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(Research Article)

Experimental investigation on the effect of EGR rate variation on emissions in optimized PCCI-DI diesel engine

Getachew Alemayehu [1,*], Ramesh Babu Nallamothu [1], Adem Siraj [2] and Rajendiran Gopal [3]

[1] *Department of Mechanical Engineering, Adama Science and Technology University, Ethiopia.*
[2] *Department of Mechanical Engineering, Addis Ababa Science and Technology University, Ethiopia.*
[3] *Department of Motor Vehicle Engineering, Defense University, College of Engineering, Ethiopia.*

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Abstract

Combustion in diesel engines is focusing towards unexplored combustion concepts where innovative combustion ideas are being developed following several engine control factors. Advanced low temperature combustion engines for automotive applications are one of the improvements in this regard. The test was conducted on a single cylinder, four stroke and air cooled diesel engine. The scope of this study is to investigate the impact of EGR rate variation (25%, 35% and 45 % EGR rates) on emission reductions in PCCI-DI diesel combustion approach showing a reduction of NOx–soot trade-offs than the conventional diesel combustion approach. The PCCI-DI diesel combustion in this setup is optimized applying the algorithm of grey relational analysis together with Taguchi method. This investigational setup used a methanol port injection and advanced injection timing for PCCI formation. Emission results from different EGR settings in the optimized PCCI-DI combustion scheme were analyzed and compared using surface and contour plots. From the experiment higher EGR rate resulted a decrease in NOx productions but an increase in HC, CO and smoke due to the combustion mode of the experimental setup. The study indicated that excess EGR application should be avoided to have an optimum PCCI-DI combustion having lower emission results.

Keywords: EGR rate; PCCI-DI combustion; Low temperature combustion; Grey-Taguchi; Emission

1. Introduction

Proper combination of EGR rates and advanced combustion resulted PCCI combustion. In LTC engines, charge dilution (with either air or EGR) is usually used to avoid higher NOx formation by decreasing the combustion temperature inside the combustion chamber [1]. High level of EGR was used to realize low-temperature combustion which largely reduced NOx emissions. It was obviously found out that EGR is the most important engine working parameter for the realization of PCCI combustion mode and its dilution effect contributes to the increase in HC and CO emissions. PCCI operation attains a desired ignition delay through one of a contributing factor which is the extensive use of EGR. Knowing the percentage or rate of EGR that has to enter into the cylinder is important to have lower emission results. The premixed charge compression ignition (PCCI) combustion mode was be achieved by using large amounts of exhaust gas recirculation (EGR) together with advanced fuel injection timing strategy. Higher use of EGR and optimized SOI control parameters help for the realization of LTC technologies and these keep NOx and soot emissions low in diesel combustions. Applying higher EGR forms longer ignition delay. From investigations they mentioned that this will allow better premixing of air–fuel mixture which results in less fuel-rich pockets followed by low temperature combustion. These will enable the engine to simultaneously reduce NOx and soot level.

* Corresponding author: Getachew Alemayehu Lakew
Department of Mechanical Engineering, Adama Science and Technology University, Ethiopia.

Experiments were carried out using 40% by volume of iso-butanol-diesel and n-pentanol-diesel blends aiming to assist partially premixed low temperature combustion with low EGR rates and modified injection timing in DI diesel engine in-order to minimize NOx with PM trade-off [2]. Reduction in NOx emission by 13 % for PCCI mode of combustion along with 30% EGR were resulted in comparison to conventional CI mode of combustion due to low combustion temperature formed inside the cylinder. Delaying and controlling of the combustion applying EGR were made possible and further increase in EGR rate would lead to combustion instability [3]. EGR has been applied to PCCI combustion in a research conducted on in a single-cylinder direct injection common-rail diesel engine with low engine speed and low load. Results showed that as EGR rate increased, IMEP was increased due to the decrease of negative work during the compression stroke and due to dilution and thermal effects of EGR; NOx emissions were decreased [4].

EGR delays the O_2 flow rate into the combustion chamber of the engine and results reduction of local flame temperature, which helps to reduce thermal NOx and also studies showed that through extension of the ignition delay EGR would delay the start of combustion. Studies found out the application of large amount of EGR up to 54% in a PCCI combustion system helps in retarding the ignition timing by diluting the gas mixture [5]. High temperature formed in the combustion chamber leads NOx emission generation in the exhaust. Controlling this peak combustion temperature helps to reduce NOx and studies showed that Exhaust Gas Recirculation (EGR) is one of the effective methods in overcoming this challenge by forming lean air-fuel mixture.

Investigations indicated that by recirculating exhaust gas into the combustion cylinder dilution can take place which decreases the O2 concentration in the combustion cylinder. Various investigations indicated that in applying EGR, there is a trade-off between increase in soot, CO and UHC and reduction in NOx. The finding showed that for greater than 50% EGR, particulate emissions increased significantly, implying that use of particulate trap was suggested. Also the effect of EGR on different engine performance factors mainly thermal efficiency, brake specific energy consumption, smoke opacity etc. were investigated by different researchers. Applying EGR at higher loads was found difficult due to deterioration in diffusion combustion which resulted in an excessive increase in smoke and PM. whereas at low loads, UHC contained in the EGR would possibly re-burn in the mixture, resulting lower unburned fuel in the exhaust and improved brake thermal efficiency [6]. PCCI combustion is obtained with a proper combination of high EGR and advanced combustion. EGR is a useful method for reducing NOx formation and LTC features [7]. A trade-off relationship between NOx and smoke emissions was observed in an experiment conducted using EGR and intake boost on a partially premixed compression ignition combustion mode [8]. It was clearly pointed out that EGR is the most important engine working parameter for the realization of PCCI combustion mode and its dilution effect of EGR contributes to the increase in HC and CO emissions [9].

2. Experimental setup and methodology

The experiment was conducted on a single cylinder, 4-stroke diesel engine. Its specification is shown in Table 1. A computer controlled test bench having a dynamometer coupled with the engine and other modified and adapted components were used for the test as shown in Figure 1. NOx, HC, CO and smoke were measured using an exhaust emission analyzer which helped to have a direct reading. The conventional single cylinder diesel engine is modified to PCCI-DI mode of operation by adapting compressed air assisted port injection of methanol. Making advanced injection timing of 25o crank angle before TDC and proper EGR setting were also used as techniques of modifying the conventional engine to PCCI-DI mode. Dieseline which is a mixture of diesel and gasoline (90:10 in % of diesel to gasoline) was applied through direct injection.

Table 1 Test engine specification and operational conditions

TM3/02	**One cylinder, 4-stroke, diesel**
Bore (mm)	69
Stroke (mm)	60
Speed (RPM)	3600
Power HP (KW)	4.8 (3.5)
Torque (maximum)	10.4 Nm @ 2400 rpm
Methanol port injection system	Air-blast methanol port injection in 3 bar pressure

For EGR system, Workshop manufactured 12 in number tubes were used in designing the cooler which used water as a coolant. Table 2 indicates the dimensions of the cooler used for the EGR system.

Table 2 Dimensions of the EGR cooler

Number of tubes	12
Inner diameter	18 mm
Tube length	400 mm
Tube thickness	1 mm

In choosing and adapting the EGR cooler dimensions for manufacturing and assembly various published articles were referred [10, 11]. For the EGR system applied for the experiment a separate reservoir for the coolant water was arranged. External electrical heating mechanism was developed to warm the circulating EGR coolant water just to have comparable coolant temperature with the actual coolant temperature in a radiator of a conventional engine. The combustion applies dual fuel combustion technique by using direct injection of dieseline (pre blend of diesel and gasoline) and compressed air assisted port injection of methanol.

1-Engine, 2-Motor, 3- EGR cooler, 4- EGR valve, 5- Coolant reservoir, 6-Intake port, 7- Dieseline reservoir, 8 - Methanol reservoir, 9- Air Compressor, 10- Smoke meter, 1- Control unit.

Figure 1 Experimental engine setup in PCCI-DI conditions

2.1. Optimization Method for the PCCI-DI diesel engine

Grey relational approach was applied for the optimization approach. The signal to noise (S/N) ratio was computed following the lesser being the better for lower emission results.

$$\frac{S}{N} = 10\ \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} y_{ij}^{2}\right) \ldots\ldots\ldots\ldots(1)$$

Normalizing calculations for S/N ratio

$$Z_{ij} = \frac{\max\left(y_{ij}, i = 1,2,\ldots\ldots n\right) - y_{ij}}{\max\left(y_{ij}, i = 1,2,\ldots\ldots n\right) - \min(y_{ij}, i = 1,2,\ldots\ldots n)} \ldots\ldots\ldots\ldots(2)$$

S/N values lower being better

n - number of measurements taken in a trial, y_{ij} - i^{th} result in j^{th} experiment

3. Results and discussion

3.1. NOx Emissions

Increased in EGR rate resulted a decrease in NOx emissions due to the dilution and thermal effects from the EGR as shown in Figure 2. In-cylinder temperature can be judged from NOx amount. Premixing conditions helped to have minimized NOx emissions during better load operating condition, which is assisted by the EGR application.

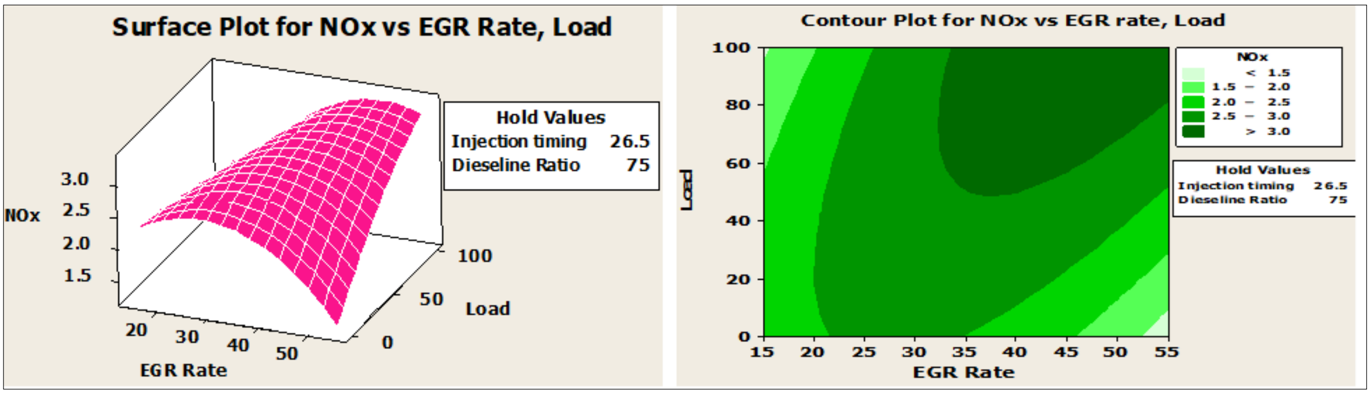

Figure 2 Surface and Contour plots of NOx vs EGR Rate, load

The contour plot indicated in Figure 2 reveals that in conditions of low loads there are results of low NOx but demanding larger EGR rates. These lower load results are obtained due to the impact of high EGR affecting the amount of oxygen from the dilution effect which decreases the rate of chemical reaction. In these study this effects are minimized through the application of pressurized air from the air compressor into the inlet port which improves the thermal efficiency and degree of combustion.

3.2. HC Emissions

Higher EGR rate leads an increase in HC where as a decrease in NOx productions. This is due to the low combustion temperature of the PCCI-DI mode set up that caused due to lower combustion temperatures results in reduced oxidization of HC molecules. The other probable cause is the lower cetane number of the fuel used for the test affects the auto ignition features which enhance the quenching impact that could increase HC productions.

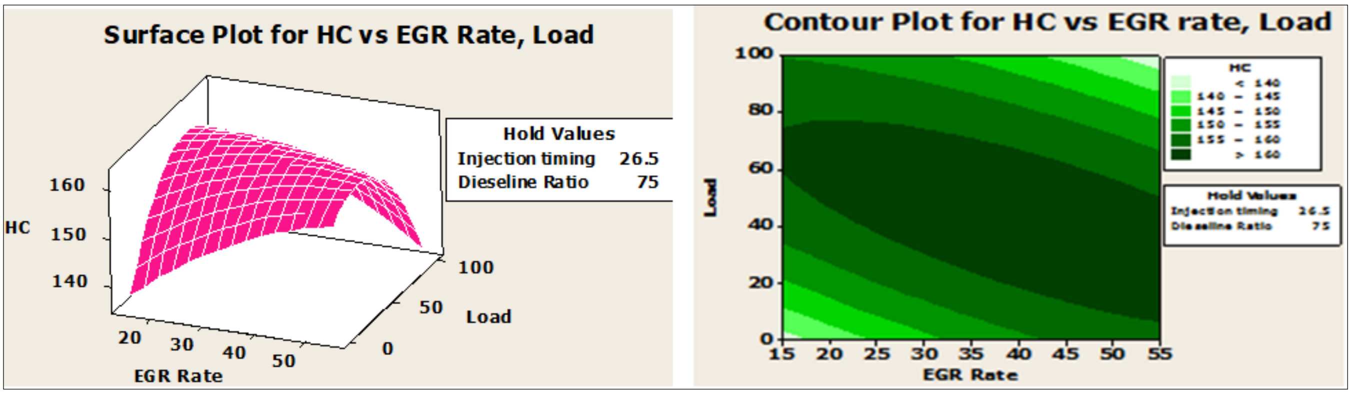

Figure 3 Surface and contour plots of HC vs EGR Rate, load

The lean mixture formation in premixed combustion and lower temperature of combustion basically contributed a lot for the reduction of NOx. In this experiment higher EGR rates resulted another trade-offs between CO, HC emissions with that of smoke emissions.

3.3. CO Emissions

Increase in EGR rate resulted increased productions of HC and CO (particularly at higher EGR rates) due to the combustion mode of the experimental setup which is a low temperature mode of combustion due to the use of EGR. That couldn't effectively combust or burn. It is well known that CO and HC emission results are also due to the incomplete combustion in the cylinder. At low load conditions and proper EGR rate combination HC and CO were minimized but at higher loads both HC and CO were increased due to the effect of EGR as shown in Figure 3,Figure 4 and Figure 5 that brings shortage of oxygen.

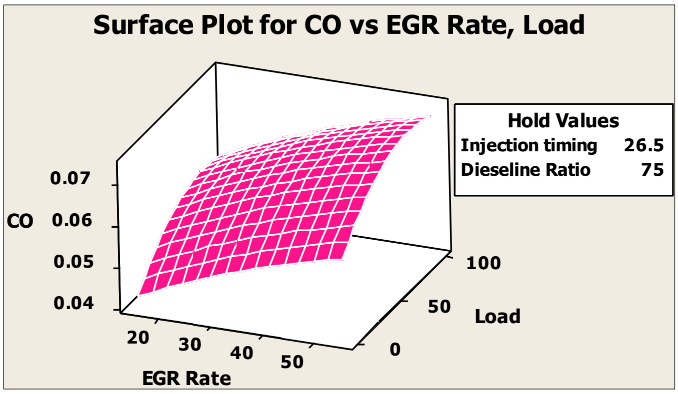

Figure 4 Surface plot of CO vs EGR Rate, load

The application of EGR results lean mixture and this together with the ignition delay increases the premixing time of air and fuel. The intake air/fuel mixture is diluted by the increased EGR rate which lowers the oxygen amount as discussed above. This has an impact on the combustion rate due to the decrease in combustion temperature causing less fuel burning which results an increase in HC and CO.

3.4. Smoke Emissions

Lower smoke values were registered by lowering EGR rates in both lower and medium loads as displayed in Figure 5.

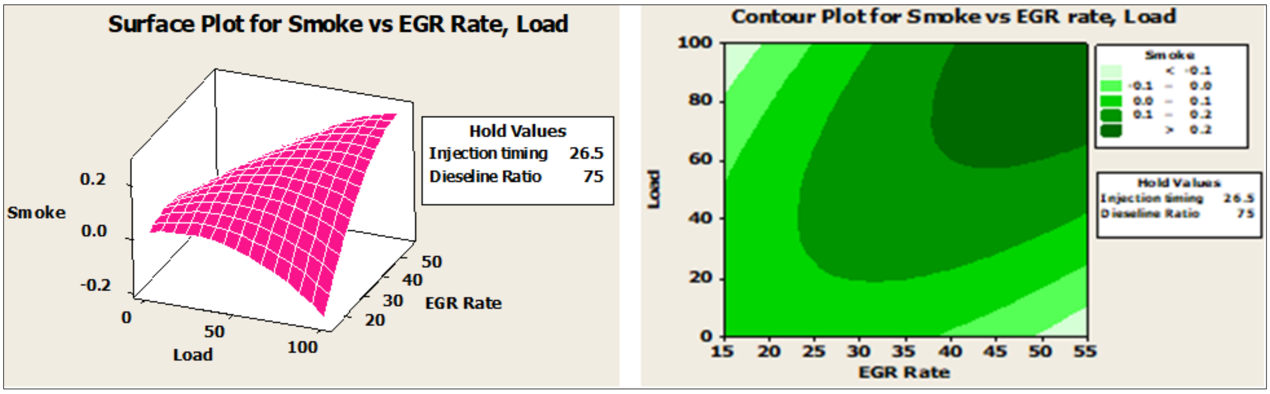

Figure 5 Surface and contour plot of Smoke vs EGR Rate, load

As indicated in Figure 3 the increase in EGR rate results a decrease in NOx amount and there is greater increments in CO amount. Since the higher EGR ratio weakens the combustion but this effect is minimized by applying cold type EGR. This shows that CO with NOx trade off relations is minimized with the increase in EGR rate that is mostly difficult to attain in conventional diesel engines.

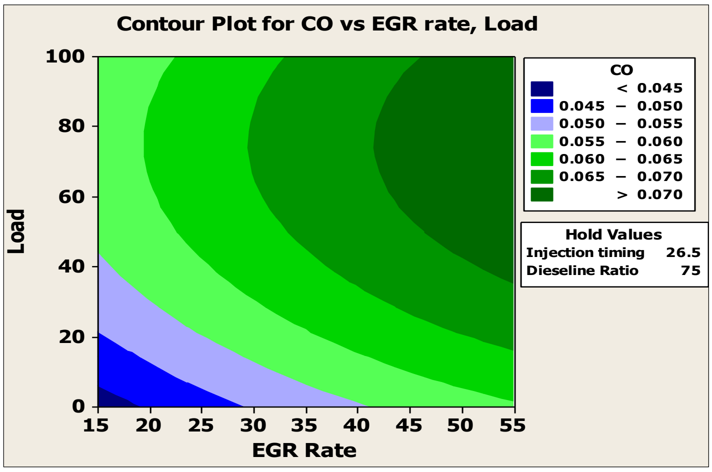

Figure 6 Contour plot of CO vs EGR rate, load

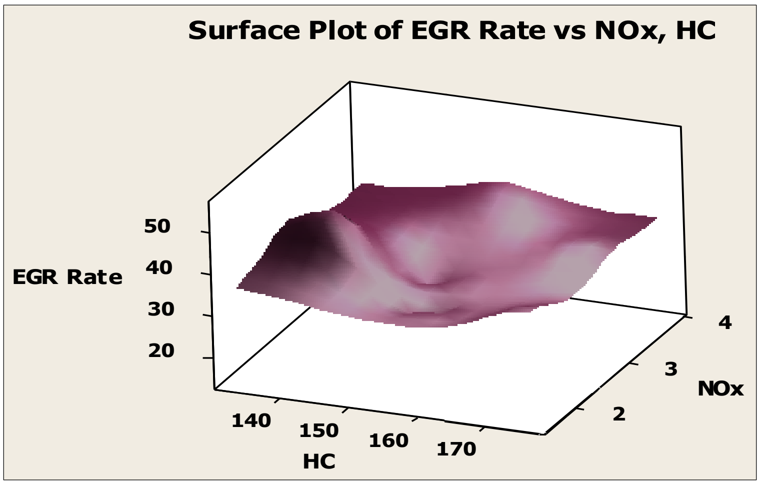

Figure 7 Surface plot of EGR Rate vs NOx, HC

Similarly HC also indicated a minimized or improved trade-off relations with NOx that is for the increase in EGR rate HC and NOx emissions are showing almost similar tendencies which was challenging in conventional diesel combustion. The creation of improved air-fuel premixing in this combustion setup contributes formation of less fuel-rich pockets in addition to forming a low temperature combustion which helped for the optimal production of CO, HC, and NOx and smoke amounts. From the above results of figure 3, Figure 4, figure 6 and Figure 7; CO, HC and smoke results are increasing in relation to the increase in EGR rate. In this regard excess EGR application should be avoided to minimize luck of oxygen which affects the emission results. Cooled exhaust gas through EGR cooler was made to recirculate into the combustion chamber which reduces the cylinder temperature. This is due to the presence of water and carbon dioxide in the exhaust gas which are having high specific heat capacity. This has made the impact for the reduction of NOx in the PCCI-DI setup. Affecting the combustion characteristics to enable the features of PCCI combustion mode were made effective by utilizing EGR particularly through varying and optimizing EGR rate.

In this investigation the EGR rates used for the several tests indicated that they affect the combustion stability and emission results. From this finding it was observed that increasing EGR rate has the effect of minimizing smoke and NOx emissions on this methanol port injected PCCI-DI combustion setup of a diesel engine. On the contrary effect of increase in HC and CO emissions were obtained but due to the optimization work on the operating parameters the increase in percent is better than the previous study results.

Also this experimental study tried to investigate EGR rate impacts on engine load conditions and thermal efficiencies. For the chosen experimental engine setup optimized EGR rate were found which has compromised effect on emission and combustion of this LTC of the PCCI type experimental set up. From the experiment the effect of different EGR levels or rates on smoke amount were seen and from the ranges of EGR rates applied for the tests as the EGR rate increases smoke level increased. In most cases applying EGR at upper loads was found challenging which is due to the decrease in the diffusion combustion that result an excessive increase in smoke level. At lower loads, the HC which is available in the EGR could probably recirculate for combustion again in the mixture, causing lower unburned fuel in the exhaust which improves the thermal efficiency. In addition, hot EGR would increase the intake charge temperature that would affect the combustion and the exhaust characteristics.

4. Conclusion

Most studies explained that EGR is considered as the most significant engine operating parameter/factor affecting the results of emissions. Considering these explanations this study investigated the impact of EGR rate variation on emissions on PCCI-DI diesel engine. Due to the dilution and thermal effects from the EGR increasing the EGR level or rate caused a reduction in NOx but an increase in HC and CO emissions. From the experiment larger EGR rates were demanded to decrease NOx at low load conditions. Higher EGR rates also resulted another trade-offs between HC, CO emissions with that of smoke emissions. By lowering EGR rates in both lower and medium loads, lower smoke values were registered. Minimizing the trade-off relations of CO with NOx were attained by increasing the EGR rate which is mostly difficult to attain in conventional diesel engines. Similarly improved trade-off relations of HC with NOx were observed which indicates that for the increase in EGR rate HC and NOx emissions are showing almost similar tendencies which was challenging in conventional diesel combustion. In this regard excess EGR application should be avoided to minimize luck of oxygen which affects the emission results. Presence of water and carbon dioxide in the recirculating exhaust gas made its contribution for the reduction of NOx in the PCCI-DI experimental setup. In this investigation the EGR rates used for in several tests indicated that they affect the combustion and emission results. From this finding it was observed that increasing EGR rate has the effect of minimizing smoke and NOx emissions on this methanol port injected PCCI-DI combustion setup of a diesel engine. On the contrary effect of increase in HC and CO emissions were obtained but due to the optimization work on the engine operating parameters together with the impacts of compressed air assisted methanol port injection and proper ratio of dieseline direct injection the increase in percent is better than the previous study results. In most cases applying EGR at upper loads was found challenging which is due to the decrease in the diffusion combustion which made an excessive increase in smoke level.

Compliance with ethical standards

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Disclosure of conflict of interest

Authors fully declare that there is no conflicting of interests.

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