Exhaust Gas Recirculation system to lower the NO_x emission from a compression ignition engine using CNG as secondary fuel

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Abstract: Emissions from diesel engines are very harmful for the environment and for human health. An experimental and comparative study having been done with diesel engines, referred to as dual-fuel (Diesel + CNG) engines and also incorporate there EGR system to extremely minimize NOx emission. The use of compressed natural gas (CNG) as a partial supplement for liquid diesel fuel is a very promising solution for reducing pollutant emissions, particularly nitrogen oxides (NOx) and particulate matters (PM), from conventional diesel engines. In most applications of this technique, natural gas is inducted or injected in the intake manifold to mix uniformly with air, and the homogenous natural gas–air mixture is then introduced to the cylinder as a result of the engine suction. It is seen that because of lower thermal efficiency and higher carbon monoxide (CO) and unburned hydrocarbon (HC) emissions; particularly at part load. The use of exhaust gas recirculation (EGR) is expected to partially resolve these problems and to provide further reduction in NOx emission as well.

Keywords: Diesel engine, CNG, Dual fuel mode, EGR, DOE software.

1. INTRODUCTION

Now a day's lots of research works are going on in the field of renewable energy to replace conventional sources of energy because of the sublimation of conventional energy in day by day. Internal Combustion (IC) engines are studied for decades. Besides the Increasing of thermal efficiency of an IC engines, it is now the main aims of scientists and engineers are to reduction of pollutants exhaust. Two typical types of IC engines are there Spark Ignition (SI) and Compression Ignition (CI) engines. In SI engines a homogenous mixture of fuel and air is compressed till the mixtures is ignited by introduction of spark in the mixture. On the other hand in CI engine, the air is compressed inside the mixture and a fuel with high reactivity is injected to air. Due to high temperature and pressure of air, auto ignition of fuel occurs inside the engine and combustion happens. Therefore, the CI engines have higher compression ratio which resulted to higher thermal efficiency of this type of engines in comparison with SI engines [1]. In the combustion chamber of a normal diesel engine, natural gas under the pressures requires a higher ignition temperature than diesel (about 800 ºC vs. 500 ºC) to maintain an acceptable ignition delay period of less than 1 millisecond. In spark ignition engines fuelled by CNG higher electric energy is required from the ignition module (from 40 MJ to 60 MJ). This phenomenon causes that self-ignition of the natural gas-air mixture is not possible in diesel engines. Such system requires electric ignition or injection of small dose of diesel oil as a pilot dose for initiation of ignition [2]. It is practically observable the diesel engines emit relatively high levels of NOx and particulate matter as well as other harmful pollutants such as hydrocarbon and smokes. Presently, NOx emission regulations are being met by in-cylinder and post-treatment techniques. Newer technologies are being developed by engine manufacturers to reduce the amount of particulate and smoke emissions. However, the growing public concern to improve air quality and a lot more stringent exhausts regulations have necessitated the innovation of higher techniques to meet the higher standards. In the subsequent sections, the literature related to this work is presented. In dual fuel (liquid and gaseous one) combustion system, reduce the particulate emissions and nitrogen oxides from the engine emissions can be achieved by in traducing the dual fuel with EGR system. The results of this study revealed that there was a higher ignition delay for dual fuel compare to diesel operation. It was found that the smoke and NOx emission can be cut down by the use of CNG as the supplement of diesel fuel [3].

There are several factors which affect the formation of NOx in the engine and they are listed below:

The air-fuel ratio: plays a major role in determining the amount of emission of NOx as oxides of nitrogen are formed by the reaction of nitrogen in the fuel with oxygen in the combustion air. When the air to fuel ratio is greater than one which indicates that the combustion is in the lean condition, the fuel mixture has considerably less amount of fuel and excess amount of air. Engines designed for lean burning can achieve higher compression ratios and hence produce better performance. However, it will generate high amount of NOx due to the excess oxygen present in the air [4].

Combustion temperature: is also one of the primary factors that influence the formation of NOx. The formation of NOx is directly proportional to the peak combustion temperature, with higher temperatures producing higher NOx emissions from the exhaust [5]

The firing and quenching rates also influence the rate of NOx formation where a high firing rate is associated with the higher peak temperatures and thus increases the NOx emission. On the other hand, high rates of thermal quenching result in lower peak temperatures and contribute to the reduction of NOx emission [6]

Engine parameters such as load and speed of engine also influence the NOx emissions from the exhaust. When the engine is running under lean conditions, it emits less NOx. However the nitric oxide (NO) emissions will consequently increase as the engine load increases. The effect of load becomes less significant when the engine is running close to stoichiometric air to fuel ratio. On the other hand, engine speed may increase or decrease the NO emissions as higher engine speed increases the burned gas mass fraction and thus offsets the peak temperature, depending on the exact engine conditions

The most common of the alternative fuels is natural gas that is usually made available after processing as “pipeline processed natural gas”. It is supplied for engine applications normally as compressed natural gas, (CNG), or occasionally in its cryogenic liquid form, (LNG). The composition of the gas in its natural untreated state varies widely depending on its source, treatment and local conditions. However, after it’s processing when destined for transport to its ultimate consumption points its composition becomes less widely variable and made up mostly of methane. Accordingly, much of the work and information available relating to natural gas as an engine fuel consider methane to be an adequate representation of the whole fuel [7]. NOx emissions are mainly damaged by two factors, the occurrence of oxygen in the demand and the response temp, which promotes chemical activity during both the formation and destruction stages. During the formation stage, the effect temperature is near the adiabatic flame temperature, which is a consequence of the oxygen concentration in the charge, the first temperature and pressure and the area fuel-air ratio. EGR reduces the oxygen attention in the charge and, consequently, the combustion pressure and temperature [8]. EGR has a top potential to reduce NOx emissions to the allowable levels. Their results however showed that durability, cost and packaging were major concerns in the setup on this technique. The report said that the limit for NOx reduction in a DI diesel engine is diesel engine combustible. They reported that stoichiometric diffusion combustion produces high flame temperatures and high levels of NOx. That they also noted that diluents can be added to decrease the flame temperatures up to the point where combustion begins to deteriorate.Based upon investigations taken out on a diesel powered engine [9]. In diesel engine the NOx formation was modeled Zeldovich mechanism and the results were multiplied by a calibration factor to predict the NOx formed during combustion in the diesel engine which includes both NO and NO2. For diesel fuel, the value the calibration factor is 1.533 which is the ratio of molecular weight of NO2 to NO [10].

The aim of this work is studying the influence of using different percentage of EGR with Duel fuel (D+CNG) to reduce the emissions parameters and also developed the engine efficiency and finally the experimental values are graphed DOE software.

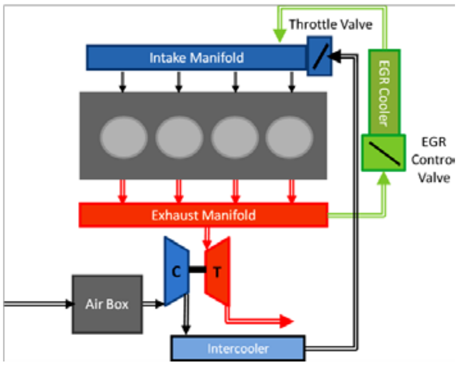


Figure 1: EGR - Exhaust Gas Recirculation [11]

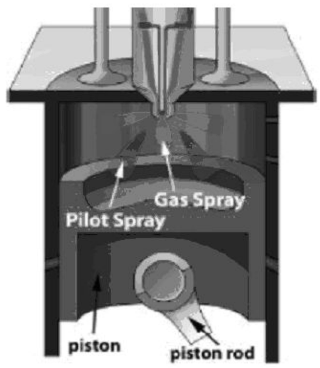


Figure 2: High Pressure Direct Injection of CNG and diesel oil [12]

2. NO_X FORMATION MECHANISM

Due to the post flame combustion process inside the cylinder the temperature is already too high and in this high temperature zone, NO is formed. Zeldovich mechanism is reported for analysis of NO inside the combustion chamber [1]. The principal reactions at near stoichiometric air-fuel mixture governing the formation of NO from molecular nitrogen are:

$$O + N2 = NO + N$$
$$N + O2 = NO + O$$
$$N + OH = NO + H$$

Levendis YA et al.[13] described initial rate controlled NO formation (i.e. when [NO] / $[NO_2]_e$<<1) when [NO] denotes the molar concentration of the species and $[O_2]e$ and $[N_2]_e$ denotes the equilibrium concentration, through this equation.

$$\frac{d[NO]}{dt} = \left(\frac{6 \times 10^{16}}{T^{0.5}}\right) exp + \left(\frac{-69.096}{T}\right) [O_2]_e^{0.5} [N_2]_e mol \frac{s}{cm^3} \quad (1)$$

This equation is able to show NO formation rate with respect to oxygen concentration and temperature. In addition to this, cetane improving additives also able to reduce NOx. But, reduction reported is not adequate and also these additives are expensive. Therefore, retarded injection is a good option to reduce NOx formation in diesel engines.

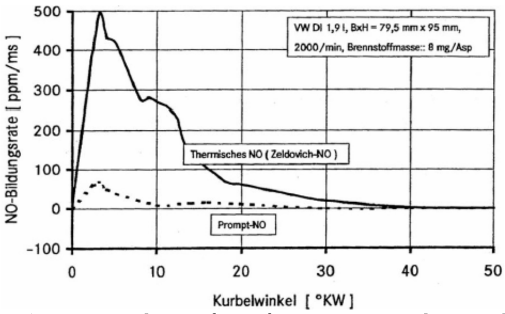


Figure3 : Simulation of NO_x formation in Diesel Engine [14]

If the temperatures stay below a certain level during the whole combustion process, the formation of NO_x can be avoided almost completely fig. 3.

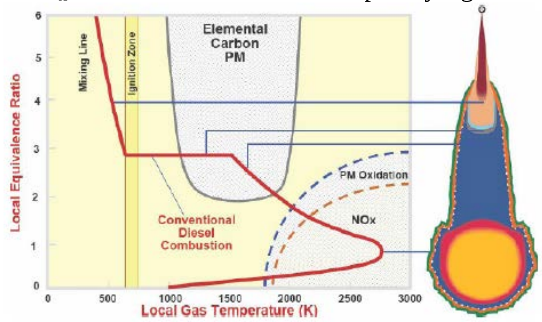


Figure4: Emission formations in conventional diesel combustion[14]

3. EXHAUST GAS RECIRCULATION SYSTEM

Exhaust gases contains CO_2, N_2 etc. that replaces the fresh air intake inside the cylinder. This ultimately reduces the availability of oxygen for combustion and lower formation of NO_x happened. To overcome these issues, an optimized EGR (%) is to be identified that balance lower NO_x formation without having considerable drop in performance of engine. EGR (%) is represented as equation 2, where MEGR is the mass of exhaust gas recirculated and MI is the total mass of intake inside the cylinder (MI= Ma (mass of air induced) + Mf (mass of fuel injected) + MEGR).

$$EGR(\%) = \frac{M_{EGR}}{M_I} \times 100 \quad (2)$$

Descants et al. [10] used NDIR-based CO2 concentration measurement at the intake ($[CO_2]_{int}$) and exhaust manifold ($[CO_2]_{exh}$) for the determination of EGR rate.

$$EGR(\%) = \frac{[CO_2]_{Intake\ gas} - [CO_2]_{Ambient}}{[CO_2]_{Exhaust\ gas} - [CO_2]_{Ambient}} \quad (3)$$

It is clear from the results reported by Descants et al. [10] that exhaust emission form EGR engine was lowered compared to non EGR engine emissions. But, toxic substance inside exhaust gas found unchanged however totals quantity of toxic substance emission reduced for same volumetric concentration.

Table 1 : Technical Specifications of test engine

MAKE	HM STRIDE
BHP	10 HP
SPEED	1500 RPM
COMPRESSION RATIO	23:1
BORE	73 mm
STROKE	88.9 mm
ORIFICE DIAMETER	17 mm
TYPE OF IGNITION	COMPRESSION IGNITION
METHOD OF LOADING	HYDRAULIC DYNAMOMETER

4. EXPERIMENTAL SETUP AND METHODOLOGY

4.1Test Engine

The test engine used in this study was four cylinder, four-stroke, air-cooled, naturally aspirated and direct injection compression ignition engine coupled to hydraulic dynamometer (made HM STRIDE). Here a small modification had done to investigate the effects of performance and emission characteristics with duel fuel (CNG and Diesel) mode. It had a compression ratio of 23:1 and was capable of developing 7.45 kW of power at 1500 rpm. EGR equipments also incorporated with the setup. The detailed specifications of the engine are given in Table 1.

4.2 Methodology

The schematic diagram of the engine setup is shown in Fig. 6. The quantity of EGR can be regulated by a control valve installed in the EGR loop. An EGR Mixer was provided in EGR loop to dampen the fluctuations of the pulsating exhaust. An orifice was installed in the EGR loop to measure the flow rate of re-circulated exhaust gas and the percentage of recirculated exhaust gas were fixes up by the EGR software.. Fuel consumption measurement was done using a gravitational manometer. Oxygen, CO, NOx, and CO2 were measured by gas analyzer (Make: AVL, DIGAS Model: 444N). The exhaust gas opacity was measured by a smoke opacity meter (Make: AVL, India Made, Model: 437C). To achieve the objectives of the study, engine was run under normal operating condition and at different EGR rates. The data for HC, NOx, CO, smoke opacity, exhaust gas temperature, and fuel consumption were recorded. Then, engine performance and emission patterns were compared. Optimum EGR rate was found on the basis of performance and emissions of the engine. Then, the engine was run by diesel only, with diesel and EGR and with diesel plus CNG plus EGR. With the four load (0 kg, 2kg, 4kg and 6kg) condition and by the above mentioned condition total 40 numbers of test experiments were performed.

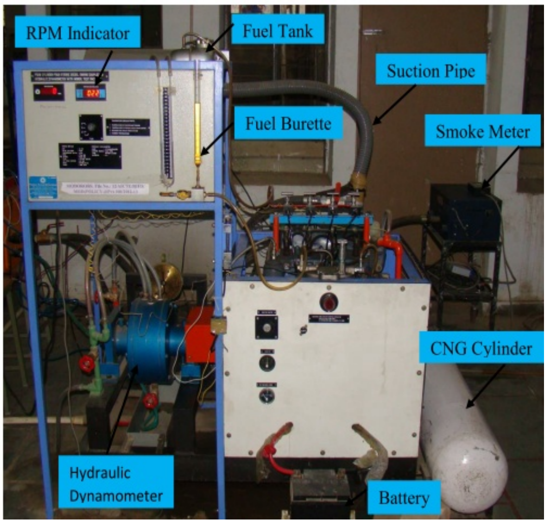


Figure 5: Test engine with CNG cylinder

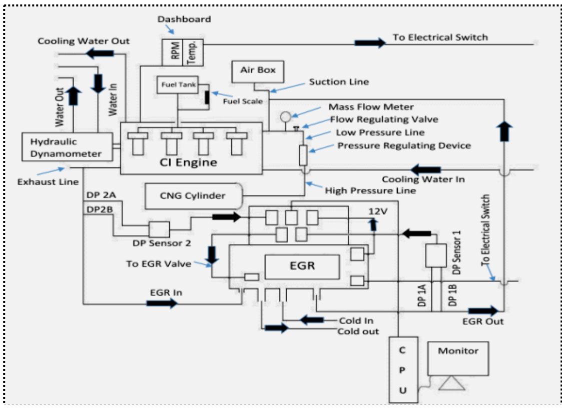


Figure 6 : Schematic diagram of experimental test engine with EGR

5. RESULT AND DISCUSSION

5.1Performance characteristics and emissions of diesel engine with different EGR quantities

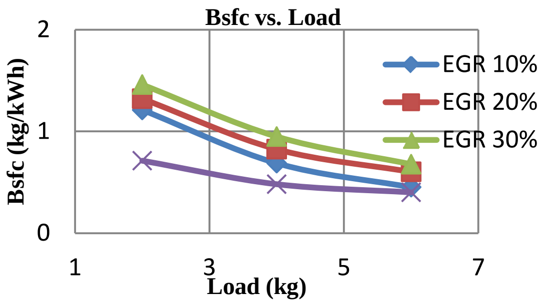


Figure 7: BSFC for different load conditions with percentage of EGR

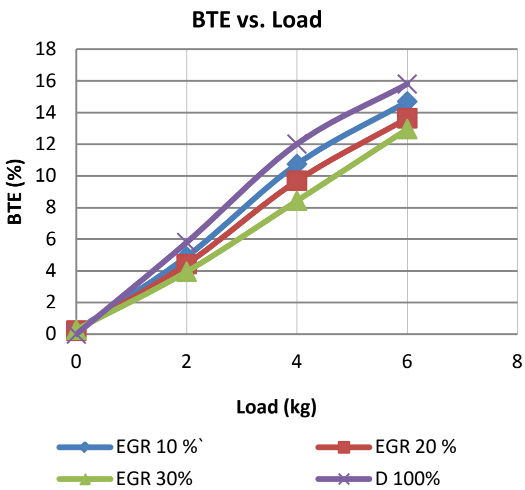


Figure 8 : BTE for different load conditions with percentage of EGR

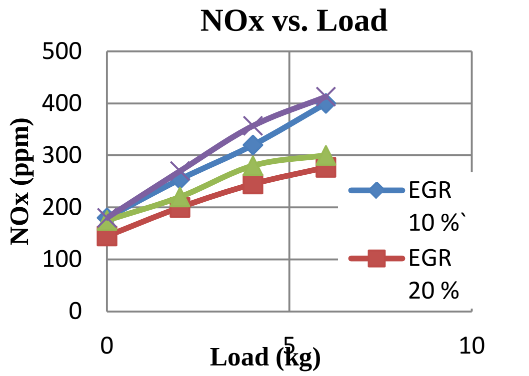


Figure 9 : NOx emission for different load conditions with percentage of EGR

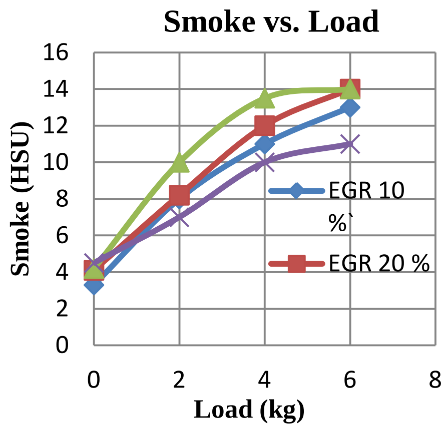
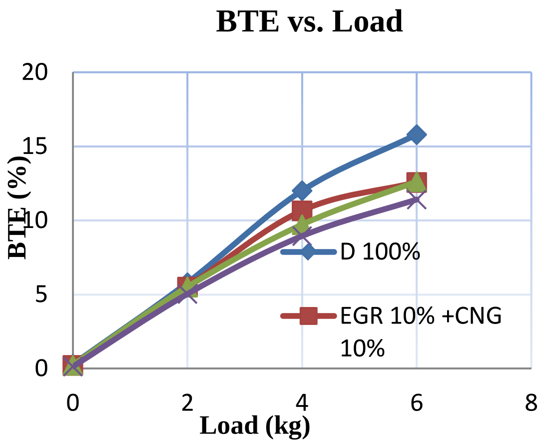
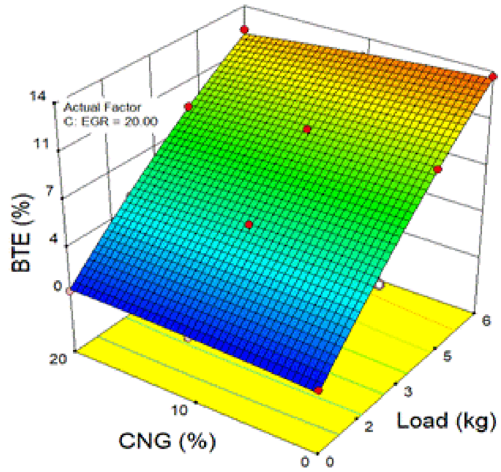


Figure 10 : Smoke emissions for different load conditions with percentage of EGR

5.2 Engine performance and emission characteristics for dual fuel (CNG10 + D90) with EGR



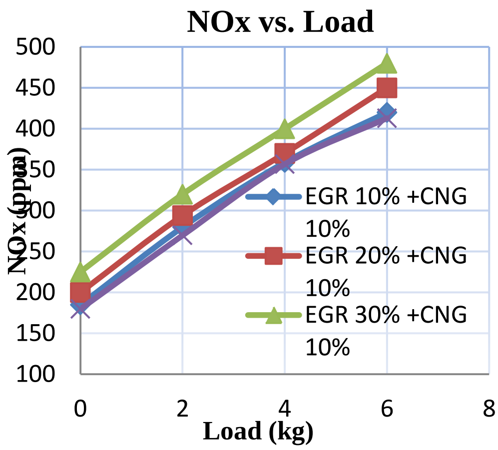
(a)



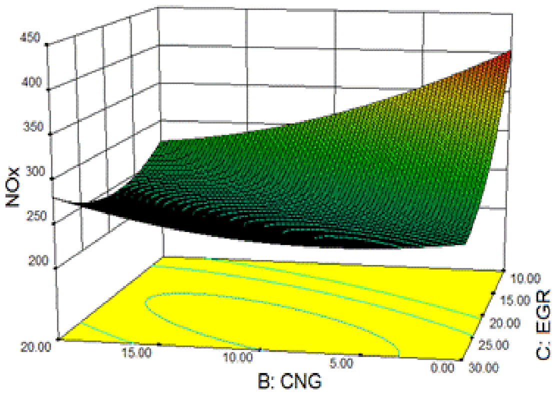
(b)

Figure 11 : BTE for dual fuel (CNG 10%) mode at different EGR (a) experimental (b) DOE model

It can be seen that the dual-fuel engine suffers from lower brake thermal efficiency at part loads, in comparison with conventional diesel mode. This is because of the very lean mixture of gaseous fuel and air at part load and the associated poor fuel utilization efficiency. Concerning the application of EGR to dual-fuel mode, Figure shows that the utilization of a low percentage of EGR of 10% causes almost no change in the brake thermal efficiency at low loads. At medium loads, a slight improvement in the thermal efficiency is obtained with 20% EGR. This may be attributed to the re-burning of some of the hydrocarbons that is contained in the EGR. At high loads, however, slight decrease of the brake thermal efficiency is observed, due to the reduced oxygen concentration that adversely affect the combustion process. The same phenomena were observed when applying EGR 30% with 10% of CNGs at duel fuel mode.



(a)



(b)

Figure 12:NOx emission for dual fuel (10%CNG) mode at different EGR (a) experimental (b) DOE model

NOx emission was decreased by blending of CNG with diesel fuel of test engine without any modification in the engine operating conditions. The minimum NOx emission was recorded for 10 % EGR under dual fuel mode.

4. CONCLUSION

In the present research, experimental investigations were conducted to study the effect of EGR on performance and emissions of a duel fuel (Diesel + CNG) engine. EGR displaces oxygen in the intake air by exhaust gas re-circulated to the combustion chamber. Exhaust gases lower the oxygen concentration in combustion chamber and increase the specific heat of intake manifold. The intake air is mixes with CNG, which results in lower flame temperatures. Reduced oxygen and lower flame temperatures affect performance and emissions of diesel engine in different ways. Thermal efficiency and BSFC is slightly decreased at lower loads with EGR and duel fuel conditions as compared to without pure Diesel. But at higher loads, thermal efficiency and BSFC are almost similar with EGR than without EGR. Exhaust gas temperature is decreased with EGR, but NOx emission decreases significantly. It can be observed that diesel with 10% EGR and 10% CNG rate is found to be effective to reduce NOx emission substantially without deteriorating engine performance in terms of thermal efficiency, BSFC, and emissions. At lower loads, EGR reduces NOx without deteriorating performance and emissions. At higher loads, increased rate of EGR reduces NOx to a great extent but deteriorates performance and emissions. Thus, it can be concluded that higher rate of EGR can be applied at lower loads. EGR can be applied to diesel engine without sacrificing its efficiency and fuel economy and NOx reduction can thus be achieved. The increase in CO, HC, and particulate matter emissions can be reduced by using exhaust after-treatment techniques, such as diesel oxidation catalysts (DOCs) and soot traps.

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