

High-Speed Characterization of ECN Spray A Using Various Diagnostic Techniques

Maarten Meijer

Eindhoven University Of Technology

Jonas Galle

Ghent University

L.M.T. Somers

Eindhoven University Of Technology

J.G.H Griensven

Technical University - Eindhoven

Sebastian Verhelst

Ghent University

ABSTRACT

Diesel spray experimentation at controlled high-temperature and high-pressure conditions is intended to provide a more fundamental understanding of diesel combustion than can be achieved in engine experiments. This level of understanding is needed to develop the high-fidelity multi-scale CFD models that will be used to optimize future engine designs.

Several spray chamber facilities capable of high-temperature, high-pressure conditions typical of engine combustion have been developed, but because of the uniqueness of each facility, there are uncertainties about their operation. The Engine Combustion Network (ECN) is a worldwide group of institutions using combustion vessels, whose aim is to advance the state of spray and combustion knowledge at engine-relevant conditions. A key activity is the use of spray chamber facilities operated at specific target conditions in order to leverage research capabilities and advanced diagnostics of all ECN participants. The first target condition, called "Spray A", has been defined with detailed ambient and injector conditions.

For this paper, we describe results from the constant-volume pre-burn vessel at Eindhoven University of Technology. The executed measurements include a wide range of diagnostics to characterize "spray A" in reacting and non-reacting conditions in great detail. Observations of spray penetration, ignition, liquid length and flame lift-off location by using several high-speed imaging diagnostics are discussed and compared with other ECN participating institutes.

Comparison Spray A data from the other participating institutes, as it was presented during the 2nd ECN workshop is gathered from the ECN website database [1]. It can be concluded that the obtained results from the standardized ECN spray diagnostics, show satisfactory similarity, despite of the challenge to reach similar boundary conditions (ambient and injector) in each of the unique facilities. The differences in results are within the measurement deviation and uncertainty or can be explained by the usage of (slightly) different injectors. Combining the results of the different measurement techniques provides an overall (time resolved) overview where the different phases of fuel injection are directly linked and summarized. The presented overview provides a direct input for (CFD) modeling validation.

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INTRODUCTION

Spray A is related to a relatively low-temperature diesel engine combustion condition relevant to engines that use a moderate rate of EGR. The most relevant boundary conditions and injection properties are summarized in [table 1](#). A more detailed description can be found at www.sandia.gov/ecn [1]. The selected injection lay-out and injection pressure are based on modern advanced common-rail injection systems. In addition the injector, common rail, fuel line and specific details such as the location of the fuel line are specified to ensure consistent hydraulic effects during injection.

A single-component diesel surrogate fuel; n-dodecane, is chosen to enable a complete specification of the chemical and physical properties of the fuel. Furthermore, n-dodecane is often used as a single component surrogate fuel; because it's H/C ratio and boiling temperature characteristics are comparable to diesel. Detailed chemical kinetic mechanisms exist for n-dodecane allowing full treatment of the combustion chemistry [2].

Table 1. Overview “spray A” boundary conditions and hardware. *Ambient conditions are referred to the core properties in the vessel

Ambient gas density* [kg/m ³]	22.8
Ambient oxygen conc [vol%]	0 & 15%
Ambient gas temperature* [K]	900
Ambient gas velocity [m/s]	< 1
Nozzle outlet diameter [μm]	90 (single nozzle)
Nozzle K factor [-]	1.5
Discharge coefficient [-]	0.86
Mini-sac volume [mm ³]	0.2
Injection pressure (MPa)	150
Fuel	n-dodecane
Fuel temperature [K]	363
Injection duration [ms]	1.5

EXPERIMENTAL SETUP

The used test apparatus for the presented work is the Eindhoven High Pressure Cell (EHPC). Main vessel dimensions and other main characteristics are given in [table 2](#) and an image of the set-up is presented in [figure 1](#). More comprehensive details regarding this particular setup can be found in [3].

Table 2. Main combustion vessel characteristics

Window aperture	100 mm
Chamber volume	1260 cm ³
Injector mounting	Horizontally, side window
Injector tip protrusion	5 mm
Mixing fan location	Upper corner near injector
Fan speed	App. 1900 rpm
Spark plug position (2x)	Opposite Diagonal corners, top & bottom.
Inner body temperature	453K
Combustible gas fill	sequential

The EHPC is an optically accessible constant volume combustion vessel where elevated temperature and pressure conditions are created by using the so-called pre-combustion method. The desired ambient conditions at the moment of fuel injection are created by igniting a carefully selected combustible premixed gas mixture inside the combustion chamber. The constant volume high pressure combustion vessel is optically accessible through three 50 mm thick Sapphire windows with a diameter of 100mm. The inner combustion chamber walls are heated to 453 K.

Following the spark-ignited premixed combustion, the combustion products cool down over a relatively long time due to heat transfer to the vessel walls and the vessel pressure slowly decreases. Multiple spark plugs are utilized in combination with high capacity coils to provide consistent ignition of fuel-lean mixtures. A mixing fan stirs the gases during filling and throughout the complete experiment to minimize mixture density and temperature non-uniformities. A relatively low fan speed is selected in order not to exceed the prescribed ambient gas velocity of 1 m/s. When the desired pressure and temperature are reached, the diesel fuel injector is triggered and fuel injection occurs.

An important aspect of the ECN is to perform experiments under well-defined and controlled conditions. The characterization of these conditions for the EHPC and a comprehensive review on these conditions for other institutes can be found in ref [2, 4].

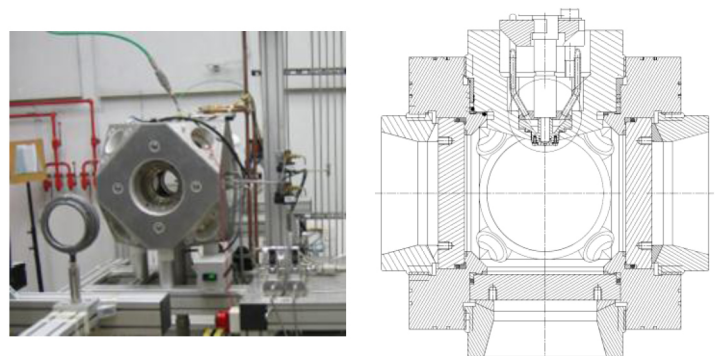


Figure 1. Used experimental set-up: the EHPC pre-burn combustion vessel. Right schematic: top view.

ECN “Spray A” Hardware

A limited set of well characterized dedicated injectors is available for ECN “spray A” diagnostics. All injectors are manufactured according to the same specifications but small differences still exist. Therefore each individual injector is characterized in large detail [1]. For the TU/e experiments, described in this paper, “Spray A” injector with serial number 679 is used.

The different nozzles used by the different participating institutes are shown in table 3. When comparing results from the different participating institutes, it is important to consider the effects of the differences in nozzle diameters. Corrections were made, based on earlier reported OD models for the nozzle diameter for the flame lift-off length (FLOL) [5], liquid length (LL) and spray penetration [6].

Table 3. Nozzles and their measured diameter used by the different institutes for “spray A” measurements. The theoretical diameter is 90 μ m (*data obtained from ECN2 workshop)

Institute	nozzle	Nom. Diameter*
Sandia	#677	84.1
IFPEN	#678	88.6
CMT	#675 & #678	89.4 & 88.6
TU/e	#679	83.7

As high-speed measurement of fuel pressure can add much information about the hydraulics within the fuel system, and their impact on rate of injection, the location of the fuel pressure measurement is specified. This is done to promote repeatability at different facilities. All other prescribed “spray A” hardware (as indicated in the introduction section) is implemented on the EHPC set-up before starting any experiments.

Beside the standardized ECN hardware, system upgrades have been implemented to improve the measurement accuracy and repeatability. The most significant modification is the location and design of the injector window. The injector is mounted horizontally on the side of the vessel and the mounting window has a conical shape (see the schematic in Figure 1). The motivation for this is to place the injector tip outside the cold boundary layer. The horizontal mounting of the injector at the mid plane of the vessel avoids injecting in the hot gasses which are located in top of the vessel (buoyancy driven) after the pre-burn event. A ceramic injector tip cover is used to avoid an increase in temperature of the fuel due to exposure of the injector tip to the hot gasses inside the vessel after the pre-burn event.

Because of the hardware modifications, boundary conditions are re-evaluated (validated for earlier obtained results described in [4]). Injector fuel and gas (core) temperature are measured with a thermocouple instrumented “dummy” injector and fine wire thermocouples respectively. The fine wire thermocouple experiments were performed in order to define the ratio of the core and bulk temperature of

the ambient gas. The last can be derived from the ideal gas law and the measured pressure during and after the pre-combustion. The ratio was found to be 1.08 for spray A conditions in the EHPC set-up which is similar to the value found before implementing the hardware modifications to the set-up. Knowledge of this ratio allows injecting at the correct conditions based on the pressure measurements. The used methods are described in more detail [4]. The fuel temperature distribution inside the injector is shown in figure 2. Based on the results presented in figure 2 and the fact that the required amount of fuel for one injection is located up till 4mm inside the injector body volume, it can be concluded that the fuel temperature uncertainty reduced to 5 K.

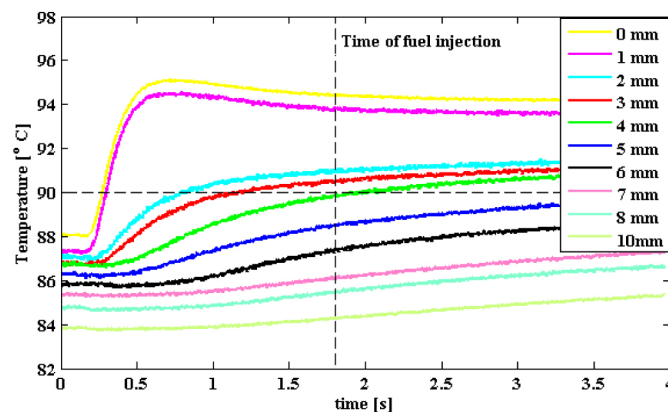


Figure 2. Injector fuel temperature distribution at different locations inside the injector nozzle.

FLAME LIFT-OFF LENGTH

An important and often studied characteristic of direct fuel spray combustion is the location where the flame front initiates and stabilizes during an injection event. The distance from the injector of reaction zone stabilization after the time of auto-ignition is traditionally called the Flame Lift-Off Length (FLOL). The FLOL has a strong effect on diesel combustion. Flame lift-off allows fuel and air to premix upstream of the lift-off length, which affects the combustion and soot formation processes downstream [5]. In this section FLOL measurement techniques and results are discussed. A high speed imaging method is implemented in order to obtain a time-resolved overview of the FLOL behavior.

The presented FLOL measurements are based on intensified high speed recordings. The detection of high-temperature chemiluminescence from excited-state OH (OH*) indicates the location of the flame [5]. Normally OH* measurements are executed with a (single shot) ICCD camera and a relatively long exposure time (app. 0.5 ms). In this case the low intensity signals are intensified by a high speed intensified relay optic system (LaVision IRO) which is lens coupled to a high speed camera (Phantom V7.3). A 310 (10 nm FWHM) optical bandpass filter is used for the experiments in order to capture the light emitted by the OH*-molecules and to block and avoid overexposure primarily

caused by soot incandescence as much as possible. A schematic overview of the setup is shown in figure 3 and the used settings for the camera and intensifier are shown in table 4.

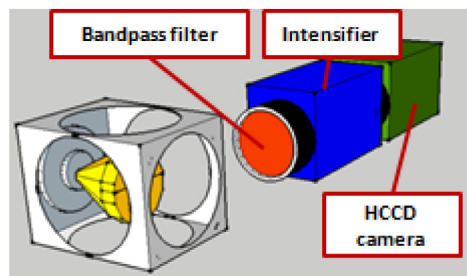


Figure 3. Schematic overview of the optical set-up used for FLOL measurements.

Table 4. Settings flame lift-off length measurements.

Frame rate	21 [kHz]
Resolution	0.2041 [mm/px]
Gating time	20 [us]
Gain [%]	75 [%]
Bandpass filter	310 [nm]

Post-processing of the FLOL recordings is done in 2 different ways. The first method is dedicated to make a direct comparison with the obtained measurement data from the other participating ECN institutes; Sandia, IFPEN and CMT. These institutes all used single shot ICCD cameras with a relatively long exposure time to capture the steady FLOL resulting in a “chip averaged” image [7],[8]. Therefore for each TU/e experiment, a time-averaged image was generated by averaging the individual shots within the steady FLOL period of the injection.

For direct CFD modeling validation, the time resolved evolution of the location of OH* will give a better insight in the evolution of the flame. For this method both the minimum and maximum location are of interest. In this case, the minimum distance can be regarded as the traditionally defined FLOL and the head of the flame as the maximum flame penetration.

The time averaged FLOL threshold is traditionally defined as; the position at which 50% of the maximum intensity from the “knee” value is reached. The intensity profile is obtained along axial spray axis [7]. An example of an obtained intensity profile is shown in figure 4.

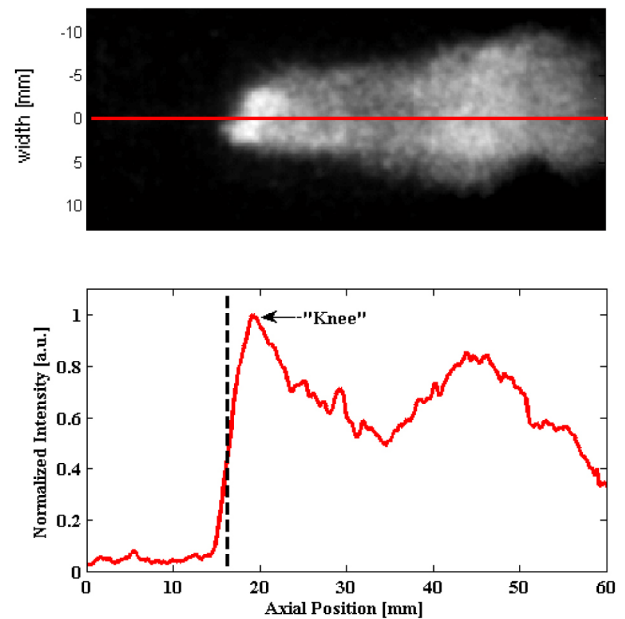


Figure 4. Time averaged FLOL post-processing method. Showing the FLOL based on the 50% max intensity.

One conclusion drawn from the obtained images is that the used measurement approach suffers from internal reflections from the, uncoated and therefore (too) shiny, combustion vessel walls. The slight increase in intensity observed from the injector tip at 0mm up-till app. 15 mm downstream reveals this effect on the intensity profiles. Although this is an undesired effect, it appears not to influence the obtained result since this “noise” is far below the used threshold value.

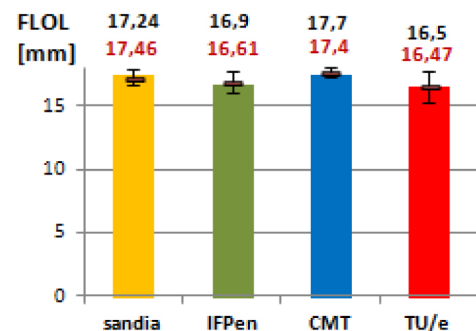


Figure 5. Comparison of the flame lift-off length (FLOL) between different institutes. The original values are shown in black at the top; the corrected values for the nozzle diameter [5] are shown in red below (data from the ECN2 workshop).