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Engine Combustion Network (ECN): Characterization and comparison of Diesel spray combustion in new high-pressure and high-temperature chamber

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1. Introduction

In order to provide new accurate data about diesel spray and combustion processes to improve a better understanding of physical processes and also the modelling concepts and models themselves, several new combustion chambers have been developed to reach thermodynamic conditions of actual Common-rail diesel engine [1–3]. The new One Shot Engine (NOSE) has been designed to simulate these thermodynamic conditions at High Pressure-High Temperature [4][5] to study the diesel spray and combustion. The advantage of this kind of set-up in comparison to pre-burn or flue chambers is that the initial gas mixture can be well controlled in terms of species and mole fraction. Indeed, as example, the combustion of spray in more realistic environment can be done without H₂O and CO₂ or with species, representing the burnt gases. Therefore, our first objective was to share the experimental results required by Engine Combustion Network (<https://ecn.sandia.gov>) [6] which represents the international reference in the establishment of high-quality and quantitative data sets for engine spray combustion to develop and improve models.

The purpose of this work is to present experimental results from different classical data already available by ECN and to discuss about the limitations of NOSE. For that, first the non-reactive standard Spray-A condition (900 K, 60 bar, and 22.8 kg/m³ with pure Nitrogen) was reached to evaluate the accuracy of the set-up in terms of liquid and vapor penetration lengths, respectively characterized by Schlieren and Diffused-Back Illumination. The NOSE set-up was also improved to provide conditions for different ambient temperatures (800 K and 850 K). Second, in

reactive conditions, the Lift-Off Length (LOL) was measured by OH* chemiluminescence images. Last, different techniques as the Schlieren and OH* chemiluminescence were used to measure Ignition Delay (ID) and compared.

The consistency of the data obtained from liquid length and spray penetration indicates a good level of repeatability and outlines a global agreement with the ECN dataset. Mainly differences are observed for ID and LOL, due to variations and inhomogeneities of the temperature field, especially in the case of 800 K. To provide a more homogeneous temperature field, different compression ratios (CR) have been tested and the chamber temperature characterized by using 4 fine wire thermocouples of 25 μm diameter. Results show that homogeneous temperature inside chamber leads to higher ID than inhomogeneous conditions.

2. Research Method and Procedure

2.1 Experimental set-up

NOSE set-up is based on one-cylinder low-speed diesel engine of 18 HP at 750 rpm. This cylinder is 155 mm bore diameter and 177.8 mm stroke (Fig. 1). The original cylinder head was replaced by a dedicated chamber, designed by extending the combustion chamber for supporting optical technique measurements and studying Diesel sprays. The operating condition (900 K ambient gas temperature, 60 bar cylinder pressure and 22.8 kg/m³) is relative with real operating condition in the engine by using moderate exhaust gas recirculation (EGR).

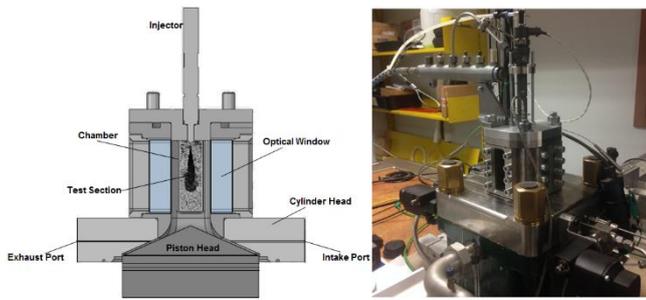


Fig. 1. The NOSE chamber: cross-section view (left) and complete chamber view (right).

To achieve standard Spray-A condition, the compression ratio was set up at 15:1 by modifying the shape of the piston head. The main specifications of NOSE chamber given in Table 1. Further details about the chamber design, thermal characterization chamber, specification of the injection system, and data acquisition system can be found in previous study [4].

Table 1. Main specifications of NOSE.

Specifications	Value
Sweep volume	3600 cm ³
Bore x Stroke	155 x 177.8 mm
Compression ratio	15:1
Number of optical window	4
Window size	25 x 80 mm
Intake gas (able to switch)	N ₂ , O ₂ , Air and Other
Cooling system of Engine	Water
Engine speed (at TDC)	~100 rpm

The experimental set-up about the different optical techniques needed to characterize macroscopic spray of non-reactive and combustion parameters has been described in detail elsewhere [4], and only a short summary will be given here.

The Diffused-Black Illumination (DBI), consisting of only two main components: white color-LED light source and camera, was implemented to determine liquid penetration length (LL). High-sensitivity Schlieren technique based on the measurement of the bending light source through the testing section was set-up to estimate the vapor spray penetration (S). To detect the main flame of ignition delay (ID), a Photomultiplier tube side-on with a high voltage power supply and a band-pass filter of 307 nm (FWHM 10) was used to follow the temporal OH* chemiluminescence. It was also compared to the values obtained from high speed Schlieren. Finally, an ICCD was used with a 60 mm f/3.5 UV lens and equipped with a 310 nm (FWHM10) band-pass filter to measure the distance between the injector tip and the stabilized flame of the high-temperature reaction zone, defined as the Lift-Off Length (LOL).

3. Results and Discussion

Results and Discussion are divided into five different sections. Liquid length results as function of the ambient temperature is shown in the first section. Then the temporal development of vapor spray penetration is presented. An important part is dedicated to the impact of the Compression Ratio on the homogeneity of the chamber, a discussion about the temperature field is presented. Last, ID and LOL versus ambient gas temperature for different CR are presented and compared to previous results from ECN.

3.1 Liquid length

Fig. 2 shows the results of averaged LL obtained from 12 repetitive tests versus ambient gas temperature and compared to IFPen [7]. For ECN condition (900 K), the results of LL obtained with this set-up are between 11.7 mm and 11.1 mm, with an average of 11.4 mm and 1.7 % Standard Deviation (STD). Overall, the results from this work are 5% lower in average than in [7].

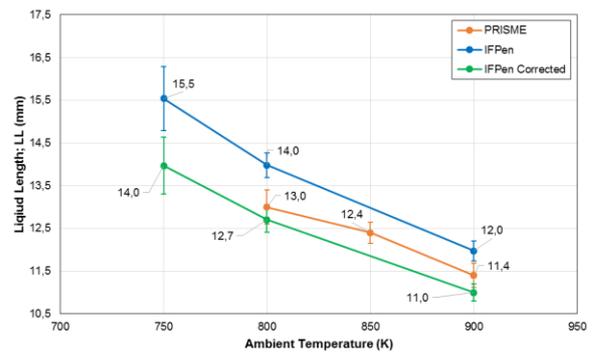


Fig. 2. LL versus ambient gas temperature compared to IFPen

3.2 Vapor Spray penetration

The vapor spray penetration length (S) is defined at front spray that crosses with spray axis [8]. S is determined by using standard code available from ECN to reduce uncertainties from post-processing.

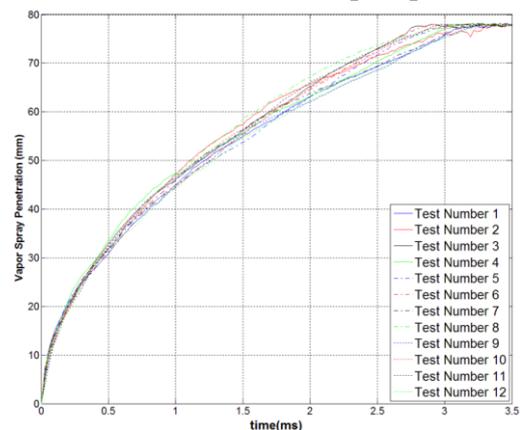


Fig. 3. Vapor spray penetration length (S) profile of 12 repetitive tests.

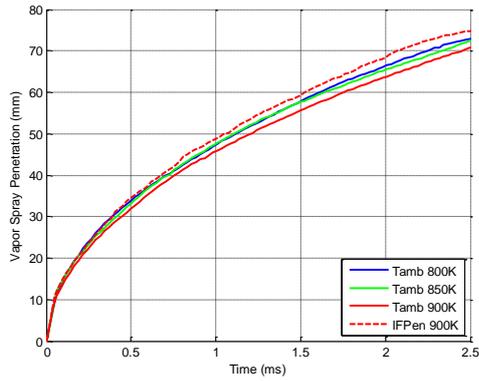


Fig. 4. Comparison of vapor spray penetration length to IFPen.

Fig. 3 shows the results of S for 12 tests done at the same condition of $CR=13.5$: a very good accuracy is obtained below 20 mm (% of STD), and until 78 mm, the global trend is similar even if STD represents until ...%. From 78 mm, the effect of the edge of the optical window is indicated by the non-evolution. 2 ms after Start of Injection, a variation of about 8% in values can be observed on S . The comparison of these results from IFPen values confirms the discrepancy after 0.8 ms after start of injection. This can be explained by the difference of momentum and gas flow inside the chamber due to the difference set-up. Especially in Fig.4, this effect can be observed at 900 K. The trend of 800 and 850 K is slightly higher than 900 K. These differences may be due to the gas density variations.

3.3 Thermal characterization

A slight inhomogeneity of temperature inside the chamber can lead to different results on ID and LOL. In previous work [1], LOL measurements from IFPen were lower than those from Sandia, even if both used preburn chamber. This shorter lift-off length is consistent with the shorter measured ID at IFPen, as studies show that sprays with shorter ignition delay tend to have a shorter lift-off length [9].

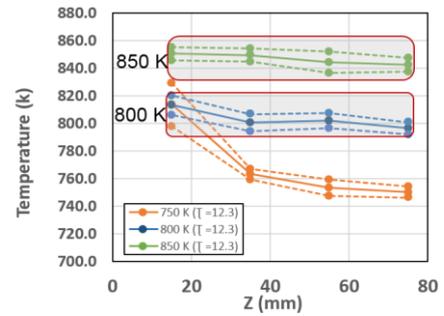
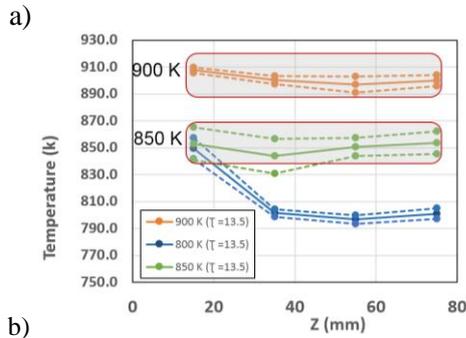


Fig. 5. Thermal characterization of NOSE for 2 CRs (a) $CR=13.5$. (b) $CR=12.3$. The gray region represents the range of homogeneous temperature zone where STD is lower than 2%.

In addition, ID and LOL are known to be highly sensitive to ambient temperature [10] which implies that there is a temperature difference between the two facilities. Thus, the slight difference between LOL and ID measurement from different set-ups can be attributed to the difference between initial temperature of cooling and heating chamber leading to get inhomogeneous gas temperature at TDC.

A thermal characterization of the chamber has been performed for NOSE set-up and it was improved to provide homogenous conditions for different ambient temperatures as 800 K and 850 K by changing the CR by modifying the thickness of the plate between piston roof and the piston base. As illustrates the graph of the temperature in function of the distance from the tip of the injector (z) for the different compression ratio (Fig.5), where the value of each point is averaged over 5 ms around TDC, a slight decreasing at the beginning is observed then the temperature stabilizes. The appearance of two homogeneous regions for each CR is very clear; for example $CR=12.3$, two homogenous regions have been obtained for $T=850$ K and $T=800$ K. One can also notice that in the case of 750 K, to get homogenous region at 750 K, higher cooling temperature is needed which not possible to reach due to water temperature which cannot exceed 97°C . Therefore, the measurements with NOSE apparatus with homogeneous temperature can not be done below 800 K. By improving the quality of the homogeneity, in the next section the impact of this homogeneity on ID and LOL will be discussed.

3.4 Effect of CR on Ignition delay

In this part, the results of ignition delay from Schlieren technique, identified as the hot flame ignition delay, are presented. As expected, IF decreases with the increase of ambient temperature (Fig. 6), due to the increase of fuel atomization and evaporation rate.

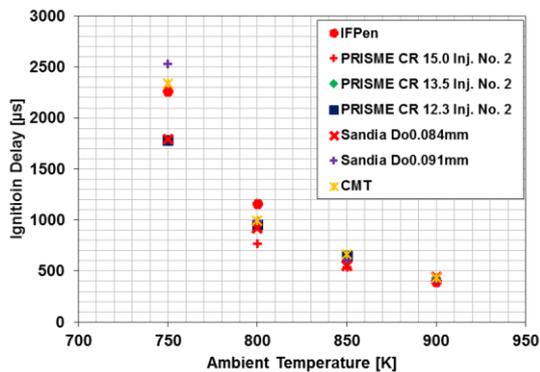


Fig. 6. Measured ID versus ambient gas temperature for different CR.

The comparison of the measured ID for different ambient temperatures compared to data available in ECN presents slight differences. As 750K, the temperature field in NOSE is less homogeneous, the discrepancy with previous results is higher. This difference decreases as function of the increase of temperature also for all data. Slight differences can be expected as the injectors are not rigorously identical, even if the electronic command was maintained.

3.5 Effect of CR on Lift-Off Length

The LOL is determined by the region where the flame stabilizes, and where the spray and flame front velocities are balanced. A longer LOL will provide more time and space for fuel droplet evaporation and mixing with ambient air.

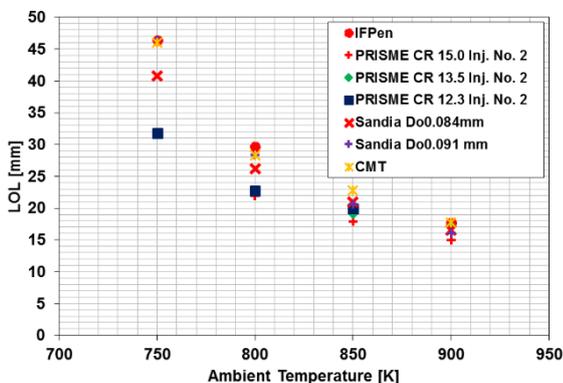


Fig. 7. Measured LOL versus ambient gas temperature for different CR compared to previous results [...].

The average LOL at 900 K is shown to be very close (Fig.7), as measured by either IFPen or Sandia. Once again, it is a significant accomplishment considering the complexities of the experiments. All LOL results are 5 mm different at 850 K. But this difference increases when temperature decreases. At 750 K, the results of PRISME CR12.3 give the shortest LOL even if the ID was similar than Sandia (Fig.6). Despite the good improvement on ID due to the homogenous temperature, LOL results are more different, the effect of temperature distribution, particularly closer to the injector, will be explored in the future.

4. Conclusion

A new experimental set-up was designed, improved and ameliorated to guarantee high quality level of the results based on Spray A conditions. By adapting the compression ratio of the NOSE, the ambient temperature can vary from 750 K to 900K. But the homogeneity is less reached at low temperatures. Despite the agreement in quasi-steady liquid length, ID and LOL values remain in comparison with previous results from ECN different. The characterization of the temperature will be continued but also the effect of different species in the ambient gases will be studied to evaluate their impact on the combustion development and soot production/oxidation.

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