AN ASSESSMENT OF FUEL-JET CHARACTERISTICS AND AUTOIGNITION DELAY FOR BIODIESEL B20 BY SIMULATION TOOLS

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The use of biodiesel mixtures has become a part of everyday life. The current implementation of B7 biodiesel at the pump and the premise that the near future will make B20 biodiesel compulsory leads to the necessity of an in-depth analysis of how this type of fuel affects the jet characteristics and ignition delay in a compression ignition engine. An experimental and numerical study was carried out to analyze the mentioned characteristics of a tractor diesel engine at full load. Maximum torque and maximum power operating conditions were analyzed. An 3D CFD model was developed for jet characteristics, jet propagation, and ignition delay analysis. As a practical result of this study, the usage of biodiesel B20 fuel (with B7 as an intermediary) is not associated with a substantial change in efficiency and performance and it's usage could lead to lower levels of emmissions.

Keywords: biodiesel, ignition delay, jet characteristics, CFD.

1. Introduction

Internal combustion engines are still the main source of power in multiple applications including automotive, marine, industrial equipment, agricultural equipment, industrial tools, stationary power generation, etc. In the transport sector, there are about 1.4. billion passenger vehicles and about 380 million commercial vehicles in use worldwide today, consuming about 35% of the total oil used globally.

Pollutant and greenhouse gas emissions of internal combustion engines have a notable impact on the environment and their reduction is an objective of great interest. Due to increasingly stringent government regulations and high end-user requirements, reducing fuel consumption and pollutant emissions have been key targets for the internal combustion engine industry R&D community in recent

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years. Major advances have been made through the implementation of new technologies and innovations specific to internal combustion engines as well as to the exhaust gas after-treatment systems. As a result, the regulated pollutant emissions of particles (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and unburnt hydrocarbons corresponding to new vehicles have been substantially reduced, also carbon dioxide (CO_2) emissions have been reduced by about 30% thanks to the improvement of technologies and the reduction of fuel consumption in the last 30 years.

Currently, only a mixture of diesel fuel with biodiesel in a volumetric ratio of 7% alternative fuel to pure diesel is sold at gas station pumps in Romania. European directives have forced fuel producers in member states to align with EU legislation. The objectives to reduce pollutant emissions take into account the increase of the volumetric percentage of biofuel to pure diesel to 20% in the coming years, so there is a need to study in detail the behavior of compression ignition engines and the effect of diesel/biofuel mixtures on performance, economy and specific pollutant emissions of the systems generating mechanical, thermal and electrical energy equipped with diesel engines. Biodiesel can make a notable contribution to reducing emissions of carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and smoke by its production technology (being a bio-renewable fuel) as well as the concentration of oxygen present in its composition.

To have a more complex understanding of the underlying effects of the usage of higher biodiesel volumetric fractions during the combustion process it is necessary to analyze the fuel jet characteristics. Numerous studies have been carried out to analyze the jet characteristics. Concerning spray penetration Subramanian and Subhash Lahane [1] have studied the effects of B10 and B20 biodiesel on a single-cylinder diesel engine and concluded that penetration distance is higher with the biodiesel blends than with pure diesel fuel. Park et al. [2] studied the effects of pure biodiesel and biodiesel B80D20 and concluded that the mixture has shorter spray tip penetration than the reference pure biodiesel fuel. Whang et al. [3] studied the spray characteristics of waste cooking oil biodiesel in a single-cylinder engine and concluded that the spray tip penetration is longer in biodiesel compared to pure diesel fuel. Concerning the Sauter mean diameter, Kegl et al [4] concluded that one of the major contributors to good combustion is droplet dimension and this, in turn, leads to the assumption that the SMD has an important role in combustion characteristics. Hwang et al. [5] studied the spray characteristics of different oils and concluded that biodiesel has 13% higher SMD than pure diesel fuel. Boggavarapu et al [6] analyzed injector hole size influence on jet characteristics when using diesel and Jatropha methyl ester on a diesel, common rail fueling system and concluded that cavitating injector nozzle holes lead to smaller SMD while larger entry radius nozzle holes lead to larger SMD. Regarding spray cone angle Ghurri et al. [7] studied the effect of biodiesel usage on spray characteristics in an atmospheric chamber and concluded that biodiesel usage leads to a smaller spray cone angle compared to pure diesel. Yu et al. [9] analyzed the effect of biodiesel on spray characteristics in a constant volume chamber and concluded that the spray cone angle of biodiesel is 16% narrower than that of pure diesel. Naguyen et al. [9] used different blends of fish oil biodiesel in pure diesel fuel in a single-cylinder internal combustion engine and concluded that the variation of biodiesel content (0% to 100%) leads to a reduction of spray cone angle (from 1.3% to 10%).

2. Experimental and numerical study of injection characteristics when using biodiesel

An experimental study of the effect of biodiesel B20 (volume fractions of 20% soy methyl ester in pure diesel) on jet characteristics has been carried out in the National University of Science and Technology Politehnica Bucharest tractor engine compression ignition lab, in order to have input data for further simulation model validation. The physicochemical properties of the tested fuels are presented in Table 1. The layout and components of the engine testbed aere presented in an previous work [10].

Table 1

Physicochemical properties of the tested fuels

Properties	Diesel	B7	B20	B100	Method of testing
Density (g/cm^3)@20C°	0.82	0.8467	0.8565	0.8864	SR EN ISO 3675
Viscosity (cst)@20C°	2.53	2.6	5.12	8.06	SR EN ISO 3104
Flash point (C°)	58.5	66.5	85	184	SR 5489
Cetane number	51.1	51.2	55.5	53.2	EN ISO 516598
Cold filter plugging point (C°)	-24	-	-18	-	SR EN 116 2016
Cloud point (C°)	-16	-	-10	-4	SR EN 23015
Pour point (C°)	-20	-17	-15	-10	SR 13552
Lower heating value (MJ/kg)	41.87	41.98	40.59	37.34	ASTM D240

The engine specifications are presented in Table 2.

Table 2

Main engine specifications

Diesel engine	4-stroke
No. of cylinders	4 in line, vertical
Bore x stroke (mm)	102 x 115
Displacement (cm^3)	3759
Fueling system	Direct injection (DI)
Maximum brake torque (Nm) at 1400 rpm	228
Rated power (kW) at 2400 rpm	50
Compression ratio	17.5:1
Combustion chamber shape	Bowl in piston
Injector holes number and diameter (mm)	5 and 0.54

A simulation model has been made to highlight injection and jet parameters using AVL HYDSIM software. The numerical simulation model was created by defining a mechanical section that includes a Delphi DP200 radial injection pump with a rotary distributor and a Delphi hydraulic injector. The specific physicochemical properties have been implemented for each of the 3 fuels under test. A definition of the main elements of the fueling system was done with details related to the fuel lines, and system inlet pressure as well as data related to the snubber valve, nozzle body, and others. A schematization of the model is presented in another published work [11].

A different model was created by using RK-DIESEL software. The main geometrical properties of the model and some of the injection parameters are presented for example in Figures 2 and 3.

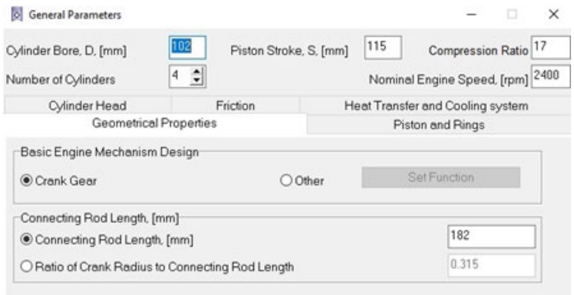

Fig.2. RK-DIESEL general geometrical data

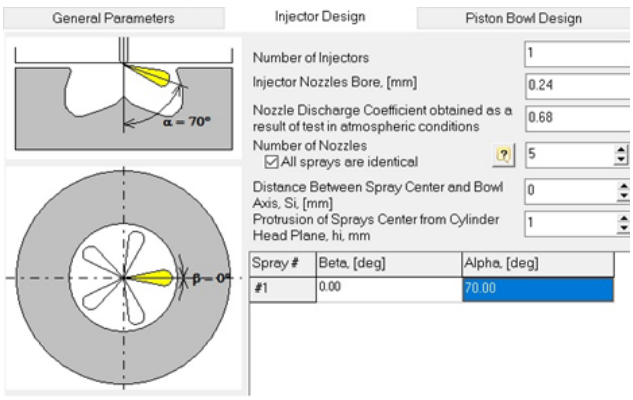

Fig.3. RK-DIESEL injector design parameters

To highlight certain differences and a refined view of the in-cylinder processes a 3D computational fluid dynamics model has been created using AVL FIRE software. An example of the input data is presented in Figures 4, 5, and 6 concerning the main geometrical parameters, injection layout, and mesh discretization.

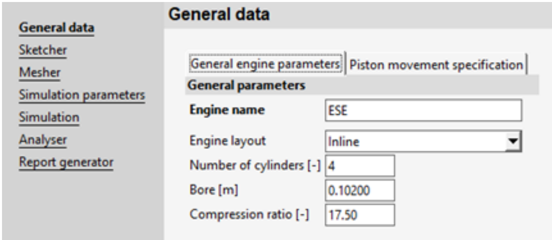

Fig.4. AVL-FIRE main geometrical parameters

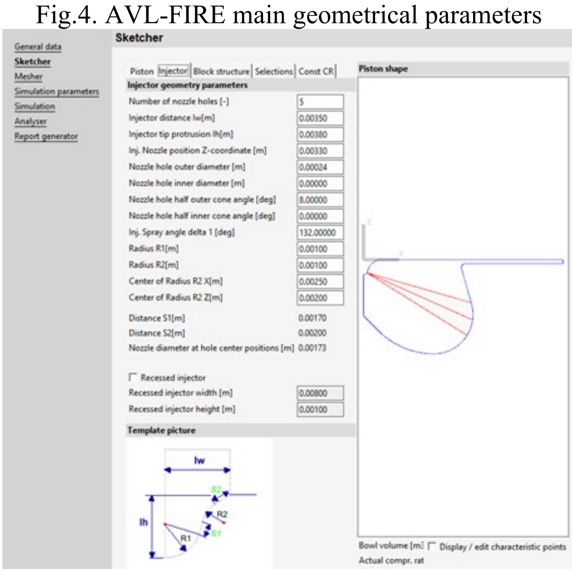

Fig.5. AVL-FIRE injector geometry design parameters

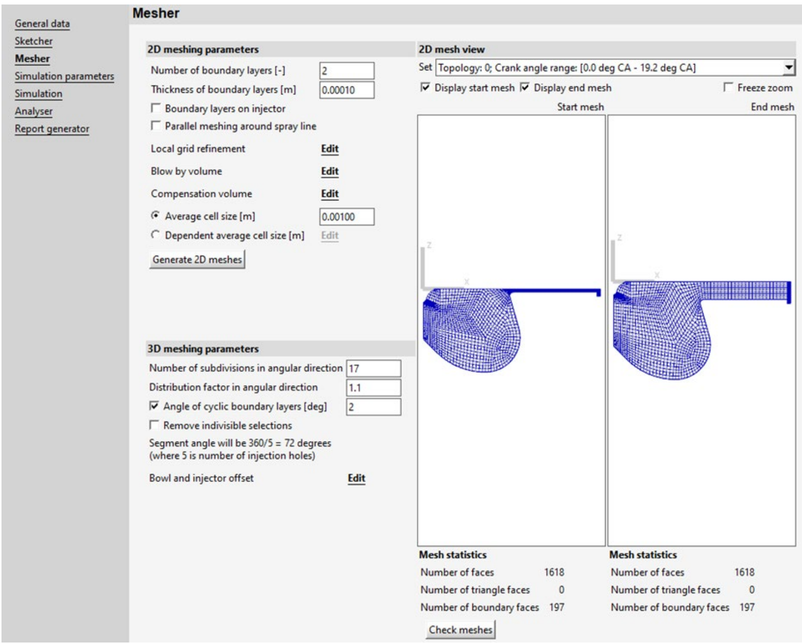

Fig.6. AVL-FIRE mesh discretization parameters

Model validation was carried out using experimental data from the test bench, in full load condition. The main focus was on maximum torque speed and maximum power speed conditions presented in revolutions per minute (rpm) (1400rpm respectively 2400rpm). The data for validation were the needle lift diagram and rail pressure diagrams. First, the AVL HYDSIM model was validated (Figures 7 and 8).

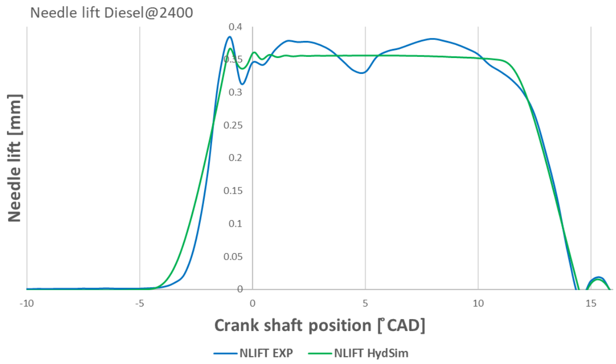

Fig.7. Needle lift HYDSIM model validation

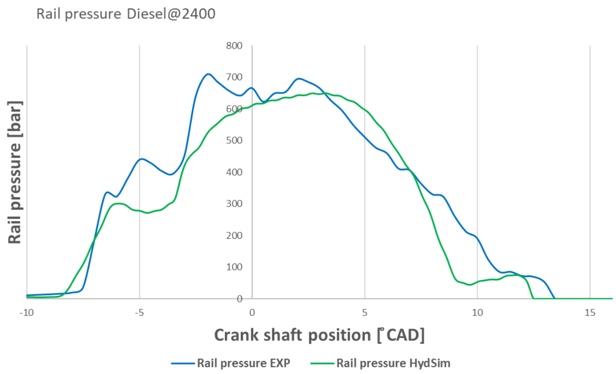

Fig.8.Rail pressure HYDSIM model validation

After the validation, the AVL HYDSIM model became the reference for the other two models created with RK-DIESEL and AVL FIRE.

The fuel jet formation and impingement characteristics are essential in the analysis and diagnosis of the combustion process in the internal combustion engine. Optimizing these parameters, as the cone angle, the Sauter mean diameter or the jet penetration into the combustion chamber helps to better understand the processes developed inside the combustion chamber and could lead to improvements in efficiency, performances and pollutant emissions levels.

The results obtained for spray penetration are presented in Figures 9, 10, 11, and 12.

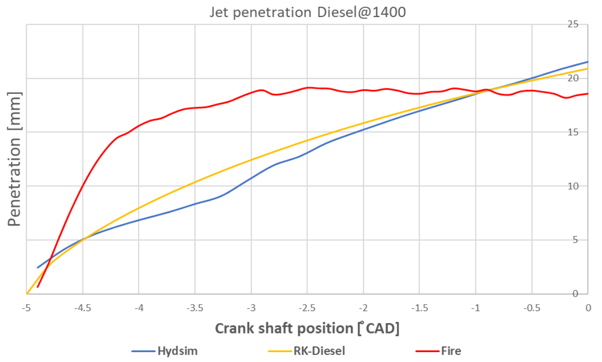

Fig.9. Jet penetration results for Diesel fuel@1400rpm

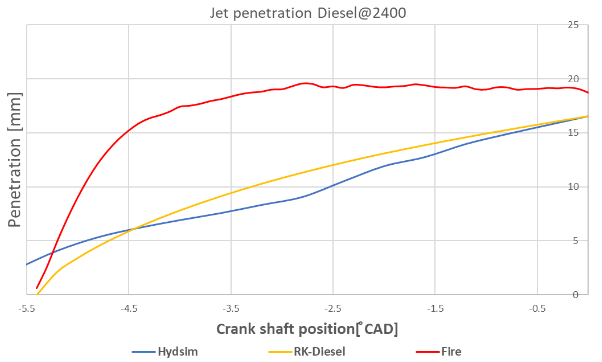

Fig.10. Jet penetration results for Diesel fuel@2400rpm

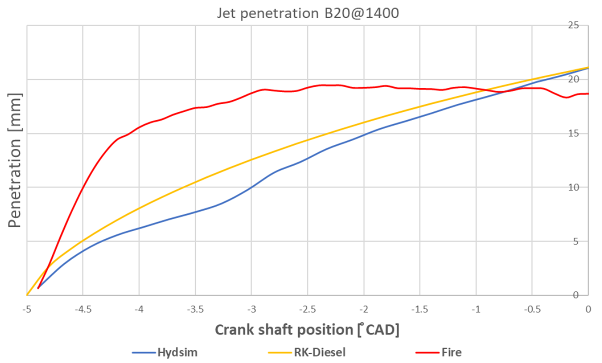

Fig.11. Jet penetration results for B20 fuel@1400rpm

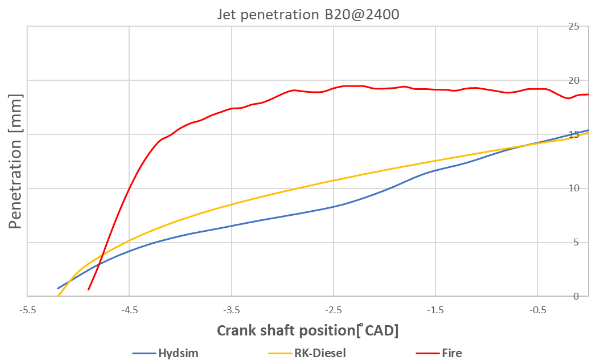

Fig.12. Jet penetration results for B20 fuel@2400rpm

A satisfactory correlation of the jet penetration results with errors below 5% was obtained between the AVL HYDSIM and the RK-DIESEL. The results obtained from AVL FIRE were satisfactory for the maximum torque condition, for both analyzed fuels, with an error of up to 5% compared to the reference, but errors of 21% and 31% respectively were obtained for the maximum power regime for Diesel fuel, respectively B20. It remains to be determined what additional changes need to be made to the AVL FIRE numerical model to reduce the level of errors for the 2400 rpm too.

Regarding the mean Sauter diameter, a good overlap of the data obtained from all the calculation programs compared to the reference was obtained. The errors for the mean Sauter diameter values are less than 5%. The results are presented below in Figures 13, 14, 15, and 16.

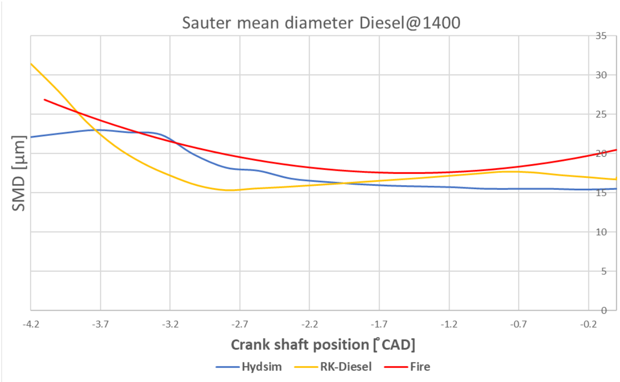

Fig.13. Sauter mean diameter results for Diesel fuel@1400rpm

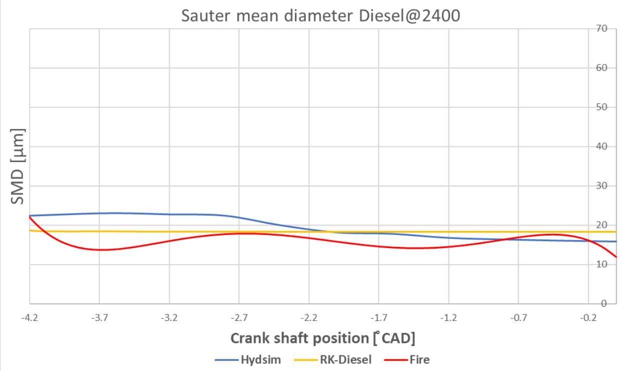

Fig.14. Sauter mean diameter results for Diesel fuel@2400rpm

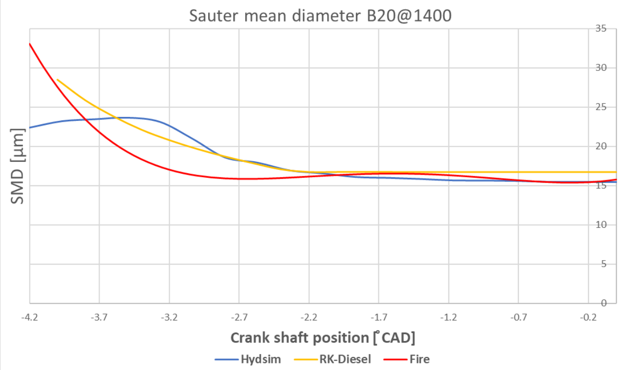

Fig.15. Sauter mean diameter results for B20 fuel@1400rpm

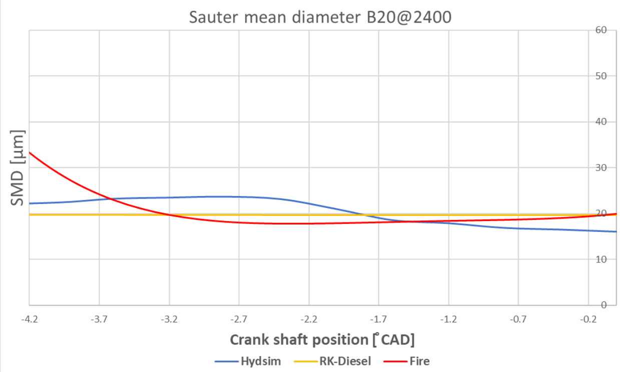

Fig.16. Sauter mean diameter results for B20 fuel@2400rpm

The observation that the mean Sauter diameter increases slightly in the case of B20 compared to Diesel for both regimes can be made. However, this does not significantly affect the duration of the autoignition delay for B20 at 2400 rpm where its value is practically the same, 5.16 versus 5.14 crank angle degrees (CAD) (average of the 4 experimental values + models). At the 1400 rpm regime, however, the increase in the duration of the autoignition delay is 12% from 4.07 to

4.57 CAD, which could explain the more difficult vaporization and oxidation of some drops of larger diameters and therefore an increase in smoke emission.

Regarding the jet cone angle, a satisfactory correlation was obtained between the data obtained from the reference and the RK-DIESEL calculation program. The data obtained for RK-DIESEL are presented in Figures 17, 18, 19 and 20.

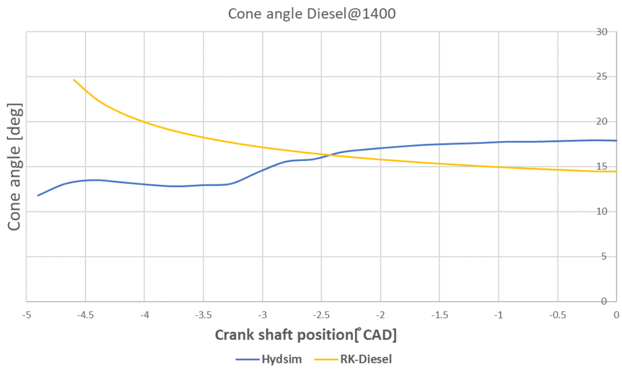

Fig.17. Cone angle results for Diesel fuel@1400rpm

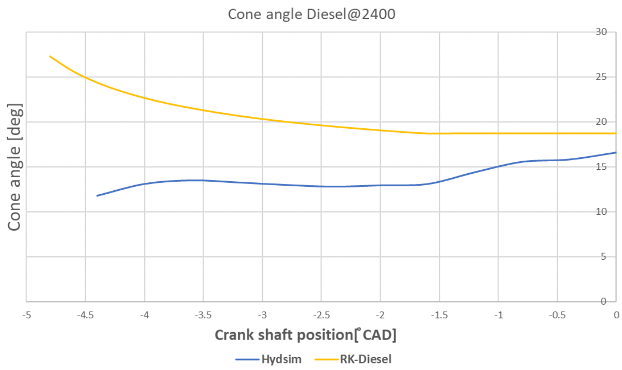

Fig.18. Cone angle results for Diesel fuel@2400rpm

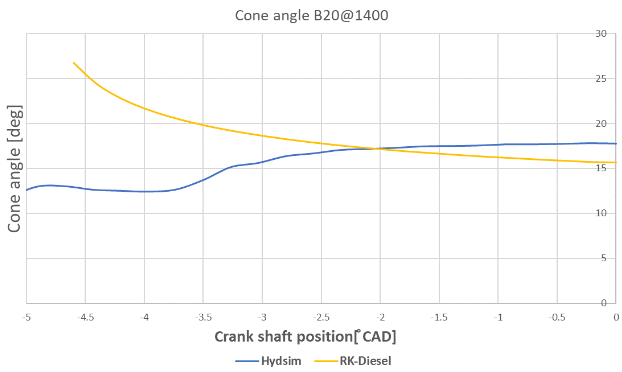

Fig.19. Cone angle results for B20 fuel@1400rpm

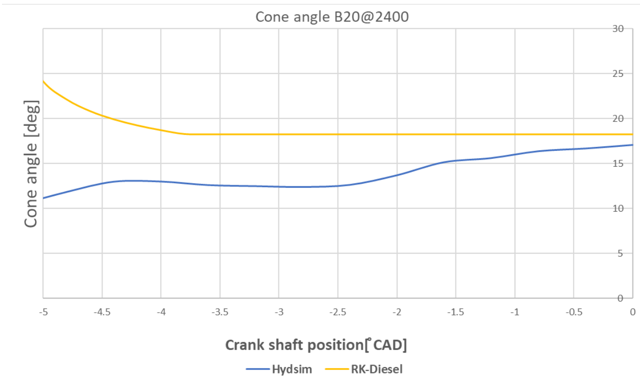

Fig.20. Cone angle results for B20 fuel@2400rpm

In the AVL FIRE software, the cone angle is predefined at a value of 16 CAD. Figure 21 shows the propagation of the fuel jet (the break-up model) where you can see the differences in particle diameters from the start of the injection to the time 1.25 ms. The jet is fully formed after the value of 1.25 ms and this point is chosen as being half the injection time. This is approximately 20 CAD and 1.25 ms means 10.5 CAD at 1400 rpm, respectively 18 CAD at 2400 rpm.

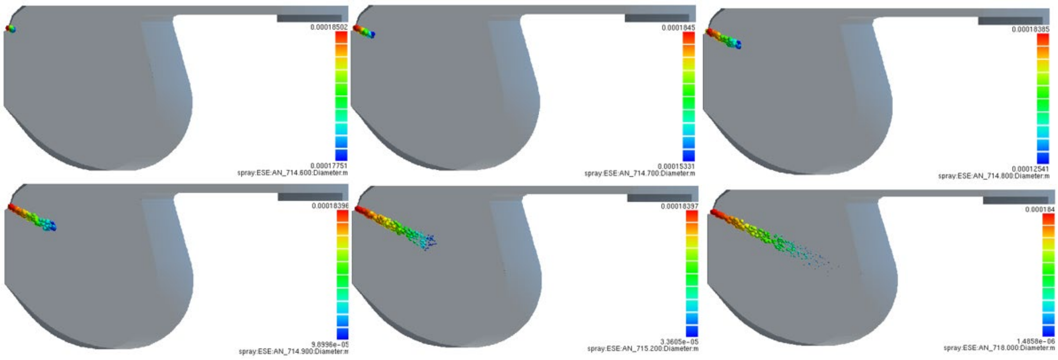

Fig.21. AVL-FIRE Jet in cylinder jet propagation for Diesel fuel @2400rpm

Autoignition delay is an essential parameter that, if determined with high accuracy, can ensure better combustion control and could lead to the improvement of performance parameters, efficiency, and pollutant emissions levels.

In the case of experimental determinations, the autoignition delay was estimated using the indicated diagram, respectively the heat release rate diagram, the start of combustion being considered as the transition point from the negative to the positive range of the heat release rate curve.

RK-DIESEL software utilizes a CHEMKIN tabular calculation for diesel and biofuel. This model was developed by DIESEL-RK programmers. Uses an autoignition delay map calculated with CHEMKIN for various: temperatures, cylinder pressures, EGR, and air/fuel ratios.

In the case of the AVL FIRE, due to its complexity in solving numerous species of chemical reactions, the start of combustion, respectively, the autoignition delay, were determined as the moment when the presence of the OH radical in the cylinder was sensed (above the value of $1*10^{-10}$). The results are presented in Figure 22.

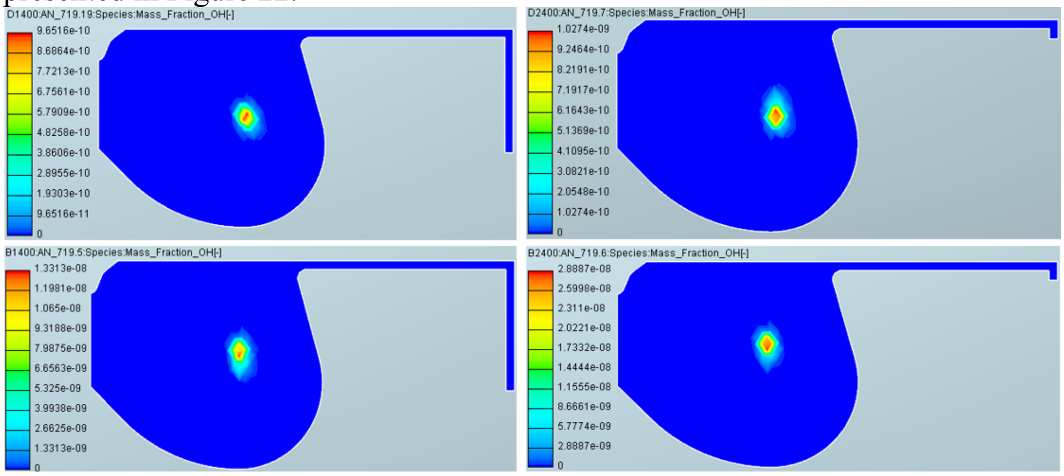

Fig.22. AVL-FIRE OH mass fraction presence for Diesel fuel @2400rpm (start of combustion)

The complete autoignition results are presented in Table 3.

Ignition delay results

ID Diesel [°CAD]			ID B20 [°CAD]		
regime	1400	2400	regime	1400	2400
Experimental	4	5	Experimental	4.66	5.085
RK Diesel	3.964	5.12	RK Diesel	4.55	5.27
Fire	4.19	5.2	Fire	4.5	5.1
ε Diesel (error)			ε B20 (error)		
RK Diesel	0.90%	-2.40%	RK Diesel	2.36%	-3.64%
Fire	-4.75%	-4.00%	Fire	3.43%	-0.29%

Table 3

A good correlation of the results could be observed, all values being below the margin of 5% compared to the results obtained from the experimental data acquired in the test stand.

5. Conclusions

Satisfactory results were obtained for jet penetration, with errors below 5%, between the AVL HYDSIM and RK-DIESEL. The results for the AVL FIRE calculation program were satisfactory for the maximum torque condition, for ~~all~~ both analyzed fuels, with an error of up to 5% compared to the reference, but errors of 21% and 31% respectively were obtained for the maximum power condition. Concerning Diesel fuel, respectively B20 it is to be determined what changes need to be made to the CFD model to obtain a satisfactory correlation for the 2400 rpm as well.

A good overlap of the data obtained from all the used numerical simulation software compared to the reference was obtained. The errors for the mean Sauter diameter values are in the range of less than 5% for the tested conditions and fuels.

Regarding the jet cone angle, a satisfactory correlation was obtained between the data obtained from the reference (AVL HYDSIM) and RK-DIESEL with errors below 5% for all tested regimes and fuels.

The AVL FIRE software, when properly calibrated, can give a very refined view of the processes inside the cylinder, throughout the combustion cycle. Using particle breakup models, it can be simulated the shape of the fuel jet injected into the cylinder.

Autoignition delay can be estimated with a reasonable approximation, using various specific determination methods by one and/or multi-dimensional numerical simulations. The results showed a good correlation of the data obtained by simulation software with the experimental data.

The advantage of using 3D CFD software concerning autoignition delay is that there is a possibility to estimate the geometrical location of the start of combustion moment.

Using properly calibrated models it can be assumed that satisfactory data can be obtained through predictions only using numerical simulations, for different other fuels to save material resources that are consumed through experimental determinations.

All the results obtained trough numerical simulation need to be validated by solid experimental data. The results obtained for B20 show that this fuel can be used in propper conditions of the tested engine without any new adjustment to the fueling system in respect with the initial adjustment.

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