

# Combustion Visualization of Partially Premixed and Non Premixed Diesel Fuel on Single Cylinder Optical Engine

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## Abstract

Ignition and flame propagation phenomenon of diesel fuel combustion was investigated in an optical single cylinder engine. Conventional non-premixed diesel combustion and partially premixed combustion types were investigated. Experiments were performed on an optical single cylinder, heavy duty, four-stroke compression ignition engine with a quartz elongated piston bowl and 45° mirror was used for visualization as a measurement technique. Self-ignition, flame propagation, heat rejection and effects on number of pilot injections on combustion visualization are investigated. In conventional diesel with closed and far pilot and partially premixed charge compression ignition (PCCI) tests were performed.

**Keywords:** Combustion, PCCI, Optic engine, Flame propagation, Single cylinder

## 1. INTRODUCTION

Diesel engines are the main stream in the heavy duty applications today and this will continue to be a main stream on the future applications considering high thermal efficiency of compression ignition combustion. Current and possible future emission regulations of commercial heavy duty vehicles are mainly focused on NO<sub>x</sub> and soot emissions which become more restricted with latest EU6 regulations and future emission regulations will even be more restrictor. Although having after-treatment systems, capable to reduce the NO<sub>x</sub> emissions up to 99%, thanks to modern SCR technology, and soot emissions up to % 99 with diesel particulate filters, helps to deal with the regulations, due to component cost, package and the demand of urea dosing to convert NO<sub>x</sub> emissions exhaust aftertreatment system cost significantly increased in the recent years and become comparable to even base engine cost. In addition, high fuel prices and environmental effects, efficient engines are required to survive for the industry considering the threat of electrification. It is critical to understand the combustion behavior of conventional diesel combustion and alternative ways both to design efficient engines and correlation activities of 3D combustion simulations.

In diesel engines, due to the characteristics of the non-premixed region, combustion takes place both on the fuel rich, low temperature zone which causes soot emissions; and

the diffusion controlled zone producing NO<sub>x</sub> emissions as shown in Figure 1. In this study both conventional non-premixed and partially premixed charged diesel combustion (PCCI) visualizations are investigated in terms of flame propagation and heat rejection.[1]

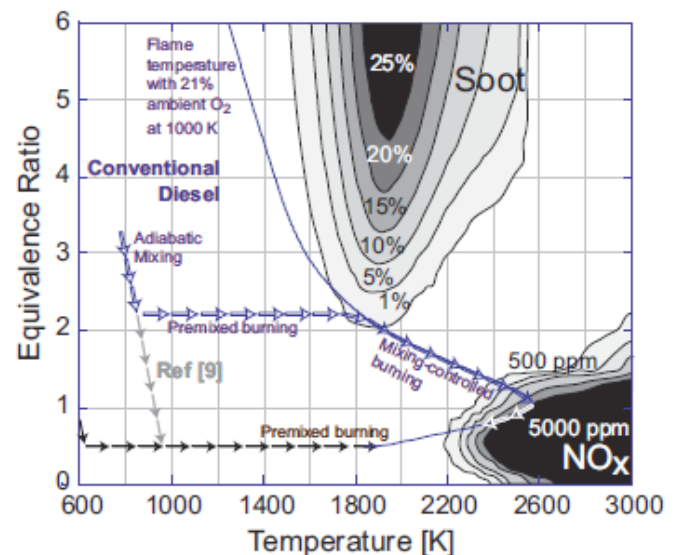


Figure 1: Depiction of conventional and two variants of low temperature combustion on the ER-T plane.[2]

Optical single cylinder engines are key devices to visualize the combustion process of different combustion modes, injection properties, air to fuel mixing quality, spatial distri-

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bution of NO<sub>x</sub>, soot emissions, ignition delay and knocking properties. [3][4] The engine is mentioned in this study is an modified single engine. Additional parts as elongated piston and window cassettes are integrated to the engine.

In this study, section 2 describes the of optical single operating and measurement techniques. In section 3, conventional and alternative combustion paths of diesel combustion visualization are results shown and discussed about the findings.

## 2. EXPERIMENT

### 2.1 Optical Diesel Engine

Optical single cylinder engine used in study is designed and manufactured by Ford Otosan. It is a four-valve, four stroke diesel engine, based on Ecotorq 13lt Heavy Duty Commercial Engine. Engine head, liner and injection system are carried over from this engine. During measurements, engine is driven by dynamometer and fuel is injected on the motored engine. All auxiliary systems such as fuel, cooling and lubrication except valve train are driven by external systems. The specifications of optical engine data are described in Table 1 below.

**Table 1** Specification of the engine

Models	Size (mm)
Bore x stroke [mm]	130 x 160
Connecting rod [mm]	310
Compression ratio	13:1
Squish [mm]	1.2
Displacement [lt]	2.1
Swirl ratio	1.2
Number of valves	4
Intake valve closing	140 degCA BTDC

Upper side of the engine has window cassette system that has an access to visualize swirl and tumble measurement via PIV system. At the middle section of the engine an elongated piston is positioned. Combustion chamber part of the piston is made of quartz glass. Figure 2 shows the section view and full visualization of the engine. Light emitted from combustion chamber is exited through the quartz piston and reaches the mirror which is positioned on the middle of the elongated piston. Light reflected through the 45° mirror is received by a high speed camera. Visible area of the combustion chamber is limited with the quartz piston area within the radius of 92 mm shown in Figure 3.

Compression ratio of the engine is 13:1 which is lower than thermodynamic engine. It is due to maximum cylinder pressure of the engine is limitation of 110 bar. This limit is related with the quartz glass durability.

Moreover, combustion heat causes thermal gradient for quartz piston resulting another limiting factor. For this reason, engine is running only for 12 cycles in order to protect the engine from the excessive heat. Transparent piston bowl shape is a bit different from the thermodynamic engine in order to avoid optical distortions. In order to eliminate the

optical distortions, a curvature shape is designed for the bottom piston surface. Therefore, distorted image in the curvature top curvature is compensated on the bottom surface. . In many applications, very smooth/simplified or flat surfaced piston bowl shapes are used in the experiments. [5] In this study, a curved bottom surface is used to reduce the optic distortions and thermodynamic engine similar piston is used in order to replicate the combustion behavior as much as possible.

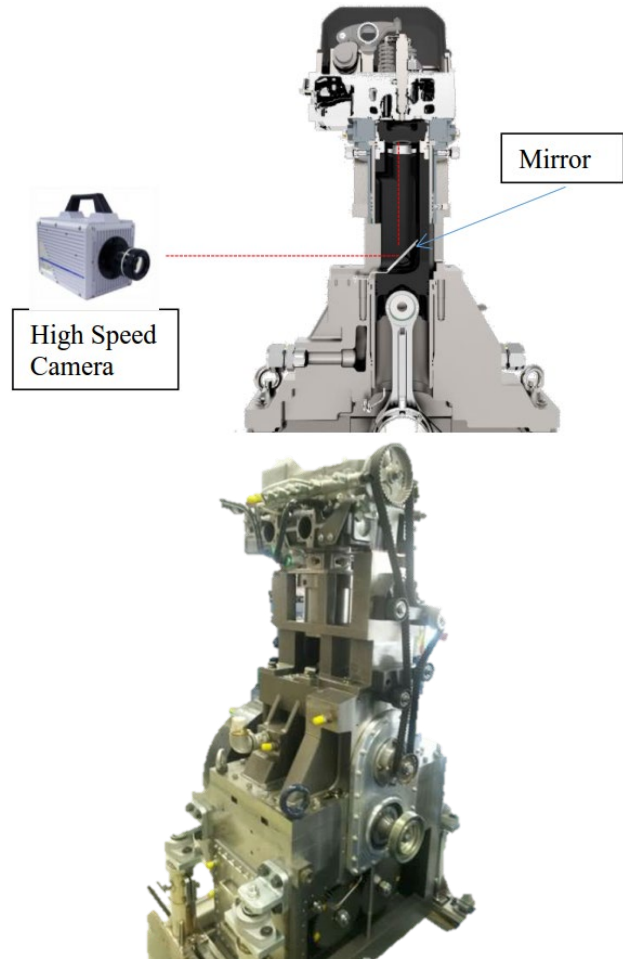


Figure 2: Optical single cylinder engine

In addition, many optic engine operations, skip-fire technique is used to decrease the thermal load and heating up the glass elements in the engine. Skip-fire technique, fuel injected for a couple cycle and then fule-cuts of in order to cool down the surface periodically. On the other hand, transient behavior of this technique can change the residual gas fraction of the engine. In this work, continuous firing is used to simulate steady state regime and number of total fired cycles is limited.[6]

Fuel injection system is carried out from the commercial heavy duty engine. Fuel pump is driven by an electrical pump externally with a maximum rail pressure capability of 2500 bar. Common-rail systems with solenoid actuated injectors are used in the measurements. Injector fuel flow rate is 850cc/30sec@100bar. A 8 nozzles injector with a 0.180 mm nozzle diameter and 150° spray angle injector is used.

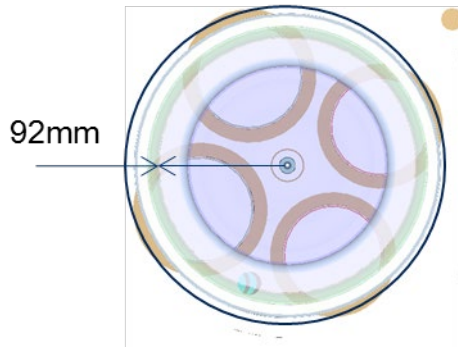


Figure 3: Piston bowl and visible are of the combustion chamber

## 2.2 High Speed Camera Measurements

Combustion images are recorded by high speed camera system. Most of the applications, lasers are used to as a light source for visualization. In this work, combustion itself is used as a light source. A high speed RGB camera (Photron SA5) with a frame rate of 40.000 fps is used to obtain images with a 320 x 256 resolution. System is equipped with a 70 mm focal length of f4.0 lens. A parallel signal line from the fuel injector current is used for triggering high speed image capturing.

## 2.3 Engine Operation & Measurement Systems

For indicating data acquisition, an AVL Indicom in cylinder pressure measurement system with non-cooled piezoelectric pressure sensor is used. In cylinder pressure data is recorded simultaneously and pressure values are averaged of the combustion cycles of 12 cycles. Pressure data is recorded with 0.5 crank angle sampling rate.

During the measurements, engine is conditioned approximately 3-4 hours before starting the engine. Engine coolant and oil temperatures are set to 80°C. Then, engine is motored to reach the intake manifold pressure set point. It takes about ~60 secs to reach the flow regime. Boost temperature is controlled via both heat exchangers and electrical heater. In the heating period in advance of motoring, engine is positioned to the valve overlap to make an air flow circulation passing from intake valve to the engine and then exits form exhaust ports to heat-up the combustion chamber of the engine, ports and intake surge tanks.

Boost pressure is controlled via controlled pneumatic valve which connected to the compressed air line.

Operating conditions, effective compression ratio of the engine are summarized at Table 2.

Table 2 Operating Parameters

Models	Intake Manifold Pressure	In cylinder Pressure @TDC
Pressure [bar] abs.	1.6	30
Temperature [°C]	90	

An automatic operation algorithm is used in the measurements. Dynamometer control system (AVL Puma) is responsible for the all the operations of the single stage measurements. In the first step, after starting the engine dyno controller stabilizes the engine at given speed set point. Then, boost pressure starts to increase up to pre-set value. Once the in-cylinder TDC pressure of the motoring engine reaches the target value, fuel injection starts. At this stage, simultaneously high speed camera starts to capture the images. After 12 cycles, fuel injection cuts off and engine costs down.

## 3. RESULTS

### 3.1 Non premixed Combustion with Diesel Fuel

In this section, non-premixed compression ignited diesel fuel visualization results are discussed. In-cylinder pressure, injection signals are measured, heat release rate is calculated. A pilot injection is used to illuminate and heat up the combustion chamber to able to see the main injection of the spray initiation and flame-lift-off length. Operating conditions are shown in Figure 3 below.

Table 3 Engine Operation on Diesel Cycle

Models	Intake Manifold Pressure
Engine Speed [rpm]	1100
Injected Fuel [mg/stroke]	30
Pilot injection ratio [%]	50
Rail pressure [bar]	800

At this operation point, a pilot injection is performed at 11 deg crank angle (CA) before top dead center (BTDC) and a main injection is started at 2 deg. CA after top dead center (ATDC) in Figure 4. In the measurement, pilot injection starts to ignite at 7 deg. CA BTDC and main injection starts to ignite 6 deg. CA ATDC.

Figure 5 shows the whole combustion imaging of the engine cycle. Duration between pilot and main injection is very low that main injection occurs before the pilot injection combustion. As a result, main injection spray pattern and flame-lift-off length cannot be seen. In the pilot injection combustion, flame starts to propagate near the injection center and simultaneously occurs in the same manner for all injected nozzles. Swirl effect on the combustion can also be observed that, flame also propagates on the swirl center up to 45° on the clockwise direction.

In the second phase, in order to visualize the spray pattern of the main injection, two piloted injection strategy is performed. In this strategy, first pilot is injected at 10degCA BTDC, a second pilot is injected at 3 degCA BTDC and a far main injection is performed at 11 degCA ATDC. As it is seen in the Figure 6, first ignition initiates at 7 degCA

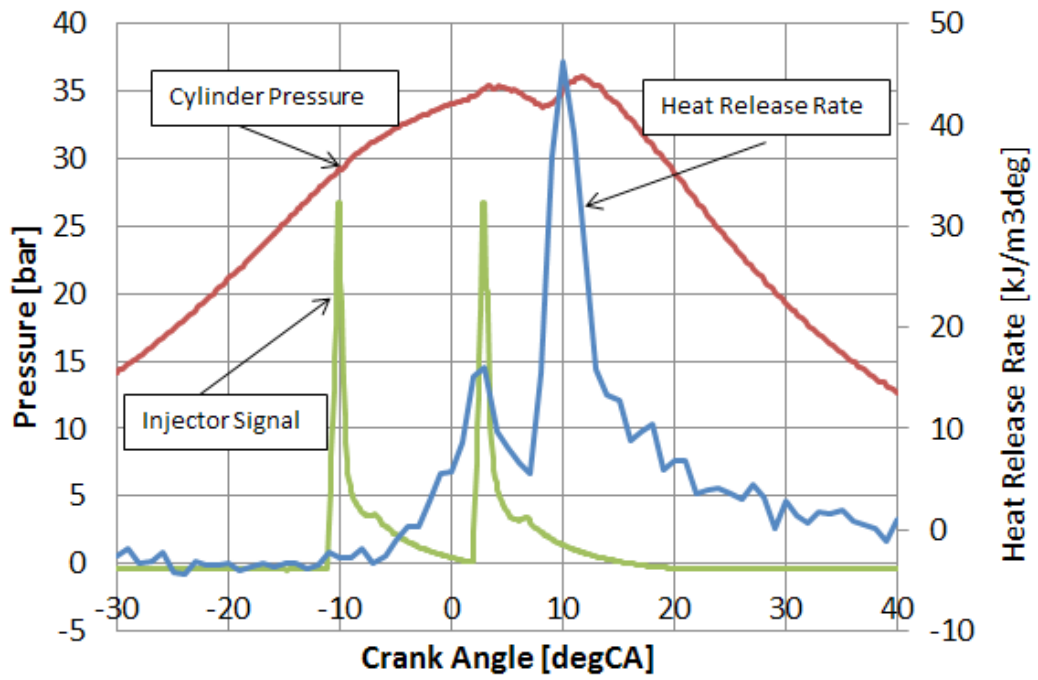


Figure 4: Measured in cylinder pressure, heat release rate and injection signal

Crank Angle		Crank Angle	
5 degCA ATDC		9.5degCA ATDC	 40000 fps 1/40000 sec 320 x 256 Random Manual 800 ... frame : 1850 +3.750 ms(3)
6.5 degCA ATDC	 40000 fps 1/40000 sec 320 x 256 Random Manual 800 ... frame : 1830 +3.250 ms(3)	12.5degCA ATDC	 40000 fps 1/40000 sec 320 x 256 Random Manual 800 ... frame : 1870 +4.250 ms(3)
8 degCA ATDC	 40000 fps 1/40000 sec 320 x 256 Random Manual 800 ... frame : 1840 +3.500 ms(3)	15.5degCA ATDC	 40000 fps 1/40000 sec 320 x 256 Random Manual 800 ... frame : 1890 +4.750 ms(3)

Figure 5: Flame propagation of the combustion chamber

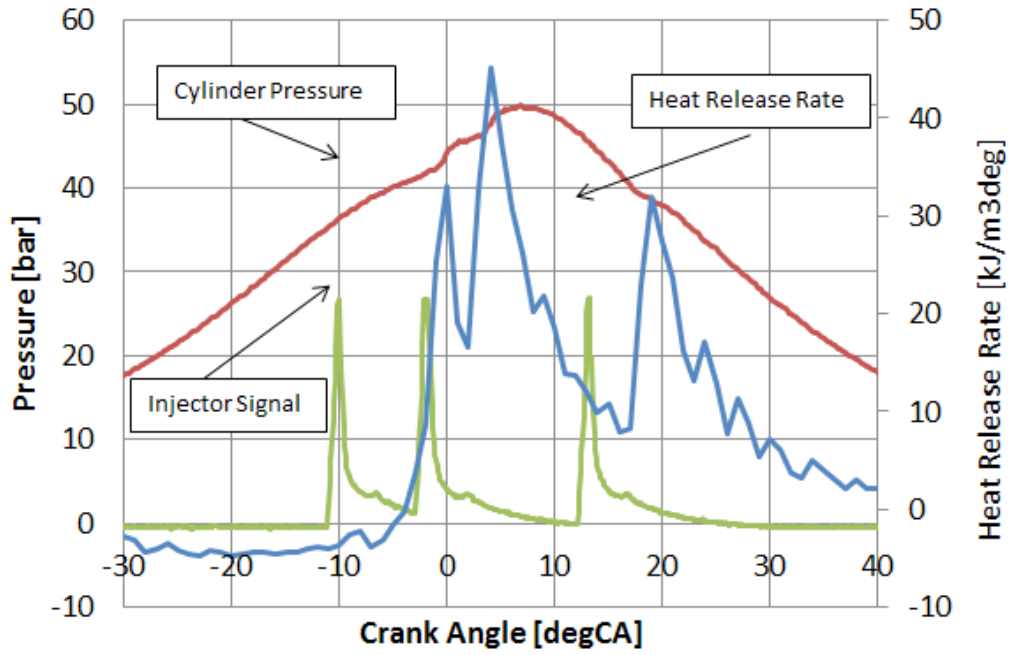


Figure 6: Measured in cylinder pressure, heat release rate and injection signal







Crank Angle		Crank Angle	
1.1 degCA ATDC		19.1degCA ATDC	
5.0 degCA ATDC		23.0degCA ATDC	
15.3 degCA ATDC	<p>40000 fps 1/40000 sec 320 x 256 Random Manual 800 ... frame : 3489 +4.725 ms(5)</p> 	29 degCA ATDC	

Figure 7: Flame propagation of the combustion chamber

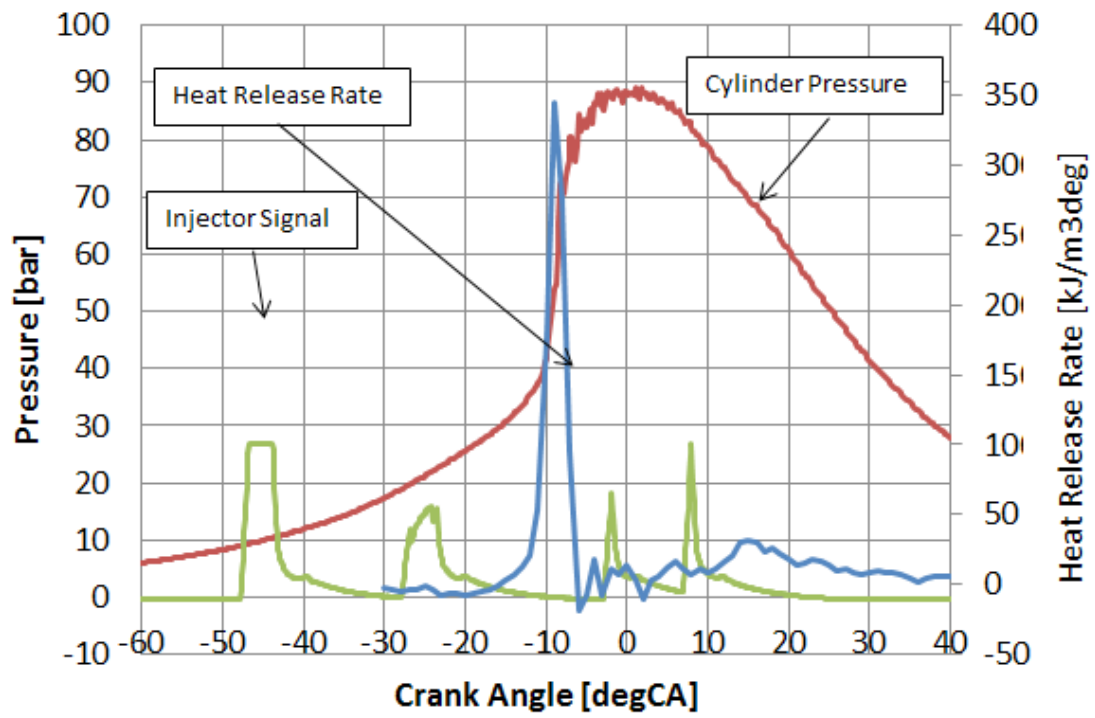


Figure 8: Measured in cylinder pressure, heat release rate and injection signal

Crank Angle		Crank Angle	
10.4 degCA bTDC		8.0degCA bTDC	
9.5 degCA bTDC	<p>40000 fps 1/40000 sec 320 x 256 Random Manual 800 ... frame : 3570 +6.750 ms(5)</p>	6.8degCA bTDC	
8.7 degCA bTDC		2.0 degCA bTDC	

Figure 9: Flame propagation of the combustion chamber

BTDC. Second pilot injection contributes to combustion at 5 degCA ATD and main injection starts to ignite at 17deg ATDC. Operating conditions are shown in Table 4 below.

**Table 4** Engine Operation on Diesel Cycle

Models	Intake Manifold Pressure
Engine Speed [rpm]	1100
Injected Fuel [mg/stroke]	45
Pilot1 injection ratio [%]	33
Pilot2 injection ratio [%]	33
Rail pressure [bar]	800

In two piloted injection strategy, spray penetration length and the flame lift-off length can easily be seen. It is important for further correlation study of the combustion and spray simulations. As it is seen in the Figure 7, ignition starts around the fuel injector due to the closed pilot injections. Moreover, at 1.3 deg. CA main injector spray profile is observed. In addition, at 29 deg. CA, a small flame occurs near the fuel injector on the injector closing event. It is due to low fuel spray velocity and combustion takes place near the injector region.

### 3.2 Partially Premixed Combustion Diesel Fuel

Partially premixed combustion is an alternative way to reduce the NO<sub>x</sub> and soot emissions of the conventional diesel combustion event.[7] The idea of the partially premixed combustion is to inject the fuel far from the ignition limits that on the low temperature and pressure conditions of the cycle. As a result, fuel is preliminary mixed with air and starts to combust both assisted with main diesel injection near top dead center region or self-ignite over infinite regions near TDC. Premixed injection promotes the mixing which contributes the low soot regions to avoid local fuel rich regions. In this strategy, combustion is free from the local fuel rich regions. Therefore, temperature increase is limited resulting low NO<sub>x</sub> production.

Partially premixed combustion can be initiated by using very early injection timing. In this work, a pilot injection is performed at 48 deg. CA BTDC and a second pilot at 28 deg. CA BTDC. Operating conditions are shown in Table 5 below.

**Table 5** Engine Operation on Diesel Cycle

Models	Intake Manifold Pressure
Engine Speed [rpm]	1100
Injected Fuel [mg/stroke]	45
Pilot1 injection ratio [%]	40
Pilot2 injection ratio [%]	30
Main injection ratio [%]	15
Post injection ratio [%]	25
Rail pressure [bar]	800

Pressure rise rate is so steep for premixed combustion shown in Figure 8.

Moreover, in order to protect the engine, two post injections are used to combust the mixture in case of misfire conditions. Premixed combustion starts near liner region at ~10

deg. CA BTDC. Flame is not propagated like conventional diesel and suddenly ignites uniformly all over chamber. It is also observed that, the two post injections combusts near the injector zone. Light intensity is lower and flame is more uniform than the conventional diesel combustion. Combustion visualization results are shown in Figure 9 below.

## 4. CONCLUSION

Combustion visualization of conventional non-premixed, diffusion controlled and partially premixed combustion is performed. Considering, closed coupled pilot injection investigation, main injection combustion starts near injector region and a smooth heat release curve can be obtained. In the far pilot injection strategy, flame propagation is not attached to the pilot flame. This brings a light source of visualization of spray penetration length and flame lift-off length. Ignition delay of combustion, similar spray pattern preparation and flame propagation homogeneity the conventional diesel combustion is important to have good mixing properties of fuel and air. This can increase air utilization of the engine and thermal efficiency.

Secondly, in partially premixed combustion case, combustion occurs immediately and more homogenous on the combustion chamber and very rapid heat release rate production is observed. This can bring a low NO<sub>x</sub> and soot strategy due to homogenous combustion. It will be an alternative way to have better efficiency low emission engine operations.

## 5. ACKNOWLEDGEMENTS

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