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Performance of a CI Engine Operating in Highly Premixed Late Injection and Low Temperature Combustion Mode to Achieve Cleaner Emission – A CFD Analysis

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ABSTRACT

A comprehensive study on a single-cylinder four-stroke cycle Diesel engine that runs in HPLI and LTC modes to achieve a cleaner emission than existing normal diesel combustion has been carried out in this CFD analysis. The impact of HPLI and LTC mode on the engine's performance is also examined. Low Inlet Temperature and varying percentages of cooled EGR technology with Injection Timing Retardation were employed to accomplish HPLI and LTC mode. The program utilized for this investigation was ANSYS FORTE 19.2, which was developed by ANSYS. CHEMKIN, a very efficient and comprehensive pre-defined industry-standard chemical kinetics software, is included with this package. At 323K, 353K, 383K, and 413K, this analysis was carried out at various amounts of EGR ranging from 0% to 60%. The results reveal that as the EGR temperature rises, the heat release rate and ignition delay decrease. With an increase in EGR percentage from 0% to 60%, EINOx was lowered from 77.3 g/kg fuel to 1.99 g/kg fuel burned at 323K temperature. EINOx increased from 10.3 g/kgfuel to 14.7 g/kgfuel for 40% EGR with the increase in EGR Temperature. CO increased from 41.8 g/kgfuel to 385 g/kgfuel for 30% EGR with an increase in EGR Temperature. However, when considering UHC and CO emissions, it has been discovered that the percentage of EGR should not be increased further than 50% to reduce NOx emissions. That will also increase CO and UHC emissions. With a high proportion of EGR (40%) and a low temperature, the results were better.

Keywords: EGR, Forte, ITR, LTC, Emission

1. Introduction

Internal combustion engines have been playing a key role in human development since the past century and a half. Along with the advantages, engines have several disadvantages, including higher fuel costs and more pollution. As a result, scientists began working on more efficient combustion technologies that may deliver exceptional fuel efficiency while simultaneously decreasing pollution. As worries about fuel economy and pollution develop, the internal combustion engine industry has been looking for better alternatives to spark ignition (SI) and compression ignition (CI) engines. The homogeneous charge compression ignition (HCCI) engine is one of the possibilities that has been under intense study in recent years. [1]. Low NOx and soot emissions can result in good engine efficiency. A uniform mixture of air and fuel is compressed until it reaches auto-ignition temperature and auto-ignition occurs at the end of the compression stroke, followed by a combustion phenomenon that is substantially faster than CI or SI combustion. [2]. The advantages and disadvantages of a Homogenous Charge Compression Ignition (HCCI) engine with diesel fuel were examined by Gray and Ryan [3]. In comparison to standard diesel ignition at the half load zone, this study found that HCCI with early injection might reduce NOx emissions by 98 percent. The issues of premixed lean diesel combustion were investigated by Akagawa, Miyamoto, Harada, Sasaki, Shimazaki, Hashizume, and Tsujimura [4]. They claimed that the HCCI's HC and CO discharge levels are unusually high, and that fuel economy suffers in the early injection HCCI mode.

Late injection has two key advantages. For starters, they are simple to install on standard diesel engines. The injection and combustion processes are not totally decoupled, for example. Injection timing can be used to control them. The Modulated Kinetics (MK) combustion system was developed by Nissan Motor Corporation [5,6]. Kimura created a low-temperature, premixed charge combustion method that produces ultra- clean emissions [7]. M.M. Hasan, M.M. Rahman, and K. Kadirgam [8] released a review paper which offers a new definition of combustion with considerable efficiency gains. Because the start of ignition is not controlled directly and the heat release is not regulated, the operating range for HCCI combustion is limited in terms of speed and load.

Environmental degradation, stringent emission legislation, depletion of petroleum reserves, fuel supply security, and global warming have all driven study and development of engines that use alternative combustion principles and can run on renewable fuels. Low Temperature Combustion (LTC) is cutting-edge internal combustion (IC) engine combustion idea that has received a lot of importance in recent years. The diffuse combustion principles of traditional spark ignition (SI) and compression ignition (CI) are radically different from LTC. LTC technology has significant advantages in terms of decreasing NOx and particulate matter (PM) emissions, as well as specific fuel consumption. The two challenges that must be resolved before LTC technology can be commercially used in car engines are ignition time control and heat release rate (HRR). In the LTC, the temperatures range from 1200 to 1400 K, and the

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equivalence ratio is lower than conventional combustion in diesel engine [9]. Advanced fuel injection timing, or a premixed charge, and a postponed start of combustion (SoC), caused by charge dilution, give superior air-fuel time to be mixed before SoC. [10]. It lessens the need for a high equivalency ratio, which reduces the in-cylinder combustion temperatures necessary for soot and NOx formation. The LTC engines can be divided into homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), as well as reactivity-controlled compression ignition (RCCI) engines according on the fuel reactivity, injection time, and charge conditioning (i.e., charge generation). [11]. By mixing preheated fuel with intake air or by infusing fuel early in a compression stroke, the homogenous charge can be produced. The homogenous charge exhibits a high-pressure rise rate (PRR) with lack of direct control over SoC, and simultaneously auto-ignites at many places [12]. A PCCI was suggested by Ayoma et al. [13] to give a combination of the beginning of fuel injection and Start of Combustion in order to lessen the quick PRR. To achieve PCCI combustion, a variety of approaches are used, including fuel injection at higher pressure, premixing some fuel by vaporizing in the intake manifold, using heavy EGR, and a decrease in engine CR [11,14]. The difficulty of delaying the SoC with the intake air management system persists at high load as the equivalency ratio increases [15].

One of the forms of HCCI technology is Highly Premixed Late Injection. In HPLI mode, a lean fuel mixture is injected into the engine cylinder with a high swirl ratio of recirculated exhaust gas. The fuel injection timing is slowed, resulting in a longer combustion time. The fuel is usually injected after TDC (Top Dead Center). As a result, the air-fuel mixture becomes more homogeneous, and combustion becomes cleaner. The air- fuel equivalence ratios available with HPLI combustion are diverse. This technology employs a significant amount of EGR. The thermal efficiency of this engine is better than that of a regular diesel engine. One of the most important parameters in managing diesel combustion is injection timing. When fuel is injected into a diesel engine cylinder that is already filled with compressed air, combustion happens. The fuel surpasses its auto-ignition temperature and combustion happens when it comes into contact with high-temperature, high pressure air. It takes some time for the fuel to ignite when it is injected into the engine cylinder. However, the fuel injection timing is delayed in the ITR approach. The injection time was set to 3-degree aTDC for this simulation. Exhaust gas recirculation (EGR) allows for significant NOx emission reductions in a variety of diesel engines, such as light- duty engines, heavy-duty engines, as well as low-speed two-stroke marine engines. The EGR reduces NOx emissions by trying to lower the oxygen levels in the combustion chamber and accumulating heat. Hybrid systems, high- and low-pressure cycle EGR, and other topologies have been suggested. EGR is often used in gasoline engines to improve efficiency and lessen pumping work. EGR helps to reduce nitrogen oxide (NOx) emissions in exhaust gas. Nitrogen oxides are created in engine cylinders during the combustion process. This is accomplished by returning some of the engine's exhaust gases to the combustion chambers. This study focuses on investigating the consequences of using diesel with 30-60% of EGR at different temperatures with retardation of the injection timing and their effect on different emission parameters.

2. Computational Methodology

To simulate the operation of the HPLI and LTC Engine in steady state, ANSYS Forte is combined with the incredibly effective sophisticated chemistry solver module CHEMKIN. The complete Reynolds-averaged Navier- Stokes (RANS) equations can be solved using this software. For compressible, gas-phase flows, mass, momentum, and energy conservation laws are stated as model transport equations, which capture the turbulent aspect of the flow. The flow field is described using the k-model developed by the Re-Normalization Group (RNG).

In order to generate mesh, a sector with a 72-degree angle has been used as the computational domain (Fig.1). At the periodic faces of the sector in this instance, periodic boundary conditions have been implemented. The main benefit of employing sector mesh is that it speeds up calculation and lowers costs as compared to using the engine's entire geometry. Table 2 contains engine specifications. Thermodynamic features and chemical reaction processes of diesel are incorporated to the CFD code in order to accurately describe the combustion event of diesel. The detailed chemical kinetics of diesel includes 74 fundamental reactions and 35 gas phase species.

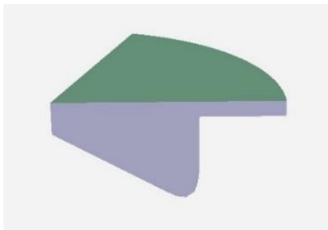

Fig.1 72˚ Sector Mesh

Table 1 Mesh Independency Results of various grid size

No. of Cells	P_{max} (MPa)	Thermal Efficiency	Computational Time
16200	14.60	41.82	44 min 20 sec
20340	14.66	41.70	59 min 49 sec
26910	14.65	41.55	1h 11 min 2sec
35700	14.72	41.74	1h 38min 45sec
49560	14.73	41.62	2h 10min 37sec

A numerical grid shown in Fig. 2 containing 35700 cells was adopted to model the combustion chamber sector geometry after accomplishing the grid-independent results.

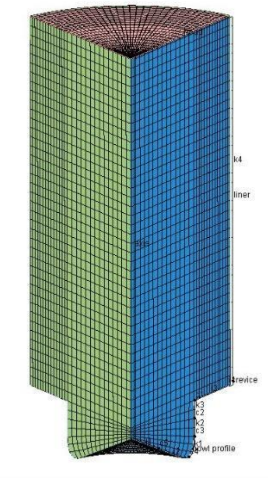

Fig. 2 Sector Mesh of 72˚ with 35700 cells

The percentage of EGR has been calculated using the following Eq. (1).

$$EGR\% = \frac{m_{EGR}}{m_a + m_f} \tag{1}$$

Here,

m_a = Mass of air
m_f = Mass of fuel
m_{EGR}= Mass of EGR

Table 2 Engine Specifications

Number of Cylinder	1
Bore	8.9 cm
Stroke	10.0 cm
Connecting Rod Length	20.0 cm
Compression Ratio	16.0
Engine Operating Speed	1500 rpm
Sector Angle	72 Degree
Squish	0.196 cm

2.1 Initial Condition

The initial condition of the composition of air- fuel and EGR mixture for 30-60% EGR are given in Fig.3. The temperatures at the intake were set to be 323K, 353K, 383K, 413K to attain Low Temperature Combustion. The swirl ratio was set to be 3.6 with high EGR percentage and the injection timing was set to be 3˚ aTDC to achieve HPLI mode of combustion.

2.2 Boundary Conditions

Piston, head, liner have been considered as the wall boundaries in Ansys Forte unlike many more complicated boundaries of Fluent. Table 3 indicates the properties in boundaries.

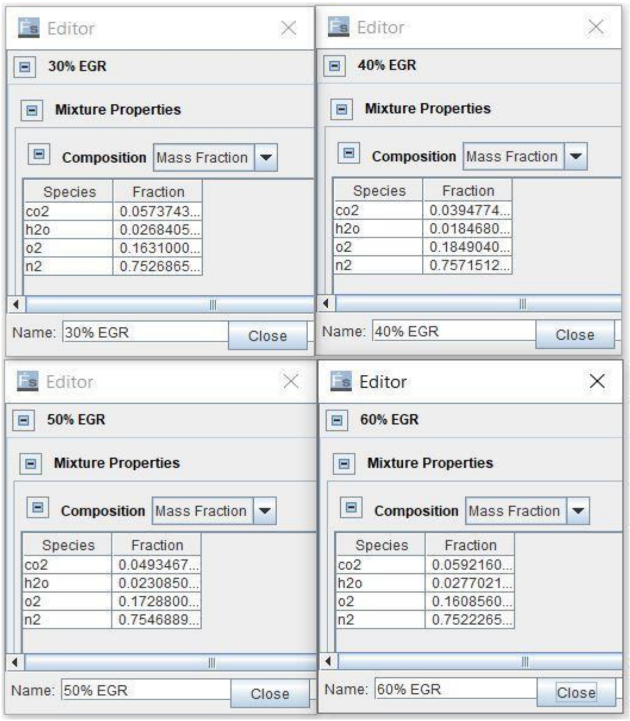

Fig.3 Mixture Composition for 30-60% EGR

Table 3 Boundary Conditions

Boundary	Wall model	Temperature (K)
Piston	Law of the wall	500
Head	Law of the wall	470
Liner	Law of the wall	420

3. Results & Discussion

3.1 Effect on in-cylinder pressure

The effect of the percentage of EGR on in-cylinder pressure and heat release rate are shown in Fig.4, Fig.5.

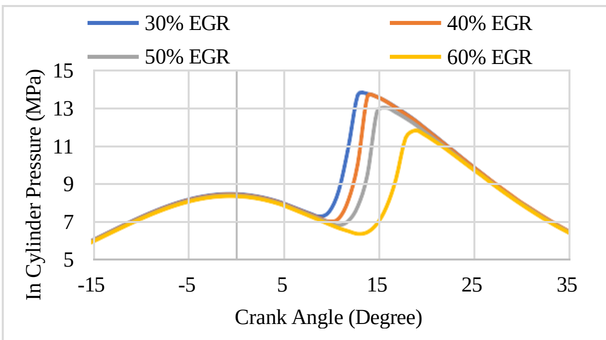

Fig.4 Effect of EGR percentage on In- Cylinder Pressure when T_{EGR} = 323K

From the Fig.4, it is seen that with the increase in EGR percentage, the pressure inside the cylinder decreases. This is because with the increase in EGR percentage less amount of fresh air enters the combustion chamber. Moreover, the ignition delay increases and the piston moves downward. As a result, the pressure rises declines. For temperature 323K, the maximum pressure is 13.6 MPa while the minimum pressure is 11.8 MPa.

3.2 Effect on Ignition Delay and Duration of Combustion

The effect of EGR percentage and temperature are shown in Fig.5, Fig.6.

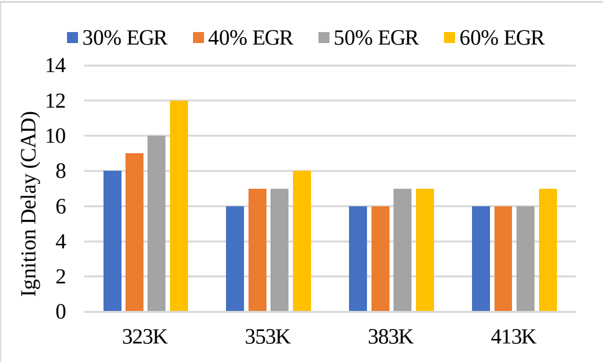

Fig.5 Effect of EGR percentage and EGR temperature on Ignition Delay

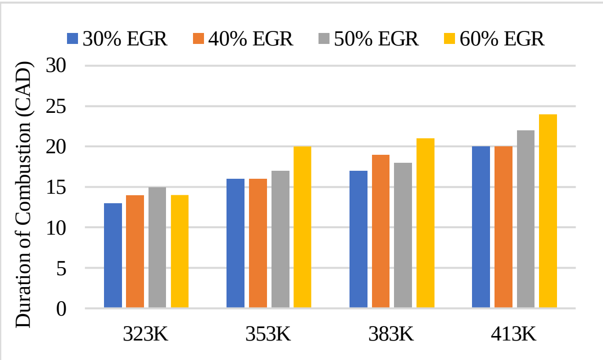

Fig.6 Effect of EGR percentage and EGR temperature on Duration of Combustion

After the fuel injection into the engine cylinder, it delays some time to get mixed with the inside high temperature and high-pressure air and to form a combustible air-fuel mixture. This delay is known as ignition delay. As the ignition delay increases, the air-fuel mixture becomes more homogenous and it results in better combustion. From Fig.5, it is observed that the ignition delay decreases with the temperature increases. This is because with the increase in EGR temperature the in-cylinder temperature increases Due to this, the air-fuel mixture reaches the auto-ignition temperature faster. So, the ignition delay decreases with the increase in EGR Temperature. With the increase in EGR percentage less amount of fresh air enters into combustion chamber. As a result, it takes more time for air-fuel mixing and hence Ignition Delay increases.

Duration of Combustion is the duration of 10-90 % Heat Release. This is generally measured in terms of Crank Angle Degree. From Fig.6, it is observed that the duration of combustion increases with the increase of both EGR percentage and temperature. As the cylinder temperature as well as pressure increase, the turbulence inside the cylinder increases. This increase in turbulence increases the homogeneity of the air-fuel mixture. So, the more homogenous mixture requires a slightly larger time to burn completely compared to the less homogenous mixture. That's why the duration of combustion increases with the increase in EGR percentage and temperature.

3.3 Effect on EINOx

The effects of EGR percentage and EGR Temperature on EINOx are shown in Fig. 5.

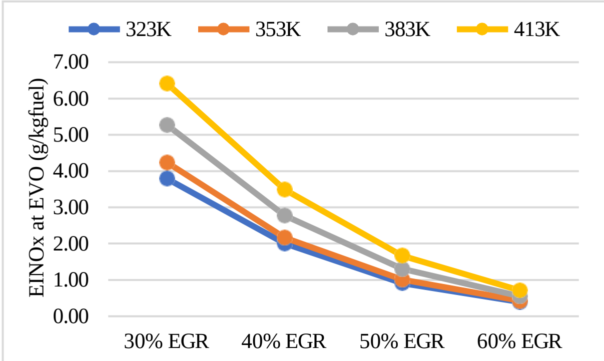

Fig.7 Effect of EGR Percentage and T_{EGR} on EINOx

Recirculating the exhaust gas in the engine cylinder is a justified method of NOx reduction in a diesel engine. EINOx stands for Emission Index of Nitrogen Oxides. From Fig.5, it is seen that, the Emission Index of nitrogen Oxides (EINOx) increases with the increase in temperature. This is because, as the EGR temperature increases and as a consequence, the intake temperature and the in-cylinder temperature increase. The Energy required for Nitrogen to form N-O chemical bonds, is supplied from the heat energy due to excess in-cylinder temperature and in-cylinder pressure. So, as the temperature increases, the amount of EINOx also increases. It can be said that it would be better if the engine is operated at a lower temperature. EGR percentage significantly affects NOx formation. Using 60% EGR produces 0.39-0.71-gram EINOx per kg of fuel burnt at 323K-413K temperature. Whereas, 30% EGR produces almost 3.79 grams to 6.42-gram EINOx per kg of fuel burnt. Since, ignition delay increased and the duration of combustion decreased, the combustion became faster and less amount of EINOx was produced. Though much EGR produces less NOx, it should not be used more than 50%. It produces less NOx, not due to its emission performance. Rather, for less amount of fresh air introduction into the combustion chamber. The best result showed 323K temperature with a high percentage of EGR (40%-50%).

3.4 Effect on CO Emission

The effect of EGR percentage an EGR temperature are shown in Fig.8.

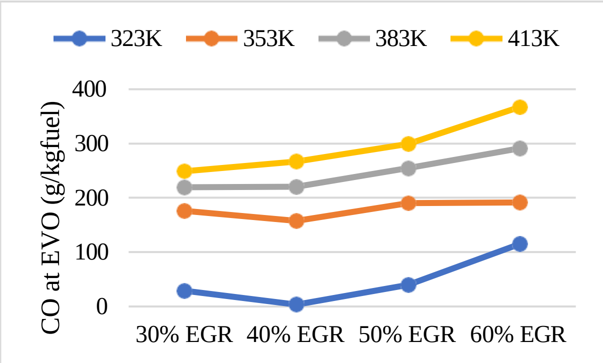

Fig.8 CO Emission when Exhaust Valve Open

From Fig.8, it is observed that the CO formation declines from 28.8g/kgfuel to 3.15 g/kgfuel for 30% to 40% EGR at 323K temperature. After that, CO formation increases a lot to 115 g/kgfuel. At lower temperature, this effect is more significant. As the temperature of EGR increases, the amount of CO formation increases. For 40% EGR it became 3.15g/kgfuel to 267g/kgfuel. CO is the outcome of the incomplete combustion of hydrocarbon. As the EGR temperature increases, more Nitrogen reacts with air or in other words, with oxygen. As a result, there remains less air for the fuel to combust properly. So, the amount of CO increases with the increase of temperature for a high percentage of EGR.

3.5 Effect on Soot Formation

Soot is the residue of fuel after combustion. The effect on Soot formation when the exhaust valve open is shown in Fig.9.

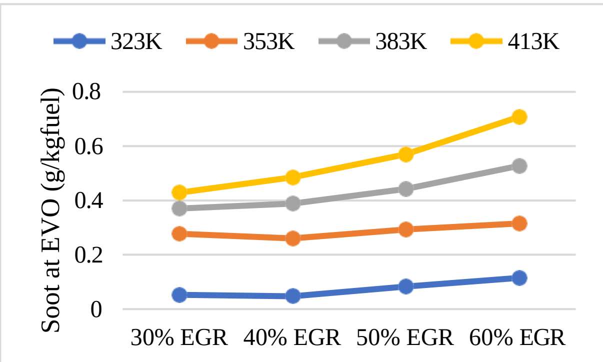

Fig.9 Soot formation at Exhaust Valve Open

Since, in a diesel engine, the air-fuel mixture entering the combustion chamber ignites spontaneously due to high pressure and temperature, soot forms. The air-fuel mixture creates some fuel dense pockets when ignited. And thus, soot formation occurs. Soot is the residue of fuel after combustion. The less the amount of soot, the cleaner the emission and the better the combustion is. The amount of soot increases with the increase of both the percentage of EGR and EGR Temperature.

3.6 Effect of Injection Timing Retardation (ITR)

Since this study has been executed with a retarded injection timing, it is necessary to observe its effect and determine whether it is useful or not. The effects of Injection Timing Retardation on EINOx and CO emission are shown in Fig.10., Fig.11 To study the effects, T_{EGR} = 323K was considered with 40% EGR.

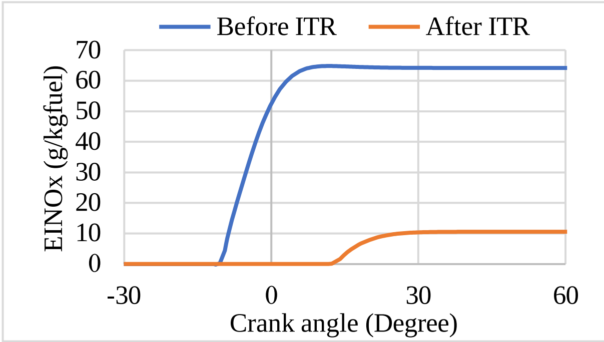

Fig.10 EINOx before and after ITR

The amount of NOx produced also reduces to a great extent due to ITR as shown in Fig.10. Before ITR the amount of EINOx was 64.2 g/kgfuel, whereas using ITR reduced that to 10.5 g/kgfuel.

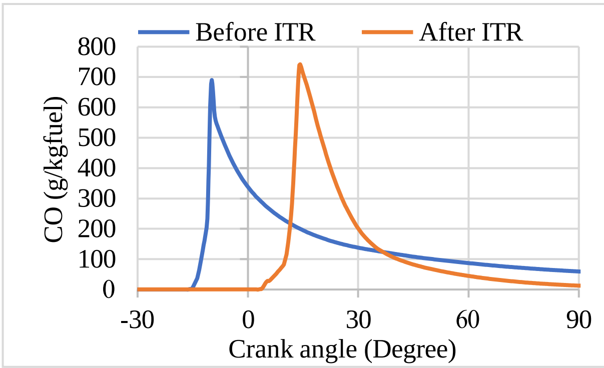

Fig.11 CO before and after ITR

Injection Timing Retardation lessens the emission of CO also. The amount of CO formation reduced from 59 g/kgfuel to 12.3 g/kgfuel after the injection timing was retarded.

4. Conclusion

The effects of EGR %, EGR temperature, and injection timing retardation on the in-cylinder pressure, ignition delay, duration of combustion, and emissions of EINOx, CO, and soot from a single cylinder diesel engine in HPLI and LTC mode are investigated numerically in this work. By mass, the EGR percentage ranges from 30% to 60%. The following succinct summary of the study's key findings:

i. EGR addition lowers in-cylinder pressure and in-cylinder temperature. This results in suppressing engine knock. Increasing EGR

Temperature also increases in-cylinder pressure.

ii. Ignition Delay is increased with the increase in EGR percentage but, decreased with the increase in temperature. The combustion duration increased with the temperature rise.

iii. The Amount of NOx formation tremendously decreased with the increase in EGR percentage. To compensate for CO and NOx emissions, it has been found that the most optimized operating conditions are 323K among the four EGR Temperatures with a high percentage of EGR (~40%).

iv. Controlling EGR percentage and temperature with Injection Timing Retardation, Low temperature Combustion (LTC) can be attained with the Highly Premixed Late Injection (HPLI) mode of operation.

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NOMENCLATURE

ATDC	After Top Dead Centre
BTDC	Before Top Dead Centre
SOI	Start of Injection
CFD	Computational Fluid Dynamics
EGR	Exhaust Gas Recirculation
CO	Carbon Monoxide
EVO	Exhaust Valve Opening
NO	Nitrogen Oxides
UHC	Unburnt Hydrocarbon
HPLI	Highly Premixed Late Injection
LTC	Low Temperature Combustion