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Ozone applied to the homogeneous charge compression ignition engine to control alcohol fuels combustion [☆]

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HIGHLIGHTS

- Ozone was useful to control combustion phasing of alcohol fuels in HCCI engine.
- Ozone helps to improve the combustion and advance its phasing.
- Butanol is more impacted by ozone than methanol and ethanol.
- HCCI combustion parameters may be controlled by managing ozone concentration.
- Kinetics demonstrates that alcohol fuels are initially oxidized by O-atoms.

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ABSTRACT

The present investigation examines the impact of seeding the intake of an HCCI engine with ozone, one of the most oxidizing chemical species, on the combustion of three alcohol fuels: methanol, ethanol and n-butanol. The research was performed through engine experiments and constant volume computations. The results showed that increasing the ozone concentration led to an improvement in combustion coupled with a combustion advance. It was also observed, by comparing the results for each fuel selected, that n-butanol is the most impacted by ozone seeding and methanol the least. Further analyses of the experimental results showed that the alcohol fuel combustion can be controlled with ozone, which presents an interesting potential. Finally, computation results confirmed the experimental results observed. They also showed that in presence of ozone, alcohol fuels are not initially oxidized by molecular oxygen but by O-atoms coming from the ozone decomposition.

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1. Introduction

Reducing pollutant emissions to improve air quality and decreasing fuel consumption due to the depletion in fossil resources are currently the main challenges for the automotive field. To address these issues, various advanced combustion modes which may be applied to the internal combustion engine have emerged [1]. Among them, the Homogeneous Charge Compression Ignition (HCCI) engine is particularly interesting. Considered as a hybrid between Spark Ignition (SI) and Compression Ignition (CI) engines, the HCCI combustion mode achieves low nitric oxide

(NO_x) and particle matter (PM) emissions coupled with a high efficiency similar to that of CI engines [2]. It also offers the possibility to use a wide range of fuels, making it very attractive for alternative fuels coming from non-petroleum sources such as alcohol fuels, vegetable oils or biodiesels [3]. However, before an HCCI engine becomes operational, several challenges have to be overcome, in particular concerning control of the combustion process [4–6].

Several strategies have been explored to efficiently control the HCCI combustion process. As this process is fully governed by kinetics and as the temperature is one of the key parameters in this field, the intake temperature effect was investigated. Machrafi et al. [7] reported results on the n-heptane and PRF40 combustion and showed that increasing the intake temperature results in a promoting effect. Cool and main flame phasing advance when the intake temperature increases. This is due to the higher temperatures reached inside the combustion chamber. Similar effects were published by Dubreuil et al. [8] also on n-heptane as well

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as two other fuels. The variation of the intake temperature was also studied by Mohammadi et al. [9] for the combustion of a natural gas. Their results also showed an advance of the combustion ignition but combustion tends to knock for high intake temperatures. However, high temperatures give the possibility to ignite leaner mixture. Maurya et al. [10] observed similar results with ethanol as fuel and extended the analysis to a cycle-to-cycle study. Raising the temperature leads to an improvement of the combustion because covariance of the indicated mean effective pressure decreases while the covariance of the pressure gradient increases due to knock occurrence. Finally, recent studies used this parameter as a control parameter to achieve cleaner combustion and improve efficiencies [11,12].

Another key parameter to control the combustion timing is the fuel. Each fuel auto-ignites more or less easily and can be consumed more or less rapidly as a function of its properties. This therefore conditions the overall combustion process. As HCCI engines allow fuel flexibility, a wide range of fuels have been investigated previously [13–16]. This include studies on primary reference fuels (n-heptane, isooctane as well as blends of both) [7,17,18], on gaseous fuel [19,20], even on alcohols [21,22]. Further investigations considered mixtures of fuels according to various principles such as the preparation of a new fuel from two fuels [23,24], the mixture of a gas and a liquid fuel in front of the combustion chamber [25,26] or by creating a fuel stratification inside the combustion chamber with the help of a port injection and a direct injection [27–30]. The latter is mainly called reactivity controlled compression ignition (RCCI) [31] and may allow to extend high load limits.

In recent years, the implementation of exhaust gas recirculation (EGR) has been widely used on CI engines to meet NO_x requirements. This strategy has also been applied to the HCCI engine, not primarily to reduce pollutant emissions but rather to control the combustion phasing. Researchers studied the EGR effect on the combustion of reference fuels [8,18] and showed that by increasing the EGR rate, cool and main flames phasing are delayed due to the oxygen reduction in the charge. This results from the dilution combined with the heat capacity of the CO₂ and H₂O which are main components of the exhaust gases. Furthermore, if the fuel can ignite easily, high EGR rates may be used to maintain an effective combustion. Fathi et al. [32] studied the EGR effect on n-heptane/natural gas fuels and also observed that ignition is delayed and combustion duration is prolonged. Moreover, they observed that EGR allow a pressure rise rate attenuation due to lower in-cylinder temperatures. Finally, according to Sjöberg et al. [33], EGR can be used to control the combustion process and extend HCCI to high loads. However, a high EGR quality and a homogeneous mixture with the charge are required. In fact, two kinds of EGR strategies can be used and are respectively called external EGR and internal EGR. The first consists of a real recirculation of the exhaust gases and is therefore considered as cooled EGR. The second consists in maintaining exhaust gases inside the combustion chamber with a high in-cylinder temperature by controlling a negative valve overlap. Literature results [34,35] on both kind of EGR strategies showed that external EGR can be used to extend the high load limits due to its diluting effect while internal EGR can prevent misfire at low loads due to thermal effects. Both kind of EGR allow a control of the HCCI combustion and experimental results demonstrate that an enhancement of the cycle-to-cycle variation is possible. Furthermore, a recent study using EGR strategy [36] reported a close-loop control of the HCCI combustion and allowed to reach combustion under stoichiometric conditions. Finally, according to the results presented above, EGR presents a thermal effect, a dilution and a heat capacity modification but considering its use in an HCCI engine, a chemical effect have

to be analyzed. Some studies were therefore conducted by using EGR components separately. Sjöberg et al. [37] experimentally compared the effect of the main components of the EGR with a simulated EGR. Results showed that the water have a significant chemical impact, demonstrating an effect quite similar to this of a simulated EGR. Furthermore, they also compared the simulated EGR with a real one, showing that the real EGR allows a better combustion. Therefore, the presence of incomplete combustion products such as carbon monoxide, unburned hydrocarbon and nitrogen oxides play an important role. Results on CO and HC showed no significant effect on the combustion timing while nitric oxide demonstrated a promoting effect [8,38]. Dubreuil et al. [39] investigated the nitric oxide effect on reference fuels and observed a promoting effect on both cool and main flames for concentration lower than 100 ppm. For higher concentrations, the cool flame phasing decreases while the main flame is steady. Contino et al. [40] also investigated the nitric oxide effect and reported its promoting effect to enhance the HCCI combustion of the isooctane. Finally, chemical species such as NO_x demonstrated they have an oxidizing potential. Controlling the HCCI combustion through the use of such species is attractive.

Recently, we carried out a study to compare the effect of NO_x with another oxidizing chemical species, ozone [41]. Results demonstrated that the effect of ozone is much greater than that of NO_x, resulting in a strong and fast improvement of HCCI combustion coupled with a significant combustion advance. Other studies considered the effect of ozone on the combustion of various fuels and also observed its promoting effect. Nishida and Tachibana [42] studied the ozone effect on natural gas and concluded that ignition timing can be controlled by managing the ozone concentration. Similar results were observed by Mohammadi et al. [9] on natural gas. By varying the equivalence ratio, they showed that ozone can maintain the combustion at low equivalence ratio but at high equivalence ratio, the use of ozone lead to knocking. Finally, they also observed that above a certain value of ozone concentration, there is a saturation. Such results were also observed in an investigation on gaseous fuel with high proportion of methane [43]. Yamada et al. [44] experimented the ozone as an improver for the combustion of DME and showed that the use of this oxidizing species leads to an earlier thermal ignition and impacts the cool flame of this fuel. These results show that ozone acts on the beginning of the combustion. Foucher et al. [45] investigated the ozone seeding on an HCCI engine fuelled with n-heptane. They observed that low concentrations of this oxidizing chemical species are needed to strongly advance the combustion phasing which is combined with a higher heat release rate on the cool flame. Finally, they showed that a cycle-to-cycle control by ozone is possible demonstrating that this kind of control is promising. Referring to these results, we extend the analysis to primary reference fuels [46] and observe similar results than previous researches. All the PRF selected showed a similar effect on their respective phasing as well as higher cool flame heat release rate with the exception of the isooctane. The latter presents only a main flame heat release rate and the effect on the phasing is more significant than on the other fuels studied. Finally, further investigations with isooctane were carried out under various intake temperatures [47]. Results at low intake temperatures showed that controlling the combustion is possible by using ozone. Moreover, it was confirmed that the ozone acts on the beginning of the fuel oxidation by occurring a weak cool flame. Finally, all the authors agree on the fact that the promoting effect of the ozone results in its decomposition into an oxygen molecule and an O-atom, the latter allowing a faster oxidation of the fuels.

Ozone is a powerful oxidant and HCCI combustion process is governed by chemical kinetics. By injecting ozone, the kinetics is modified and fuel oxidation occurs earlier. Managing the amount

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