

The Influence of Fuel Properties on Transient Liquid-Phase Spray Geometry and on CI-Combustion Characteristics

Uwe Horn, Helena Persson, Rolf Egnell and Öivind Andersson

Lund University

Erik Rijk

Eindhoven University of Technology

Copyright © 2009 SAE International

ABSTRACT

A transparent HSDI CI engine was used together with a high speed camera to analyze the liquid phase spray geometry of the fuel types: Swedish environmental class 1 Diesel fuel (MK1), Soy Methyl Ester (B100), n-Heptane (PRF0) and a gas-to-liquid derivate (GTL) with a distillation range similar to B100.

The study of the transient liquid-phase spray propagation was performed at gas temperatures and pressures typical for start of injection conditions of a conventional HSDI CI engine. Inert gas was supplied to the transparent engine in order to avoid self-ignition at these cylinder gas conditions.

Observed differences in liquid phase spray geometry were correlated to relevant fuel properties. An empirical relation was derived for predicting liquid spray cone angle and length prior to ignition. Fuel dependent differences in heat-release and emission characteristics from an all-metal engine at similar test conditions were explained by the former correlation and observations from the transparent engine.

It turned out that the cylinder gas density had the strongest effect on both the measured liquid spray angle and the liquid length for fuel with high volatility. Moreover it was observed that the inverse correlation between liquid spray length and cylinder gas density decreased with fuel volatility which had a strong effect on combustion and emission characteristics under highly premixed combustion at low load conditions.

The injection pressure was found to be a major combustion controlling parameter in order to compensate for deteriorated combustion properties of low volatile fuels at highly premixed combustion.

Even though B100 and GTL have similar volatility and liquid spray properties, the combustion behaviour differed considerably which was explained by the difference of oxidizer-fuel ratio at locally fuel-rich conditions.

INTRODUCTION

The increasing price levels on the fuel market open for the substitution of conventional fuel-types by alternative fuel-types. Alternative fuels have therefore gained increasing interest. Large scale application of alternative fuel types in today's diesel combustion engines, however, makes it necessary to compensate for observed fuel dependent variation in combustion- and emission-characteristics in order to meet future emission legislation.

The impact of fuel properties (Table 1) on the CI combustion process and the behaviour of the liquid phase spray characteristics have already been researched extensively. In order to predict the maximum liquid penetration length and angle with respect to fuel properties and combustion conditions several relations have been derived. [1-5]

Table 1: Properties of the tested fuels

Fuel Property	PRF0	MK1	B100	GTL
T ₁₀ [°C]	100	204	355	313
T ₅₀ [°C]	100	229	356	339
T _{90,B} [°C]	100	265	362	364
kinematic viscosity [mm ² /s] (40°C)	~0.35	1.78	4.06	5.98
surface tension [N/m]	~.020	~.025	~.023	0.03
density (15°C) [g/l]	683	813	885	804
LHV _m [MJ/kg]	44.4	43.15	37.2	46.9
LHV _v [MJ/l]	~30.32	35.08	32.88	~30
C _{p,liqu} [kJ/kgK]	~2.16	~2.4	~2.6	2.8
Q _{vap} [kJ/kg]	~310	~250	~240	~230
SAFR [m/m]	15.3	14.9	12.53	14.7
auto-ignition temperature [°C]	220	255	285	325
C (w%)	84	86	77	86
H (w%)	16	14	11	14
O (w%)	0	0	10	0
CN	~60	57.1	56	>70
ICN	~60	24	56	~50
FCN	~60	~70	55	~70

Within the scope of this study it is investigated how the fuel properties, the injection pressure and the cylinder gas conditions influence the transient liquid phase spray characteristics between start of injection (SOI) and start of combustion (SOC).

The fuel dependent spray measurement results from a transparent engine are used as an empirical liquid spray database. This database was used in order to explain observed differences of an all-metal engine performance at varying operating points with respect to fuel and spray properties.

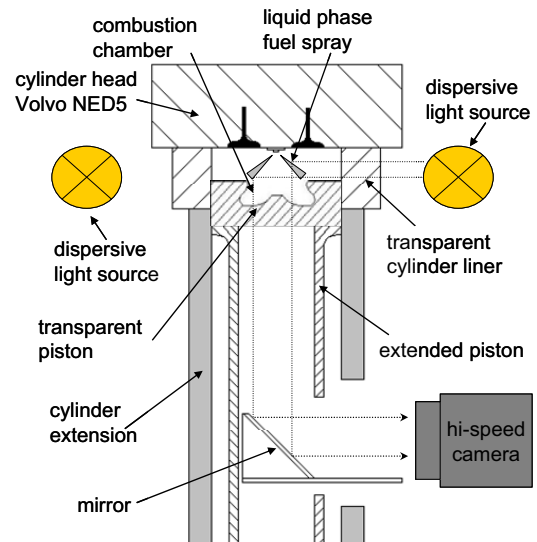
A fuel parameter correlation analysis between the fuel properties from Table 1 and the spray measurement data (cf. Appendix–Table 7) shows that the fuel boiling range, the viscosity and the liquid mass specific heat capacity have a strong correlation with each other. Within the scope of this study, the correlation of these fuel properties is called fuel volatility. The fuel volatility is quantified by either the boiling point for PRF0 or the mid-point distillation temperature T50 for other fuel types.

ENGINE EXPERIMENTS

In order to limit the number of experimental variables, both transparent engine and all-metal engine experiments were based on a single injection strategy with a top-hat shaped fuel rate.

TRANSPARENT ENGINE SETUP

The transparent engine was equipped with optical access through the piston and the cylinder liner. The transparent cylinder liner access was used to illuminate the liquid phase of the spray with dispersive light sources in order to minimise local high-intensity reflection from engine components.

**Figure 1: Transparent Engine Setup**

The transparent piston was used for filming the illuminated injection process with a high speed camera (Phantom V 7.1 – Vision Research) at a sampling rate of 24096 frames per second. In order to avoid self-ignition at metal-engine-like cylinder gas conditions, inert gas (burner exhaust gas) was fed to the transparent engine inlet.

The engine geometry was based upon a CI passenger car engine (Volvo i5d) with the following properties:

Table 2: Specifications for Transparent and Metal Engine

Cylinder Head type	Volvo i5d
Bore	81 mm
Stroke	92.3 mm
Displacement	480 cm ³
Compression Ratio $r_{c,eff,transp}$	13.5
Compression Ratio $r_{c,stat,metal} / r_{c,eff,metal}$	16.15 / 15.6
Injection Cone Angle	140°
Injector Type	solenoid
Injection Nozzle Hole (Number x Diameter)	7x0.14 mm

A capacitive pressure sensor (AVL GU12s-10) was used for in-cylinder pressure indication. The effective compression ratio ($r_{c,eff}$), the cylinder gas temperature and the cylinder gas density at TDC ($T_{CylGas,TDC}$, $\rho_{CylGas,TDC}$) were derived from the polytropic correlation between cylinder gas pressure, inlet pressure and inlet temperature by assuming a constant polytropic coefficient of $\kappa = 1.35$:

$$r_{c,eff} = \frac{p_{CylGas,TDC}^{\frac{1}{\kappa}}}{p_{inl}} \quad (1)$$

$$T_{CylGas,TDC} = T_{inl} \cdot r_{c,eff}^{\kappa-1} \quad (2)$$

$$\rho_{CylGas,TDC} = \frac{p_{CylGas,TDC}}{R_{CylGas} \cdot T_{CylGas,TDC}} \quad (3)$$

The measurement variables for the liquid spray study are shown in Table 3:

Table 3: Measurement Variables

$\rho_{CylinderGas, TDC} [kg/m^3]$	15 ... 30
$T_{CylinderGas, TDC} [K]$	800 ... 1000
$p_{Inj} [MPa]$	20 ... 100

The inlet gas pressure and temperature were chosen in order to generate all-metal engine application-like cylinder gas conditions at TDC.

The injection duration was chosen from the start of injection (SOI) to the end at steady state spray conditions. The measurement signal was saturated at a distance of 22 mm from the injection nozzle due to liquid spray impinging on the combustion chamber wall.

METAL ENGINE SETUP

The all-metal engine measurements were carried out with a similar engine as during the spray tests. The cylinder head, the piston, and the common-rail (CR) injection system of a Volvo i5d HSDI Diesel engine with the specifications shown in Table 2 were used. The effective compression ratio of the metal engine was higher compared to the transparent engine.

The most important sensor signals used for the analysis are depicted in Figure 2:

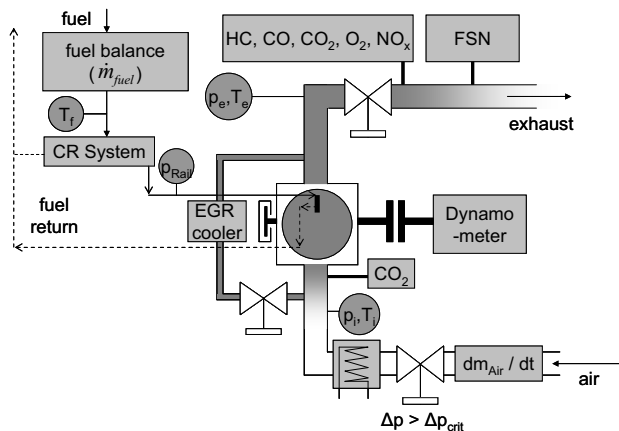


Figure 2: Experimental Setup

Smoke emissions were measured with a smoke meter (AVL415S). NOx emissions were measured with a chemiluminescence analyser whereas HC emission measurements were done by means of a flame ionization analyser (FIA). Intake CO₂, exhaust O₂, CO and CO₂ sample gases were dehumidified before IR measurement. NOx and HC emissions were measured at a temperature of 191°C.

Fuel mass flow was measured by a fuel balance (Sartorius cp8201) over a time span of 120 seconds. For increased accuracy at low load conditions, fuel mass flow was also derived from the intake air mass flow and air-fuel ratio (λ) derived from exhaust gas measurements.

The intake pressure was controlled directly by an external compressor. The intake air mass flow was measured by a thermal mass flow meter (Bronckhorst IN-FLOW). In order to prevent pressure oscillations to propagate from the intake manifold upstream into the flow meter, the flow meter was situated upstream a pipe diameter contraction causing a super-critical flow. The measurement error of the flow meter is specified as not being higher than 0.4% of the minimum measured flow. The maximum emission measurement error is not above 0.5%. The overall maximum measurement error of the calculated fuel mass flow is thus 0.9% of the measured value.

The cylinder pressure was measured with a piezoelectric pressure sensor (Kistler 6056) at an engine-speed dependent sample rate of 0.2°CA. High resolution measurement data was averaged from 150 engine cycles whereas low resolution measurement data was sampled over a time period of 120 seconds.

The test conditions shown in Table 4 were chosen in order to relate engine load and fuel type depending combustion characteristics to transient liquid spray characteristics:

Table 4: Engine test conditions

Engine speed	1200 rpm
IMEP	~2 ... 10 bar
Inlet temperature	80 °C
Inlet pressure	1 ... 2 bar _{abs}
Injection pressure	200 ... 700 bar

EXPERIMENTAL RESULTS – TRANSPARENT ENGINE

The following picture shows a typical raw image for the four examined fuel types:

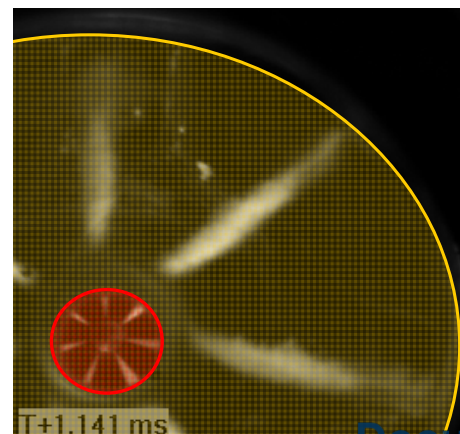


Figure 3: Liquid Phase Spray Raw Image for MK1

The inner spray region (red area in Figure 3) was used to determine the liquid phase spray angle by the correlation:

$$\tan\left(\frac{\Theta_L}{2}\right) = \left(\frac{A_{\text{Spray}}}{L_{\text{Area}}^2}\right)_L \quad (4)$$

In order to calculate the transient liquid length, the outer spray region (yellow area in Figure 3) was used to determine the average intensity of an arc within the liquid spray phase at a certain axial distance and comparing it to an intensity threshold value. [6]

The liquid fuel characteristics of the inner region differ from the outer region fuel characteristics due to the fuel spray break-up process which entails a larger number of droplets in the outer regions compared to the inner region which has a close proximity to the injector nozzle holes.

The correlation between liquid phase spray characteristics, measurement conditions and fuel type are depicted in Table 5 and Table 6. A positive correlation between the measurement variables p_{Inj} , ρ_{Gas} , T_{gas} and the liquid spray characteristics L_{meas} , Θ_L , v_{L90} means that the spray parameters increase together with the measurement variables. A negative correlation stands for the opposite behaviour.

Table 5: Measurement Variable Correlations

R_{MeasVar}	L_{meas} [mm]	Θ_L [deg]	v_{L90} [m/sec]
p_{Inj} [bar]	0.19	0.64	0.61
ρ_{Gas} [kg/m ³]	-0.37	-0.05	-0.28
T_{gas} [K]	-0.17	0.00	-0.08

Cylinder gas density (ρ_{Gas}) and temperature (T_{gas}) correlated negatively with the maximum liquid spray length. The time-averaged spray propagation velocity v_{L90} was defined as the quotient of 90% of the maximum measurement liquid length and the time needed to reach that length. This propagation velocity correlated positively with the injection pressure.

In the following the results of a fuel type dependent linear correlation analysis of measurement variables to spray parameters is presented (Table 6).

Table 6: Fuel Dependent Measurement Variable Correlation of the Maximum Liquid Spray Length, the Liquid Spray Angle and the Average Spray Propagation Velocity

	PRF0	MK1	GTL	B100
density[g/l]	683	813	804	885
T50 [°C]	100	229	339	356
L_{meas}				
p_{Inj} [bar]	0.12	0.27	0.26	0.35
ρ_{Gas} [kg/m ³]	-0.84	-0.71	-0.43	-0.62
T_{gas} [K]	-0.38	-0.35	-0.19	-0.35
Θ_L				
p_{Inj} [bar]	0.08	0.68	0.84	0.84
ρ_{Gas} [kg/m ³]	-0.76	-0.05	0.04	0.05
T_{gas} [K]	-0.31	0.00	0.03	0.08
$v_{L,\text{mean}}$				
p_{Inj} [bar]	0.20	0.74	0.87	0.84
ρ_{Gas} [kg/m ³]	-0.21	-0.34	-0.33	-0.45
T_{gas} [K]	0.07	-0.20	-0.08	-0.20

The correlation coefficients give an indication on the sensitivity between the measurement input variables (p_{Inj} , ρ_{Gas} , T_{gas}) and the measurement output variables (L_{meas} , Θ_L or $v_{L,\text{mean}}$). A positive correlation coefficient stands for a positive effect of the measurement variables and the output variables and vice versa.

For the low volatile fuel types (MK1, GTL, B100), the injection pressure (p_{Inj}) had a strong correlation to liquid spray angle, liquid spray length and the liquid spray propagation velocity (v_{L90}); no correlation was observed for the PRF0 fuel type (cf. Table 6 – Θ_L , p_{Inj}).

The influence of cylinder gas density on the liquid penetration length (L_{meas}) correlates with fuel volatility (Table 6 – L_{meas}). For $v_{L,\text{mean}}$, an increasing correlation of cylinder gas density to fuel density (cf. Table 6 – density) was observed. The positive response of L_{meas} and $v_{L,\text{mean}}$ on p_{Inj} can be counteracted by increasing cylinder gas density which correlates negatively to both $v_{L,\text{mean}}$ and L_{meas} .

For the fuel type PRF0 a strong negative correlation between cylinder gas density, gas temperature and liquid spray angle Θ_L was observed. The negative correlation of cylinder gas density, gas temperature and Θ_L for the PRF0-case (Table 6 – Θ_L) is explained by its evaporation behaviour: For PRF0 an increase of ρ_{gas} , T_{gas} together with low fuel density improves air-entrainment, increases the evaporation velocity and entails a lower liquid fuel fraction during the injection process; Θ_L decreases as the measurement signal responds on liquid fuel only. This behaviour was not observed for the heavier fuel types, it is concluded that evaporation rates prior to combustion are less affected by cylinder gas temperature and density due to the low volatility.