene is illustrated in Fig. 10 at $T_C = 770$ K and $p = 1$ MPa. H-atom abstractions will yield allylic and alkylic radicals. In the case of allylic radicals, the recombination reaction with $\text{H}\dot{\text{O}}_2$ radicals is favored. The addition of $\dot{\text{O}}\text{H}$ will produce pentanal and formaldehyde, hydroxy- cyclic ethers or hydroxyl-ketohydroperoxides [24]. These reactions constitute a source of $\dot{\text{O}}\text{H}$ radicals. The hydroxyl radical additions on double bond represent the main difference in the oxidation process of 1-pentene compared to *n*-pentane and 3-pentanone.

In the Fig. 10 conditions, it represents almost half of the fuel conversion. This behavior originates the unsensitivity to H_2 blending of 1-pentene on the IDTs and will be discussed later.

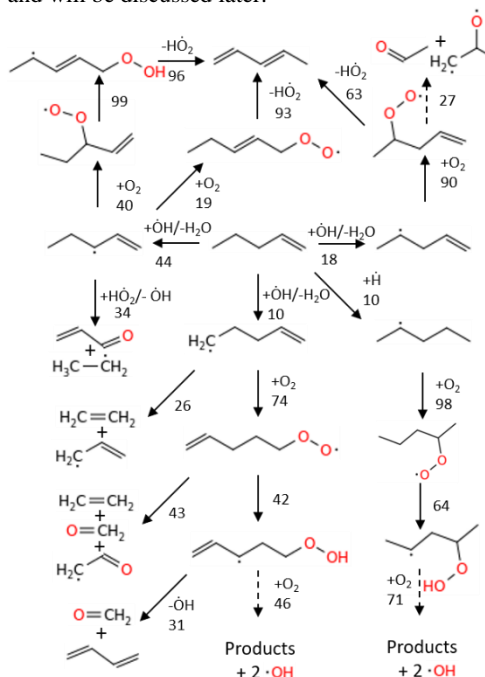


Fig. 9- Flux analysis carried out for 1-pentene oxidation at $\phi=1$, $p = 1$ MPa, $T_C = 770$ K and 10% fuel consumption.

4.2 Sensitivity analysis with and without hydrogen

A brute-force sensitivity analysis has been performed in the same conditions as the rate of production analysis and is displayed in Fig. 11. One can first note that the reactions of *n*-pentane + $\dot{\text{O}}\text{H}$ forming the pentyl radicals do not all contribute to an increase of the reactivity. The formation of the pentan-3-yl radical only marginally leads to radical chain-branching, as the elimination of $\text{H}\dot{\text{O}}_2$ from the $\text{R}\dot{\text{O}}_2$ radical is preferential to internal isomerization into the $\dot{\text{Q}}\text{OOH}$ radical in that case. 63.7% of the 3-peroxy-pentyl radical forms pent-2-ene and a hydroperoxyl radical, a reaction with a strongly positive sensitivity coefficient. The formation of 1- and 2-pentyl radicals in turn increases reactivity, as well as the relevant addition to O_2 or decomposition of 4-hydroperoxy-pentan-2-one. The influence of hydrogen in this reaction scheme can be understood with help from Fig. 8. Sensitivity analysis with hydrogen shows an inhibiting effect of reactivity via $\text{H}_2 + \dot{\text{O}}\text{H} = \dot{\text{H}} + \text{H}_2\text{O}$, a reaction whose sensitivity coefficient is negligible without hydrogen. This reaction converts $\dot{\text{O}}\text{H}$ radicals into water in large quantities, as demonstrated in Section 4.1. However,

$\dot{\text{O}}\text{H}$ is essential to the initial conversion of the fuel in the low temperature combustion temperature range.

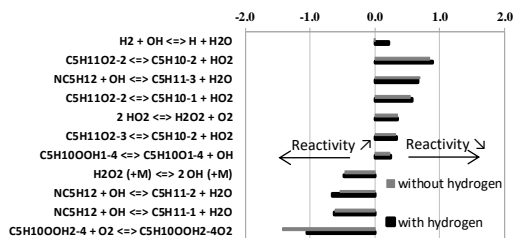


Fig. 10- Sensitivity analysis on the ignition delay time of stoichiometric *n*-pentane/ O_2/N_2 mixtures at $p = 1$ MPa and $\text{TC} = 765$ K.

The sensitivity analysis of pentanone/'air' mixtures on the IDTs without and with hydrogen is presented in Fig. 12. Globally, the reactions forming the pentan-3-on-2-yl radical and the reactions leading to the formation of the ketohydroperoxide $\text{CC}(\text{OOH})\text{C}(=\text{O})\text{C}(=\text{O})\text{C}$ promote the reactivity. The reactions of elimination of $\text{H}\dot{\text{O}}_2$ forming pentenone inhibit the reactivity. The blending of pentanone with H_2 as a very similar effect as for *n*-pentane. H_2 depletes the radical pool by undergoing H-atom abstraction, mainly by $\dot{\text{O}}\text{H}$, slowing the fuel conversion and therefore reducing the overall reactivity.

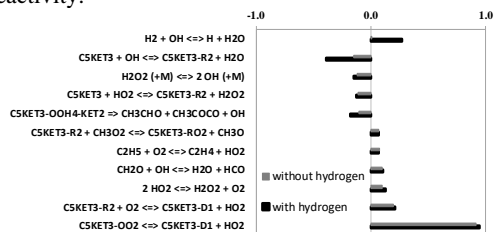


Fig. 11- Sensitivity analysis on the ignition delay time of stoichiometric 3-pentanone/ O_2/N_2 mixtures at $p = 2$ MPa and $\text{TC} = 700$ K.

To understand why hydrogen does not have a significant effect on 1-pentene, sensitivity analyses were performed with and without hydrogen in Fig. 13. In contrast with the *n*-pentane case shown in Fig. 11, the sensitivity analysis does not show a reaction specific to the hydrogen sub-mechanism, and the sensitivity coefficients for the other reactions are very similar with and without hydrogen.

The most sensitive reaction on the increase of reactivity is the formation of pent-1-en-5-yl radical by H-atom abstraction by a hydroxyl radical. As shown in Fig. 10, this radical can add onto O_2 , leading to the low-temperature chain branching reaction sequence. To the contrary, the most abundant radicals formed by H-atom abstractions are pent-1-en-3-yl and pent-1-en-4-yl, their formation showing an inhibiting effect on reactivity. Both of them mainly add onto O_2 and yield pentadiene and an hydroperoxyl radical. The reaction

of the resonance stabilized radical pent-1-en-3-yl with $\text{H}\dot{\text{O}}_2$ exhibits a large negative sensitivity coefficient, promoting reactivity. This reaction releases an $\dot{\text{O}}\text{H}$ radical able to further convert the fuel. As previously observed for unsaturated hydrocarbons, the reactivity in the low temperature range is controlled by the reactions with $\text{H}\dot{\text{O}}_2$ [25]. Under the conditions of Fig. 7, the rate of production of $\dot{\text{O}}\text{H}$ is divided by 2 when H_2 is introduced in the pentane/'air' system in comparison to the case without hydrogen. In the conditions of Fig. 10, the rate of production of $\dot{\text{O}}\text{H}$ remains constant without and with hydrogen during the oxidation of 1-pentene. The bond dissociation energy of H_2 is 104 kcal/mol, 99 kcal/mol for the weaker C-H bond in *n*-pentane and only 82 kcal/mol for the weaker bond in 1-pentene [26]. One can postulate that the H-atom abstraction reactions by $\dot{\text{O}}\text{H}$ with H_2 and *n*-pentane compete whereas the balance between $\text{H}_2 + \dot{\text{O}}\text{H}$ and 1-pentene + $\dot{\text{O}}\text{H}$ is in large favor of 1-pentene + $\dot{\text{O}}\text{H}$. It explains the fact that the sensitivity analysis on IDT with hydrogen do not point the reaction $\text{H}_2 + \dot{\text{O}}\text{H} = \dot{\text{H}} + \text{H}_2\text{O}$ as strongly inhibiting the reactivity as for *n*-pentane and 3-pentanone.

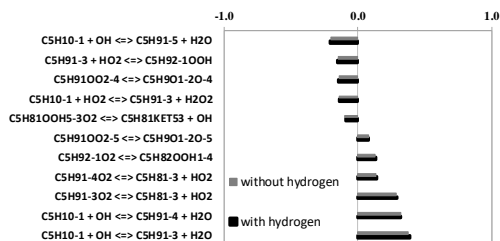


Fig. 12- Sensitivity analysis on the ignition delay time of stoichiometric 1-pentene/ O_2/N_2 mixtures at $p = 1.5$ MPa and $\text{TC} = 770$ K.

5. Conclusion

The effects of hydrogen addition on *n*-pentane, 3-pentanone, and 1-pentene were experimentally and numerically investigated, taking advantage of similar chemical structures but different functional groups. The experiments were performed at different pressures (2, 1.5 and 1 MPa), equivalence ratios (1 and 0.5), and with different hydrogen proportions (0, 25, and 50%) in the U-Lille rapid compression machine. Three models from the literature were validated experimentally, so reaction pathway analysis and sensitivity analysis were carried out to better understand the effect of hydrogen in the temperature range 650 K-970 K.

In the case of *n*-pentane and 3-pentanone, a decrease of the global reactivity towards ignition is observed when hydrogen is added in all conditions. This effect is moderate however reproducible, demonstrating a clear trend for these two fuels. Kinetic analysis shows that the conversion of hydroxyl radicals through reaction with H_2 to form

water and H-atoms is responsible for this effect. H-atoms are indeed quickly converted into hydroperoxyl radicals, whose contribution to low-temperature chain-branching is limited.

Hydrogen has however no detectable effect on the ignition delay times of 1-pentene. The reason for this absence of effect lies in the higher relative importance of hydroperoxyl radicals in the low-temperature oxidation of alkenes, as well as the favored abstraction of H-atoms in 1-pentene in comparison to hydrogen.

Currently, the incentive towards using renewable hydrogen as a fuel, both in internal combustion engines and in aeronautic turbine, is rising. This study aims to provide reliable kinetic models with a clear view of the effect of hydrogen on three different fuels. This effect is shown to be not so significant, and the rate of production analysis with and without hydrogen are the same. This means that no further hydrocarbon related emissions are taking place, and that hydrogen is decreasing the number of unburnt hydrocarbons, carbon dioxide and carbon monoxide by replacing part of the fuel that is leading in the first place to these emissions.

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