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Influences of diesel pilot injection on ethanol autoignition - a numerical analysis

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Abstract. The aim of this study is to highlight the influences of the diesel pilot quantity as well as the timing on the autoignition of ethanol and the pollutant emissions resulting from the combustion process. The combustion concept presented in this paper requires the injection of a small quantity of diesel fuel in order to create the required autoignition conditions for ethanol. The combustion of the diesel droplets injected in the combustion chamber lead to the creation of high temperature locations that favour the autoignition of ethanol. However, due to the high vaporization enthalpy and the better distribution inside the combustion chamber of ethanol, the peak temperature values are reduced. Due to the lower temperature values and the high burning velocity of ethanol (combined with the fact that there are multiple ignition sources) the conditions required for the formation of nitric oxides are not achieved anymore, thus leading to significantly lower NOx emissions. This way the benefits of the Diesel engine and of the constant volume combustion are combined to enable a more efficient and environmentally friendly combustion process.

1. Introduction

In light of the current efforts to clean the air in cities all around Europe by banning cars with diesel engines due to their high levels of particulate matter (PM) and nitric oxides (NO_x), the current study proposes a solution that could reinvent the Diesel process with the aid of renewable fuels, in this case bioethanol [1]. Even if the current solution implies the use of a small quantity of diesel – that anyway represents under 10% of the total amount of fuel supplied to the cylinder – for future solution the diesel fuel could be replaced with renewable solutions like dimethylether, which has been proved by many researchers to be a viable solution for diesel [2-5]. A survey of the available literature has showed that there are numerous studies about the use of ethanol fumigation [6-9] and diesel-ethanol blends [10-15], but very few studies that cover such a process that involves a separate direct injection of both fuels (diesel and ethanol), in which the diesel pilot injection is used to create the required conditions for the autoignition of a main ethanol injection, which is believed to be due to its higher complexity. The aim of this solution is to reduce the NO_x and soot emissions, while taking advantage of the higher efficiency of the Diesel process. If one takes into account that the current solutions to address these pollutants are selective catalytic reduction (SCR) and/or NO_x traps for nitric oxides and diesel particulate filters (DPF) for the PM, which are actually aftertreatment solutions, the solution presented above becomes a very attractive alternative because it affects the combustion itself. The current paper is continuation of a previous study in which the solution was compared with pure diesel combustion [1]. The main limitation of this study is that, currently, there is no experimental test bench available to back up the simulation results, but this is being addressed by the authors with the development of such a test bench.

2. Methodology

The study of the proposed combustion process involving the autoignition of a main ethanol injection with the aid of a diesel pilot injection required the development of a specific simulation strategy which was presented in [1]. This strategy involved the following steps: a) Run the simulation with diesel fuel to obtain the reference case; b) Run a second simulation with diesel fuel up to the main injection event; c) Stop the simulation just before the main injection and change the fuel from diesel to ethanol; d) Run the simulation from the point of main injection. The sector simulation model is based on a single cylinder research engine (SCRE) AVL 5402 with the following characteristics:

Table 1 Technical data of the engine

	Value	M.U.
Bore x Stroke	85 x 90	[mm] x [mm]
Compression ratio	17.1	[-]
Displacement	510.7	[cm^3]
Intake	1 Tangential port 1 Swirl port	
Power (naturally aspirated)	6	[kW]
Injection system	BOSCH Common Rail	
Injector (injection holes x diameter)	8 x 0.12	[-] x [mm]
Injection pressure	80	[MPa]

Following the development of the simulation model an extensive validation for diesel and a blend of diesel and ethanol was done for different speeds and loads, which is presented in [1]. To improve accuracy of the input data a more detailed simulation model was also used [16, 17]. The experimental data required for the testing was gathered using the equipment in the Laboratory of research, testing and homologation of internal combustion engines (TESTECOCEL) of the Department of Automotive and Transport within the Technical University of Cluj-Napoca [18]. The set-up of this laboratory for the SCRE used for this study is presented in Figure 1.

Figure 1. TESTECOCEL Laboratory set-up for SCRE AVL 5402

In the previous studies the injection timing and pilot quantities were the same as for the conventional Diesel combustion. To further the knowledge regarding the proposed combustion process, for this study the pilot injection parameters quantity and timing where changed to identify their influence on the combustion of the main ethanol injection. The influence was evaluated with respect to the temporal evolution of in-cylinder pressure and temperature, rate of heat release, accumulated heat released, ignition delay and pollutant emissions (NO and soot), as well as to the spatial evolution of the equivalence ratio, temperature and NO. The studied cases are presented in table 2. The engine speed was the same in all cases: 1500 [min^{-1}].

Table 2 Description of the simulated cases

D100_E100 case	Pilot		Main	
	Quantity [mg]	Timing [°CA] bTDC	Quantity [mg]	Timing [°CA] bTDC
0.5mg_24mg	0.5	21	24	0,6
0.5mg_24mg_4degCA	0.5	25		
1mg_24mg	1	21		
1mg_24mg_4degCA	1	25		
2mg_24mg	2	21		
2mg_24mg_4degCA	2	25		

The limitations of the study arise from the employed simulation strategy, which introduces an error in the total amount of energy and in the absolute value of pollutant emissions. However, a closer analysis of the results revealed that this error is lower than 3% in all cases [1].

3. Results and discussions

3.1. Quantity

For a better understanding of the phenomenon the analysis has been split in two parts: temporal evolution – where the parameters of interest are analyzed based on their evolution during the cycle – and spatial evolution – where cuts inside the cylinder at different crank angles are done to show the distribution of fuel, temperature and NO.

3.1.1. Temporal evolution. The temporal analysis of the results showed that the highest pressure was obtained in the case D100_E100_2mg_24mg (Figure 2), which was to be expected, since in this case the total fuel quantity is the highest. Due to the high diesel pilot quantity there is also a high pressure and temperature (Figure 3) increase, which leads to favourable autoignition conditions and a sufficient amount of energy for the main ethanol injection. As a result the rate of heat release shows lower peak values and a less steep increase compared to the other two cases.

The second highest pressure was obtained in the D100_E100_0.5mg_24mg. This is due to the fact that the lower pilot quantity leads to a larger ignition delay of the second stage of ethanol combustion. The heat released by the 0.5 [mg] pilot is enough to lead to the autoignition of the first ethanol drops, but, as the main injection of ethanol continues, the energy required for combustion is competing with the energy required for the evaporation of the fuel. This then leads, earlier than in the D100_E100_1mg_24mg case, to a stagnation of rate of heat release, until the ethanol is sufficiently mixed with air and heat is released again. Due to the fact that during this second stage of combustion the burnt quantity is larger in the D100_E100_0.5mg_24mg case than in the D100_E100_1mg_24mg case and due to the high burning velocity of ethanol, there is a rapid pressure increase that leads to a higher peak pressure. In the D100_E100_1mg_24mg case the stagnation is a bit more retarded and, as a result, the amount of fuel that is burnt in the second stage is smaller and the combustion evolves with an inferior speed. The phenomenon is also visible in the temperature curves (Figure 2). It must be noted that the maximum mean temperature in the cylinder corresponds to the amount of energy supplied to the cycle with the highest value for D100_E100_2mg_24mg and the lowest value for D100_E100_0.5mg_24mg.

A closer analysis also shows that, in the case D100_E100_2mg_24mg the combustion takes place in a single stage and not in two stages like in the other two case with 0.5 and 1 [mg] diesel pilot. The less violent combustion would also lead to lower mechanical stress of the engine components. However, in order to have a complete understanding, this would require additional experimental results.

The temporal development of combustion determines the end products of the process. Since the parameters of the pilot injection have a strong influence on the combustion process, the emissions vary significantly (Figure 4).

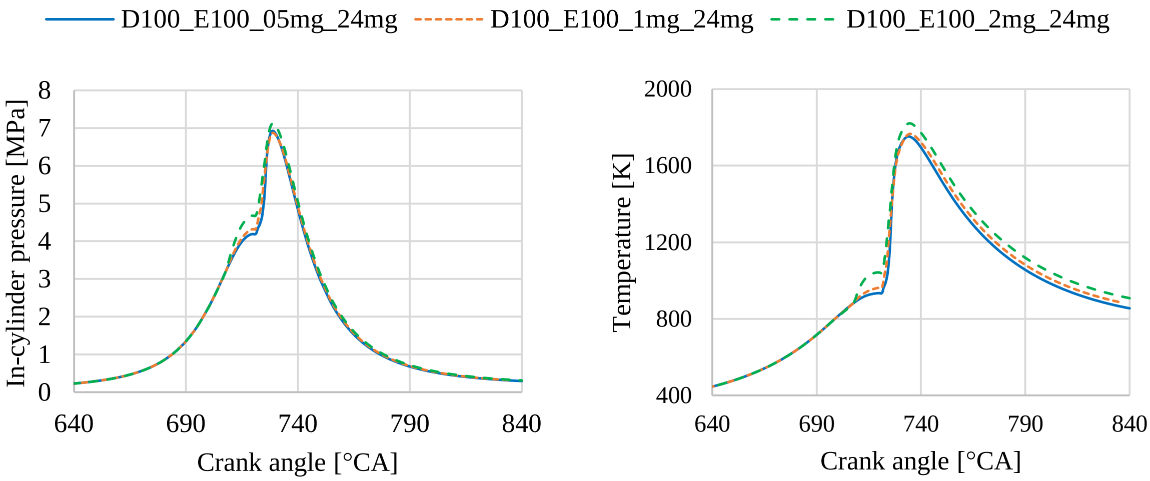

Figure 2. In-cylinder pressure and temperature evolution for a pilot advance of 21 [°CA]

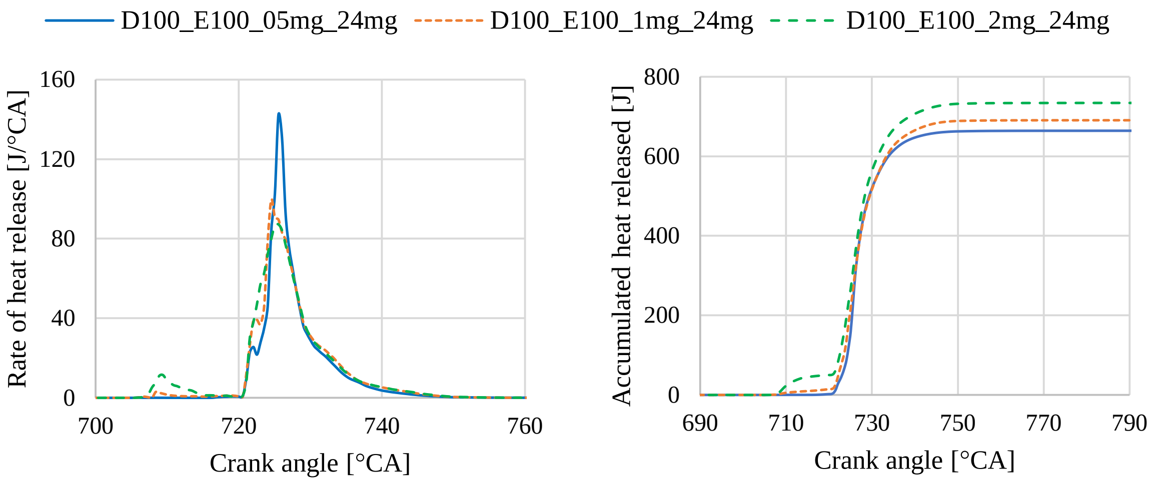

Figure 3. The rate of heat release and the accumulated heat released for a pilot advance of 21 [°CA]

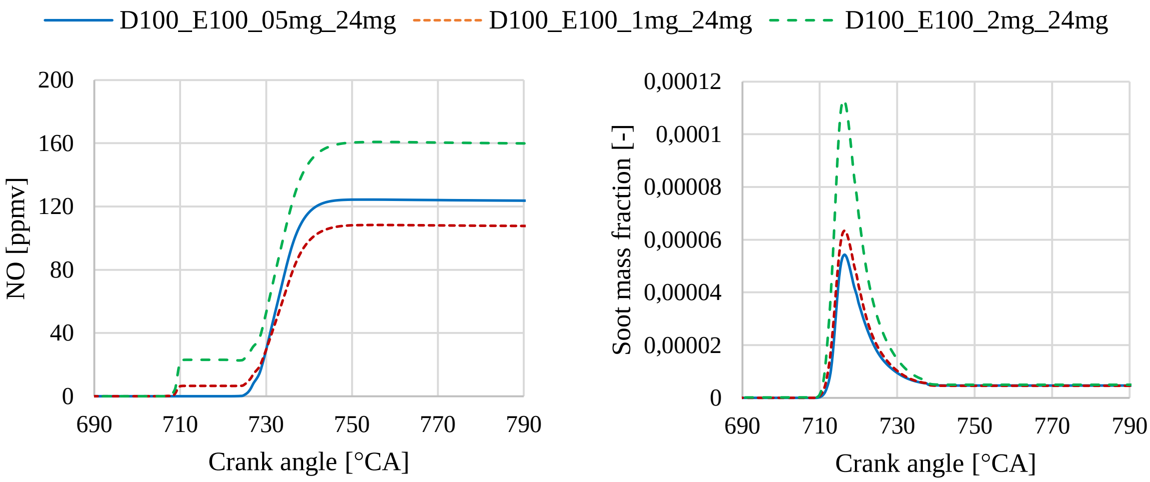

Figure 4. The temporal evolution of NO and soot for a pilot advance of 21 [°CA]

The analysis of NO showed that the highest values are obtained in the D100_E100_2mg_24mg, which is a direct result of the higher diesel quantity. The more interesting aspect is that the lowest values were obtained in the D100_E100_1mg_24mg case. The larger values in the D100_E100_0.5mg_24mg case are however a result of the larger ignition delay and of the larger quantity burnt in the second stage of the process. With respect to soot, the influence of the pilot quantity on the end values is very small.

3.1.2. Spatial evolution. In Figure 5 is presented the spatial distribution of the fuel (equivalence ratio), temperature and NO at 723, 730 and 740 [°CA] for the three cases with a pilot advance of 21 [°CA].

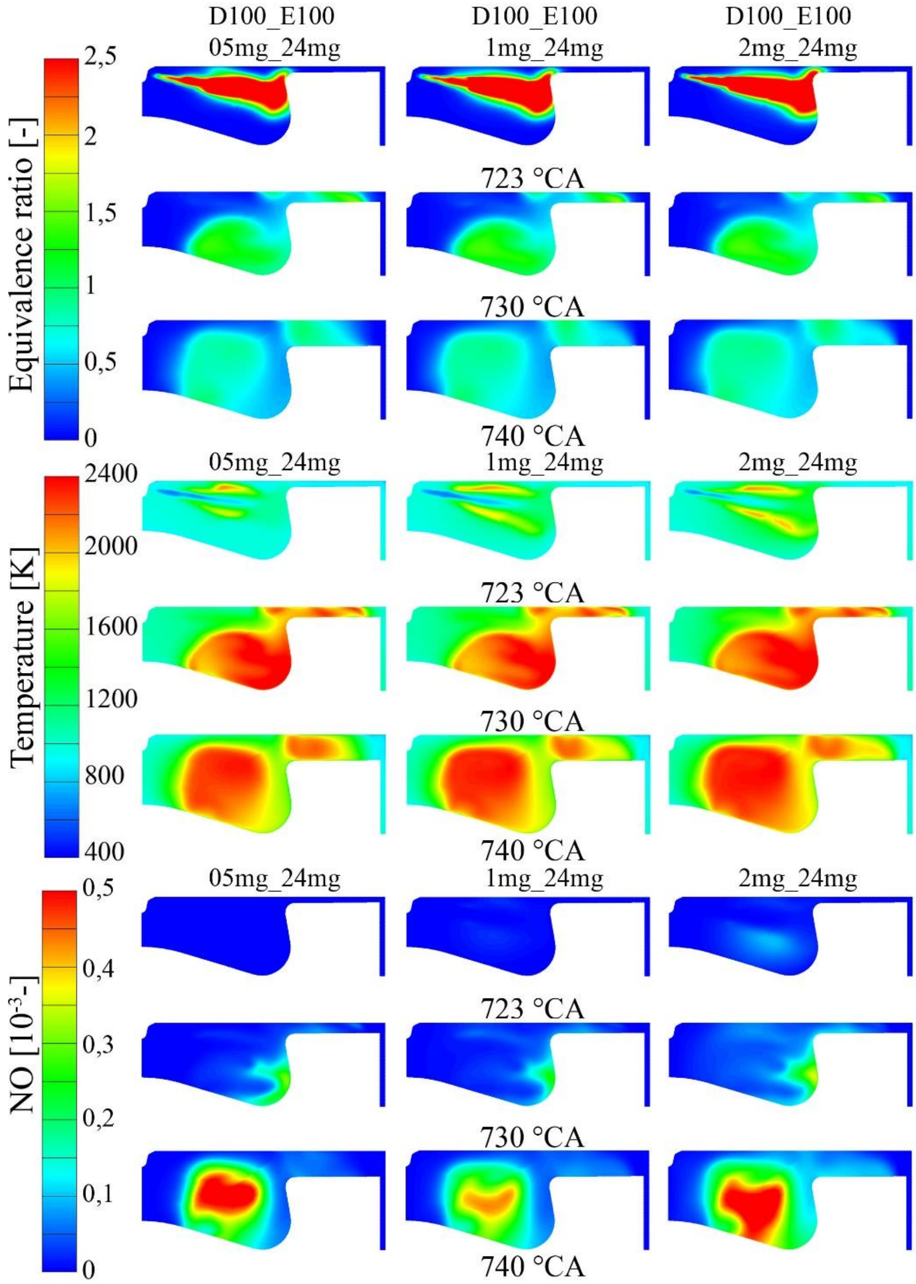

Figure 5. Equivalence ratio, temperature and NO spatial distribution at different crank angles for a pilot advance of 21 [°CA]

For the D100_E100_2mg_24mg case higher NO values (see Figure 5) are to be expected due to the higher amount of diesel fuel that leads to a higher pressure and higher local temperatures in the combustion chamber. The other two cases require a more detailed analysis of the images combined with the temporal evolution of the variables of interest. The point of interest for these two cases is around 730 [°CA] because this were the NO values in the D100_E100_05mg_24mg case overcome the values of the D100_E100_1mg_24mg case. The combined analysis shows that the larger amount of fuel that burns in the second stage of the D100_E100_05mg_24mg case leads to higher local temperatures (see Figure 5 for 730 [°CA]) that then lead to higher NO formation rates.

3.2. Timing

The second part of this study was the effect of the pilot timing on the variables of interest. In this sense, the pilot diesel injection advance was increased by 4 [°CA] for all three quantities.

3.2.1. Temporal evolution. Compared to the initial cases with an advance of 21 [°CA], when the advance is increased to 25 [°CA], the main difference that can be noticed is for the D100_E100_05mg_24mg_4degCA – where 4degCA designates the additional 4 [°CA] compared to the first three cases. Between the other two cases D100_E100_1mg_24mg_4degCA and D100_E100_2mg_24mg_4degCA one can observe similar differences as presented at 3.1.1.
By increasing the advance, in case D100_E100_05mg_24mg_4degCA one can notice a very late combustion which would seriously impair the operation of the real engine. In this case the combustion starts at 746.5 [°CA], which can be seen in the cylinder pressure and temperature as well in the rate of heat release. A closer analysis of this revealed that the combination of small pilot quantity, increased ignition delay and charge movement leads to a much to lean mixture that cannot ignite. The injection of ethanol aids in the formation of a rich enough mixture, but the high enthalpy of vaporization further increases the ignition delay. When it finally starts, the combustion evolves with a very low heat release rate and as a result the accumulated heat released is much lower than in the other cases. Also, the temperature is much too low and therefore, the end NO values are very low.

When comparing the values of the variables of interest of the cases with 21 [°CA] advance with those of the cases with 25 [°CA] there are only very small differences with respect to in-cylinder pressure and temperature. The increase pilot injection advance of the D100_E100_1mg_24mg_4degCA case revealed a single stage combustion with a lower peak value compared to the D100_E100_1mg_24mg case, which can be seen in the rate of heat release. The end values of NO and soot are somewhat higher in this case, but the difference is negligible.

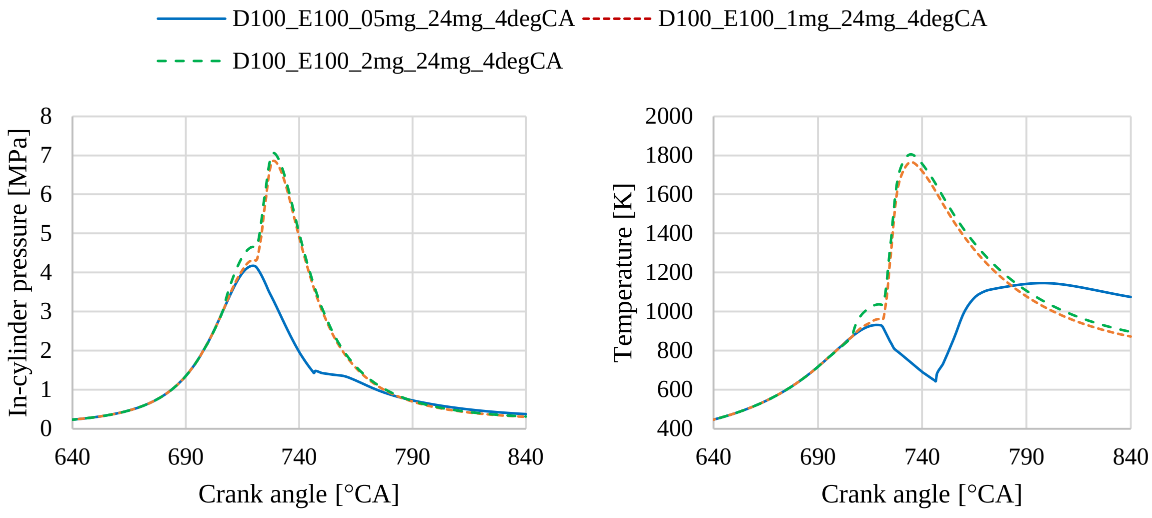

Figure 6. In-cylinder pressure and temperature evolution for a pilot advance of 25 [°CA]

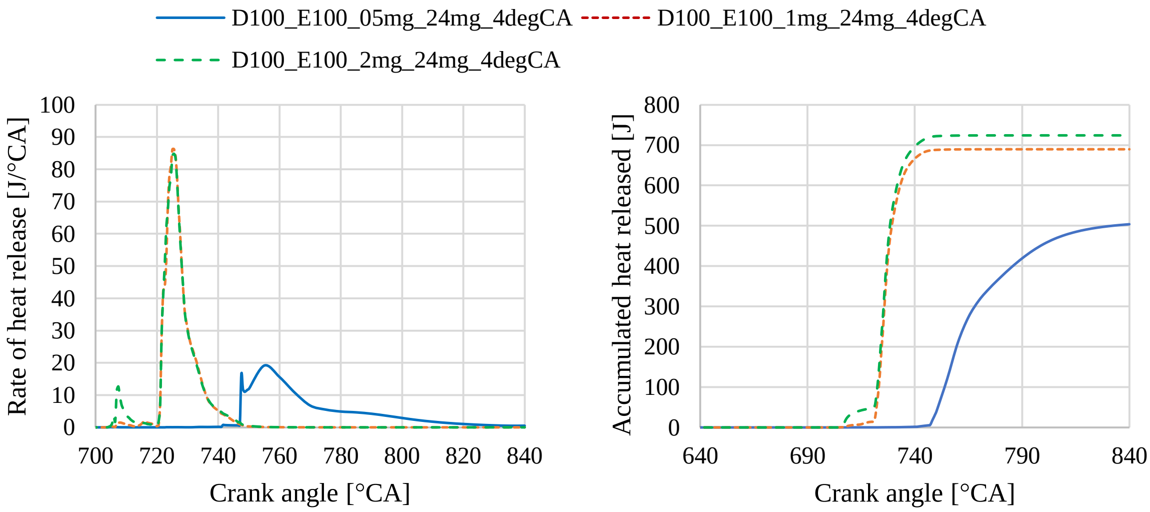

Figure 7. The rate of heat release and the accumulated heat released for a pilot advance of 25 [°CA]

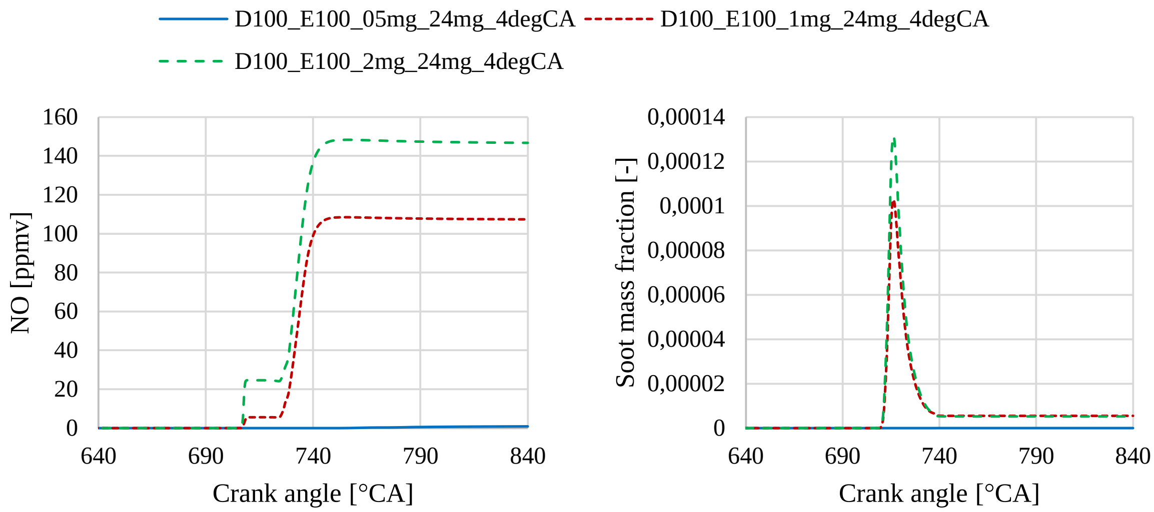

Figure 8. The temporal evolution of NO and soot for a pilot advance of 25 [°CA]

Between the D100_E100_2mg_24mg_4degCA case and the D100_E100_2mg_24mg case the trends are similar with one difference: the NO values decrease by approximately 8% when the pilot advance is increased, which is a result of the lower ignition delay of the main injection of ethanol.

3.2.2. Spatial evolution. The analysis of the spatial distribution of fuel, temperature and NO shows that there is a negligible influence of the increased pilot injection advance in the cases with 1 and 2 [mg] of diesel pilot quantity. However, it needs to be mentioned that the lower NO values obtained in the D100_E100_2mg_24mg_4degCA case compared to the D100_E100_2mg_24mg case are a result of the fewer points with temperatures, thus affecting the nitric oxides formation rates.

As highlighted above, for the D100_E100_05mg_24mg_4degCA, there is no combustion of the diesel pilot which can be observed in the temperature values inside the combustion chamber. As a result, the main ethanol injection is more compact and does not impinge on the piston wall like in the other cases. Also, by combining the cooling effect of the fuel vaporization and the increase of the combustion chamber volume, the ignition delay is further increased. This results in a very late combustion with a very low efficiency that would not be desired in the real engine. Due to the very low local temperatures the NO emissions that result are negligible.

As in the cases with 21 [°CA] and as it was highlighted at 3.1.3, the highest NO concentrations are obtained in the case with 2 [mg] diesel pilot quantity. Even if the combustion of ethanol produces very similar amounts of NO in both cases, D100_E100_1mg_24mg_4degCA and D100_E100_2mg_24mg_4degCA, the higher values of nitric oxide resulting from the combustion of 2 [mg] of diesel lead to a higher end value.

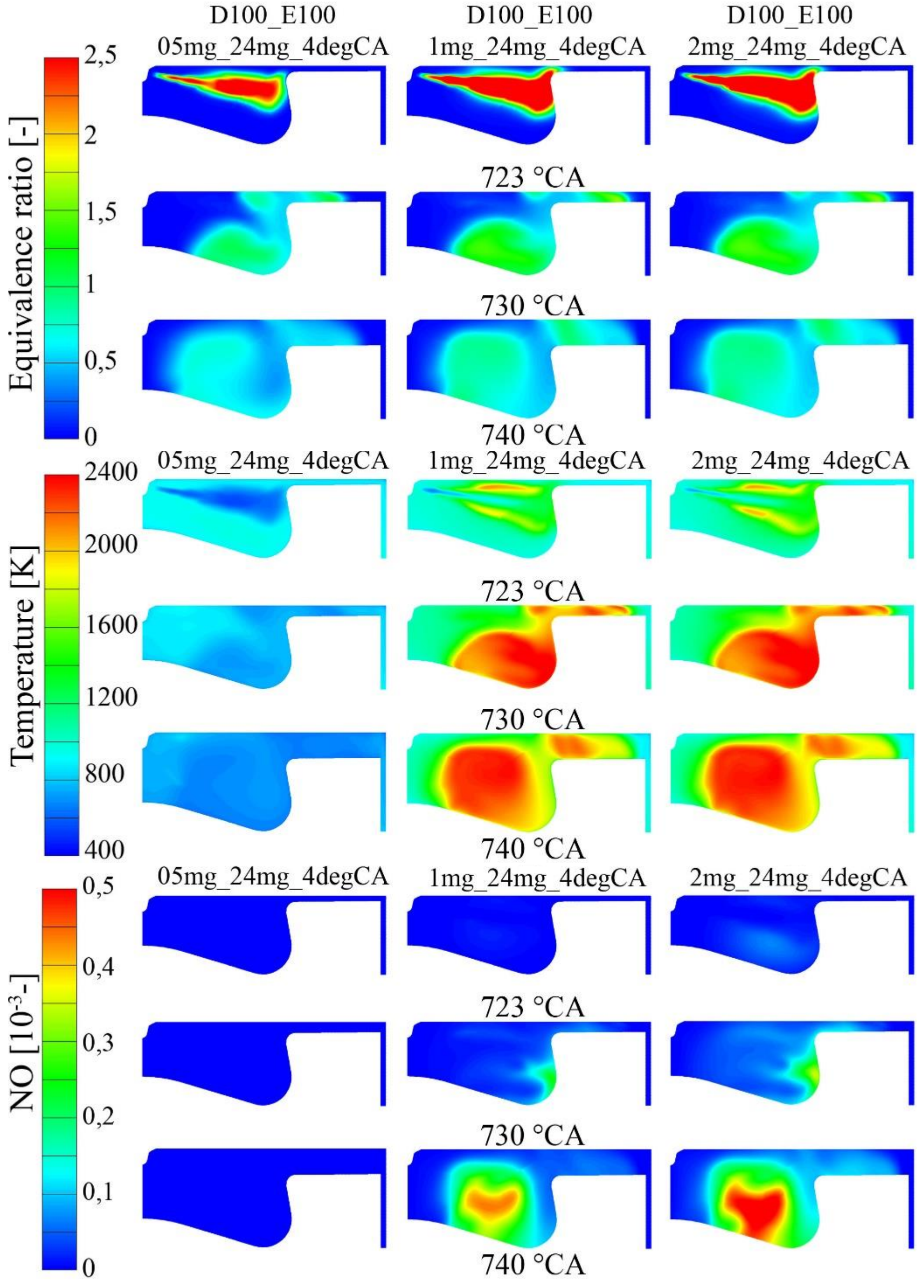

Figure 9. Equivalence ratio, temperature and NO spatial distribution at different crank angles a pilot advance of 25 [°CA]

4. Conclusions

This study comes to further the knowledge and understanding of a newly proposed combustion process that involves a pilot diesel injection and a main ethanol injection. The idea is to use combine the higher efficiency of the Diesel process with a more clean combustion of a renewable fuel with the aim of considerably reducing the NO emissions. In the sense mentioned above three diesel pilot quantities – 0.5, 1 and 2 [mg] – with two different timings – 21 and 25 [°CA] – were studied with the aid of simulation. Based on the obtained results the following main conclusions can be drawn:

- for an advance of 21 [°CA] the a pilot quantity of 0.5 and 1 [mg] leads to a two stage combustion of ethanol; a pilot quantity of 2 [mg] leads to a single stage combustion;
- increasing the advance to 25 [°CA] causes a single stage combustion in the case with 1 [mg] of diesel pilot as well;
- and advance of 25 [°CA] combined with a high ignition delay leads to too lean conditions that cause the pilot injection to not burn; as a result, the ignition delay of the main ethanol injection is very high and the combustion takes place with a very poor efficiency;
- the lowest NO emissions were obtained for a diesel pilot quantity of 1 [mg].

Based on the above analysis it was concluded that for this case, with a main injection quantity of 24 [mg] of ethanol the optimum diesel pilot quantity is 1 [mg]. Also, this shows that there is a strong correlation between the diesel pilot quantity, diesel pilot advance – by using the pilot injection, the required autoignition conditions of ethanol are created – and the combustion of the main ethanol injection.

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