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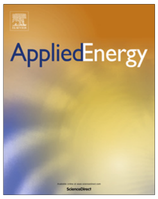

The effect of ethanol blending on mixture formation, combustion and soot emission studied in an optical DISI engine

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HIGHLIGHTS

- Catalyst heating points were analyzed using optical measurement techniques.
- E20 shows stronger soot radiation and higher soot concentration as isooctane.
- Different mixing formation of isooctane and E20 was determined.
- Strong mixture stratification was identified for both fuels.
- Remaining droplets and fuel rich regions are the main source for soot formation.

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ABSTRACT

In various research studies, ethanol blended fuels have shown reduced particulate matter (PM) emissions in comparison to gasoline and its surrogate fuels in direct-injection spark-ignition (DISI) engines. However, there are also studies reporting increased particulate concentration for fuels with low ethanol content. In this work the mixture formation and sooting combustion behavior of isooctane and the mixture E20 (20 vol% of ethanol in isooctane) is analyzed for catalyst heating operation. These operating conditions are critical as they strongly contribute to overall soot emissions in driving cycles. Simultaneous high speed imaging of OH*–chemiluminescence and natural soot luminosity measurements are performed in combination with primary particle concentration measurements using a laser induced incandescence (LII) sensor in the engine exhaust duct. At these operating conditions E20 exhibits a higher sooting tendency as compared to isooctane. In order to identify the reason for increased soot formation, the mixture formation process is analyzed by planar laser induced fluorescence (LIF) measurements. The results show that soot was formed in fuel rich regions with incomplete evaporated fuel droplets remaining from the injection event. A different evaporation process of E20 fuel spray and mixing behavior is indicated showing a more compact rich mixture cloud with surrounding lean areas near the spark plug region. This mixture stratification is characterized by higher cyclic variations and constitutes a significant source of soot formation.

1. Introduction

Global CO_2 emissions from the transportation sector account for about 23% of the total CO_2 emissions. 75% of this CO_2 is produced by road transportation, which is a significantly growing sector worldwide. Furthermore, the fuel supply heavily depends on fossil fuels and crude oil [1]. New emission standards and limitations force car manufactures to reduce CO_2 fleet emissions drastically.

The use of alternative, renewable fuels could be a promising strategy. Considering the production of alternative fuels from biomass a nearly closed carbon life cycle can be achieved. Using

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Abbreviations: aTDC, after top dead center; bTDC, before top dead center; CA, crank angle; CO_2, carbon dioxide; E20, 20 vol% of ethanol in isooctane; EV, exhaust valve; DISI, direct injection spark ignition; IMEP, indicated mean effective pressure; IV, inlet valve; Lambda/λ, air–fuel ratio; LIF, laser induced fluorescence; LII, laser induced incandescence; NEDC, new european driving cycle; OH*, hydroxyl radical; OP, operating point; PM, particle matter; ROZ, research octane number; TEA, triethylamin.

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modern industrial production processes a CO_2 reduction potential between 35% [2] and 80% [3] depending on the process and production conditions is possible. Among other biofuels, ethanol can be considered as alternative fuel with promising future potential. Currently, ethanol is already blended with gasoline (E5, E10 i.e. 5% or 10% of ethanol in gasoline, respectively) in many European countries and the US. With the directive 2009/28/EC the European Commission has set the target of a 10% share of energy from renewable sources in transport by 2020 [2]. Because of that, it is expected that higher ethanol contents will show up in future (e.g. E20).

Besides the use of alternative fuels modern engine combustion concepts like gasoline direct injection can contribute to CO_2 reduction. For direct injection spark ignition (DISI) engines the main advantages in comparison to port fuel injection engines are improved fuel economy, better transient response, and lower emission levels [4]. However, those engines suffer from higher particulate matter emission [5,6] because of a complex mixture formation process. The underlying reason is a reduced mixing time of fuel and air, which leads to complex handling of the mixture formation process at engine operation.

In general, the term particulate matter comprises engine exhaust pollutants in the liquid or solid phase. The main component of PM is carbon which is formed by the combustion process itself. Generally, this is referred as soot. In diesel engines particle emission is governed by soot formation processes at high temperatures (1700–2600 K) [7] and rich mixture zones as well as soot oxidation processes with the presence of oxidizing species. Detailed information about the soot formation and oxidation processes in general [8] and in engine combustion can be found in [9,10]. For soot formation in DISI engines similar conditions exist with the same mechanisms as in diesel engine particle formation. In DISI engines soot is also produced at high combustion temperatures and rich local mixture zones [11].

Soot formation in DISI engines underlies several mechanisms and sources. In general, soot can be produced at rich mixture gaseous conditions (air–fuel ratio below 0.5 [7]) and by burning of liquid fuel in a diffusion flame. Liquid fuel can either be created by incompletely evaporated fuel droplets from the injection process or component wetting. In references [11,12] the main particle sources in DISI engines are presented and analyzed by optical measurement techniques systematically. In general, liquid fuel wetting and the resulting poolfire can be considered as the most important soot formation mechanism contributing to PM [11]. In a study of Stojkovic et al. [13] it was found out that soot which is formed by poolfire late in the cycle, can persist until the exhaust stroke. Here further oxidizing is unlikely because of low temperatures (1500 K) and weak premixed combustion intensity. If poolfire is avoided by appropriate injection strategies, in the stratified operation mode, locally fuel rich mixture zones and incompletely vaporized liquid fuel droplets are significant for soot formation [4]. In several engine studies stratified operated engine combustion was analyzed by imaging techniques [14,15]. The soot formation was mainly characterized by several randomly distributed bright luminous spots surrounded by the burned gas phase. Those bright spots where created by mixture inhomogeneities and burning fuel droplets, which can remain from the injection event. In a study of Oh et al. [16] high speed imaging was conducted in order to analyze the flame propagation in a stratified operated engine. The combustion shows two different kinds of characteristics. First a premixed combustion and second a mixture controlled combustion (luminous flame – soot incandescence signal) was found. Kuwahara et al. [17] performed a similar study. Here UV chemiluminescence (wavelength band 270–370 nm) and thermal flame (luminous flame, wavelength band 510–590 nm) propagation was analyzed. The UV flame propagates rapidly and covers the whole field of view. Afterwards thermal flame proceeds in the reaction zone behind a second flame front. Stojkovic et al. [13] investigated the oxidation behavior of inhomogeneous mixture combustion. They concluded that as long as soot from fuel droplets is formed early in the cycle, it can burn rapidly due to high temperature (2000–2400 K) and fast mixing with surrounding lean air–fuel mixture.

The soot formation mechanism “inhomogeneous mixture” and “fuel droplet combustion” is especially important for catalyst heating operation mode, which is characterized by spark retard strategy and late injection in order to heat up the exhaust gas system at engine startup for proper three-way-catalyst operation. Concerning the New European Driving Cycle (NEDC) more than 30% of particulate mass and number is emitted in the first 3 min startup phase of a 2.0 l gasoline direct injection (GDI) turbo engine [5]. Together with the more stringent particulate matter emission limits for spark ignition engines (e.g. EURO6) soot formation has to be addressed in this context [18].

The question arises whether ethanol blending could be a promising measure in order to reduce particulate matter at those engine operation conditions. In various research studies, ethanol blended fuels have shown reduced PM emissions in comparison to gasoline and its surrogate fuels [19–21] in DISI engines. However, there are also studies reporting increasing particulate concentration for gasoline engine fuels with higher ethanol content [22,23]. Maricq et al. identified ethanol blends <20 vol% to be of small benefit for particulate number emission reduction. A significant decrease in PM exhaust emission was measured for higher ethanol contents (>30 vol%) [24]. Karavalkis et al. [25] and Lee et al. [26] obtained similar results for fuels with low ethanol content. Here, blends with intermediate ethanol content (e.g. E20) did not necessarily show PM mass reductions. In a high-speed imaging study of Storch et al. [12] different ethanol-isooctane blends were analyzed for different sooting mechanisms. In general soot emission was reduced with increasing ethanol content. But for a catalyst heating operation point E20 showed higher soot concentration than pure isooctane, which could not be explained in that study and will be further addressed in this work. Possible reasons for this opposing behavior of increased particle formation with ethanol content may be found in physical properties of the fuel which determine the mixture formation. In Table 1 the physical and chemical properties of ethanol and isooctane (surrogate fuel) are listed.

In Table 1 the physical and chemical properties of ethanol and isooctane (surrogate fuel) are listed. For ethanol the engine efficiency can be increased by larger engine charge cooling because of its high enthalpy of evaporation and the feasibility of higher compression ratios resulting from a high research octane number. In general, the sooting tendency of a fuel is determined by physical mechanisms (e.g. atomization, evaporation) and chemical processes (reaction kinetics, carbon–oxygen ratio). Ethanol has higher liquid fuel density, surface tension and viscosity than isooctane.

Table 1
Physical and chemical properties of ethanol and isooctane [27–29].

Fuel	Ethanol	Isooctane
H/C – ratio/O/C – ratio	3/0.5	2.25/–
Boiling point (°C)	78.0	99.2
Density (g/cm^3) @ 20 °C, 1 bar	0.79	0.72
Dynamic viscosity @ 1 bar, 25 °C (mPa s)	1.104	0.4718
Heat of vaporization (kJ/kg) @ 20 °C	904	297
Research octane number (RON)	109	100
Stoichiometric air–fuel ratio (kg/kg)	9	15.2
Lower heating value (MJ/kg)	26.8	44.3
Adiabatic flame temperature @ 25 °C, $\lambda = 1$ (K)	2195	2266
Laminar burning velocity @ 25 °C, $\lambda = 1$ (cm/s)	45	35

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