

# Influence of Fuel Composition on Exhaust Emissions of a DISI Engine during Catalyst Heating Operation

Helge Dageförde and Thomas Koch  
Karlsruhe Institute Of Technology

Kai W. Beck and Ulrich Spicher  
MOT GmbH

## ABSTRACT

Particle number measurements during different real world and legislative driving cycles show that catalyst heating, cold and transient engine operation cause increased particle number emissions. In this context the quality of mixture formation as a result of injector characteristics, in-cylinder flow, operation & engine parameters and fuel composition is a major factor. The goal of this paper is to evaluate the influence of different biogenic and alkylate fuels on the gaseous and particle number emission behavior during catalyst heating operation on a single-cylinder DISI engine. The engine is operated with a late ignition timing causing a high exhaust enthalpy flow to heat up the catalyst, a slightly lean global air fuel ratio to avoid high hydrocarbon emissions and a late injection right before the ignition to reduce the coefficient of variance of the indicated mean effective pressure.

While the local fuel enrichment through the late injection helps to stabilize the inflammation and combustion process it can also lead to very high particle number emissions due to poor mixture formation. Based on the experimental results with RON 95 fuel the particle emission behavior with different biogenic fuel blends (E40, B40), alkylate fuels and toluene is examined. The variation of the fuel composition shows how certain molecules (aromatics, alcohol) affect the particle emissions while the adaption of the boiling curve directly influences the mixture formation in general. Furthermore, the results demonstrate the potential of biofuels to reduce the particle number emissions of modern GDI engines.

**CITATION:** Dageförde, H., Koch, T., Beck, K., and Spicher, U., "Influence of Fuel Composition on Exhaust Emissions of a DISI Engine during Catalyst Heating Operation," *SAE Int. J. Fuels Lubr.* 6(3):2013, doi:10.4271/2013-01-2571.

## INTRODUCTION

In recent years the investigation of particle number emissions of GDI engines has become more and more important. While soot emissions of diesel engines are a widely investigated matter the particle formation, oxidation and number emission of gasoline engines with direct fuel injection are comparatively new issues. Due to the respirability of those particles and the health damaging effect respectively the reduction and limitation of the emitted particle number of GDI engines are pressing R&D and political goals.

Particle number (PN) measurements during different real world and legislative driving cycles show that during catalyst heating, cold and transient engine operation the highest number concentrations occur [1]. The focus of this paper is set on catalyst heating operation, which tends to result in high

particle number emissions because of the combination of high injected fuel mass, weak in-cylinder flow movement and cold engine walls [2]. Therefore in this context the quality of mixture formation as a result of injector characteristics, in-cylinder flow, engine operation & hardware parameters and fuel composition is a major factor. A further challenge is to keep the gaseous raw emissions on a low level and supply a high exhaust enthalpy flow for a quick catalyst heating-up while maintaining a low coefficient of variance (COV) of the indicated mean effective pressure (IMEP).

In several publications the benefit of an optimized injection strategy is discussed. For GDI engines with a centrally mounted hollow cone injector a multi-pulse injection strategy with a short injection pulse right before the ignition timing can lead to an engine operation with low particle number emissions ( $< 10^5$  p/cm<sup>3</sup>) while keeping the

COV of IMEP on a comparatively low level [2,3]. The split-up of the fuel injection reduces or even avoids wall wetting and improves the vaporization through an increased air entrainment. The last short injection pulse, which is coupled to the ignition timing, leads to a local fuel enrichment and increased turbulence at the spark plug [4]. While the turbulence supports the stabilization of the inflammation and combustion process the local fuel enrichment and the very short duration between the last injection pulse and ignition timing can lead to a substantial increase of the particle number emissions. Therefore the timing and injected fuel mass must be chosen carefully and precisely. To further improve the mixture formation with multi-hole injectors and to meet the increased demands for a precise fuel injection even in the ballistic operating mode component supplier advance their injection systems. Kufferath et al. [5] pointed out that through laser drilling the injection holes can be manufactured with smoother surfaces and sharper edges, which increases the turbulence and improves the spray break-up respectively. Moreover, laser drilling allows individual injection hole diameters & shapes, creating a new degree of freedom in the spray pattern design process. Moreover the authors present a software-based solution (Controlled Valve Operation) to improve the precision of the injected fuel mass in the ballistic operating mode. The benefit of reduced particle number emissions under various engine operation conditions without compromising the gaseous exhaust emissions could be confirmed by experimental and numeric investigations [6]. Another promising approach to improve the mixture formation with multi-hole injectors is a further increase of the injection pressure. Schumann et al. demonstrated on a single-cylinder engine that an injection pressure of up to 800 bar enables stratified catalyst heating operation which not just lowers particle number but also nitrogen oxide and hydrocarbon emissions [7]. Besides injection system & operating strategy adjustments, measures to increase the in-cylinder flow turbulence through e.g. variable intake valve lift, valve timing and flow motion devices are common practice to improve the combustion stability [8,9,10]. Furthermore, a more intense in-cylinder flow supports the fuel spray evaporation and mixture homogenization, which helps to reduce particle number emissions through wall wetting and/or areas of high fuel concentration.

Besides the discussed operation and hardware parameters the fuel composition is a fundamental factor on the engine operation and emission behavior. The unlasting availability of fossil fuels raises the demand for alternatives. Moreover, a fuel composition that reduces harmful exhaust emissions is desirable especially with respect to the growing worldwide vehicle population.

An increase of the biogenic proportion in gasoline can reduce the demand for fossil fuels assuming that a sustainable production process for the biogenic fuel is chosen (2<sup>nd</sup> generation biofuels). Originally introduced as a substitute for

methyl tert-butyl ether (MTBE), ethanol is the most widely used renewable fuel worldwide today with a well-established large-scale production process. Besides the advantage of a high octane rating it also shows some disadvantages to gasoline like a lower caloric value, a higher latent heat of vaporization and a higher degree of corrosiveness.

However recent investigations reveal butanol as a promising alternative. According to Wu et al. butanol produced from corn could lead to a fossil energy saving of 39-56 % in combination with reduced greenhouse gas emissions of up to 48 % [11]. Butanol offers several advantages compared to ethanol as a (fractional) gasoline substitute and was already proven as a possible alternative several years ago [12]. Regalbuto et al. [13] have summarized the advantages from multiple publications. A few shall be mentioned: butanol is less corrosive and prone to water contamination. From this point of view it could be handled by the existing fuel distribution infrastructure and by today's combustion engines. It further offers a higher caloric value (butanol: 36.4 MJ/kg; ethanol: 24.8 MJ/kg) and a lower latent heat of vaporization (butanol:  $\approx 592$  J/g; ethanol:  $\approx 910$  J/g), although the last aspect does not necessarily induce a better spray vaporization.

Aleiferis and van Romunde conducted an extensive analysis of the spray development of various fuels in an injection chamber [14]. The higher viscosity and surface tension of butanol compared to ethanol leads to bigger droplets. In combination with the higher boiling temperature this causes a worse atomization behavior. Nevertheless, since the chemical characteristics of butanol are closer to those of gasoline than the chemical characteristics of ethanol are, internal combustion engines can be operated with butanol blended fuels or even neat butanol without significant impact on the combustion process [15].

Regarding the gaseous exhaust emissions an impact on the hydrocarbon emissions is announced in several publications, but some authors observe an increase through butanol blended fuels [13,16] and some measure a decrease [17,18]. Altogether it depends on several aspects like the engine operating point and injection system; therefore no explicit conclusion can be drawn. Furthermore, it is strongly down to the used isomer.

Regalbuto et al. investigated the operation and emission behavior of a PFI engine with n-butanol, isobutanol and 2-butanol (all 30 %-by-mass-blends with gasoline) [13]. The measurements at different engine loads revealed that the easier abstraction of the OH group from a secondary carbon followed by a higher formation of non-oxygenated intermediates leads to significantly more hydrocarbon emissions during the operation with 2-butanol. Besides remarkably lower nitrogen oxide emissions could be observed during engine operation at low loads with the isobutanol-blended gasoline. The authors assume that "prompt" NO<sub>x</sub> emissions might explain the difference calling for a closer investigation of the combustion kinetics. When it

comes to particle number or soot emissions the flame chemistry of tert-butanol and isobutanol shows elevated levels of soot precursors [19] but to which extend this result, measured on a flame burned in pure oxygen, can be transferred to the combustion process of a SI engine is open. Although all butanol isomers can be produced from fossil fuels, the straight-chain molecule structure (1-butanol or n-butanol) is the usually outcome of a biomass-based production process [20].

Thewes et al. studied the influence of neat ethanol and butanol fuel on the exhaust emission behavior on a single-cylinder engine with a centrally mounted injector in comparison to RON 95 gasoline [16]. They observed that engine operation with butanol in general and especially with 1-butanol leads to increased hydrocarbon and particle number emissions while neat ethanol just causes increased hydrocarbon emissions. The reason for the rise is assumed to be improper mixture formation, which could be affirmed by oil dilution measurements during cold engine operation. This fits to the investigations of Jin et al. who measured a rise of propene, 1,3-butadiene, and acetylene emissions through an increased butanol fraction in a blend, which cause benzene formation [20]. Benzene is a known precursor in the soot and particle formation process respectively.

The particle number emission of a DISI engine operated with ethanol- and butanol-blended gasoline was investigated by Lee et al. [21]. The authors found out that both E10 and isoB16 fuel causes a rise of the particle number emissions. At low loads E10 leads to a higher increase, at high loads it is isoB16. It is assumed that the already mentioned disadvantages in spray break-up and vaporization is the reason for that. However the operation with E85 fuel leads to a significant reduction of the particle number emissions not just compared to E10 and isoB16 but also to regular gasoline fuel. A possible explanation is that the high amount of oxygen improves the mixture formation and particle oxidation process in a higher degree than the worse spray break-up (due to the increased surface tension, viscosity and general vaporization) compromises it.

It was already mentioned that benzene or rather aromatic hydrocarbons in general support the particle formation process. A reduction is a promising approach to reduce the particle number emissions respectively. Fuel with almost no aromatic compounds is already established in the application area of handheld machinery in which the operators are directly exposed to exhaust gases. The identification of the carcinogen effect of aromatic compounds led to the introduction of alkylate fuels several years ago to reduce the health threat on people working with handheld machinery and their surroundings. Figure 1 shows the composition of alkylate fuel in comparison with RON 95 fuel. Previous investigations mainly focused on the gaseous emissions of small two- and four-stroke SI engines. A summary of various experimental results published until 2008 can be found in the

final report “Application Areas and Benefit of Alkylate Fuels”<sup>1</sup> [25]. Most recent investigations, which also compare the influence of different RON 95- and alkylate fuel-blends on the combustion and gaseous emission behavior of small two-stroke SI engines, were published by Bertsch et al. [22].

The intention of this paper is to investigate the influence of biogenic and alkylate fuels on the combustion and emission behavior of a state of the art single-cylinder DISI engine with centrally mounted fuel injector. The engine runs in catalyst heating operation mode, a challenging operating point since it demands both a high exhaust enthalpy flow with an adequate combustion stability and low particle number & gaseous emissions. The focus is set on the evaluation of the particle number emissions as well as the trade-off between them and the combustion stability (COV of IMEP).

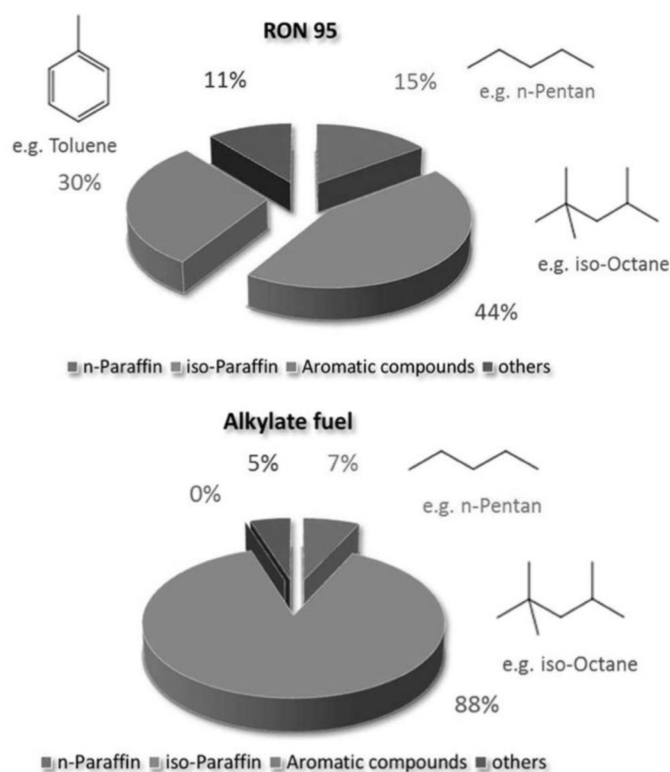


Figure 1. Composition of RON 95 and alkylate fuel [22].

## EXPERIMENTAL SETUP

### Engine

For the investigation a single-cylinder DISI engine with centrally mounted fuel injector was used. It is equipped with a variable intake valve lift system. The fuel injector and spark plug are in a longitudinal arrangement; they are in the same section plane as the crankshaft. The injector is positioned parallel to but not on the cylinder axis. The important engine data are summarized in Table 1.

<sup>1</sup>Title translated into English; original title: see References

**Table 1. Engine data**

|                            |                                                          |
|----------------------------|----------------------------------------------------------|
| Displacement ( $V_d$ )     | 498 cm <sup>3</sup>                                      |
| Stroke                     | 90 mm                                                    |
| Bore                       | 84 mm                                                    |
| Compression ratio          | 12:1                                                     |
| Intake valve spread angle  | 120° CA                                                  |
| Exhaust valve spread angle | 120° CA                                                  |
| Intake valve lift (ivl)    | 1.5 mm / 4.0 mm                                          |
| Exhaust valve lift (evl)   | 9.7 mm                                                   |
| Rail pressure              | 150 bar (cone injector)<br>200 bar (multi-hole injector) |

## Fuels

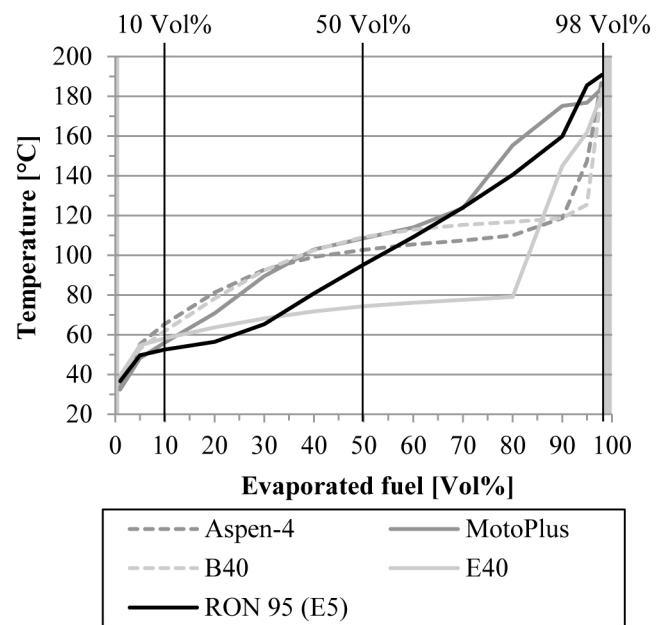
The goal of this paper is to investigate the influence of various fuels on the exhaust emissions especially the particle number concentration. The basis for the comparison is the operation with commercially available RON 95 fuel blended with 5 Vol% of ethanol (E5). To evaluate an increased biogenic fraction, two RON 95 (E5) based blends were prepared: one with 40 Vol% of ethanol (E40) and another

**Table 2. Fuel properties**

|                                                                           | RON 95 (E5) | E40   | B40   | Aspen-4 | MotoPlus | Toluene |
|---------------------------------------------------------------------------|-------------|-------|-------|---------|----------|---------|
| <b>Density</b> [g/cm <sup>3</sup> ]<br>(at 20 °C)                         | 0.75        | 0.76  | 0.78  | 0.7*    | 0.70     | 0.87    |
| <b>Caloric value</b> [MJ/kg]                                              | 42.35       | 36.36 | 38.7* | 44.6*   | 44.55    | 40.94   |
| <b>RON</b> [-]                                                            | 95          | 104   | 97*   | 95      | 95       | 110     |
| <b>Kin. viscosity</b><br>[10 <sup>-6</sup> mm <sup>2</sup> /s] (at 20 °C) | 0.53*       | 0.93* | 1.80* | 0.53*   | 0.53*    | 0.7     |
| <b>Surface tension</b><br>[mN/m] (at 20 °C)                               | 20*         | 21*   | 22*   | 20*     | 20*      | 29      |
| <b>Evaporation heat</b> [J/g]                                             | 420         | 620*  | 490*  | 420*    | 420*     | 347     |
| <b>Carbon mass fraction</b><br>[%]                                        | 84.25       | 72.38 | 76.50 | 84.0*   | 84.19    | 86.74   |
| <b>Hydrogen mass fraction</b><br>[%]                                      | 13.51       | 13.11 | 13.50 | 16.0*   | 15.81    | 13.26   |
| <b>Oxygen mass fraction</b><br>[%]                                        | 2.24        | 14.51 | 10.00 | 0.0*    | 0.00     | 0.00    |
| <b>Aromatics volume fraction</b><br>[%]                                   | 28.3        | 21.8  | 17.0  | <0.1    | <0.1     | 100.0   |
| <b>Stoich. A/F</b> [-]                                                    | 14.27       | 12.16 | 13.03 | 15.1*   | 15.10    | 14.51   |

\* based on published values (no test fuel specific data)

with 40 Vol% of 1-butanol (B40). The 1-butanol (or n-butanol) isomer was chosen, because butanol produced from biomass usually forms a straight-chain molecule structure [20]. The potential to reduce particle formation by eliminating the fraction of aromatic compounds in the fuel composition was investigated with two commercially available alkylate fuels (“Aspen-4” and “Viking MotoPlus”). Although they have the same C, H and O mass fraction their boiling curves are rather different. Moreover, the engine was operated with neat aromatic hydrocarbon fuel (toluene) to emphasize the effect on the particle emission behavior. Some selected fuel properties are summarized in Table 2. The boiling curves are illustrated in Figure 2. The boiling point of neat toluene is at 111°C.

**Figure 2. Fuel boiling curves.**

## Injectors

In the introduction of this paper the importance of the fuel injection system to achieve low particle number emissions and an adequate combustion stability during catalyst heating operation has been already emphasized. When it comes down to the fuel injector for a centrally mounted position there are basically two possible types: a hollow cone injector usually used in engines that operate in homogeneous and stratified mode as well as a multi-hole injector that solely (more or less) operates with a homogeneous air fuel mixture. Catalyst heating operation with a short injection pulse right before the ignition timing is in some way in between the two operating modes. The evaporation behavior of the last short shot is

crucial for both the improvement of the combustion stability and the degree of particle formation. To take the importance of the injector nozzle into account and to get a better separation between the influence of the fuel and the injection system on the combustion and emission behavior, the investigations were conducted with a hollow cone and a multi-hole injector. It is essential to emphasize that just the influence of the injector nozzle was of interest and not the possibilities of different ways of actuation. The injector properties are summarized in Table 3 while Figure 3 illustrates the spray targeting with respect to the spark plug position.

**Table 3. Injector properties**

|                                              | Hollow cone injector           | Multi-hole injector               |
|----------------------------------------------|--------------------------------|-----------------------------------|
| $Q_{stat}$ [g/min]<br>(at 100 bar n-heptane) | 740                            | 820                               |
| Max. rail pressure [bar]                     | 150                            | 200                               |
| Spray type [-]                               | hollow cone<br>90° spray angle | six hole spray<br>75° spray angle |

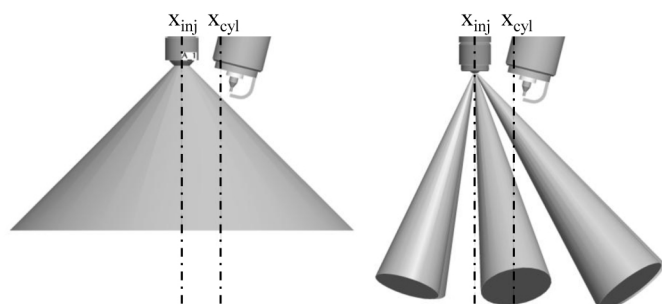


**Figure 3. Spray targeting of hollow cone injector (left) and multi-hole injector (right).**

The two spray cones of the multi-hole injector directed to the spark plug are bent to a wider angle. This supports the local fuel enrichment and generation of turbulence around the spark plug through the short injection pulse right before ignition timing during catalyst heating operation. Furthermore, the asymmetric spray pattern fits well to the already mentioned eccentric position of the injector<sup>2</sup> leading to a relatively uniform fuel distribution of the main injection in the combustion chamber during the intake stroke. The situation with the hollow cone injector is vice versa. The eccentric position in combination with a wide spray angle is a disadvantage for the straight cone shaped spray and can lead to increased spray-wall interaction. On the other hand the wide spray angle leads to a smaller distance between fuel

spray and spark plug compared to the operation with the multi-hole injector which results in a decreased risk of piston wetting and a further improvement of the local fuel enrichment and turbulence generation at the spark plug through the short injection pulse right before ignition timing<sup>3</sup>.

## PN Measurement Equipment

To measure the particle number concentration in the exhaust pipe a chamfered sample probe was mounted and connected with the AVL 489 Particle Counter Advanced. The short (0.5 m) sample line between probe and primary dilution (Chopper diluter) was heated to 190 °C. After the primary dilution the exhaust gas flew through another heated line in the measurement device, where it passed an evaporation tube and another dilution stage. All combined these three devices form the “Volatile Particle Remover” (VPR) that operates according to the guidelines of the “Particle Measurement Programme” (PMP). Depending on the particle number concentration in the exhaust pipe the overall dilution was adjusted between 100:1 and 2000:1 to keep the particle number concentration at the inlet of the measurement device

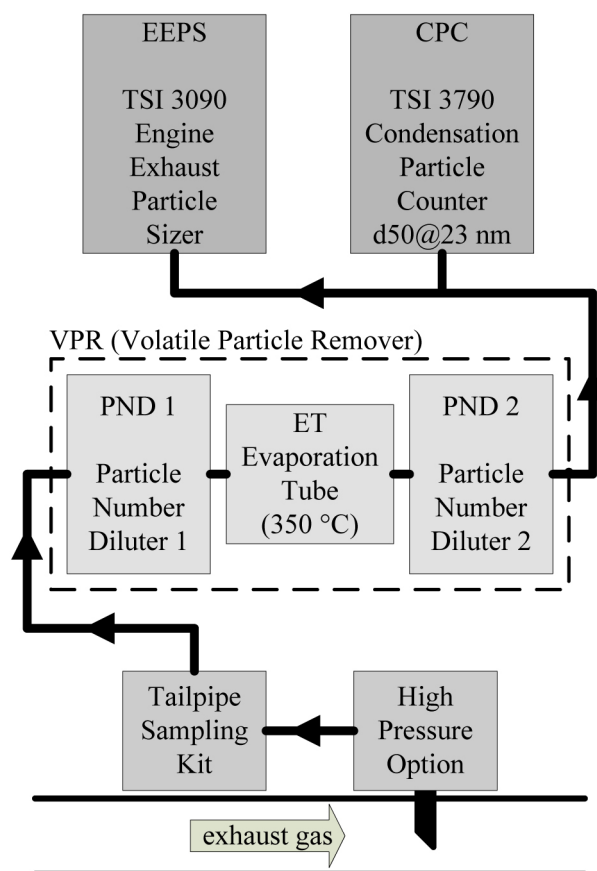


**Figure 4. PN measurement setup**

<sup>2</sup>CAD data: distance between injector centerline ( $x_{inj}$ ) and cylinder centerline ( $x_{cyl}$ ): 9.7 mm

<sup>3</sup>CAD spray targeting: min. distance between spark plug and a) multi-hole spray: 4.0 mm, b) hollow cone spray: 1.9 mm.

<sup>4</sup>Linear response to particle concentration from 1 to  $10^4$  p/cm<sup>3</sup> with  $R^2 > 0.95$ ; counting accuracy of  $\pm 10\%$  against a traceable standard