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Synergistic Effects of High Boost Pressure and Fuel Injection Strategy on Diesel Engine Performance

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ABSTRACT

A study on the synergistic effects of high boost pressure and injection strategies on diesel engine performance were investigated. The highest gross indicated thermal efficiencies (ITE_g) are at the intake pressure of 0.3 MPa. The soot and NO_x emissions increase with increasing intake pressure. But once intake pressure which reaches 0.2 MPa has less effect on the diesel engine performance. Overall, intake pressure has larger effects on ITE_g and emissions than injection pressure; intake pressure also has larger effects on ITE_g than start of injection (SOI), but SOI has larger effects on emissions than intake pressure.

Keywords: intake pressure, injection strategies, diesel engine, thermal efficiency, emissions

NONMENCLATURE

Abbreviations	
AHRR	Apparent Heat Release Rate
ATDC	After Top Dead Center
HRR	Heat Release Rate
ITE_g	gross Indicated Thermal Efficiency
SOC	Start Of Combustion
SOI	Start Of Injection
TDC	Top Dead Center

1. INTRODUCTION

In recent years, research on diesel engines with the aim of increasing efficiency while meeting the performance and emission requirements has been widely explored. It was demonstrated that at higher power density levels with reduced friction resulted in higher engine efficiency [1]. Passenger car diesel engines have already reached specific powers greater than 100 kW/L [2], heavy-duty diesel engines are yet to reach beyond 30 kW/L [3]. The maximum power density that an engine can deliver is primarily limited by the amount of air that is inducted into each cylinder for each cycle. Meanwhile, the pressure of intake air can also have significant impacts on the combustion process.

Numerous studies have been carried out to discuss the effects of the intake pressure on diesel engine performance. Jayashankara [4] showed that the increase of intake pressure led to shortened combustion duration, decreased maximum heat release rate, increased cumulative heat release, increased NO_x and decreased soot emissions. Desantes et al. [5] found that increased intake pressure resulted in higher in-cylinder charge air density that improved fuel/air mixing and late-cycle oxidation quality, higher intake pressure also advanced the start of combustion (SOC) and thereby decreased the time available for fuel and air premixing.

Meanwhile, fuel injection strategy has been a major measure to improve the performance and emissions of diesel engines. In terms of start of injection (SOI), Suryawanshi et al. [6] observed that the NO_x emission was decreased with retarded injection timing with negligible effect on fuel consumption rate. Similar trend in brake thermal efficiency and exhaust gas temperature was observed with retarded injection timing while maximum cylinder gas pressure and ignition delay was decreased. In terms of injection pressures, Moon et al.

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[7] found that in-nozzle bubble formation and air ingestion are promoted at high injection pressures. Özkan [8] showed that the thermal efficiencies inversely proportional with injection pressure.

In diesel engines, the development of fuel jet with simultaneous evaporation of fuel and mixing with air, controls the heat release rate (HRR), there by the engine power and efficiency [9]. Hence, interactions between air and fuel reactions have to be considered. Anggono et al. [10] studied intake pressure and fuel injection timing on diesel engine. The experimental results further reveal that for HRR, the advancement of injection timing causes the differences between various intake pressures to be more apparent.

Based on the aforementioned studies, it is found that most existing work have been done on the effects of intake pressure or fuel injection parameters separately. In order to further improve the understanding of synergistic effects of the two measures, the effects of high boost pressure and injection strategies on diesel engine performance were investigated cooperatively in this work. The current work can provide a valuable reference on the utilization of high boost pressure and fuel injection parameters on diesel engine.

2. EXPERIMENTAL AND NUMERICAL METHODS

2.1 Experimental methods

The experiments were conducted on a modified six-cylinder diesel engine, wherein the sixth cylinder was isolated from the other five for test purposes, with independent fuel injection system, intake temperature and pressure regulating systems, and so on. The schematic of facility arrangement is illustrated in Fig. 1.

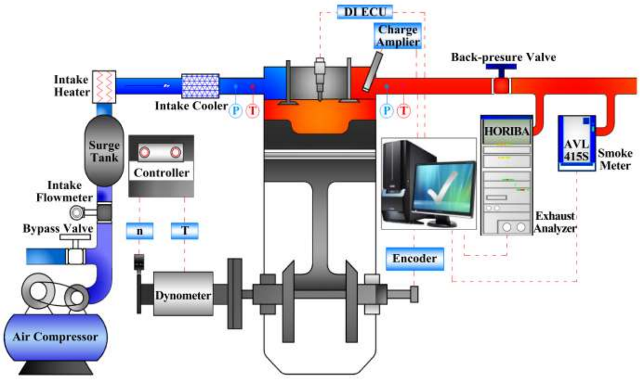


Fig. 1. Schematic of experimental facilities.

In section 3.1, the SOI was 2 °CA after top dead center (ATDC), the injection pressure was varied from 40 MPa to 120 MPa; in order to study the effects of intake and injection pressure, the intake pressure was varied from 0.1 MPa to 0.4 MPa. In Section 3.2, the injection pressure was 100 MPa, the SOI was varied from -6 °CA ATDC to 6 °CA ATDC; in order to study the effects of intake pressure and SOI, the intake pressure was varied from 0.1 MPa to 0.4 MPa. In all operating conditions, the engine speed was 1200 rev/min and the intake temperature was 30 °C; to make sure the in-cylinder peak pressure does not exceed the limit, the fuel mass was 15 mg per cycle, which also leads to lower equivalence ratio. Equivalence ratios of 2 °CA ATDC SOI and 100 MPa injection pressure are shown in Table 1. The equivalence ratio decreases as the intake pressure increases.

Table 1 Equivalence ratios

Intake pressure (MPa)	Equivalence ratio
0.1	0.22
0.2	0.11
0.3	0.07
0.4	0.05

2.2 Computational model and validation

CFD analysis was conducted to investigate the in-cylinder process of fuel spray and flame in order to clarify the impact of high boost pressure and injection strategies on diesel engine performance. The 3-D CFD engine combustion modelling was performed using CONVERGE [11]. As shown in Fig. 2, the simulated cylinder pressure and HRRs were found to agree well with experimental data measured at different intake pressures.

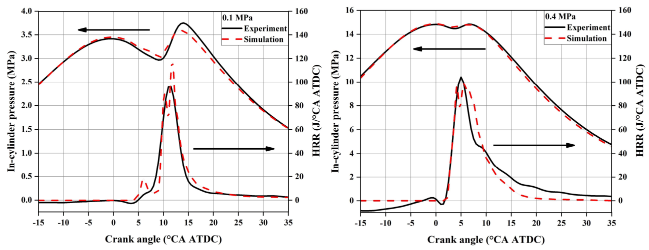


Fig. 2. Validation of 3D model.

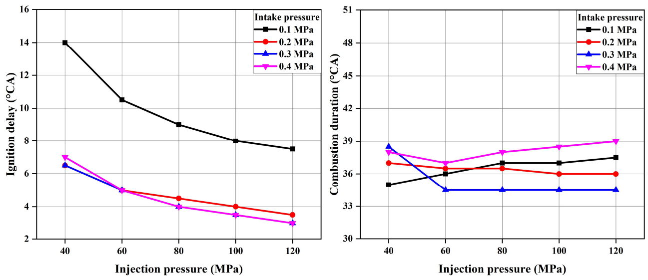
3. RESULTS AND DISCUSSION

3.1 Synergistic effects of intake air and injection pressure on diesel engine performance

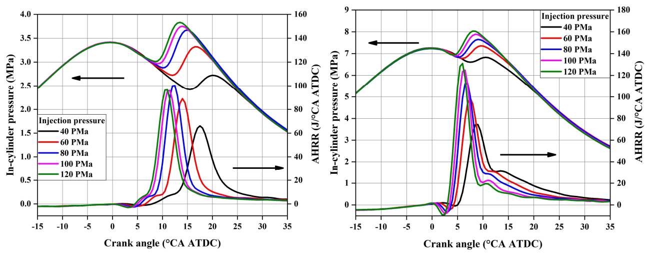
Fig. 3 shows the effects of intake and injection pressure on combustion characteristics. The ignition delays at 0.1 MPa are in general longer than other intake pressures at all injection pressures. When the intake pressure is higher than 0.2 MPa, the collision frequency between oxygen and fuel molecules increases, the reaction between molecules is easy to be induced, and the influence of intake pressure is negligible. The higher injection pressure makes the droplets susceptible to breakup processes. Thus, the ignition delay is shortened as the injection pressure increase. It is similar to the trend of ignition delay with different intake pressure, that once the intake pressure reaches 0.2 MPa, the injection pressure has less effect on the ignition delay. It is seen that the intake pressure has larger effects at lower intake pressure and smaller effects at higher intake pressure on ignition delay than the injection pressure.

As the intake pressure increases, firstly, the in-cylinder air density increases and spray dispersion increases, which results in more entrained air in the spray and faster evaporation [12]. Secondly, the in-cylinder oxygen mass density is increased. Thirdly, the in-cylinder average temperature is lowered. Fourth, the in-cylinder air density increases and the heat transfer loss is increased. When the intake pressure is less than 0.3 MPa, the air density and the in-cylinder oxygen mass density are lower which result in longer combustion duration. As the intake pressure is greater than 0.3 MPa, the heat transfer loss is higher and the in-cylinder average temperature is lower to make the combustion duration longer. At 0.3 MPa, the in-cylinder environment with high oxygen mass density and appropriate average temperature, the fuel reaction is the most intense and the combustion duration is the shortest except for the case with injection pressure of 40 MPa wherein the combustion duration is the longest because of poor atomization at low injection pressure. At higher injection pressures, the combustion duration is basically unchanged.

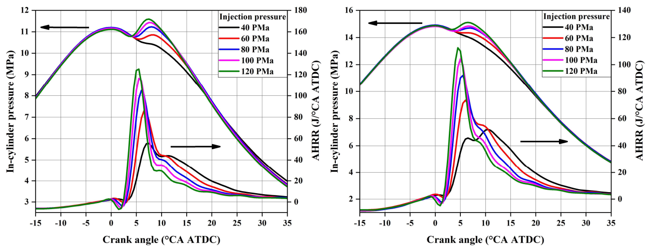
As the intake pressure increases from 0.1 MPa to 0.4 MPa, the peak value of the compression pressure at TDC is gradually increased from 3.4 MPa to 14.8 MPa as a result of more in-cylinder trapped mass at higher intake pressure. The increment in the peak value of the compression pressure is about 3.8 MPa for every 0.1 MPa increase in intake pressure. As injection pressure increases, the injection duration is shortened and the fuel atomization is improved; although the ignition delay is slightly shortened, the premixed burn fraction and peak apparent heat release rate (AHRR) increases. When the intake pressure is higher than 0.2 MPa, the intake pressure has less effect on the peak AHRR. The peak AHRR and combustion phasing determine the peak of combustion pressure. As the injection pressure increases, the combustion phasing is advanced and the peak AHRR is increased, which results in the increase and advance of combustion pressure.



(a) Effects of intake and injection pressure on ignition delay and combustion duration



(b) In-cylinder pressure and AHRR at 0.1 and 0.2 MPa intake pressure



(c) In-cylinder pressure and AHRR at 0.3 and 0.4 MPa intake pressure

Fig. 3. Effects of intake and injection pressure on combustion characteristics.

Fig. 4 shows N_2 mass in spray area and air utilization ratios under different intake pressures. The entrained air at 0.1 MPa intake pressure is always the lowest due to the lowest air density. As intake pressure increase, as mentioned before, the higher in-cylinder density can promote the spray dispersion and ambient air entrainment, and leads to faster fuel-air mixing. But the penetration rate of the fuel spray decreases with the increase of intake pressure which was shown in Fig. 5. The entrained air is increased insignificantly at higher intake pressures. The calculations of air-fuel mixture capture the trends in the experiments of ignition delay, wherein the higher intake pressure leads to faster fuel-gas mixing and shortens the combustion duration. However, as shown in Fig. 6, the higher temperature area of 0.1 MPa intake pressure is larger but the combustion temperature is lower due to the retarded combustion phasing. At higher intake pressure, although the combustion temperature is higher, the high temperature area gradually decreases and the combustion duration increases. As mentioned before, the effect of these aspects makes the shortest combustion duration at 0.3 MPa intake pressures and longer combustion duration at other intake pressures.

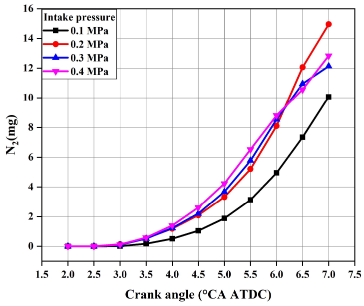
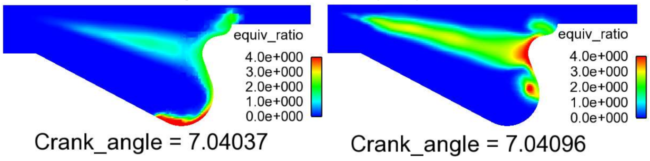
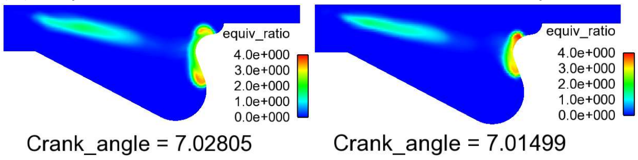


Fig. 4. N_2 mass in spray area.

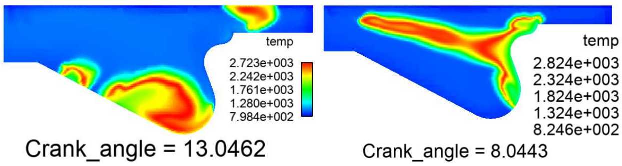


(a) equivalent ratio at 0.1 and 0.2 MPa intake pressure

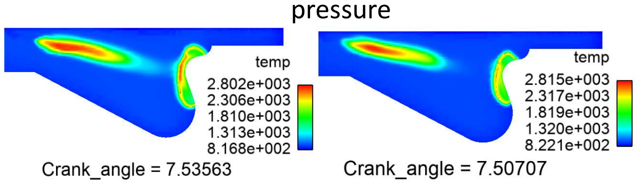


(b) equivalent ratio at 0.3 and 0.4 MPa intake pressure

Fig. 5. The equivalent ratio distribution of different intake pressures at 7 °CA ATDC.



(a) In-cylinder temperature at 0.1 and 0.2 MPa intake pressure



(b) In-cylinder temperature at 0.3 and 0.4 MPa intake pressure

Fig. 6. Effects of intake pressure on in-cylinder temperature at CA50.

Fig. 7 shows the effects of intake and injection pressure on performance. Gross indicated thermal efficiency (ITE_g) means that it is calculated only on the combustion and expansion stroke. ITE_g is used to better reveal the influence mechanism of intake pressure on the combustion process which typically depends on combustion duration, combustion phasing and heat transfer loss. The heat transfer loss depends on combustion temperature and in-cylinder air density. On one hand, ITE_g is inversely correlated with to the combustion duration. The longer the combustion duration is, the lower the ITE_g is. The 0.3 MPa intake pressures are the shortest combustion duration and the other intake pressures are longer. The combustion becomes less isochoric with the increase of combustion duration, which leads to the reduction in ITE_g. At higher intake pressures, as mentioned before, the combustion phasing is less affected by the intake pressure, but the lower combustion temperature and higher in-cylinder air density increase the heat transfer loss. So the highest ITE_gs are at the intake pressure of 0.3 MPa because of the shortest combustion duration and lower heat transfer loss. As the injection pressure increases, ITE_g first increases and then decreases. The injection pressure determines the penetration rate of the fuel spray, and the optimal penetration rate can get the highest ITE_g. If the penetration rate is too large or too small, it will reduce ITE_g. At 0.1 MPa, as the injection pressure increases, the ignition delay shortens and the combustion phasing advances and is closer to TDC, providing benefit in ITE_g. Thus, the injection pressure corresponding to the highest ITE_g is higher. From 0.2 MPa to 0.4 MPa, the in-cylinder pressure gradually increases, which results in the increase of injection pressure corresponding to the highest ITE_g. In general, the intake pressure has larger effects on ITE_g than the injection pressure.

The effect of intake pressure on emissions is similar to its effect on other performance. The soot and NO_x emissions at 0.1 MPa are in general lower than other intake pressures. When the intake pressure is higher than 0.2 MPa, the influence of intake pressure on emissions is negligible. At 0.1 MPa, the soot emissions are lower due to the longer ignition delay. At higher intake pressures, although the ignition delay is basically unchanged, the increase of in-cylinder oxygen mass density leads to the decrease of soot emissions and the decrease of in-cylinder average temperature leads to the increase of soot emissions, which offset each other, and finally leads to the basically unchanged soot emissions. Although in-cylinder average temperature is lower at higher intake pressures, NO_x emissions increase because higher in-cylinder oxygen mass density is the dominated factor.

As the injection pressure increases, the soot emissions decrease towards zero. Although the ignition delay is shortened, the fuel spray atomization quality is improved, and the fuel spray atomization quality is dominant at the lower injection pressure. At higher injection pressure, the improvement of fuel spray atomization quality leads to the decrease of soot emissions and the shortening of ignition delay leads to the increase of soot emissions, which offset each other, and finally make the basically unchanged soot emissions. As the injection pressure increases, the quality of fuel spray atomization is improved and the combustion pressure and temperature increases, which leads to the increase of NO_x emissions. In general, the intake pressure has larger effects at lower intake pressure and smaller effects at higher intake pressure on emissions than the injection pressure.

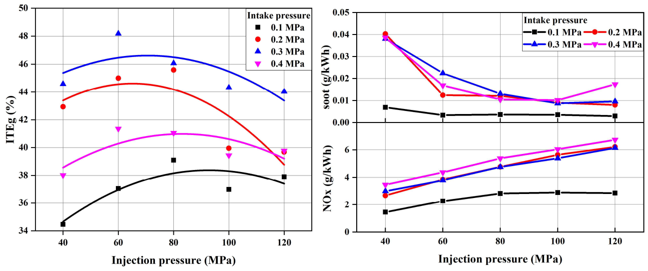
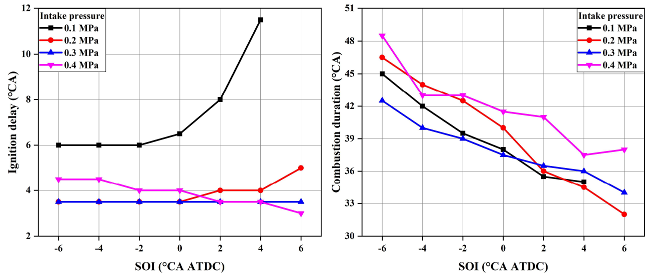


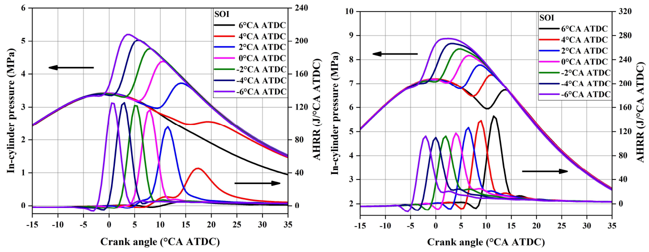
Fig. 7. Effects of intake and injection pressure on performance.

3.2 *Synergistic effects of intake air and SOI on diesel engine performance*

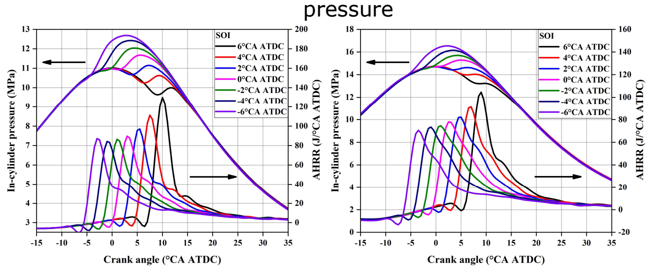
Fig. 8 shows effects of intake pressure and SOI on combustion characteristics. At 0.1 MPa intake pressure, as SOI advances, the in-cylinder pressure and temperature increase, and the ignition delay decreases gradually. At the three injection timings before 0 °CA ATDC, although the in-cylinder temperature and pressure decrease with the advance of injection timing, the in-cylinder temperature and pressure are near the maximum with the injection going on, so the ignition delay is basically unchanged and the shortest. At higher intake pressures, as SOI changes, the in-cylinder temperature and pressure changes, but higher in-cylinder oxygen mass density results in the basically unchanged ignition delay. As SOI advances, diffusion burn fraction increases, which prolongs the combustion duration. It can be seen that SOI has larger effects on ignition delay and combustion duration than the intake pressure. When the SOI is 6 ° CA ATDC at 0.1 MPa intake pressure, the ignition delay and combustion duration of the operating point are not shown in the Fig. 8 (a) due to the lower in-cylinder temperature and pressure result in misfire. At 0.1 MPa intake pressure, the in-cylinder oxygen mass density is lower, the reaction is faster and the peak AHRR increases as the advance of injection timing. At higher intake pressures, the in-cylinder oxygen mass density is higher, the diffusion combustion ratio increases and the peak AHRR decreases as the advance of injection timing. The compression pressure at the SOC is higher which leads to the combustion pressure increase as the advance of injection timing.



(a) Effects of intake pressure and SOI on ignition delay and combustion duration



(b) In-cylinder pressure and AHRR at 0.1 and 0.2 MPa intake pressure



(c) In-cylinder pressure and AHRR at 0.3 and 0.4 MPa intake pressure

Fig. 8. Effects of intake pressure and SOI on combustion characteristics.

Fig. 9 shows effects of intake pressure and SOI on performance. As the injection timing and combustion phasing advance and is closer to TDC, providing benefit in ITE_g. Meantime, the combustion temperature and heat transfer loss are increased, reducing ITE_g. The effect of these aspects offset each other, and finally leads to increase ITE_g slightly. However, at 0.1 MPa intake pressure and 4 °CA ATDC SOI, the in-cylinder temperature and pressure are lower, the injection timing is retarded, and the ignition delay is longer, which leads to combustion in the late expansion process and the ITE_g decreases sharply. At 0.4 MPa and -6 °CA ATDC, the in-cylinder pressure is higher and the combustion phasing moves forward, the compression negative work increases and ITE_g decreases sharply. In general, intake pressure has larger effects on ITE_g than SOI.

At 0.1 MPa intake pressure, as the injection timing advances, the in-cylinder combustion temperature and pressure increases, soot emissions decrease, while NO_x emissions increase. At higher intake pressures, the in-cylinder oxygen mass density is higher, SOI only has effects on NO_x emissions, which has small effects on soot emissions. In general, SOI has larger effects on emissions than intake pressure.

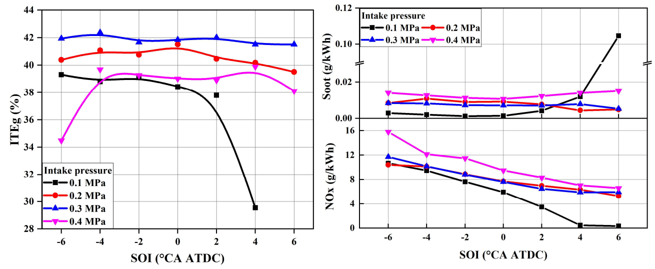


Fig. 9. Effects of intake pressure and SOI on performance.

4. CONCLUSIONS

1. The highest ITE_gs are at the intake pressure of 0.3 MPa. The soot and NO_x emissions increase with increasing intake pressure.

2. As the injection pressure increases, ITE_g first increases and then decreases; from 0.2 MPa to 0.4 MPa, the increase of injection pressure corresponding to the highest ITE_g; soot emissions decrease and trend to zero, NO_x emissions increase.

3. As the injection timing advances, ITE_g increases slightly; soot emissions decrease, while NO_x emissions increase at 0.1 MPa. At higher intake pressures, injection timing only has effects on NO_x emissions, which has small effects on soot emissions.

4. Once intake pressure reaches 0.2 MPa, the intake pressure has less effect on the diesel engine performance. Overall, the intake pressure has larger effects on ITE_g and emissions than the injection pressure; the intake pressure also has larger effects on ITE_g than the SOI, but the SOI has larger effects on emissions than the intake pressure.

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REFERENCES

[1] Dahodwala M, Joshi S, Krishnamoorthy H, Koehler EW, Franke M. Evaluation of System Configurations for Downsizing a Heavy-Duty Diesel Engine for Non-Road Applications. SAE International Journal of Engines 2016;9:2272–85.

[2] Beatrice C, Blasio GD, Belgiorno G. Experimental analysis of functional requirements to exceed the 100 kW/l in high-speed light-duty diesel engines. Fuel 2017;207:591–601.

[3] Nielsen B, Sladek W, Müller M, Eberle F. The Latest Heavy-duty Engine Generation from Mercedes-Benz Part 1: Aims and Design. MTZ Worldwide 2016;77:48–53.

[4] B. Jayashankara, V. Ganesan, Effect of fuel injection timing and intake pressure on the performance of a DI diesel engine – A parametric study using CFD, Energy Conversion and Management 2010;51: 1835-48.

[5] Desantes J, Benajes J, García-Oliver JM, Kolodziej CP. Effects of intake pressure on particle size and number emissions from premixed diesel low-temperature combustion. International Journal of Engine Research 2014;15:222–35.

[6] Suryawanshi JG, Deshpande NV. Effect of Injection Timing Retard on Emissions and Performance of a Pongamia Oil Methyl Ester Fuelled CI Engine. SAE Technical Paper 2005;2005-01-3677.

[7] Moon S, Huang W, Li Z, Wang J. End-of-injection fuel dribble of multi-hole diesel injector: Comprehensive investigation of phenomenon and discussion on control strategy. Applied Energy 2016;179:7–16.

[8] Özkan M. A Comparative Study on Energy and Exergy Analyses of a CI Engine Performed with Different Multiple Injection Strategies at Part Load: Effect of injection pressure. Entropy 2015;17:244–63.

[9] Jayashankara B, Ganesan V. Effect of fuel injection timing and intake pressure on the performance of a DI diesel engine – A parametric study using CFD. Energy Conversion and Management 2010;51:1835–48.

[10] Anggono W, Ikoma W, Chen H, Liu Z, Ichiyanagi M, Suzuki T, et al. Investigation of intake pressure and fuel injection timing effect on performance characteristics of diesel engine. IOP Conference Series: Earth and Environmental Science 2019;257:12037.

[11] Richards K, Senecal P, Pomraning E. CONVERGE (v2.3), Madison (WI): Convergent Science.

[12] Naber JD, Siebers DL. Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays. SAE Technical Papers 1996;105:82-111.