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EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF A NONE SWIRLING HOLLOW CONE INJECTOR

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ABSTRACT

In this work, the performance of a new type of non-swirling hollow cone injector is assessed both experimentally and numerically. MIE and Schlieren images taken in a high temperature high pressure constant volume cell are used to determine the liquid penetration length and evaporation location respectively. The measured images are compared with 3D-CFD simulations to validate a newly implemented Rosin-Rammler distribution model for the initial droplet distribution of the fuel spray emerging from the non-swirling hollow-cone injector.

The resulting model is applied to study the influence of several injection parameters on the mixture formation in a free floating piston engine in view of potential application in HCCI combustion processes. The degree of evaporation and homogenization attainable is assessed for different single component fuels as well as for several injection times, pressures and spray cone angles.

Exemplarity, it is shown that for n-heptane a late injection combined with a high injection pressure and if possible a small spray cone angle is favorable to obtain a good evaporation and a relatively well homogenized mixture. Furthermore, this analysis reveals that an improvement of the mixture homogenization by an optimization of the injection parameters based on CFD results is feasible.

EXPERIMENTAL SETUP

The experiments were carried out in a constant volume, high temperature high pressure cell (HTDZ); Figure 1 shows a schematic of the combustion chamber which is optically accessible via 5 sapphire windows. The apparatus is charged with pre-heated technical air from high pressure gas bottles. This enables independent variation of gas pressure and temperature up to 80 bar and 800 K, i.e. part load Diesel conditions without requiring pre-combustion. To avoid heat losses, the chamber walls are temperature controlled by means of electrical heating cartridges up to 800 K. During combustion, the chamber is designed to withstand pressures up to 200 bar. Up to 5 sapphire windows allow for optical access. Due to the well known initial and boundary conditions this arrangement is highly suitable for model validation purposes [1].

Injection System

Fuel is injected by means of a common-rail injection system and a piezoelectric hollow cone injector from Siemens. Maximum injection pressure is 200 bar which is controlled by means of a piezo-resistive pressure transducer placed just upstream of the injector in the fuel rail.

Measurement Conditions

The initial air temperature in the cell varied between 373 K up to 523 K; the pressure between 2 and 15 bar. Injection pressure was set to 120 bar. Iso-octane was used as fuel, its temperature depends on the cell temperature, for a cell temperature of 150° C the fuel temperature in the tip is around 373 K. The amount of injected fuel was kept very small, 1 mg per injection, by using a short injection durations of 0.1 ms.

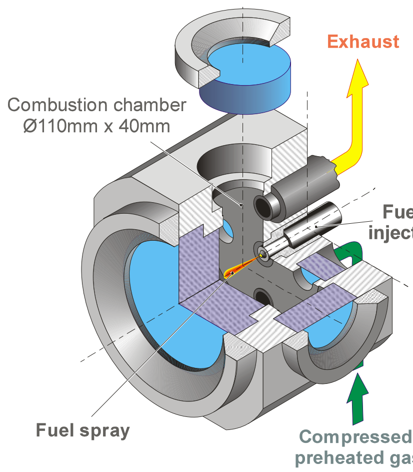

Figure 1 - High temperature high pressure cell

Optical measurements

Two optical techniques were employed to investigate the evolution of the liquid and vapor phase of the fuel spray. To visualize the liquid phase of the fuel spray the Mie-scattering technique was applied: An Ar-Ion Laser beam is expanded to form a laser sheet which enters the observation domain via the large window opposite the fuel injector, which guarantees a uniform light distribution on both sides of the hollow cone spray. To qualitatively show the fuel vapor phase penetration, the Schlieren method was used: Light from a flash lamp is expanded to a beam of parallel light by means of a 0.3 mm pinhole and a lens which then passes through the observation domain perpendicular to the spray axis. A schematic of the arrangement is given in Figure 2: The pale blue visualizes the laser sheet used for the MIE-scattering, the red line symbolizes the light path for the Schlieren technique. Images are recorded by means of a PCO a Sensicam for both measurement techniques.

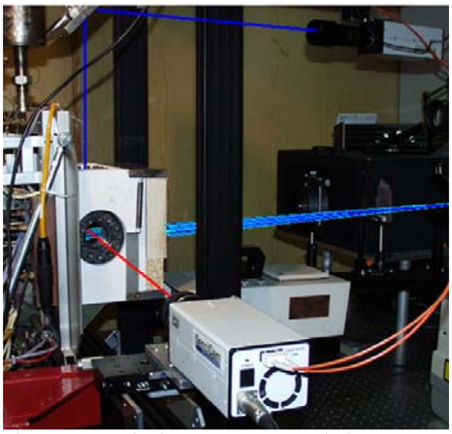

Figure 2 - Optical measurement techniques

MODEL VALIDATION

The simulations are performed with the CFD solver STAR-CD [2] using the built-in Langrangian/Eulerian multiphase modeling framework. Standard modelling practice has been followed to calculate droplet secondary break-up, evaporation and collision. The primary atomisation has been user coded and optimised based on the experimental data available; the prescribed parameters include the initial droplet size distribution of the Rosin-Rammler type, the mass flow rate, injection velocity and direction as well as the inner and outer cone angle of the spray. Furthermore, the fuel properties as a function of temperature have been implemented. To reduce computational cost, a 12° sector is modeled which has approximately 36,000 cells. Figure 3 shows a comparison of the liquid core at different time steps where the Mie images are compared with a slice for the CFD calculations.

As can be seen, the penetrations and cone angles agree quite well. It can be observed, however, that further investigations are required to improve the predictions

INFLUENCE OF FUEL INJECTION PARAMETERS ON MIXTURE FORMATION

The previously validated model is subsequently applied to study the influence of injection on mixture formation in a single stroke free floating piston engine. In particular, the effect of injection timing, pressure and spray cone angle on fuel evaporation and fuel-air homogenization is investigated. Since HCCI combustion relies on lean and homogenous mixtures to reduce simultaneously both NO_x and soot emissions, a good understanding of the aforementioned processes is indispensible to extend the HCCI working range.

Experimental Setup

The single stroke engine considered in the present work is used for simulation of the compression and expansion stroke of a real engine, offering however optical access in both axial and radial direction. More details concerning the set-up can be found in [3,4]. The apparatus is of the free floating piston type and hence lacks a fixed crankshaft resulting in a highly flexible machine able to operate at a wide variety of operating conditions as given in table 1.

Table 1 - Engine operating conditions

Bore	84 mm
Stroke	120 – 250 mm
Compression ratio	5 – 27 mm
Simulated engine speed	1000 – 3000 rpm
Maximum cylinder pressure	200 bar

Computational approach

The methodology applied is analogous as for the closed chamber, for the free floating engine however the piston motion needs to be prescribed based on the experimentally recorded piston position. For efficient calculations, a 12° sector is modeled which has approximately 25,000 cells at BDC. The reference conditions used for all simulations throughout this study are summarized in table 2.

Table 2 – reference conditions for simulation

Lambda	2.1
Compression ratio	16
Intake pressure	1.2 bar
Intake temperature	300 K
Cylinder wall temperature	330 K

Influence of injection parameters

The analysis is based on the total evaporated fuel mass and the mixture homogeneity. To characterize the latter, a 'homogenization index' is defined based on the standard deviation of the 3D fuel mass fraction field. To account for unequal cell sizes, the deviations are mass averaged, resulting in the index given in (0.1).

$$\sigma = sqrt\left[\frac{\sum m_i\left(Y_i-\overline{Y}\right)^2}{m_{tot}}\right] \quad with \quad \overline{Y}=\frac{\sum m_i Y_i}{m_{tot}} \quad (0.1)$$

Analogously, a temperature homogenization index can be

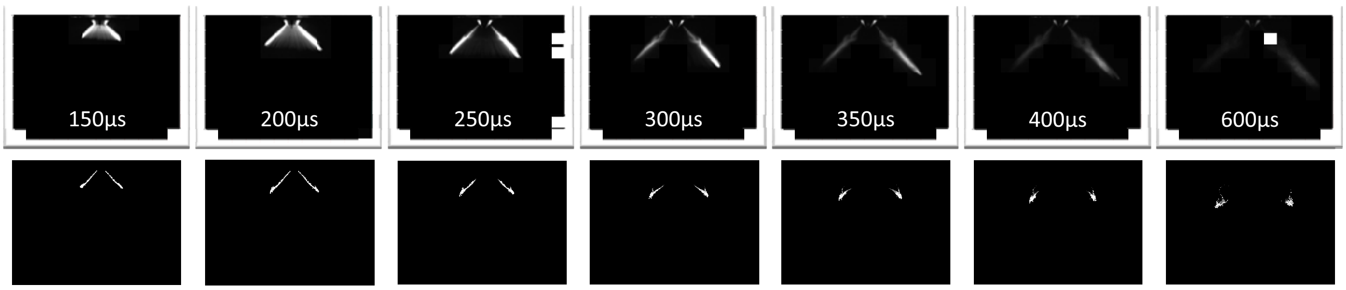

Figure 3 - Comparison between experimentally determined and calculated spray penetration

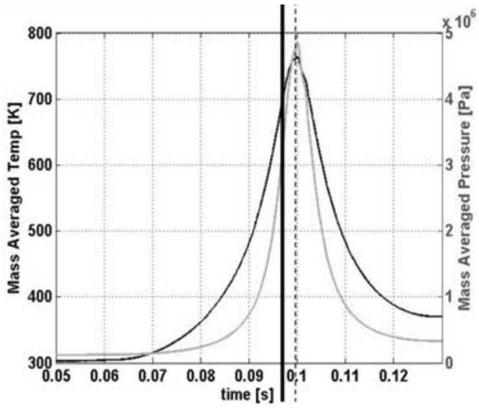

Figure 4 - reference case pressure and temperature history

defined. It should be noted that a good homogenization and therefore a low value of the standard deviation is strived for. More detailed information on the fuel air-mixing can be obtained by post-processing the simulation results and visualizing the flow as has been demonstrated in [6]. In addition, the distribution of the fuel over the lambda and temperature range can be analyzed by means of joint probability density functions (not shown). Since homogenization is crucial during ignition and combustion only, the main focus lies at achieving a high evaporation and a good homogenization between 4 ms before TDC and TDC. In this timeframe, conditions are such that ignition can be expected (T > 700 K, p > 30 bar), as illustrated by the pressure-temperature traces for the simulated set-up (Figure 4). In the remainder of the paper, results are given for a representative time equal to 0.097 sec or 3 ms before TDC. The same trends, however, can be observed for all time steps in the ignition relevant time frame.

Injection timing - The influence of injection timing is shown in Figure 5(a). The minimum in the evaporated fuel curve suggests that the percentage of evaporated fuel is determined by the balance between evaporation rate and time till entrapment of the droplets in the crevice between piston and cylinder liner. The later the injection starts, the higher temperature inside the chamber and therefore higher evaporation rate can be observed. This effect is expected to lead to an increasing percentage of fuel evaporated as injection is delayed. At intermediate injection timings, however, the rate increase is not enough to offset the fact that droplets sprayed onto the wall have less time to evaporate before they get trapped in the crevice. Homogenization is mainly determined by the time available for fuel-air mixing, as can be seen from the increasing inhomogeneity as injection is delayed.

Injection velocity - Since the single stroke engine is filled through small inlet channels instead of inlet valves and operates with a flat piston, injection is the main turbulence generator. The increasing turbulence with increasing injection velocity enhances the air-fuel mixing, resulting in a strong reduction of the inhomogeneity as can be seen in Figure 5(b). The influence on the fuel evaporation, however, is less pronounced.

Spray cone angle – With decreasing spray cone angle, the liquid spray impacts less perpendicular to the wall. The resulting larger impact angle allows the droplets to spread out along the wall, creating a larger surface to evaporate from and a better distribution of the evaporated fuel. Furthermore, the distance the spray travels from injector to wall increases with decreasing spray cone angle. Due to this increased distance the spray is more developed by the time he reaches the wall and the time available for droplet break-up is slightly larger. Both effects result once again in a better evaporation and distribution of the fuel vapor, as can be seen in Figure 5(c).

Influence of the fuel – Figure 6 shows the influence of the injection velocity, this time, however, for an n-dodecane, instead of n-heptane injection. As can be seen, does an increase in the injection velocity in this case not necessarily leads to better evaporation and homogenization. Some more simulations are needed to determine the reason for the observed behavior. The presented results, however, already demonstrate that much care must be taken when transferring results from one fuel to the other.

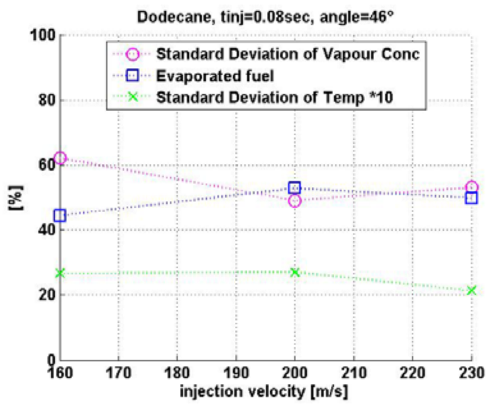

Figure 6 - evaporation and homogeneity 3 ms before TDC (t=0.097 sec) as a function of injection velocity using n-dodecane as fuel

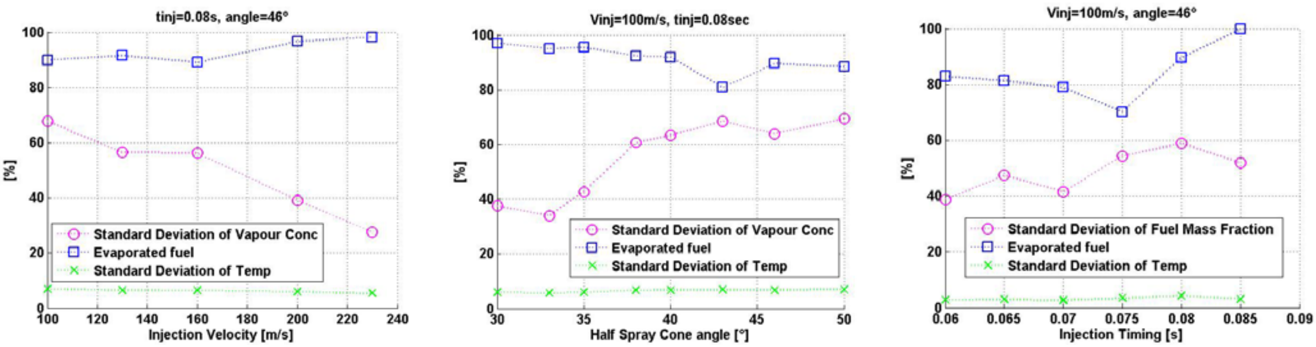

Figure 5 – Evaporation and homogeneity evaluated 3 ms before TDC (t=0.097 sec) as a function of (a) time at start of injection (b) injection velocity (c) half cone spray angle using n-heptane as fuel [7]

CONCLUSIONS

Optical experiments in a high temperature high pressure cell with constant volume of a non-swirling hollow cone spray have been used to validate a newly developed atomisation sub-model which was then applied to study mixture formation in a free floating piston engine. The effects of injection timing, pressure and spray cone angle on the fuel evaporation and fuel-air homogenization have been assessed for different fuels using 3D-CFD simulations. It has been demonstrated that for n-heptane and the operating condition considered, a complete evaporation and inhomogeneities less then 30 percent can be achieved using late injection and high velocities. Furthermore, this analysis reveals that CFD can be used to asses the influence of several parameters relatively quickly (10 to 12 hrs). More important, it has shown to be a very valuable tool to gain insight into the complex interaction of injection, fuel-air mixing, as well as the influence of wall impingement and crevices present in the engine.

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