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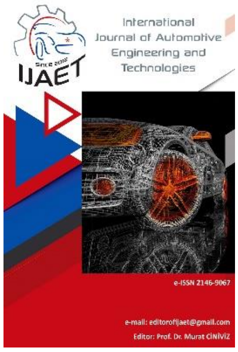

Original Research Article

A comprehensive investigation of injection strategies for improving diesel engine combustion under cold start development

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ABSTRACT

Starting at cold temperatures ranging from -30°C to 0°C has been a concern for all diesel engines, especially for future diesel engines that need to meet tighter carbon emission standards. Combustion instability and increasing smoke emissions are rising concerns during the cold start of diesel engines. Cold ambient conditions cause long cranking periods or complete misfire events in diesel engines; therefore, they produce a large proportion of pollutants within the cylinder due to incomplete combustion. In this study, a comprehensive investigation of multiple injection strategies was conducted under cold-start conditions to identify an optimal injection strategy that improves diesel combustion stability, cold-startup performance, and decreases white smoke emissions at cold ambient temperatures. This study found that cold start-up performance can be improved by eliminating misfire and lowering time to clean up white smoke with a three-injection strategy (two pilots and one main injection, simply named Pilot-Pilot-Main).

Keywords: diesel engine, cold start, injection strategies, performance

1. Introduction

Diesel engines are gaining more popularity and are being widely used as a prime mover in various applications. These engines have undergone significant improvements over the past decade. This development is primarily driven by stricter emission regulations, demand for higher performance, and better fuel economy. The utilization of turbocharging, electronically controlled fuel injection systems, exhaust gas recirculation, and after-treatment systems has further enhanced the capability of diesel engines to achieve lower emission, high power density, and low fuel consumption. Despite this advancement in engine technology, the problem of poor combustion, unacceptable levels of white smoke emissions, and HC compounds during cold starting in diesel engines is still a concern. Combustion instability is mainly due to the diesel fuel's higher viscosity, density, and lower volatility at lower compression temperatures and pressures, which makes atomization and evaporation difficult to trigger chemical reactions and subsequent stable ignition (Lodi et al., 2020; Rokni, Moore, &

Gavaises, 2021). Such conditions result in a poor air-fuel mixture that leads to misfires with a high proportion of unburned HC, CO, and white smoke emissions, causing the engine to perform poorly.

The diesel engine combustion process is complex, heterogeneous and is classified into four main stages (Farikhah, Elsharkawy, Saad, & Atia, 2023): Stage one, from the start of needle lift to the start of heat release, is the ignition delay period. Stage two, the kinetic or premixed burning stage, is when spontaneous ignition starts and burns fuel of ignitable air-to-fuel ratio (A/F) accumulated during the ignition delay period. Stage three is the main diffusion period from the end of stage two to the end of fuel injection, and stage four is the diffusion and end-burning period, when any fuel remaining in the cylinder is burned (Fig.1). The rate of combustion in the afterburning stage is dependent on the oxidation rate (Kawabe et al., 2023).

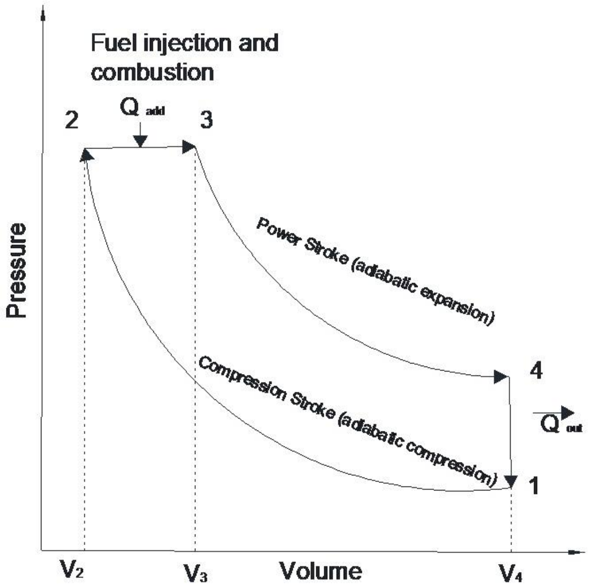


Figure 1 p-v diagram of 4-stage diesel engine

Diesel combustion is characterized by lean overall Air Fuel ratio (A/F). In turbocharged diesel engines the A/F ratio at idle exceed above stoichiometric equivalence ration of about 14.4:1. Therefore, excess air present in the cylinder after the fuel has combusted continues to mix with burning and already burned gases throughout the combustion and expansion processes. At the opening of the exhaust valve, excess air along with the combustion products are exhausted, which explains the oxidizing nature of diesel exhaust.

Although combustion occurs after vaporized fuel mixes with air, forms a locally rich but combustible mixture, and the proper ignition temperature is reached, the overall A/F ratio is lean. In other words, most of the air inducted into the cylinder of a diesel engine is compressed and heated, but never engages in the combustion process. Oxygen in the excess air helps oxidize gaseous hydrocarbons and carbon monoxide, reducing them to extremely small concentrations in the exhaust gas.

Incomplete combustion may result from poor mixing and bulk quenching (Shim, Park, & Bae, 2020), resulting in unburned HC and white smoke. During the delay period, the injected fuel mixes with air and locally forms over-lean, over-rich, and combustible mixture areas. The over-lean or over-rich mixture areas do not support complete combustion, resulting in incomplete combustion and high emissions. Combustible mixture ignites and supports combustion as the flame propagates unless faced with bulk quenching (Larmi, 2021; Sheheta, 2019).

Several factors affect the combustion and emissions of diesel engines. The ignition delay period plays a very important role in the diesel combustion process and in combustion instability. The physical delay is dependent upon the fuel injection, spray penetration, liquid fuel droplet formation, heat transfer from the surrounding air to the droplets, evaporation of fuel, and mixing of fuel vapor and air. The mechanism of misfiring is the failed autoignition process (Hmida et al., 2021). Autoignition will only take place at certain locations in the gaseous fuel-air mixture where temperature, pressure, and equivalence ratios are favorable to the chemical reaction, whereas the chemical delay includes the process of decomposition of the fuel molecules by mixing temperature and pressure.

The concept of combustion instability was first hypothesized by Henein et al. (1992), followed by the cold start studies (Han et al., 2001), which led to single-cylinder diesel engine research (Emiroğlu, & Şen, 2018; Sener, Yangaz & Gul, 2020) in describing the cyclic pattern of firing and misfiring phenomena observed during cold start investigations. The high-speed in-cylinder data was acquired from the start of the engine crank until idle speed. Other important signals recorded were fuel injector needle lift and fuel line pressure. For all the tests, fixed injection timing was used. The test results revealed that the engine may operate on the regular four-stroke cycle at normal operating ambient temperatures or may skip one cycle after each firing cycle at moderately low temperatures, i.e., operate in an eight-stroke cycle mode. The 8-stroke cycle is a modification of the traditional 4-stroke cycle and involves additional strokes to improve engine efficiency and reduce emissions. It includes eight strokes: intake, compression, power, exhaust, additional intake, additional compression, additional power, and additional exhaust. At lower temperatures, the engine may skip two cycles after each firing cycle, i.e., operate in 12-stroke cycle mode. The 12-stroke cycle further extends the concept of the 8-stroke cycle by adding even more strokes to enhance engine performance and emissions control. It includes twelve strokes: intake, compression, power, exhaust, additional intake, additional compression, additional power, additional exhaust, additional intake 2, additional compression 2, additional power 2, and additional exhaust 2. As the ambient temperature gets lower, more misfiring cycles may occur. These modes are reproducible and are found to depend mainly on the ambient temperature. Four kinds of fuels with different cetane numbers and volatility were tested, and this type of operation occurred with all of them.

The reduced compression ratio (CR) enhances the engine power due to the increase in specific indicated work output at low engine loads. It also leads to higher thermal efficiency and lower peak rates of heat release, which could be attributed to a reduction in heat transfer loss. Therefore, the mean gas temperature in the cylinder was reduced with a reduced compression ratio and a longer ignition delay time due to the low gas temperature and low oxygen concentration (Moradi, Gharehghani, & Misalim, 2020). However, reducing CR lowers the in-cylinder mean gas temperature and leads to poor fuel vaporization and autoignition capabilities, which induce the problem of cold start ability in CI engines (Duan, Lai, Jansons, Guo, & Liu, 2021).

2. Cold Startability

The cold startability of an engine can be arbitrarily defined as the ability of the engine to quickly start and run with minimum assistance from the starter and to continue to run without faltering. A combination of factors, including fuel properties, engine design, battery performance, oil viscosity, coolant temperature, and engine management systems, collectively contribute to the cold startability of an engine. By addressing these factors, manufacturers can enhance the reliability and performance of vehicles in cold climates. It is therefore possible to assess its startability through continuously monitored cranking torque. A significant reduction in cranking torque could then be considered a measure of engine startability. Also, the variations in cranking torque could be used as an indication of the degrees of stability during and after the starting periods. Fluctuations in the starting torque magnitude serve as a clear indicator of potential misfiring issues. Assessing startability can also involve analyzing in-cylinder pressures and observing smoke emissions. However, employing two-stroke analysis and monitoring cranking torque provides deeper insights into fuel evaporation and combustion dynamics, particularly during cold startup (Liang et al., 2022).

Problems in the cold starting of diesel engines are related to autoignition, which is largely susceptible to changes in the air temperature near the end of the compression stroke. Some of the problems are reduced performance, combustion instability and increased fuel consumption (Elbanna et al., 2022). Low compression temperatures during cold starting lower the rate of the autoignition processes, causing combustion to start late in the expansion stroke and a drop in IMEP (indicated mean effective pressure), which eventually results in the complete failure of the engine to start. Cold starting of diesel engines is characterized by long cranking periods and combustion instability, leading to an increase in fuel consumption and the emission of undesirable hydrocarbons that appear as white smoke.

Many investigators pointed out that ambient temperature is one of the most critical or important factors affecting the starting of diesel engines (Lu et al., 2023; Abdullah et al., 2021). Combustion instability increases if ambient temperature decreases, which is reflected by many ignition delay relationships. In general, a lower ambient temperature means higher lube oil viscosity, higher friction caused by moving engine parts, more heat loss and blow-by loss from cylinder charge caused by a lower cranking speed, and therefore more chances of ignition failure. Many researchers have experimented with the addition of ether in the fuels to increase the cold startability. However, this increases primary pollutants like CO (Sezer, 2019; Soltic et al., 2024).

The present work focuses on improving cold startability without the addition of any harmful additives. This is the novelty of the present work.

3. Experimental Setup and Instrumentation

3.1 Experimental setup

For the investigation, a direct injection turbocharged diesel engine with the following specifications (as shown in Table 1) was utilized: it's a heavy-duty, four-stroke-cycle, three-cylinder engine. The experimental setup and instrumentation layout are depicted in Figure 1. The inter-cooler was omitted as it was deemed to have negligible impact on the intake process during cold starts. To maintain the engine's coolant temperature at ambient levels throughout cold start development, a coolant tower was connected to the engine. Throughout the development tests, 1-D Special Low Cetane Ultra Low Sulfur Diesel (ULSD) was consistently used. It contains 97% less sulfur than low sulfur diesel and is free of paraffin wax. These factors lower the cloud and pour point of the fuel, thus preventing fuel getting gel in cold weather temperature. To minimize cylinder-to-cylinder variation and prevent exhaust gas condensation, the exhaust gas recirculation system was isolated. Although the original hardware includes a diesel oxidation catalyst (DOC) after treatment meeting BS4 emissions standards, it was omitted from the investigation for cold start development purposes.

The engine was positioned in a cold room with adjustable ambient temperatures ranging from -30°C to 0°C. To simulate real cold start conditions, the fuel tank was also placed in the cold room and pre-conditioned to the desired temperature alongside the engine. The engine was mounted on a sturdy metallic skid and linked to a parasitic load unit (PLU), it contains with stator and rotor which are mounted coaxially, opposite to one another. Stator plays role of inductor contains several electromagnets which generate magnetic fields when electricity continuously flows through the stator coils, thereby producing eddy current in the mass of the rotor acting as a braking energy on the engine generating parasitic load which controls engine speed and load. This setup helps mimic the parasitic load on the bare engine for the cold start development which is close to parasitic load on engine fitted in a vehicle. The engine instrumentation includes the following:

1. A cylinder pressure transducer
2. A needle lift sensor
3. An optical shaft encoder
4. Intake and exhaust pressure transducers
5. Intake and exhaust temperature thermocouple
6. A crankcase pressure transducer
7. Oil temperature thermocouple
8. Fuel temperature thermocouple

Table 1 Engine Specification

Description	Specification
Compression Ratio	16.85
Firing Order	1-3-2
No of Valve Per Cylinder	4
Injection System	Common Rail with Piezo Injector
Aspiration	Turbocharged

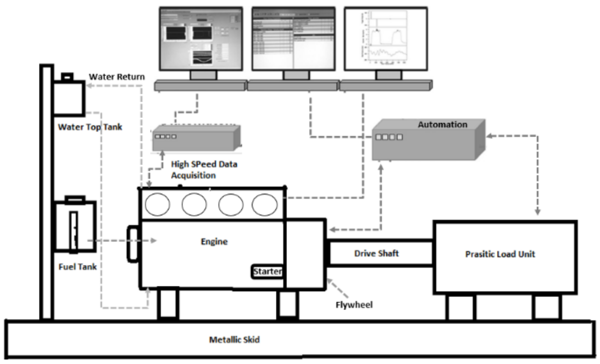


Figure 2 Schematic Engine Setup in Cold Room

An optical shaft encoder was mounted on the gear train side of the crankshaft damper to ascertain the instantaneous angular velocity and determine the position of the top dead center (TDC). The TDC signal was synchronized with that of cylinder -1. Cylinder -1 was equipped with a flush mount Kistler pressure transducer to measure the in-cylinder gas pressure. The combustion pressure in the cylinder was analyzed at 0.1 intervals of crank angle over a 50-cycle measurement period, and these pressure data were compared relative to the rate of heat release during engine operation. Combustion stability was assessed by examining the coefficient of variation of indicated mean effective pressure (COVimep). A Kistler 6-series pressure transducer was installed in cylinder -1 and connected to a charge amplifier, which converts the electrical charge produced by the piezoelectric sensors into a voltage signal. This voltage signal is then captured by the OSIRIS and displayed as the in-cylinder pressure signal. In the common rail fuel system, pressure is measured using an Engine Control Unit (ECU) high-pressure piezo-resistive sensor. The pressure sensor is affixed to the high-pressure fuel line of cylinder -1 using a specialized mounting clamp. Its placement is strategically chosen to be in close proximity to the fuel injector, allowing for the detection of drops in fuel line pressure, which in turn indicate the onset of fuel injection. A charge amplifier is employed to convert the electrical charge generated by the rail pressure sensor into a voltage signal.

3.2 Instrumentation- Injector Current Probe Sensor

The sensor is affixed to the electrical connection of the piezo injector in Cylinder -1 to record the commencement of the injection pulse, the pulse's duration, and the quantity of injection events transpiring per cycle. The current probe captures the waveform of the current signal traveling to the injector. The illustrated piezo injector signal sample is shown in Figure 2. In the context of a piezo injector signal sample, various terms describe different aspects of the signal's behavior. Rising time refers to the duration it takes for the voltage signal to reach its maximum value once applied to the piezoelectric crystals, indicating the time it takes for the injector to open fully. Peak time marks the moment when the voltage signal reaches its highest point, indicating maximum injector opening. Charging time refers to the period during which the voltage is applied to the piezo crystals, causing them to deform and the injector to open. Hold time represents the duration for which the voltage signal is maintained at its peak level to ensure proper fuel delivery. Injection duration encompasses the entire period during which fuel is actively injected into the combustion chamber, from the start of charging until the end of hold time. Charge and discharge phases refer to the process of applying voltage to the piezo crystals (charge) and allowing them to return to their original state (discharge) after fuel injection. Discharging time denotes the duration for the piezo crystals to return to their initial shape, closing the injector and completing the fuel injection cycle. These parameters collectively characterize the timing and behavior of the piezo injector signal sample, crucial for precise control of fuel delivery in diesel engines.

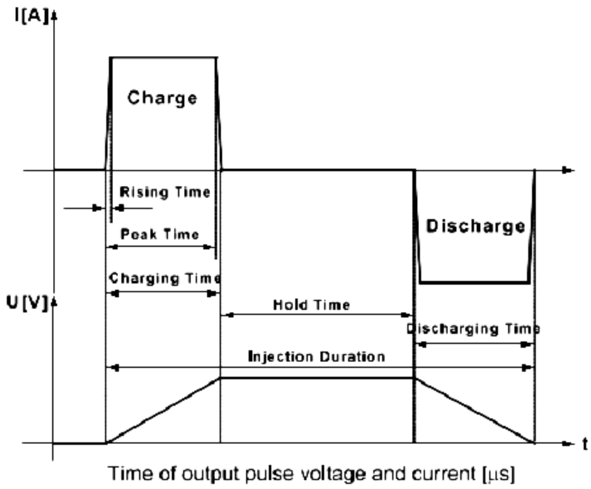


Figure 3 Current and voltage waveform which drives the piezo injector

3.3 Temperature measurements

The temperatures at various engine positions were monitored and recorded during engine operation to comprehend the temperature distribution during transient and steady-state conditions. K-type thermocouples were employed to monitor temperatures at the following locations:

1. Coolant water (in/out) temperature
2. Compressor inlet air temperature
3. Ambient temperature
4. Intake manifold temperature
5. Exhaust manifold temperature

6. Exhaust pot temperatures

The engine, installed in the cold room, is coupled with a parasitic load unit (PLU). This PLU, an electromagnetic retarder controlled by an electric current command, is mounted alongside the engine on a large metallic structure known as a skid, as illustrated in Figure 1. The PLU facilitates the assessment of cold start performance in the cold room through two distinct types of tests:

1. Torque Profile
2. Speed Profile

The torque profile test employs a user-input torque curve to load the engine during cranking, simulating a precise engine start in a vehicle. A fixed load applied functions as a parasitic load relative to speed, aiming to determine the time required to attain idle speed under specified cold ambient conditions. In contrast, the speed ramp test does not apply a fixed parasitic load but instead seeks to identify the maximum parasitic load at which the engine can still accelerate at each speed. With user-defined speed and ramp duration inputs, the PLU loads the engine while controlling speed according to the speed ramp command. This test evaluates the engine's torque generation capability at various engine speeds under specified cold ambient conditions.

To ascertain the optimal injection strategy under cold ambient conditions, a broad-level single-factor design of the experiments (DOE) was conducted at a -5°C ambient temperature using 15W-40 oil. Low ambient temperatures result in reduced peak compression temperatures, impeding fuel vaporization and leading to inadequate fuel-air mixing. To mitigate combustion noise factors and promote ignition, all experiments utilized intake grid heat to elevate combustion air temperature. Table 2 outlines the single-factor DOE encompassing various injection strategies, evaluated alongside both running speed and torque profiles at -5°C ambient temperature. Diesel engine cold start conditions present the most challenging scenario for autoignition and combustion processes due to low rotating speeds during cranking, resulting in unreliable startup and significant variation between startups. To minimize the impact of test conditions on experimental data, the engine is cold-soaked for 10 hours between cold starts to maintain consistent boundary conditions. Each iteration, as referenced in Table 2, involves collecting data from three repeated cold startups, with three replications under each cold start strategy and a 10-hour engine soak time between startups. Figure 4 illustrates the test sequence followed for evaluating injection strategies.

"2-inject" and "3-inject" refer to fuel injection strategies in diesel engines, involving multiple injections per combustion cycle to enhance performance, emissions, and fuel efficiency. In the 2-inject strategy, two injections occur per cycle: one during compression or early power stroke and another later, supplying most fuel for power generation. The 3-inject strategy adds a third injection, usually during expansion or early exhaust stroke, to reduce emissions further. Both strategies are common in modern diesel engines, offering precise control over combustion timing and emissions, ultimately improving performance and fuel efficiency (Zhang et al., 2022).

Table 2 Design of Experiment Injection Strategy Evaluation

Study	Iterations	Comments
Baseline	Pre-Main (2-Inject)	
Study A	Pre-Main (2-Inject)	Reduced start fuel
Study B	Pre-Pilot- Main (3-Inject)	
Study C	Pre-Pilot- Main (3-Inject)	Main timing advance 5° CA
Study D	Pre-Main (2-Inject)	Holding rail pressure flat 40 mpa
Study E	2-Inject increase separation	
Study F	Pre-Pilot-Main (3-Inject)	Increase separation PI2-PI3
Study G	Pre-Pilot-Main (3-Inject)	Increase separation PI3-M

Figure 4 Test Sequence

4. Results and Discussions

At -5°C ambient temperature, various injection strategies outlined in Table 2 are investigated to enhance cold start combustion performance and reduce white smoke emissions. The examination includes pre-main injections and two pilot injections preceding the main injection, with all engine cold startup iterations extending from engine crank initiation until reaching idle speed (800 rpm). This approach is adopted to assess the time required to achieve idle speed and the duration for white smoke elimination at -5°C ambient temperature.

Figure 5 illustrates the speed versus time profile for the baseline cold start injection strategy (pilot followed by main). The initial combustion event occurs approximately 3.5 seconds after engine cranking commences. However, subsequent to the initial ignition, a phase of intermittent combustion is apparent, characterized by alternating ignition and misfires. This phenomenon arises from the engine's limited starting capability in cold conditions. To address this intermittent combustion phase (occurring between 9 to 28 seconds), high-speed in-cylinder data analysis was conducted, focusing on cylinder pressure, heat release, injector nozzle lift, and parameters associated with ignition delay.

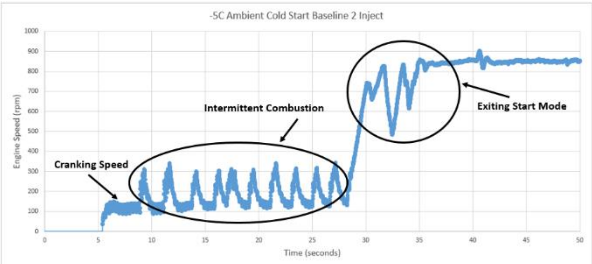


Figure 5 Intermittent Combustion at -5C Ambient Temperature

Figure 6 represents the concatenated data of an instantaneous engine speed compared at a -5°C ambient temperature. Engine speed traces are recorded using an optical shaft encoder from cylinder -1. The red curve represents the baseline startup with a two-injection strategy (pre-main). It is observed that the starter is engaged for a longer crank time compared with the blue curve with the three-inject strategy. The cranking period depends on a combination of physical and chemical parameters such as fuel droplets, fuel vapor concentration, gas temperature. Red curve with baseline had two injection fuel strategy injecting larger amount of fuel thus increasing temperature drop in combustion chamber were as three injection strategy in blue had two small pilot of fuel injection required small amount of heat for the liquid droplets to vaporize due to small fuel mass injected. The difference in starter engagement times could stem from variations in starting conditions, fuel delivery, engine health, or other factors affecting the ignition process. Identifying the specific reason would require further investigation into the vehicle's systems and operating conditions.

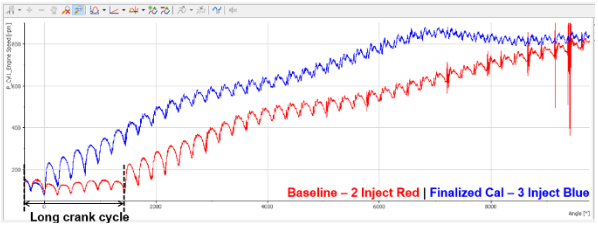


Figure 6 Engine Startup Compare Ambient Temperature -5°C

Following the initial combustion cycle, the engine exhibited a pattern of firing and misfiring, as illustrated in Figure 7. During a misfire cycle, the instantaneous engine speed decreases, with the speed after the expansion stroke being lower than that before the compression stroke it is revealed in first plot of Fig 7 for first 9000 crank angle. It is also evident in the second plot in Figure 7 for the same crank angle causing unstable combustion leading rise in the in-cylinder pressure causing significant misfire. We can Conversely, in a fired cycle, the speed increases during the expansion stroke. When the engine misfires for one cycle, this operation is termed as an eight-stroke cycle operation, while if it misfires for two consecutive cycles after a firing cycle, it is referred to as a 12-stroke cycle operation (Omanovic et al., 2021). With complete combustion it is evident speed traces at high speed is lot more stable with no pressure rise rate in-cylinder.

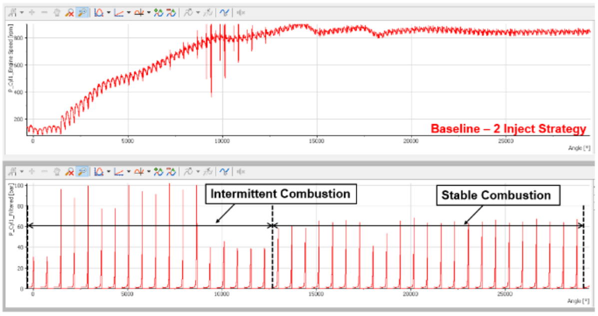


Figure 7 Baseline Engine Startup -5°C Ambient Temperature – Two- Inject Strategy

Figure 8 depicts the engine startup at -5°C ambient temperature, showcasing enhanced engine startup performance with the introduction of the three-injection strategy.

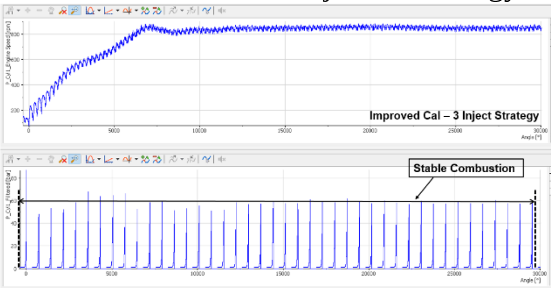


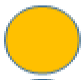
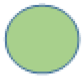
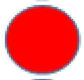
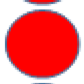
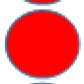
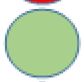
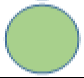
Figure 8 Engine Startup -5ºC Ambient Temperature - Three- Inject Strategy

The first plot of instantaneous engine speed illustrates a notably brief crank time and a more thorough combustion cycle. The second plot of in-cylinder pressure traces depicts a steady pressure as the engine ascends to idle speed. This consistent cylinder pressure signifies stable combustion and improved repeatable startup performance.

Table 3 showcases various injection strategies examined through the speed ramp and torque profile tests. These assessments aimed to evaluate engine startup performance by assessing engine torque capability, time taken to reach idle speed, and white smoke emission. Based on the findings presented in Figures 7, 8 and Table 3, the introduction of a pilot injection, promoting cool flame reactions to create an activated environment for main injection, significantly enhances cold start performance. Notably, the speed ramp test did not observe significant differences in torque generation capability at various rotational speeds, as depicted in Figure 9. Mean torque in each case is shown with the horizontal line.

The torque profile test, illustrated in Figure 10, was employed to assess the time required to reach idle speed during engine cold start-up at -5°C ambient temperature with various multiple injection strategies. The plotted data in Figure 10 represents the average of three cold startups. It is evident that configurations with two pilots exhibit superior and more consistent starting performance compared to the original fuel injection strategy at -5°C ambient temperature. Furthermore, further enhancements in cold start performance are observed with the incorporation of three injections (Pilot-Pilot-Main). This test highlights that the optimal performance is achieved with the three-injection strategy. The increased number of pilot injections potentially facilitates thermal stratification within the combustion chamber of each cylinder, leading to higher homogeneity in thermal conditions among all cylinders. This observation aligns with prior research reported by the authors (Hwang et al., 2017; MacMillan et al., 2009; Park et al., 2019), reaffirmed in this study under cold cranking conditions and during the transition to idle speed. However, cold idle performance may still be suboptimal at low loads and reduced temperatures.

Table 3 Result Injection Strategy Evaluation

Study	Iterations	Comments	30 sec Speed ramp	Torque profile
Baseline	Pre-Main (2-Inject)			
Study A	Pre-Main (2-Inject)	Reduced start fuel		
Study B	Pre-Pilot- Main (3-Inject)			
Study C	Pre-Pilot- Main (3-Inject)	Main timing advance 5º CA		
Study D	Pre-Main (2-Inject)	Holding rail pressure flat 40 MPa		
Study E	2-Inject increase separation			
Study F	Pre-Pilot-Main (3-Inject)	Increase separation PI2-PI3		
Study G	Pre-Pilot-Main (3-Inject)	Increase separation PI3-M		

Neutral	Worse	Improvement

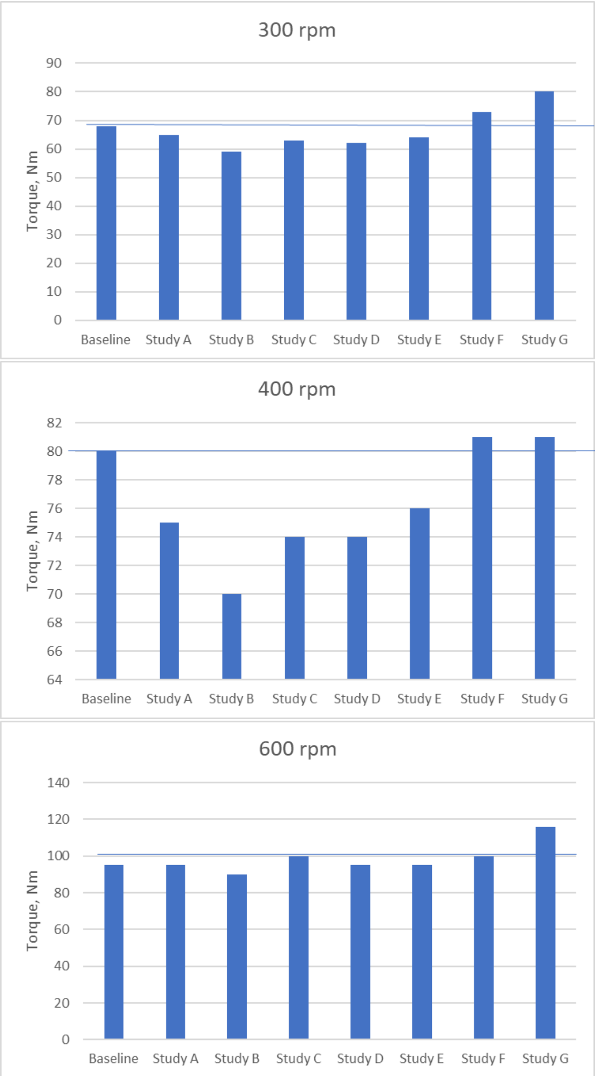


Figure 9 Torque Generation at -5°C Ambient Various Injection Strategy

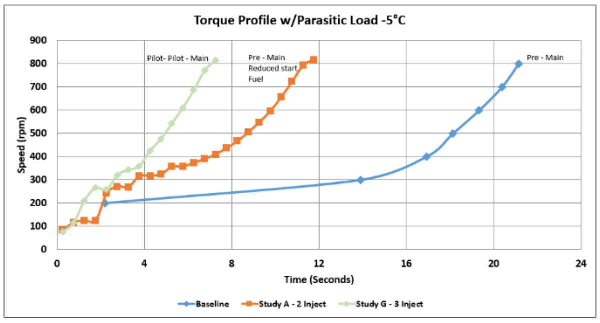


Figure 10 Time to Idle Optimize Injection Strategy

Starting at lower ambient temperatures necessitates longer cranking periods and results in increased production of liquid and gaseous hydrocarbons, commonly known as white smoke. The duration of the cranking period is influenced by a combination of physical and chemical parameters, which fluctuate throughout the cranking cycle. Physical parameters contribute to the formation of a stoichiometric or slightly rich mixture of fuel vapor and air, with fuel vapor concentration dependent on factors such as fuel volatility, gas temperature, pressure, rate of heat transfer to the liquid, and evaporation time. On the other hand, chemical parameters impact the rate of autoignition reactions, particularly sensitive to mixture temperature, charge energy (fuel cetane number), and fuel-vapor concentration. Diesel atomization is hindered by low diesel temperature, resulting in increased diesel viscosity and surface tension that inhibit diesel vaporization. The rise in mixture temperature during cranking is attributed to reduced heat transfer from hot gas to the walls and reduced blow-by during compression and expansion, consequently reducing the ignition delay period at higher cranking speeds. Following a misfiring cycle, the engine decelerates for one or more cycles, allowing additional time at top dead center (TDC) for combustion reactions to proceed and facilitate firing.

5. Conclusions and Recommendations

In this study, an extensive examination of multiple injection strategies was carried out on a four-stroke diesel spray combustion engine to identify an optimal injection strategy that enhances the cold start capability of diesel engines. This investigation utilized a high-pressure common rail injection system and a constant-volume combustion chamber. To comprehend the primary factors influencing cold startup performance, a combination of advanced tools was employed to observe and explain various phenomena under such conditions. Engine cold startup performance was evaluated through speed ramp and torque profile tests, monitored via in-cylinder high-speed data. A single-factor study was conducted with various injection strategies to assess engine cold startup performance. Engines and fuel were soaked in cold rooms to simulate boundary conditions at -5°C ambient temperature. The following conclusions were drawn:

1. The addition of a pilot injection improved diesel engine cold startup performance by eliminating misfires and reducing the time required to clear white smoke. The three-inject strategy (comprising two pilots and one main injection, referred to as Pilot-Pilot-Main) emerged as the most effective configuration.
2. Cold Starting performance was improved with implementing three injection strategy with time to reach to an idle taking 7.5 seconds as compared to baseline with 21 seconds (Refer Fig 10)
3. Significant improvement in the white smoke was revealed using three injection strategy with time to clearing white smoke was 1 second.
4. Pilot injections required a minimal amount of heat for the vaporization of liquid droplets due to their small fuel masses. Consequently, the temperature drop in the constant-volume combustion chamber was diminished. The low energy dissipation of pilot injections also facilitated ignition. The slight heat release from pilot injections before the subsequent main injection aided in the vaporization of the main injection, thereby enhancing combustion stability and reducing white smoke.
5. The three-injection strategy, with optimized injection timing and separation between the injections, demonstrated superior performance in terms of reaching idle speed within a consistent cold startup at -5°C ambient temperature, with reduced white smoke. Analysis of the heat release rate and in-cylinder pressure rise indicated stable combustion performance. Therefore, the three-injection strategy was confirmed as optimal at -5°C ambient temperature with optimized injection timing and separation between the pilot3 and main injections.
6. The three-injection strategy exhibited superior cold startup performance at -5°C ambient temperature. Further optimization of the injection strategy is necessary at colder ambient conditions, such as -10°C and below, to enhance cold startup performance and prevent misfires. Additionally, to understand the gaseous emissions emitted during engine startup, it is recommended to analyze exhaust samples using a portable emission analyzer.

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