Numerically modeling of diesel engine and analysis the effects of double injection strategies on performance and pollutant emissions

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Abstract

Modern diesel engines should have higher pollutant emissions standards with better performance and by using split injection strategies which could optimize the air – fuel mixture, this purpose could be achieved. After achieving the successful validation between modeling and experimental results for both single and double injection strategies, for the first time and in this paper, double injection strategies with new nozzle configuration were used in which number of nozzle holes were doubled and located below the previous holes and then double injection strategies were implemented in a case that for each pulse of injections upper or below holes were used, then this study focused on the effects of the new nozzle configuration holes angle in each pulse of injections. This study confirms that split injection could decrease Nox emission, because it has lower maximum in-cylinder temperature than single injection case due to its separate second stage of combustion, also results showed that using new nozzle configuration with two rows of holes could be more effective in decreasing pollutant emissions without any significant effects on engine performance.

Keywords: *Diesel Engine, Double injection, Emissions, Nozzle, Performance.*

1. Introduction

Compression ignition (CI) engines have better thermal efficiency than spark ignition (SI) engines which leads to a rising interest in this type of engines that have better fuel economy characteristics, but CI engines produce more NOx and soot emissions than SI engines, therefore many projects have been carried out to investigate how to reduce pollutant emissions in these engines.

Modern CI engines could inject fuel at any point in the cycle by the using of electronically controlled fuel injection systems, there for it is possible to use double injection strategies. It is shown that double injection strategies could reduce pollutant emissions in diesel engine and many projects have been carried out to achieve this purpose.1 Double injection strategies divide the one fuel injection pulse in to two injection pulses and amount of injected fuel in each pulse and delay time between two injection pulses could control the air-fuel mixture in double injection strategies. Tow et al reported that long delay time between two injection pulses could reduce particle emission with no change in NOx emission.2 K.L. Tay et al studied the effects of triangular and ramp injection rate-shapes on the compression ignition engine and reported that the combustion process and emissions formation could be controlled by injection rate-shaping and Triangular rate-shape injections could give higher in-cylinder pressure rise rates as compared to ramp rate-shape injections.3 Ladommatos et al studied the effects of EGR in DI diesel engine, it was shown that EGR could reduce NOx and increase particulate emissions.4 Vaneyas et al studied the effect of multiple injection in a diesel engine and reported that NOx emissions reduced significantly compared to the single injection strategy. Ehleskog et al investigated the effects of multiple injection on pollutant emissions, they reported that dividing the main injection in to three or four parts reduced NOx emission but particulate matter increased.5 F. Payri et al investigated multiple injection in a low compression ratio direct injection diesel engine and reported that multiple injection improved the combustion stability and by dividing the pilot injection with larger amount in to two medium pilot injections, total heat release increased.6 R. Mobasheri et al investigated the effects of advanced injection strategies and their study confirmed that multiple injection could control both NOx and soot emissions.7 S. Jafarmadar et al numerically modeled double injection in diesel engine and reported that by injecting 75% of the total fuel in first pulse with 20 CA delay time, more reduction of NOx and soot emissions would be achieved.8 R. Meloni et al reported that the emission minimization has been always obtained when 65% and 70% of the total fuel, injected in the main injection pulse of split injection.9 M. Herfatmanesh et al carried out an experimental study on the single and two-stage injection strategies by using in-cylinder high-speed spray imaging and combustion visualisation technique, their study proved that there was an interaction between combustion and fuel injection. They also reported that two-stage injection strategies could reduce NOx, soot and uHC emissions, however there were some cases with higher soot emissions, because of the interaction between two consecutive fuel injection events that the second pulse of injected fuel to the burning regions affected soot oxidation.10 Z. Zheng et al studied the effects of pilot injection parameters on pollutant emissions and reported that smoke emissions decreased when interval between pilot and main injection increased but NOx emissions decreased first and then increased.20 P. Das et al investigated the effects of main injection timing and their results showed that retarded main injection timing could control combustion phasing and cause significant improvements in smoke and NOx emissions.21 L. Qiu et al investigated different injection strategies in a light duty diesel engine and reported that increasing the pilot - main intervals lead to more homogeneous mixture, higher thermal efficiency and lower Nox emission.23 X. Li et al studied the effects of split injection in a double swirl combustion system and reported that in optimum cases pilot injection could increase Nox emission and decrease BSFC, also their studies showed that smaller fuel mass ratio in pilot injection with shorter dwell time could cause better thermo- atmosphere utilization than single injection strategy.24 A. Sarangi et al studied the effects of split fuel injection in diesel engine and reported that significant soot formation took place from the second injection pulse and majority of it subsequently oxidized because of a slightly higher flame temperature and slightly higher oxygen concentration than in single injection strategy.27 J.Benajes et al reported that in optimum cases of split injection strategies, it was possible to achieve very low levels of nitrogen oxides and low combustion noise with reasonable fuel consumption and smoke emissions.28

Many researchers investigated the effects of changing the nozzle geometries on pollutant emissions. Guntram et al studied the effects of using narrow spray cone angle injector nozzle configuration on performance and pollutant emissions and reported that in optimum cases it could reduce Nox emission at the expense of a modest increase in fuel consumption.11

H.J. Kim et al analyzed the impact of fuel spray angle and injection timings in a high speed diesel engine with two injector at spray angle of 60 and 150 degree and reported that 60 degree injector could exhibit higher combustion pressure, heat release rate and IMEP.25 A. Nemati et al studied the effects of injection characteristics on combustion and emissions of a gasoline fuelled heavy duty compression ignition engine and their studies confirmed that by increasing the nozzle hole diameter, in-cylinder pressure, temperature and NOx emission formation were decreased due to the increase in droplet size that leaded to wall impingement and deficient combustion.12 A. Uludogan et al explored the use of multiple injection with different injector locations and angels, they reported that locating the injectors at the edge of the engine bowl could decrease soot emission.13 S. Lahane et al studied the impact of nozzle holes configuration on fuel spray, wall impingement and NOx emission of a diesel engine for biodiesel - diesel blend and reported that Spray penetration distance, sauter mean diameter and ignition delay decreased with modified nozzle configuration which could be a reason for lesser smoke and Nox emissions.26

Based on these preceding investigations it was concluded that double injection strategies and nozzle configuration could reduce pollutant emissions, so for the first time and in this present study, CFD simulation were conducted to investigate double injection by using new nozzle configuration with two rows of holes in which for each pulse of injection upper or below holes were used then effects of changing nozzle holes angle in each pulse of injection were studied. All these results were compared to the single injection strategy to find the optimum case

2. Numerical study

The Computational Fluid Dynamics Simulation (CFD) were carried out on the caterpillar 3401 direct injection diesel engine and for model validation, results compared with those obtained from the experimental investigation.14 The main specifications of the fuel injection system and engine are shown in table 1&2.

Three different size of the mesh which contained 15000 ,35000 and 50000cells at TDC were considered to pre-investigate the grid independency study, then because of the symmetrical location of the injector which has six holes, CFD simulation performed for a 60 degree section from intake valve closed (IVC) to exhaust valve open (EVO). The case with 35000 cells at TDC was accepted to give adequate grid independency, Fig 1 shows this cells at TDC.

K-ε turbulence model was used to simulate turbulent flows in the combustion chamber, for modeling the atomization of the spray and its droplets, standard wave break up model was selected.15 Dukowics model was applied to treat the evaporation and heat-up in the droplets.16 Eddy Break –Up (EBU) model was chosen to model the combustion.15 NOx emission formation was modeled by Extended zeldovich mechanism and soot emission was modeled by the Kennedy, hiroyasu, magnusse mechanism.15

As could be seen in table 3 comparisons between modeling and experimental results were divided in to two different part: first part carried out for single injection strategy and second part for double injection strategy.

Comparisons between the modeling and experimental results for in-cylinder pressure are shown in Fig 2 and for NOx and soot emissions are shown in Table 4, these results show that present CFD simulation performs very well for modeling the simple injection strategy of the engine.

Double injection strategy with the configurations that were shown in table 5 were simulated and Comparisons between the modeling and experimental results for pollutant emissions were shown in table 6, these results indicate that present simulation performs very well for modeling double injection strategy of the engine too.

table1. Engine specifications

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

table2. Injector fuel system specifications

Number of nozzle hole	6
Nozzle hole diameter	0.26 mm
Start of injection	9 BTDC
Injection duration	21.5 ° CA
Fuel injected	0.1622 g/cycle

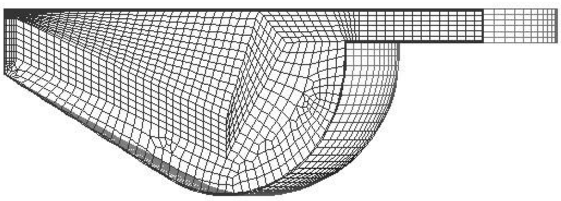
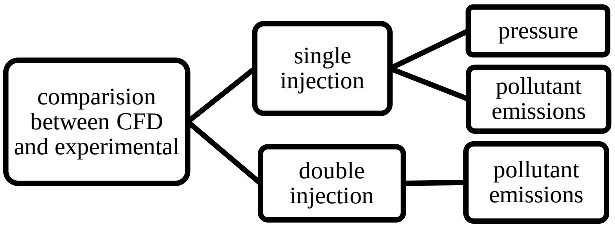


Fig 1. Outline of computational grids at TDC

Fig3. Comparison between modeling and experimental results



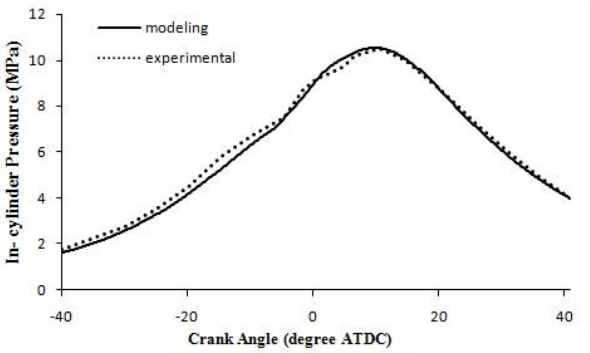


Fig 2. Comparison of modeling and experimental in-cylinder pressure for single injection strategy

table4. Comparison between the predicted and measured NOx and soot emissions for single injection strategy

emission	Modeling results	Experimental results
Nox (g/kg-Fuel)	37.18	39.2
Soot (g/kg-Fuel)	0.48	0.47

Table5. Configuration of the experimental double injection strategy

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

table6. Comparison between the predicted and measured NOx and soot emissions for double injection strategy

emissions	Modeling results	experimental results
Nox (g/kg-fuel)	32.8	29.8
Soot (g/kg-fuel)	0.365	0.35

3. Results

After achieving the successful validation between modeling and experimental results in the previous section, in this study new nozzle configurations were used in which number of nozzle holes were doubled and located below the previous holes, the schematic of these nozzle were shown in Fig 3, as could be seen in this figure, this nozzle had two rows of holes in which each row had six holes, then double injection strategies were implemented and for each pulse of injections upper or below holes were used, then effects of changing new nozzle configuration holes angle be considered to discuss the effects of double injection, height of injection and nozzle holes angle simultaneously. Fig 4 shows how nozzle angle were measured in this paper

For the simplicity, labeling scheme were used in this paper, single injection case was labeled by base, typical two stage injection case with base engine nozzle was labeled by double and two stage injection cases with new nozzle configurations that had two rows of holes were labeled by two numbers in which first and second numbers showed the first and second pulse holes angles, also when upper row injected first it was labeled by u and when below row injected first it was labeled by b. all these labels were shown in table 7 and the Summary of this CFD study were shown in table 8.

Heat Release rate for the cases that upper and below row injected first is shown in Fig 5 and Fig 6, both of these figures indicate that Heat Release rate separates in to two parts with two different picks in comparison to single injection case (base) and maximum rate of heat release reduces because of the increasing in the entrainment of fresh air and the cooling caused by the second pulse of injection.22 these behaviors of the heat release rate cause changes in in-cylinder pressure and temperature at the combustion chamber as could be seen in Fig 7 till Fig 8, for example, two stage injection cause to decrease the Maximum in-cylinder temperature and increase it at the end of the expansion as could be seen in Fig 7 and Fig 8.

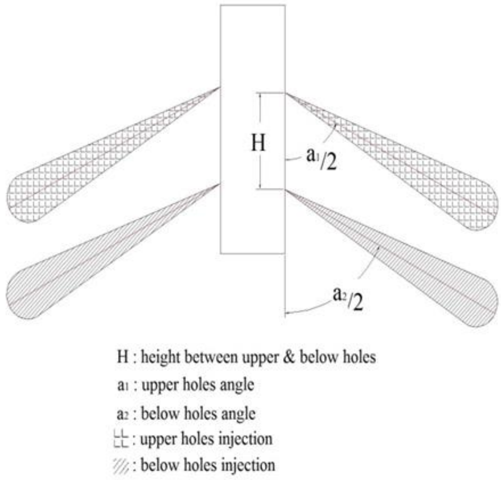


Fig 3. Schematic of these nozzle

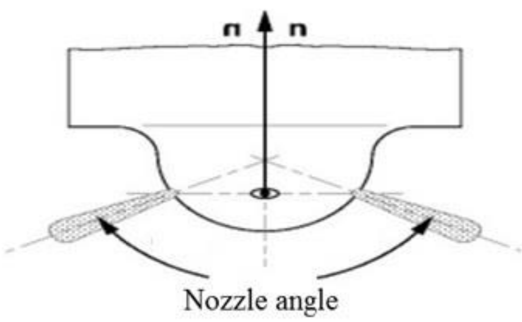
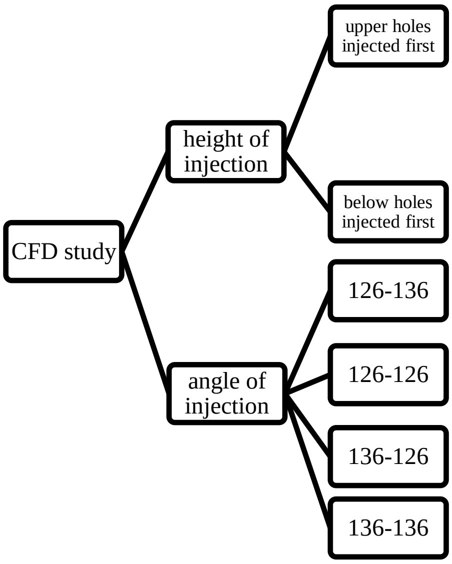


Fig 4. Measuring nozzle angle in this paper [15]

table7. Labeling scheme used in this paper

Default nozzle	Base engine nozzle
Two row nozzle	Nozzle with two rows of holes
base	Single injection case with base engine nozzle
double	two stage injection case with base engine nozzle
126-136-u	two stage injection case with new nozzle configuration that had two rows of holes and first pulse nozzle holes angle was 126 degree and second pulse nozzle holes angle was 136 degree and upper row injected first
126-136-b	two stage injection case with new nozzle configuration that had two rows of holes and first pulse nozzle holes angle was 126 degree and second pulse nozzle holes angle was 136 degree and below row injected first
126-126-u	two stage injection case with new nozzle configuration that had two rows of holes and first pulse nozzle holes angle was 126 degree and second pulse nozzle holes angle was 126 degree and upper row injected first
126-126-b	two stage injection case with new nozzle configuration thathad two rows of holes and first pulse nozzle holes angle was 126 degree and second pulse nozzle holes angle was 126 degree and below row injected first
136-126-u	two stage injection case with new nozzle configuration that had two rows of holes and first pulse nozzle holes angle was 136 degree and second pulse nozzle holes angle was 126 degree and upper row injected first
136-126-b	two stage injection case with new nozzle configuration that had two rows of holes and first pulse nozzle holes angle was 136 degree and second pulse nozzle holes angle was 126 degree and below row injected first
136-136-u	two stage injection case with new nozzle configuration that had two rows of holes and first pulse nozzle holes angle was 136 degree and second pulse nozzle holes angle was 136 degree and upper row injected first
136-136-b	two stage injection case with new nozzle configuration that had two rows of holes and first pulse nozzle holes angle was 136 degree and second pulse nozzle holes angle was 136 degree and below row injected first

Table8. Summary of this CFD study



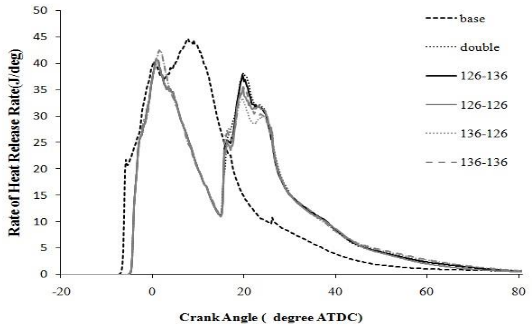


Fig 5. Heat release rate for the cases that upper row injected first

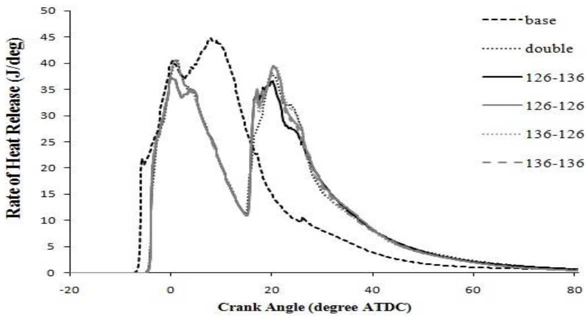


Fig 6. Heat release rate for the cases that below row injected first

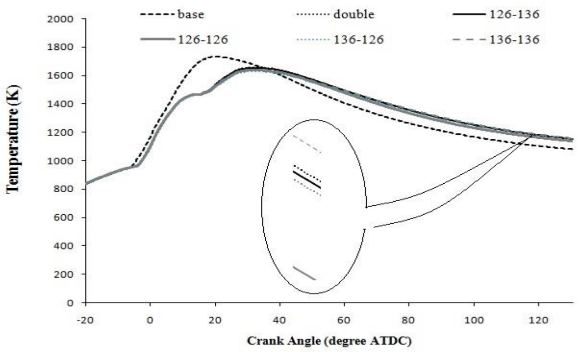


Fig 7. In-cylinder temperature for the cases that upper row injected first

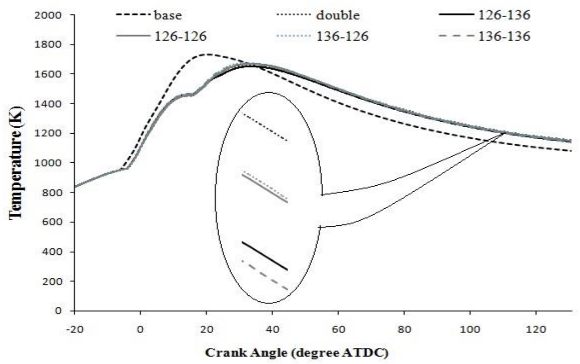


Fig 8. In-cylinder temperature for the cases that below row injected first

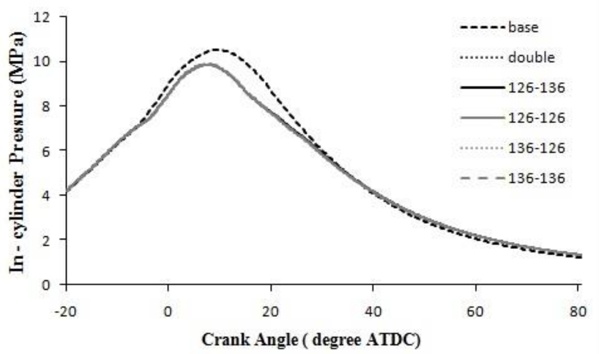


Fig 9. In-cylinder pressure for the cases that upper row injected first

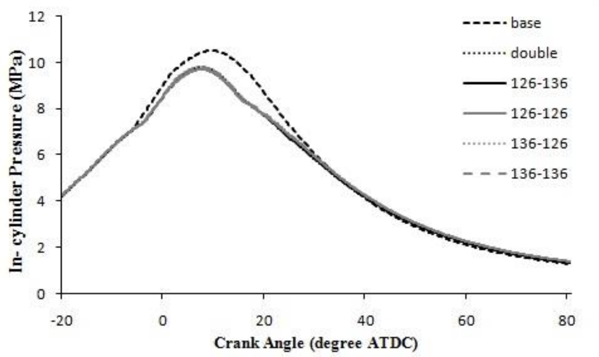


Fig 10. In-cylinder pressure for the cases that below row injected first

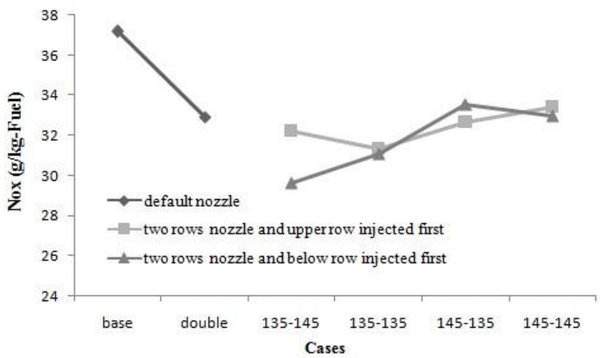


Fig 11. NOx emission

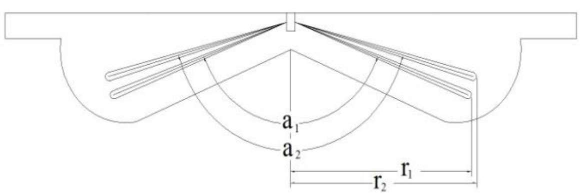


Fig 12. Schematic of the injected fuel with two different angle

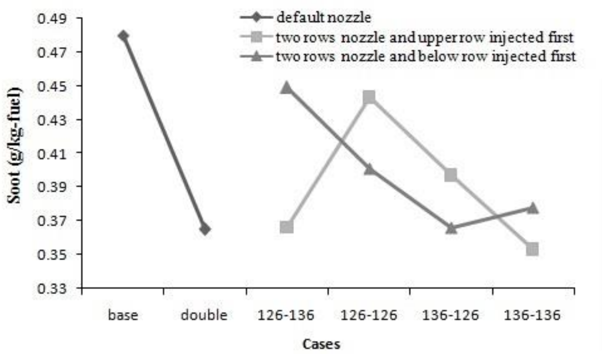


Fig 13. Soot emission

Nox emissions are shown in Fig 11, results indicate that two stage injections could decrease Nox emission due to the decrease in in-cylinder maximum temperature that reduce NOx emission formation. The effect of using new nozzle configuration with two rows of hole seems to be important in decreasing NOx emission in which 126-136 case when below row injected first (126-136-b) could decrease NOx emission more than other cases, increasing both rows holes angles lead to increase NOx emission because it helps to better air - fuel mixing and increase in-cylinder temperature as could be seen in Fig 12, these results are in agreement of those reached by H.J. Kim et al which studied the effects of narrow spray cone angle and reported that narrow spray angle injector could increase mixture formation period at the same conditions.[25]

From Fig 11 it is also considered that changing nozzle holes angle be more effective in the first pulse of injection, this is because of the fact that second pulse of injection located at expansion stork.

percentage of decrease or increase in pollutant emissions and performance of the engine in compared to the single injection strategy (base) were listed in table 9 and as could be seen in this table, changing nozzle configuration did not have any significant effects on both BMEP and BSFC so it is concluded that this method could affect pollutant emissions with no significant changes on engine performance.

table9. Percentage of decrease or increase in pollutant emissions and performance of the engine

	NOX (g/kg-fuel)	Soot (g/kg-fuel)	BMEP (bar)	BSFC (kg/kwh)
double	11.51↓	23.95↓	1.11↑	1.13↑
126-136-u	13.31↓	23.75↓	0.42↑	1.83↑
126-136-b	20.25↓	6.45↓	0	2.27↑
126-126-u	15.70↓	7.70↓	1.37↓	3.66↑
126-126-b	16.38↓	16.45↓	1.37↑	0.94↑
136-126-u	12.10↓	17.29↓	0.68↓	2.97↑
136-126-b	9.81↓	23.75↓	1.8↑	0.49↑
136-136-u	10.14↓	26.45↓	0.68↑	1.53↑
136-136-b	11.24↓	21.25↓	1.54↑	0.74↑

As mentioned before maximum decrease in Nox and soot emission could be achieved in 126-136-b and 136-136-u cases respectively but 126-136-u case seems to be the optimum case in which both of these emissions could be decreased. also this table shows that when Nox emission decrease, soot emission increase and vise versa, because of the fact that higher temperature in the combustion chamber cause to increase in Nox formation and soot emission oxidation.
[11,13]

These results are in the same manner with those received by the previous researchers for split injection strategies in which they reported that these strategies could cause changes in the combustion characteristics that could lead to a decrease in NOx emission.[7,8,10,22]

As mentioned earlier, the effect of simultaneous considering split injection with different nozzle configuration was investigated for the first time in this study, but the results were in the same manner of those achieved from the single injection investigations.

Conclusion

Present work investigated the effects of double injection strategies with new nozzle configuration and different nozzle holes angle then results compared with single injection strategy to achieve the optimum case.

-Double injection divides heat release rate in to two main parts which affects in-cylinder temperature and pressure.

-Results confirm that double injection strategies could decrease pollutant emissions.

-Double injection strategies with new nozzle configuration affect pollutant emissions without any significant changes in engine performance.

- Maximum reduction of Nox emission could be achieved in 126-136-b case.

- Maximum reduction of Soot emission could be achieved in 136-136-u case.

- Optimum case for reduction of both Nox and Soot emissions could be achieved in 126-136-u case.

- Increasing nozzle holes angle cause to increase Nox formation.

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