International Journal of Automotive Engineering, Vol. 10, No. 2, (2020), 3243-3254

Iran University of Science and Technology

International Journal of Automotive Engineering

Journal Homepage: ijae.iust.ac.ir

ISSN: 2008-9899

Computational Study of the Effects of Using Pilot Injection in a Heavy Duty Dual-Fuel Diesel-H2 Compression Ignition Engine

Vahid Manshaei[1*], Mohammad Javad Noroozi[1*], Ali Shaafi[1]

[1]Department of Mechanical Engineering, Ayatollah Boroujerdi University, P.O. Box: 69199-69411, Borujerd, Iran

ARTICLE INFO

Article history:

Received : 28 Feb 2020

Accepted: 30 May 2020

Published:1 June 2020

Keywords:

Combustion simulation

Hydrogen combustion

Pilot fuel quantity

Performance

Emissions

A B S T R A C T

In this research, the separate and simultaneous effects of pilot-main injection dwell time, pilot fuel quantity, and hydrogen gas addition on combustion characteristics, emissions formation, and performance in a heavy-duty diesel engine were investigated. To conduct the numerical study, valid and reliable models such as KH-RT for the break-up, K-Zeta-F for turbulence, and also ECFM-3Z for combustion were used. The effects of thirty-one different strategies based on two variables such as pilot-main injection dwell time (20, 25, 30, 35, and 40 CA) and pilot fuel quantity (5, 10, and 15% of total fuel per cycle) on NDC and DHC were investigated. The obtained results showed that by decreasing pilot-main injection dwell time due to shorter combustion duration and higher MCP, MCT, and HRRPP, amounts of CO and soot emissions decreased at the expense of high NOx formation. Also, increasing pilot fuel quantity due to higher combustion temperature and less oxygen concentration for the main fuel injection event led to an increase of NOx and soot emissions simultaneously. The addition of H2 due to significant heating value has increased IP and improved ISFC at the expense of NOx emissions but considerably decreased CO and soot emissions simultaneously.

*Corresponding Author

Email Address: Mo.j.noroozi@gmail.com; m.j.noroozi@abru.ac.ir

https://doi.org/10.22068/ase.2020.535

1. Introduction

Due to the high level of NOx and soot emissions produced by compression ignition diesel engines, every year emissions regulations become stringent. However, higher thermal efficiency, lower fuel consumption, and more durability compared to spark ignition and gas engines made diesel engines more popular and widely used in the transportation industry, power generating, and also agriculture [1-3]. Many researchers from all over the world have conducted extensive researches on diesel engines to reduce emissions formation and enhance engine performance simultaneously [4-10]. In their paper, How et al. [11] examined the effects of direct injection timing and split injection strategies on performance, emissions formation, and combustion characteristics of a medium-duty diesel engine. Their results showed that retarding the injection timing along with using a triple injection strategy decreased NOx emissions by less than 100 ppm compared to baseline operation case. They also indicated that multiple split injection strategies are an effective way to simultaneously decrease NOx and soot emissions when the SOI timing is fine-tuned.

D'Amboise and Ferrari [12] performed experiments on the effects of pilot injection characteristics on low-temperature combustion in a light-duty diesel engine. They reported that by increasing dwell timing between the pilot and main injection, CO emission increased and increasing of pilot quantity was accompanied by more CO compared to the baseline case. They also indicated that by increasing the pilot fuel quantity, NOx emissions increased, and also increasing of the dwell timing led to more NOx formation. In their experimental study, Wei et al. [13] explored the effects of pilot injection on a 6-cylinder, turbocharged diesel engine. Their results showed that using pilot injection increased MCP and MCT and also reduced the amount of CO emission compared to a single injection strategy. Increasing the pilot fuel quantity led to increase in MCP and MCT. Furthermore, NOx emissions increased. In another research work, Plamondon and Seers [14] conducted a parametric study on the effects of pilot injection strategies on the performance and emissions formation of a light-duty diesel engine. They reported that using pilot injection increased the reactivity of early main-injection timing by shortening the ignition delay period. They also demonstrated that the optimum double-injection strategy achieved by retarding main-injection timing allowed the reduction of both soot and NOx emissions compared to the optimum single injection strategy.

In other researches, the focus of the investigations was on using renewable fuels such as H2 gas for better emissions and higher performance. The clean combustion of hydrogen which produces zero CO_2, CO, UHC, and soot emissions attracted lots of attention to use hydrogen gas as a clean fuel in compression ignition diesel engines. Extensive researches have been conducted to explore the possibility and influence of using hydrogen gas on the combustion process, emissions formation, and performance of diesel engines [15-17]. In their study, Karagoz et al. [18] conducted an experimental study on the effects of hydrogen gas addition on combustion characteristics, emissions formation, and performance of a diesel engine. According to their obtained results, the addition of hydrogen gas decreased CO (by nearly 69.2%) and soot (by 58.6%) emissions simultaneously. They also indicated that peak in-cylinder pressure value increased by 36.2% compared to neat diesel combustion. Furthermore, a significant increase of nearly 110.94% was acquired in the heat release rate peak point. Serrano et al. [19] conducted a detailed study on the effects of hydrogen gas addition on performance and emissions formation in a compression ignition diesel engine. They reported that increasing of H_2/Diesel ratio made soot decreased but NOx emissions increased due to higher combustion temperature caused by hydrogen addition to combustion chamber compared to pure diesel combustion.

According to the literature review, applying a pilot injection strategy and increasing the dwell timing between injection events resulted in more carbon-based emissions formation such as CO and soot. Moreover, addition of hydrogen gas leads to less soot and CO emissions in the exhaust gases. For this reason and in the

[DOI: 10.22068/ase.2020.535]

following of previous studies, this numerical research aims to investigate the simultaneous effects of using pilot injection strategies and hydrogen gas additions in a heavy-duty diesel engine. This research is divided into three sections; the first part discusses about the effects of hydrogen gas addition and pilot injection characteristics such as dwell time and fuel quantity on in-cylinder pressure, temperature, and heat release rate. In the second and third parts, the effects of study strategies on emissions formation (such as NOx, soot, and CO) and engine performance will be discussed respectively.

2. Model description

The AVL ESE Fire code was used for diesel/hydrogen dual-fuel combustion simulation. The computational mesh was created using AVL ESE Diesel Tool [20] and since the injector have six holes and the symmetrical location of the nozzle is at the center of the combustion chamber, the CFD calculations were performed on a 60 degrees segment. Exhaust and intake ports were not included in the computational mesh because this study only was concentrated on the in-cylinder flow and combustion process. Calculations were started at IVC and end at EVO event. The ground of the bowl was meshed with three continuous layers for a proper calculation of the heat transfer through the piston wall. The same initial and boundary conditions were used for all the computations. The averaged cell size was 2 mm, and an exact number of cells in the mesh were 31300 and 77650 at TDC and BDC, respectively. The present resolution was found to give adequately grid independence. Figure 1 shows the computational grid at TDC. The sub-models used in Fire code are based on other researcher's papers that are very usable and valid. Table 1 represents the Computational sub-models used in the CFD code.

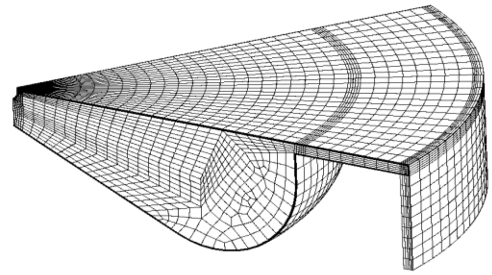


Figure 1: The computational grid at TDC

Table 1: Computational sub-models

Turbulence model	K-Zeta-F [21]
Turbulence dispersion model	O'Rourke [22]
Particle interaction model	Nordin [23]
Wall interaction model	O'Rourke and Amsden [24]
Evaporation model	Dukowicz [25]
Breakup model	KH-RT [26]

3. Engine Specifications and Model Validation

A heavy-duty caterpillar 3401 single cylinder Oil Test Engine (SCOTE) was used for all the engine simulations [27]. The engine specifications are listed in Table 2.

Table 2: Engine Specifications [27]

Engine Type	**Heavy Duty Turbo-Charged Diesel Engine**
Number of Cylinders	1
Bore (mm) x Stroke (mm)	137.16 x 165.1
Geometric compression ratio	16.1:1
Displacement Volume (L)	2.44
Connecting rod Length (mm)	261.6
TDC Clearance gap (mm)	1.97
Engine Speed (rpm)	1208
Piston Shape	Stock
Bowl Volume (cc)	110.8
IVC (CA)	217
EVO (CA)	490

[DOI: 10.22068/ase.2020.535]

IMAP (bar)	2.0
IMAT (K)	313

Table 3 presents the specifications of the fuel injection system [27].

Table 3: Fuel injection system specifications [27]

Injector Holder	**Bosch CRIN 2**
Nozzle Type	Sac
Sac Volume (mm^3)	0.7
Number of Injector Holes	6
Spray Angle (Degree)	145
Nozzle Hole Diameter (mm)	0.25
Injection Pressure (bar)	755
Discharge Coefficient (-)	0.69
Hydraulic Flow (cc per 30 sec @ 100 bar)	1000
Fuel Temperature (K)	341
Total Fuel per Cycle (mg)	172.2
Fuel Injection Timing (CA)	350
Fuel Injection Duration (CA)	16.8

Table 4 and Table 5 show the Diesel and H2 fuel chemical specifications, respectively.

Table 4: Diesel fuel chemical specifications [27]

Specific Gravity @ 15.5 C (-)	0.856
Viscosity @ 40 C (cSt)	2.71
Surface Tension @ 25 C	30
Lower Heating Value (MJ/Kg)	42.526
Cetane Number	46.1
H/C ratio	1.74

Table 5: Hydrogen gas chemical specifications [28]

Property	**Unit**	**Values**
Adiabatic flame temperature ($\varphi = 1$)	[K]	2480
Auto-ignition temperature in air	[K]	858
Density	[Kg/m^3]	0.0824
Flame velocity ($\varphi = 1$)	[ms^{-1}]	1.85
Flammability limits	[% vol. in the air]	4 - 75
Lower heating value	[MJ/kg]	119.7
Minimum ignition energy ($\varphi = 1$)	[MJ]	0.02

Figure 2 shows the comparison of in-cylinder mean pressure and rate of heat release of experimental [27] and present numerical research work. The results achieved from simulations are based on the assumption of a uniform wall temperature of 420 K for the cylinder wall and 520 K for the cylinder head and the piston top. As illustrated in Figure 2, the trends predicted by the model are reasonably close to experimental results, although there are still some differences as can be seen in this figure. These discrepancies could be related to experimental uncertainties in input parameters to the computations such as the precise injection duration, start of injection timing, and gas temperature at IVC.

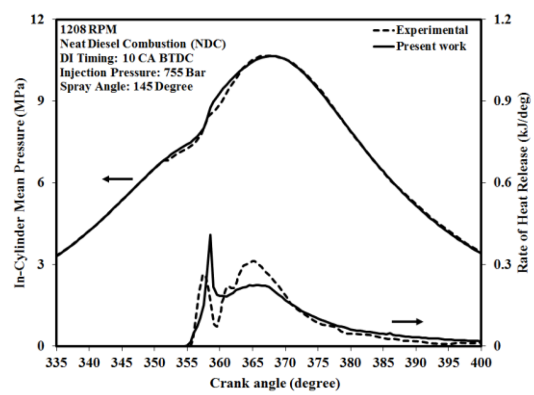


Figure 2: Comparison of experimental [27] and numerical results of in-cylinder mean pressure and rate of heat release for the baseline operation case.

Regarding emissions formation, Table 6 reports the comparison of experimental and numerical emissions formation for baseline operation case. As can be seen from Table 6 emissions formation is well predicted by the models compared to experimental results.

Table 6: Comparison of current research and experimental [27] results of emissions for the baseline operation case.

[DOI: 10.22068/ase.2020.535]

Emissions (g/kg. fuel)	NOx	CO	soot
Current research	52.91	2.75	0.27
Experimental	49.8	3.1	0.31

4. Study strategy

Based on the success achieved in verifying the baseline operation case with experimental result in the previous section, this numerical research aims to examine the effects of pilot injection strategies on the combustion process of a heavy-duty compression ignition diesel engine under pure diesel and hydrogen-diesel combustion conditions. Pilot-main injection dwells time, and pilot fuel quantity are two variables that their effects are the primary purpose of this research. In addition to baseline operating case, 31 injection strategies based on two variables, dwell time (20, 25, 30, 35, and 40 CA by varying main injection timing and constant pilot injection timing at 40 CA BTDC) and pilot fuel quantity (5, 10, and 15 percent of total fuel per cycle) have been considered and their effects on combustion characteristics (in-cylinder mean pressure, temperature, and HRR), emissions formation (NOx, soot, and CO), and engine performance (ISFC and IP) under neat diesel and diesel-hydrogen (80-20% energy fraction) combustion were investigated.

5. Results and discussion

5.1. Effects of Study Strategies on the Combustion Characteristics

Figure 3 shows the effects of pilot fuel quantity on the combustion characteristics. As indicated in this figure, by increasing the pilot fuel quantity MCP, MCT, and HRRPP increased.

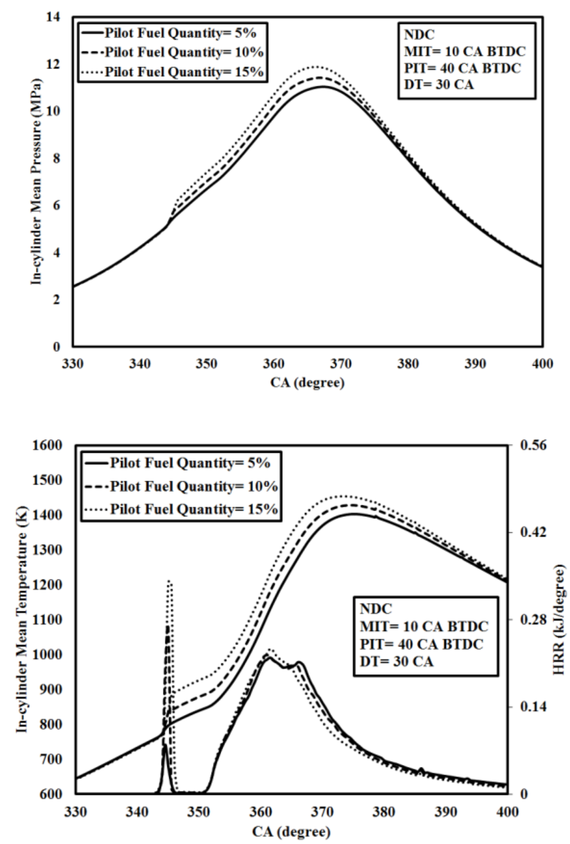


Figure 3: Effects of study strategies on combustion characteristics

Pilot fuel injection at early timings due to lower in-cylinder pressure and the temperature inside the combustion chamber led to more available time (longer ignition delay period) and subsequently, more fuel could evaporate, accumulate, and burn in premixed combustion mode. Because the burning rate is significantly higher during the premixed combustion compared to diffusive mode, as reported in Fig. 3, increasing pilot fuel quantity led to the increment of MCP, MCT, and HRRPP since more portion of diesel fuel burned in premixed combustion mode.

Figure 4 shows the effects of pilot-main injection dwell time on the combustion characteristics. As can be seen from this figure, by retarding the main injection timing due to

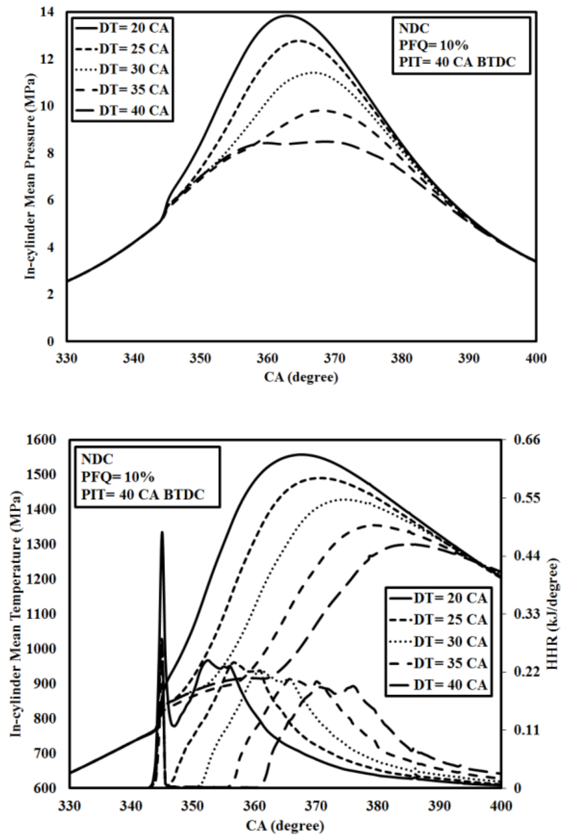


Figure 4: Effects of study strategies on combustion characteristics

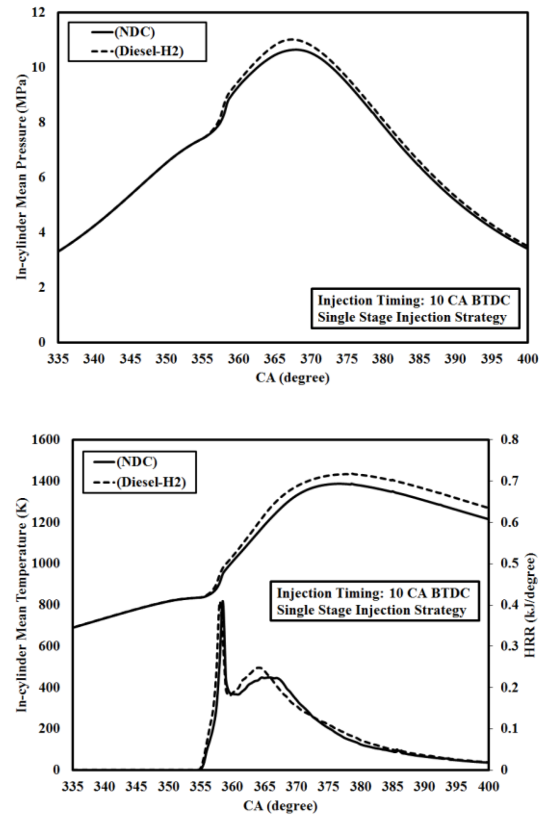


Figure 5: Effects of H2 addition on the combustion characteristics

higher in-cylinder pressure and temperature at the end of the compression stroke, the ID period becomes shorter, and most of the evaporated fuel burns in diffusive combustion. As indicated earlier, since the burning rate is noticeably lower during diffusive combustion compared to premixed mode, postponing the main fuel injection event led to lower pressure and temperature rise rate and subsequently, based on Figure 4, MCP, MCT, and HRRPP significantly decreased.

Figure 5 shows the effects of hydrogen gas addition on in-cylinder mean pressure, temperature, and HRR trends. As can be seen from Figure 5, the addition of hydrogen gas into the combustion chamber noticeably increased MCP, MCT, and HRRPP simultaneously. Due to higher heating value and faster combustion rate of H2 gas compared to other gaseous and liquid fuels, the addition of H_2 considerably improved the fuel oxidation process and subsequently, in-cylinder pressure and temperature of combustion considerably increased.

5.2. Effects of Study Strategies on the Emissions Formation

Figure 6 shows the effects of pilot-main injection dwell time, pilot fuel quantity, and hydrogen gas addition on the soot-NOx trade-off. As can be seen from Figure 6, by advancing main fuel injection timing the amount of soot emission first increased and then decreased. Also, NOx emissions gradually increased as MIT was advanced. Advancing main fuel injection timing led to more evaporated fuel to burn in premixed combustion and subsequently caused higher MCP, MCT, and HRRPP simultaneously. As a result, due to the higher combustion temperature, the amount of NOx emissions increased and soot oxidation process

[DOI: 10.22068/ase.2020.535]

improved. In another word, by decreasing the DT due to shorter combustion duration, MCP, MCT, HRRPP increased. Also, as can be seen from Figure 6, NOx emissions increased and due to the improvement of the air-fuel mixture oxidation process, soot emission decreased for 20 CA DT. As indicated in Figure 6 using a pilot injection strategy for NDC mode considerably increased soot emission compared to baseline single-stage injection strategy. By spraying the amount of fuel at early timings (e.g. 5% of total fuel at 40 CA BTDC) due to mixture formation before the main fuel injection event, in-cylinder oxygen concentration decreases for main fuel injection event and as a result, fuel oxidation process for the main injection event deteriorates. Thus, based on Figure 6, soot emission increases. Furthermore, as indicated in Figure 6, the addition of hydrogen gas significantly increased NOx emissions and improved soot oxidation. As indicated earlier, due to the high heating value of hydrogen gas, the addition of H2 into the combustion chamber leading to a significant impact on in-cylinder pressure and temperature of combustion and as a result, soot emission decreased, but NOx significantly increased compared to NDC mode.

As illustrated in Figure 6, increasing pilot fuel quantity due to higher combustion temperature and less oxygen concentration for the main fuel injection event led to an increase in the amounts of NOx and soot emissions simultaneously. For this reason, a simultaneous increase in NOx and soot level by the addition of the pilot fuel quantity must be considered as one of the disadvantages of using pilot injection strategies.

Figure 7 shows the effects of pilot-main injection dwell time, pilot fuel quantity, and hydrogen gas addition on the CO-NOx trade-off.

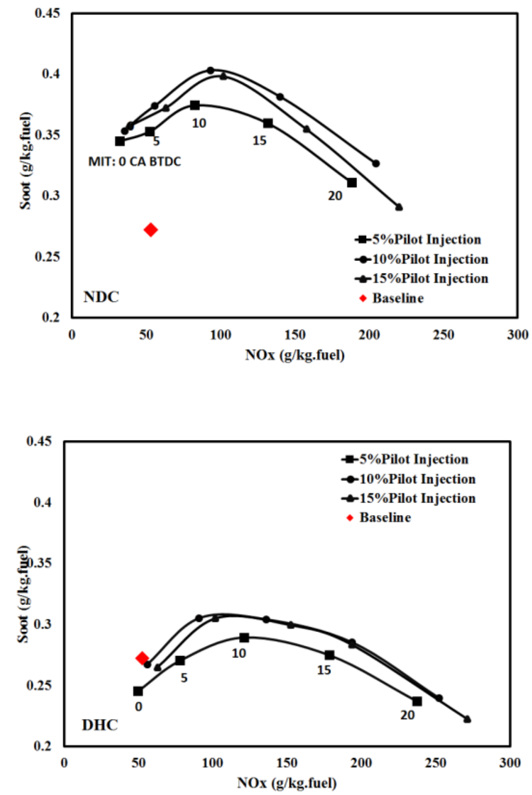
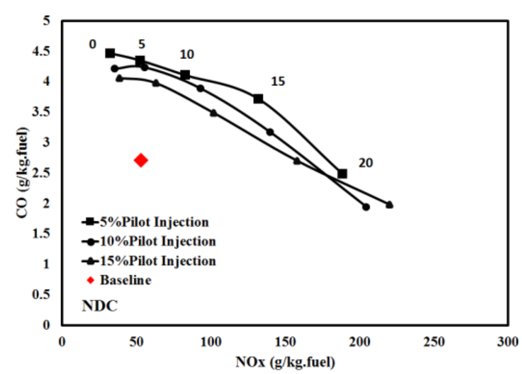


Figure 6: Effects of study strategies on the soot-NOx trade-off



[DOI: 10.22068/ase.2020.535]

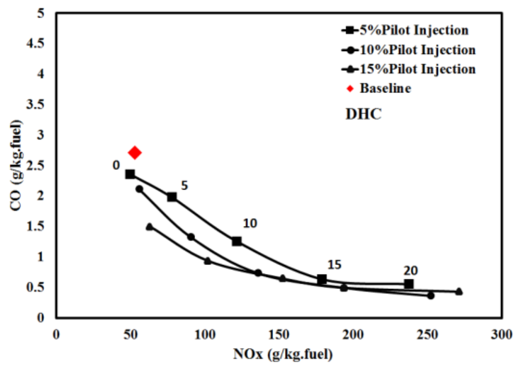


Figure 7: Effects of study strategies on the CO-NOx trade-off

As can be seen from Figure 7, by advancing the main fuel injection timing the amount of CO emission decreased. As indicated earlier, advancing the main fuel injection timing led to more premixed fuel combustion and higher pressure and temperature rise rate that could increase MCP, MCT, and HRRPP. As a result, due to higher combustion temperature, air-fuel mixture oxidation improved and subsequently, the amount of CO emission decreased. As illustrated in Figure 7, by increasing pilot fuel quantity the amount of CO emission due to higher combustion temperature decreased. Higher combustion temperature led to the improvement of the air-fuel mixing and oxidation process and as can be seen in Figure 7, the amount of CO emission due to the improvement of carbon species oxidation decreased. Furthermore, the addition of hydrogen gas due to higher combustion temperature compared to NDC mode significantly reduced CO since by substitutioninig a part of diesel with hydrogen gas the level of carbon species participated in the combustion process decreases.

5.3. Effects of Study Strategies on the Engine Performance

Figure 8 shows the effects of pilot-main injection dwell time, pilot fuel quantity, and hydrogen gas addition on the IP-NOx and the ISFC-NOx trade-off.

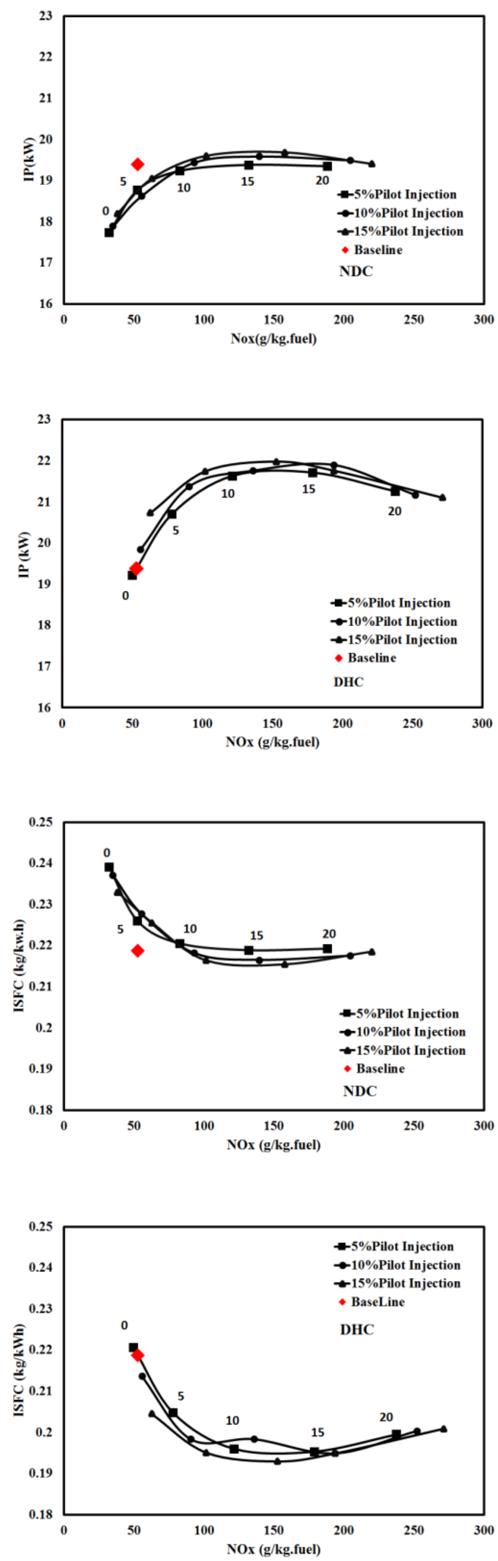


Figure 8: Effects of study strategies on the IP-NOx and the ISFC-NOx trade-off

[DOI: 10.22068/ase.2020.535]

As indicated in Figure 8, by advancing the main fuel injection timing the IP increased and ISFC improved. As indicated earlier, by advancing main fuel injection timing due to more premixed fuel combustion and higher pressure and temperature rise rate, the MCP, MCT, and HRRPP increased. As a result, higher combustion temperature led to the improvement of the air-fuel mixing and oxidation process that could increase IP and improve ISFC simultaneously. In another word, by decreasing the pilot-main injection DT, due to shorter combustion duration and higher pressure and temperature rise rate, the air-fuel oxidation process improved, and as can be seen from Figure 7, IP increased, and ISFC improved under NDC and DHC engine operating conditions.

As illustrated in Figure 8, increasing pilot fuel quantity due to more mixture formation before the main fuel injection event that could increase MCP, MCT, and HRRPP, led to the improvement of IP and ISFC. Furthermore, the addition of hydrogen gas due to high heating value and faster combustion rate led to an increase in the MCP, MCT, and HRRPP. As a result, higher IP and lower ISFC achieved under DHC compared to NDC mode.

6. Conclusions

In this research, the separate and simultaneous effects of pilot-main injection dwell time, pilot fuel quantity, and the addition of H2 gas on combustion characteristics, emissions formation, and performance of a single-cylinder heavy-duty diesel engine have been investigated. Results showed that:

- The induction of hydrogen gas into the cylinder increased MCP, MCT, and HRRPP compared to NDC mode. The higher combustion temperature improved the mixture oxidation process, and as a result, soot and CO emissions considerably decreased. However, because of the high heating value of H2 gas and higher combustion temperature under DHC operating conditions, more NOx emissions formed compared to NDC mode.
- Increasing pilot fuel quantity due to higher combustion temperature and less oxygen concentration for the main fuel injection event led to an increase in the amounts of NOx and soot emissions simultaneously.
- By decreasing pilot-main injection dwell time, due to shorter combustion duration and the improvement of the air-fuel oxidation process, CO and soot emission decreased at the expense of high NOx emissions.
- Applying a pilot injection strategy due to mixture formation before the main fuel injection event, led to a reduction of in-cylinder oxygen concentration for main fuel injection event and as a result, the fuel oxidation process for the main injection event deteriorates and subsequently, soot emission increases.

Overall, applying a pilot injection strategy along with substitutioning of a part of diesel fuel with hydrogen gas is a very effective way to enhance engine performance as well as decrease carbon-based emissions such as soot and CO emissions. However, since the combustion temperature considerably increases, this strategy leads to a high level of NOx formation in the exhaust gases. For this reason, using this strategy must be along with acquiring NOx after-treatment system to compensate the excess level of NOx formation.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Abbreviations

[DOI: 10.22068/ase.2020.535]

BDC	Bottom Dead Center
BTDC	Before Top Dead Center
CA	Crank Angle
CFD	Computational Fluid Dynamic
CO	Carbon Monoxide
DHC	Diesel Hydrogen Combustion
DI	Direct Injection
DT	Dwell Time
EVO	Exhaust Valve Opening
HRRPP	Heat Release Rate Peak Point
ID	Ignition Delay
IMAP	Intake Manifold Air Pressure
IMAT	Intake Manifold Air Temperature
IMEP	Indicated Mean Effective Pressure
IP	Indicated Power
ISFC	Indicated Specific Fuel Consumption
IT	Injection Timing
IVC	Intake Valve Closing
MCP	Maximum Combustion Pressure
MCT	Maximum Combustion Temperature
MIT	Main Injection Timing
NDC	Neat Diesel Combustion
NOx	Nitrogen Oxides
PFQ	Pilot Fuel Quantity
PIT	Pilot Injection Timing
SOI	Start of Injection
TDC	Top Dead Center

References

[1] M. Ebrahimi, S. A. Jazayeri, Effect of hydrogen addition on RCCI combustion of a heavy duty diesel engine fueled with landfill gas and diesel oil, international journal of hydrogen energy, Vol. 44, No. 14, pp. 7607-7615, 2019.

[2] F. M. Hossain, M. N. Nabi, R. J. Brown, Investigation of diesel engine performance and exhaust emissions of microalgae fuel components in a turbocharged diesel engine, Energy conversion and management, Vol. 186, pp. 220-228, 2019.

[3] G. Ospina, M. Y. Selim, S. A. Al Omari, M. I. H. Ali, A. M. Hussien, Engine roughness and exhaust emissions of a diesel engine fueled with three biofuels, Renewable Energy, Vol. 134, pp. 1465-1472, 2019.

[4] H. Chen, R. Huang, H. Huang, M. Pan, W. Teng, Potential improvement in particulate matter's emissions reduction from diesel engine by addition of PODE and injection parameters, Applied Thermal Engineering, Vol. 150, pp. 591-604, 2019.

[5] G. Edara, Y. S. Murthy, J. Nayar, M. Ramesh, P. Srinivas, Combustion analysis of modified light duty diesel engine under high pressure split injections with cooled EGR, Engineering Science and Technology, an International Journal, Vol. 22, No. 3, pp. 966-978, 2019.

[6] H. Huang, Z. Zhu, Y. Chen, Y. Chen, D. Lv, J. Zhu, T. Ouyang, Experimental and numerical study of multiple injection effects on combustion and emission characteristics of natural gas–diesel dual-fuel engine, Energy conversion and management, Vol. 183, pp. 84-96, 2019.

[7] X. Li, C. Guan, Y. Luo, Z. Huang, Effect of multiple-injection strategies on diesel engine exhaust particle size and nanostructure, Journal of Aerosol Science, Vol. 89, pp. 69-76, 2015.

[8] L. Xu, X.-S. Bai, M. Jia, Y. Qian, X. Qiao, X. Lu, Experimental and modeling study of liquid fuel injection and combustion in diesel engines with a common rail injection system, Applied Energy, Vol. 230, pp. 287-304, 2018.

[DOI: 10.22068/ase.2020.535]

[9] M. K. Yesilyurt, The effects of the fuel injection pressure on the performance and emission characteristics of a diesel engine fuelled with waste cooking oil biodiesel-diesel blends, Renewable energy, Vol. 132, pp. 649-666, 2019.

[10] A. Yousefi, H. Guo, M. Birouk, Effect of diesel injection timing on the combustion of natural gas/diesel dual-fuel engine at low-high load and low-high speed conditions, Fuel, Vol. 235, pp. 838-846, 2019.

[11] H. G. How, H. H. Masjuki, M. Kalam, Y. H. Teoh, Influence of injection timing and split injection strategies on performance, emissions, and combustion characteristics of diesel engine fueled with biodiesel blended fuels, Fuel, Vol. 213, pp. 106-114, 2018.

[12] S. d'Ambrosio, A. Ferrari, Effects of pilot injection parameters on low temperature combustion diesel engines equipped with solenoid injectors featuring conventional and rate-shaped main injection, Energy Conversion and Management, Vol. 110, pp. 457-468, 2016.

[13] H. Wei, C. Yao, W. Pan, G. Han, Z. Dou, T. Wu, M. Liu, B. Wang, J. Gao, C. Chen, Experimental investigations of the effects of pilot injection on combustion and gaseous emission characteristics of diesel/methanol dual fuel engine, Fuel, Vol. 188, pp. 427-441, 2017.

[14] E. Plamondon, P. Seers, Parametric study of pilot–main injection strategies on the performance of a light-duty diesel engine fueled with diesel or a WCO biodiesel–diesel blend, Fuel, Vol. 236, pp. 1273-1281, 2019.

[15] F. Christodoulou, A. Megaritis, Experimental investigation of the effects of simultaneous hydrogen and nitrogen addition on the emissions and combustion of a diesel engine, international journal of hydrogen energy, Vol. 39, No. 6, pp. 2692-2702, 2014.

[16] J. Zhou, C. Cheung, C. Leung, Combustion, performance and emissions of a diesel engine with H2, CH4 and H2–CH4 addition, International journal of hydrogen energy, Vol. 39, No. 9, pp. 4611-4621, 2014.

[17] J. Zhou, C. Cheung, W. Zhao, C. Leung, Diesel–hydrogen dual-fuel combustion and its impact on unregulated gaseous emissions and particulate emissions under different engine loads and engine speeds, Energy, Vol. 94, pp. 110-123, 2016.

[18] Y. Karagöz, İ. Güler, T. Sandalcı, L. Yüksek, A. S. Dalkılıç, Effect of hydrogen enrichment on combustion characteristics, emissions and performance of a diesel engine, International journal of hydrogen energy, Vol. 41, No. 1, pp. 656-665, 2016.

[19] J. Serrano, F. Jiménez-Espadafor, A. López, Analysis of the effect of different hydrogen/diesel ratios on the performance and emissions of a modified compression ignition engine under dual-fuel mode with water injection. Hydrogen-diesel dual-fuel mode, Energy, Vol. 172, pp. 702-711, 2019.

[20] A. FIRE, User Manual, 2014.

[21] M. Popovac, K. Hanjalic, Compound wall treatment for RANS computation of complex turbulent flows and heat transfer, Flow, turbulence and combustion, Vol. 78, No. 2, pp. 177, 2007.

[22] P. o'Rourke, Modelling of drop interactions in thick sprays and a comparison with experiments, I. Mech. E., C, Vol. 404, No. 80, pp. 101-116, 1980.

[23] P. N. Nordin, 2001, Complex chemistry modeling of diesel spray combustion, Chalmers University of Technology Sweden,

[24] P. J. O'Rourke, A. Amsden, A spray/wall interaction submodel for the KIVA-3 wall film model, SAE transactions, pp. 281-298, 2000.

[25] J. K. Dukowicz, Quasi-steady droplet phase change in the presence of convection, Los Alamos Scientific Lab., NM (USA), pp. 1979.

[DOI: 10.22068/ase.2020.535]

[26] V. K. Sarre, Ch., Tatschl, R., Spray Modelling/Atomisation–Current Status of Break-Up Models, in Proceeding of.

[27] M. J. Tess, C.-W. Lee, R. D. Reitz, Diesel engine size scaling at medium load without EGR, SAE International Journal of Engines, Vol. 4, No. 1, pp. 1993-2009, 2011.

[28] F. Christodoulou, Hydrogen, nitrogen and syngas enriched diesel combustion, Thesis, 2014.

[DOI: 10.22068/ase.2020.535]