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Numerical modeling of the effects of changing injection duration in double injection strategies in a DI diesel engine

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Pollutant emissions from diesel engines are significantly affected by fuel injection strategies that could reduce NOx and Soot emissions. For the first time and in this study, numerical simulations were performed to consider the influences of changing the injection duration in each pulse of the double injection strategies on in-cylinder parameters and pollutant emissions. Results confirmed that double injection strategies could influence the in-cylinder temperature, which leads to a reduction in NOx and soot emissions. Additionally, it is seen that decreasing the injection duration could increase the in-cylinder peak pressure and temperature. It could also reduce the soot emission owing to the better fuel atomization. Moreover, RATE+0.5CA case, which injection duration for each pulse increases 0.5 CA, was selected to be the optimum case in reduction of pollutant emissions.

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1 Introduction

Pollutant emissions from internal combustion engines could initiate harmful effects on environment, so unions implement strict emission standards to prevent it. Euro standard is one of them, which is implemented within the European Union. These strict emission standards lead to many projects that have been carried out to investigate how to reduce pollutant emissions from these engines. [1]

Controlling the combustion process is one of the important challenges that could reduce the pollutant emissions from diesel engines. Perusing over the previous literatures shows that the split injection strategies and different "injection rate" shape could give the flexibility over the mixing process that have direct impact on the engine combustion. Numerous researchers studied these strategies and some of them are as follows:

Desantes et al. [2] carried out an experimental study to investigate the potential of four different fuel injection rates and reported that by increasing the injection time, brake specific fuel consumption (BSFC) and dry soot emissions were increased. D'Ambrosio et al. [3] studied the pilot–main injection strategies in a diesel engine in order to evaluate their effects on emissions and fuel consumption. Their results showed that NOx and soot emissions could be decreased simultaneously in the late premixed charge compression ignition (PCCI) double-injection strategies by using exhaust gas recirculation (EGR) rates close to 50%, because of intensified fuel premixing and reduced peak combustion temperature. Belardini et al [4] compared two different combustion system by using numerical modeling and experimental investigation to explain emission behavior of the engine, they also defined mixing parameter to achieve more useful use of numerical simulation in combustion system. Syed Aalam et al. [5] investigated the effects of fuel injection pressure on single cylinder common-rail direct injection (CRDI) diesel engine characteristics. The findings demonstrated that increasing the fuel injection pressure caused an increase in the in-cylinder pressure, heat release rate, brake thermal efficiency, and NOx emission, but also it could reduce the CO, HC and smoke emissions. Jeon et al. [6] considered the effects of multiple injection strategies on the flame temperature and soot distributions in an optical compression ignition (CI) engine. The results indicated that the multiple injections could enhance the atomization process and led to improvement of the combustion performance and fuel economy as the injection timing occurs nearer to the main injection. The pilot injection combustion contributes to the main spray development which results in reduction of heterogeneity in the combustion chamber. This perhaps suppresses the soot formation and the foregone strategy could lead to a better flame temperature distribution over the entire combustion chamber affecting the NOx emission formation. Winfried et al. [7] considered the usability of food industry waste oils as fuel for diesel engines and their results confirmed that NOx emission was decreased. However, engine performance could stay at a constant level. Maghbouli et al. [8] reported that the triple injection strategy in lower engine speeds could increase the cylinder pressure, HRR, and subsequently output power, however, it had almost no effect on the work done by the engine at higher engine speed. Petranović et al. [9] reported that biodiesel blends could reduce nitrogen oxide emissions in comparison with the regular diesel. Hu et al. [10] reported that injection parameters have significant impacts on the pollutant emissions and injection timing has the great effects on the NOx emissions.

These researches confirmed that different fuel injection strategies could play an important role in controlling the combustion process and reduction of pollutant emissions in diesel engines. In this paper simultaneous effects of double injection strategies with variation in the fuel injection duration in each pulse of injections are considered.

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2 Numerical study

In this study, Caterpillar 3401 diesel engine was selected to perform numerical simulation from intake valve closed till exhaust valve open, and some of the specifications of this engine are illustrated in Table1.

Conservation of mass, moment, and energy equations were solved by using finite volume scheme. The discretized conservative equations were solved by SIMPLE (Semi-Implicit Method for Pressure Linked Equation) algorithm to calculate pressure–velocity linked field. Atomization of the spray and its droplet, turbulent flows, and combustion process in the combustion chamber were simulated by standard wave break up, K-ε, and EBU (Eddy Break –Up) models.

Table 1. Engine specifications [11]

Bore	**13.719 cm**
Stroke	**16.51 cm**
Compression Ratio	**15.1:1**
Connecting rod length	**26.162 cm**
IVC	**147° BTDC**
EVO	**134° ATDC**
Engine speed	**1600 rpm**
Number of nozzle hole	**6**
Nozzle hole diameter	**0.26 mm**
Start of injection	**9 BTDC**

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Injection duration	**21.5 ° CA**
Fuel injected in single injection	**0.1622 g/cycle**
Amount of injected fuel in the first pulse	**50% of the total fuel**
Start of the first pulse of double injection	**-6 CA ATDC**
Delay time between two injection pulses	**9 CA**

The grid independence study was considered first to achieve the optimum size of cells, thereafter, simulation results compared with experimental data [11] to ensure the validity of simulation results. Recent researchers have considered only the in-cylinder pressure of single injection strategy to ensure the validity of single and split injection strategies [12, 13]. However, in this study, pollutant emissions for both of these strategies were also compared to validate them separately. These comparisons were shown in Figs1-3, and as could be seen, it could confirm the validity of the numerical simulation in this study.

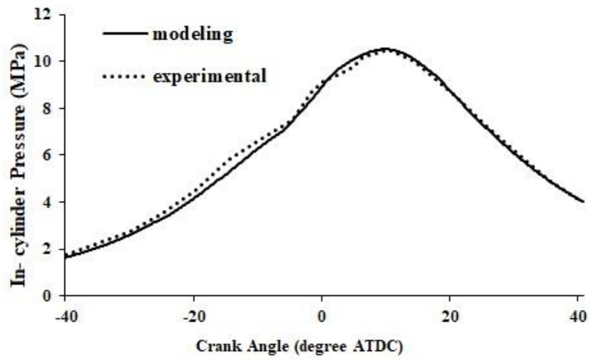

Figure 1. Comparison of modeling and experimental in-cylinder pressure and heat release rate for single injection strategy

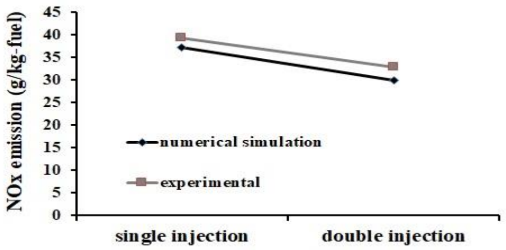

Figure 2. Comparison between the predicted and measured NOx emission for the single and double injection strategies

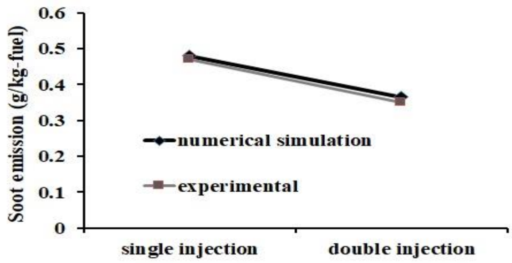

Figure 3. Comparison between the predicted and measured soot emissions for the single and double injection strategies

3 Results

Fuel - air mixing dynamics can be controlled by fuel injection strategies. Therefore, in this study, single injection strategy is converted to double injection strategy and then effects of variation in the injection duration in each pulse is investigated. Labeling schemes with their definitions and schematic of this study are presented in Table 2 and Fig. 4.

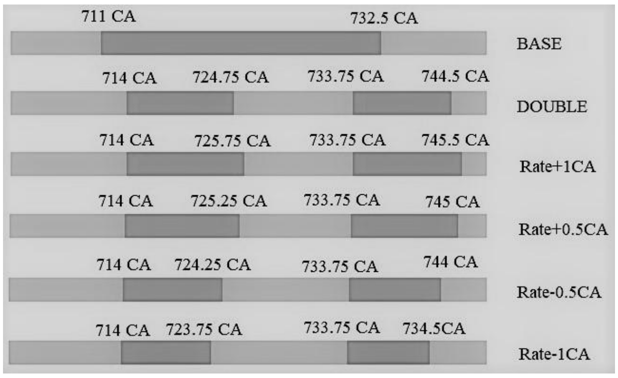

Figure 4. Schematic of injection schemes in this study

As was mentioned above, injection duration was changed in each pulse of double injection strategies, but amount of injected fuel was kept unchanged, this means that injecting the same amount of fuel with different injection durations could affect fuel injection velocities that has direct effects on the engine performance and pollutant emissions

Table 2. Labeling scheme that was used in this study

label	Defination
BASE	Single injection strategy
DOUBLE	Double injection strategy
RATE+1CA	Injection duration of each pulse increased 1 CA
RATE+0.5CA	Injection duration of each pulse increased 0.5 CA
RATE-0.5CA	Injection duration of each pulse decreased 0.5 CA

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RATE-1CA	Injection duration of each pulse decreased 1 CA

Fig.5 shows heat release rate (HRR) and it can be seen from this figure that HRR rising for the single injection strategy starts earlier than double injection strategies because of the earlier fuel injection, as seen from Fig. 4. Conventional diesel combustion consists of four main phases, namely the ignition delay, premixed combustion phase, mixing control combustion, and late combustion phases [14]. Split injection strategies could change the portion of them, which the portion of premixed combustion phase is increased while the other phase portions are decreased. It is also found that these strategies have two different peaks in their heat release rate diagram. All of these characteristics of double injection strategies could be explained by the injection timing of each pulse of injection that could influence fuel atomization and evaporation process owing to the fact that each injection pulse locates at different in-cylinder condition. [15, 16] Decreasing the injection duration could give higher HRR peak because of the higher injection rate that lead to better fuel atomization and evaporation during the premixing phase. The results are in concord with those reported by Tay et al. [17] in which they studied the effects of triangular and ramp injection-rate shapes on the pollutant emissions.

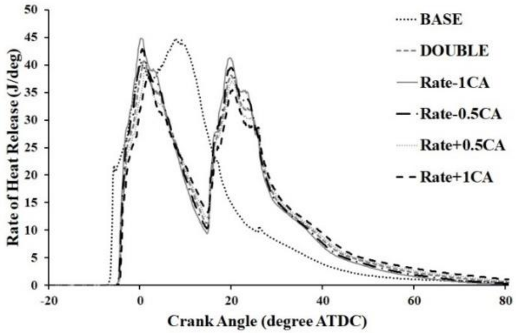

Figure 5. Heat release rate for the studied cases

Fig. 6 indicates that in-cylinder temperature has two peaks in double injection strategies. It is also concluded that maximum of it could be dwindled in comparison with Base case. Besides, shortening the injection duration in each pulse could trigger a better fuel atomization that lead to a higher in-cylinder temperature. [17, 18]

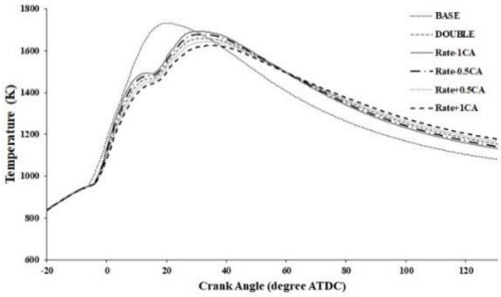

Figure 6. In-cylinder temperature for the studied cases

In-cylinder pressure versus CA period is presented in Fig. 7. It is seen that the pressure rise for the single and double injection strategies are different because of their different start of injections as could be appreciated from Fig. 4. The same trend could be found for the in-cylinder pressure of all double injection strategies. However, there are some differences in their peaks owing to the reduction in the injection duration which leads to an increment in the in-cylinder pressure. Furthermore, the RATE-1CA case has the maximum increase due to the higher fuel injection velocity that causes to have a better fuel atomization and evaporation. [17, 18]

NOx emission is illustrated in Fig. 8, as could be seen, double injection strategies can decrease it owing to the fact that these strategies could change the in-cylinder temperature pattern which could control this emission formation (see Fig. 6). It is also found that decreasing the injection duration, which leads to an increment in injection rate, could be resulted in higher NOx emission. For this reason, RATE-1CA case has an increment compared with the Base case. Furthermore, maximum reduction in this emission occurs in RATE+1CA case. These results are in concord with those reported in [17- 20].

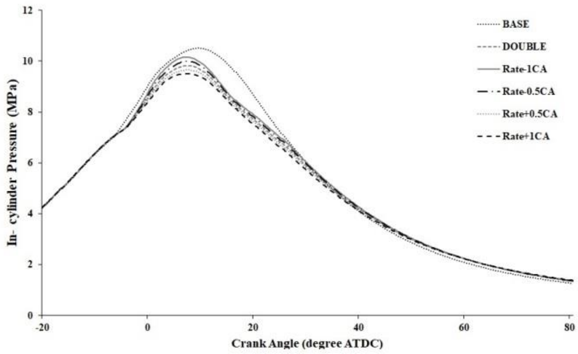

Figure 7. In-cylinder pressure for the studied cases

Soot emission is presented in Fig. 9, these results confirm that two stage injections affect this emission concentration because of the better fuel- air mixture homogeneity. As can be seen from Fig. 6, two stage injections lead to higher temperature in later part of the expansion stroke that enhances this emission oxidation. Furthermore, decreasing the injection duration could reduce this emission formation through its better fuel atomization and evaporation that could lead to better combustion and reduction in the fuel rich zone.[21, 22] Moreover, maximum reduction in this emission happens at RATE-1CA case, however, RATE+1CA case shows an increment due to the heterogeneity of the fuel-air mixture.

For selecting the optimum case in this study, percentage of change in comparison with Base case (single injection strategy) is shown in Fig. 10. It is evident that RATE+1CA case could decrease NOx emission more than other cases. Nevertheless, it leads to an increment in soot emission. It is also found that RATE-1CA case could decrease soot emission more than other cases with a slight increase in NOx emission. Moreover, RATE+0.5CA case is the optimum case which both emissions can be further reduced compared to DOUBLE, RATE-0.5CA and RATE-1CA, RATE+1CA cases.

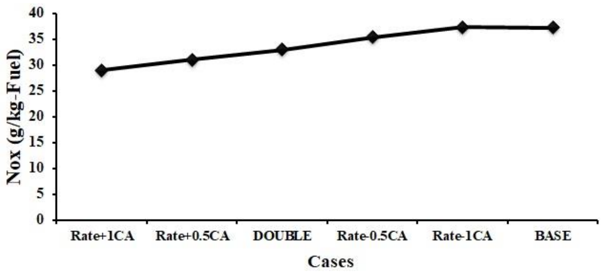

Figure 8. NOx emission for studied cases

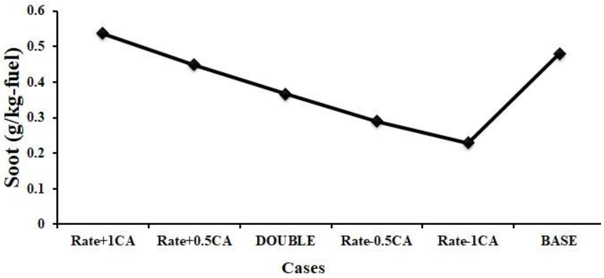

Figure 9. Soot emission for studied cases

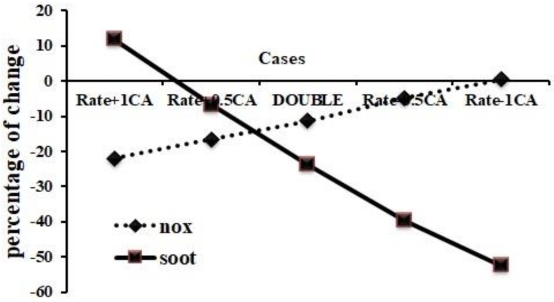

Figure 10. Percentage of change in pollutant emission for studied cases

4 Conclusion

Double injection strategies accompanied by different injection duration were explored in this study. The main conclusions to be drawn from this study are as follows:

Heat release rate has two peaks owing to the double injection strategies. It was also observed that combustion phase durations were changed. Reducing the injection duration could boost the combustion as a result of the better fuel atomization, this in own turn increases the HRR peak. Thus, the RATE-1CA case has the highest one.

NOx emission was gone down in two stage injection through the decrement in maximum temperature of the cylinder. Furthermore, this emission formation was decreased by increasing the injection duration for each pulse of double injection strategies. Therefore, maximum reduction was seen in RATE+1CA case, which injection duration for each pulse increases 1 CA.

Double injection strategies decrease soot emission through the reduction in fuel rich zones owing to the better fuel-air mixing process. Furthermore, this emission oxidation also could be improved as a result of higher temperature at later parts of expansion stroke. Moreover, decreasing the injection duration could intensify the mixing and combustion processes and resulted in lower soot emission, therefore maximum reduction was seen in RATE-1CA cases.

The optimum case to reduce both of the pollutant emission simultaneously is found to be the RATE+0.5CA case, which injection duration for each pulse increases 0.5 CA.

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