



# Investigation of soot formation of spark-ignited ethanol-blended gasoline sprays with single- and multi-component base fuels



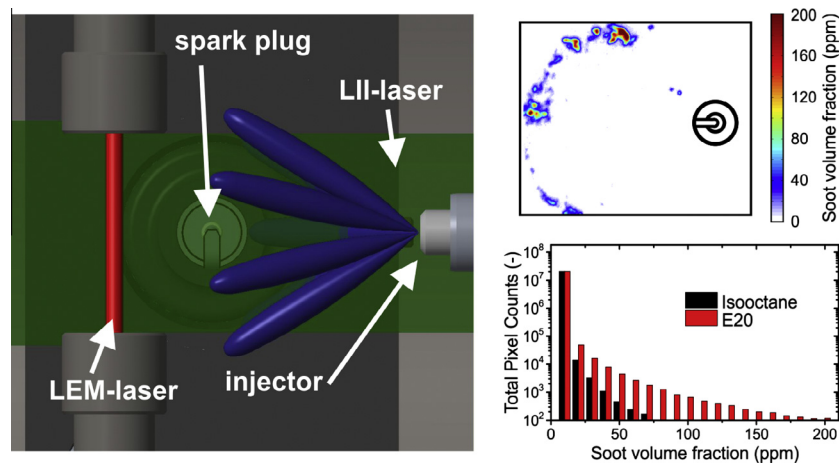
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## HIGHLIGHTS

- Soot formation was quantified in spray combustion under DISI-conditions in a CVC.
- Laser induced incandescence and laser extinction measurements were coupled.
- Soot is mainly formed in the spray front due to droplet combustion.
- Increased sooting tendency of E20 compared to pure isoctane and gasoline.
- Physical fuel properties govern soot formation mechanisms in E20 mixtures.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Soot formation in DISI-(direct-injection spark-ignition) sprays is analyzed for ethanol-mixtures under stratified charge conditions. The investigation is conducted in a constant volume chamber (CVC), which is equipped with a spark ignition system. The operating conditions of the chamber are 0.8 MPa and 473 K. In previous studies, soot luminosity imaging indicated higher sooting tendencies for E20 (20 vol.% of ethanol in isoctane) sprays in comparison to pure isoctane and pure ethanol, however, no quantification of the soot distribution was possible. In this study, 2D laser-induced incandescence measurements (LII) in combination with laser extinction measurements (LEM) were performed for measurement of soot volume fraction distribution in the spray flame. The results show that soot is mainly formed in the spray front due to droplet combustion. Furthermore, soot volume fraction results confirm an increased sooting tendency of E20 compared to pure isoctane under the investigated conditions although the chemical properties of ethanol should reduce soot formation. This behavior can be explained by the delayed evaporation of E20 in comparison to isoctane due to physical fuel properties (mainly the enthalpy of evaporation), which are more important for soot formation especially at these short mixing times. Similar

**Abbreviations:** aVSOI, after visible start of injection; CCD, charge-coupled device; CO<sub>2</sub>, carbon dioxide; CVC, constant volume chamber; DISI, direct injection spark ignition; DVPE, dry vapor pressure equivalent; E20, 20 vol.% of ethanol in isoctane; FWHM, full width at half maximum; IC, internal combustion; Lambda/λ, air-fuel ratio; LEM, laser extinction measurement; LIF, laser induced fluorescence; LII, laser induced incandescence; OP, operating point; PFI, port fuel injection; PM, particle matter; RON, research octane number; Tollso, toluene-isoctane mixture; VSOI, visible start of injection.

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trends were found for the more complex multi-component fuel mixture isooctane-toluene (Tollso) and gasoline, both blended with 20 vol.% ethanol. Here, single combustion cycles were observed, where E20 exhibits higher soot volume fraction.

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## 1. Introduction

The usage of bioethanol in modern DISI (direct-injection spark-ignition) engines may form an essential contribution for reaching future CO<sub>2</sub>-emission limits. However, the combustion process chain of DISI engines is more complex as compared to port fuel injection (PFI), which leads to increased particulate matter (PM) emission levels [1]. Thus, the reduction of soot formation and PM exhaust emission in order to comply with stringent particle emission limits, e.g. EURO6 [2,3], becomes challenging.

Ethanol could be a promising alternative fuel for the reduction of soot emissions. Pure ethanol can be considered as a low sooting fuel because of its chemical character. The molecule has a high oxygen-to-carbon ratio leading to lower concentration of important intermediate soot precursor species [4]. Furthermore, also the shorter carbon-chain length may be beneficial for soot reduction [5]. There are various research studies showing that DISI engine exhaust PM emissions can be reduced by large fuel ethanol contents [6–8]. Other studies also show that lower ethanol contents (e.g. E10, E20) can be advantageous regarding particle emission reduction [9,10]. On the contrary, Maricq et al. [11] analyzed lab scale diffusion flames and stated that the PM mass and number reduction potential is within the measurement uncertainty for ethanol contents between 0% and 20% in gasoline, whereas ethanol contents above 30% show significant PM mass and number reduction. Chen and Stone [12] showed that during engine cold start PM mass and number increased continuously with increasing ethanol content. This result was explained by mixture inhomogeneities caused by poor evaporation at low temperature due to the high enthalpy of evaporation of ethanol (see Table 1). Similar results were obtained by Daniel et al. [13] and by Chen et al. [14].

In Refs. [15–17] especially low ethanol contents (e.g. E10, E20) were studied showing even increased PM mass emissions, however, no concrete explanation for this behavior was provided. For clarification of these effects, different soot formation mechanisms were investigated using an optically accessible engine. Especially at a catalyst heating operation point, E20 showed stronger sooting tendency than the pure base fuel isooctane [18]. In a mixture formation study at catalyst heating operation [19] tracer-LIF (laser-induced fluorescence) was used showing significant mixture stratification for E20, which resulted in incomplete mixing and distinct fuel-rich regions. The reasons of this behavior were assumed to be caused by non-ideal evaporation of isooctane and ethanol, as well

as the high enthalpy of evaporation of ethanol, which leads to strong cooling effects associated with delayed evaporation of the sooting component isooctane. High occurrence frequency of the distinct fuel rich zones of E20 correlated well with higher particle concentrations in the exhaust gas measured by LII (laser induced incandescence).

In the studies presented above different types of gasoline fuels were blended with ethanol. Isooctane is commonly used in combustion and spray formation experiments in spark ignition engines as surrogate fuel. Especially, the aromatic components such as toluene, benzene or xylene strongly influence the sooting tendency of the fuel [20]. Gasoline contains up to 35 vol.% of aromatic components [21] including toluene as octane number enhancer up to 15 vol.% [22]. In a study of Choi et al. [23] the soot formation of isooctane was analyzed for varying toluene contents in counter-flow diffusion flames. The results show that sooting tendency increases continuously with increasing toluene content. In addition, Witkowski et al. [24] studied the sooting properties of different fuels in a laminar co-flow diffusion flame. A mixture of 50% of isooctane, 30% of toluene and 20% of n-heptane was found to be an adequate surrogate fuel in order to model the sooting tendency of gasoline in terms of soot volume fraction and morphology.

However, single effects of chemical and physical fuel properties on soot formation cannot simply be separated in multi-component mixtures. Thus, the first part of this study solely focuses on the base fuel of pure isooctane. In the second part a mixture of 65 vol.% isooctane and 35 vol.% toluene was studied, while the second part addresses a multi-component reference gasoline fuel. All fuels were blended with ethanol in order to study its influence on soot formation. Spray combustion of different ethanol mixtures is systematically analyzed in a constant volume chamber (CVC) under simplified and well-defined conditions (for details of the CVC see Ref. [25]). The chamber was equipped with spark plug ignition system, and different ambient conditions were studied representing stratified charge operating points, which are comparable to the late injection of the catalyst heating operating point mentioned above [19]. In Ref. [25] qualitative high-speed imaging of soot luminosity at moderate temperature (473 K) and pressure (0.8 MPa) showed stronger droplet combustion for E20 in comparison to isooctane in accordance to IC engine measurement in Ref. [19]. For a deeper insight into the underlying processes, quantitative measurements are necessary, which are in the focus of the present paper.

**Table 1**  
Physical and chemical properties of ethanol, isooctane and toluene at 20 °C, 0.1 MPa [20,42].

Property	Unit	Ethanol	Isooctane	Toluene
H/C-ratio/O/C-ratio	–	3/0.5	2.25/–	1.14/–
Boiling point	°C	78.0	99.2	110.7
Density	g/cm <sup>3</sup>	0.79	0.72	0.86
Dynamic viscosity @ 25 °C	mPa s	1.104	0.4718	0.59
Surface tension	N/m	0.0223	0.0187	0.0285
Heat of vaporization	kJ/kg	904	297	409.3
Stoichiometric air-fuel ratio	kg/kg	9	15.2	13.6
Lower heating value	MJ/kg	26.8	44.3	40.9
Adiabatic flame temperature @ 25 °C, Φ = 1	K	2195	2266	2317

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