

On the Potential of Oxygenated Fuels as an Additional Degree of Freedom in the Mixture Formation in Direct Injection Diesel Engines

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ABSTRACT

The current and future restrictions on pollutant emissions from internal combustion engines require a holistic investigation of the abilities of alternative fuels to optimize the combustion process and ensure cleaner combustion. In this regard, the Tailor-made Fuels from Biomass (TMFB) Cluster at Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University aims at designing production processes for biofuels as well as fuels optimal for use in internal combustion engines. The TMFB Cluster's scientific approach considers the molecular structure of the fuels as an additional degree of freedom for the optimization of both the production pathways and the combustion process of such novel biofuels. Thus, the model-based specification of target parameters is of the utmost importance to improve engine combustion performance and to send feedback information to the biofuel production process. In particular, computational fluid dynamics is used to underscore the role of the thermo-physical properties on the soot emissions in internal combustion engines. Utilizing a preliminary established sensitivity analysis, it was possible to identify C8 straight chain oxygenated molecules as the optimal candidate for the inherent reduction of soot emissions within the mixture formation process. Additionally, the Oxidation Potential Number (OPN) is presented as a new indicator of the inherent soot reduction inside diesel spray plumes.

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INTRODUCTION

Research in previous decades has focused on alternative fuels for application in Internal Combustion Engines (ICE). The main reasons are not only limited fossil fuel resources, but also the overall CO₂ Well-To-Wheel (WTW) emission balance. Biofuels are better suited than fossil-derived fuels in terms of trade-offs between WTW CO₂ emissions/production costs. According to a report by the Joint Research Center of the European Commission released in 2014, biofuels represent the best short-term choice as an alternative for standard gasoline and diesel fuels, allowing more than 50% reduction in the overall WTW CO₂ emission, while keeping production costs competitive with fossil derived fuels [1]. In Europe, the cost of biofuel production, after taxes, is similar to that of fossil-derived gasoline and about 10% higher when compared to fossil-derived diesel [2]. Previous works have proven that biofuels can reduce in-cylinder pollutant formation in compression ignition (CI) combustion, since their oxygen content, their lower heating value (LHV), and their lower self-ignitability has shown the potential to improve the soot-NO_x trade-off [3, 4, 5]. That is why the Tailor Made Fuel from Biomasses (TMFB) Cluster at

Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University focuses its interdisciplinary approach on the discovery of novel oxygenated fuels.

The TMFB is an interdisciplinary research project founded by the German federal and state governments to promote science and research in German universities. Biologists, chemists, physicists, as well as process and combustion engineers have joined their efforts to find oxygenated fuels that are ideal for applications in ICE. In the past five years of research, lignocellulose was established as the starting material to develop new biofuels to prevent competing with food industry production. The lignin/hemicellulose platform was proposed to derive novel biofuels via selective production pathways for CI engines, such as di-n-ethers, furans, and 1-alcohols [6, 7]. Recently the TMFB Cluster has aimed, on one side, at developing new production pathways of novel biofuels and, on the other side, at defining model-based combustion performance indicators to be included into the design process. The definition of such performance indicators is of the utmost importance for realizing tailor-made fuels for ICE. The molecular structure is regarded as an additional degree

of freedom to improve combustion performance in ICE. Thus, new techniques to find possible biofuel candidates need to be developed. The strategy adopted is presented in Figure 1. A direct link between the fuel molecular structure and the engine performance has been investigated. Quantitative structural properties relationships (QSPR) and group contribution methods (GCM) are used to model the thermo-physical properties of a fuel, which directly influence the most relevant processes present in ICE.

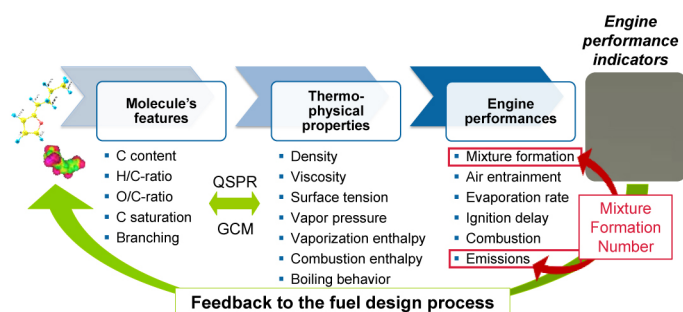


Figure 1. Structure of the research methodology established to seek the characteristic mixture formation number.

The long-term goal of this study is to introduce the sooting tendency of a fuel inside the biofuel design process to impose cleaner CI combustion as a boundary condition. However, the development of a correlation between the molecular structure and the soot emissions on the basis of detailed reaction kinetics for all possible biofuel candidates at varying engine operating conditions would lead to an extensive experimental and simulative effort. Thus, a model-based approach was chosen. The influence of the molecular structure on the engine soot emissions is studied under three different aspects: intrinsic fuel tendency to form soot, air/fuel mixture tendency to oxidize soot, and fuel self-ignitability.

This study has focused on the mixture formation process and its influence on soot emissions in CI combustion. The mixture formation of different fuels was studied in order to define a characteristic number capable of describing the soot oxidation potential of the air/fuel vapor mixture inside a diesel-like spray plume. Several studies have shown that the soot formation is affected by the thermodynamic boundaries of the air/fuel mixture prior to the first ignition kernel (i.e., within the lift-off length) inside the partially premixed reaction zone of a laminar diffusion flame [8, 9, 10]. Thus, the mixture formation and the physico-chemical ignition delay play a fundamental role in the quality of combustion. Both processes are influenced by the thermo-physical properties of the fuel and consequently by its molecular structure. It was shown that the spray penetration length largely depends on the fuel and air density [11] and that the fuel's boiling behavior controls its evaporation rate [12], and thus the share of mixture involved in the auto-ignition process. Recently, in the study of Reddemann et al [13], a correlation between the spray cone angle under cold evaporative conditions and the fuel density and dynamic viscosity was derived, confirming the importance of the fuel thermo-dynamic properties on the mixture formation and the air entrainment process. In the first paragraph of this study, the methodology developed to define this characteristic number is described, which is referred to as "Virtual Fuel Approach" (VFA) in a previous authors' work. It is a simulative methodology

that studies the role played by the thermo-physical properties of the fuel on the in-cylinder air/fuel equivalence ratios (λ) under cold evaporative conditions [14]. It was developed using a computational fluid dynamics (CFD) software package in order to monitor the air/fuel mixing process from an in-cylinder point of view while taking a complex set of engine boundaries into account, e.g., the air motion, the piston bowl geometry, the nozzle layout, etc. Afterwards, the Oxidation Potential Number (OPN) is presented as a new indicator of the inherent soot reduction inside a diesel spray plume. Next, the fuels which have been investigated in the VFA study are described together with the implementation of the CFD study. Later, the experimental facilities used to validate the CFD models are briefly presented. The second paragraph shows the results of the sensitivity analysis performed for the fuel thermo-physical properties, with particular focus on the molecules which have shown the highest OPNs over a range of four different part loads. In conclusion, a summary of the results and an outlook on the future work is given.

MATERIAL AND METHODS

The Virtual Fuel Approach: A Sensitivity Study to Define the Oxidation Potential Number

The VFA is a computer aided engineering methodology that was developed to analyze the effect of the thermo-physical properties of the fuel on air/fuel mixing in cold evaporative conditions.

Thus, the effect of the reaction kinetics of the fuel was not taken into account and only the effect of the properties, such as liquid density, dynamic viscosity, surface tension, enthalpy of vaporization, and vapor pressure on the air entrainment process and evaporation was considered. The role played by the molecular structure on the ignitability is the subject of future work and will be coupled with the results of this study as mentioned above. Figure 2 explains the VFA process. The methodology consisted of calibrating a CFD code, i.e., KIVA 3V Release 2 in two separate steps. First, the CFD model was calibrated with regards to spray, combustion, and emission behavior for reference diesel fuel EN590 at different engine part load operating points. Afterwards, a sensitivity analysis of the local air/fuel ratios at varying thermo-physical properties under examination was performed in cold evaporative conditions. The assumption made was that the models describing the breakup process and the consequent evaporation available in the CFD code were accurate enough to perform a sensitivity analysis of the fuel properties. The decision to focus more on part load operating conditions took into consideration that - in small bore diesel engines - the spray interactions with the combustion chamber walls are dominated by the spray pattern, directly affecting the combustion process. At these engine loads, the lower in-cylinder air density is not enough to atomize the spray properly and to avoid the fuel impingement on the combustion chamber walls. Furthermore, the high exhaust gas recirculation (EGR) rates used to counteract NO_x emissions contribute - together with the fuel impingement - to an increase in soot emissions.

The fuels analyzed were n-alkanes, 1-alcohols, and di-n-ethers with a range of C8 - C16 carbon atoms in the molecular structure. Each variation in property was performed by increasing the molecular structure of 2 carbon atoms and 4 hydrogen atoms. The details of the

domain of investigation of the fuels are given in the next paragraph. The sensitivity analysis was performed by varying each property independently from the other, which is why the methodology was named “Virtual.” Single properties were varied according to five chain lengths at a constant engine load over a range of four part load operating conditions. The boundary conditions adopted to perform this analysis were set at a given operating point: constant injected mass and constant rail pressure. Although this strategy is not based on real engine applications, where different fuels are screened while keeping the injected energy constant at a given engine load, to derive conclusions on the influence of each property on the local air/fuel equivalence ratios it was necessary to keep the injected mass constant. Constant rail pressure was ensured for each simulation by adjusting the duration of injection while keeping the injection rate shape the same. Thus, the change in spray momentum due to the needle opening strategy was negligible.

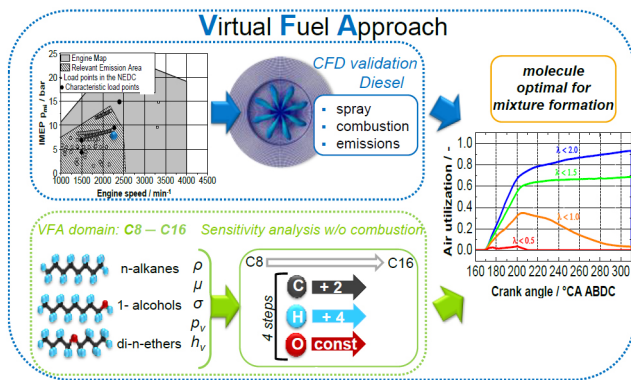
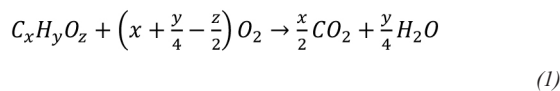


Figure 2. Flow chart of the VFA main implementation steps.

The monitoring parameter used to study the air/fuel mixing process was the “Air Utilization” (AU). Assuming a reaction of complete combustion, the moles necessary to completely burn the fuel in presence of air are derivable by the stoichiometry as follows:



where the term $\left(x + \frac{y}{4} - \frac{z}{2}\right)$ represents the required moles of oxygen to completely burn one mole of fuel. Air utilization is a non-dimensional parameter which represents the ratio of effective oxygen volumetric fraction over the stoichiometric one, as shown in Equation 2:

$$AU = \frac{Vol|_{\lambda_i}}{Vol|_{totalchamber}} \quad (2)$$

where ‘i’ stands for the different λ values of 0.5, 1.0, 1.5, and 2.0 as defined in Equation 3.

$$\lambda_i = \frac{o}{2 \cdot C + 0.5 \cdot H - O} \quad (3)$$

Over the combustion duration, this parameter monitors different air/fuel shares that are relevant for soot formation inside ICE as explained in Figure 3. An explication of the air utilization is provided on the left-hand side of Figure 3. It shows the air/fuel equivalence ratios which are involved in the soot formation and oxidation during the combustion process. The simplifications made in this study were made in order to consider only two main shares of the air/fuel mixture:

1. rich range ($\lambda < 1$) to monitor the share of mixture involved in the soot formation;
2. lean range ($1 < \lambda < 2$) to monitor the share of mixture involved in the soot oxidation process.

The rich and lean ranges of mixture were monitored from start of injection (SOI) to exhaust valve opening (EVO), since the CFD simulation included only the high pressure cycle and not the gas exchange phase. The air/fuel mixture not involved in the soot formation, and oxidation ($\lambda > 2$) was considered not of interest; thus, it was defined as unused air. Previous studies have demonstrated that the air utilization correlates well with in-cylinder soot formation [15, 16] and that it can be used to optimize the mixture formation process prior to ignition through the improvement of spray/bowl interactions [17].

As mentioned above, a characteristic number was defined, starting from the definition of the air utilization, and named OPN. This number aims at representing the overall quality of the air/fuel mixture during the range of time from SOI to the EVO, with regard to soot emissions, in a single parameter. Thus, it looks at the soot oxidation potential available inside the spray plume assuming that, since liquid fuel is injected inside the combustion chamber, the formation of soot inside the rich air/fuel vapor zone cannot be avoided in standard CI combustion. The main assumption is that a spray prone to mix with the surrounding air improves the evaporation and air entrainment process. These aspects increase the diffusion of oxygen into the vapor mixture, thus promoting soot oxidation reactions.

In order to establish a criterion to evaluate the inherent reduction of soot emissions during the mixture formation process for each property variation, the share of the lean mixture was divided by the rich one and by the unused air.

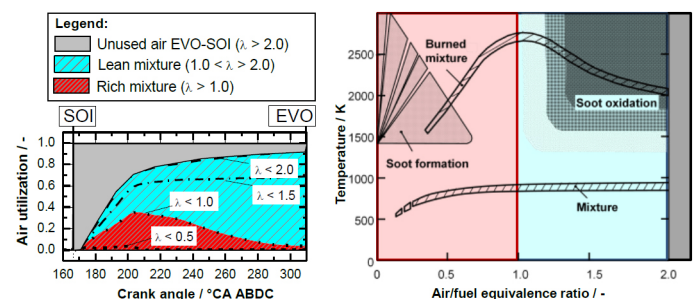


Figure 3. Explication of in-cylinder air utilization and its correlation with soot emissions [18].

Equation 4 introduces the OPN:

$$OPN = \frac{\int_{SOI}^{EVO} AU|_{1 < \lambda < 2} \times \int_{SOI}^{EVO} AU|_{total}}{\int_{SOI}^{EVO} AU|_{1 < \lambda} \cdot \int_{SOI}^{EVO} unused\ air} \quad (4)$$

With the introduction of the OPN, it was possible to quantify a number for the share of the lean mixture weighted over the rich share of mixture at different engine operating points, since the unused air largely depends on the aerodynamic drag related to the in-cylinder air density. The OPN was defined as a non-dimensional number and follows the rule “the bigger it is, the better is the expected soot oxidation potential.” The OPN with respect to the other stoichiometry-based indices, such as the oxygen equivalence ratio introduced by Chen et al. in [19], monitors the mixture in ranges of equivalence ratios which are relevant for soot emissions in CI combustion. It also takes the ultra-lean mixture into account which is not involved in CI combustion (i.e., $\lambda > 2$). It is important to notice that the OPN - in the case of the VFA sensitivity analysis, which is performed by varying only one parameter at a time - directly translates the influence of the thermo-physical properties on the mixing process. However, when comparing real fuels to each other at a given operating point, it establishes the performance of the fuel in terms of mixture formation and soot oxidation potential.

Fuels Investigated

As mentioned above, the domain of investigation chosen to perform the sensitivity analysis consisted of straight chained molecules. The fuel families studied were n-alkanes, 1-alcohols, and di-n-ethers. An example of C8 molecules for each family is given in Figure 4. Among all the possible molecule combinations, these families were chosen on the basis of the following assessments:

1. Straight chained molecules are desired due to their carbon atom saturation level. They are more reactive with oxygen than their respective isomers and ring structured molecules; thus, more prone to form radicals and self-ignite [20]. Moreover, the higher reactivity of straight chained molecules is beneficial with regard to soot formation and oxidation, assuming the “H-abstraction-C2H2-addition” (HACA) mechanism for polycyclic aromatics' (PAH) growth [21, 22].
2. The chain length of the molecule must not be shorter than C7 with regard to the n-alkanes because n-heptane meets the minimum ignitability standard for diesel fuel in Europe with a Derived Cetane Number (DCN) of 53.8 [24]. Since n-heptane had been extensively investigated [5, 10, 13, 24] in the previous TMFB research campaign, it was decided to start with a minimum chain length of C8. The maximum range was established considering that n-hexadecane (C16) shows similar thermo-physical properties as diesel fuel and corresponds to a maximum Cetane Number (CN) of 100.
3. The oxygenated families chosen have the same molecular structure as the respective n-alkanes representatives plus one oxygen atom inside the molecule's chain. As can be seen in Figure 4, 1-alcohols and di-n-ethers differ from each other only by the oxygen functional group. These families were chosen

on the basis of previous TMFB works, where representatives of both families have performed well with regards to engine performance and soot emissions [3, 4]. 1-Alcohols and n-alkanes increase their ignitability when their chain length increases; di-n-ethers on the other hand do not show a clear trend. The 1-alcohols are the least reactive fuels analyzed followed by n-alkanes and di-n-ethers. A reduction in the CN was then included inside the domain of investigation for future studies on the ignitability since it was concluded in previous works that the self-ignitability is not necessarily desirable for CI combustion applications when a partially homogenized combustion should be realized to decrease soot formation [3, 4, 25].

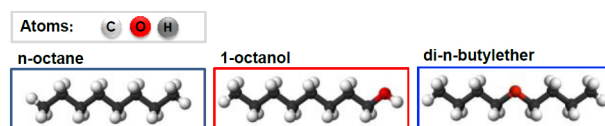


Figure 4. C8 molecules of n-alkanes; 1-alcohols and di-n-ethers [23].

Realization of the VFA Approach

Once the domain of investigation as C8 - C16 for the different fuel families was defined, it was necessary to establish a trend between the fuel molecular structure and the thermo-physical properties analyzed in order to conduct the sensitivity analysis. Thus, linear regression analysis was used to determine the influence of an increment of 2 carbon atoms inside the molecular structure on the boiling behavior of the fuel, density, viscosity, etc.

In Figure 5, examples of the VFA curves which were implemented in the CFD code are given for each fuel family. In the top-left plot of Figure 5, the investigation domain of the liquid density at 20 °C is presented. N-alkanes and di-n-ethers families increase their density with the increase in molecular chain length, 1-alcohols show a different trend due to the local polarity caused by the hydroxyl group, which is counteracted by the chain length increase due to the protection of the steric hindrance of adjacent groups [26, 27]. The dynamic viscosity, vapor pressure, and surface tensions were analyzed via linear regression analysis, since it was required to establish the influence of the change in the molecular structure on the boiling behavior of the fuels. A thermodynamic model was used to predict these properties where there was a lack of data in literature. The starting dataset consisted of: Di-n-Butyl Ether (DNBE) (C8), Di-n-Hexyl Ether (C12), Di-n-Octyl Ether (C16) for the di-n-ethers; 1-Octanol (C8), 1-Dodecanol (C12), 1-Hexadecanol (C16) for the 1-alcohols, and n-octane (C8), n-decane (C10), n-dodecane (C12), n-tetradecane (C14), n-hexadecane (C16) for the n-alkanes [28, 29]. The temperatures analyzed ranged from melting temperature (T_m) to critical temperature (T_c). For all the fuels, similar trends were observed in terms of viscosity, vapor pressure, and surface tensions with the variation of temperature. Thus, for the sake of brevity, only one family is plotted in Figure 5; i.e., 1-alcohols for dynamic viscosity, alkanes for vapor pressure, and di-n-ethers for surface tension.

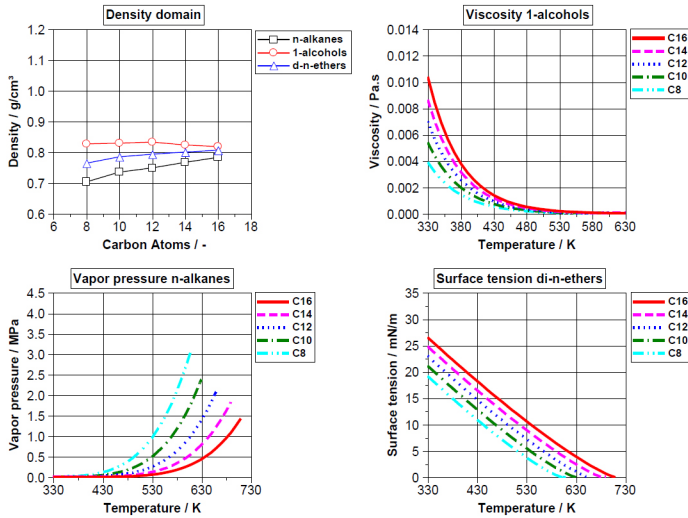


Figure 5. Observation domain of liquid density at 20 °C, viscosity, vapor pressure, and surface tension [14].

In the top right graph of Figure 5, the dynamic viscosity for the 1-alcohols is plotted over the temperature, sorted by carbon content. The temperatures represented range from the injection temperature of 330 K up to T_c . By looking at the viscosity curves at a fixed temperature, fuels with shorter chain length show a lower viscosity than the long-chained ones. The thermo-dynamic model used to predict the curves is the Andrade equation:

$$\mu = e^{(A+BT)} \quad (5)$$

Where:

μ is the dynamic viscosity;

T is the temperature.

A and B are constants which require at least two sets of viscosity/temperature data to be determined as shown in Equations 4.1 and 4.2.

$$A = \ln(\mu_1) - B/T_1 \quad (5.1)$$

$$B = \ln(\mu_2/\mu_1) / \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \quad (5.2)$$

In the bottom left plot in Figure 5, the vapor pressure curves are given for n-alkanes. The trend of the vapor pressure behavior with increasing chain length, at a given temperature, is as follows: fuels with shorter chain length are more prone to vaporize. The Clausius - Clapeyron thermodynamic law was utilized for the sensitivity analysis of the vapor pressure and the heat of vaporization, since these thermo-physical properties depend on each other as stated in Equation 6:

$$d(\ln P_v) / d\left(\frac{1}{T}\right) = -\Delta H_v / R \cdot \Delta Z_v \quad (6)$$

Where:

P_v is the vapor pressure;

ΔH_v is the enthalpy difference between saturated vapor and liquid;

ΔZ_v is the compressibility factor difference between saturated vapor and liquid;

R is the universal gas constant.

An assumption was made regarding the dependence of the term $\Delta H_v / \Delta Z_v$ on the temperature in order to integrate Equation 5. Both enthalpy and compressibility factors are functions of the temperature and both decrease with rising temperature providing a compensating effect [28]. Therefore, this group constant was evaluated at the normal boiling temperature (T_{nb}) in this study and the term $\Delta H_v / \Delta Z_v$ at T_{nb} was studied through a linear regression analysis to define its dependence on the molecule's carbon atoms for each fuel family. The same approach was applied to derive the pressure at T_{nb} ($P(T_{nb})$) and T_{nb} . The regression equations can be found in Table I in Appendix I. The last property analyzed was the surface tension. In the bottom right plot in Figure 5, the trends for the variation of the carbon content and temperature are shown for the di-n-ethers. The overall trend is as follows: shorter chain length molecules have a lower surface tension at a given temperature. The Brock and Bird thermodynamic correlation listed in Equation 7 was used to derive the curves, where the surface tension correlates with the temperature. The reason lies in the coding of the CFD software, which does not take the density variation with temperature into account. A more detailed model, such as the Sudgen-Macleod correlation, where the surface tension correlates with the liquid and vapor density through the Parachor temperature-independent parameter, goes beyond the scope of this paper as the influence of temperature on the liquid density is minor.

$$\sigma / \left(P_c^{2/3} \cdot T_c^{1/3} \right) = (0.132 \cdot \alpha_c - 0.279) \cdot (1 - T_r)^{11/9} \quad (7)$$

Where:

σ is the surface tension;

P_c is the pressure at critical point;

α_c is the Riedel parameter (1954) according to the Miller (1963) formulation;

T_r is the reduced temperature at the critical point, i.e. T/T_c ;

T_{br} is the reduced temperature at the boiling point.

In this case, a regression analysis was used to establish the dependency of P_c on the carbon atom content and three curves were defined for the fuel families under study (given in Table 1 in the Appendix).

Cold Evaporative High Pressure Chamber Measurements

Experiments designed to capture the spray behavior and air entrainment process at part load operating conditions were performed at the Institute of Heat and Mass Transfer (WSA) of the RWTH Aachen University. Here, a high pressure vessel for optical investigations was used to analyze diesel fuel under cold evaporative conditions over a set of thermodynamic boundaries related to part-load engine operating loads. The details of the experimental setup used to carry out the experiments were described by Reddemann et al. in a previous study [13]. The injector details are given in Table 1 together with the operating load points that were used to calibrate the CFD code in order to enhance the spray model confidence level at part loads. Macroscopic high-speed visualization was used to capture the evolution of the spray propagation process and its consequent evaporation independently from the fuel ignitability. The experimental set-up consisted of a high-speed camera, a continuous light source and the vessel. The spray-cone angle and the liquid penetration length were measured to capture the macroscopic characteristics of the atomization process and the consequent air entrainment. Light scattered in the liquid phase was detected by the high-speed camera resulting in a 4 ms video with 120 frames for one single injection. For sufficient statistical accuracy, 20 injection videos were recorded for each single operating condition.

Table 1. High pressure vessel specifications and operating points used to validate the spray model for diesel fuel.

Temperature / K	300	700	300
Air density / kg/m ³	25	25	50
Pressure / bar	22	50	43
Injection pressure / bar	720	720	720
Fuel injection system	BOSCH Piezo Common Rail, 3 rd generation		
Max. injection pressure / bar	2000		
Injector holes	8		
Hole diameter / μm	109		
Hole r/d	0.125		
Hole L/d	9.4		
Nozzle cone angle / °	153		

Single Cylinder Diesel Research Engine

Measurements in part load operating conditions were performed on the single-cylinder diesel research engine present at the Institute for Combustion Engines (VKA) at RWTH Aachen University in order to calibrate the combustion model for diesel. The engine featured a high-efficiency combustion system optimized to achieve the best possible combustion characteristics in terms of low emission levels and high fuel efficiency. It was equipped for a high fuel injection pressure, advanced air charging system, and cooled EGR in order to achieve low intake manifold temperatures even at the highest EGR rates. A compression ratio of 15:1 was selected to represent acceptable peak pressures despite the increased charge density at diesel operating conditions. With this compression ratio, the combustion system reached a specific output of 80 kW/l at maximum peak firing pressures of 190 bar. Further details regarding the engine calibration can be found in [4, 25]. The engine's technical specifications are listed in Table 2.

The operating points that were analyzed in the CFD analysis are the characteristic load points (LPs) marked with black dots in Figure 6, representative for a C-class vehicle within the New European Driving Cycle (NEDC). The net indicated mean effective pressure (IMEP) was varied from a minimum of 4.3 bar to a maximum of 14.8 bar and the engine speed from 1500 min⁻¹ to 2400 min⁻¹. Although the spray/bowl interactions play an important role in the combustion performance at part loads, the LP 4 was analyzed to include at least one operating point considered to reflect real driving conditions. Table 3 summarizes the engine calibration for the operating LPs listed in Figure 6.

Table 2. Single cylinder research engine specifications

Displacement / cm ³	390
Stroke / mm	88.3
Bore / mm	75
Compression ratio	15:1
Valves/cylinders	4
Fuel injection system	BOSCH Piezo Common Rail, 3rd generation
Max. injection pressure / bar	2000

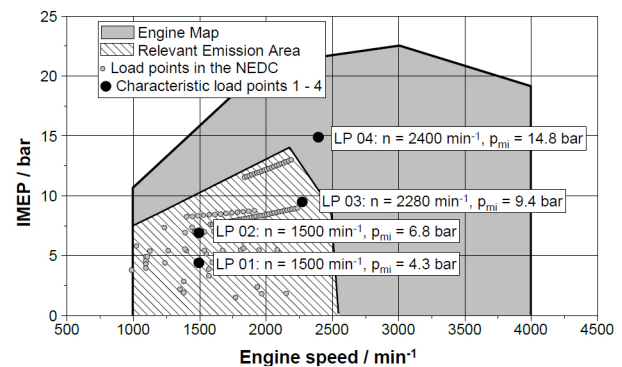


Figure 6. Single cylinder engine map and the characteristic load points analyzed in this study (black dots) [30].

Table 3. Calibration of the characteristic load points analyzed.

Load Point (LP)	LP 1	LP 2	LP 3	LP 4
Combustion center / °CA BTDC	-6.6	-5.8	-9.2	-10.8
Rail pressure / bar	720	900	1400	1800
Boost pressure / bar	1.07	1.5	2.3	2.6
Air density at TDC / g/m ³	14	22	34	39
EGR rate / %	43	46	47	38
Injected mass / mg	9	15	20	29
Main injection begin / °CA BTDC	-11	-8	-3	-4.5
Injection duration / °CA	5	6.5	10	13
Euro6 NO _x level g/kWh	0.2	0.4	0.4	0.6

The same reference diesel fuel tested in the high-pressure vessel was used in the single cylinder research engine. Both experimental facilities featured the same nozzle layout. During the engine calibration, only main injections with rectangular shaped injection profiles were adopted, while EGR sweeps were performed to comply with the EURO 6 NO_x limits.