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Effect of Exhaust Gas Recirculation on Combustion and Emission Performance of a Dual Fuel CI Engine – A Numerical Investigation

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ABSTRACT

Due to the depletion of Diesel fuel and higher cost, it is desirable to find alternative fuel with lower cost and better combustion and emission characteristics. As, gaseous fuel is cheaper than liquid fuel, one of the effective solutions to obtain better engine performance is replacing a portion of liquid fuel by gaseous fuel in CI engine which is called dual fuel CI engine. In dual fuel engine, main gaseous fuel is provided through intake manifold by premixing with air and the mixture is ignited by injecting liquid pilot fuel at near the end of the compression stroke. The process is cost effective as well as the engine obtain higher thermal efficiency and lower soot, CO, UHC emission. But NOx emission is increased in CI engine with dual fuel mode which adversely affected the human health and pollute the environment. By applying Exhaust Gas Recirculation (EGR), NOx emission and knocking of the engine can be reduced. In this numerical simulation, the effect of EGR on combustion and emission performance of dual fuel CI is investigated through ANSYS Forte 18.1. In this study, gasoline is considered as main gaseous fuel and diesel is considered as liquid pilot fuel. Effect of EGR on various engine parameters such as in-cylinder pressure, temperature, heat release rate, ignition delay, combustion duration, NOx, CO and UHC emission is investigated. It is seen that, in-cylinder peak pressure is reduced to 50.65% and in-cylinder maximum temperature is reduced to 60.19% for the addition of 40% EGR. NOx emission is reduced to 57.19% for the addition of 10% EGR, 21.32% for 20% EGR, 1.57% for 30% EGR and 0.014% for 40% EGR.

Keywords: Exhaust Gas Recirculation, Diesel-Gasoline Dual Fuel CI Engine, Combustion and Emission Performance

1. Introduction

Internal combustion engine plays an important role in the modern era. The progress of civilization was accelerated after the invention of the IC engine. Internal combustion engines are generally operated on liquid or gaseous fuel. Due to the rapid depletion of diesel fuel and its higher cost, gaseous fuels (such as gasoline, natural gas, methanol, hydrogen etc.) are get attention as alternative fuel due to lower fuel and maintenance costs. To adapt to the competitive market, researchers have focused on reducing cost as well as environmental safety. To meet these requirements, researchers developed a CI engine that's run with both liquid and gaseous fuel. Internal combustion engines are generally operated on liquid or gaseous fuel. If two fuels are taken in widely varying proportions to run an engine, such a type of engine is called dual fuel CI engine. The engine is operated by introducing the homogeneous mixture of air and gaseous fuel through intake port and ignited by the injection of liquid pilot fuel at the end of the compression stroke [1]. Dual fuel combustion process also reduces the emission of soot, CO, CO_2 but an increase in NO_x [2]. NO_x affects human health both directly and indirectly. It can cause headaches, breathing problems, reduction of lung functions, loss of appetite, eye irritation, and corroded teeth. This increases air pollution and causes health hazards. So, designers have to fulfill the environmental requirements during engine designing. In recent times, many types of research are going to reduce harmful emissions to meet the acts of environmental safety.

In internal combustion engines, Exhaust Gas Recirculation (EGR) is an effective nitrogen oxide (NOx) reduction technique in different forms which is accomplished by recirculating different portions of the engine exhaust gas back to its cylinder. EGR is implemented by replacing a portion of air-fuel mixture with the same portion of exhaust gas from the exhaust port without affecting the air-fuel ratio. Exhaust gas mainly consists of CO_2 and H_2O, which is act as inert gas and can absorb combustion heat which reduces in-cylinder peak temperature. It also increases the ignition delay and retard the start of combustion Besides this, EGR reduces the O_2 concentration of the intake charge. NO_X is formed when the oxygen and nitrogen of air are subjected to high temperatures. As EGR contents (i.e. CO_2 and H_2O) reduce both the Oxygen concertation and in-cylinder peak temperature, the formation of NOx is decelerated. As EGR replaces the charge of the air-fuel mixture, it reduces the charge available for combustion. That's why it reduces the consumption of fuel as well as reduces knock by reducing in-cylinder peak temperature and pressure [3].

To achieve better combustion and emission performance by applying EGR, numerous researches are carried out. Yuanli Xu et al. [4] investigated the effects EGR rate under different speed on combustion performance of the on dual fuel (gasoline-diesel) engine. By applying hot EGR, NOx and soot emission was properly reduced. M. Ghazikhani et al. [5] were investigated the effects of EGR on CO and UHC emission on dual fuel HCCI-DI engine. As a result of increasing the EGR rate, CO emission was increased due to reduce the concentration of oxygen and that's leads to incomplete combustion. UHC is also increased due to lower in-cylinder temperature caused by EGR.

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G.H. Abd-Alla [6] published a paper to review the effects of EGR on both diesel and dual fuel CI engine. NOx emission and combustion rate was reduced for both cases. V. Pirouzpanah et al. [7] investigated to improve the pressure, temperature, heat release rate and species concentration by applying EGR on dual fuel (Diesel–gas) engine. EGR improve the emission characteristics by reducing NOx but increasing the CO and UHC. Effects of EGR, EGR temperature on the combustion and emission performance on diesel-biogas dual fuel engine was experimentally investigated by Saket Verma et al. [8]. They found that increasing EGR rate improve the performance as well as reduces the NOx emission at low load. High EGR rates slightly decreases in engine efficiency. Yuwei Zhao et al. [9] studied the effects of dimethyl ether (DME) and cooled EGR on DME-diesel dual fuel engine. Higher DME premixing ratio caused lower NOx emission and smoke but higher CO and UHC emissions. With increasing the EGR rate, NOx emission reduced sharply but increase in smoke, CO and UHC. In-cylinder pressure, temperature, heat release rate is also decreased. Eiji Tomita et al. [10] analyzed to obtain higher thermal efficiency and lower emission by applying EGR on a supercharged natural gas-diesel dual fuel CI engine. Ignition delay period was prolonged, luminous intensity, flame and NOx emission is decreased with increasing EGR rate. Ganesh Duraisamy et al. [11] studied the effects of hot and cooled EGR on methanol-diesel Reactivity Controlled Compression Ignition (RCCI) engine. The results concluded that 26% cooled EGR reduces NOx, smoke emission and improve the thermal efficiency at 76% methanol. M.M. Abdelaal et al. [12] published an experimental paper to investigate the way to reduce pollutant emission, particulate matters (PM), Nitrogen Oxide (NOx) in a diesel-natural gas dual fuel engine by applying EGR. The results concluded that in-cylinder peak pressure is reduced, ignition delay period prolonged and NOx emission is reduced by increasing the EGR rate. But, CO and UHC emission increases with increasing EGR rate. Miqdam Tariq Chaichan [13] employed an investigation on the impacts of cooled EGR on the combustion and emission performance of diesel-hydrogen dual fuel engine. Results show that additional hydrogen increases NOx emission and decreases whereas NOx emission reduced and PM increases with increasing cooled EGR. N. Saravanan et al. [14] investigated the effects of EGR on various engines parameters on dual fuel (hydrogen-diesel) engine. The results show that the smoke, particulate matter and NOx emission can be reduced by using hydrogen in dual fuel mode with applying EGR. Sarthak Nag et al. [15] studied to looking for fuels with clean emission without compromising engine performance in hydrogen-diesel dual fuel engine. The results show that NOx, CO, PM emissions reduces with increasing EGR rate.

The numerical studies on the effects of EGR on combustion and emission performance on diesel-gasoline dual engine is very limited. Though few parameters are investigated on dual fuel engine for different fuel is mentioned in literature. Therefore, this study will attempt to bridge this gap by investigating the effects of EGR on both combustion performance (in cylinder temperature, in-cylinder pressure, Ignition delay, combustion efficiency, duration of combustion) and emission characteristics (NO_x, CO, UHC emission) on Dual fuel (diesel-gasoline) CI engine. Temperature and NOx distribution will also be visualized through this study.

2. Computational Methodology

A commercially available software ANSYS Forte incorporated with highly efficient advanced chemistry solver module CHEMKIN is used to simulate the Dual Fuel Engine operation. This software involves the solution of full Reynolds-averaged Navier–Stokes (RANS) equations. Model transport equations of mass, momentum, and energy conservation laws are formulated for the compressible, gas-phase flows, and represent the turbulent nature of the flow. Re-Normalization Group (RNG) k-ε model is employed as the turbulence model to describe the flow field. A sector of 45^o angle is considered as computational domain and for mesh generation (Fig.1). Here, periodic boundary conditions are applied at the periodic faces of the sector. The key advantage of using sector mesh is that it saves the computational time and cost compared to using the whole geometry of the engine. Engine specifications are given in Table-1. To accurately model the combustion event of natural gas, thermodynamic properties and chemical reaction mechanisms of natural gas are added in the CFD code. Detailed chemical kinetics of natural gas include 425 gas phase species and 3128 elementary reactions.

A numerical grid shown in Fig. 1 containing 31696 cells was adopted to model the combustion chamber sector geometry after accomplishing the grid-independent results.

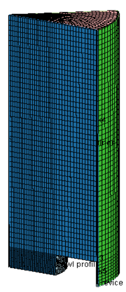

Fig. 1 Sector Mesh of 45˚ with 31696 cells

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

$$EGR\% = \frac{m_{EGR}}{m_a + m_f + m_{EGR}} \quad (1)$$

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

Table 1 Engine Conditions

Number of Cylinder	1
Bore	13.716 cm
Stroke	16.510 cm
Connecting Rod Length	26.160 cm
Compression Ratio	16.0
Engine Operating Speed	1300 rpm
Sector Angle	45 Degree
Squish	0.62 cm

2.1 Initial Condition

The initial temperature and pressure are set to 400K and 6 bars. Pilot fuel is injected at -25° ATDC. The injected amount of pilot fuel in every cycle is 90 mg. The composition of the air-fuel and EGR mixtures were different for different percentages of EGR. The mole fraction for 0-40% EGR rates.

2.2 Boundary Condition

Piston, head, liner are the boundaries of this considered sector mesh. The properties of these boundaries are mentioned in Table 2.

Table 2 Boundary Conditions

Boundary	Wall model	Temperature (K)
Piston	Law of the wall	500
Head	Law of the wall	500
Liner	Law of the wall	430

3. Result & Discussion

3.1 Effect of EGR on in-cylinder pressure and In-cylinder Temperature

The effect of EGR percentage on in-cylinder pressure and in cylinder temperature are shown in Fig.2, Fig.3.

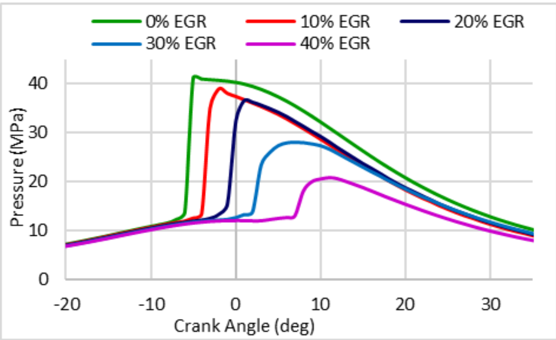

Fig.2 Variation of in-cylinder pressure with crank angle for different EGR rate

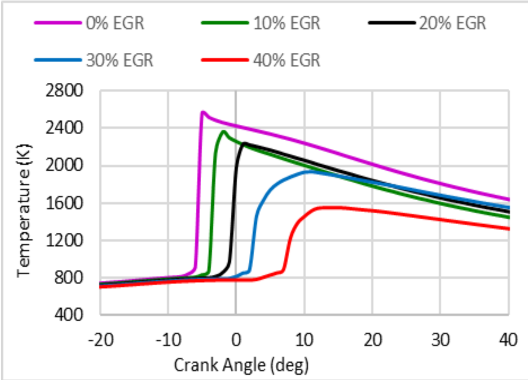

Fig. 3 Variation of in-cylinder temperature with crank angle for different EGR rate

From Fig. 2 and Fig. 3, it is evident that the in-cylinder pressure and in-cylinder temperature rise is reduced gradually by increasing the EGR rate. With applying EGR, a portion of the air-fuel mixture is replaced by inert exhaust gas which mainly consists of water vapor and CO_2. Water vapor and CO_2 have a high specific heat capacity and act as inert gas. So, O_2 concentration is reduced by increasing the rate of EGR. The heat released by the ignition of pilot fuel is absorbed by EGR contents. These suppress the process of combustion and dampen the rise of pressure and temperature. Moreover, the ignition delay period is prolonged due to the reduction in Oxygen contents available for combustion. So, the combustion process is shifted subsequently to expansion stroke with EGR rate were increases in in-cylinder volume. So, the peak pressure is reduced. For 0%, 10%, 20%, 30% and 40% EGR rates the maximum in-cylinder pressure is 41.22 MPa, 38.93 MPa, 36.55 MPa, 28.14 MPa and 20.88 MPa respectively. It is seen that, in-cylinder peak pressure reduced to 50.65% for the addition of 40% EGR. The in-cylinder maximum temperature for 0%, 10%, 20%, 30% and 40% EGR rate is 2565 K, 2364 K, 2219 K, 1929 K and 1544 K respectively. Maximum in-cylinder temperature is reduced to 60.19% for the addition of 40% EGR.

3.2 Effect of EGR on Ignition Delay and Duration of Combustion

The effect of EGR percentage on Ignition Delay and Duration of Combustion are shown in Fig.4, Fig.5.

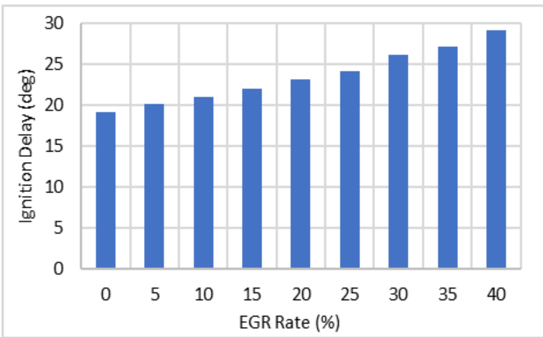

Fig.4 Effect of EGR percentage on Ignition Delay

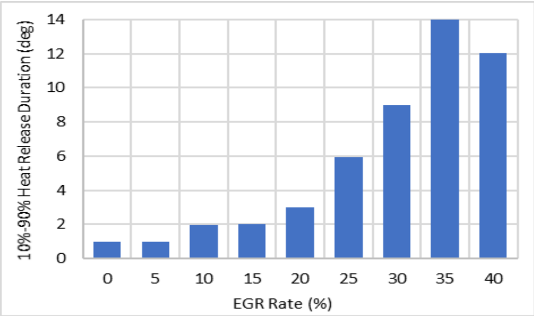

Fig.5 Effect of EGR percentage on Duration of Combustion

From Fig. 4 and Fig. 5, it is seen both Ignition Delay and Duration of Combustion is prolonged with increasing the EGR rate. The start of combustion (SOI) is retarded with an increasing EGR rate. EGR contains inert exhaust gas which slows down the combustion process by absorbing a considerable amount of heat. So, the mixture takes considerable time to reach self-ignition temperature. The requirement of time is prolonged with the rise of the EGR rate. Thus, the start of combustion is retarded. Ignition delay is the difference between the start of injection and the start of combustion. So, the Ignition delay is prolonged with the rise of the EGR rate. Moreover, when rising the EGR rate, the combustion reaction becomes slow because of gradually reduces the concentration of available O_2. So, heat release duration is increased with the rise of the EGR rate. Ignition delay for 0%, 20% and 40% EGR rate is 19^o, 23^o and 29^o. Combustion duration is 0.98^o, 2.97^o and 12^o respectively.

3.3 Effect of EGR on Combustion Efficiency

The effects of EGR percentage on Combustion Efficiency is shown in Fig. 6.

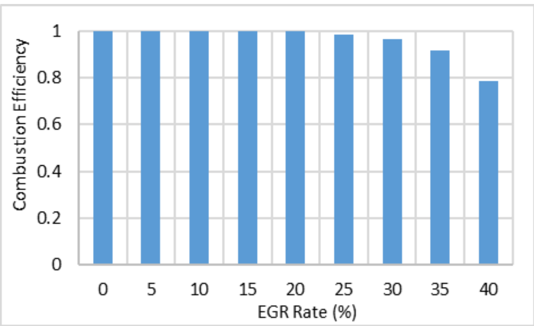

Fig.6 Effect of EGR percentage on combustion efficiency

In the case of a lower EGR rate (0%-20%), there is sufficient available O_2 concentration to burn the air-fuel mixture. Moreover, the in-cylinder temperature and pressure are also sufficiently high to obtain self-ignition temperature can be obtained within a short time as well as a lower ignition delay period. So, almost all air-fuel mixtures can burn properly. So, combustion efficiency is 100% in these cases. Combustion efficiency is gradually decreased by increasing the EGR rate consequence of reducing available O_2 for initiating combustion. In the case of a high EGR rate (20%-40%), in-cylinder temperature becomes lower with rising EGR rate and retarding start of combustion (SOC) also. As a result, a considerable amount of air-fuel mixture can't obtain self-ignition temperature within combustion duration. So, this unburned fuel contents escape with exhaust. That's why combustion efficiency becomes lower in the case of a high EGR rate (30%-40%). The combustion efficiency for 30% and 40% EGR rate is 91.7% and 78.34%.

3.4 Effect of EGR on NOx Emission

The effect of EGR percentage on NOx emission is elucidated in Fig. 7.

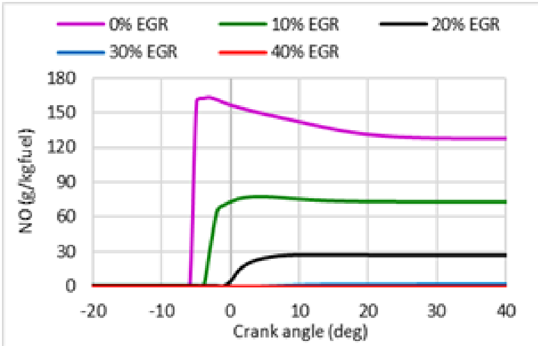

Fig.7 Variation of NOx emission rate with crank angle for different EGR rate

The formation of NOx in a combustible zone is due to a thermal mechanism called Zeldovich Mechanism.[16] NOx formation occurs when combustion temperature rises above 1400K and subjected to higher oxygen concentration. The formation rate of NOx increases with increasing the both combustion temperature and oxygen concentration and vice versa. Duel fuel combustion consists of two combustion configurations. One is non-premixed combustion of small amount of diesel pilot fuel which is responsible for the major portion of the NOx formation due to rich combustible zone. Another one is premixed gaseous gasoline main fuel combustion which is responsible for the less portion of NOx due to lean local zone [12]. EGR has a significance contribution to reduce the NOx emission rate. When EGR is applied, a portion of air-fuel mixture is replaced by exhaust inert gas which is mainly consists of carbon dioxide and water vapor. So, oxygen concentration reduced by applying EGR. These EGR contents increase the specific heat capacity which decelerate the combustion process and reduce the in-cylinder temperature. Due to reduction in oxygen concentration and temperature, NOx can't be formed as before (at 0% EGR rate). Thus, NOx formation is reduced by increasing the EGR rate. The NOx emission rate for 0%, 10%. 20%, 30% and 40% EGR rate is 127.29 gm/kg-fuel, 72.8 g/kg-fuel, 27.14 g/kg-fuel, 2 g/kg-fuel and 0.019 g/kg-fuel. NOx emission is reduced to 57.19% for the addition of 10% EGR, 21.32% for 20% EGR, 1.57% for 30% EGR and 0.014% for 40% EGR.

3.5 Effect of EGR on Unburned Hydrocarbon (UHC) Emission

The effect of EGR on UHC Emission is shown in Fig.8.

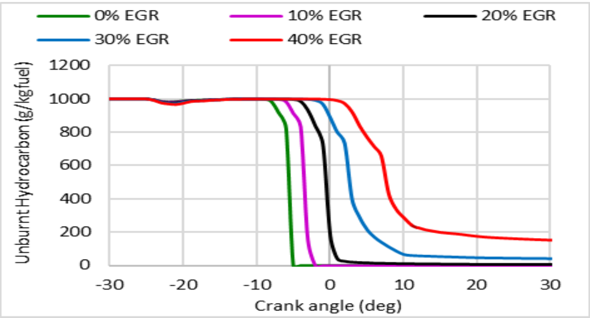

Fig.8 Variation of UHC emission rate with crank angle for different EGR rate

In the case of lower rate of EGR (0%-20% EGR rate), there is sufficient amount of oxygen to burn the air-fuel mixtures. After injecting the diesel pilot fuel, the both non-premixed diesel fuel and premixed gasoline burn quickly. So, combustion efficiency is almost 100% in these cases. Thus, negligible amount of unburned hydrocarbon is found in exhaust. In the case of higher rate of EGR (20%-40% EGR rate), a portion of air-fuel mixture is replaced by EGR contents. So, oxygen concentration is considerably reduced. In-cylinder temperature is also reduced due to absorbing heat released by combustion. Due to insufficient oxygen concentration and low temperature shorter combustion duration, a portion of air-fuel mixture remain unburned. Thus, rate of UHC emission is increased with increasing EGR rate. For 0%, 10%, 20%, 30% and 40% EGR rate, UHC emission is 0 g/kg-fuel, 0.049 g/kg-fuel, 4.82 g/kg-fuel, 38 g/kg-fuel and 142.54 g/kg-fuel respectively.

3.6 Effect of EGR on CO Emission

The effect of EGR percentage on NOx emission is elucidated in Fig.9.

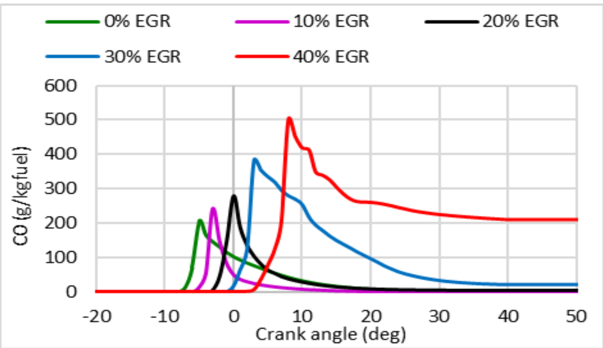

Fig.9 Variation of CO emission rate with crank angle for different EGR rate

By increasing EGR rate, it has been seen that rate of unburned hydrocarbon (UHC) is increased. The UHC react with in-cylinder oxygen at high temperature and produced CO. Because, this reaction can't further progress to produce CO_2 because of short available time for combustion. So, the rate of CO emission is increased with increasing the EGR rate. For 0%, 10%, 20%, 30% and 40% EGR rate, CO emission is 0.573 g/kg-fuel, 0.079 g/kg-fuel, 6 g/kg-fuel, 21.88 g/kg-fuel and 210.22 g/kg-fuel respectively.

3.7 Effect of EGR on in-cylinder temperature distribution

The effect of EGR percentage on temperature distribution is elucidated in Fig.10.

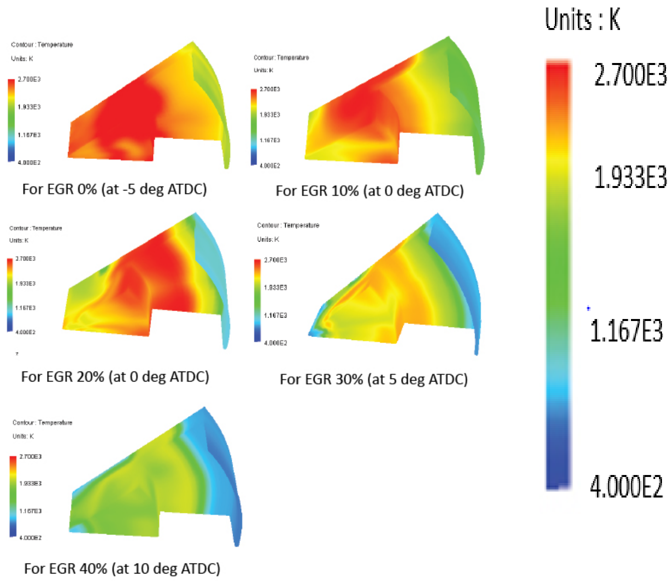

Fig 10. Effect of EGR on in-cylinder temperature distribution

3.8 Effect of EGR on NOx distribution

The effect of EGR percentage on NOx distribution is elucidated in Fig.11.

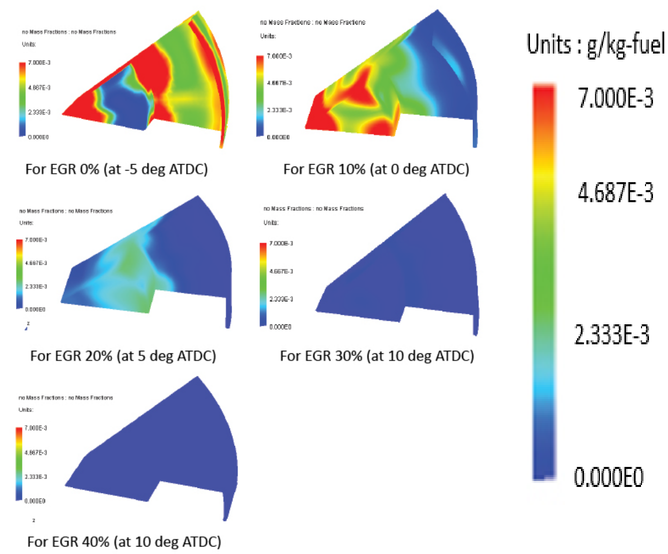

Fig 11. Effect of EGR on NOx distribution

4. Conclusion

In this numerical study, the effects of EGR on combustion and emission performance of diesel-gasoline dual duel CI engine has been investigated.. The major findings are summarized below:

1. The in-cylinder temperature and pressure gradually reduce with the increase of EGR percentages, as EGR contents absorbs heat release by the combustion and dampen the rise of pressure.
2. Both Ignition delay and combustion duration are prolonged for higher EGR rates. Heat released by combustion is absorbed O_2 concentration in cylinder which reduced with applying EGR. That's why, the air-fuel mixture requires more time to reach self-ignition temperature and complete the combustion process.
3. Combustion efficiency falls when EGR rates exceeds 20%. After exceeding EGR 20% rate, O_2 concentration and in-cylinder temperature is not sufficient to complete the combustion of whole air-fuel mixture. So, CO and UHC emission is also increased with increasing the EGR rates.
4. The NOx emission is decreased with the increase of EGR rates. NOx is formed in high temperature with higher O_2 concentration. As, both the temperature and O_2 concentration is reduced with EGR, NOx emission is reduced.
5. After 30% EGR rates, combustion efficiency falls gradually and CO, NOx emission increases undesirably. So, it is recommended to apply EGR from 20-30% in diesel-gasoline dual fuel CI engine.

8. References

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