

Investigation of Fuel Effects on Spray Atomization and Evaporation Studied for a Multi-hole DISI Injector with a Late Injection Timing

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ABSTRACT

The influence of fuel composition on sprays was studied in an injection chamber at DISI conditions with late injection timing. Fuels with high, mid and low volatility (n-hexane, n-heptane, n-decane) and a 3-component mixture with similar fuel properties like gasoline were investigated. The injection conditions were chosen to model suppressed or rapid evaporation. Mie scattering imaging and phase Doppler anemometry were used to investigate the liquid spray structure. A spray model was set up applying the CFD-Code OpenFOAM. The atomization was found to be different for n-decane that showed a smaller average droplet size due to viscosity dependence of injected mass. And for evaporating conditions, a stratification of the vapor components in the 3-component fuel spray was observed.

INTRODUCTION

Among the different combustion concepts of gasoline engines with direct injection, the spray-guided technologies with charge stratification offer the highest potential to reduce fuel consumption. In spray-guided direct injection spark ignition (SG-DISI) engine concepts, the central position of the injector with a small distance to the spark plug is preferred. Under partial load conditions, charge stratification is preferable to reduce fuel consumption. For operating points with late injection, the fuel is injected into a pressurized cylinder and, close to the spark plug an ignitable mixture is positioned. The main challenge is to ensure an ignitable mixture at the spark plug for all engine operating points when applying different worldwide available fuel compositions. A high amount of synthetic or regenerative fuel components like ethanol in gasoline mixtures can significantly change

the mixture formation and combustion processes, especially in those SG-DISI-engine concepts. This fuel impact on spray behavior can be hardly predicted by current CFD-models (Computational Fluid Dynamics) as they are based on simplified correlations not covering fuel-dependent cavitation and atomization behavior. Additionally, models based on diesel injection may not properly work for gasoline injectors as well [1]. Regarding fuel-dependent spray atomization, only few fundamental studies using simple throttle or model nozzle geometries were published in the literature [2, 3] where the cavitation and turbulent flow behavior are very different from realistic multi-hole nozzles. Furthermore, most of the spray process steps and their interactions are still not well understood [4]. Therefore, measurement data of the spray process including the turbulent nozzle flow, atomization, evaporation and droplet collision effects are necessary for a deeper insight into spray processes and model improvements. Especially, the fuel dependent atomization and evaporation of single and multi-component fuels are still discussed in the literature.

Kelly-Zion et al. [5] measured the qualitative vapor distribution and mixing of a low and high volatility component in a port fuel injection SI engine using two laser-induced-exciplex fluorescence techniques (LIEF). It was observed that batch distillation takes place already in the suction duct. Therefore, the liquid entering the cylinder is mostly composed of the heavy boiling components of the fuel. Also for direct injection engines with early injection and near ambient gas temperatures, a distillation-like evaporation can be assumed i.e. the release of light and heavy ends takes place at different times and locations in the cylinder. High volatility fuel components evaporate faster and low volatility components remain in the droplet and determine the droplet evaporation and breakup at

later droplet lifetimes. However, the long mixing time and charge motion in the intake and compression stroke enhances mixing of the light and heavy boiling ends in the vapor phase with air, so that almost no vapor component stratification takes place for early injection. This behavior was described by Williams et al. [6] who applied three fuel tracers with different volatility in laser-induced fluorescence measurements.

Han and Steeper [7] conducted experiments with a two-component fuel doped with three fluorescent tracers of different volatility classes in an engine. For late injection timing, an incomplete mixing of the different fuel components at ignition time was found. Also a demixing of the fuel components was shown by Egemann and Leipertz [8] with Raman-measurements in an evaporating two-component fuel spray of high volatility benzene and the high boiling point fuel n-decane in a 1:1 mixture. The measurements were conducted in a high pressure-high temperature injection chamber at 3.0 MPa and 250°C.

In contrast to this, Hoffmann et al. [9] detected a very similar vapor distribution of different boiling point fuel components for sprays at diesel engine conditions (injection pressure $p_F = 60$ MPa, chamber pressure $p_c = 5$ MPa, chamber temperature $\vartheta_c = 527^\circ\text{C}$) by means of laser-induced fluorescence indicating a very rapid evaporation, i.e., a co-evaporation of the fuel components occurs. From this, it can be concluded that the multi-component fuel spray evaporation under a high pressure atmosphere is still a research topic with many open questions. Especially, there is still a lack of quantitative information about the fuel vapor distribution at the spark plug at the point of ignition for SG-DISI engines with late injection. A stratification of fuel components changes the local fuel/air ratio and controls the ignition, combustion and pollutant formation. The spark plug is usually positioned at 10-15 mm from the injector nozzle for spray-guided concepts and ignition starts approximately 1 to 2 ms after start of injection for stratified engine operating conditions in the presence of evaporating droplets.

For a deeper insight into atomization and evaporation processes, in this study a 3-component fuel was observed in comparison with several single component model fuels in an optical accessible pressurized and heated injection chamber. The liquid spray structures and evaporating droplets of a 12-hole solenoid DISI-injector were analysed by Mie imaging and phase Doppler anemometry (PDA). A simplified 3-component fuel was chosen to describe effects of main fractions in the fuel. This fuel mixture was proved and validated to model the realistic spray behavior of a multi component gasoline fuel under charge stratification conditions [10, 11]. Also, a numerical implementation of this simplified surrogate fuel into CFD (Computational Fluid Dynamics) reduces the computational effort. For this, the open source code OpenFoam 1.5 was applied.

EXPERIMENT AND MODEL DEFINITION

MODEL FUEL AND EXPERIMENT

A chamber pressure of 1.5 MPa and a temperature of 400°C were chosen to model late injection timing. These conditions refer to the end of injection close to the ignition time point, see Figure 1. For this injector, the investigated operating point refers to an indicated mean effective pressure (imep) of approximately 2.7 bar.

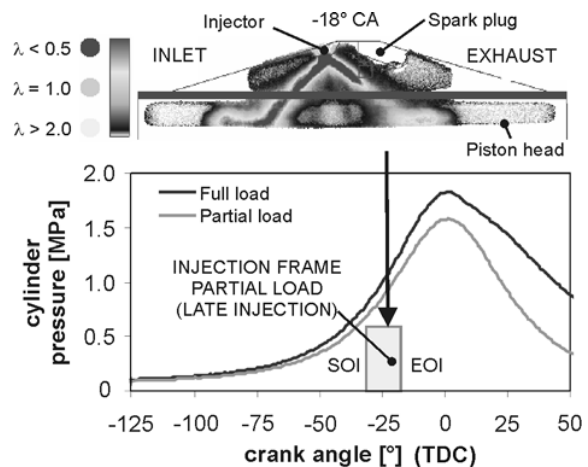


Figure 1: Optical accessible engine with arrangement of the injector close to the spark plug and typical injection frames for partial load conditions. Recording time point is 18°CA (crank angle) before TDC

Additionally, the experiments were also conducted at 20°C and 1.5 MPa to study the fuel dependent atomization. A constant air flow through the injection chamber heats the chamber and scavenges it from one injection to another (air flow velocity < 0.2 m/s) by an injection repetition rate of 1 Hz. The fuel and the injector were conditioned to 70°C similar to engine wall temperatures. The injection pressure was set to 10 MPa with a flexible fuel system. The controlling time of the solenoid-injector (BOSCH, based on the HDEV1.2 with a conical nozzle tip) was kept constant for all investigated fuels at 700 μs , however, an effective injection time of 950 μs results due to a delayed needle closure. A small injected mass of approximately 6.5 mg/pulse was adjusted in accordance to the partial load operating point.

The broad boiling range of gasoline fuels can be modeled with mixtures of n-alkanes (see Table 1).

Table 1: Fuel properties at atmospheric boundary conditions (25°C, 0.1 MPa) [12-15]

	hexane	heptane	decane	3-comp. f.	gasoline
ρ [kg/m ³]	656	664	717	705	720-775
ϑ_b [°C]	66	99	176	66-176	35-210
σ [mN/m]	17.89	19.65	23.37	19.78	22.00
ν [10 ⁻⁶ m ² /s]	0.45	0.58	1.21	0.57	0.53 [1]
p_v [kPa]	19.90	6.06	0.171	-	45.00

ρ = density, ϑ_b = normal boiling point, σ = surface tension, ν = kinematic viscosity, p_v = vapor pressure

During this study, a surrogate 3-component fuel was used to model the boiling curve of gasoline. It contains 35% (by volume) of n-hexane with high volatility, 20% of the high boiling point fuel n-decane, and 45% of n-heptane which covers the middle part of the gasoline boiling range.

To describe the macroscopic spray propagation of the liquid phase, an integral Mie scattering technique using illumination by flash lamps was applied, see Fig. 2. Integral Mie Imaging and phase Doppler anemometry were used consecutively.

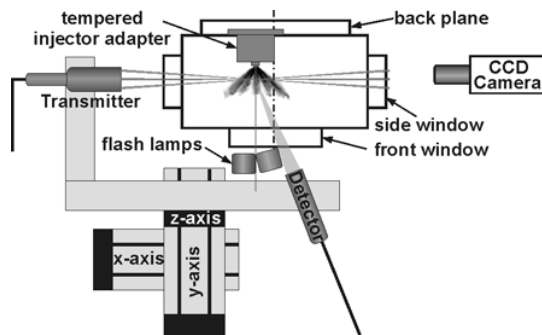


Figure 2: Experimental setup to study the fuel dependent liquid spray structure

The scattered light was detected perpendicular to the measurement plane with a CCD camera with 1,280x1,024 pixels and a dynamic range of 12 bit. Averaged images were calculated from 32 single-shot images. Droplet size and velocity measurements were performed using phase Doppler anemometry in a distance of 10, 15, and 20 mm from the injector tip in several measurement locations, see Fig. 3. The beams of a 5 W argon ion laser (514.5 and 488.0 nm) were split into two parts and utilized for the laser Doppler anemometer.

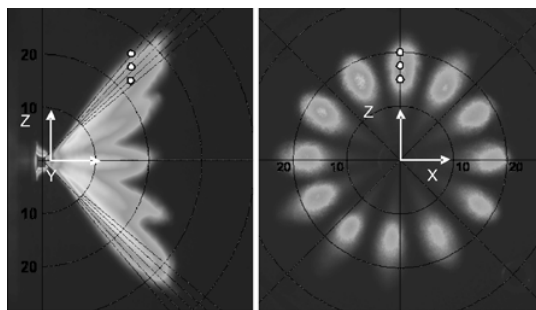


Figure 3: Integral (left) and radial light sheet illuminated sprays (right) with marked PDA-measurement locations in a plane 15 mm from injector tip; Images taken for n-decane at 1,250 μ s after visible start of injection (v. SOI), non-evaporating conditions; (image taken from [16])

The laser beams, one of them shifted in frequency by 40 MHz, were overlapped in an intersection volume by a transmitter optic using a 310 mm collimator lens. The resulting probe volume contained 18 fringes with a fringe spacing of about 4 μ m. The used fiber PDA analysis system leads to a droplet size measurement range of up to 140 μ m. The probe volume was positioned within the spray field using a three-dimensional traversing unit. The scattered light

was detected using an optical receiver with a lens of 300 mm focal length and a receiving aperture mask for small particles. The Brewster angle was chosen for signal detection in order to make the PDA arrangement most insensitive for changes in refraction index due to fractionation and temperature rise in the boiling droplets. For a statistical analysis, 1,200 injections at each measurement location were conducted and 20,000 validated bursts were defined as an abort criterion, respectively. Further details of the PDA measurement setup can be found in ref [16]. For calculation of the droplet size distributions, the droplet size intervals were kept constant for all fuels with an interval width of 0.81 μ m ranging from 0.1 to 50 μ m.

MODEL DEFINITION

Spray model

The spray propagation was simulated for a pressure chamber with a mesh volume of 20 x 20 x 50 mm³ with the 3D-CFD-Code OpenFoam 1.5. Only one jet of the 12-hole injector was modelled since there were no jet-to-jet interactions in the experiments, see Fig. 3. For this, an Euler-Lagrange approach in the RANS context (Reynolds Averaged Navier Stokes) was applied. The inner region of the mesh had a finer resolution (0.32 x 0.32 x 1 mm) and contains the whole spray, see Fig. 4. The nozzle outlet was defined 0.5 mm inside the grid to avoid numerical errors. The surrounding atmosphere was defined as quiescent at initial conditions. The Rail pressure in the experiments was adjusted to be 10 MPa, however, the fuel pressure in the injector was defined to be lower (6.4 MPa) according to the pressure drop in the throttle, at the needle seat and the nozzle holes.

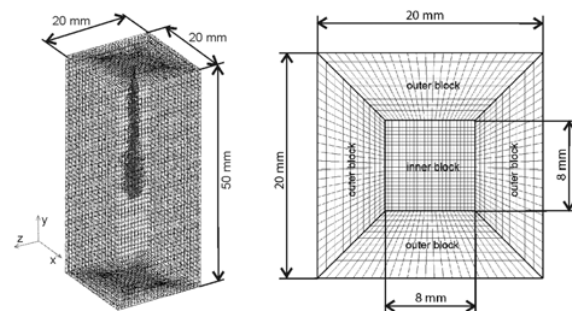


Figure 4: Mesh for spray calculation shown for a typical jet at 1.000 μ s after SOI (left); a finer mesh was applied in the spray region (inner block) and a coarser one at the outer regions

The initial spray angle of the single jet was 20°, which was assumed as constant during the whole injection duration. The nozzle diameter was 125 μ m, see Table 2. The initial droplet diameter range of 1-120 μ m was generated by a Rosin-Rammler distribution which showed a peak at 60 μ m, see Fig. 5. For a statistical representation of the liquid phase in the Lagrangian formulation of the discrete droplet model, a certain number of parcels were defined to represent different groups of identical drops. The number of parcels defines the accuracy of the spray model.

pointed out that 5,000 parcels were sufficient to model the spray in terms of spray shape, penetration and droplet size distribution.

Table 2: Injection model parameters

Injection parameter	value
Injection pressure p_F	6.4 MPa
Spray angle	20°
Nozzle bore diameter d_0	125 μm
Fuel temperature ϑ_F	70°C
Number of computational parcels	5,000

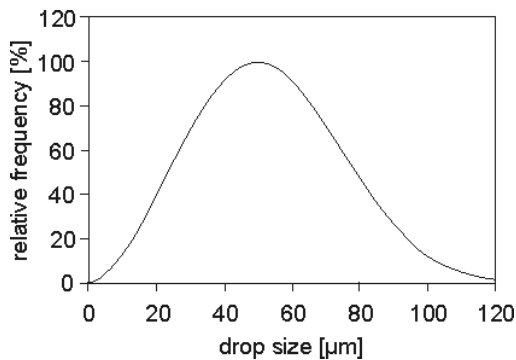


Figure 5: Initial drop size distribution at the nozzle exit modeled by a Rosin-Rammler function

The utilized sub-models for the spray processes atomization, collision, turbulent droplet dispersion, evaporation as well as droplet drag and turbulence are given in Table 3.

Table 3: Applied spray models of the calibrated CFD-Model

Sub-process	Model
Droplet drag	Standard
Turbulence	RNG-k-epsilon
Droplet breakup	ETAB
Collision	trajectory
Droplet dispersion	Stochastic dispersion
Evaporation	Infinite diffusion model

The droplet breakup due to aerodynamic forces has been accounted for by the ETAB-model (Enhanced Taylor-Analogy Breakup) proposed by Tanner [17]. This model is based on an approach by O'Rourke and Amsdan [18] that describes the droplet deformation as a one-dimensional, harmonic, damped oscillation in analogy to a spring-mass system. The included oscillation frequency ω and the deformation time t_d are defined as following:

$$\omega^2 = \frac{64\sigma}{\rho_d d^3} - \frac{1}{t_d^2} \quad (1)$$

$$t_d = \frac{\rho_d d^2}{10\eta_L} \quad (2)$$

The included parameters are the liquid dynamic viscosity η_L , the surface tension σ , the fuel density ρ_d and the droplet diameter d . The droplet breakup occurs for Weber numbers $We > 6$. In the Weber number, the density of the ambient gas ρ_g , the droplet radius r_d , the relative velocity between droplet and gas u_{rel} as well as the surface tension σ is included:

$$We = \frac{\rho_g r_d u_{rel}^2}{\sigma} \quad (3)$$

Two limiting cases were considered: one for low Weber number around six and other for stripping breakup for very large Weber numbers. In the first case breakup occurs when $\omega t_{bu} = \pi$. For high Weber numbers in the stripping breakup regime, the breakup happens much earlier in the oscillation period, i.e. when $\omega t_{bu} \ll \pi$. The breakup time t_{bu} for the respective regime are defined as:

$$t_{bu} = \begin{cases} \pi \sqrt{\frac{\rho_d d^3}{64\sigma}} & \text{(bag breakup)} \\ \sqrt{3} \frac{r_d}{u_{rel}} \sqrt{\frac{\rho_d}{\rho_g}} & \text{(stripping breakup)} \end{cases} \quad (4)$$

The resulting droplet size (radius r_d) was calculated according to Tanner [17]:

$$\frac{r_d}{r_{d,0}} = \exp[-K_{bu} t_{bu}] \quad (5)$$

$$K_{bu} = \begin{cases} k_1 \omega & \text{(bag breakup)} \\ k_2 \omega \sqrt{We} & \text{(stripping breakup)} \end{cases}$$

The equations contain a breakup parameter K_{bu} depending on the breakup regime and, therefore the Weber number. The two correction factors k_1 and k_2 are defined in the model with an default value of 0.2 and will be discussed later.

In the original collision model of O'Rourke [19], the droplet interactions are described statistically with probability density functions in which the parcels tend to collide if they are in the same cell. The collision frequency depends on the computational grid size irrespective of the droplet velocity vector or position in the cell. To compensate this, the trajectory-model proposed by Nordin [20] was applied, which is an advancement of O'Rourke's model formulation, in which the collision occurs if the trajectories of two parcels intersect at a certain collision time even if they are in different cells. However, in both models either droplet coalescence or bouncing is considered, but droplet breakup or separation is neglected.

To describe the droplet evaporation, the infinite diffusion model (or infinite conductivity) was used. For multi-component fuels, the species concentration (which is spatially uniform in distribution inside the droplet) and the droplet temperature depend only on time. This is valid for the liquid fuel having infinitely large heat conductivity which is enhanced by forced