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Effects of Triple Injection Strategies on Performance and Pollutant Emissions of a DI Diesel Engine Using CFD Simulation

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ABSTRACT

One of the main controlling parameters in diesel engine combustion is the fuel – air mixing process that has direct effects on engine performance and pollutant emissions, reviewing over previous literature showed that split injection strategies could satisfy this purpose very well. For the first time and in this paper, pilot and double injection strategies were combined and formed new triple injection strategy that has not been considered by any other researchers. In this study after achieving successful validation between modeling and experimental results for both single and double injection strategies, optimization of triple injection strategy was conducted, in which first pulse of double injection strategy divided in to two pulses, then amount of injected fuel in each pulse kept constant and different delay times between first and second pulse of injections were investigated. For better understanding the processes the injections were done inside the engine, diagrams of heat release rate, in cylinder temperature, in cylinder pressure, NOx and soot emissions were presented. Results showed that decreasing the delay time between second and third pulse of injections could decrease the ratio of premixed combustion of third pulse and in optimum cases, reduction in both NOx and soot emissions could be achieved in comparison with single and double injection strategies, without any significant effects on engine performance. Furthermore, triple injection strategy with second pulse of injection that started at 4 crank angle before top dead center was selected to be the optimum case in reduction of both emissions.

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1. INTRODUCTION

High fuel consumption and noxious gas emission caused many engine manufactures to be interested in developing new method to achieve fuel conservation and emission reduction.

Mixing process in diesel engine is very important in which it could affect combustion process that has direct effects on engine performance and pollutant emissions. This mixing process could be controlled by split injection strategies and many researchers investigated on these to achieve the optimum cases, some of these investigations are discussed as follows :

Das et al. [1] reported that retarded main injection timing could control combustion phasing and had significant improvements in reduction of smoke and NOx emissions. Semin et al. [2] reported that conversion of diesel engine to a CNG sequential injection could increase the pressure performance in the intake manifold of the engine. Khoushbakhti et al. [3] reported that performance and emission parameters in low percentage of exhaust gas recirculation (EGR) could result in better behavior in compare to the high percentage of EGR. Park et al. [4] applied multiple injection strategies in which including pilot injection, split injection, post injection and reported that pilot injection strategy with advanced main injection resulted in the lowest NOx emission, indicated specific fuel consumption (ISFC) and the highest indicated mean effective pressure (IMEP). Jafarmadar et al. [5] reported that at optimum case of injections, NOx and soot emissions are lower than the other cases. Because, the premixed combustion which is the main source of the NOx formation is relatively low. Furthermore, The

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more quantity of the second injection into the lean and hot combustion zones, leads to high soot oxidation rates. Jafarmadar et al. [6] concluded that the differences of the optimum split injection scheme for direct and indirect injections (DI and IDI) diesel engines were related to the delay time between the injections. Also, main differences of the in-cylinder flow field between the single injection and split injection cases were due to the fuel injection schemes. Mansoury et al. [7] reported that applying an air-cell could be an effective method to reduce the Soot emission from a direct injection diesel engine because of the increasing in mixing and availability of enough air in the diffusion combustion. Their results also showed that this method could lead to simultaneous reduction of NOx exhausting from engine due to reduction of internal temperature of cylinder. Khatamnezhad et al. [8] reported that advanced injection timings were able to produce combustion with lower soot level because of the better air fuel mixture at longer ignition delay and longer spray penetration.

These preceding investigations caused this paper to study the effects of triple injection strategies on performance and pollutant emissions of diesel engine using computational fluid dynamics method, in which after achieving successful validation between numerical and experimental results, double injection strategy was converted to triple injection strategy by means of one pilot injection pulse and two other injection pulses, then all results compared with those achieved by single and double injection strategies.

2. NUMERICAL STUDY

Numerical simulation was conducted on the caterpillar 3401 direct injection diesel engine, from intake valve closed (IVC) to exhaust valve open (EVO), with the specifications of the engine that are summarized in Tables 1-3 [9].

AVL FIRE software was used in this study to solve the conservation equations and simulate the combustion and emission formation processes. Furthermore, SIMPLE (Semi-Implicit Method for Pressure Linked Equation) algorithm was used to solve the pressure–velocity linked field. The temporal discretization was implicit and the time step was selected small enough to satisfy the stability criterion. Some of the simulation parameters of this study are listed at Table 4.

Dynamic mesh was implemented in this study. Number of cells varied from top dead center (TDC) to bottom dead center (BDC) and Hexahedral cells have been used for the grid generation as their better accuracy and stability than tetrahedral cells. The grid independence study was performed on three different cell sizes of mesh, that contained 15000, 35000, and 50000 cells at top dead center (TDC). It was observed that 35000 cells at top dead center (TDC) could be selected to give enough grid independency. Before the simulation, the CFD model was validated with experimental data. Therefore, results compared with those achieved from the experimental investigation [9].

Reviewing over previous studies for numerical modeling of split injection strategies in diesel engines confirmed that most of the researchers used only in cylinder pressure curve of single injection strategy for validation of the single and double injection strategies, but in this paper, additional validation was used through the pollutant emissions for both of the single and double injection strategies [10].

TABLE1. Engine specifications [9]

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

TABLE 2. Fuel injector configurations and single injection specifications [9]

Number of nozzle hole	6
Nozzle hole diameter	0.26 mm
Start of injection	9 BTDC
Injection duration	21.5 ° CA
Fuel injected	0.1594 g/cycle

TABLE 3. Configurations of the double injection strategy [9]

Amount of injected fuel in the first pulse	50% of total fuel
Start of the first pulse of injection	-6 CA ATDC
Delay time between two injection pulses	9 CA

TABLE 4. Some of the simulation models that used in this study

Combustion	Eddy Break –Up (EBU)
Atomization of the spray and its droplets	Standard wave break up
Turbulence	K-ε
Evaporation and heat-up in the droplets	Dukowics model
NOx emission	Extended Zeldowich
Soot emission	Kennedy, Hiroyasu and Magnussen

Comparison between numerical simulation and experimental data are shown in Figures 1 and 2. According to the mentioned comparison, the CFD model could predict the engine combustion phasing and pollutant emissions with acceptable accuracy.

3. RESULTS

Fuel injection in each pulse of split injection strategies meets different in cylinder conditions, therefore, amount of injected fuel in each pulses and delay time between them are the main controlling parameters. After achieving successful validation with experimental results in previous section, the main purpose of this study that was converting double injection strategy to triple injection strategy was performed.

In this study, one pilot injection pulse was implemented before double injection pulses that converted sample double injection strategy to triple injection strategy, in which, 5% of the total fuel was injected in pilot pulse, earlier than other pulses, then 45% of the total fuel was injected in the second pulse with different start of injections, (6, 4, 2, 0 crank angle before top dead center), furthermore, rest of the fuel was injected in third pulse.

The configurations of the labeling schemes that were used in this study are shown in Table 5.

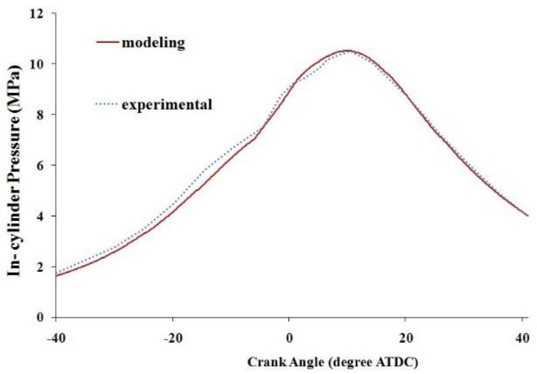

Figure 1. Comparison between modeling and experimental in-cylinder pressure for single injection strategy

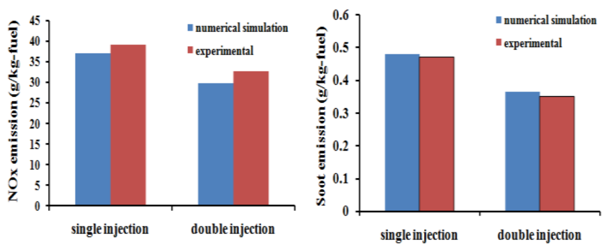

Figure 2. Comparison between the predicted and measured NO_x and soot emissions for the single and double injection strategies

TABLE 5. Definition of labeling scheme that used in this study

Label	Definition
base	Single injection strategy
double	Double injection strategy
triple_0	Triple injection strategy in which second pulse started 0 CA before TDC
triple_2	Triple injection strategy in which second pulse started 2 CA before TDC
triple_4	Triple injection strategy in which second pulse started 4 CA before TDC
triple_6	Triple injection strategy in which second pulse started 6 CA before TDC

As could be seen in this figure, double injection strategy by injecting 50% of the total fuel in each pulse, labeled by double, triple injection strategies are labeled by triple-A, in which, A indicates the start of second pulse of injection before the top dead center.

Main parameters that are considered in this paper are converting double injection strategy to triple injection strategies and retarding the injection timing of second pulse of injections.

Controlling the combustion process is one of the most important parameters that could affect the engine efficiency, in which too early combustion causes efficiency drop and too late combustion increases the chance of misfire, therefore to investigate the effects triple injection strategies that were used in this study heat release rate, in-cylinder temperature, in-cylinder pressure, NOx emission, Soot emission, and brake mean effective pressure were considered.

Rate of heat release is shown in Figure 3, as could be seen in this figure, split injection strategies could decrease maximum rate of heat release and also divide it in to two and three parts in double and triple injection strategies, respectively. First pulse of injection in triple injection strategies could be named as pilot injection, it could lead to early combustion with a distinct premixed heat release that affects engine performance. Furthermore, increasing the delay time between first and second pulse of injection causes to move the heat release rate of second pulse of injection toward the expansion stroke with the same tendency. But the main differences occurred with the initiation of the third pulse combustion, in which long dwell duration between second and third pulse leads to sharp increase in third pulse of combustion. Comparison between double and triple injection strategies shows that triple injection strategies have better combustion efficiency than double injection strategy, because lower in-cylinder temperature and pressure in the pilot pulse causes the vapor fuel phase to have longer residence time in the combustion chamber and leads to a proper mixing with the in-cylinder air. These results are in good agreement with those achieved by Qiu et al. [11]

In-cylinder temperature and pressure for different studied cases are shown in Figures 4 and 5, as mentioned in previous part, two and three peaks are seen in these figures for double and triple injection strategies, respectively.

Pilot injection causes to increase the in cylinder temperature and pressure before the main injection. But, these strategies lead to decrease the maximum of them compared to the single injection strategy. Furthermore, the triple_6 case shows double injection strategy, would be higher than maximum in cylinder pressure and temperature.

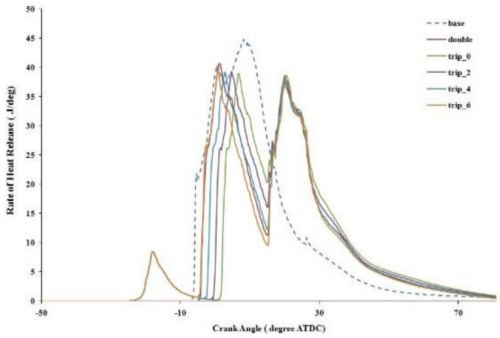

Figure 3 . Heat release rate for studied cases

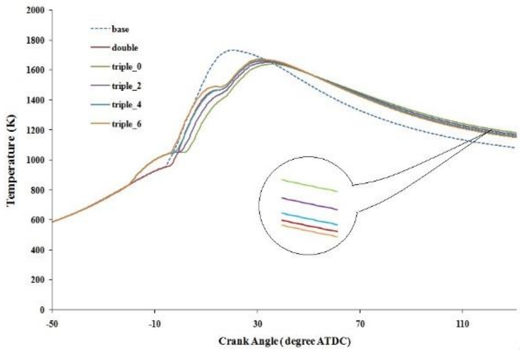

Figure 4. In-cylinder temperature for studied cases

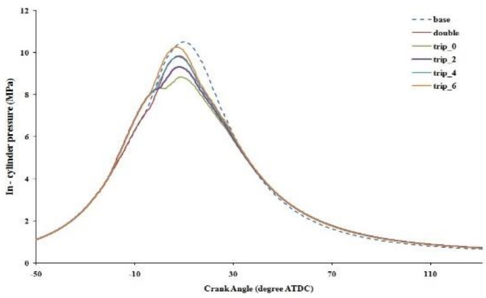

Figure 5. In-cylinder pressure for studied cases

Because in this case, pressure and temperature inside the cylinder is not sufficient enough to ignite the fuel; therefore, large amount of evaporated fuel is accumulated during the ignition delay period; it would leads to rapid burning rate and rise in the pressure and temperature.

For better understanding the effects of injection timings of each pulse of injections on combustion process, in cylinder temperature contours are shown in Figure 6 at the beginning of the fuel injection for second and third pulse of injections.

As it be observed in these figures, second pulse of injections met approximately the same in cylinder temperature without any significant differences. But, the main differences happen at the beginning of the third pulse of injection, in which fuel jet reached to higher in cylinder temperature because of the better combustion of the previous pulses. These results are in good agreement with those reported by Li et al. [12] in their pilot combustion, they produced the thermos atmosphere, which was a higher temperature region that located in the center of the chamber and led to promote evaporation and combustion of the local fuel.

According to these figures, characteristics of heat release rate, temperature and pressure diagrams one could understood, because any injected fuel pulse, at each studied cases, meets different in cylinder conditions, that could affect fuel evaporation and atomization which has direct effects on fuel - air mixing and combustion processes.

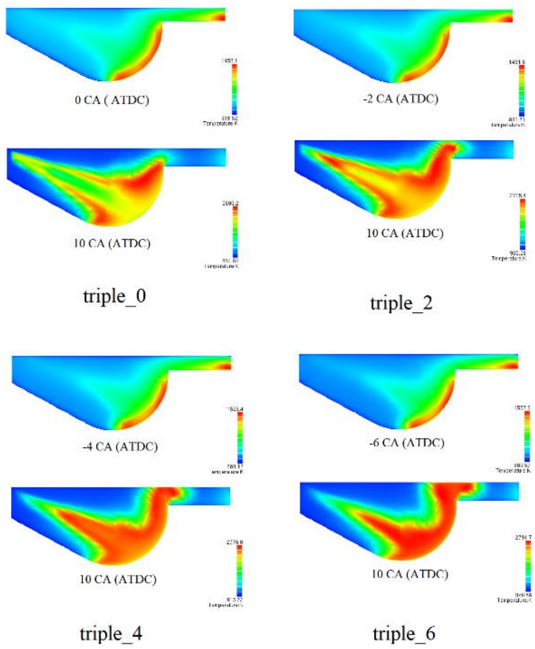

Figure 6. Contours for in cylinder temperature in triple_0, triple_2, triple_4 and triple_6 cases for second and third pulse of injections

Therefore, the mentioned considerations in previous parts could be concluded in which, advances in the injection timing of second pulse of injection causes injected fuel to meet higher in-cylinder pressure and temperature conditions that leads to better combustion characteristics. Therefore, higher in-cylinder pressure, temperature and heat release rate could be achieved.

Soot emission is shown in Figure 7, indicates that multiple injection strategies decrease soot emission due to the end pulse of injections. In fact, multiple injection strategies could introduce extra energy for mixing and higher temperature in the combustion chamber in compared to single injection strategy leads to better soot oxidation. Furthermore, advancing the injection timing of the second pulse of injection could decrease the soot emission because of the best combustion performance. That could decrease soot emission formation, moreover, triple_6 case has the best reduction in soot emission.

NOx emission is shown in Figure 8, indicates that it could be decreased because of the reduction in the in-cylinder maximum temperature that could decrease NOx emission formation. The obtained results is in good agreement with data roported by Verbiezen et al [13]. In fact, NOx formation is primarily due to the thermal NO formation mechanism, in which raising in the in cylinder temperature above the threshold limit, leads to a sudden increase in the NO concentration.

Increasing the delay time between first and second pulse of injection causes to decrease NOx emission. Maximum decrease in NOx emission is achieved in triple_0 case due to the maximum decrease in the higher cylinder temperature (see Figure 4). These results are in good agreement with data reported in literature [11, 13].

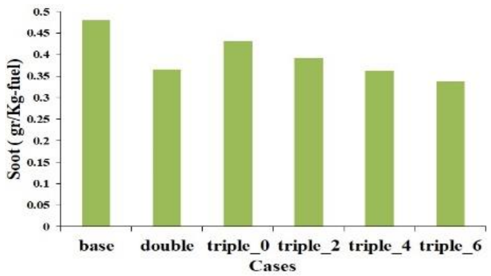

Figure 7. Soot emission for studied cases

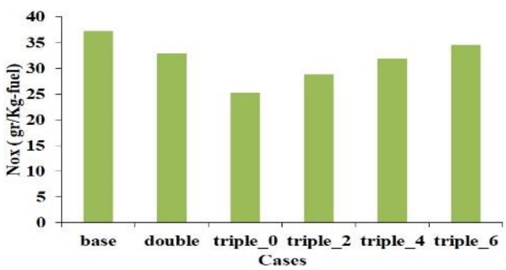

Figure 8. NO_x emission for studied cases

To achieve the optimum case of this study, percentage of decrease or increase in pollutant emissions and brake mean effective pressure (BMEP) of the engine in compared with single injection strategy are summarized in Table 6. As could be seen in Table 6, triple_0 case has the maximum reduction in NOx emission and triple_6 case has the maximum reduction in soot emission, without any significant changes in engine performance. By detailed view of this table along with Figures 7 and 8, it is concluded that when NOx emission decreases, soot emission increases and vice versa, because, higher temperature in the combustion chamber causes an increment in NOx formation and soot emission oxidation. Furthermore, triple_4 case is selected to be the optimum case in reduction of both pollutant emissions. Moreover, results confirm that these strategies could reduce pollutant emission without significant effects on engine performance.

Percentage of increase in HC and CO_2 emissions compared to single injection strategy are illustrated in Figure 9, as could be seen in this figure, triple injection strategies caused an increment in CO_2 emission in comparison with single injection strategy. However, these changes are in the same order for all triple injection strategies. Furthermore, changes in HC emission showed triple_6 case has the maximum decrease, because better utilization of fuel- air mixture could be achieved in this case. Moreover, retarding the second pulse of injection leads to an increment in HC emission.

TABLE 6. Percentage of increase or decrease of engine parameters in compared with single injection strategy

	NO_x (%)	Soot (%)	BMEP (%)
triple_0	32.22↓	10.2↓	1.8↓
triple_2	22.53↓	18.33↓	0.5↓
triple_4	14.2↓	24.37↓	0.6↑
triple_6	6.93↓	29.79↓	1.37↑
double	11.51↓	23.95↓	1.11↑

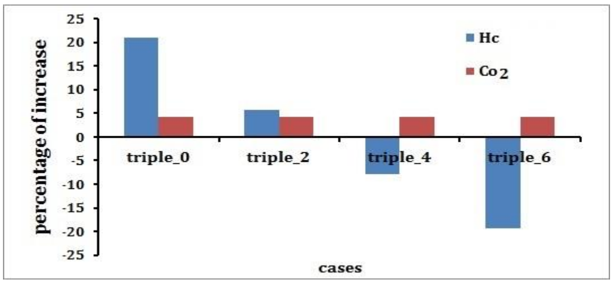

Figure 9. Percentage of changes in HC and CO_2 for studied cases in compared with single injection strategy

4. CONCLUSION

Split injection strategies could control the mixture concentration that lead to different combustion characteristics, which affect engine outlet pollutant emissions. The main purpose of this study was converting double injection strategy to triple injection strategy. Hence, after validation with experimental results, triple injection strategies were studied and optimization conducted to achieve the optimum case.

Obtained results can be briefly discussed as below:

-Triple injection strategies could decrease maximum rate of heat release and also divide it in to three parts.

- Increasing the delay time between first and second pulse of injection leads to move the heat release rate of second pulse of injection toward the expansion stroke with the same tendency.
- Long dwell duration between second and third pulse of injections led to sharp increase in heat release rate.
- Triple injection strategies with long dwell duration between first and second pulse of injections, showed higher decrement in in-cylinder temperature and pressure.
- Triple injection caused to decrease maximum in cylinder temperature and pressure compared to the single injection strategy.
- This study shows that triple injection strategy can reduce the NOx emission compared to single injection strategy, since it decreases the peak temperature inside the combustion chamber. Also, it is found that retarding the injection timing of the second pulse of injection could reduce NOx emission formation. Furthermore, Maximum reduction in NOx emission could be achieved in triple_0 case without any significant effects on engine performance.
- Triple injection strategies could reduce soot emission because of their better fuel-air preparation, this mechanism would reduce the fuel rich zones and leads to decrease in soot emission formation. Furthermore, detailed view on in-cylinder temperature shows an increment in temperature at later parts of expansion stroke that could increase soot emission oxidation. It could be found that maximum reduction in soot emissions could be achieved in triple_6 case without any significant effects on engine performance.
- Triple_4 case could reduce both of the pollutant emissions without any significant effects on engine performance.
- By the optimizations that were caried out in this study, reduction in pollutant emissions without any significant effects on engine performance was achieved.
- HC emission decreased in optimum cases of triple injection strategies, in which maximum decrease was achieved in triple_6 case, because of the better utilization of fuel-air mixture. Furthermore, retarding the second pulse of injection leads to an increment in HC emission.

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چکیده

اختلاط سوخت و هوا یکی از پارامتر های کلیدی در احتراق موتور های دیزلی است که تاثیر مستقیمی بر آلاینده های منتشره و عملکرد موتور دارد، مروری بر کار های انجام یافته پیشین مشخص نمود که پاشش چند مرحله ای سوخت نقش مهمی در این زمینه دارد. برای اولین بار و در این مقاله با ترکیب پاشش پایلوت اینجکشن و پاشش دومرحله ای، پاشش سه مرحله ای جدیدی انتخاب گردید که تاکنون توسط محققان قبلی بررسی نگردیده بود.در این مقاله پس از اعتبار سنجی نتایج برای حالات پاشش تک مرحله ای و دو مرحله ای و اطمینان از صحت روش عددی حاضر، پاشش سه مرحله ای سوخت با ثابت نگه داشتن مقدار سوخت پاشیده شده در هر مرحله و بررسی تاثیر زمان بین مراحل پاشش سوخت مورد بررسی قرار گرفت. برای درک بهتر فرایند های اختلاط و احتراق داخل محفظه احتراق موتور، نمودار های آزاد سازی گرما ، دما و فشار داخل محفظه احتراق ، آلاینده های دوده و اکسید های نیتروژن نمایش داده شده اند. نتایج نشان دادند که کاهش زمان تاخیر پاشش سوخت بین مراحل اول و دوم پاشش سوخت، باعث کاهش احتراق پیش آمیخته در مرحله سوم پاشش سوخت می شود، همچنین در حالت بهینه، کاهش همزمان آلاینده های اکسید نیتروژن و دوده بدون تاثیر چشمگیر بر عملکرد موتور امکان پذیر است.

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