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Study of emissions for a compression ignition engine fueled with a mix of DME and diesel

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Abstract. Currently, there is a growing demand for diesel engines, primarily due to the relatively low fuel consumption compared to spark-ignition engines. However, these engines have a great disadvantage in terms of pollution because they produce solid particles that ultimately form particulate matter (PM), which has harmful effects on human health and also on the environment. The toxic emissions from the diesel engine exhaust, like particulate matter (PM) and NO_x, generated by the combustion of fossil fuels, lead to the necessity to develop green fuels which on one hand should be obtained from regenerative resources and on the other hand less polluting. In this paper, the authors focused on the amount of emissions produced by a diesel engine when running with a fuel mixture consisting of diesel and DME. Dimethyl ether (DME) is developed mainly by converting natural gas or biomass to synthesis gas (syngas). It is an extremely attractive resource for the future used in the transport industry, given that it can be obtained at low costs from renewable resources. Using DME mixed with diesel for the combustion process, besides the fact that it produces less smoke, the emission levels of particulate matter is reduced compared to diesel and in some situations, NOx emissions may decrease. DME has a high enough cetane number to perform well as a compression-ignition fuel but due to the poor lubrication and viscosity, it is difficult to be used as the main fuel for combustion

1. Introduction

More stringent global pollution rules force the automotive industry to adopt various solutions to limit pollutant emissions below the regulated level. To meet this goal, car manufacturers have had to find all sorts of solutions to be able to reduce vehicle emissions, starting from fitting them with diesel particulate filters and sophisticated exhaust after-treatment systems, up to increase the production of hybrid or fully electric vehicles. This option makes the purchase price of the car to be higher due to high production costs.

Due to the fact that The European Union set a target to EU countries to use at least 10% of their transport fuels from renewable sources by 2020, many studies and research have carried out on the use of less polluting fuels for so-called green fuels due to lower emissions than conventional fuels [1].

DME is a gaseous ether at atmospheric pressure and room temperature, with a reduced carbon to hydrogen ratio having the chemical formula CH3-O-CH3. The storage, handling and transport requirements for DME are similar to LPG because of their similar properties. At atmospheric conditions of 0.1 MPa and 298 K, DME is an invisible gas. By increasing the pressure to 0.5 MPa at standard temperature it passes from the vapor phase to the liquid phase. DME gas is denser than dry air, and the density of DME in liquid phase is 660 kg/m^3 at normal temperature and pressure [2][3][4]. One of the great advantages of this fuel is that it can be obtained from a multitude of raw materials such as coal, natural gas or biomass [6][4]. In this paper, we will focus on the potential of using Dimethyl ether

(DME) in different proportions in a blend with diesel, this paper focuses on the emission trend for particulate matter and NOx.

2. DME Properties

In his chemical structure, DME has no direct C-C bond and has a higher oxygen content than other fossil fuels, having as well good evaporation properties [5]. DME cetane number is between 55-60 being higher than conventional diesel which has a cetane value between 40-55 (table 1), thus making it suitable for diesel engines. Due to the high oxygen content of approximately 34.8%, DME supports the combustion process and plays a significant role in reducing emissions. The high cetane number of DME makes to have a lower auto-ignition temperature compared to pure diesel fuel (figure 1) [2][3][5][7][8].

Table 1. Physical and chemical properties of DME and diesel [2]

Property	DME	Diesel
Chemical formula	CH_3OCH_3	C_8 to C_{25}
Molecular weight	46.07	96 ~
Vapor pressure at 20 ^{0}C [bar]	5.1	< 0.01
Boiling temperature [^{0}C]	-25	150 - 380
Liquid density at 20 ^{0}C [kg/m^3]	660	800 - 840
Liquid viscosity at 25 ^{0}C [kg/ms]	0.12-0.15	2 -4
Gas specific gravity [vs air]	1.59	-
Lower heating value [MJ/kg]	28.43	42.5
Cetane number	55 - 60	40 - 55
Stoichiometric A/F ratio [kg/kg]	9.0	14.6
Enthalpy of vaporization at NTP[a] [kJ/kg]	460 [-20 ^{0}C]	250[a]

DME has low toxicity, there is no significant risk if it is inhaled, therefore, it does not have toxic effects for normal use and, at the same time, contact with the skin has no adverse effects[2][9]. In terms of LHV (lower heating value), DME has a LHV of 28.3 [MJ / kg] compared to diesel which has 42.5 [MJ / kg] [2]. This may be a disadvantage due to the fact that more fuel should be injected per cycle. In

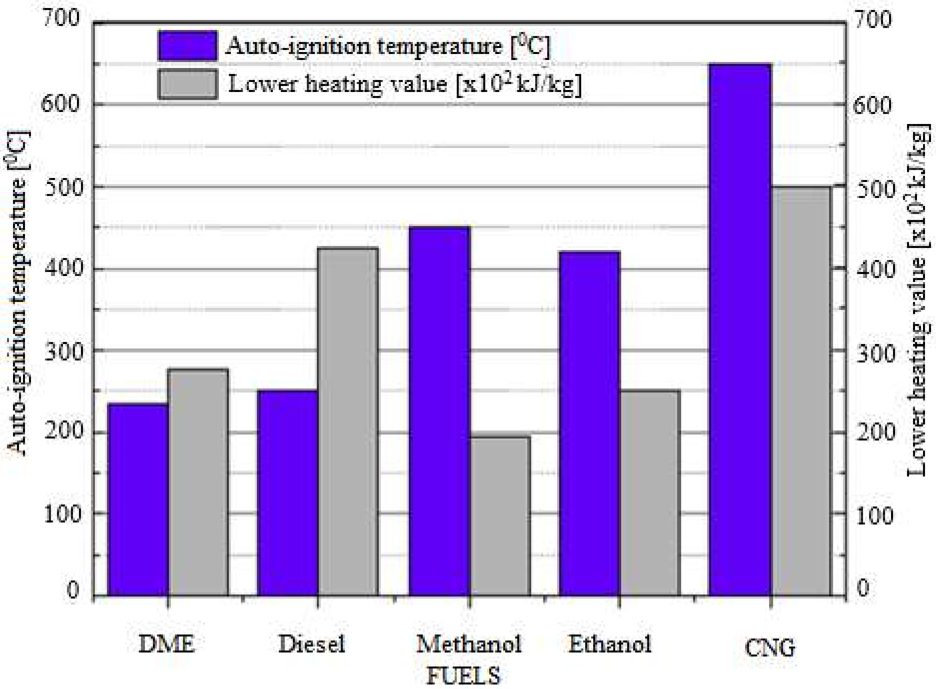

Figure 1 Auto-ignition temperature and heating values of various fuels [2]

terms of existing drawbacks in the application of DME as fuel for compression-ignition engines, is that DME has low lubrication characteristics and low viscosity compared to diesel, which causes fuel leakage and a bigger wear on moving parts of the injection system, thus requiring the use of additives to prevent fuel leakage and surface wear [2][4][5][10][11].

2.1. DME Production

Normally the production of dimethyl ether includes two step process [4] :

- Conversion of syngas to methanol
- Dehydration of methanol to dimethyl ether

The chemical reactions described by Troy et al [4] for DME formation are :

- Methanol synthesis :

$$CO + 2H_2 \rightarrow CH_3OH \quad (1)$$

- Methanol dehydration :

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \quad (2)$$

- Water-gas shift :

$$H_2O + CO \rightarrow H_2 + CO_2 \quad (3)$$

- Net Reaction :

$$3H_2 + 3CO \rightarrow CH_3OCH_3 + CO_2 \quad (4)$$

2.2 DME Impact on Pollutant Emissions

Research on emissions produced by DME shows a downward trend in pollutant emissions especially in the case of particulate matter produced by the engine. These studies which have been taken into account, treats the case of the use of pure DME, as well as the case of mixing DME and diesel. Troy et al [4] present that the advantages of dimethyl ether over conventional diesel include reduced emissions of NOx, hydrocarbons and carbon monoxide and that DME does not produce soot (figure 2). According to

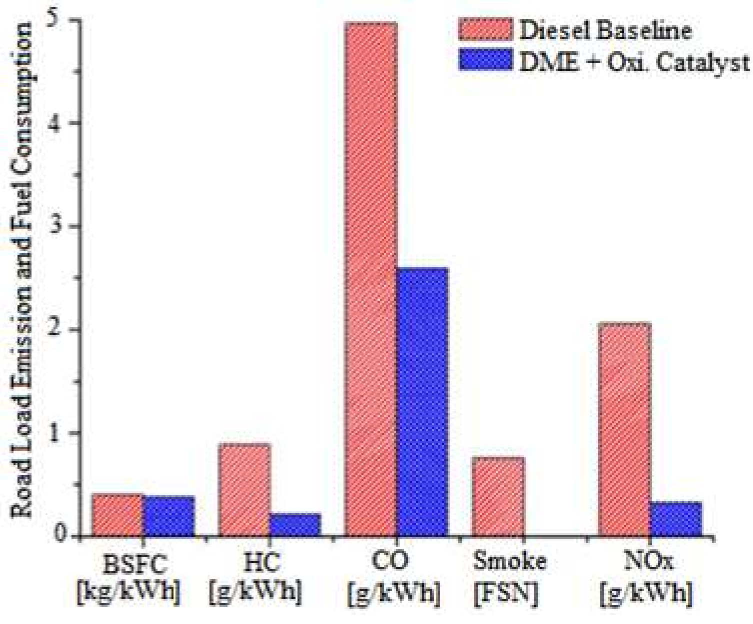

Figure 2 Road load test data comparing engine emissions using diesel and neat DME [4][18]

Ohno et al [12], they point out that the DME combustion characteristics include a similar thermal efficiency with diesel fuel, but with lower NOx emissions and without soot emissions.

A study of a DME blend and diesel was made by Wang et al[13] and they highlighted that the impact on emissions varies depending on engine operating conditions, at a high engine load, it reduces the smoke emissions around 58% to 68% for a mixture of DME and diesel compared to pure diesel. An interesting fact they describe is by adding DME, NOx emissions decrease a little, while CO emissions and unburned HC emissions increase under most operating conditions. Park et al [14] have shown the advantage of oxygen content in fuel in terms of lowering soot emissions.

There are some papers showing that NOx emissions increase if DME is added in a blend with diesel. Kim et al [15] reported higher NOx emissions with DME compared to diesel for all injection strategy. Park et al [16] submit that the emissions of NOx is higher for DME compared to diesel and the application of EGR is necessary to reduce the NO_X emissions during DME combustion.

3. Methodology

For this study the diesel particulate filter DPF was modeled using AVL BOOST. This way it was possible to consider correlations and connections between the amount of soot, the type of DPF channel structure and the type of fuel used for combustion. By using AVL BOOST simulation the authors were able to highlight the emission trend for a fuel mixture of diesel and DME in different proportions. Based on the obtained data it was possible to study an injection strategy to improve the emissions[17].

3.1. Engine Model

The model for this study is based on a single cylinder research diesel engine, namely the AVL 5402 of the Testecocel laboratory, from The Department of Automotive Engineering and Transports, Faculty of Mechanics of Technical University of Cluj Napoca. The technical data of the engine was used for the development of simulation model. The diagrams and the experimental data have been extracted from the testbed measurements and stored in the post processing software AVL CONCERTO. The Cylinder of the model is connected with the Engine element and it defines the type of engine used, operating speeds, moments of inertia and the brake mean effective pressure (BMEP). The combustion model used for simulation was the AVL MCC Model (Mixing Controlled Combustion), a model that predicts the rate of heat release (ROHR), NOx and accumulated Soot emissions based on the quantity of fuel injected in the cylinder and the turbulent kinetic energy introduced by the injection process. To calculate the injection rate of the combustion process, the normalized rate of injection (ROI) was used. This determines the fuel injection rate with respect to time [17].

The simulation model was built based on the single engine Cylinder Research Engine 5402 with the following technical data :

Table 2. 5402 Engine Technical Data

Parameter	Value	M.U.
Number of cylinders	1	[-]
Bore x Stroke	85 x 90	[mm]
Compression ratio	17.1	[-]
Maximum power	6	[kW]
Rated speed	4200	[min^{-1}]
Combustion system	4 valve	[-]
Displacement	510.7	[cm^3]

Based on the data from table 2, a simulation model was created in AVL boost. The simulation model in AVL BOOST was built by adding the constructive elements presented in the table above, respecting the technical data of the AVL 5402 single-cylinder engine. The simulation model presented in figure 3 contains the following elements: SB1; SB2 - Boundary elements, MP1; MP2 - measuring points, C1 - cylinder, CAT1 - catalyst, PF1 - particulate filter.

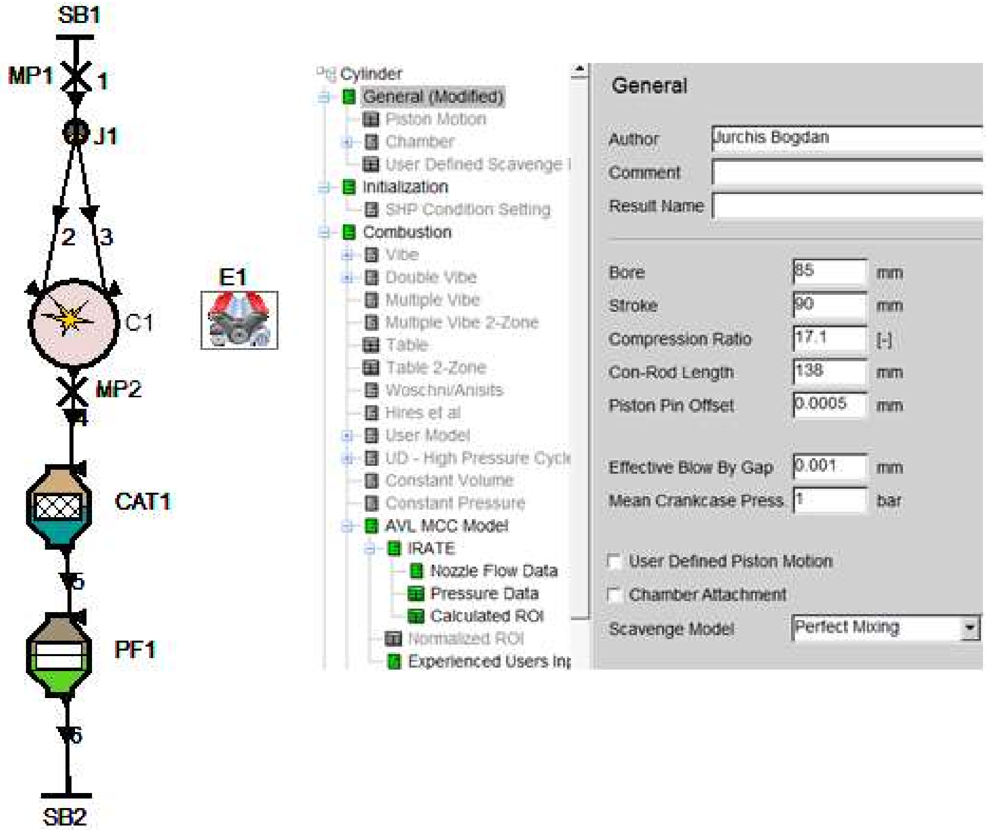

Figure 3 The AVL BOOST simulation model

3.2 Model Validation

The model was validated by comparing the pressure curves at 2000 rpm between the simulation and the experimental case, for the validation model we used pure diesel as fuel (figure 4). Based on the above

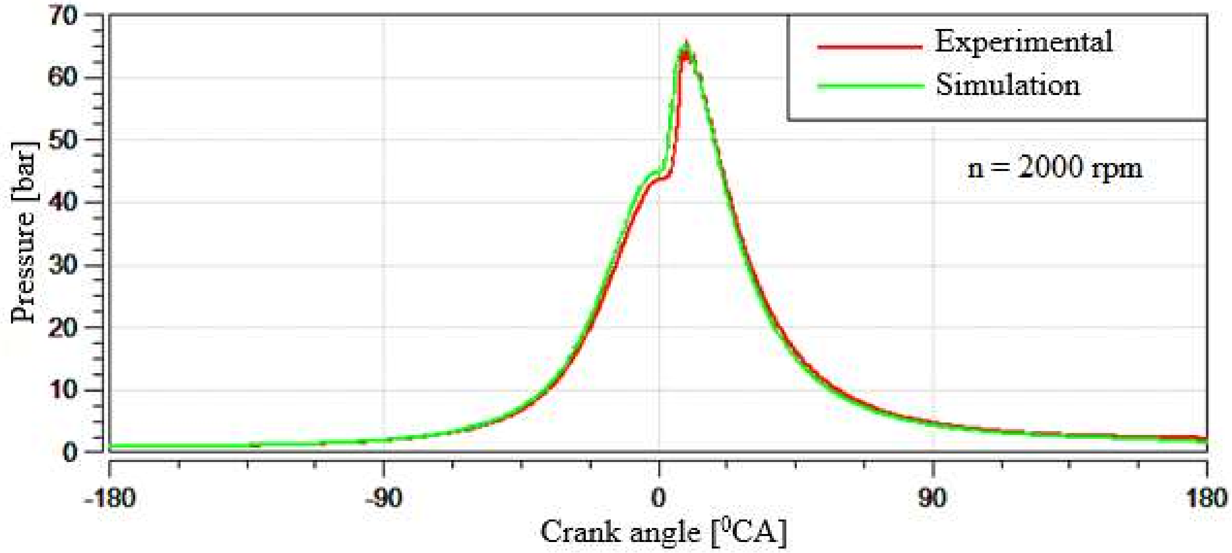

Figure 4 Model validation at 2000 min^{-1} fueled with pure diesel

chart it was considered that the simulation data is in accord with the experimental data and the simulation model can be used to highlight the NOx and PM emissions.

4. Results and discussions

In this paper, the tests that have been carried out have revealed that DME is a fuel that can be taken into account in terms of less polluting fuels. Tests have shown that adding DME favors burning due to increased oxygen content, producing less smoke after burning. The proportion we used in this paper was 10% or 20% DME in a blend with pure diesel at different engine speeds the emissions of soot were reduced by the addition of DME for all engine speeds as shown in the figure 5 at 1500 min^{-1}, figure 6 at 2000 min^{-1} and figure 7 at 2500 min^{-1}. Comparing cases between DME10 and DME20 showed that increasing the proportion of DME reduces the soot accumulation for all engine speed as it can be observed in figure 5, figure 6 and figure 7. From here it can be concluded that DME is a sootless fuel which can be used in a blend with diesel to reduce particulate matter. The change in injection rate did not yield any notable results in terms of particulate emissions.

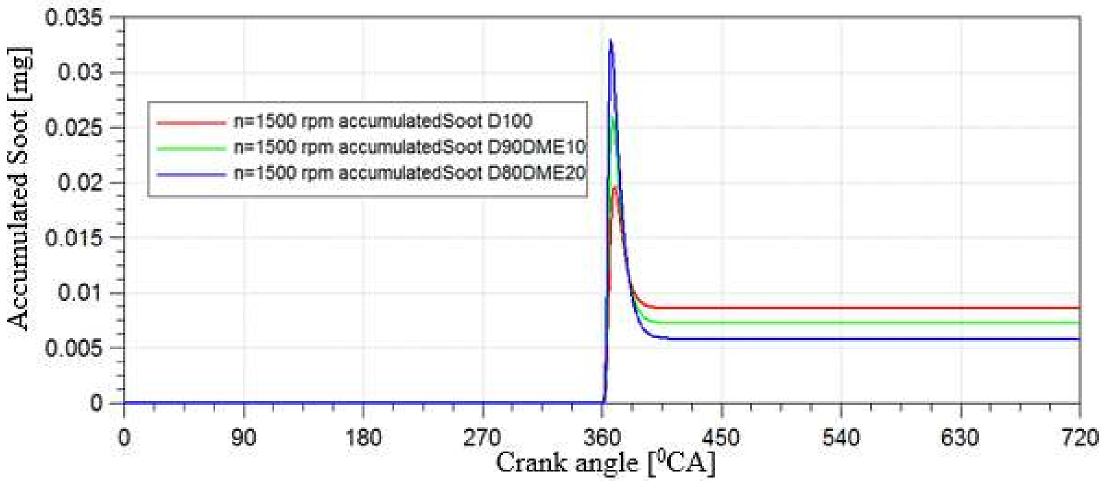

Figure 5 Soot accumulation for n=1500 min^{-1}

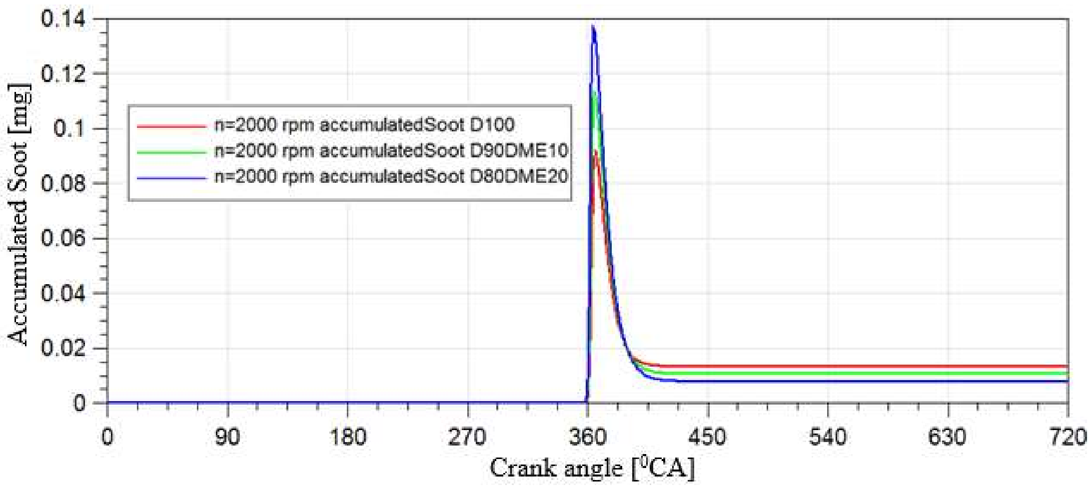

Figure 6 Soot accumulation for n=2000 min^{-1}

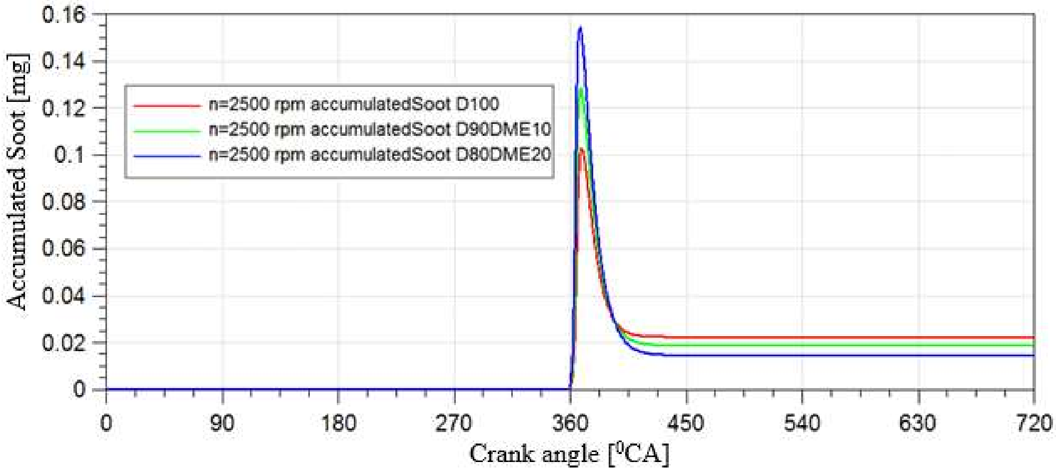

Figure 7 Soot accumulation for n=2500 min^{-1}

Another analysis that has been carried out in this paper is about the NOx emissions produced when operating with a mixture of diesel and DME. The amount of NOx produced was directly proportional to the amount of DME injected, as can be seen in the figure 8, figure 9, and figure 10 for all engine speeds.

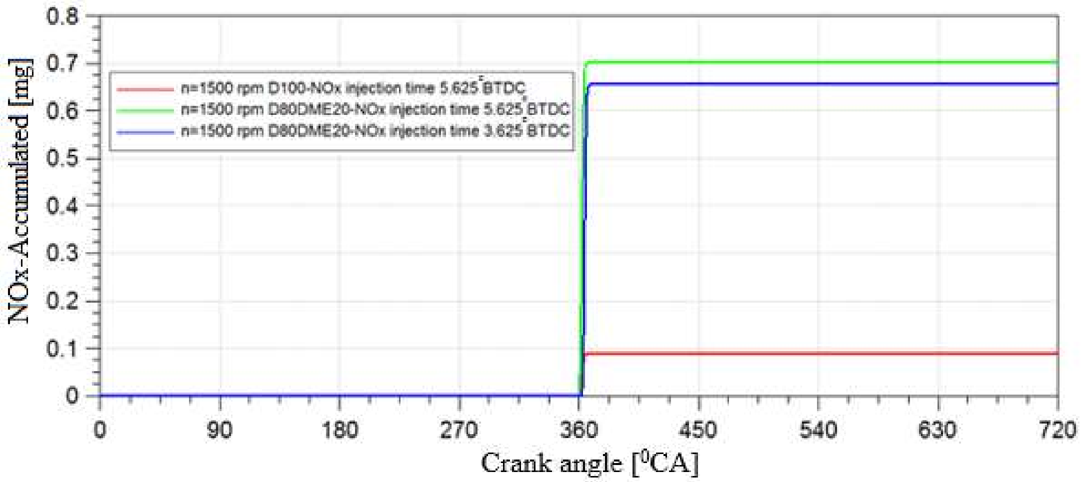

Figure 8 NOx emissions for n=1500 min^{-1}

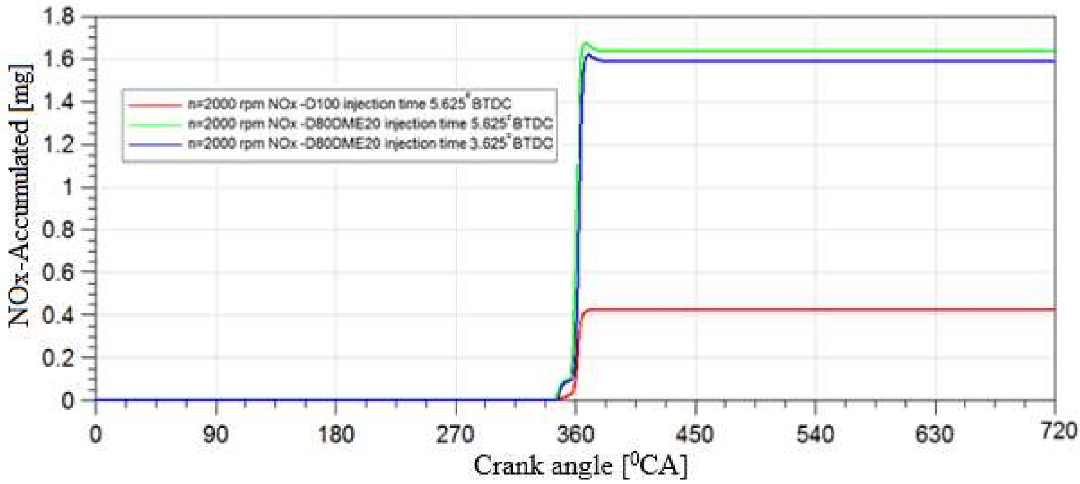

Figure 9 NOx emissions for n=2000 min^{-1}

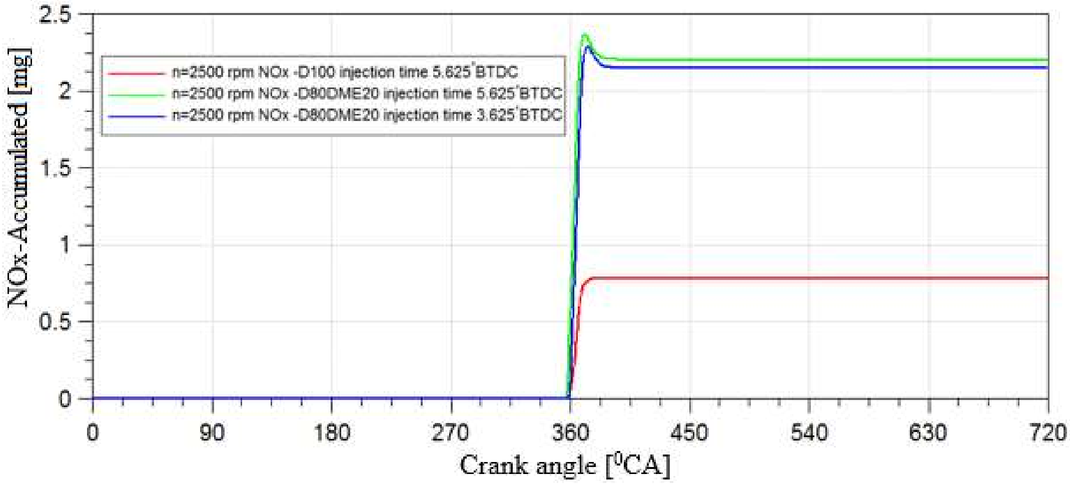

Figure 10 NOx emissions for n=2500 min^{-1}

Tests have shown that NOx emissions have increased slightly compared to pure diesel, and this trend has been kept for all engine speeds, DME20 producing more NOx than DME10. After many simulations it resulted that modifying the injection rate from 5,6250 BTDC to 3,6250 BTDC, brings a NOx reduction but not enough comparable to diesel so that another solutions for lowering NOx have to be considered by adding DME to the diesel.

5. Conclusions

The purpose of this work was to track pollutant emissions of soot and NOx by adding different proportions of DME mixed with diesel.

General conclusions that can be drawn from the tests are:

- DME is a fuel that improves the burning process by producing less soot due to its oxygen content
- Soot emissions decreases if the amount of DME is increased for all engine speeds
- NOx emissions are higher by adding DME compared to diesel for all engine speeds
- It has been noticed that the change in the injection pressure has reduced the NOx emission but not enough compared to diesel, so exhaust gas after-treatment systems such as the gas recirculation valve should be used to engines that are fueled by a mix of DME and diesel

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