Investigation on the Effects of Quadruple Injection Strategy on Noise, Performance and Emission Characteristics of the Automotive Diesel Engine

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Abstract

Internal Combustion engine (ICE) emissions, noise and fuel economy have a significant impact on environmental pollution especially with on road or automotive ICE. Thus, the challenges are multi-fold for engine developer/research engineer (R&D), especially for a diesel engine as they need to deal with stringent emissions norms [Example- BS-IV, BS-VI or Real driving emission (RDE)] in line with mandated fuel economy norms as per applicability [for example, heavy-duty fuel economy (HDFE) or corporate average fuel efficiency/economy (CAFE)]. Fuel economy norms are targeted towards reduction of carbon footprint or CO_2 emissions (in gm/km) to control global warming by improvement of fuel consumption over last norms. Diesel or Compression ignition (CI) engine is a very popular automotive power source (on road and off -road) due to its mileage, part load efficiency and durability though it has some inherent problem like combustion noise and soot emissions. Currently, diesel engine combustion noise (CN/radiation) has also gained significant attention, as it is associated with the passengers and pedestrians' discomfort along with noise pollution. Exhaust After treatment system has big role to meet the emission regulation but it has much less effect on fuel efficiency other performance like torque or brake thermal efficiency [BTE] and combustion noise (CN). Here, In-Cylinder emission reduction techniques plays the significant role on combustion characteristics. Thus, combustion characteristics influence the efficiency and pollutant formation level of engine simultaneously. Furthermore, combustion characteristics of diesel engines depends on several factors like – design of combustion chamber, turbocharger, Exhaust gas circulation (EGR)**,** Injector Nozzle , fuel injection strategy and its parameters (e.g.- Fuel injection Pressure (FIP), Injection Timing, Start of injection (SOI), Injection Dwell, Rate shaping, Fuel Quantity). Here, EGR is a proven in-cylinder NOx reduction methodology but reverse effect on Soot emission. Higher EGR percentage depending on engine size with suitable measures (e.g. - fuel injection characteristic, compression ratio, Air intake) is the simplest method to achieve low temperature combustion (LTC) which may give simultaneous reduction in NO_x, and Particulate emissions.

The Multiple fuel injections are nothing but splitting the total injected fuel quantity of each cycle to multiple pulses, to achive better control on the spatial fuel delivery to improve the air usage in the combustion chamber (Figure 2.1). In Multiple injections, mainly three types of injection pulses are there namely a) pre-injections (or pilot injections), b) main injection and c) post/After-injections, as shown in Figure 2.1. It is well-known that a DI diesel engine combustion process are divided into four phases namely – ingnition delay , pre-mixed burning, diffusion/mixing conrolled combustion and late burning. The multiple injections plays key role in combustion processes which utimately control

igintion delay, premixed and diffusion control phases. Lastly, it control the combustion chamber inside heat realease rate (HRR) , combustion pressure, bulk gas temperature. These are the enablers to control BSFC, Torque, emissions and combustion noise.

Therefore, fuel injection strategy plays a key role in the simultaneous reduction of emissions and noise without penalizing fuel economy due to its better control on the combustion process. Fuel injection strategy in combination with common rail direct injection (CRDI) technology and heavy or high EGR is also a promising low-temperature combustion (LTC) methodology. The CRDI technology provides flexibility to experiment with various injection strategies based on parameters, such as injection pressure, fuel quantity and injection timing, which are influential to engine combustion management.

The major research in the domain of direct injection Compression engine with different injection strategies, Injection parameters, alternative fuels, EGR- LTC and predictive combustion models mainly to reduce emissions and improve performance. Many of them were in combination with EGR and multiple injection Strategies to achieve the same. It also revealed that adoption of multiple injections along with suitable EGR rate [i.e.- Low (<30%) or Medium (>30%- <45%) or High (>45% - <60%) or Heavy(>60%)] on the basis engine size/configuration appears to be an encouraging technique to take care of Thermal efficiency, Performance (BSFC or fuel economy) and emissions to meet the regulatory norms. Adoptation of EGR specially high or heavy percentage allows to achive low teamperature combustion (LTC) condition. However, all these researches give limited insights on quadruple injections strategy consisting of double pilots (early and pilot or ep) and one-post injection pulse in combination with high EGR-LTC on diesel engine. Studies of the influence of multiple injection strategies upon vehicle level fuel economy and noise performance have not been reported yet.

Considering these research gaps, we have focused on the comprehensive assessment of multiple injections, including the newest quadruple injection. This thesis deals with study on the effects or potentialities of quadruple injection schedules over three triple injections, two double injections on a classic six-cylinder heavy-duty CRDI engine at different operating conditions (loads and speeds (low-to-high)) and injection parameters (Injection Timing , Post injection Dwell) using design of experiments (DoE) approach. The study is further sub divided into 5 key researches; namely (i) Assessment of multiple injections (Double, Triple, Quadruple) over single injection (Main) at full load; (ii) Comparison and optimization of quadruple injection strategy (epMa) over Triple injections (pilot-main-after; pMa)

with variable main injection timing ; (iii) Comparative Analysis of quadruple injection strategy (epMa) over baseline Triple injections (pilot-main-after; pMa) and double injection (Pilot-Main; pM) with fixed e main injection timing (SOI Main), (iv) Assessment of the quadruple injection strategy (epMa) over three different Triple injections (early-main-after [eMa], early- pilot- main [epM] and pilot-main-after [pMa]) with fixed main injection timing; and (v) Effect of the quadruple injection strategy with different pilot and post injection timing. Fuel efficiency, Torque and Brake thermal efficiency (BTE) are considered under performance evaluation. Brake specific fuel consumption (BSFC) measured in all the studies. In addition, Vehicle level fuel economy has been evaluated as a requirement of HDFE norms in one of study. In few of the investigations, Pass by noise (PBN) at vehicle are captured along with Rig level noise (Nearby Noise; NBN) performance. One of unique focus of this research is to evaluate the outcome in real time or vehicle application.

The study shows that Quadruple injection strategy is superior in providing optimum results in emissions (NOx, PM, THC, CO) and combustion noise (CN)[@Rig level and @ Vehicle level Pass by Noise (PBN)]. This gives the optimum results in BSFC, CSFC (contestant speed fuel consumption), Torque and brake thermal efficiency (BTE) performance w.r.t other combinations and base triple injections (pMa). Also, the comparative study shown that Quadruple (epMa) injection strategy is superior to provide optimum (BSFC, overall emissions) results in comparison to Triple and Double injection strategies for all aspects. Smoke level is marginally higher at lower speed range for Quadruple injection scheduling whereas NOx emission level is lowest among the injection strategies

Further, Quadruple injection strategy with retarded early and advanced pilot and advanced post injection dwell timing is superior in providing optimum results in emissions and combustion noise (CN)[both Rig level and Vehicle level Pass by Noise (PBN)]. This gives the best results in brake specific fuel consumption (BSFC), Torque and brake thermal efficiency (BTE) performance w.r.t other Quadruple injection combinations (timing of ep and DtA) and base triple injections (pMa). In contrary, the quadruple injection strategy having advanced double pilots with delayed post injection dwell; shows the best CN reduction. Best smoke results found with the combination of retarded pilots and advanced post injection dwell. This study shows the importance of injection timing specially the twin pilots (early, pilot) along with post injection dwell and SOI main. Furthermore, it indicates the potentiality of newest Quadruple injection strategy (epMa) over Triple, double and single injection.