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An Investigation Of Some Combustion Characteristics Of Turbocharged Diesel Engines With Exhaust Gas Recirculation

Eihab A Raouf [1, *] and Kamal Nasreldin Abdalla [2]

[1] Mechanical Engineering Department, Unaizah Engineering College, Qassim University, Unaizah, KSA.

[2] Mechanical Engineering Department, Faculty of Engineering, Khartoum University, Sudan.

Abstract

The objective of the present study is to investigate the effect of Exhaust Gas Recirculation (EGR) on ignition delay period, combustion start, and combustion duration in a diesel engine. Study results showed that the ignition delay period increased as the EGR ratio increased because fresh air became less available, resulting in a lower air/fuel ratio which in turn delayed the start of combustion. On the other hand, combustion duration also increased as the EGR ratio increased. Moreover, engine speed also affected combustion characteristics, the ignition delay period increased as the engine speed increased, increased EGR rate reduced fresh charge makes the combustion less efficient which in turn extended the combustion duration. For instance, during the range of engine speeds between 1000 and 4000rpm, the increase of ignition delay period varied from 1.7^o to 3.5^o Crank Angle (CA). The combustion start was delayed as the engine speed increased, at the 0% EGR setup, the combustion timing ranged between 4.9^o to 3.8^o CA before Top Dead Center (bTDC) during engine speed from 1000 to 4000rpm respectively. Finally, the combustion duration was increased as the engine speed increased, the duration increased from 36.6^o to 55.8^o during engine speed from 1000 to 4000rpm respectively.

Keywords: Exhaust Gas Recirculation, Turbocharged Diesel Engines, Combustion Characteristics.

1. Introduction

Exhaust gas recirculation (EGR) is an emission governor tool which is implemented to reduce major nitrogen oxides (NOx) emission from diesel and petrol engines. EGR works by returning part of the exhaust gas back to the engine intake system, thus reducing the oxygen in the inlet air stream to deliver some inert gases to the combustion process, dropping combustion temperatures and then decreasing the quantity of NOx released. NOx is formed in the combustion chamber at high temperatures and good availability of atmospheric nitrogen and oxygen. In modern diesel engines, the EGR gas is cooled with a heat exchanger to permit the introduction of a greater mass of recirculated gas [1]. The EGR valve is the chief device in the EGR system and usually is closed. It links the exhaust manifold to the intake manifold and is controlled by either a vacuum or an electric motor. The purpose of the EGR valve is to regulate the amount of exhaust gas being returned contingent on the engine speed and load (see Figure 1) [2].

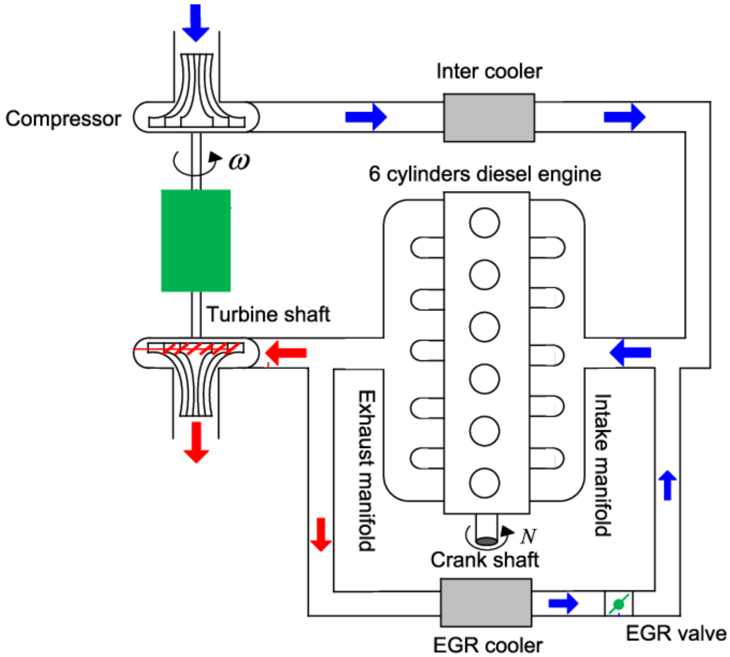

Figure 1. Turbocharged diesel engine with EGR [2]

The ignition delay (ID) in a diesel engine is known as the time lag between the start of fuel injection (SOI) to the start of the fuel combustion (SOC). Ignition delay period vary from one fuel to another. Engine ID data with diesel fuels of different Cetane numbers within the normal range of 40 and 55 show that it decreases with increasing Cetane number [3]. Compression temperature, injection pressure, air velocity, engine load, and engine speed affect the ignition delay. It was found that under ordinary operating conditions, compression pressure and temperature are the main factors, and other elements have only secondary effects. Minimum ID is achieved at normal operation conditions, in which the ignition timing occurs at 10 to 15° crank angle before top dead center (CA – bTDC). The quality of the ignition within practical limits do not have a major effect on ID, increasing the injection pressure yields small decrease in ID [4]. A strong dependence of ignition delay on charge temperature occur below 1000 K, above this value the effect of intake air, is not significant. Increasing in engine speed increases the air velocity and turbulence, reduces ID slightly in milliseconds; in terms of CA degree, ID increases almost linearly [5]. Residual gases decrease oxygen concentration, and hence increases ID. Physical and chemical properties of the diesel fuel is significant. ID of the fuel is well-defined by its Cetane number. An Empirical formula is proposed to computing the injection delay (τi), (see Equation 1-1) [6].

$$\tau_i = 10^{-2}\, B \left(\frac{T_{strat\ inj}}{P_{strat\ inj}}\right)^{0.5} e^{\frac{E_i}{RT_{strat\ inj}}} \qquad 1\text{-}1$$

where

B = Bo (1 - kn); Bo = 3.8×10-4; empirical coefficient, according to investigation results, achieved throughout tests of a diesel engine.

k = 1.6×10-4 multiplier, involved empirical coefficient k, that assesses effect engine speed (estimates effect turbulence of charge in the engine cylinder).

Pstart inj (MPa) and Tstart inj (K) are the pressure and temperature of cylinder charge at the moment of start fuel injection;

$\left(\frac{T_{strat\ inj}}{P_{strat\ inj}}\right)^{0.5}$ multiplier, estimates effect charge density (fresh air) in volume unity of combustion chamber (at the moment fuel injection);

$e^{\frac{E_i}{RT_{strat\ inj}}}$ multiplier (exponential function), that calculates rate pre-ignition reactions founded on chemical kinetics postulates.

Ei relative activation energy of pre-ignition reaction, Ei = (21….25) ×103 kJ/kmol;

R-universal gas constant, R = 8.312 kJ/kmol.K.

Cetane number (CN) is an inverse function of a fuel's ignition delay, in a diesel engine, a higher Cetane number has a shorter ID than lower Cetane number. Usually, diesel engines work fully with a CN from 40 to 55. Diesel with lesser Cetane number has extended ID, needing additional time for the combustion process to be finished. Therefore, a higher speed engine operates more efficiently with higher Cetane number fuels. Cetane number can be increased by additives such as organic peroxides, nitrates, nitrites, and various sulphur compounds. Typical diesel fuels have CN of 40 to 55 (high speed 50 – 60, low speed 25 – 45) [7].

Injection duration is known as the interval of time through which the fuel enters the combustion chamber from the injector. It is the difference between the start of injection (SOI) and end of injection (EOI) and is associated with injection amount, the injection period is controlled by the load and speed demand. It is known that if the injection period is increased far beyond certain limits some fuel may not get the time to burn which is uneconomical and creates some pollution problems. The injection timing is a very significant factor, to ensure good combustion, and it is affected by valve timing and ignition timing, considered as the main parameters that contribute to better engine performance [8].

Combustion duration (CD) is well-defined as the crank angle period between start of combustion (SOC) and end of combustion (EOC). CD (in milliseconds) drops as the engine speed (in rpm) rises due to the strong effect of charge flow turbulence. As the engine speed rises, the turbulence of the charge in the cylinder rises leading to improved heat transfer between the burned and unburned zones. In an engine working at lean or rich mixtures the CD is likely to increase, and is more largest at lower engine speeds. This is due to the less thermal energy liberated from the leaner mixture which rises the ID and slows the flame propagation. The temperature of the flame is less at lean and rich mixtures. Additionally, the incomplete combustion as a result of oxygen lack at rich mixtures also has an opposing result over the flame speed. The CD decreases as the compression ratio (CR) rises. This is due to the upsurge of the end of compression pressure and temperature and reduction in the fraction of residual gases. This produces a convenient condition for lessening the lag of ignition and rises the flame speed. Both CO and NOX emissions are lesser when the combustion duration is greater. This indicates that the settings of the least emissions are not the same as those for the best performance [9]. Further, the range of 4-6 milliseconds appearances favorable for all engine speeds regarding CO, is not the same situation at lower speeds for NO emissions. Also, CO and NO emissions are less when the CD is longer. This is because it permits much time for the combustion to complete, therefore the formation of CO is decreased. On the other hand, reducing the CD behind a specific limit decreases the formation of NO, due to the less time of exposure of combustion products to the cylinder's peak temperature. If the mixture is rich, the CD reduces, because of the rich mixture, the formation of CO and HC increase [10].

The injection system of the diesel engine poses an important role in the improvement of combustion. The most important element of the diesel engine is the fuel injection system, even a slight fault can cause a major loss of efficiency of the combustion and an increase in engine noise and emissions [11].

2. Objective

The objective of this research is to investigate the influence of exhaust gas recirculation (EGR) on the combustion parameters of a diesel engine such as duration of injection, ignition delay, the start of combustion and combustion duration, at different engine speeds and different EGR ratios.

3. Methodology

3.1 Diesel Engine Specifications

The Toyota 2KD-FTV is a 2.5 L four stroke cycle, four cylinders, water-cooled turbocharged diesel engine, manufactured by the Toyota Motor Corporation in 2001. The engine specifications are shown in Table 1 below:

Table 1: Engine Specifications [12]

Engine Code	2KD-FTV
No. of Cylinder & Arrangement	4-cylinder, In-line
Gas Exchange	Turbocharger
Number of Valves	16-valve (DOHC) - 4 per cylinder
Fuel System	Direct Injection 4-Stroke Common Rail Diesel Engine
injection timing	6.5^{o} - before TDC
Displacement	2,494 cm^3
Bore × Stroke	92 mm × 93.8 mm
Compression Ratio	18.5 : 1
Max Output	75 kW at 3400 rpm
Max Torque	200 N.m at 2400 rpm
Crankshaft center distance	46.9 mm
Connecting Rod Length	158.5 mm
Intake Valve	Open: 20^{o} CA – before TDC
	Close: 49^{o} CA – after BDC
Exhaust Valve	Open: 55^{o} CA – before BDC
	Close: 22^{o} – after TDC
Injector nozzle bore	0.16 mm
Number of nozzle per Injector	3
Ambient parameters	Pressure 1 bar, Temperature 313 K

3.2 Diesel Fuel Properties

Table 2. shows the Diesel fuel specification that are used in the simulation software package.

Table 2. Diesel Fuel Properties

Chemical composition of the fuel	$C_{15} H_{28}$
Composition mass fraction	C = 0.87, H = 0.126, and O = 0.004
Sulfur fraction in fuel	0.150 %
Fuel Calorific value	43.45 MJ/kg
Heat capacity	255.68 J/K. mole
Cetane number	56.5
Fuel density at 323 K	930 kg/m^3
Surface tension factor of fuel at 323 K	0.031 N/m

Dynamic viscosity coefficient of fuel at 323 K	0.035 pa. s
Specific vaporization heat	250 kJ/kg
Molecular mass of fuel	208

3.3 Research Approach

The experiments were conducted using the simulation program Diesel-RK. Diesel engine operating conditions are as follows: -

1- At different engine speeds (1000, 2000, 3000 and 4000 rpm).
2- At different EGR ratios (0%, 10%, 20% and 30%).

3.4 Simulation Software Validation

The use of computer-based tools such as simulation software (Diesel-RK) is to help in understanding internal combustion engine performance. Modeling and simulation are currently used for many applications in the Mechanical engineering fields. It succeeded in similar applications in industry, due to its cost, safety, and environmental advantages over operational testing. This reason raised the interest in the use and development of modeling and simulation in operational testing and evaluation [13]. To carry out the validation of the software, a comparison was conducted between the maximum design brake power of the engine at a specified speed to the brake power obtained by the software at the same speed. Referring to Table 1, the maximum design output power of the engine (2KD-FTV) is 75 kW at 3400 rpm, whereas the power obtained by the program at 3400 rpm was 73.4 kW (see Figure 2), thus the effectiveness validation ratio of the Diesel-RK software is almost 97.8%.

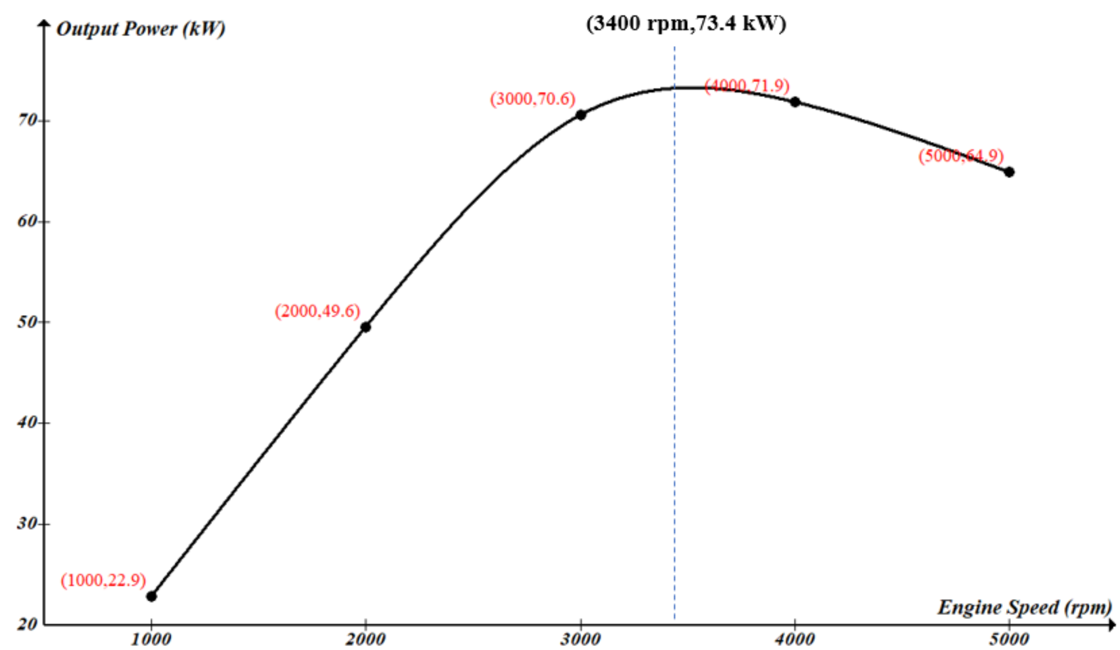

Figure 2. Brake power versus engine speed (2KD-FTV).

Another engine parameter (torque) is used to validate the effectiveness of the diesel-RK software, the maximum torque of the engine (2KD-FTV) is 200 Nm at 2400 rpm (see Table 2), whereas the torque obtained by the Diesel-

RK at 2400 rpm was 212 Nm (see Figure 3), 106% is the comparison ratio between the result of the software and the standard value.

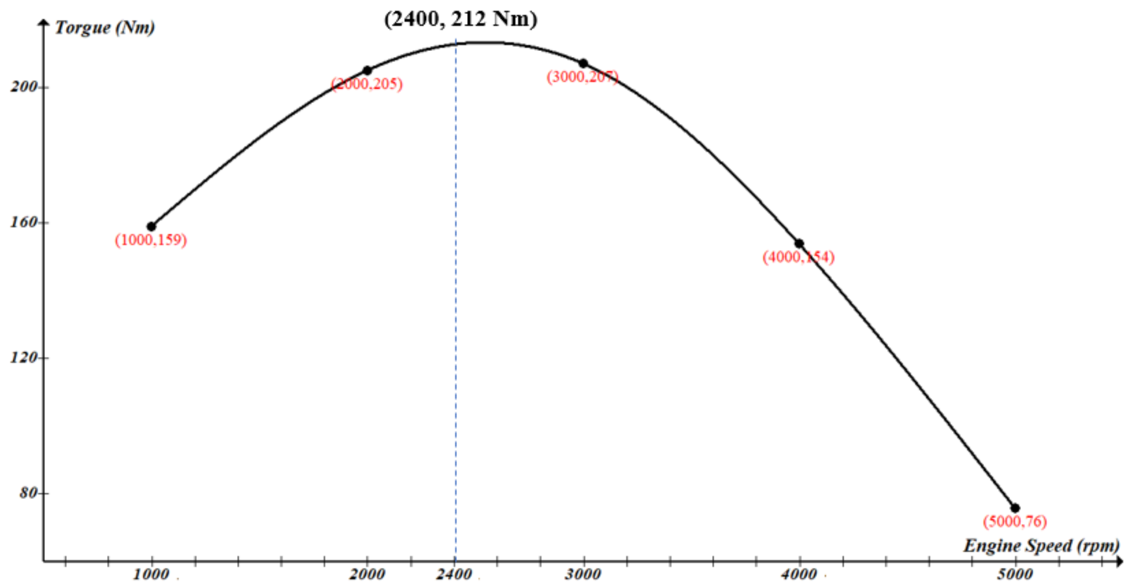

Figure 3. Torque versus engine speed (2KD-FTV)

The data listed in Table 3 were obtained from the Diesel – RK simulation software, after applying all the specifications of the engine (2KD-FTV), the Table shows the combustion characteristics in terms of injection duration, ignition delay, the start of combustion, and combustion duration versus engine speeds.

Table 3: Experimental Data

Engine Setup	Engine Speed (rpm)	Injection Duration (deg. CA)	Ignition Delay Period (deg.)	Start of Combustion (deg. bTDC)	Combustion Duration (deg.)	Brake Power (kW)
00% EGR	1000	30.0	1.4	4.9	36.0	22.9
	2000	30.3	2.1	4.3	38.2	49.6
	3000	29.1	2.3	4.1	40.8	70.6
	4000	27.9	2.6	3.8	44.2	75.0
10% EGR	1000	29.2	1.6	4.8	36.2	20.9
	2000	29.5	2.3	4.1	38.4	45.6
	3000	28.4	2.5	3.9	44.4	64.6
	4000	27.3	2.8	3.6	53.4	67.8
20% EGR	1000	28.3	1.7	4.7	37.4	18.8
	2000	28.7	2.6	3.8	43.6	41.1
	3000	27.6	2.9	3.5	50.4	57.7
	4000	26.5	3.5	2.9	57.6	59.4
30% EGR	1000	27.4	2.1	4.3	36.6	16.3
	2000	27.7	3.1	3.3	41.0	36.1
	3000	26.7	3.4	3.0	46.0	50.5
	4000	25.7	3.9	2.4	50.8	51.5

4. Results and Discussions

4.1 Ignition Delay Period (CA degree)

The time interval between the start of injection and the start of combustion is known as the ignition delay period, measured in terms of crankshaft angle degrees (deg.). The ignition delay period involves chemical and physical delays, both of which are present simultaneously. Increasing the Cetane number (CN) of the fuel reduces ignition delay and results in improved performance of the diesel engine. Other properties of fuel affect ignition delay period such as latent heat, surface tension, volatility, and viscosity. The increase in intake air temperature reduces the delay period, however, this is not desirable since it reduces the air density, which reduces volumetric efficiency and power output. A higher compression ratio lowers ignition lag, as the compression ratio increases, fuel particles are brought closer together, reducing the duration of combustion with the introduction of diesel fuel. When exhaust gas is mixed with fresh air in the intake manifold, it reduces air purity, which tends to increase ignition delay.

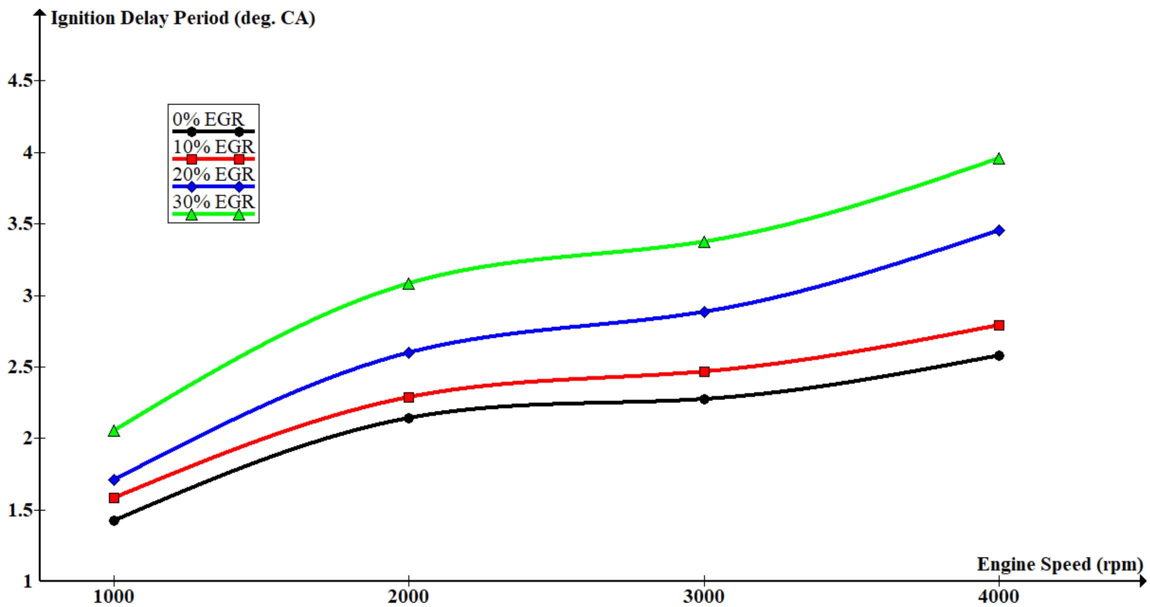

Figure 4. Ignition delay period versus engine speed.

Figure 4 illustrates the effect of the EGR system on ignition delay, When the EGR ratio is increased, the ignition delay period also increases, due to a reduction in fresh air. EGR system reduces the fresh air and supplies an inert gas instead of fresh air to the combustion chamber. For instance, when the engine running at 4000rpm utilizing an EGR ratio of 0%, 10%, 20%, and 30%, the ignition delay is found to be 2.6, 2.8, 3.5, and 3.9^{o} CA, respectively, as a result of EGR, the ignition delay duration is increased by 7.1%, 25.7%, and 33.3 % in comparison to the engine without EGR (0% ratio).

In Figure 4, the ignition delay period also increased with increasing engine speed until it reached its maximum value at 4000 rpm, after which it began to decrease, this phenomenon occurred across all engine setups (see Figure 4). For example, during setup 20% EGR ratio, the ignition delay periods at 1000, 2000, 3000, and 4000 rpm are equal to 1.7, 2.6, 2.9, and 3.5^{o} CA. As a result of this study, it can be concluded that the ignition delay increased with an increase in engine speed and an increase in the EGR ratio. The increase in ignition delay caused by EGR is due to a reduction of fresh air, which delays ignition. As the engine speed increased, the start of combustion was delayed due to insufficient amount of fresh air. When the engine speed increases, more ignition duration is required.

4.2 Start of Combustion (degree bTDC)

The elements that play a major role in the combustion process are the temperature of the intake air, fuel atomization, fuel spray penetration, the temperature of the fuel, as well as fuel properties. Furthermore, the compression ratio has an impact on the vaporization of the fuel, which in turn affects the mixing of the fuel with the air and the quality of combustion.

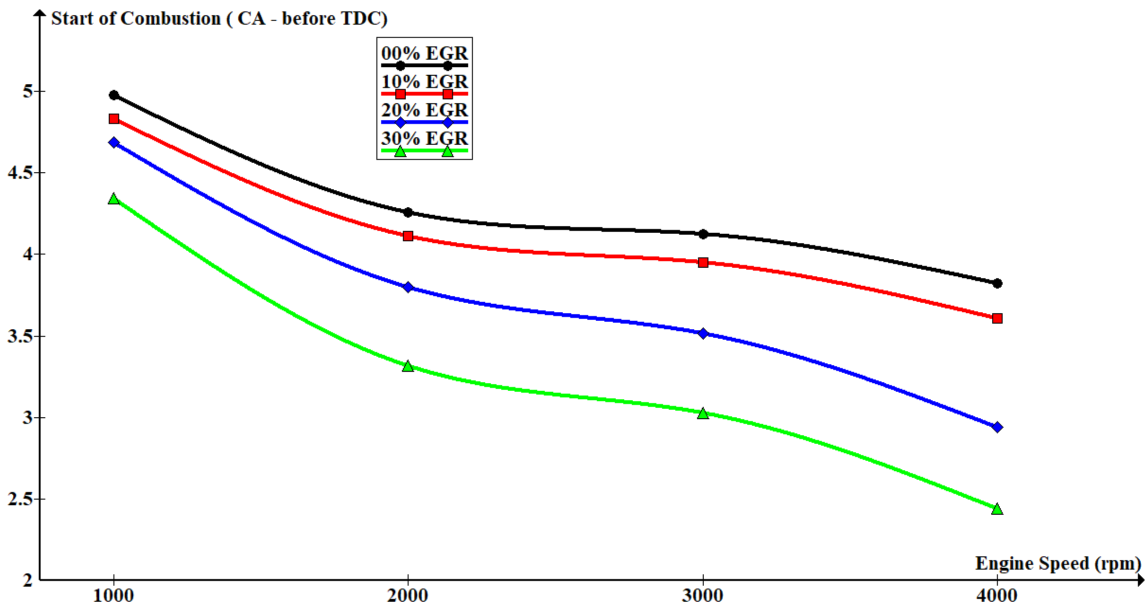

Figure 5: Start of combustion versus engine speed.

Figure 5 shows that at all engine setups were being investigated, with an increase in engine speed, the timing of combustion is delayed, measured in crank angle degrees. For instance, at 0% EGR and 1000rpm setup, combustion timing started at 4.9° CA before TDC, while the combustion timing at 2000, 3000, and 4000 rpm took place at 4.3°, 4.1°, and 3.8° CA bTDC respectively. As a percentage, combustion start was delayed at a rate of 12.2%, 16.3%, and 22.4% respectively compared to combustion start at 1000rpm. With increasing speed, the combustion starts delay increases.

Additionally, in the presence of the EGR, the combustion start delay increased as the EGR ratio increased. Figure 5 illustrates the variation of the combustion starting time as a function of different EGR ratios and engine speeds (a few crank angles degrees before top dead center). Diesel fuel is typically injected at high pressure and high velocity into the engine's injector tip via small holes or nozzles. Small droplets are formed and penetrate the combustion chamber. The atomized fuel absorbs heat from the compressed air. Rapid ignition of mixture occurs, which is considered the beginning of combustion. Diesel combustion is described by overall A/F ratio, when fresh air is mixed with recycled exhaust gas, this action leads to reducing the amount of charge, thereby lowering the air/fuel ratio (rich mixture), which in turn delayed the combustion starting time. For example, at setup 0% EGR and 3000rpm the combustion started at 4.1o CA bTDC, however, at the same engine speed and setups 10%, 20%, and 30% EGR ratios, the combustion started at 3.9°, 3.5°, and 3° CA bTDC respectively. The delay in the starting of the combustion increased with the increase in the EGR ratio.

4.3 Combustion Duration (CA deg.)

The combustion duration in an internal combustion engine is the period bounded by the engine crank angles known as the start of combustion (SOC) and end of combustion (EOC), respectively. The combustion duration is a measure of how long it took the fuel to be fully combusted. Figure 6 and results in Appendix A demonstrate that increased

EGR rates resulted in slow combustion. Thus, the ignition delay is increased, the combustion duration is prolonged, and the heat release rate is decreased. At all engine setups, the combustion duration increased as the engine speed increased. At operation condition of 20% of EGR, the combustion durations at 1000, 2000, 3000, and 4000 rpm were 36.6°, 41.0°, 47.0°, and 55.8° CA, respectively. The combustion duration of the engine is shorter when the engine is running at a lower speed, with increasing engine speed in rpm, combustion duration in milliseconds increased. Lower volumetric efficiency and more fuel flowing through high speeds lead to an extension in combustion duration.

In addition, as the EGR ratio increased, the combustion duration increased (see Figure 5). In the case of engine speed 3000 rpm and operating conditions 0%,10%,20%, 30% EGR, the combustion durations were 40.8°, 44.4°, 47.0°, and 50.4° CA respectively. The increase of the EGR quantity leads to two effects, the delay in start of combustion and an increase of combustion duration. Increased EGR rate reduced fresh charge and made the combustion less efficient which in turn extended the combustion duration.

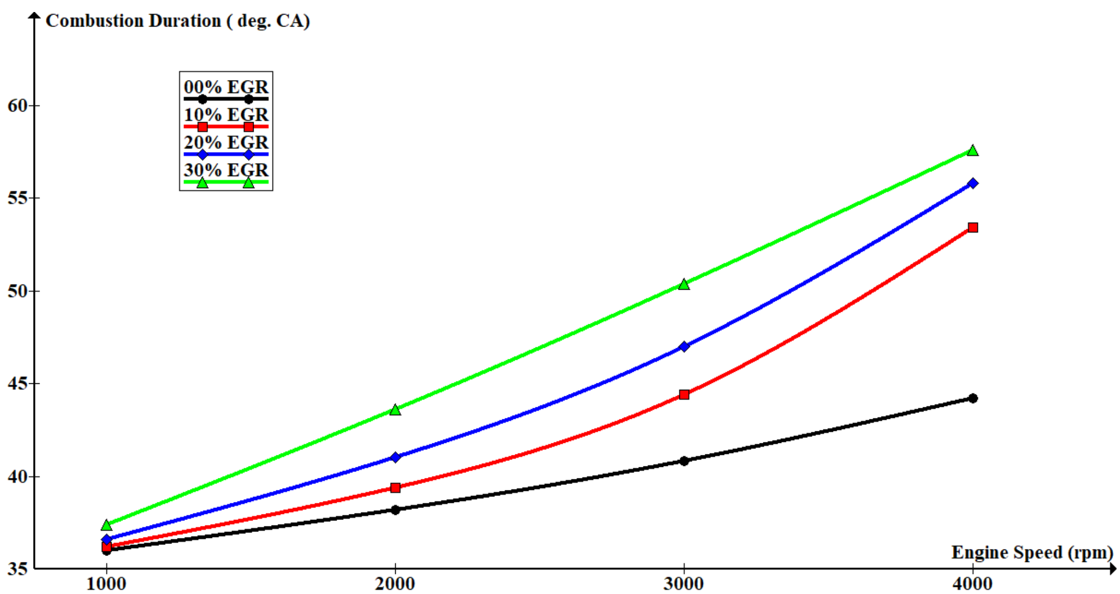

Figure 6. Combustion duration versus engine speed

5. Conclusion

Exhaust Gas Recirculation (EGR) is a method of reducing nitrogen oxide emissions (NOx), which is used on diesel and gasoline engines. Thermal efficiency and brake power decreases due to EGR technology. EGR systems also affect combustion characteristics such as ignition delay timing, start of combustion, and combustion duration. This study illustrates how EGR can influence combustion characteristics in general, and can be summarized as follow:

1- As both engine speed and EGR ratio increased, ignition delay duration increased. Ignition delay affects pressure and temperature inside the cylinder, which are both important to NOx formation, it also impacts engine efficiency. Ideally, an engine should have the shortest delay possible.

2- When engine speed and Exhaust Gas Recirculation ratio increase, combustion start becomes delayed. Too much gas will burn when the piston returns to BDC if the combustion timing is delayed. This will result in less work being produced.

3- Emissions and thermal efficiency are also affected by the length of burning time. The length of combustion duration increased with increasing engine speed and EGR ratio.

Nomenclatures:

aTDC	After Top Dead Center ° CA	EVC	Exhaust Valve Closing
A/F	Air / Fuel Ratio	EVO	Exhaust Valve Opening
aBDC	After Bottom Dead Center ° CA	HC	Hydrocarbon
bBDC	Before Bottom Dead Center ° CA	IC	Internal Combustion Engine
BDC	Bottom Dead Center	ID	Ignition Duration
bp	Brake Power kW	IVC	Intake Valve Closing
Bsfc	Brake Specific Fuel Consumption	IVO	Intake Valve Opening
bTDC	Before Top Dead Center ° CA	NA Engine	Natural Aspirated Engine
BTE	Brake Thermal Efficiency	NO	Nitric Oxide
CA	Crank Angles °	NOx	Nitrogen Oxides
CD	Combustion Duration	rpm	Revolution per Minute
CI	Compression Ignition	SI	Spark Ignition
CN	Cetane Number	TC Engine	Turbo Charged Engine
CO	Carbon Monoxide	TDC	Top Dead Center
EGR	Exhaust Gas Recirculation		

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Conflicts of Interest

The authors declare there is no conflict of interest regarding the publication of this paper.

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