

Experimental Optimization of Engine Operating Parameters for Low Emissions in Diesel Engine in PCCI-DI Combustion Mode



Getachew Alemayehu Lakew

A Dissertation Submitted to

The Department of Mechanical Engineering

School of Mechanical Chemical and Materials Engineering

Presented in Fulfillment of the Requirement for the Degree of Doctor of
Philosophy in Automotive Engineering

Office of Graduate Studies

Adama Science and Technology University

December, 2022

Adama, Ethiopia

**Experimental Optimization of Engine Operating Parameters for Low
Emissions in Diesel Engine in PCCI-DI Combustion Mode.**

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Declaration

I hereby declare that this Dissertation entitled “**Experimental Optimization of Engine Operating Parameters for Low Emissions in Diesel Engine in PCCI-DI Combustion Mode**” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials used for this thesis have been duly acknowledged through appropriate citations.

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we, the supervisors of this dissertation, hereby certify that we have read and revised the dissertation entitled “**Experimental Optimization of Engine Operating Parameters for Low Emissions in Diesel Engine in PCCI-DI Combustion Mode**” prepared under our guidance by Getachew Alemayehu submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Automotive Engineering. Therefore, we recommend the submission of the dissertation to the department for further review and defense.

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DEDICATION

This work is in memory and dedication to my beloved wife Genet Desalegn Negassa, lately passed away on Jan. 03- 2020.

“FOREVER IN MY HEART”

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ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of variance
ASTU	Adama Science and Technology University
CA BTDC	Crank angle before top dead center
CDC	Conventional Diesel Combustion
CH₃OH	Methanol
CI	Compression ignition
CN	Cetane Number
CO	Carbon Monoxide
COV	Coefficient of Variation
DI	Direct injection
DICI	Direct Injection Compression Ignition
DME	Dimethyl ether
DoE	Design of Experiments
EGR	Exhaust Gas Recirculation
GRA	Grey relational analysis
HC	Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
IMEP	Indicated Mean Effective Pressure
K	Kelvin
LTC	Low temperature combustion
NO_x	Oxides of Nitrogen
P	Pressure
PCCI	Premixed Charge Compression Ignition
PCCI-DI	Premixed charge compression ignition direct injection
PFI	Port fuel injection
PM	Particulate matter
PPC	Partially premixed compression
PPCI	Partially premixed compression ignition
PPM	Parts Per Million
RCCI	Reactivity controlled compression ignition
S/N	Signal-to-noise

SI	Spark ignition
SOC	Start of combustion
SOI	Start of ignition
T	Temperature
TDC	Top dead center
UHC	Unburned hydrocarbon
VCR	Variable compression ratio
ϕ	Equivalence ratio

ABSTRACT

Researches worldwide are nowadays focusing on finding out more energy efficient and ultra-low emission engines for automotive applications which could bridge the gap between conventional and electric vehicles. The desire to reduce exhaust emissions particularly NO_x (Oxides of Nitrogen) and PM (Particulate matter) by many researchers had shown promising results through low temperature combustion (LTC) approaches. This emerging advanced combustion concept in Premixed Charge Compression Ignition (PCCI) mode attracted global attention in maximizing engine efficiency and meeting stringent emission norms compared to the conventional. Even though LTC combustion mode results in prominent advantages in terms of simultaneous reduction of both NO_x and PM in addition to lower specific fuel consumption, it basically suffers from the problem of HC (Hydrocarbon) and CO (Carbon Monoxide) emissions which make the concept that has yet to find commercial success. This study conducted experimental investigations for the objective of finding optimized operating parameters; injection timing, % of exhaust gas recirculation (EGR), dieseline ratios and engine load for lower emissions in LTC engine operating in PCCI-DI (Premixed Charge Compression Ignition-Direct Injection) combustion mode. The engine set up uses dieseline direct injection and methanol port injection. Methanol having high oxygen content and high volatility component was injected through air-blast port injection using a workshop air compressor into the intake manifold with 12cm PFI positions to the intake valves to form a premixed homogeneous mixture. For the study a single-cylinder diesel engine was adapted to PCCI-DI combustion mode of operation. Emission results were measured, optimized and analyzed. This study confirmed dieseline direct injection with methanol port injection is capable of reducing emissions and better NO_x with HC and CO trade-offs which minimized the drawbacks of PCCI combustion that could enable the commercialization of advanced combustion LTC engines. Algorithm applying a hybrid of grey relational analysis together with Taguchi method is used in obtaining optimized results. For the design of experiments and conducting tests Taguchi's L_9 orthogonal array was applied. The Taguchi's S/N ratio which was found using the emission results was used to obtain grey relational grade. 3D surface and contour plots for the control factors versus emissions were developed and discussed. Optimum combination of the control operating parameters was found using the analysis of grey relation and analysis of variance (ANOVA). Following the multi-response optimization; advanced injection of 25° BTDC, 25% EGR, dieseline 90:10 in % and load 75 % ($A_2B_1C_3D_3$) is optimal combination resulting reduction of 68.02% NO_x and 62.37% in smoke comparing with baseline. In addition, in this experimental setup the impact of different EGR configurations (No EGR, Cold EGR and Hot EGR) on Exhaust Emissions of PCCI-DI engine were studied. Results showed that both cold and hot EGR configurations resulted in lower emission of NO_x plus smoke at different loads. At low loads hot EGR showed promising results of lower HC and CO than cold EGR with a difference of 18.33% and 33.3% respectively. NO_x and smoke reductions occur simultaneously and better trade-offs were obtained using cold EGR configuration. Further investigation particularly on applying port injection of alcohol together with better EGR configuration on PCCI-DI (LTC engines) should be studied in better equipped laboratory setups in order to minimize the drawbacks of LTC engine for its commercialization.

Key Words: ANOVA, Dieseline, Grey Relational Analysis, LTC, Methanol, Optimization, PCCI-DI, Emission

PUBLICATIONS

Journal Papers

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CHAPTER ONE

INTRODUCTION

A novel approach should be investigated for internal combustion engines and fuels for fuel economy improvement and exhaust emission reductions. In the world of today engines which are the main source of transportation power are one of the most key machines for transforming the energy of hydrocarbon fuels into useful mechanical work. Motor vehicle manufacturers are finding it difficult to maximize profit on one hand and meet environmental compatibility requirements on the other. Developing cleaner and efficient engines by researchers and engine manufacturers is unquestionable due to tightening legislation for emissions and increasing demand for fuel economy.

Combustion in IC engines are moving towards unexplored combustion concepts where innovative combustion theories are being developed following several engine control parameters. Advanced low temperature combustion engines for automotive applications are one of the developments in this regard. Achieving optimal efficiency and emission behaviors of these future combustion engines requires new approaches or methodologies of fuel use and engine control parameters.

Low Temperature Combustion (LTC) strategy has received much attention from the engine combustion research community due to its provision of simultaneous low NO_x and soot emissions together with high thermodynamic cycle efficiency. LTC is able to meet strict emission criterions in the absence of expensive and complex exhaust after treatment systems. Main forms of achieving low temperature combustion strategy includes; Homogenous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI), Reactivity Controlled Compression Ignition (RCCI), and Partially Premixed Combustion (PPC). These strategies are achieved by modifying engine control parameters and fuel type (Maurya, 2018). Which control parameters of an engine operation with which types of conventional as well as alternative fuels including alcohols should be matched and optimized for these strategies were not fully addressed by researchers.

Homogenous Charge Compression Ignition (HCCI)

The operating mode in HCCI is similar to conventional SI engine in charge preparation strategy and similar to CI engines in combustion initiation process. Even though HCCI operation mode called “homogeneous” uses premixed charge, in real engines, there are always thermal in-homogeneities (due to wall heat transfer and convection) and fuel concentration in-homogeneities (Dec JE, 2015) (difficulties in preparing fully homogeneous charge). The HCCI engine is operated on globally leaner mixture in order to control the combustion rate, which leads to lower combustion temperature (Maurya, 2018). Researchers reported that though there is a good thermodynamic characteristic of HCCI combustion, the technique of HCCI approach possesses the difficulty of managing the combustion features related to ignition timing and heat release rate (Dempsey, A. B. Walker et al. 2014) which are also common features in conventional engines.

Reactivity Controlled Compression Ignition (RCCI)

Reactivity-Controlled Compression Ignition (RCCI) strategy is also in the category of partially premixed compression ignition i.e. dual fuel LTC strategy. In this strategy, two fuels of different auto-ignition reactivities (high and low reactivity) are used for premixed charge preparation by in-cylinder fuel blending. The RCCI engine can also be operated on a single fuel by adding small amount of cetane improver (Maurya, 2018) in directly injected fuel.

Partially Premixed Combustion (PPC)

Sometimes it is also referred as PCCI. In PPCI fuel is injected during the compression stroke to allow sufficient premixing before ignition and also the direct fuel injection helps to modulate mixing time. In diesel PPCI mode, two different strategies of direct injection are used, namely, early direct injection and late direct injection with respect to conventional diesel combustion (CDC) injection timings (Hardy WL and Reitz RD, 2006). PPCI strategies produce fuel stratification in cylinder by direct injection of either a portion or all of the fuels.

Premixed Charge Compression Ignition (PCCI)

PCCI is similar to HCCI where a part of charge is premixed and the rest is direct injected to achieve less NO_x and soot emissions (Srihari, Thirumalini et al. 2017). This concept is a hybrid between HCCI and conventional DICl combustion. PCCI combustion is distinguished from HCCI combustion since PCCI involves in-cylinder injection and features significant equivalence ratio gradients with the fuel and air mixture. Fuel in PCCI combustion usually is directly injected in the combustion chamber in the vicinity of top dead center (Miao, Zhang et al. 2011). PCCI is usually more suitable for diesel fuel engines and not dependent on early fuel injection (Kobayashi, Najima et al. 2007).

Researchers found that the traditional NO_x–soot trade-off that exists with conventional diesel combustion can be defeated with diesel PCCI. It is low temperature combustion strategy typically used for diesel-like fuels. Sometimes it is also referred as PPCl are proposed to achieve higher engine load (Maurya, 2018) while keeping the benefits of HCCI mode. The drawbacks of HCCI having limited operating range were proposed to be overcome by PCCI through introducing concentration stratification to control the combustion rate. The possibility of overcoming the difficulty of combustion phasing control, misfire at low and knocking at high loads, cold start problem, difficulty in homogeneous mixture preparation, high rate of pressure rise and high level of noise, high level of HC and CO emissions etc from HCCI engine through PCCI engine were studied. The study also indicated that the combustion characteristics of PCCI could potentially enable the use of emission control devices. It also showed successful development of Diesel and Petrol fueled PCCI for heavy duty vehicles, for the cases HCCI engine cannot achieve NO_x and PM emission standards (Selvan, Dhinesh et al. 2018).

PCCI is one of the most promising solutions that combine the advantages of both SI and CI combustion modes. It gives thermal efficiency close to the compression ignition engines and resolves the associated issues of high NO_x and PM simultaneously (Bhiogade Girish E. and Suryawanshi Jiwak, G. 2017). PCCI shows lowest fuel consumption and NO_x emission but higher HC emission. PCCI potentially achieves ultra-lean burning under higher compression ratio than possible in conventional SI engines and elimination of NO_x and PM to an extent not possible in an ordinary CI engine (Aoyama T., et al. 1996; Najt P. and Foster D.E., 1983; Thring R.H., 1989).

PCCI is a promising concept for achieving low emissions at part load operations. This technique can be successfully applied to conventional direct injection CI engines with low costs and fewer modifications (Bhiogade Girish E. and Suryawanshi Jiwak, G., 2017). The brake thermal efficiency in PCCI mode little decreases comparing to CI mode but NO_x and Smoke emissions decreases drastically in PCCI mode comparing to CI mode of operation. EGR percentage was used up to 30 %. Further increased in EGR % was increasing HC and CO emission also combustion instability (Bhiogade, G., Suryawanshi et al. 2016).

PCCI combustion is obtained with a proper combination of high EGR levels and advanced combustion. A lower SOI than 16 °CA bTDC is not able to allow the engine to enter the PCCI combustion mode, regardless of the EGR level (D' Ambrosio, S. Iemmolo et al. 2016). Which EGR level is appropriate in line with proper time of injection for best emission results is still unsolved issue in such advanced combustion engines particularly in PCCI approaches.

PCCI-DI Combustion

In this mode of combustion both port injection and direct injection are used to supply the fuel into the combustion chamber. An added advantage is its dual fuel capability and improvement of combustion characteristics. A Premixed Charge Compression Ignition Engine with direct injection (PCCI-DI) helps in overcoming these limitations of operating range and control of combustion. The reduction in NO_x in the PCCI-DI is advantageous since it reduces the effect on environment causing acid rain and smog (Srihari S. and Thirumalini S, 2017). The combination of premixed charge compression ignition and conventional direct-injection compression ignition combustion is studied in a DME engine. This combustion mode is referred to as PCCI-DI combustion (Ying W., Longbao et al. 2010; Yuwei, Zhao et al. 2021)

There is a reduction of NO_x emission up to 28% with PCCI-DI in Diesel-Diesel mode when compared to conventional DI mode. This could be due to the comparatively lower combustion temperature obtained when using PCCI-DI mode. There is a reduction in smoke opacity with PCCI-DI engine when compared to that of Diesel-Diesel and conventional DI mode. CO₂ emissions are decreased with PCCI-DI setup. HC and CO emissions are increased considerably with PCCI-DI mode (Ying W., Longbao et al. 2010). How to

avoid these HC and CO increments without affecting the other emission reductions particularly NO_x and particulate matters in this PCCI-DI mode of operation is unresolved question for researchers in the field. Considering the above mentioned advantages and features this study used the PCCI operating mode together with the direct injection (DI) approach.

Even though LTC engine gets consideration from the combustion research community for its higher thermal efficiency along with simultaneous reduction of NO_x and PM to ultralow levels, it has many challenges which makes their production and commercialization not yet successful. Their limited operating load ranges, poor combustion timing controllability, high combustion generated noise, HC and CO emissions are limitations. This research work aims to work on the emission challenges of HC, CO and smoke productions particularly on the premixed charge compression ignition-direct injection (PCCI-DI) combustion mode without significantly penalizing other performance parameters. The research work used experimental and DoE (design of experiments) approaches in minimizing the challenges through optimizing the chosen operating parameters of injection timing, EGR % and diesel/air ratios. During the optimization process, algorithm of grey relational analysis hybrid with Taguchi method was implemented. In designing of experiments and conducting tests Taguchi's L₉ matrix was applied. Such research efforts could be part of solutions in minimizing the growing global environmental concerns.

1.1 Background

Developing more energy-efficient and environmentally friendly combustion strategies which enable us to use significantly less petroleum and reduce greenhouse gas and other regulated emissions is unquestionable. Researches (Dempsey, A. B. Walker et al. 2014; Kannan, 2016; Solouk, Shahbakhti M. et al. 2014; Rajesh Kumar B. and Saravanan S, 2016) revealed that low temperature combustion strategy will increase efficiency beyond current state-of-the-art engines and reduce engine-out emissions of nitrogen oxides (NO_x) and particulate matter (PM) to near-zero levels. LTC or low temperature combustion mode is a leading strategy to maintain combustion temperature below the formation temperature of NO_x and soot and has shown a promising application in light vehicle diesel/gasoline engines. Exploiting the potential synergy between LTC strategies and basic

operating parameters needs many research efforts. Altering and optimizing operating Parameters for low temperature Combustion Engines is necessary to meet emission standards and expected operational load ranges. New fuels are also essential for LTC strategies in maximizing the thermodynamic efficiencies and operability across a wide speed/load ranges (Burger J. L., Gough R. V et al. 2013). The Premixed Charge Compression Ignition (PCCI) principle under LTC strategy is a comparatively innovative concept which has shown the possibility of high efficiency, lower emissions of nitrogen oxides (NO_x) and soot below future emission regulations; that has yet to find commercial success.

Premixed charge compression ignition (PCCI) is a combustion concept under low temperature combustion strategy typically used for diesel-like fuels. In PCCI strategy, typically diesel is injected early in the compression stroke to prepare the premixed charge (Maurya, 2018). It has been recently developed with the aim of tackling the problem of high emissions level of traditional direct injection diesel engines.

The use of fuel blends (incorporating fluids such as natural gas or gasoline) for compression ignition engines may aid in efforts to reduce nitrogen oxides (NO_x) and particulate matter emission. Researches indicated that methanol works well as an engine fuel, with low energy consumption, low emissions and low environmental and health impact (Martin Tunér, 2015). Lower CN and raised volatility fuels were also shown to be most suitable for PCCI (Leermakers, C. A. J. Bakker et al. 2013) concept, with the reactivity determining the possible load range.

In early direct injection PCCI combustion, various strategies exist such as premixed lean diesel combustion, multiple stage diesel combustion, homogeneous charge intelligent multiple injection combustion, premixed compression ignition, uniform bulky combustion system and narrow angle direct injection (Maurya, 2018). The PCCI-DI concept is a compromise to full PCCI in that only a portion of the fuel is premixed and the majority of combustion is still controlled by injection timing. Studies showed that the best potential for reducing NO_x by PCCI-DI combustion exists at the lighter load conditions. Also they pointed out ways of exploring further the full NO_x reduction potential of PCCI-DI combustion. The study revealed that further investigations to be done in PCCI-DI combustion to optimize the combustion should be explored such as reduced compression ratio, piston bowl changes, and injector nozzles with a high number of small holes and narrow spray angles (Kannan, 2016).

An investigation made (Kanda T., Hakoziaki T. et al. 2005), on premixed charge compression ignition (PCCI) combustion which is achieved by the early injection of conventional diesel fuel to the combustion chamber. Their studies showed that effective reduction in NO_x emissions but challenge of the promotion of the formation of a fuel wall-film on the piston bowl wall, which was one major cause for increased soot, HC and CO emissions. By using secondary injection of a small amount of fuel at the appropriate timing they found out that both IMEP and COV were improved.

The objective of this research work is optimizing the control parameters for less NO_x, HC, CO emissions and better load combinations using experimental investigation and DoE. The control parameters include injection timing, EGR and fuel ratios of direct injected dieseline and manifold injected methanol fuels. For the experiment conventional diesel engine was adapted to LTC engine of the PCCI combustion mode in which the other objective establishing LTC diesel engine setup was fulfilled.

Since this kind of investigation would require a significant number of runs, the statistical design of experiment methodology was adapted to reduce significantly its number. As per the DoE approach, a set of factors; injection timing, rate of exhaust gas recirculation (EGR) and premixing ratios of dieseline fuel, were optimized. For each of them, two levels “high” and “low” were defined in a range of reasonable values. The evaluation of the effects and the weight of each factor and their combination on the outputs were obtained by combining the levels of all the factors. Moreover, the experimental design allowed the experimenter in identifying the optimum combination of factor levels enabling to achieve the predefined target (Simpson, 1998). For many process optimization problems in industries, the root cause of the problem is sometimes the interaction between the factors rather than the individual effect of each factor on the output performance characteristic or response (Antony, 2003). The effect of one control factor is dependent upon the other control factor which is also confirming that the interaction plots are used to compare the relative strength of the effects across control factors. Experimenters used DoE to obtain an optimized calibration for the best trade-off among the expected output values (Patel, 2012). A hybrid of the algorithm grey relational analysis with Taguchi method was implemented which helped during the multi response optimization procedure. Grey-Taguchi was implemented in several IC engine optimization works and was found a convenient optimizing tool.

Applying LTC engines in the automotive industry can act as a bridging technology for a fully electric vehicle fleet until when the battery technology becomes cheaper, the battery charging infrastructure becomes more accessible and the electric power generation cycle becomes cleaner (Solouk, Shahbakhti, M. et al. 2014).

Low Temperature Combustion Principle

In the pursuit of developing an engine having ability to yield ultralow NO_x and soot emission along with higher thermal efficiency, several new CI combustion strategies have been demonstrated in the last two decades. A common name for these combustion strategies is LTC mode. It is an advanced combustion concept for internal combustion engines. In LTC strategy, adequate premixing between the fuel and air is created to avoid diffusion combustion in a globally dilute environment. The combustion of lean fuel–air mixture leads to lower combustion temperatures in the cylinder. In LTC engines, charge dilution (with either air or EGR) is typically used to avoid high NO_x formation by lowering combustion temperature (Maurya, 2018) in the cylinder.

1.2 Statement of the Problem

Engine manufacturers and research communities have long recognized the benefit of developing emission reduced diesel engines as per the current strict emission regulations including fuel consumption standards. In connection with this, researchers confirmed that for CI engines to meet the exhaust emission standard requirements, more investigation work should be done on engine control parameters.

Through application of various pathways under LTC techniques it was found out that smoke emissions were always near zero and NO_x emissions were controlled at a relatively low level. LTC combustion mode including PCCI-DI resulted in prominent advantages in terms of simultaneous reduction of both NO_x and PM in addition to lower specific fuel consumption (Ying W., Longbao et al. 2010). Various potential and promising ways including both experimental and numerical simulation studies for the application of LTC for both gasoline and diesel engines were investigated and ongoing for the past several years. Even though these studies showed promising results in regard to minimizing emission problems from engines particularly diesel engines, still further studies of optimization and

tuning the engine operating control parameters including fuel modifications and adaptations are needed to fix the challenges/gaps of excess HC and CO productions and their inappropriate trade-offs with NO_x in order to cope up the tough emission standards.

Studies conducted to realize the promising LTC technology or approach has faced a gap of formation of incomplete combustion products of CO and HC emissions including limitations of running at high-loads. These problems and challenges faced by this LTC approach by researchers needs further research studies in overcoming these gaps. Referred literatures indicated, avoiding the gaps/limitations of the LTC approach helps in developing an engine having ultra-low emission features which is used for automotive applications. LTC engine is not yet commercialized due to its shortcomings and limitations. Attaining simultaneous low NO_x, HC, CO emissions including better NO_x with that of HC and CO trade-offs in LTC technology including in PCCI would speed up the production and commercialization of the promising advanced combustion engines which could be competent with the electrically driven vehicles. As pointed out in the reviewed literatures, making internal combustion engines with ultra-low emission characteristics is still challenging that needs more optimization work to have the best engine possessing its operating parameters functioning in their optimized state for ultra-low emission results. This study has addressed the search of optimized engine control parameters that lower the gaps in LTC strategy of the PCCI-DI type to have low emission characteristics with insignificant impact on performance. In this study to obtain the optimized engine operating control parameters which minimize the gaps that arise from studies in LTC approach (Dec JE, 2015; Dempsey, Walker et al. 2014; Miao, Zhang et al. 2011; Kobayashi, Najima et al. 2007; Kanda, Uchimoto et al. 2005; T. Yusaf, I. hamawandl et al. 2013; Ekoto, I. W. Colban et al. 2009; Girish and Bhiogade, 2017; Park and Bae, 2013); methanol port injection and direct injection of a pre blended dieseline were applied, adapted and analyzed. Although integrating EGR helps in establishing LTC features, it has negative and positive impacts on emissions including its configurations that these gaps need further investigations. In addition it also addressed recent technology and knowledge gaps in some of our research team on the current research updates on the subject. This research work could also strengthen the Ethiopian Climate-Resilient Green Economy (CRGE) strategy. In adapting technology to the climate change, the transport sector is the one that needs modification and tune up for emission reductions that this study could be part of it. This study supports and attempted to work on health impact an issue that needs sustainability includ-

ing environmental legacy. This is part of the emission reduction initiatives that have been identified and started for implementations.

1.3 Objectives and Approaches

1.3.1 General Objective

The general objective of this study is to optimize experimentally the engine operating control factors (injection timing, EGR %, dieseline ratio and load) for low emissions in PCCI-DI combustion mode including better trade-offs between NO_x with that of HC and CO productions without penalizing performance parameters.

1.3.2 Specific Objectives

The specific objectives of this research work are:

- To analyze the effects of varying injection timing, EGR %, dieseline ratio and load on emissions on the adapted PCCI-DI engine setup using the engine test dynamometer for loading and timing measurements.
- To find the optimum operating parameters for lower emission results and better trade-offs between NO_x with that of HC and CO productions without penalizing other performance parameters.
- To analyze the emission characteristics for the obtained optimum combination of the operating parameters in the pre blended dieseline DI together with methanol port injection of a single cylinder diesel engine in PCCI-DI combustion mode.
- To verify the functionality of the grey-Taguchi hybrid optimization method and tool to find lower emission results in PCCI-DI engine set up.
- To detect the impacts of EGR configurations on exhaust emissions in optimized PCCI-DI diesel engine.

1.4 Significance of the Study

Few African countries have Euro 2 vehicle emission standards and in some others including Ethiopia, vehicle emissions are planned to be covered under fuel efficiency programs (Akumu, 2019). In Ethiopia doing basic emission reduction research and establishing advanced engine research setup which would strengthen CI engine emission reduction are not well established. This study could be part of these attempts.

This research work significantly identified the optimum combinations of the parameters; injection timing, EGR %, diesel ratio and load for better trade-off between NO_x with that of HC and CO productions without penalizing other performance parameters. The results of the study could be an input for scholarly research, policy and theories. The study results would be beneficial for potential audiences in the field which could be practitioners and professional peers, particularly those companies having the dream of commercializing LTC engines for heavy as well as light duty vehicles in solving environmental issues. The study could be also part of the research inputs in realizing the commercialization of advanced combustion engines (LTC engines) that could minimize the major concerns that appear due to heavy use of the conventional combustion engines for automotive and stationary applications; global warming, photochemical smog, carcinogenic particles, acid rains and ozone depletion. In general the significance and benefits of the study comprised the following;

- Satisfying the demand for production of low emission diesel engines through advanced combustion strategy (LTC).
- Reduce environmental impact and benefit businesses i.e. since awareness of environmental issues is growing globally; customers, investors and other stakeholders increasingly prefer to deal with technology businesses that have good environmental credentials.
- Improve the levels of air pollution which is linked with health impacts.
- Reduced fuel consumption by developing such fuel efficient engines.
- Contribution towards the current global significant achievements in engine combustions and emission reductions.
- Meeting the challenges of the future stringent exhaust emission and fuel consumption standards.
- Enable ASTU to involve in advanced combustion engine research and make a link with researchers and universities in the field globally.

1.5 Scope of the Study

The research work is delimited to experimental investigation and DoE analysis on PCCI-DI combustion mode in comparison with the conventional setup of a light duty compression ignition engine. It mainly focused on the study and analysis of emission aspects on

the chosen operating parameters and conditions. The scope of this study is to identify and analyze the optimum combination of the operating parameters (injection timing, EGR %, dieseline premixing ratio and load) for lower emission results and better trade-off between NO_x with that of HC and CO productions without significant penalizing of other performance parameters. The study also included elements of EGR configurations by investigating the influences of EGR configurations on exhaust emissions in the optimized PCCI-DI diesel engine set up.

1.6 Limitations, Gaps and Further Developments

In achieving LTC operation meeting fully the control of auto ignition, homogeneous mixture and high power output requirements in PCCI-DI combustion mode is a limitation on top of maintaining NO_x, HC and CO emissions low as per the current and future emissions standards. Since LTC combustion technology is not widely applied particularly in developing countries, adapting the conventional engine setup is a limitation due to the absence of well-equipped laboratory facilities. LTC combustion has unique features that make it more amenable to analysis. Fully perfect production of high quality engine calibrations through DoE has its own minor limitations.

Engine operating parameters (start of injection, EGR percentage, dual fuel applications and engine load) under PCCI mode of combustion resulted gaps of increasing HC and CO emissions above the acceptable ranges and unwanted trade-offs between NO_x with that of HC and CO. How these gaps to be resolved is a question that has to be addressed and need further work through identifying, proper matching and optimizing the above mentioned parameters.

Similarly gaps of emission results were found due to inappropriate matching of EGR configurations and port fuel injection strategies. Research attempts in solving the gaps particularly in port injection of alcohols for dual fuel combustion in PCCI combustion mode are very rear and needs more work. Even though dieseline was suggested for LTC strategy including PCCI, there is a gap in choosing the proper ratio of diesel and gasoline that needs further optimization and tuning.

1.7 Benefits and Beneficiaries

Vehicle industries need to focus on customer satisfaction and meeting global emission standards which will strengthen international wise market competition. Such research

works would enhance company's effort in meeting the customers' needs and requirements of global environmental standards together with fuel efficiency.

The potential beneficiaries and impacts of the study includes the following

- i. Vehicle companies and engine manufacturers, for economic benefit and meeting environmental regulations and standards, which enables them to bring their products to the market as per the standard.
- ii. Research communities, students, industrial partners and research centers in the field.
- iii. The public, securing emission free environment

1.8 Structure of the Dissertation

In this dissertation, Chapter-2 presents literature review on relevant topics and works done in the field, and Summary. Chapter-3 deals with materials and methods, Introduction, Materials, Methods, Flow chart methodology, experimental setup, experimentation and analysis, validation test, test fuels, experimental procedures, DoE and optimization tests. Chapter-4 discusses the effects of the chosen operating control parameters on emissions in PCCI-DI diesel engine setup. It consists; surface, contour and interaction plots for the emission analysis. It also includes the effect on exhaust gas temperature, impacts from different engine load applications and effect of methanol port injection/premixing. This chapter also discusses EGR % effects in PCCI-DI combustion together with experimental scheme and methodology. In addition it explains the effects of different EGR configurations on emissions in the PCCI-DI diesel engine operation. Chapter-5 describes the results and discussion which includes; experimental observations for L₉ orthogonal array, S/N ratio analysis, optimized PCCI-DI Combustion Emission test results and comparisons with baseline results, performance characteristics test comparisons and also error and uncertainty analysis. Finally conclusions made and future recommendations for better achievements were explained.

CHAPTER TWO

LITERATURE REVIEW

This literature review concentrates on reviewing the topics mentioned below that are the main focuses of this dissertation including reviewing previous investigations which are pertinent to the study. It also discusses the existing gaps and challenges from the former investigations on PCCI-DI combustion diesel engines. The optimization techniques and tools used for the study were reviewed.

2.1 Low Temperature Combustion (LTC) Engines

It is extremely desirable to reduce the amount of NO_x and soot in the exhaust gas of diesel engines. The formation of NO_x is a highly dependent on temperature phenomenon and it takes place when the temperature in the combustion chamber exceeds 2000 K. Hence, in order to reduce NO_x emissions in the exhaust, it is necessary to keep the peak combustion temperatures under control (Varshney, Gaurav et al. 2016). By virtue of their concept, low temperature combustion in IC engines can offer significant benefits compared to the conventional combustion engines in reducing pollutant emissions and fuel consumptions.

A new low-temperature premixed combustion mode on diesel engine of CA6DF (6 cylinder inline, direct injection, turbocharged, common rail and intercooling) by reconstructing key systems were conducted (Miao, X., Zhang, G. et al. 2011) to achieve the simultaneous reduction of NO_x and soot emissions in a volume production. High level of EGR was used to realize low-temperature combustion which largely reduced NO_x emissions. In this study the benefit of cooled EGR were shown in achieving the premixed combustion due to prolonging the ignition delay and also in controlling the increase of soot emissions. The study also explained that by adjusting the injection pressure, injection timing, and EGR % helps in optimizing the engine performances of two different combustion chambers in order to achieve their respective lowest NO_x and soot emissions, meanwhile avoids a significant deterioration of HC, CO emissions, and BSFC but it indicated that still there is a gap of HC and CO emissions.

2.2 HCCI, PCCI and PPCI Combustion

Conventional diesel combustion is prone to the well-known trade-off between particulate matter (PM) and nitrogen oxides (NO_x). To overcome this challenge, new combustion strategies or modes were developed, in which the premixed charge compression ignition (PCCI) is the one considered important. The PCCI combustion mode is also accompanied with HC and CO emissions.

HC and CO emissions are highly linked to ignition delay and equivalence ratio which are in turn affected by the changes in fuel composition and engine parameters. Most studies indicated that incomplete combustion of hydrocarbon fuel results HC emission. Researchers made their effort in identifying the sources of the gaps of HC and CO emissions in diesel LTC regime and some of them found out that liquid fuel film caused by spray impingement on piston bowl is a primary source of HC emissions in narrow-angle early-injection LTC. In contrast, for late-injection LTC, the over-mixing and bulk quenching mechanisms are believed to be dominant for increased HC emissions (Han, Ickes et al. 2012).

A study (Arora, 2016) indicated that the major source of HC emissions in LTC results from over-mixing regions rather than partial oxidation in under-mixing regions. It is generally believed that partial oxidation of locally rich mixture is the major source in LTC.

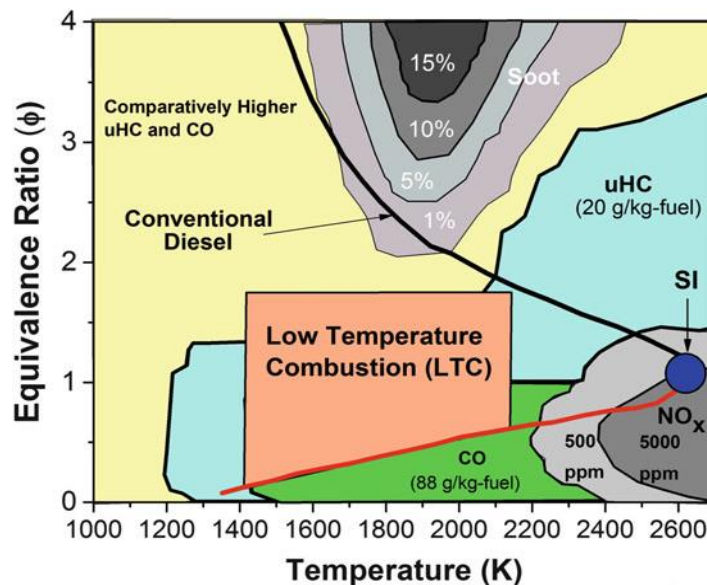


Figure 2.1: LTC operating region on equivalence ratio ϕ - T map

Studies from Figure 2.1 and Figure 2.2 indicated the formation of soot and NO_x based on flame temperature and in-cylinder local equivalence ratio. A study (Arora, 2016) revealed that the main cause of NO_x and soot emissions in the CI-mode is combustion of a stratified charge, where occurrence of local rich regions which either cause high in-cylinder temperatures that increases the NO_x formation or increases the formation of soot.

Also they explained that methods that increase mixture homogeneity contribute to reduce CO emissions from fuel-rich areas like, increasing injection pressure and extending ignition delay, reduce CO by promoting pre-ignition mixing. From the study results (figure 2.2) it was explained that sufficient time of mixing of fuel with air before ignition time avoids high NO_x and soot. Similarly by advanced injection of fuel during compression stroke promotes mixing like in PCCI combustion.

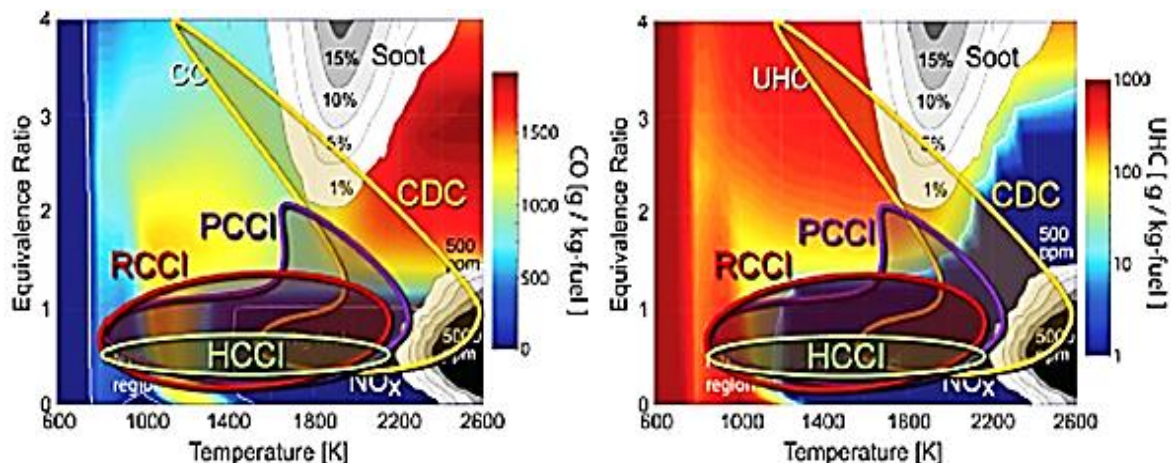


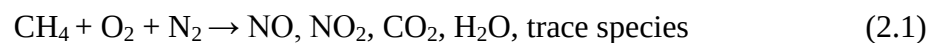
Figure 2.2: Operating regions of several combustion regimes with plots of soot, NO_x, HC and CO (Y. Lee and K.Y. Huh, 2014)

As indicated in figure 2.2, the study showed temperature ranges in which NO_x is formed which is at temperatures higher than 2000 K. Also, by decreasing cylinder temperature and minimizing fuel rich local zones it indicated the possibility of eliminating emissions of soot and NO_x. Reducing soot and NO_x emissions at the same time is still needs further study through exploring various combustion regimes. Low temperature combustion techniques such as HCCI, PCCI, PPCI and RCCI have proven to be promising alternatives to

the conventional Spark ignition and diesel combustion engines because of their ability to reduce the in-cylinder local temperatures and the rich zones simultaneously. In all the three LTC modes, the injection of fuel is either in the port or early during compression stroke in the cylinder. These resulted in the fuel being premixed, hence avoiding the local rich zones in the cylinder. The study (Kannan, 2016) also showed that higher NO_x due to the lower equivalence ratio and also soot production due to higher equivalence.

Simulation studies were conducted to analyze the characteristics of different modes of low temperature combustion (LTC) using ultra-high exhaust gas recirculation (EGR) (UHE) and modulated kinetics (MK) in a CI engine using physical models and numerical methods in KIVA-CMC. The study (Y. Lee and K.Y. Huh, 2014) indicated that the ultra-high exhaust gas recirculation (UHE) mode at the % of EGR with 68% shows conditional temperature between 1000K and 1600K, while the modulated kinetics (MK) mode at the EGR % of 48% shows conditional temperature distribution between 1000K and 2200K.

There are three generally accepted mechanisms for NO_x formation: thermal NO_x, prompt NO_x, and fuel NO_x. Thermal NO_x is formed by the high-temperature reaction (hence, the name thermal NO_x) of nitrogen with oxygen. Set of highly temperature-dependent chemical reactions determines the formation of thermal NO_x. It also appears that thermal NO formation is highly reliant on temperature. Production rate of thermal NO_x increases as temperature increases particularly at higher temperature levels. Thermal NO_x increases exponentially with temperature above about 2,000°F (1,100°C), it is generally the predominant mechanism in combustion processes, making it important in most high-temperature heating applications. Prompt NO_x is formed by the relatively fast reaction (hence, the name prompt NO_x) between nitrogen, oxygen, and hydrocarbon radicals:



Prompt NO_x is generally an important mechanism in lower- temperature combustion processes, but is generally much less important compared to thermal NO_x formation at the higher temperatures found in many industrial combustion processes. Prompt NO_x becomes more important under fuel rich conditions. Fuel NO_x is formed by the direct oxidation of organo-nitrogen compounds contained in the fuel hence, the name fuel NO_x (Öztürk and Eyriboyun, 2010).

So it was found out that applying LTC strategy helps in overcoming the conventional trade-off between NO_x and soot emissions. On the contrary the reduction of combustion temperature and oxygen contents inside the cylinder facilitates the release of concentrations of incomplete combustion products, such as unburned HC and CO which considered gaps or constraints which needs to be resolved through further engine operating parameters optimization and fuel modifications to be used.

2.3 PCCI Combustion in Diesel Engines

Higher HC and CO emissions were resulted from poor combustion phasing due to lower in-cylinder temperatures. This result forced researchers to work on new LTC strategy that they name it as a premixed charge compression ignition (PCCI) combustion which is an improvement on HCCI combustion concept in relation to combustion stability. Comparing with the conventional diesel combustion studies indicated that in PCCI combustion, control over combustion events with injection strategy is retained and a greater percentage of the total charge is premixed prior to ignition. It is mentioned that injection of fuel is at an intermediate timing between HCCI and conventional CI engine. Considering better control over the combustion events researchers discussed that PCCI mode of combustion seems better compared to HCCI mode of combustion leading to better engine performance, lower NO_x, PM emissions and significant lower HC and CO emissions that needs further studies for more substantial reduction of HC and CO emission gaps (J. T. a. A. D. N, 2007).

Toyota Central Research had developed a premixed charge compression ignition engine with a promising higher efficiency and lower NO_x emissions (Ambrosio, 2015) from combustion of premixed lean mixture.

Various experimental investigations on PCCI combustion of diesel engines in low load ranges were carried out since PCCI operation at high load leads to knocking, and from the results the possibilities of reductions of soot and NO_x emissions at the same time were confirmed.

Experimental investigations and comparisons were carried out (C. Beatrice, G. Avolio et al. 2007); among the PCCI combustion and the conventional diesel in controlling emissions (Figure 2.3). The study showed soot is double than the emission value in conventional Diesel, and it was mentioned that the experiment was conducted under very low

load conditions in both combustion modes and that low exhaust values were obtained (about 0.05 FSN). On the contrary, a very large amount of CO and HC emission gaps were faced in the PCCI combustion mode than the diesel mode.

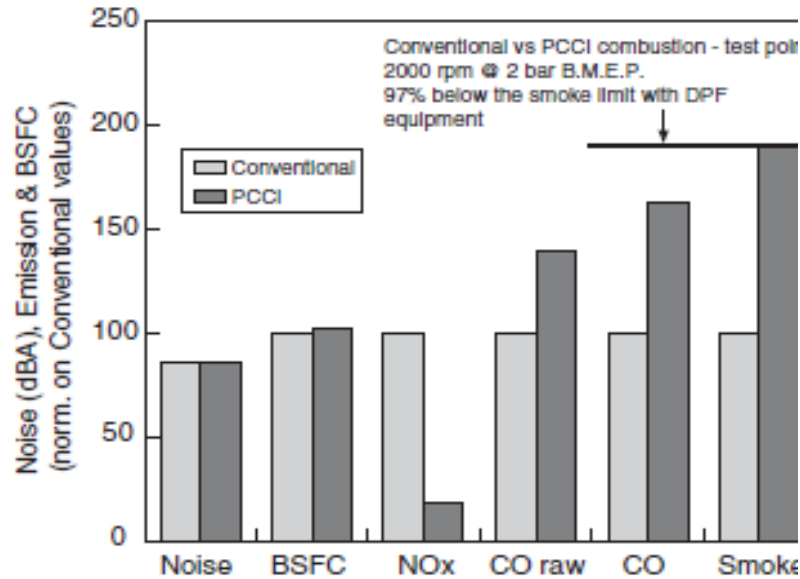


Figure 2.3: Comparison between conventional and PCCI operation mode in terms of engine performance and emissions. Engine point: 2000 rpm @ 2 bar of BMEP (C. Beatrice, G. Avolio et al. 2007)

The study (C. Beatrice, G. Avolio et al. 2007) mentioned that lower flame temperature and higher premixed charge fraction in the PCCI mode were the important features for the results in comparison to the Diesel mode.

Other experiment (B. I. Master, Chunangad K.S et al. 2003) was 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 % and modified injection timing in DI diesel engine in-order to minimize NOx with PM trade-off.

Low compression ratio technique was applied (Thangaraja, 2016) for PCCI advanced combustion system on diesel engines and the results showed the possibility of 15% NOx emission reduction at virtually constant soot levels, and also the possibility to achieve a 3% of fuel consumption reduction. THC and CO emissions appear to be higher upstream of DOC (diesel oxidation catalyst) due to the high premixed-combustion degree that was achieved, but they are lower downstream from DOC.

The possibility of reducing soot and NO_x emissions through keeping high thermal efficiency at part load conditions by applying the PCCI combustion technique needs solving various challenges related to emission and efficiency of combustion. Experimental and simulation studies were carried out to investigate the advantages of multiple-pulse fuel injection in improving engine load, emissions and thermal efficiency using high EGR and boost in diesel PCCI. The simulation study (Park J and Lee KS, 2015) confirmed that comparing with single injection the multiple-pulse injection leanness and homogeneity of the mixture has improved, particularly at high load. Engine load can be further extended in increasing P_b using multi-pulse injection, through the increased chance of molecular collision of fuel and oxygen there was advancement of ignition timing. However, the leanness and homogeneity of the mixture are improved. As a result, the CO, UHC and soot emissions are greatly decreased but require more work in avoiding these gaps of emissions. The indicated thermal efficiency is increased with not large expense or increment of NO_x emissions.

Most commonly in the LTC modes, the injection of fuel is either in the port or early during compression stroke in the cylinder which promotes mixing in both combustion modes. The LTC techniques as indicated in Figure 2.4; such as HCCI, PCCI and RCCI have proven to be promising alternatives to the conventional combustion engines because of their ability to reduce the in-cylinder local temperatures and the rich zones simultaneously

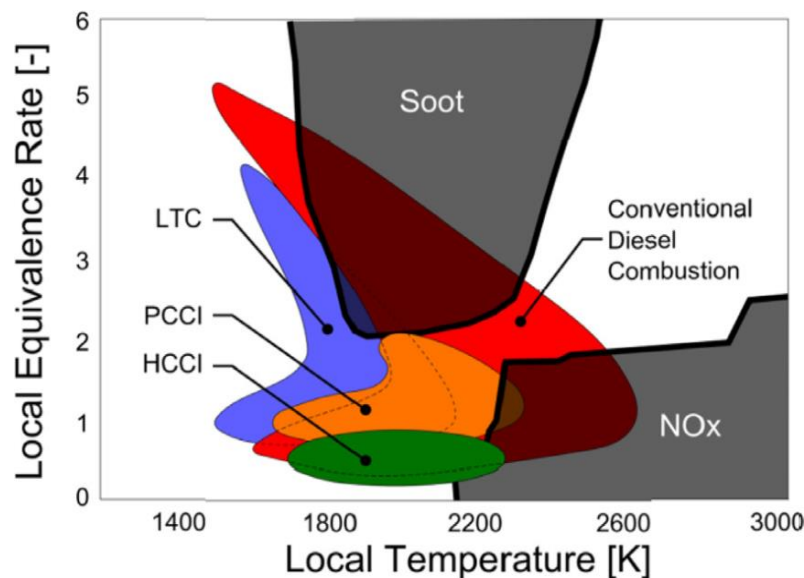


Figure 2.4: LTC and conventional CI combustion regimes in ϕ -T space (G. J. Wagner RM, Dam T et al. 2018)

The study (G. J. Wagner RM, Dam T et al. 2018) showed temperature ranges in which NO_x is formed at temperatures higher than 2000 K. Also, by decreasing cylinder temperature and minimizing fuel rich local zones it indicated the possibility of eliminating emissions of soot and NO_x. From the ϕ -T map researchers explained the temperature range in which LTC takes place, which is below the formation regime of NO_x and at local equivalence ratios below diesel soot formation regime. The two distinct zones for soot and NO_x emissions formation were clearly shown in the plot in Figure 2.4.

These LTC strategies of reducing NO_x and soot emissions in parallel, is an advanced combustion concept which lowers the high temperature leading to NO_x production regime and also avoids rich mixture leading to soot production regime. Researchers implemented several techniques to avoid locally rich regions in the combustion cylinder by forming a premixed mixture through port fuel injections, various direct injection approaches/ fuel injection parameters (injection pressure, premixed ratio, start of injection timing and spray angle).

Though with challenges/limitations of high HC and CO emissions that needs further studies, the combustion concept of PCCI in achieving low emissions at part load operations were effectively applied with minor engine modifications on conventional direct injection engines. The study (H. T. Kanda T, Uchimoto T et al. 2005) showed that the gaps of HC and CO emissions were higher in PCCI combustion mode than conventional CI mode, because of the premixed charge and fuel spray wall impingement. Reduction in NO_x 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 by applying EGR were made possible and further increase in EGR % would lead to combustion instability and higher HC and CO emissions which are gaps in the study that need further optimization and modifications. The conventional CI engine was converted into PCCI mode and it was observed from the experiments (H. T. Kanda T, Uchimoto T et al. 2005) that NO_x and smoke emissions were very less when compared with conventional CI mode for limited load range operations.

Experimental investigation (Theinnoi, Suksompong et al. 2017) on the combustion and emission characteristics of a DME-Diesel dual fuel of PCCI combustion mode on modified single cylinder compression ignition of a common rail direct injection diesel engine

was conducted. The study showed that to improve the in-cylinder combustion and to reduce the exhaust gas emission advanced injection timing by 3 °CA is required in the case of DME injection. The optimum concentration that improved brake specific energy consumption and brake thermal efficiency of the engine was the 30% DME pre-mixing ratio. By increasing the DME pre-mixing ratio the diffusion combustion was decreased. The study indicated that the NO_x emission was reduced below 50% of DME pre-mixing ratio. High NO_x, CO and HC emissions under all engine loads were found in the higher DME pre-mixing ratio, which are indicated in the study as limitations or gaps that needs more work. However, the black smoke was reduced and there was a simultaneous improvement with DME port fuel injection.

Experimental study (Kuleshov and Grekhov, 2013) conducted with High Pressure Direct Injection engine by applying PCCI-DI (premixed charge compression ignition-direct injection) combustion mode resulted major advantages in case of CO and HC emission reductions. It indicated that PCCI method is one of the promising LTC technologies observed to be of great potential if further studies are conducted on it to overcome its shortcomings of HC and CO emissions as a gap mentioned in the study. Other researchers (Pandey S., Diwan et al. 2016) also indicated the combined PCCI-DI could be an economical solution to meet Euro-IV emission norms. The possibility of replacing the conventional diesel combustion by the partial HCCI or PCCI-DI combustion was also mentioned.

The possibility of simultaneously reducing engine out NO_x and soot by 90% and 99% of the base point values, respectively were confirmed experimentally (D' Ambrosio, Iemmo et al. 2016). Also researchers explained the reductions in NO_x and smoke are always related to gaps of increase in HC and CO emissions, due to advanced injection taking place in a colder and low density environment. Moreover, bsfc and CN have shown an undesirable increase. Possibility of obtaining proper calibration through DoE in finding the best trade-offs among all the considered output values were also described in this study. Implying that, this finding proofed that DoE has the ability to effectively support the efforts of experimental peoples in optimizing engine calibration.

PCCI minimizes, or even avoids, the need of exhaust after-treatment technologies (Parks, Prikhodko et al. 2010). In PCCI combustion, injection takes place early in the compression stroke, which leads to premixed fuel air mixture formation. PCCI usually involves a

very early or late injection event (Kimura, Aoki et al. 1999) resulting simultaneous reduction in both NO_x and soot unlike conventional combustion. Previous studies indicated a decrease in CO, PM emissions and increase in NO_x and fuel efficiency when the main injection is further injected as two injections (Ehleskog, Ochoterena et al. 2007). Split injection strategies also function as promoters of partially premixed combustion regimes, where the first injection creates the necessary mixture stratification for the next injection to combust (Kumar and Saravanan, 2016). On the contrary excess values of the start of injection results an increase in HC and CO emissions above acceptable ranges. So proper and optimized combination of the operating parameters in LTC engines working in PCCI mode can provide acceptable values of emissions and load ranges. Due to heavily reduced oxygen content, low combustion temperatures and early injections, the formation of incomplete combustion products, such as CO and HC, can be significant, and can require a higher conversion efficiency of the diesel oxidation catalyst (Han, Ickes et al. 2012).

The maximum lower start of injection that could allow the engine to enter the PCCI combustion mode regardless of the EGR level; and the reductions in NO_x and Soot in relation to significant increase in HC and CO challenges were studied (Yusaf, Hamawandl et al. 2013) on conventional CI engine.

Operating Conditions

Studies (Ekoto, Colban et al. 2009) indicated that in LTC engines UHC and CO emission challenges or gaps were most problematic that needs more work particularly at lower loads and oxygen concentrations ([O₂]). Even though there is high UHC and CO emissions relative to higher [O₂] there is high combustion efficiency (~98%) as discussed in Figure 2.5.

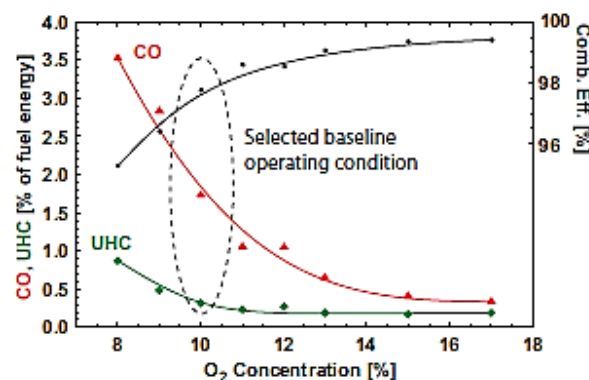


Figure 2.5: Emission and combustion efficiency as a function of dilution at maximum brake torque timing (Ekoto, I. Colban et al. 2009)

2.4 Dual Fuel Applications and Advantages

The idea of applying dual fuel in diesel engines is getting more attention considering several benefits that could be achieved in using both gas and liquid forms of the fuels. Many studies (Maurya, 2018; Theinnoi, Suksompong et al. 2017; Vignesh, S.Srihari et al. 2019; Agarwal, Singh et al. 2017; Elkelawy, 2020) were conducted in finding out the impact of applying dual fuel on the performance, emission and combustion features of different types of diesel engines including PCCI-DI engines. Most studies showed that dual fuel engines have the benefit of minimizing emissions and lowering greenhouse gases particularly from diesel engines. Dual fueling possess several advantages; flexibility of fuel use, possibility of running the engine with the conventional diesel fuel supply if the additional fuel supply arrangement fails, most fuels works on diesel engine with small modification or with no modification at all, have the effects forming lean burning that contributes in lowering the combustion temperature and emission reductions. The dual fuel approach on diesel engines is mostly adapted on the inlet manifolds or direct supply to the combustion cylinder.

Performance and emission characteristics of CI engine were studied by using diesel and methanol fuel blends. From the investigation brake thermal efficiency, BSFC and emissions of CO, smoke and HC were promising at certain percent of pilot injection and blending ratios comparing with the base line diesel. In this study it is pointed out that the presence of rich amount of oxygen in alcohol enables appropriate combustion of fuels thus resulting higher thermal efficiency (Vignesh, S.Srihari et al. 2019). Other finding (Amin, Yousefi et al. 2015) mentioned that a pre-blend of methanol/diesel having high oxygen content resulted lower emissions of CO and soot when operated on richer zones. All these indicate methanol alcohol possessing oxygen in nature offers improved combustion thus encouraging uniform combustion in the cylinder. A study (Poures, Gopal et al. 2019) conducted using alcohols were found excellent alternative substitutes in place of diesel with slight DI engine modifications.

Experimental investigation indicating the possibilities of the dual fuel application on PCCI-DI diesel engine was conducted and positive results were obtained. This was done by injecting and premixing a small amount of fuel in addition to the main injection of fuel. The type of fuels used for this study for the pre injection and main injection includes diesel and ethanol fuels with different percentage composition modes. Reduction of NO_x,

smoke and CO₂ were obtained (Srihari, S. and Thirumalini, S., 2017) with increasing challenges of HC and CO.

2.5 Taguchi Method and Grey Relational Analysis

Several researches confirmed that Taguchi method enables a broad understanding of a single and collective effect of various variables or parameters that could be found from small number of experimental runs. The question of the functionality of this method for the optimization of the chosen experimental set up was positively achieved. Taguchi method apply the orthogonal array matrix, analysis of variance (ANOVA) and signal-to-noise (S/N) ratios which is developed by a Japanese engineer Dr. Genichi Taguchi (Alvaro, 2009) In order to minimize number of experimental runs, choosing the proper size of the orthogonal array is very significant in Taguchi method which permits an equal evaluation of all factors applying specific design of experiment which permits to minimize number experimental runs. This primarily depends on the number of parameters together with levels of factor. Taguchi technique uses S/N ratio to analyze experimental results rather than using the normal average value by changing the experimental data results into a value in the optimal setting. S/N ratio from Taguchi helps to determine the degree of the quality behavior and used as objective functions for the optimization. Higher S/N ratio result indicates better quality characteristic. Due to this reason S/N ratio is used for investigating main effects and ANOVA. In maximizing the S/N ratio the choice of the factors or parameters is essential. S/N ratio comprises; lower the better, higher the better and nominal is the best.

Computing S/N ratio could be done using the following formulas (K. P. S.Natarajan and N.V.Mahalakshmi, 2018).

- Lower the better;

$$S/N \text{ ratio}(\eta) = -10 \log_{10} \left(\frac{1}{n} \sum_{i=1}^n y_{ij}^2 \right) \quad (2.2)$$

- Higher the better

$$S/N \text{ ratio}(\eta) = -10 \log_{10} \left(\frac{1}{n} \right) \sum_{i=1}^n \frac{1}{y_{ij}^2} \quad (2.3)$$

n - total number of attempts, y_{ij} - the i^{th} result of the j^{th} experiment, and $i = 1, 2, \dots, n$; $j = 1, 2, \dots, k$.

- Nominal the better

$$S/N \text{ ratio}(\eta) = 10 \log_{10} \left(\frac{\mu^2}{\sigma^2} \right) \quad (2.4)$$

Where:

$$\mu = \frac{y_1 + y_2 + y_3 + \dots + y_n}{n}$$

$$\sigma^2 = \frac{\sum (y_i - \bar{y})^2}{n - 1}$$

Normalization:

y_{ij} is normalized as z_{ij} ($0 \leq z_{ij} \leq 1$). The normalized value z_{ij} in the i^{th} emission result for the j^{th} experiment could be computed:

$$Z_{ij} = \frac{\max(y_{ij}, i = 1, 2, \dots, n) - y_{ij}}{\max(y_{ij}, i = 1, 2, \dots, n) - \min(y_{ij}, i = 1, 2, \dots, n)} \quad (2.5)$$

(Applied in S/N ratio's having lower the better)

$$Z_{ij} = \frac{y_{ij} - \min(y_{ij}, i = 1, 2, \dots, n)}{\max(y_{ij}, i = 1, 2, \dots, n) - \min(y_{ij}, i = 1, 2, \dots, n)} \quad (2.6)$$

(Applied in S/N ratio's having higher the better)

$$Z_{ij} = \frac{(y_{ij} - \text{Target}) - \min(|y_{ij} - \text{Target}|, i = 1, 2, \dots, n)}{\max(|y_{ij} - \text{Target}|, i = 1, 2, \dots, n) - \min(|y_{ij} - \text{Target}|, i = 1, 2, \dots, n)} \quad (2.7)$$

(Applied in S/N ratio's having nominal the best)

Grey relational co-efficient (indicated in chapter five) for the normalized S/N ratio is computed applying;

$$\gamma(y_o(k), y_i(k)) = \frac{\square \min + \xi \square \max}{\square_{oj}(k) + \xi \square \max} \quad (2.8)$$

Where, $j = 1, 2 \dots n$, $k = 1, 2 \dots m$, n represents number of experimental data items and m is the number of results

$y_o(k)$ - denotes reference sequence ($y_o(k) = 1$, $k = 1, 2 \dots m$); $y_j(k)$ indicates specific

comparison sequence. $\square_{oj} = y_o(k) - y_j(k)$ = deviation sequence, which denotes the difference of $y_o(k)$ and $y_j(k)$ in absolute value.

$\square \min = \min_{j \in i} \min_k y_o(k) - y_j(k)$ designates least result of $y_j(k)$.

$\square \max = \max_{j \in i} \max_k y_o(k) - y_j(k)$ designates largest result of $y_j(k)$.

ξ is in the ranges ($0 \leq \xi \leq 1$). In this study $\xi = 0.5$ (Misra, 2013).

During the optimization process to generate the Grey relational grade as indicated in chapter five, the following formula was applied;

$$\overline{\gamma_j} = \frac{1}{k} \sum_{i=1}^m \gamma_{ij} \quad (2.9)$$

$\overline{\gamma_j}$ - implies grey relational grade representing the j^{th} experiment and k denotes number of emission features.

Analysis of Variance (ANOVA)

Impact of the parameters or factors is assessed using the analysis of variance (ANOVA). It is a method of evaluating data to know reasons for difference or variance of specific factors or parameters in a data. Taguchi's technique is under the ANOVA group of statistical models which offers the tools that help for the analysis of variance in a set of data (Gopal-samy, Mondal et al. 2009). The ANOVA concept was applied by Taguchi to analyze the effects of various factors using less numbers of test specimens. In this study ANOVA analysis helped to identify and explore the important factor contributing to the PCCI-DI diesel engine emission characteristics. The ANOVA investigation is computed applying the sum of the squared deviations of the total mean of the grey relational grade.

Gray Based Taguchi Method

Grey based Taguchi is most appropriate technique which is commonly used in various field of engineering in order to solve multi response optimization problem by conducting less number of experiments. The steps followed during this technique includes (Saurav, 2008); normalizing the experimental results (between 0 to 1 ranges) mostly termed as grey relational generation, calculating the grey relational coefficients and then computing the overall grey relational grade for the responses through averaging the grey relational coefficients.

Taguchi Experimental Design

The technique of Taguchi offers a mechanism to analyze the experimental data in addition to instructing the user about Design of Experiment (DoE). In addressing the objective, design of experiment (DoE) using the Taguchi method of the orthogonal array type were applied in relation to the chosen operating parameters of the PCCI-DI diesel engine. This robust optimization technique was followed by the Grey Relational Analysis (GRA) in order to solve the multi-response optimization problem. Results were confirmed to check their truth through the Analysis of Variance (ANOVA). In applying the Taguchi method on the optimization process helps to analyze the effect of the operating parameters; injection timing, EGR %, dieseline ratio, and load for lower emission characteristics in PCCI-DI diesel engines. Finding optimum operating conditions for best performance and emissions in IC engines through Taguchi method were successful including ANNOVA methods as mentioned in various literatures (Wu ZY. 2013; Yan J and Rogalla R, 1993; Wu

ZY, Wu HW et al. 2014; Hunter C, Gardner et al. 1990; Dimitriou P, Peng Z. et al. 2013). These methods were applied in studying the impacts of various operating parameters and using alternative fuels in IC engines.

Numerous studies have been done applying the Taguchi approach to robust and optimize a system or process. This method is widely implemented (Ganapathy T, Murugesan K et al. 2009) as an optimization approach for engine analysis. To solve the multi-response characteristics linking the Taguchi method with the grey relational analysis using the grey system theory was done. Optimized matching of operating parameters of IC engine for the reduction of BSFC, NHC and PM emissions on CRDI-assisted compression ignition engine working in dual-fuel Mode were studied (Roy S, Das AK et al. 2014) using grey-Taguchi method. Experiment of optimization using grey-Taguchi method was also conducted applying several premixed charge ratios of diesel with ethanol on an engine in PPCCI combustion mode, the result (S.Natarajanl, K.Pitchandi et al. 2018) showed that 20% premixed ratio is considered optimal depending on performance factors and emissions of NO and smoke. Performance of compression ignition engine operating using dual-fuel mode with producer gas was optimized by Grey-Taguchi method. Optimum parameter setting with 80% engine load, 10% mixture of producer gas flow rate (PGFR) and biodiesel at 21.49 kg/h gave best outcome for the chosen responses (Dash, Jena et al. 2021). Taguchi using GRA approach was used in a study which resulted less emission and improved performance on a diesel engine with modified copper chromium zirconium (CuCr1Zr) catalytic coated piston comparing with the standard un-coated piston type diesel engine (Yessian1 and Varthanan 2020). Investigating the optimized process response by applying the Taguchi method together with the grey relational analysis was also used (Pohit and Misra, 2013) to solve the multiple response optimization challenge. The response includes engine performances and emission characteristics operating with Karanja oil methyl ester mixed with diesel tested on a diesel engine of a variable compression type.

An investigation to get the optimal level of operating parameters were determined by signal-to-noise ratio and grey relational analysis (Vellaiyan and Amirthagadeswaran, 2017) that lead to better response which improves the performance, combustion and emission characteristics of diesel engine. Optimum combination of operating factors on a single cylinder diesel engine was obtained through grey relational analysis together with Analy-

sis of Variance (ANOVA). This study (Geetha.N.K and Sekar.P, 2017) optimized the factors like injection timing, injection pressure and load. Investigation of the optimal process response using the grey relational analysis was also realized (Roy, Das et al. 2014) in solving the optimization problem. In this study the optimal combination of the chosen input factors to get the desired response characteristics was found by the grey relational grade and signal-to-noise ratio as a performance index. The simplicity and efficiency characteristics of the grey relational analysis and the response surface methodology (RSM) as an optimization technique were realized (Prasada Rao and B.V. Appa Rao, 2016) in optimizing the performance and emissions of the indirect injection diesel engine.

Numerous investigations used the orthogonal array in designing of experiments on the basis of L_9 orthogonal array matrix. Grey relational grade based on the grey Taguchi method is used in determining the optimum parameters. Investigators (Mustabshirha Gul, Asad Naeem Shah et al. 2015) inter-related multiple conditions optimization of numerous factors on a turbocharged, direct injection, diesel engine running with neat biodiesel and blend with diesel was analyzed using the grey–Taguchi method (GTM). Applying this optimization technique, the grey–Taguchi method converts the multiple objectives of a problem into a single-objective function. The resultant optimized combination of the input parameters was used to maximize the intended output responses. In this study ANOVA based on the software Minitab was applied in exploring the relative effects of the input variables on the output.

DoE Optimization Approach

Effective reduction of the required number of tests in an experimental program through DoE without significantly compromising the quantity and quality of the information derived from the experiment were explained and applied by researchers (McTaggart-Cowan, G. P. et al. 2012). Literatures agreed that DoE is a systematic approach that provides researchers to develop strategy in conducting experiments and decide cause-and-effect interactions. In reducing number of experiments which are needed to be conducted DoE is widely applied in various research areas. Two important terms specifically variables and level are essential in DoE. Factors refer to the independent variable which has effects on the dependent variable (response). On the other hand Level refers to a variable increment of the factor. In a factorial design every factor is set up with different levels. As required

by the DoE, a set of factors; Injection timing, EGR %, dieseline ratios and load were considered by maintaining methanol port injection in constant average injection amount and time in the experiment. For each of them, three levels were defined in a range of reasonable values. By combining the levels of all the factors, it was possible to evaluate the effects and the weight of each factor and of their combination on the outputs. Results were analyzed to determine optimum set of the chosen control parameters in order to ensure improved results of combustion and emission. In this investigation DoE containing experimental runs was used to implement variations of the controlling parameters

Relationship between emissions and load ranges of dieseline/methanol fueled PCCI-DI engine under different operating parameters (injection timing, EGR % and premixing ratios of dieseline fuels) were analyzed experimentally using DoE. In this study the DoE analysis is aiming to find out the optimal combination between injection timing, EGR %, premixing ratios of dieseline and load to reach the lowest NO_x, HC, CO and smoke productions.

The values obtained from the experiment were analyzed statically following DoE. Levels were defined in a range of reasonable values for DoE investigation. DoE was applied in finding the optimum combination of the control parameters from the collected data results for better trade-off between NO_x with that of HC and CO productions at the optimal load range arrangements.

2.6 Fuel Injection Timing

Creating the feature of LTC mode on the experimental setup includes making the fuel injection timing to be done before the start of combustion (SOC) in order to allow fuel and air mixing prior to combustion that is for homogeneous mixture formation. The study investigated and compared emission trends (NO_x, HC and CO) versus load for the chosen control parameters on Dieseline/Methanol fueled PCCI-DI mode operated diesel engine.

Investigators studied the impacts of advanced (250BTDC chosen) and retarded injection timing (21⁰BTDC chosen) and compared with the conventional injection timing (baseline diesel at 23⁰BTDC) under similar operating conditions. The experimental study indicated that CO emissions at full load for advanced (25 degree BTDC) injection timing were 25% less than the baseline diesel. While UHC emissions were high for retarded injection tim-

ing comparing with the standard and advanced injection timings. For this advanced injection timing mentioned above NO_x emissions were 10% higher when compared with the standard injection timing whereas NO_x emission was found 10% lower than the standard injection timing at the retarded injection timing (21 degree BTDC). Also the PCCI mode of operation through advanced injection timing decreases the CO and smoke emission but with a challenge of increase in UHC and NO_x emissions at fully or completely loaded conditions. Retarded injection timing decreases the CO and NO_x emissions with but with a problem of increasing UHC and smoke emissions at fully or completely loaded conditions (J. G. S. Girish and E. Bhiogade, 2017).

On the contrary other findings also confirmed that excess values of the start of injection results an increase in HC and CO emissions above acceptable ranges. So, proper and optimized combination of the combustion parameters in LTC engines working in PCCI mode needs more research that could provide acceptable values of emissions and load ranges. Current and ongoing research efforts in making LTC technology efficient through biodiesel and other alternative fuels developed a hope for further reduction investigation on HC and CO emissions. These tuning of fuel properties also helps to improve emissions of PCCI combustion modes. Injection timing in PCCI combustion usually involves a very early or late injection event which aims for the simultaneous reduction of both NO_x and soot unlike the conventional combustions.

Studies indicated that appropriate optimization of injection timing and fuel chemistry in LTC strategies including PCCI which are emerging ideas of modern combustion science can reduce emissions to a satisfactory level. Suggestion shows that there was almost no generation of soot and NO_x as a result of PCCI combustion by spraying fuel at an early timing (Kanda, Hakoziaki, T. et al. 2005). However, they also mentioned following challenges which still remain unsolved; HC and CO emissions tend to increase due to the sprayed fuel adhering to the cylinder liner, which is due to advancing the fuel injection, IMEP deteriorates due to the resulting excessively advanced ignition, there is no control of the start of the combustion event through injection timing because of the entire amount of fuel is injected when the ignition timing is retarded. From this study further studies are mandatory to fix these challenges or limitations related to injection timing. Other research studies have also described the possibility of fuel introduction into the combustion chamber through; port fuel injection, early direct injection and late direct injection in the strate-

gy of PCCI combustion. Also PCCI has been confirmed a promising concept for achieving low emissions at part load operations (Bhiogade and Suryawanshi, 2017).

Early injection is mostly applied to attain PCCI combustion and studies (Lee and Reitz, 2006) showed that injection timing highly affects combustion performance and emissions of PCCI engine that needs more work to lower its limitations and this makes injection timing to be chosen as one control parameter for this study. Another study also explained that by setting the main injection timing of diesel PCCI combustion to 28 CAD BTDC showed 32% lower level of NO_x and 8 CAD longer ignition delay than those of conventional diesel combustion while HC and CO levels were 2.7 and 3 times higher than those of conventional diesel combustion due to over-lean mixture and wall wetting of fuel (Park and Bae, 2013).

An experimental investigation carried out on a Caterpillar C-15, on-highway, heavy-duty diesel engine (Simescu, Fiveland et al. 2003) reported that main injection timing is one main variable affecting PFI-DI combustion. The study also indicated that NO_x versus (CO + UHC) trade-off appears to be more important for the PFI-DI combustion in contrast with the NO_x versus PM trade-off typically associated with standard diesel combustion indicating the purpose of this study. Homogeneous mixture was resulted from well atomized port fuel injection and the researchers revealed that further research is needed to investigate the possibilities in optimizing the timing of PCCI combustion with respect to the diesel combustion event and the amount of PCCI combusted fuel.

2.7 Exhaust Gas Recirculation (EGR) and PCCI Combustion

The premixed charge compression ignition (PCCI) combustion mode was achieved by using large amounts of exhaust gas recirculation (EGR) together with advanced fuel injection timing strategy. 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 % of EGR increased, IMEP was increased due to the decrease of negative work during the compression stroke and due to dilution and thermal effects of EGR; NO_x emissions were decreased (Park and Bae, 2011). From this study optimizing EGR % is essential to avoid its limitations due to inappropriate EGR %.

Higher use of EGR and optimized SOI control parameters help for the realization of LTC technologies and these keep NO_x 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 NO_x and soot level. 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 NO_x 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 (Kanda, Hakoziaki T. et al. 2005).

In a study EGR was found to be a very useful method to expand high load limit and reduce NO_x emission to a very small value in PCCI. The study also indicated that using high EGR at low engine load resulted simultaneous low soot, CO, UHC and NO_x emissions. At higher engine load with high EGR, the localization of single injection in extending operation range is the high soot, CO and UHC emissions; with little expense of NO_x emissions using multiple-pulse injection mode; the CO, UHC and soot emissions are decreased (B. I. Master, Chunangad K.S et al. 2003).

Another study of PCCI combustion through proper matching of high EGR % and advanced combustion were investigated. This finding showed that to allow engines to enter the PCCI combustion mode SOI should be on time regardless of the EGR level. On the other hand the study explained that significant increases in HC and CO has been always resulted during the reductions of NO_x and Soot which is also accompanied by undesirable increase of BSFC and CN that additional studies should be conducted to solve these limitations. In addition the investigation discovered the possibility of reducing simultaneously engine out NO_x and soot by 90% and 99% of the base point values, respectively (Simpson, 1998).

High temperature formed in the combustion chamber leads NO_x emission generation in the exhaust. Controlling this peak combustion temperature helps to reduce NO_x 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 O_2 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 re-

duction in NO_x. 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 (Antony, 2003).

Brake thermal efficiency in PCCI mode little decreases comparing to CI mode but NO_x and smoke emissions decreases drastically in PCCI mode comparing to CI mode of operation. EGR percentage was used up to 30 %. Further increase in EGR % resulted increasing of HC, CO emissions and combustion instability (Sandeep and Patel, 2012) which shows further optimization and tune-up works should be done on EGR % to avoid these limitations. PCCI combustion is obtained with a proper combination of high EGR and advanced combustion (Akumu, 2019).

EGR is a useful method for reducing NO_x formation and LTC features.

$$\% \text{ of EGR} = \frac{\text{Volume of EGR}}{\text{Total Charge Intake into the cylinder}} \times 100 \quad (2.10)$$

Or by using CO₂ concentration;

$$\text{EGR ratio} = \frac{[\text{CO}_2]_{\text{intake}} - [\text{CO}_2]_{\text{ambient}}}{[\text{CO}_2]_{\text{exhaust}} - [\text{CO}_2]_{\text{ambient}}} \quad (\text{ZY, HW et al. 2014}) \quad (2.11)$$

A trade-off relationship between NO_x and smoke emissions was observed in an experiment conducted using EGR and intake boost on a partially premixed compression ignition combustion mode (C. K. Thangaraja, 2016). 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 (Park and Lee, 2015; Elkelawy, Shenawy et al. 2022).

2.7.1 EGR Level and EGR Configuration on PCCI Diesel Engine

NO_x and soot reduction simultaneously were achieved through the advanced combustion approach i.e. PCCI. This could be achieved through greater level of EGR and advanced injection timing which decreases in cylinder temperature. However in this case HC and CO emissions were resulted. Which EGR configuration is appropriate for lowering the increment of HC and CO in PCCI-DI operations in diesel engines was not fully addressed by researchers. The reduction of NO_x by applying EGR in diesel engines is through reduction in oxygen amount and combustion flame temperature. PCCI combustion techniques through advanced injections mostly 25° BTDC was found useful particularly at higher levels of EGR together with low compression ratios, these resulted a reduction of NO_x and improved combustion (Maurya, 2018). Even though there are small ranges of operation and increased emissions of HC and CO (Dec JE, 2015; Dempsey, Walker et al. 2014), Researchers pointed out the great potentials of PCCI combustion strategy comparing with the other low temperature combustion (LTC) strategies. PCCI strategy resulted up to 97% NO_x reductions comparing with the conventional diesel combustion (Hardy WL and Reitz RD, 2006). Other study for PCCI operation; 25° BTDC of injection timing and IMEP of 287kPa was found best due to the reasons; lower NO_x production of 3.1g/kWh, lower CO and HC including lower smoke emissions (Srihari, Thirumalini et al. 2017). Studies (Miao, Zhang et al. 2011; Kobayashi, Najima et al. 2007), revealed that HC and CO emissions were found out 30 times greater in PCCI type of combustion comparing with the conventional CI mode of combustion which needs further investigations to fix these limitations of HC and CO emissions.

Application of EGR levels to 30 - 40% at medium and high loads resulted positive impact on HC emissions and trade-off between soot and NO_x (Selvan, Dhinesh et al 2018) EGR technique works by lowering the percentage of oxygen and reducing the combustion flame temperature since NO_x formation takes place at higher temperatures of 2000 k (Girish and Jiwak, 2017). Decreasing temperature of the exhaust gas recirculating by the EGR cooler helps the gas mixture not to reach too high temperature and mixes well with the intake air.

Applying EGR became an important governing mechanism on engines working with alternative fuels and also engines working in advanced combustion modes (Najt and Foster,

1983) including improving engine performance (Thring R.H, 1989). Also modification of engines together with the application of high quality and modified fuels are very crucial in meeting the strict emission standards.

Strategy of using maximum EGR % for parallel reduction of PM and NO_x were investigated (D' Ambrosio, Iemmolo et al. 2016) and positive results were obtained. EGR level up to 54% was tested which resulted a retardation of ignition timing; also cooled EGR with level of 50% was investigated that helped in lowering temperature in the compressed gasses. But in making the EGR level high, there will be a formation of incomplete combustion that results greater CO productions (Srihari and Thirumalini, 2017). In an experimental study conducted it uses 0 to 30% of premix ratio and from 0 to 27% of EGR variation. From the study it was found out that by increasing the level of EGR there was a decrease in NO_x amount but CO and HC were increased and challenging that requires further investigations. However for higher amount of premix and EGR levels both emissions were decreased (Najt and Foster, 1983). Combustion under PCCI mainly with beyond injection of 30° before TDC together with possessing 40 % of EGR shows very low production of NO_x at the cost of increase in HC and CO. This was resulted from the local flame temperature reduction and lower oxygen concentration (Ying W., Longbao et al. 2010).

A study was conducted using n-butanol port injection together with EGR system on diesel engines. From the study increasing the EGR level to 45%, resulted a reduction of NO_x by 97% even though a considerable soot increment was observed. By combining 47% of butanol PFI and 45% of EGR %, decrease in NO_x and soot amounts were obtained.

Based on temperature EGR is classified into the followings; Hot EGR in which the Exhaust gas is re-circulated without being cooled, Fully cooled EGR where the exhaust gas is cooled before re-circulation in to the cylinder using water-cooled heat exchanger, Partly cooled EGR in which the exhaust gas temperature is kept above its dew point temperature to avoid the condensation of water. Study (Antony, 2003) was conducted on PCCI engine having both cooled and uncooled EGR strategies, attaining significantly NO_x and soot reductions comparing with the conventional diesel combustion mode setup. UHC and CO emissions including greater fuel consumption were the challenges faced during the study and affected by the EGR configuration indicating more studies should be done on EGR

configuration to settle these challenges. Reduction of HC and CO emissions in the exhaust pipe by applying uncooled EGR strategy was also found from the investigation.

Engine manufacturing companies are working for the betterment of emission restrictions. These attempts are currently become effective through applying cold EGR that lowers the peak temperature inside the combustion chamber. This will decrease the volume of intake air that could enhance the volumetric efficiency that improves the combustion efficiency. A considerable reduction of NO_x through applying cooled EGR system has been studied (Dec JE, 2015), and the study (Kanda, T., Hakozaiki T. et al. 2005; Simpson, 1998), demonstrated the increase in PM production due to NO_x and PM trade-off relations. Applying the hot EGR configuration in PCCI combustion mode resulted better in-cylinder temperature for CO minimization and also to decrease NO_x reaction rates. Hot EGR configuration is found 12.8% reduction of the total emissions of hydrocarbon in comparison with the dual fuel PCCI baseline conditions. In addition, hot EGR would increase the intake charge temperature, which would affect the combustion and the exhaust emissions.

2.8 Methanol as Transportation Fuel

Alternative fuels using alcohols and their blends showed a promising results for transportation for both gasoline and compression ignition engines. This also includes the premixing technique in dual fuel applications. Applying methanol as an alternative fuel resulted several advantages including NO_x emission reduction. The method and use of methanol does not destruct our ecosystem having characteristics that it burns at a slower rate and at a lower temperature. There are ways of making methanol at home i.e. cheap to make compared to other alternative fuels and means of creating home business. Studies showed that higher oxygen content of methanol helps in additional oxygen in the vicinity of the diesel for enhanced and effective combustion characteristics. Also the high oxygen and low sulfur contents of methanol reduce emissions. The low viscosity nature of methanol makes it to be easily injected, atomized and mixed with air, in addition its high laminar flame propagation speed improves the thermal efficiency of the engine making the combustion process to be completed earlier (Hunter C, Gardner et al. 1990).

Methanol-fueled trucks and buses emit almost no particulate matter (which causes smoke, and can also be carcinogenic), and much less nitrogen oxide (NO_x) than using diesel-

fueled alone. It can be produced, distributed, and sold to consumers at prices that are competitive with gasoline and diesel (Parks, Prikhodko et al. 2010). Methanol–diesel blended fuel was successfully tested in a conventional diesel engine and experimental results indicated that the output power and torque for the methanol–diesel blend fueled were higher than the conventional diesel fueled alone. Other study (Kimura, Aoki et al. 1999) also confirmed that, addition of methanol to diesel reduced CO, HC and significantly PM and smoke emissions. Besides it lowers the maximum temperature rise inside the cylinder (Ehleskog, Ochoterena et al. 2007) because of the oxygen content of methanol (Kumar and Saravanan, 2016). Due to these reasons this study used methanol addition fuels as a test fuels. Difficulty of forming homogeneous diesel methanol mixture and limited researches on the area were indicated as challenges by researchers (Antony, 2003). To improve the working of diesel engine and control its emission level, a study (Han, Ickes et al. 2012) indicated methanol/diesel blend version definitely plays a very important role.

2.9 Port Fuel Injection (PFI) in LTC Engines

Experimental investigation conducted (Natarajanl, Pitchandi et al. 2018) on GEELY MR479Q port fuel injection (PFI) SI engine with PFI of methanol-gasoline blends at wide-open throttle operating conditions showed positive effects on the engine-out regulated emissions, indicating that NO_x, CO and non-methane HC emissions were all reduced dramatically (Dash, Jena et al. 2021). Studies were conducted on turbocharged, PFI spark-ignited 1.9L, 4-cylinder engine with 19.5:1 compression ratio operating un throttled using stoichiometric fueling from full power to near idle conditions, using exhaust gas recirculation (EGR). The result showed that better brake thermal efficiencies over the baseline diesel engine and low steady state NO_x, HC and CO, together with inherently low PM emissions. In addition, the study (Yessian1 and Varthanan, 2020) explained that the engine is expected to have significant system cost advantages compared with a similar diesel, mainly by virtue of its low-pressure port fuel injection (PFI) system.

2.9.1 Port Fuel Injection in PCCI Combustion

Formation of premixed mixture outside the combustion chamber is required in PCCI combustion mode. Studies and literatures indicated that certain amount of fuel will be injected into the intake manifold to form the mixture and it enters into the cylinder and the

usual conventional direct injection will be used to supply the remaining fuel. The premixing of the fuel with the intake air raises the equivalence ratio of the mixture entering the cylinder, and hence the overall homogeneous property of the mixture inside the combustion cylinder will be enhanced.

Experimental studies of PCCI combustion mode using heated diesel over unheated diesel spray on a diesel engine were carried out to investigate its impact on the performance and emissions. The study (Mohanamurugan, 2010) revealed the following conclusions; 3 to 4 bar increase of injection pressure improved the spray atomization at high temperatures of the diesel. Particularly at a fuel temperature of 80°C and an injection pressure of 4 bar resulted a spray approaching gasoline. 35% proportion of diesel port injection using PCCI mode of combustion showed improved thermal efficiency at high loads. Increasing the temperature of the port injected diesel fuel also indicated a significant decrease in HC and CO emissions. However increasing diesel temperature from 40 to 60°C resulted an increase in NO_x emission.

Port fuel injection using biodiesel combined with n-butanol were tested on PCCI and LTC combustion technologies and the study (Pohit and Misra, 2013; Bhiogade and Suryawanshi, 2017) showed that it is very effective in simultaneously reducing soot and NO_x emissions at idling speeds and their tradeoff was modified favorably. The study also pointed out that future research studies to focus on EGR strategy to wider further LTC range with soot-NO_x reduction. Higher CO and HC emissions were found in this investigation which are the disadvantages of n-butanol PCCI and LTC operations as indicated in the study mainly due to the incomplete combustion during the premixed burn phase from over-lean areas in the combustion chamber and showing an increase of 10 - 20 times dependent upon load and speed.

Other study (Agarwal, Singh et al. 2017) using methane port injection supply for dual fuel engines is found a very effective method to minimize UHC and NO_x emissions. The port injection method resulted HC levels tend to decrease while NO_x increase. From the study it was observed that, BTE was increased by 0.5 % in comparison to induction method. Results of emission levels were found with smoke 7.69 %, HC decreased by 13.33 %, CO decreased by 31.81 %, NO_x increased by 1.45 %.

2.10 Dieseline in Compression Ignition Engines

Literatures defined ‘Dieseline’ concept from the strategy of modifying the fuel properties to make it more suitable for charge compression ignition combustion. Considering gasoline and diesel which are the current most commonly used automotive fuels but their properties are not perfectly suited to charge compression ignition combustion modes. Gasoline with a high octane rating (~90-100) does not ignite readily, and with diesel having a high cetane rating (~50-60) ignites and combusts too easily. By mixing the two fuels called dieseline, the combined fuel properties are more suited to charge compression ignition combustion (Zhang, Rezaei et al. 2014). Various studies confirmed the benefit of dieseline and this study also investigated dieseline with different ratios together with methanol for PCCI combustion. The longer ignition delay and higher volatility of dieseline and also production of a more homogeneous fuel air mixture before the start of combustion were found by researchers (Yang, Yao et al. 2016). Dieseline proved to be an attractive fuel for improving the premixed combustion in CI engines. Which ratio of diesel to gasoline or dieseline is optimized combination LTC operation mainly for PCCI-DI operation is still unresolved question that this study made its effort.

Dieseline offered high fuel conversion efficiency and greatly reduced the total concentration and mean diameter of particulate matter (Wang B., Wang et al. 2015). Blending the commercial diesel and gasoline is an obvious choice to lower CN and raise volatility (Noehre, Andersson et al. 2006). Alcohol compound additives (i.e., methanol, ethanol, n-butanol etc.) are fuels infused with rich oxygen content and used to improve the combustion characteristic when blended with diesel. Nowadays, many researchers (T. Yusaf, I. hamawand1 et al. 2013; Park S, Cho J et al. 2017; Chen, Wu Z et al. 2013; Panao, 2007) are promoting the use of methanol (CH_3OH) (which is having high oxygen content and high volatility component) as an alternative fuel for internal combustion engines due to its ability to produce power with less emission (Poures, Gopal et al. 2019). The effects of methanol premixing on the intake manifold through different way application were studied by researchers and it showed that increase in the fraction of methanol resulted peak in cylinder pressure and temperature decreases (Park, Cho et al. 2017).

A study (Kalghatgi, G. T. et al. 2007), explored that an LTC strategy with gasoline-like fuels and found ultralow soot and NO_x emissions could be achieved at loads up to 15.95

bar IMEP. Fuel with lower CN and raised volatility, such as a blend of diesel and gasoline, recently termed “dieseline”, has been suggested for LTC, in particular at light loads. In gasoline LTC combustion mode, smoke emissions were near zero and NO_x emissions were controlled at a relatively low level even without EGR (Han, Ickes et al. 2010).

2.11 Summary

From the review several studies confirmed that simultaneous reductions of NO_x and soot emissions in the exhaust including reduction of fuel consumption were found compared to the conventional combustion. This is possible by avoiding peak combustion temperatures through low-temperature premixed combustion mode (LTC) in diesel engines. In both LTC modes, injection of fuel either in the port or early direct injection during compression stroke in the cylinder promotes air fuel mixing. As mentioned from the review research results forced researchers to work on new LTC strategy that they name it as a premixed charge compression ignition (PCCI) combustion which is an improvement on HCCI combustion concept in relation to combustion stability and better emission results. In the review investigators indicated that by applying proper EGR level, proper injection timing and proper engine load conditions help to realize low-temperature combustion for better engine performance and emissions. The review also indicated conventional diesel combustion is prone to the well-known trade-off challenges between particulate matter (PM) and nitrogen oxides (NO_x). Researchers also resolved this challenge through PCCI like combustion mode which is the modified LTC concept. Effect of advancing the fuel injection timing during compression stroke was studied and found promoting mixing in PCCI combustion. But these findings from PCCI combustion strategies have their own challenges and gaps which need to be resolved.

Excess values of start of injection in PCCI mode made an increase in HC and CO emissions above the acceptable ranges which is a gap that needs further work. Varying engine load conditions on PCCI mode of combustion have been found affecting the emission results which needs to be identified and optimized. Similarly, different engine load conditions during EGR application resulted different emission results which also need to be properly matched and optimized. From the review studies on the impact of EGR configurations and port injection strategies during dual fuel combustion particularly with alcohols in PCCI combustion mode are very rear and needs more work. The review showed that dual fuel engines have the benefit of minimizing emissions and lowering greenhouse gas-

es particularly in diesel engines but enough studies were not conducted particularly in tuning of these fuel properties for dual fuel applications in PCCI-DI combustion mode diesel engines. Even though dieseline was suggested for LTC strategy, there is a gap in choosing the proper ratio and optimization is not done by investigators.

CHAPTER THREE

EXPERIMENTAL SETUP AND METHODOLOGY

This chapter discusses the experimental setup and equipment's used for the study. It also includes methods and tools for the optimization process enabling the PCCI-DI diesel engine which is the modified conventional diesel engine for better emission results. The optimization methodologies applied helped to obtain optimum control operating parameters that are used to obtain lower emissions in PCCI-DI diesel engine.

3.1 Introduction

In this chapter the materials and methods of doing the experiment were discussed. It contains the contents; materials and equipment's required for the research work, schematics of the experimental setup, methods or approaches in conducting the tests, experimentation and analysis, selection of the control parameters which are influential for the intended experiment, chosen test fuels for the experiment, verification tests and DoE optimizing technique of the Taguchi's L_9 orthogonal array type. The chosen materials and methods helped in optimizing the engine control parameters; injection timing, EGR %, diesel line ratio and engine load for better trade-off between NO_x , HC, CO and smoke emissions of a diesel engine operating in PCCI-DI combustion mode. In this study experimental approach together with DoE and a hybrid of grey relational analysis with Taguchi method were used in optimizing the combustion control parameters. Engine specifications and schematic of engine test setup were made after identifying the actual experimental setup. The research methods to be employed to accomplish the objectives of the study begin with literature survey. Various related articles and publications, reading materials, books, journals, previous research works including dissertations and thesis in different level of studies were referred in order to have comprehensive understanding of the subject. Different issues related to LTC diesel engines emission control strategies applying different combustion control approaches and alternative fuels were referred.

3.2 Experimental Setup

The chosen materials and methods helped in optimizing the engine operating control parameters; Injection timing, EGR % and dieseline ratio for better trade-off between NO_x, HC, CO and smoke emissions operating in PCCI-DI combustion mode. Figure 3.1 shows schematic of experimental system. Diesel, gasoline and methanol fuels with quality standards were procured locally from the reliable sources (their property is shown in table 3.3). reaction flask, stirrer, light-duty single cylinder diesel engine connected to eddy current type dynamometer for loading and timing measurements, exhaust emission analyzer and compressor were some of the equipment's used for the experiment. The experimental set-up was instrumented to measure emissions, load ranges and related performances. Exhaust gas emission compositions of NO_x, CO, HC and smoke were measured with emission analyzer for optimized results to be indicated using plots. Data is gathered by varying engine loads mainly on 25%, 50% and 75% load settings considering previous promising research attempts and also limitation of LTC engines.

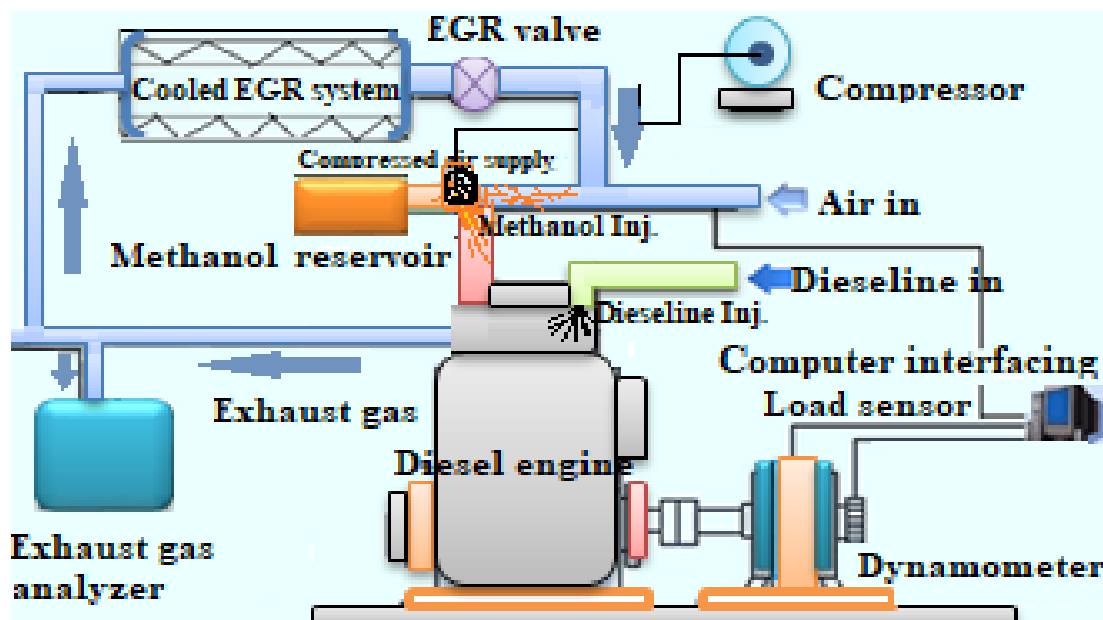


Figure 3.1: Diagram of the experimental setup



Figure 3.2: PCCI-DI diesel engine experimental setup

1-Single cylinder engine, 2-Motor, 3-EGR cooler, 4-EGR valve, 5-Water reservoir. 6- Intake port, 7-Dieseline reservoir, 8 - Methanol reservoir, 9-Air compressor, 10- Smoke Meter, 11- Control system with computer

3.2.1 Engine Setup and Specifications

The experiment was carried out on a single cylinder DI diesel engine by adapting it for the intended operational conditions and combustion type which is LTC engine operation particularly having the features of PCCI-DI conditions. Basic engine specifications and experiment conditions are indicated in Table 3.1. Modifications on the chosen engine include; modification of fuels (port injection of methanol and direct dieseline injection with different ratios), adaptation of EGR % (25, 35 and 45 %) and injection timings (23° , 25° , 30° ; advanced) were used. during PCCI-DI mode of combustion. For better homogeneity methanol was supplied on the intake manifold system rather than pre blending with dieseline. The setup is equipped with system allowing control for the dieseline injection timing and EGR control system. The EGR valve is applied on the exhaust system to allow exhaust gases into the intake manifold. The level of exhaust gas recirculation is detected on the available test engine setup on the basis of a mass flow percent. This confirmed us how EGR system is applied and important in creating LTC mode and also together with

the advanced dieseline injection adjustment enables the formation of PCCI-DI mode of combustion.

Table 3.1: Test engine specifications and experimental conditions

TM3-02. Air-cooled	Single-cylinder four-stroke diesel
Bore(mm)	69
Stroke (mm)	60
Speed (rpm)	3600
Power kW (HP)	3.5(4.8) ; N 80/1269/EEC-ISO 1585
Maximum torque	10.4 Nm at 2400 rpm
Methanol Port Injection System	Port air-blast injection of methanol (3 bar)

Computer controlled electric motor is used to start the engine and to generate the load. In order to accelerate and decelerate the combustion engine the computer controlled fuel valve is used. To attain steady-state conditions, the experimental engine was allowed to operate for 6 minutes and the unmodified test engine was made initially to run under conventional conditions to have reference or baseline records. The test engine is then adapted to work in PCCI-DI mode, by doing suitable changes in injection timing, EGR %, methanol port injection and dieseline direct injection. Average value from 3 repeated tests were taken for each required test investigations.

For EGR system, multiple tubes of 12 in number (Figure 3.5) is used for the cooler design and it uses water as a coolant. The manufactured cooler has dimensions; internal diameter 12mm, tube length 400mm and tube thickness 1mm. In choosing the EGR cooler dimensions for manufacturing and assembly; different published papers under optimized EGR coolers for single cylinder diesel engines were referred (Patel, 2012; Solouk, Shahbakhti et al. 2014; Master, Chunangad et al, 2003). Coolant coming from the radiator is mostly used in the shell and tube type heat exchangers, but for this experimental set up separate water reservoir is designed for the cooling water supply having external heating mechanism to have comparable cooling water temperature with temperature of water in a radiator. The study tried to demonstrate the potential of air-blast port injection of methanol in

parallel with diesel direct injection on emission reduction in diesel engine by applying dual-fuel combustion strategy.

The methanol port injection is a workshop air compressor assisted type positioned close to the intake valve to form the premixed charge in homogeneous mixture form.

3.2.2 Engine Adaptation and Conversion

To conduct the experimental investigation on the PCCI-DI diesel engine operating mode, it was mandatory to adapt and modify some engine systems and components from the existing conventional diesel engine into the required operating conditions and set ups. This adaptation and conversion of the conventional engine set up to the PCCI-DI set up answered the question of the possibility of establishing low temperature combustion scheme of the type PCCI-DI mode by using the available equipment's in a medium automotive workshop. New EGR cooler having its control valve units manufacturing including modification of the inlet port which delivers only air to the combustion cylinder in to a port having methanol fuel injection and premixing system are parts of the conversion and adaptation works. A components arrangement having an injection unit, amount of methanol delivery control unit, methanol reservoir and other accessories including connectors to the air compressor unit were adapted and assembled on the intake manifolds as shown above in Figure 3.1 and Figure 3.2.

New EGR cooler (Figure 3.7) was designed and manufactured that suits the experimental setup and the chosen engine based on literature survey and former published research works. This is due to the absence of appropriate EGR cooler to purchase locally having the required features. Manufacturing of the EGR cooler includes several basic activities. Choosing the proper type of cooler or heat exchanger was the first activity done in which the shell and tube type was chosen considering various benefits. After choosing the proper type of cooler, required thermodynamic properties were identified. These thermodynamic properties include; inlet temperature of water, outlet temperature of water, inlet temperature of exhaust gas and outlet temperature of exhaust gas. Choosing the dimensions of the EGR cooler components were the next activity which includes; choosing proper tube diameter, thickness, length and number. Other activities include, choosing proper shell di-

mensions; diameter, thickness and length. Choosing appropriate baffle plates which includes; baffle plate wall thickness, number of baffle plates, baffle spacing length and baffle hole diameter indicated in Figure 3.3 were done accordingly in order to manufacture the EGR cooler with available materials locally in workshop.

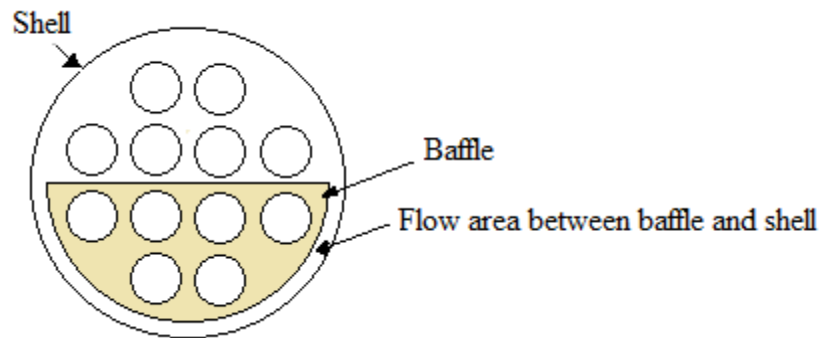


Figure 3.3: Baffle cut design used for manufacturing

Manufacturing of the EGR cooler and its assemblies based on the above design layout and input parameters. Work activities in a workshop comprise; Metal work, welding and pipe fitting and assembly works. Some of the work activities and products done during the manufacturing of the EGR cooler and its assemblies were shown in figure 3.4 to Figure 3.6.



Figure 3.4: Manufacturing of components of EGR cooler



Figure 3.5: Assembly of cooler tubes and baffle plates

The shell and the tube material are made up of aluminum. Pipe inlets arranged in perpendicular and exits were used in allowing the coolant into the EGR cooler.



Figure 3.6: Manufactured EGR cooler system assembly for the conventional engine modification

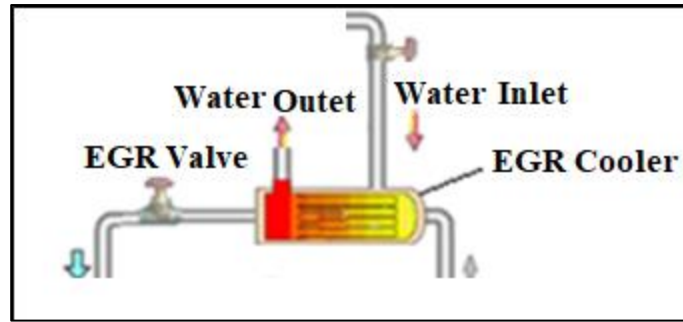


Figure 3.7: Layout of the EGR cooler

In the present work design and development of EGR system is done for Single cylinder, four strokes compression ignition engine. Shell and tube heat exchanger of EGR system as shown in Table 3.2 is designed for cooling hot gasses and increasing volumetric efficiency. Design of shell and tube EGR cooler is done with theoretical calculation. Cold EGR system is useful for effective working of exhaust gas recirculation system. The obtained results are purely based on the theoretical calculations by changing the number of tubes and diameter of tube of shell and tube EGR cooler. This EGR cooler manufacturing is mainly based on its effectiveness, simplicity and manufacturing cost. This attempt would motivate others to design, develop and manufacture a particular EGR cooler for a specific EGR system that will work efficiently in reducing engine emissions.

Table 3.2: Design specifications of the chosen and manufactured heat exchanger

Description	Specifications
Water inlet temp. (T_{c_1})	30
Water outlet temp. (T_{c_2})	60
Type of heat exchanger	Shell and tube type
Number of baffles (N_b)	1
Outer diameter of tube (d_o)	14mm
Inner diameter of tube (d_i)	12mm
Number of tubes (N_t)	12
Length of tube (L_t)	400mm

The conventional single cylinder diesel engine was suitably adapted and modified to function as PCCI-DI operating setup to conduct the experiment of optimizing the chosen engine operating control parameters or factors.

3.2.3 Fuel Supply System for the PCCI-DI Setup

Various researches confirmed the additional significant feature of LTC having fuel flexibility nature, since fuel properties substantially affect the chemical kinetics, which has a leading role in LTC. Fuels dieseline and methanol were used for this experimental investigation. Dieseline was prepared by blending diesel and gasoline fuels with different ratios which makes it having the characteristic of lower cetane number and higher volatility or in general suitable for LTC engine operating in PCCI mode. Researches revealed that increasing the percentage of gasoline decreases the cetane number of the test fuels. This forms higher resistance to auto ignition by providing longer ignition delay which would reduce fuel-rich regions and soot formation in PCCI LTC approach (Vellaiyan and Swaran, 2017). In this study identifying the chemical and physical properties of the test fuels were done before applying for the experiment.

This study tried to demonstrate the potential of methanol utilization in parallel with dieseline on the chosen diesel engine setup by applying dual-fuel combustion strategy. For this condition air-blast port injection of methanol into the intake manifold and direct injection of dieseline into the combustion chamber were arranged.

For this experiment, the majority of the fuel is directly injected into the cylinder in advance during the compression stroke and the rest of the fuel which is methanol is premixed through air-blast port injection system. This enabled to control the combustion process through the port injected premixed methanol fuel strategy and injection timing control of DI dieseline fuel. The study focused in optimizing the chosen operating parameters of the PCCI-DI engine for optimal lower emission characteristics. Methanol port injection resulted premixing of fuel, hence avoiding the local rich zones in the cylinder.

3.2.4 Methanol Port Fuel Injection (PFI) Adaptation, Calibration and Assembly

Considering the promising strategy of port fuel injection for PCCI mode of combustion this study made further optimization works through applying alcohol fuel in addition to the conventional fuels. Applying the flexibility nature of fuels basically affects the chemical kinetics which is having an important feature in LTC mode of combustions and also research findings confirmed that modifications of fuel properties have a significant role on their auto-ignition characteristics.

The question of the possibility in arranging pre calibrated methanol port injection for PCCI diesel engine operation using a medium automotive workshop was functional from this study. The air-blast port injection of methanol which is modified and adapted on the intake manifold (Figure 3.8) maintaining an injection pressure of 3bar on the experimental setup helped to form a premixed homogeneous mixture of methanol and air in the inlet. The pre-injection and premixing of methanol and air was designed and mounted on the intake manifold which is 12cm away from the intake valve by considering literature on port injection systems. (Dempsey, Walker et al. 2014; Bueschke, Wislocki et al. 2017; Saxena and Maurya, 2017; Nassiri, Nozari et al. 2007; McGee, Curtis et al. 2000; Ogawa, Setiapraja et al. 2010). This average distance of pre-injection position is close to the distances which were used by researchers to have a port fuel injection system creating a proper homogenous charge of fuel and air during the premixing stage.



Figure 3.8 Modified intake manifold and adapted EGR set up

3.2.5 Fuels, Test Conditions and Properties

Dieseline with a pre blend of diesel and gasoline in a ratio of 60%, 80% and 90% diesel by volume were used. Diesel, gasoline and methanol fuels used for the experiment have properties as shown in table 3.3. The fuel composition, molecular size and structure determine its auto-ignition capacity. Considering this; Researchers (Clark, Posada et al. 2010) studied methods of improving the control and emission characteristics through blending of fuels with different auto-ignition properties. The main differences between diesel, gasoline, methanol and blends used for the experiment are linked to the cetane number, volatility and density.

Addition of gasoline fuel into diesel fuel to have a dieseline has number of impacts on the characteristics of diesel fuel, particularly reductions of the cetane number, viscosity, flash point, pour point, and heat content. These also affects the combustion, spray evaporation and emission characteristics.

Table 3.3: Chemical and physical properties of the test fuels

Test fuels and compositions						
Property	Diesel	Gasoline	Methanol	60% D and 40 % G	80% D and 20 % G	90% D and 10 % G
Cetane number	52	13	5	37.48	44.13	49.62
Octane number	/	94	91	/	/	/
Density /(g/ml)	0.89	0.73	0.79	0.78	0.81	0.83
Viscosity (mm ² /s)	2.501	0.64	2.49	1.803	2.06	2.1
* D-diesel, G-gasoline						

The above chemical and physical properties of the fuels are partially obtained from the Material Engineering laboratory in Adama Science and Technology University and partially from calculation predictions using references (Vignesh, Srihari et al. 2019; Zhang, Rezaei, et al. 2014, ASTM international, 2011; Kirgina, Ilya A. et al. 2019; Murphy and Battelle, 1983; Hemant, Kinikar et al. 2022; Ibrahim and Farooq, 2021; Wei, Y.-J et al.

2022). Premixing ratio of a fuel describes the energy input percentage of fuels in dual fuel combustion mode.

3.2.6 Exhaust Gas Recirculation (EGR) System Control Setup and Calibration

EGR system with its control setup was installed on the inlet manifold of the experimental test setup and is achieved by a direct link between the exhaust and intake ports. Proper matching of EGR amount has been used and its control setup being installed and adapted on a single-cylinder diesel engine to allow it to enter the PCCI-DI combustion mode which is conducted with low engine speed and optimal load ranges. Different EGR % were adapted and applied in lowering the combustion temperature and to achieve optimal low NO_x, CO, HC and smoke emissions in different load ranges.

In this experimental setup the EGR % was controlled manually by varying the EGR valve position as shown in Figure 3.9 of the test layout.

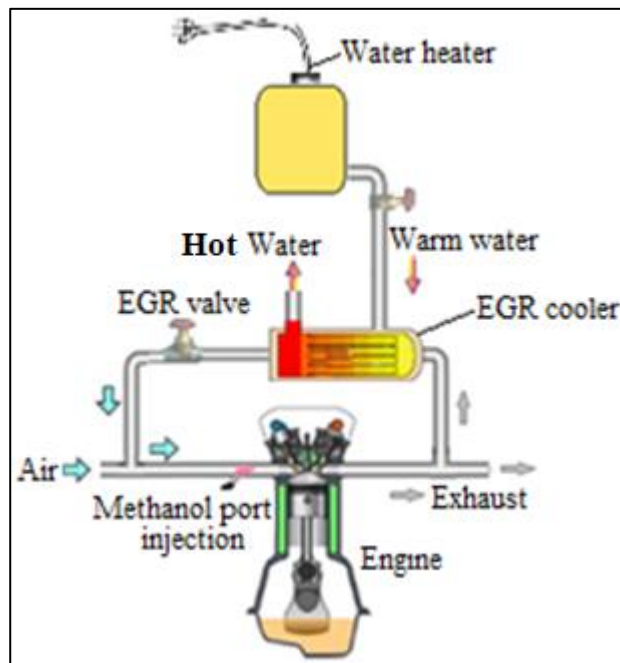


Figure 3.9: Layout of EGR system applied for the experiment

The EGR cooler used for this experiment has entrances for cooling water and exhaust gas. Likewise there are exit passages for the two fluids. Attachment of the EGR cooler with the PCCI-DI diesel engine is almost similar to most diesel engines having EGR. But instead of using water coming from the radiator, this set up uses water coming from a separate

reservoir as indicated in figure 3.9. In controlling the flow level or percentage of the recirculating exhaust gas, a manually controlled gate valve is installed in the experimental set up. Temperatures of the coolant water flowing to EGR cooler including the exhaust gas were measured using a thermometer arranged in the set up. In this experimental investigation three scenarios of EGR configurations were considered; cold EGR, hot EGR, and no EGR configurations. Shutting and draining the cooling water and blocking the EGR flow, make the scenario hot, cold and no EGR configurations.

The EGR cooler is designed with multiple tubes of 12 in number and uses water as a coolant. It has dimensions; internal diameter 12mm, length of tubes 400mm and tube thickness 1mm. choosing the EGR cooler dimensions for manufacturing and assembly for this experiment were referred from published papers under optimized EGR coolers for single cylinder diesel engines (Patel, 2012). Water flowing from radiator is mostly applied for cooling purpose in the tube and shell type of heat exchangers, but for this experimental set up separate water reservoir is designed for the cooling water supply having heating mechanism to have comparable cooling water temperature with the radiator. The effects of these EGR configurations on emissions were tested at 25 % of EGR %. Figure 3.9 shows a schematic diagram for the EGR cooling system. To attain steady-state conditions, the experimental engine was allowed to operate for 6 to 10 minutes and then the required data were collected. Even though maintaining a steady state operating condition in PCCI operation is difficult, Steady state operation was detected in this experiment in terms of engine speed, torque and exhaust gas temperatures. During this state of operation relatively no engine speed changes frequently and relatively stable exhaust gas temperature readings were used as signals for steady-state operations to reach in the mentioned average time. Average value from 3 repeated experimental tests were taken for each required test investigations.

Fully cooled EGR in which the exhaust gas is cooled close to the temperature of the fresh intake air, before re-circulation in to the cylinder using water-cooled heat exchanger, were employed for the EGR system which will help in achieving the premixed combustion through proper ignition delay.

Considering EGR the most important engine working parameter in developing PCCI combustion mode set up and its dilution effect, the EGR % was optimized for HC and CO

emission results by using the EGR valve to function on the chosen rates (25%, 35%, and 45%). The PCCI-DI engine setup was made to operate on these different percent of EGR and was found to be a very useful method for the optimization process. Promising results were obtained from the optimum EGR level combinations with the other chosen engine operating parameters that helped for simultaneous reduction of NO_x, and smoke and also relative lower CO and UHC emissions comparing with the previous investigations.

3.3 Instrumentation and Data Acquisition System on the Engine Setup

The test engine is fitted on a dynamic test bench and the test set up is instrumented by adapting LTC techniques through PCCI concept being modified on the conventional diesel combustion engine for the measurement of emissions and other parameters.

3.3.1 Data Acquisition Hardware and Control Software

Representative magnitudes or figures from the results of the experimental combustion engine; power, torque or power versus velocity, emission results, etc were computed with their characteristic curves. The unit also includes; Control software based on LabVIEW, National instruments data Acquisition board (250 KS/s, kilo samples per second), utilizing four safety systems of the categories; mechanical, electrical, electronic & software types. These are designed and produced aiming numerous quality standards. The data acquisition board has analog input/output and digital input/output.

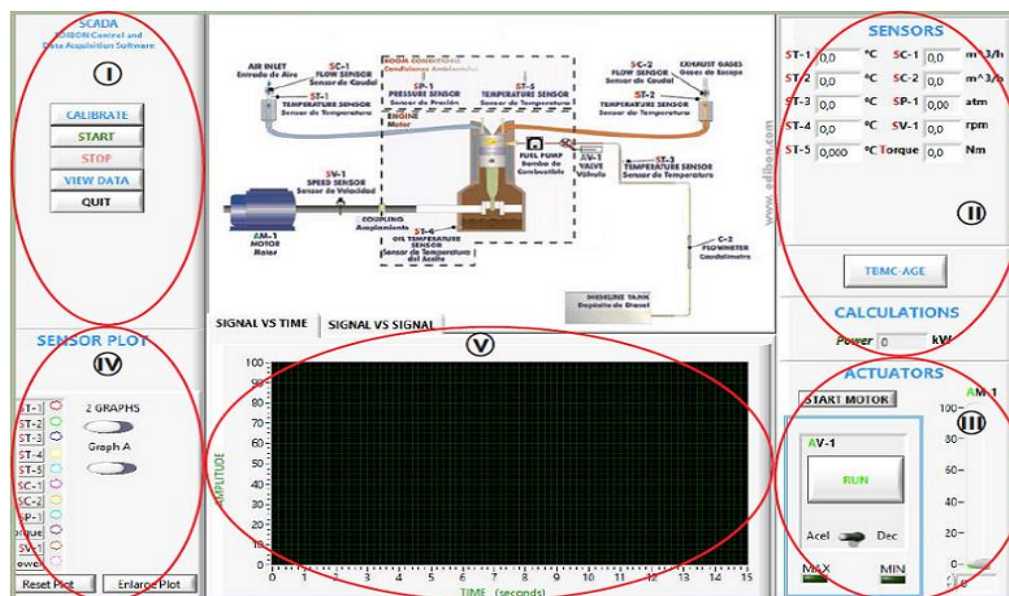


Figure 3.10: Main screen of the software

I-Main software operation possibilities, II- Sensors displays, III- Actuators controls, IV- Channel selection and other plot parameters, V-Real time graphics displays.

Provision of the control software and data acquisition permits the illustration of the measured and computed magnitudes curves, in signal versus signal charts along with their axes configurations.

3.3.2 Measurement Setup

Probes were positioned on different engine systems to measure temperature, pressure, amount of fluid flow, emission characteristics, etc during the experiment. This includes several sensors which offer measurement results of the engine variables. The instrumentations include the followings:

Speed sensor to measure the speed (rpm) of the engine, ranging from 0 – 6000 rpm. “J” type temperature sensors were mounted at different systems of the test engine. These include inlet air temperature, exhaust gases temperature, fuel temperature and engine oil temperature. Flow meter to measure the fuel consumption was installed between the fuel tank and fuel injection. Two flow sensors aimed to measure the inlet air flow to the combustion engine cylinder and exhaust gases outlet flow from the cylinder are used for measurements. For the required safe operation during the experiment, the unit includes all the safety measures including temperature limit which switch to control if any of the protection panels is open. Actuators including sensors results and their responses are shown on only one screen of the computer (Figure 3.10).

3.3.3 Exhaust Emission Measurements

Diesel engine emission formation is affected by operating parameters (engine speed, engine load, coolant temperature, fuel cetane number, fuel volatility), fuel injection parameters (high injection pressure, retarded injection timing, pilot injection, spray angle, sac volume, and engine design parameters (compression ratio, stroke/bore ratio, crevice volume, swirl) (Maurya, 2018). The test bench used has the elements computer controlled exhaust gas calorimeter and exhaust gas analyzer. Flow sensor is installed to measure the amount of the outlet flow of exhaust gases.

Table 3.4: Specifications of the exhaust gas analyzer used for the experiment

Parameter	Resolution	Accuracy	Range
Carbon Monoxide	0.01 %	+/- 5 % of reading *1	0-10 %
(Infrared)		+/- 0.06 % volume *1	Over-range 20 %
Oxygen	0.01 %	+/- 5 % of reading*1	0-21 %
(fuel cell)		+/- 0.1 % volume *1	Over-range 25 %
Hydrocarbon	1 ppm	+/- 5 % of reading *1	0-5000 ppm
(Infrared)		+/- 12 ppm volume *1	Over-range: 10,000 ppm
Carbon Dioxide	0.1 %	+/- 5 % of reading *1	0-16 %
(Infrared))		+/- 0.5 % volume *1	Over-range: 25%
Nitric Oxide*2	1 ppm	0-1500ppm +/-5% or	0-1500ppm
(fuel cell)		25ppm;	Over-range: 5000 ppm
Carbon Monoxide	0.01%	Calculated	0-15%
Corrected COK			
Sensor response T ₉₅	Nominal 20 seconds		
Warm up	Less than 2 minutes		
PC connection	Via RS 232 port		
Data-Logging	500 Tests		
Dimensions			
Weight	1kg		
Handset	220mm x 55mm x 120mm		
Probe	Insertion depth 350mm x Diameter 15mm		
	Clip handle to secure to exhaust, 4m long hose		
	Various probes available including high temperature		
Ambient Operating Range	+5°C to +45°C/10% to 90% RH non condensing		
Storage temperature	Minimum: 0°C		
	Maximum: +50°C		
Battery Charger	Input: 100-240 V ~ 47-63 Hz		
	Output: 12 V DC		
Analyzer battery run time	>4 hours from full charge with the pump running		

*1 Using dry gases at STP

*2 Standard on models

The analyzer in which the specification is shown in Table 3.4 was calibrated with clean ambient air in order to get the mentioned specification standards.

Table 3.5: Specifications of the MQY-200 Diesel Smoke Meter/Opacimeter used for the experiment

Parameter		
Environmental Conditions	Temperature	0°C ~ 40°C
	Relative Humidity	≤90%
	Supply Voltage	AC220V ± 10% 50±1 Hz
Measurement Range	Opacity (N)	0~99.90%
	Light absorption coefficient (K)	0~16.08m ⁻¹
	Speed	300~9999rpm
	Oil temp	0~200°C
	Exhaust gas temp	0~150°C
Indicating Value Error	Opacity (Absolute Error)	±2.0%
	Light absorption coefficient	0.05 m ⁻¹
	Rotational Speed Piezo Electric	50rpm
	Oil temp	±5°C (Absolute Error)
	Exhaust gas temp	±5°C (Absolute Error)
Resolution	Opacity	0.01%
	Light absorption coefficient	0.01m ⁻¹
	Speed	1rpm
	Oil temp	1°C
	Exhaust gas temp	1°C
Power Consumption		250W
The effective length of the optical channel		215mm

The smoke meter followed 15 minutes warm-up time, automatic zero resetting. Table 3.5 shows the specification of the MQY-200 diesel smoke meter/opacimeter used for the experiment

3.4 Experimental Procedures

The test was conducted on a single cylinder diesel engine which is modified and adapted for the intended objective. Exhaust emission tests including minor performance tests were done after minor engine modification including fuel modifications. The following basic test procedures were conducted during gathering the data.

1. Checking all the modifications done (methanol port injection, EGR system arrangement, injection timing, diesel to gasoline ratios for dieseline direct injection, etc) for the intended PCCI-DI engine operation are properly tuned and calibrated including functionality.

2. Check the air compressor for proper functioning of methanol port injection.
3. Check all the power supplies to the TBMC3 computer controlled test bench instrumentations are normal and as per the specifications.
4. Check the oil and fuels levels of the test engine.
5. Start the software of the computer.
6. In order to control the test unit press the “Start” on the computer screen.
7. The engine was allowed to operate at idle (no load) for warming and for steady operating conditions.
8. Control the EGR percentage using the manual EGR gate valve arranged.
9. Conduct nine experimental tests following the chosen orthogonal array test matrix (indicated on Table 5.1).
10. Register data of emission characteristics or responses as per the chosen DoE table.
11. Conduct experiments repeatedly and take data following the $L_9(3^4)$ orthogonal array test matrix for the different factor/parameter combinations.
12. Switch off the engine followed after making the engine load zero, provided that all the required data from the experiments are registered.

The experimental test procedure as well as the experimental and theoretical procedure is shown in figure 3.11.

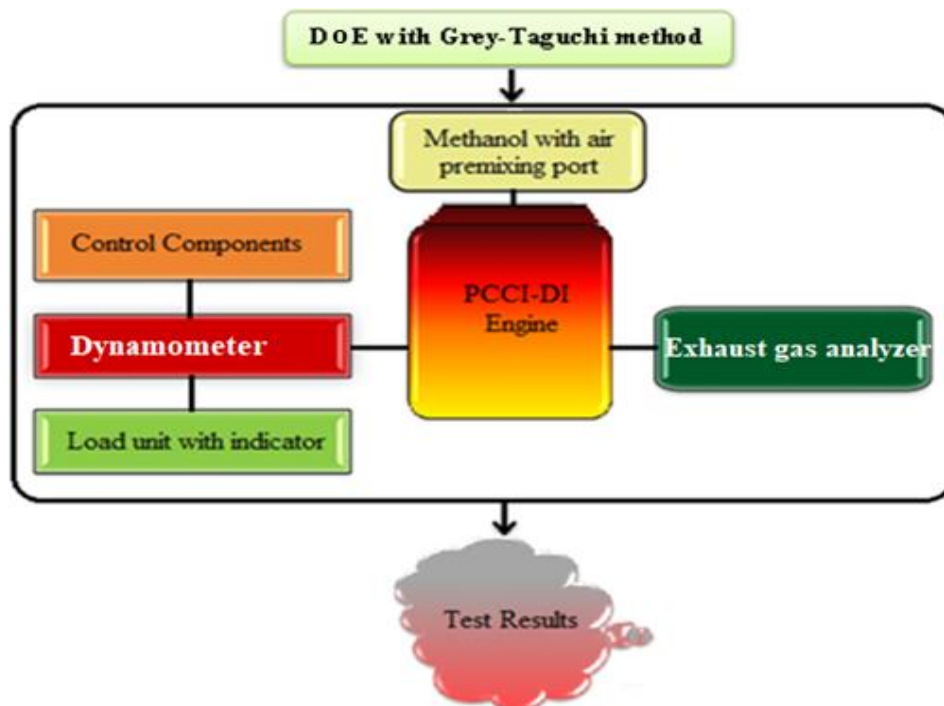


Figure 3.11: Test procedures followed during the experimental study

3.4.1 Baseline Tests

The baseline engine indicates the results of test outputs possessing the original operating parameters (injection timing of 23^0 crank angle before TDC, no EGR, diesel direct injection and speed ranges of 1500 to 2500 rpm. Throughout the experimental study injection pressure was maintained constant at their optimal conditions. The engine load percentages and trade-off relations of emissions were analyzed in relation to the different test fuel ratios, injection timing and EGR % changes. Optimized test results obtained from the methanol port injection and dieseline direct injection strategy were compared with the baseline test results (conventional diesel combustion mode) and also compared with the available literature.

3.4.2 Methanol Port Injection-Dieseline DI Dual Fuel Tests

This study has investigated methanol port injection and dieseline direct injection in CI engine by enabling PCCI-DI combustion under LTC strategy. Expected PCCI combustion reactions were accomplished through low temperature reaction of methanol, high-temperature reaction of methanol and diffusion combustion reaction of dieseline. Emission results and characteristics were studied. An in-house workshop developed port fuel supply system was fitted and adapted on engine intake manifold for port air-blast injection of methanol. Tests were conducted on this setup of dieseline direct injection with port air-blast injection of methanol.

3.5 Design of Experiments

Impacts of the chosen operating parameters and their effects including their interactions among the control variables on PCCI-DI combustion mode of the modified and adapted diesel engine were analyzed using design of experiment (DoE) and ANOVA tools. These tools were applied in order to carry out a DoE and a hybrid of grey relational with Taguchi analysis targeting to find out the optimal combination among the control factors; dieseline ratios, injection timings and EGR levels to obtain better emission results in LTC engines of the PCCI combustion modes. The developed DoE helped to do efficient analysis on the control factors that affected the results. The developed design for the experiment has 9

rows, 3 levels and 4 columns of operating control parameters. In developing the DoE and conducting the tests Taguchi's L_9 orthogonal array was implemented.

3.6 Taguchi Method for the Different Control Factor Conditions

Identifying the significant interactions among the chosen control factors in this study was made possible by applying the fractional factorial design. This helped in avoiding unnecessary large number of test points where no significant interactions were exist. Applying the Taguchi's approach in the design of experiments for this study helped in getting appropriate matching of the control factors/parameters for optimal results. The developed orthogonal array test matrix helped to analyze and study the response variables with a small number of experiments. The chosen orthogonal array test matrix significantly reduced the number of experimental arrangements to be studied. Tabulation of orthogonal array test matrix shown in Table 3.6 was developed for this experimental study as per Taguchi's approach.

3.7 Taguchi Analysis

Factors and levels chosen for the study considering their impact on emission characteristics are shown in Table 3.5. In this study Taguchi's L_9 orthogonal array was applied for experimentation as indicated in Table 3.6. The design has 9 rows, 3 levels and 4 columns of operating control parameters. Minimum numbers of runs or experiments were obtained from the expression $(L-1)P + 1$, where L is the number of levels and P is the number of parameters. The orthogonal array in Table 3.6 is an experimental design that used a small number of experimental trials in finding the key control factors affecting the output or response of the experimental results. Suitable ranges of design matrix of variables to the orthogonal arrays are set as shown in Table 3.6 after conducting number of trials or runs on the chosen control parameters.

Table 3.6: Control parameters and levels

Parameters Code	Parameters	Units	3 Levels		
			1	2	3
			-1	0	1
A	Injection timing (advanced)	CA BTDC	23	25	30
B	EGR %	%	25	35	45
C	Dieseline ratio for DI (D:G)	% By Vol.	60	80	90
D	Load	%	25	50	75

Table 3.7: L_9 (3^4) Orthogonal Array test matrix with factors

Coded Input Parameters								
Run No.	A		B		C		D	
	Injection timing		EGR %		Dieseline Ratio (D:G)		Load	
	(CA BTDC)		(%)		(% By Vol.)		(%)	
	code	actual	code	actual	code	actual	code	actual
1	-1	23	-1	25	-1	60	-1	25
2	-1	23	0	35	0	80	0	50
3	-1	23	1	45	1	90	1	75
4	0	25	-1	25	0	80	1	75
5	0	25	0	35	1	90	-1	25
6	0	25	1	45	-1	60	0	50
7	1	30	-1	25	1	90	0	50
8	1	30	0	35	-1	60	1	75
9	1	30	1	45	0	80	-1	25

Taguchi's DoE method and analysis of variance (ANOVA) were applied in this study aiming to find optimum chosen operating parameters for better engine combustion and exhaust emissions. Reducing the number of experiments was made possible by applying statistical design of the Taguchi method using the orthogonal array (Bose PK, Deb M et al. 2013). Particularly as discussed above, in this study Taguchi's L_9 orthogonal array was applied for experimentation as shown in Table 3.7. Four parameters were varied as indicated in the orthogonal array at three levels and the results of emission were recorded. Taguchi method through orthogonal array method reduces the variance for the experiment by optimizing the process parameters.

The following steps were followed in applying the Taguchi method;

- Selecting the control parameters to be investigated.
- Deciding the number of levels for the control parameters.
- Choosing suitable orthogonal array and allocating the control parameters to the array and conducting the experiments.
- Analyzing the results of the experiment and selecting the optimum level of control parameters.
- Validating the optimal control parameters through a confirmation experiment.

Operating parameters and their levels for experimental design are indicated in Table 3.6 above. Taguchi's L_9 orthogonal array design is shown in Table 3.7. To precede the experiments and the experimental results L_9 orthogonal array were used as indicated in Table 3.7 and analyzed using Taguchi approach. In this table nine tests with operating parameters of injection timing in CA, EGR in %, dieseline ratio for DI (D:G) in % and engine load in % were indicated. Terminologies of the arrays indicated as (b^c) is well defined in (Taguchi, 1990; Ross, 2005) as L : Latin square, a : number of rows, b : number of levels, and c : number of columns (factors).

The process parameters indicated in Table 3.6, are used for the experimental study including control parameters, levels, experimental setup and settings.

3.8 Optimization Using Grey Relational Analysis

S/N Ratio; Variation of result data comparative to the value of nominal data was measured using signal to noise relation. For this study two categories of S/N ratios were used; lower being better and higher being better. Computing S/N ratio was done using the following formulas (Natarajan and Mahalakshmi, 2018).

- Lower the better

$$S/N \text{ ratio}(\eta) = -10 \log_{10} \left(\frac{1}{n} \right) \sum_{i=1}^n y_{ij}^2 \quad (3.1)$$

- Higher the better

$$S/N \text{ ratio}(\eta) = -10 \log_{10} \left(\frac{1}{n} \right) \sum_{i=1}^n y_{ij}^2 \quad (3.2)$$

n - total number of attempts, y_{ij} - the i^{th} result of the j^{th} experiment, and $i = 1, 2, \dots, n$; $j = 1, 2, \dots, k$.

- Nominal the better

$$S/N \text{ ratio}(\eta) = 10 \log_{10} \left(\frac{\mu^2}{\sigma^2} \right) \quad (3.3)$$

$$\text{Where: } \mu = \frac{y_1 + y_2 + y_3 + \dots + y_n}{n}$$

$$\sigma^2 = \frac{\sum (y_i - \bar{y})^2}{n - 1}$$

The level having the highest S/N value indicates the optimal level of the operating control parameters. In this study the emission characteristics NO_x, HC, CO and smoke were treated and computed in S/N ratio for the lower being better.

Normalizing calculations for S/N ratio was done to have an evenly distributed data and upgrading the data for the analysis. y_{ij} is normalized as z_{ij} ($0 \leq z_{ij} \leq 1$). Normalized ratio S/N value which is z_{ij} representing i^{th} emission result in j^{th} experiment could be computed:

$$Z_{ij} = \frac{\max(y_{ij}, i = 1, 2, \dots, n) - y_{ij}}{\max(y_{ij}, i = 1, 2, \dots, n) - \min(y_{ij}, i = 1, 2, \dots, n)} \quad (3.4)$$

(Applied in ratios of S/N being lower the better)

$$Z_{ij} = \frac{y_{ij} - \min(y_{ij}, i = 1, 2, \dots, n)}{\max(y_{ij}, i = 1, 2, \dots, n) - \min(y_{ij}, i = 1, 2, \dots, n)} \quad (3.5)$$

(Applied in ratios of S/N being larger the better)

$$Z_{ij} = \frac{(y_{ij} - \text{Target}) - \min(|y_{ij} - \text{Target}|, i = 1, 2, \dots, n)}{\max(|y_{ij} - \text{Target}|, i = 1, 2, \dots, n) - \min(|y_{ij} - \text{Target}|, i = 1, 2, \dots, n)} \quad (3.6)$$

(Applied in ratios of S/N being best since nominal)

Grey relational co-efficient (discussed in chapter five) for the normalized S/N ratio is computed applying;

$$\gamma(y_o(k), y_i(k)) = \frac{\xi_{\min} + \xi_{\max}}{\xi_{oj}(k) + \xi_{\max}} \quad (3.7)$$

j represents 1, 2 ... n ; k denotes 1, 2 ... m ; n shows number of data items in experiment, m shows number of responses.

$y_o(k)$ denotes sequence of reference; ($y_o(k) = 1$, k denotes 1, 2... m); $y_j(k)$ indicates sequence of specific comparison.

$\Delta_{oj} = \|y_o(k) - y_j(k)\|$ = deviation sequence, representing difference in $y_o(k)$ and $y_j(k)$ in absolute value.

$\Delta \min = \min_{j \in i} \min_{k} \|y_o(k) - y_j(k)\|$ indicating minimum value of $y_j(k)$.

$\Delta \max = \max_{j \in i} \max_{k} \|y_o(k) - y_j(k)\|$ indicating maximum value of $y_j(k)$.

ξ is a coefficient in the range of 0 and 1 ($0 \leq \xi \leq 1$). For this study 0.5 is used as ξ (Tosun, 2006).

Grade for the Grey relation was generated using;

$$\overline{\gamma_j} = \frac{1}{k} \sum_{i=1}^m \gamma_{ij} \quad (3.8)$$

$\overline{\gamma_j}$ - denotes grey relational grade representing the j^{th} experiment and k designates number of emission features.

By considering grades multi response control parameter design was optimized as results shown in chapter five. Results of grades are used to identify the optimal operating parameter aiming to get best results. ANOVA is used to know the input parameters which considerably influence the responses. Determining the optimum combination of the control parameters helps in maximizing response features. Selected optimum level from the operating control factors is used in predicting and also verifying the quality characteristic.

The technique of grey relational optimization helped to develop interrelationships with in the chosen responses. Through this method the grey relational grade is obtained which helps to analyze the degree of relations of the multiple responses. During the optimization the following steps (Figure 3.12) were followed in Grey relational analysis for the experimental investigation.

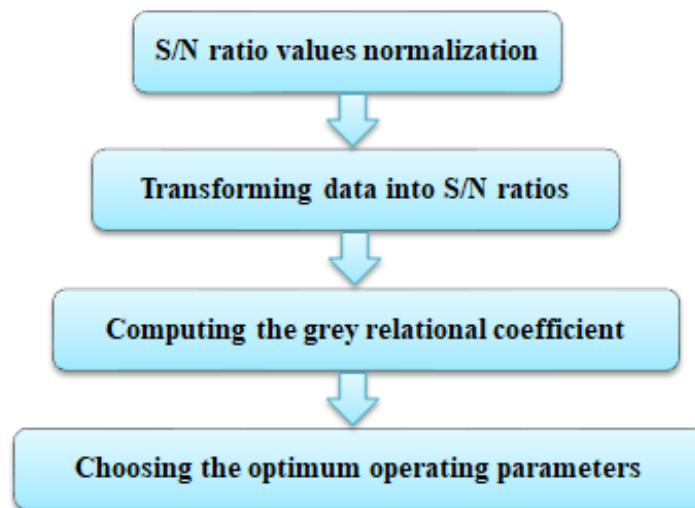


Figure 3.12: Procedures followed in grey relational analysis for the experiment

CHAPTER FOUR

EFFECTS OF OPERATING CONTROL PARAMETERS ON EMISSIONS IN PCCI-DI DIESEL ENGINE EXPERIMENTS

Influential PCCI-DI diesel engine operation control factors were chosen after intensive literature review on PCCI-DI diesel operation. The selected control factors include injection timing, EGR %, dieseline ratio and engine load. Impact of these control factors on emission results of the PCCI-DI diesel engine experimental setup were discussed below.

4.1 Effect of Dieseline Injection Timing on Emissions

Combustion characteristics are affected by the time of injection in all engines and fuel types. In this experiment the PCCI-DI combustion mode set up was made to operate in the SOI regions of 23, 25 and 30 degree (CA BTDC). In this experimental investigation the injection timing of the dieseline fuel affected the emission characteristics with insignificant effects on performance. These effects are shown in Figure 5.1 to Figure 5.8 in chapter 5. Increasing the degree of injection advance resulted reduction of HC and CO and also NO_x at lower loads but increasing tendency of NO_x at higher loads (Figure 4.1 to 4.8).

The effect of advanced injection timing (230, 250, 300 CABTDC chosen) were compared with the conventional diesel operation. From the experimental investigations in all these points of advanced injection timings, both NO_x and smoke indicated reductions from the conventional results whereas there are relative increments of HC and CO from the conventional. But these HC and CO results are promising in which the previous studies are more than in the ranges of 30-150 % increments (J. T. a. A. D. N, 2007; Ambrosio, Iemmolo et al. 2016; Aoyama T. et. al. 1996) which is done through advanced injection of diesel fuel in PCCI setup.

The type of fuel used for the direct injection in this study is dieseline which is a mixture or pre blend of diesel and gasoline fuels in different ratios. By varying the advanced injection timing of dieseline, its effects on the performance characteristics mainly emission characteristic results of the PCCI-DI combustion strategy were investigated and analyzed. The positive characteristics of dieseline which are mentioned in other advanced combustion

modes are also shown in this experimental investigation of PCCI-DI combustion mode. This includes better volatility nature for effective premixing and longer ignition delay which helps low temperature combustion.

The PCCI-DI combustion mode of operation in this study through the optimized advanced injection timing together with other optimized control factors as shown in Figures 4.4 and Figure 4.5 enables to minimize the percentage increase of CO and HC emissions at the mentioned load conditions. So, proper and optimized combination of injection timing with other operating parameters in LTC engines working on PCCI-DI combustion mode provided better emission values. Other investigations showed that late injection of diesel fuel has similar effect of lowering NO_x and soot. The effect of dieseline late injection on emissions needs to be justified with other experiments with similar setup. Aiming simultaneous reduction of both NO_x and soot, research findings explained the benefit of early or late injection timing for PCCI-DI combustion which is different from the trend of conventional combustions.

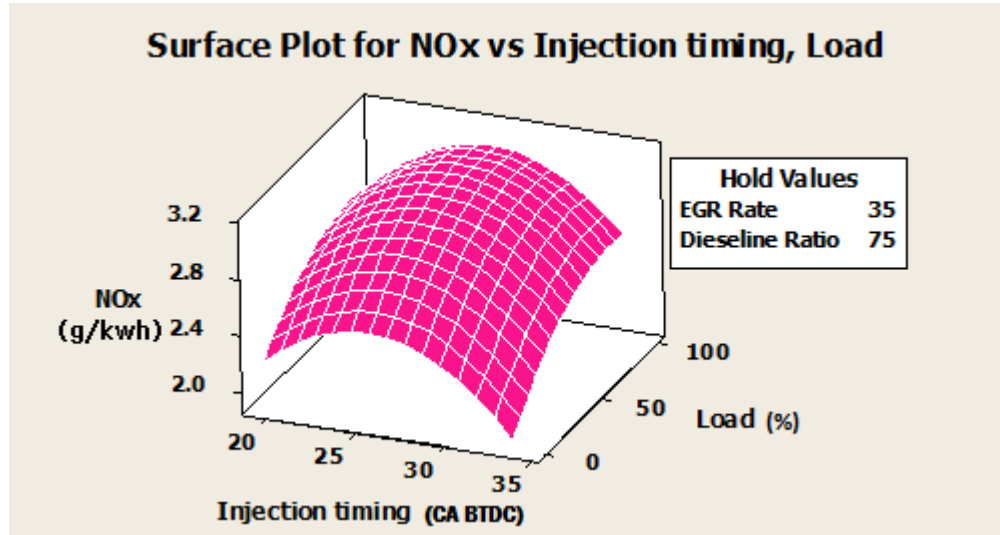


Figure 4.1: Surface plot of NO_x vs Injection timing, Load

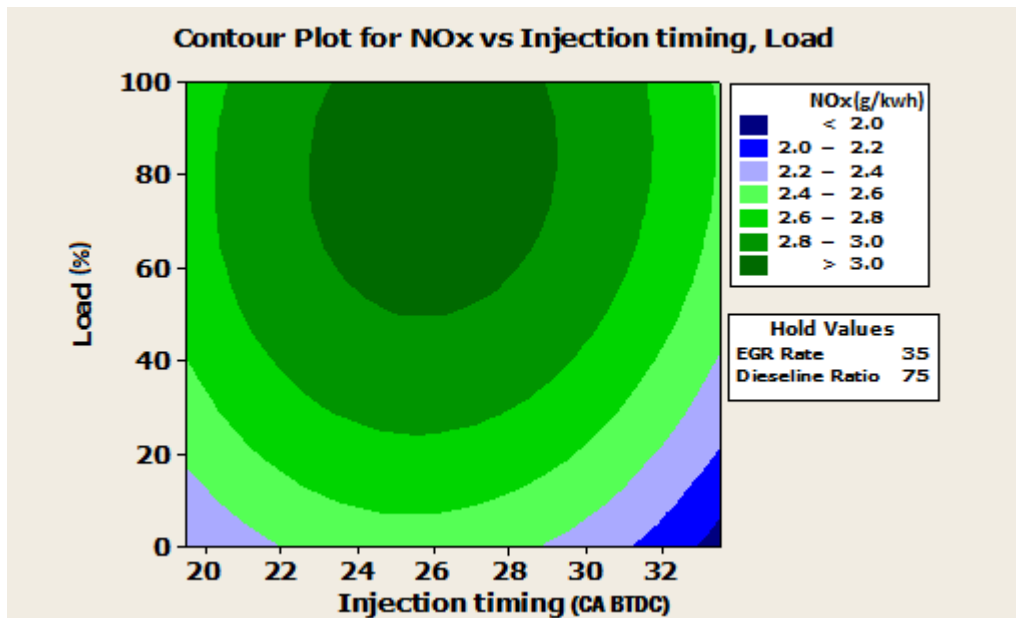


Figure 4.2: Contour plot of NOx vs Injection timing, Load

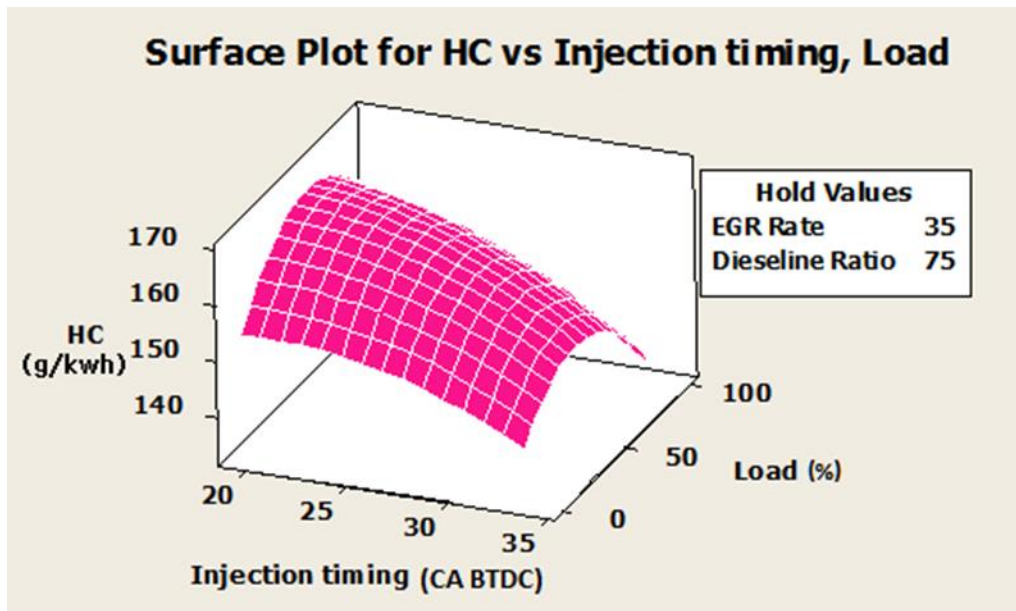


Figure 4.3: Surface plot of HC vs Injection timing, Load

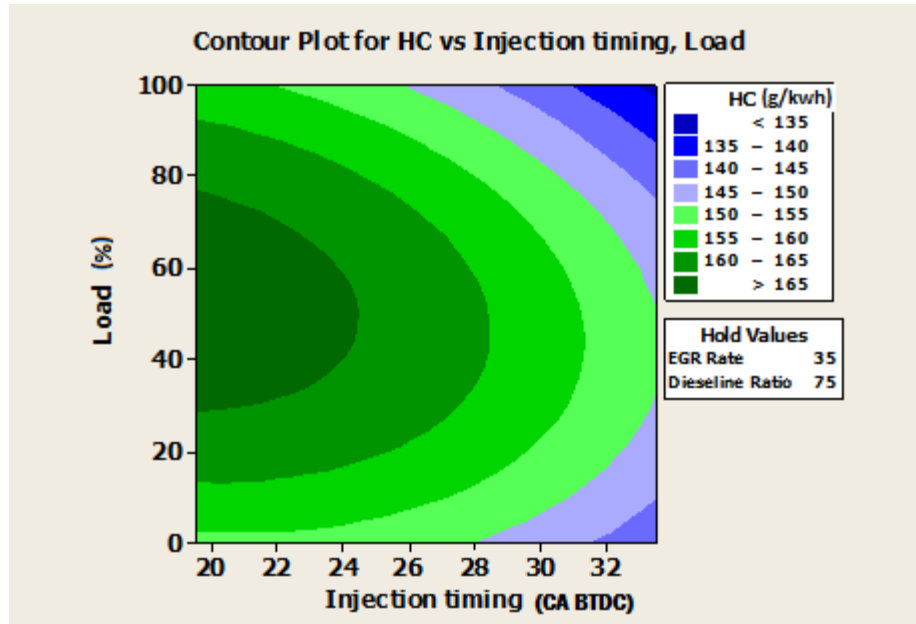


Figure 4.4: Contour plot of HC vs injection timing, load

As shown in the above figures (Figure 4.1 to Figure 4.4), at low loads and advanced injection timings in this PCCI-DI combustion setup, CO and HC emissions are promising due to better combustion efficiency. The fuel impingement on the cylinder wall due to the advanced injection timing facilitated for the increased CO and HC productions as shown in Figure 4.3 to Figure 4.6. Advancing the injection timing causes ignition delay that affects the flame reaction causing influences on HC and CO productions. Near TDC combustions having higher temperature of combustion is achieved through advanced injection timing. Longer HC and CO oxidations resulted from the combustion were facilitated through the early combustion activities. The positive impact and appropriate time of advanced injection timing on the reduction of smoke is shown in Figure 4.7 and 4.8. These figures (Figure 4.7 and 4.8) also indicated that injection timing together with proper load combinations affects the smoke production. Higher HC and CO productions are also produced due to the advanced injection timing causing rich mixture leading cylinder wall impingement effects what has been discussed above. Late injection timing also showed increased HC results.

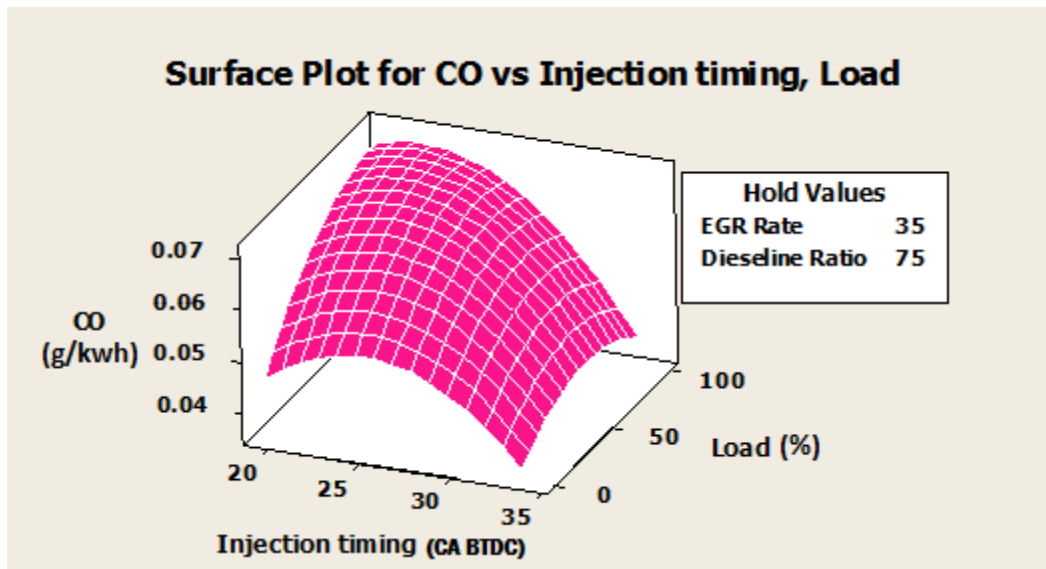


Figure 4.5: Surface plot of CO vs Injection timing, Load

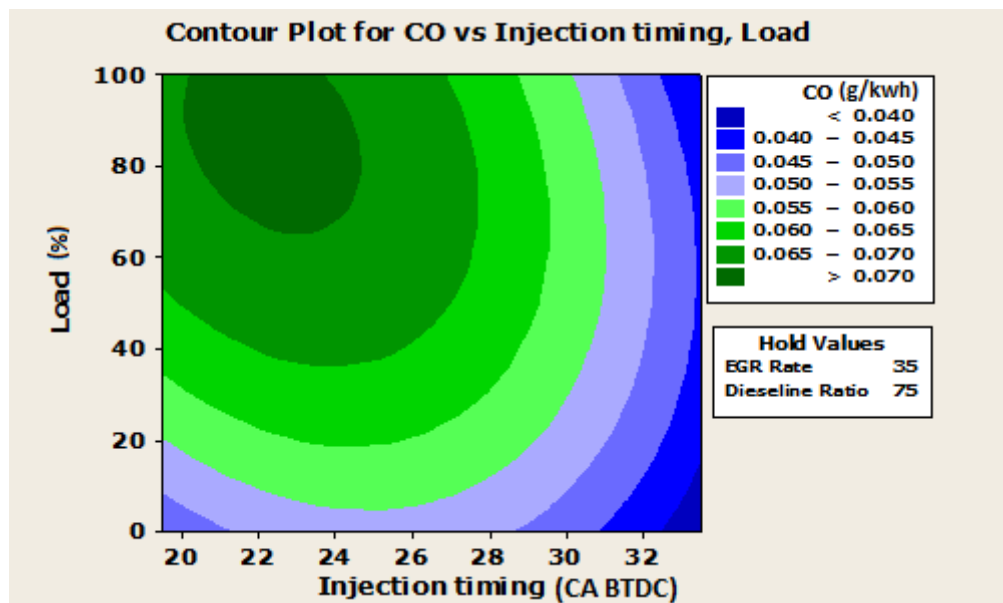


Figure 4.6: Contour plot of CO vs injection timing, load

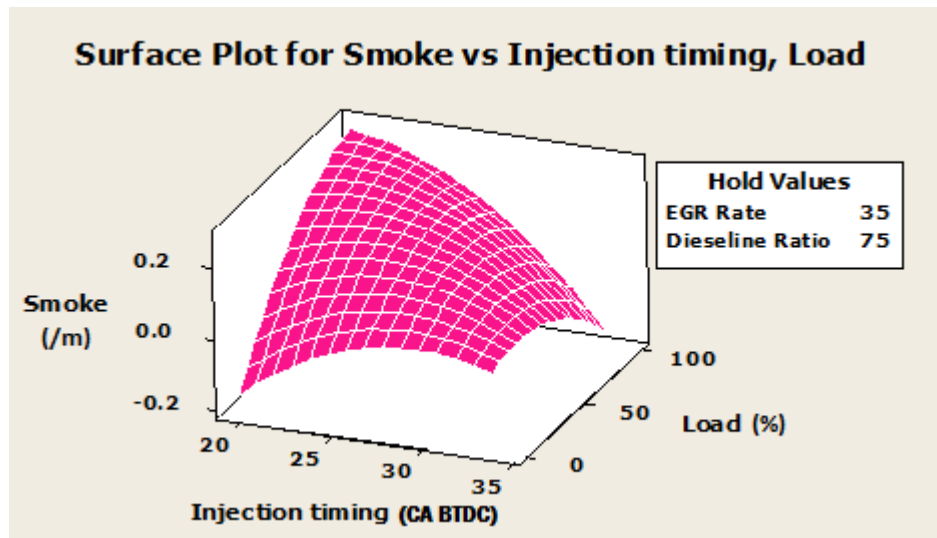


Figure 4.7: Surface plot of Smoke vs injection timing, load

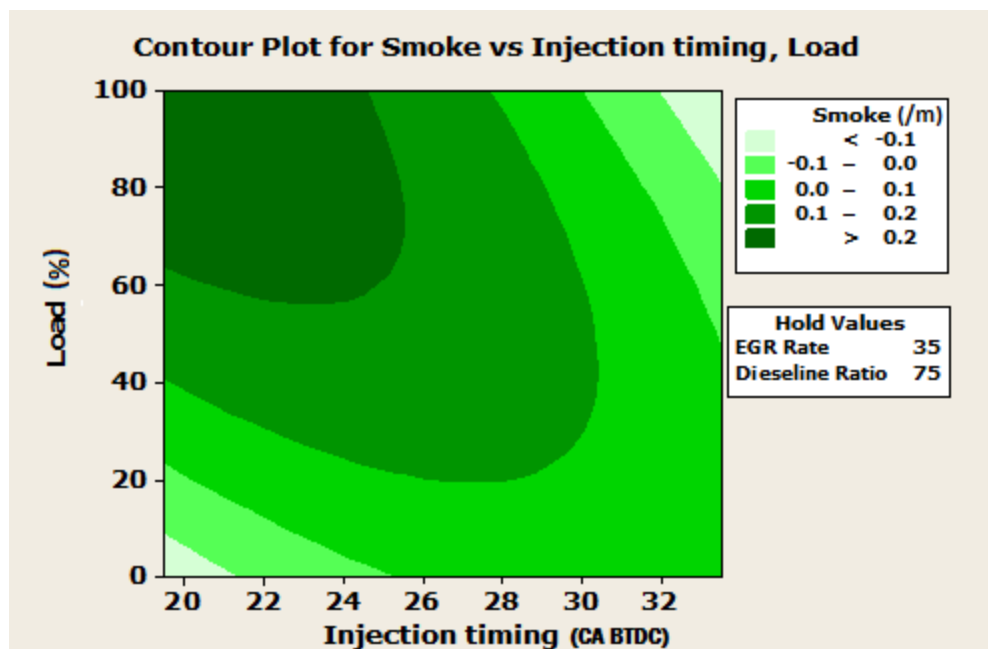


Figure 4.8: Contour plot of Smoke vs injection timing, load

4.2 Effect of Dieseline Ratio on Emissions

Several studies recommended using the dual fuel diesel and gasoline mixture which is called dieseline for various reasons. In this experiment also this benefits were obtained mainly the reduction of emissions and its appropriateness for PCCI combustion in diesel engines. The lower cetane value of diesel and gasoline mixture provided advantages in this experiment also which is by extending the time before combustion of the mixture which will prolong the ignition delay. In this experiment by changing diesel with diesel/gasoline mixture which is dieseline parallel reduction of NO_x and smoke as well as relative reductions of HC and CO were achieved together with the optimized operating control parameters.

Figure 4.9 to Figure 4.16 shows the effect of dieseline ratio on NO_x, HC, CO and smoke emissions for this experimental set up at possible engine loads applied in the test. Based on the ratio of fuel type which is tested using increased diesel proportion at lower loads resulted a decrease in NO_x and HC emissions as indicated in Figure 4.9 to Figure 4.12. In comparison to the baseline results there is reduction of NO_x in all load conditions, since PCCI-DI is working under low temperature conditions that will create low combustion temperature which lowers the production of NO_x.

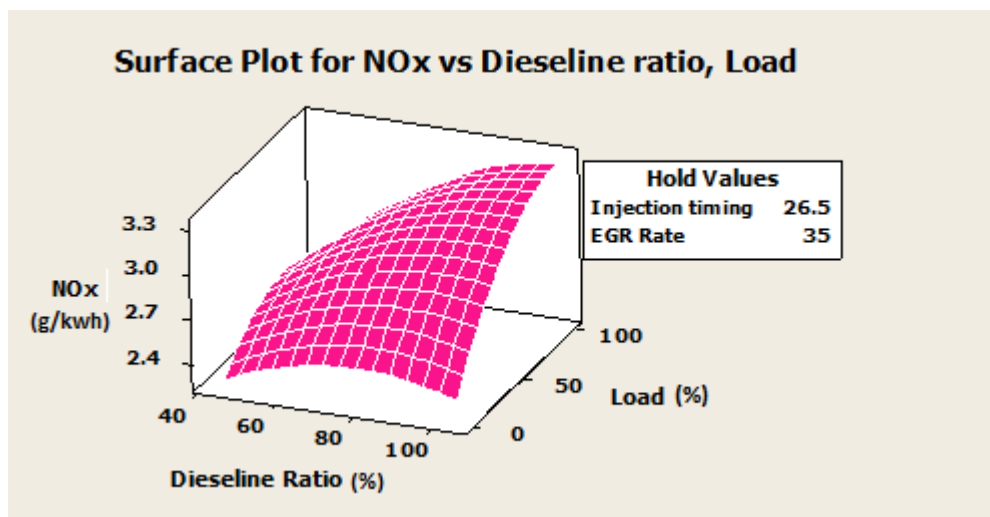


Figure 4.9: Surface plot of NO_x vs dieseline ratio, load

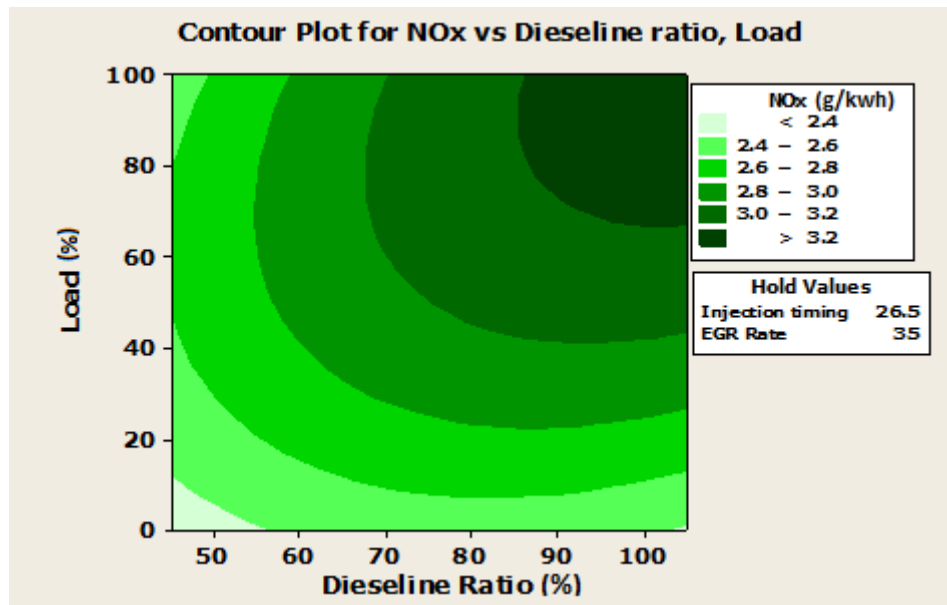


Figure 4.10: Contour plot of NOx vs dieseline ratio, load

Engine load is a very important phenomenon for the reduction of emission of oxides of nitrogen (NOx) as indicated in Figure 4.9. Increment in load resulted increase in NOx.

Based on the ratio of fuel type which is tested using increased diesel proportion at lower loads resulted a decrease in NOx, HC and smoke emissions as indicated in Figure 4.9 to figure 4.12. Similarly in comparison to the baseline results the figures 4.9 to figure 4.12 indicated that the PCCI-DI mode with the help of the chosen optimized control parameters in addition with the methanol premixing through port injection; increasing the dieseline ratio makes a reduction of NOx and smoke. This minimized trade-off relations between NOx and smoke. During the increase in load conditions as it shown in Figure 4.15 and Figure 4.16, smoke tends to increase. Amount of dieseline injection has to increase at higher loads that also lead to higher smoke production. Smoke emissions were kept low almost proximate values except at higher loads having increased values.

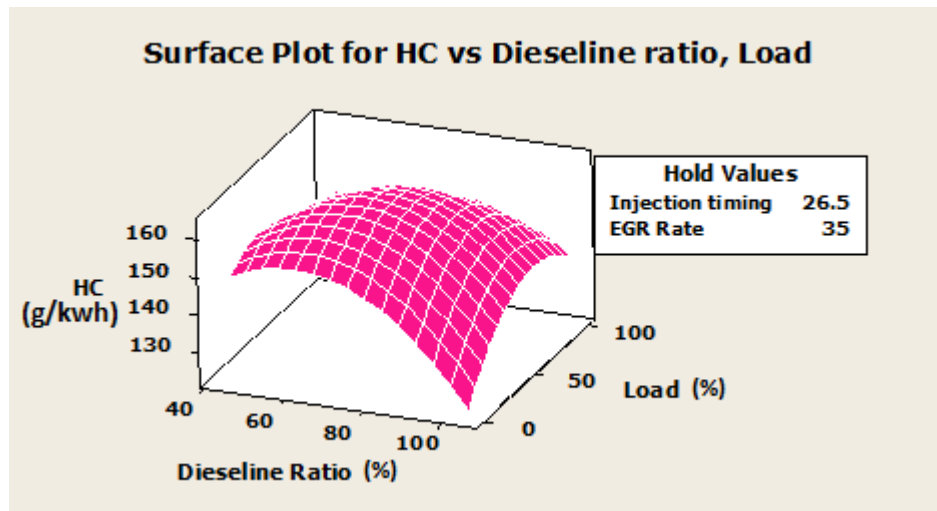


Figure 4.11: Surface plot of HC vs load, dieseline ratio

The increased proportion of gasoline increased the HC amount. At higher load conditions increasing gasoline proportion similarly increased the CO amount. This is related to the decreased cetane number and also increased ignition delay. This indicates ignition delay could be extended by increasing the ratio of gasoline. The increase in HC due to the ignition delay increment is due to the excess mixed regions that the oxidation of fuel is challenging. The increase in intake pressure on the inlet port coming from the air compressor air pressure contributed in avoiding excess production of HC. The increased in diesel ratio indicated an increasing CO characteristic as shown in Figure 4.13 below.

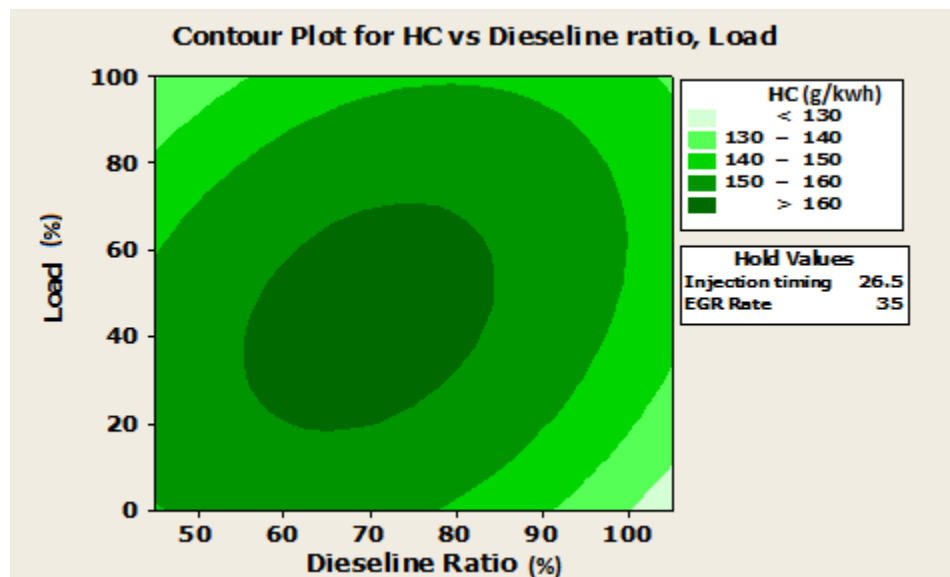


Figure 4.12: Contour plot of HC vs dieseline ratio, load

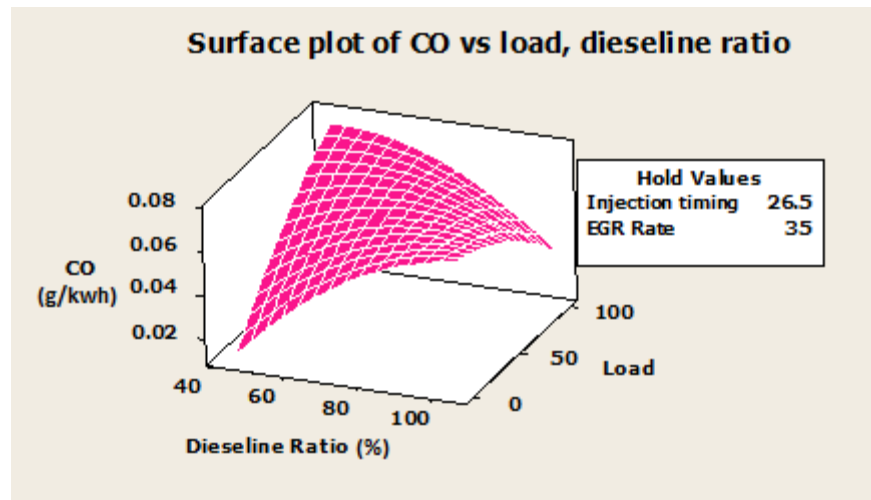


Figure 4.13: Surface plot of CO vs load, dieseline ratio

As shown in Figure 4.11 to Figure 4.13, at higher loads and higher dieseline ratio there is a slight decrease in HC and CO due to the impact of the dieseline blend.

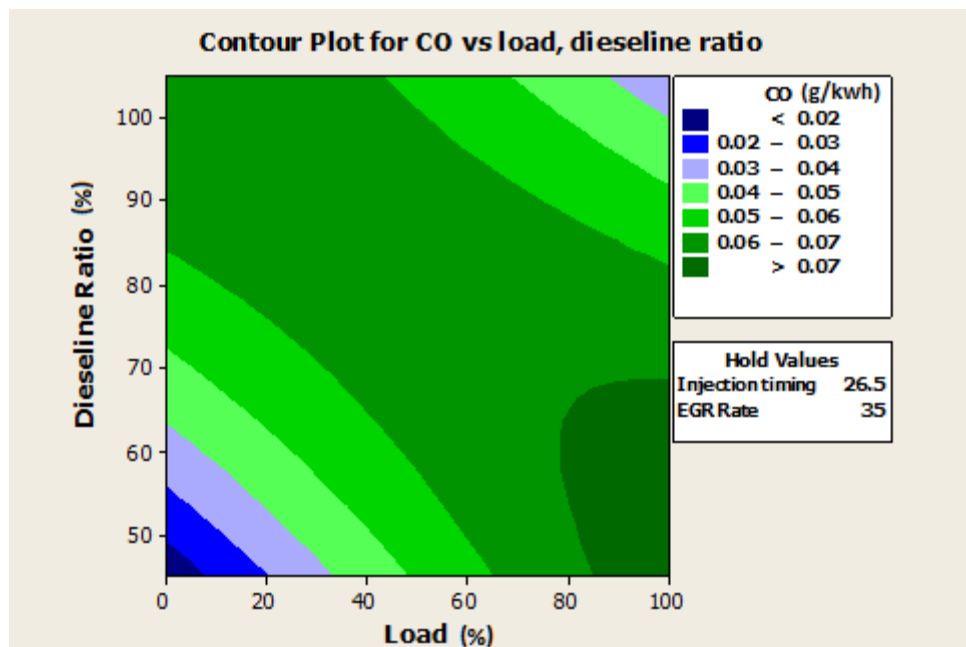


Figure 4.14: Contour plot of CO vs load, dieseline ratio

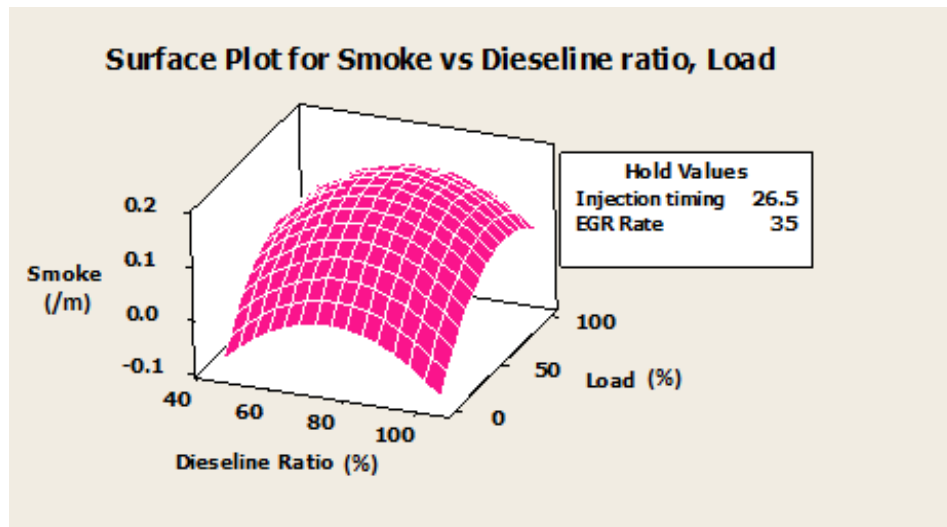


Figure 4.15: Surface plot of smoke vs dieseline ratio, load

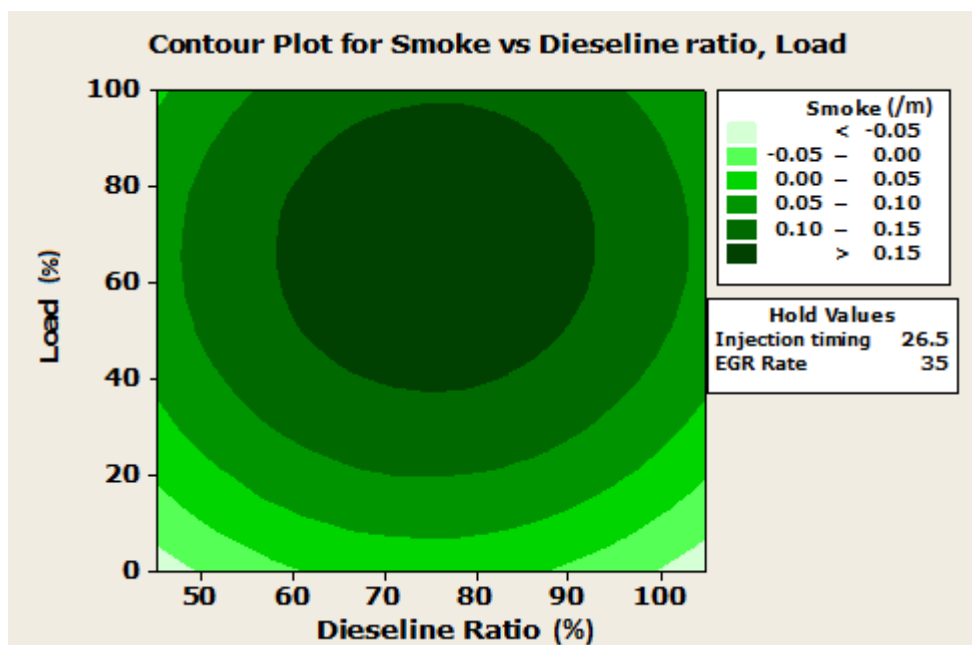


Figure 4.16: Contour plot of smoke vs dieseline ratio, load

4.3 Effect of EGR Amount on Emissions

Literatures confirmed that in creating PCCI combustion mode EGR is taken as the most significant engine operating factor but its dilution effect (influencing oxygen/fuel ratio)

has created the expected side effect of increasing HC and CO emissions in this experimental study which is a challenge not yet fully resolved. EGR also has an impact on combustion duration, heat release rate and ignition duration which affected the emission results. But through applying optimized combination techniques of the chosen control factors operating in PCCI-DI combustion mode, the percentage increase of HC and CO emissions were minimized. The existence of EGR in the combustion chamber influences the oxygen-fuel ratio, ignition delay, combustion duration and. In turn, these variations in the combustion process affect the engine performance and emissions.

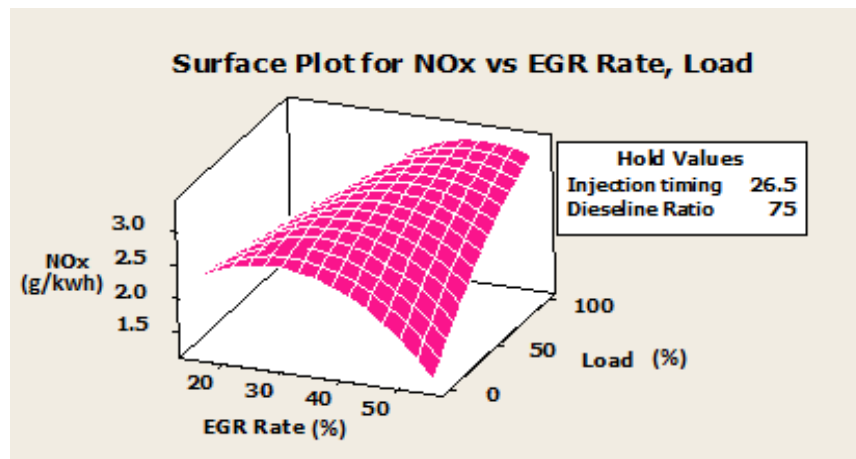


Figure 4.17: Surface plot of NOx vs EGR %, load

Increased in EGR % resulted a decrease in NOx emissions due to the dilution and thermal effects from the EGR as shown in Figure 4.17. The level of NOx emissions tended to decrease as EGR % increased. 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.

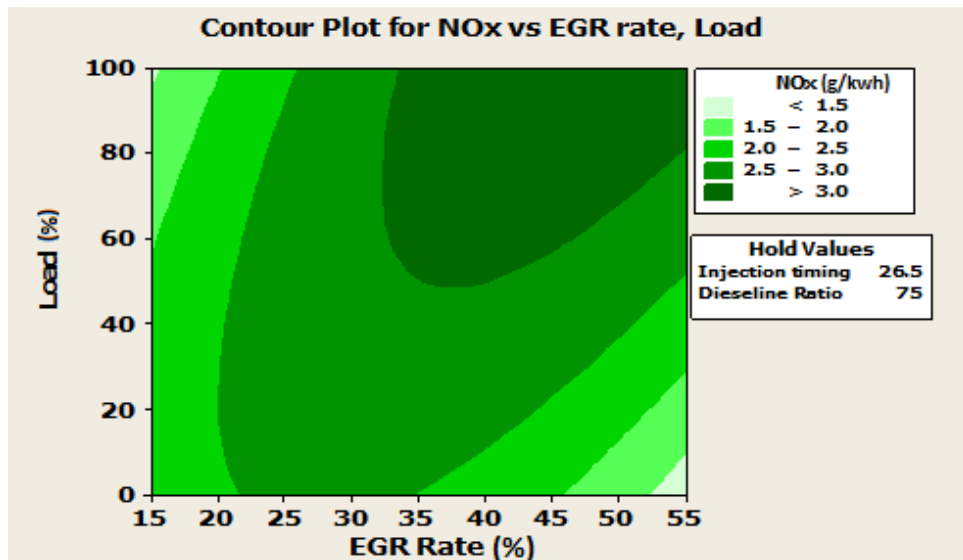


Figure 4.18: Contour plot of NOx vs EGR %, load

The contour plot indicated in Figure 4.18 reveals that in conditions of low loads there are results of low NOx but demanding larger EGR %. 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.

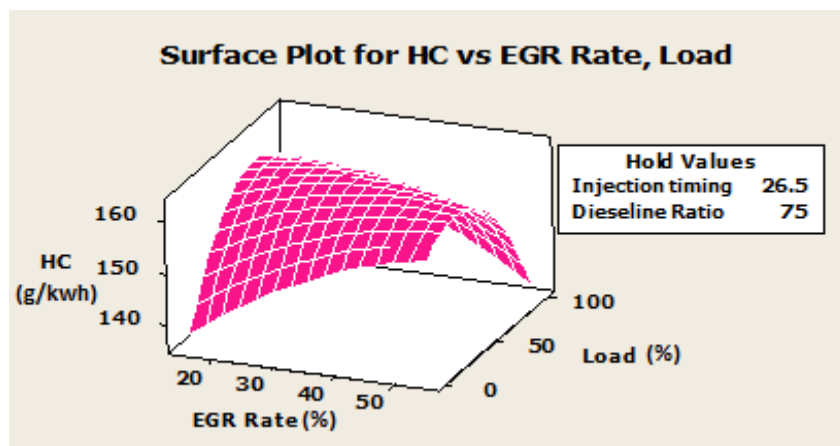


Figure 4.19: Surface plot of HC vs EGR %, load

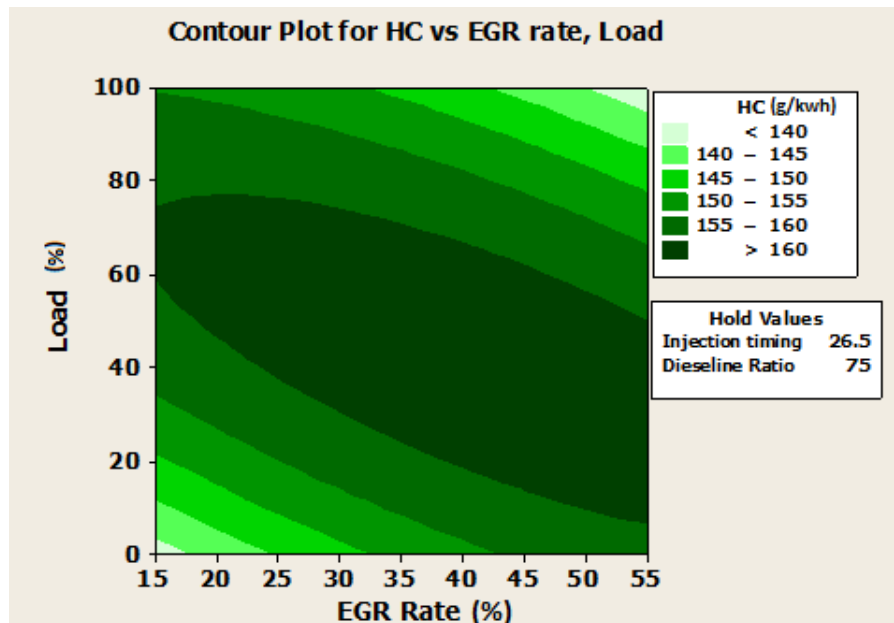


Figure 4.20: Contour plot of HC vs EGR %, load

Higher EGR % leads an increase in HC where as a decrease in NO_x 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. The lean mixture formation in premixed combustion and lower temperature of combustion basically contributed a lot for the reduction of NO_x. In this experiment higher EGR % resulted another trade-offs between CO, HC emissions with that of smoke emissions.

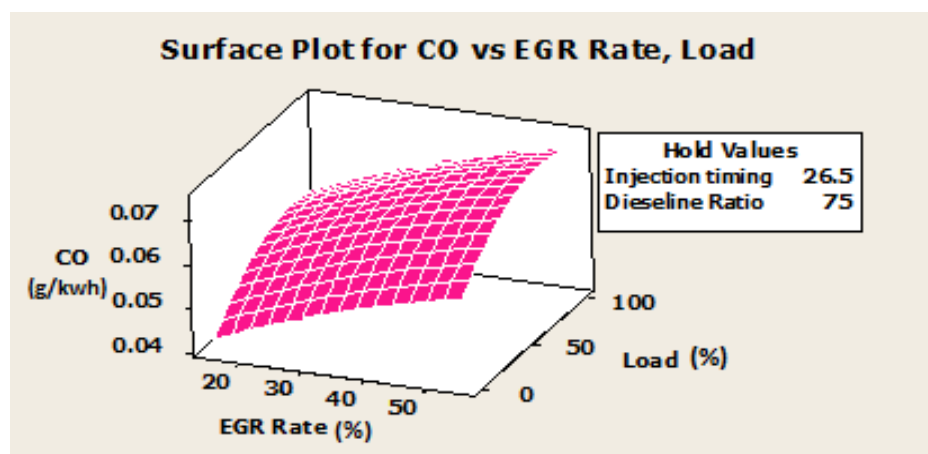


Figure 4.21: Surface plot of CO vs EGR %, load

Increase in EGR % resulted increased productions of HC and CO (particularly at higher EGR %) 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 % 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 Figures 4.19 to Figure 4.25 that brings shortage of oxygen. 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 % 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.

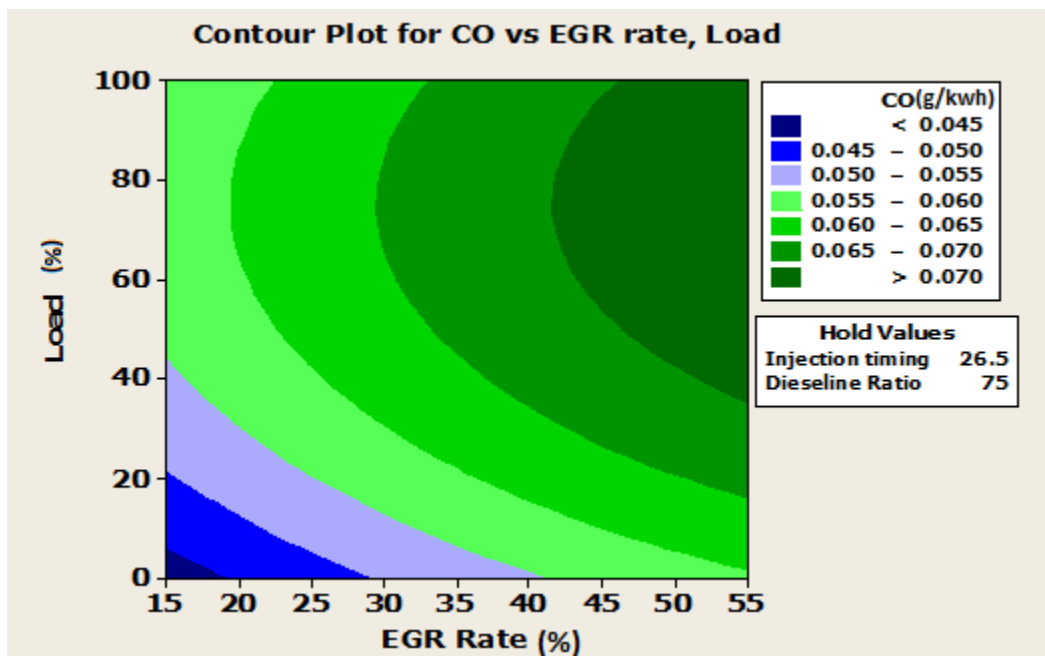


Figure 4.22: Contour plot of CO vs EGR amount load

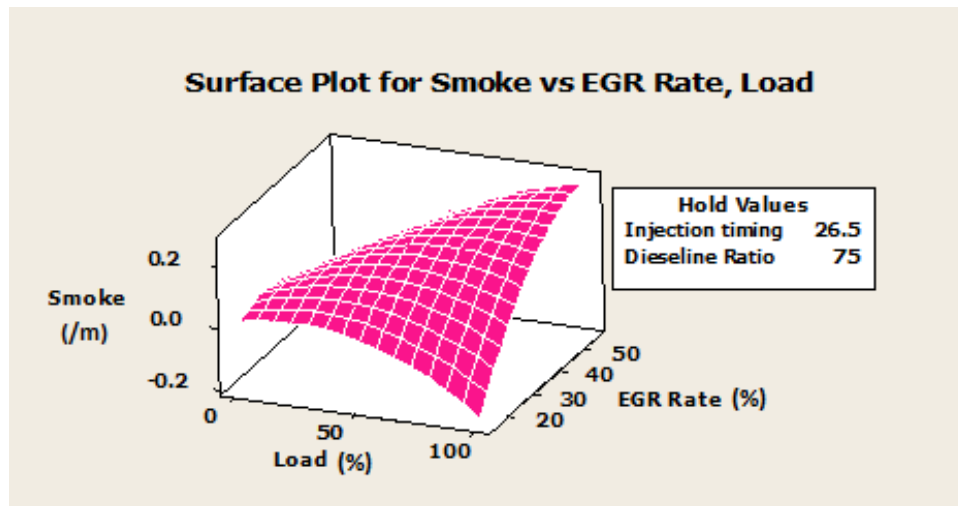


Figure 4.23: Surface plot of Smoke vs EGR %, load

Lower smoke values were registered by lowering EGR % in both lower and medium loads as displayed in Figure 4.23.

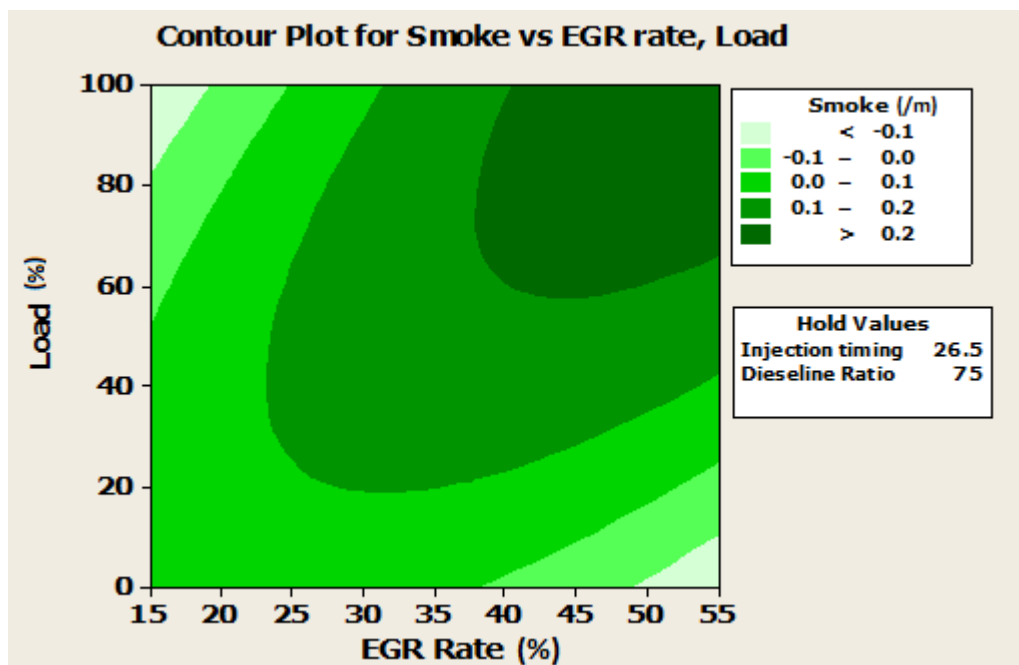


Figure 4.24: Contour plot of Smoke vs EGR %, load

As indicated in Figure 4.19 the increase in EGR % results a decrease in NO_x amount and there is greater increments in CO amount (Figure 4.21). Since the higher EGR ratio weak-

ens the combustion but this effect is minimized by applying cold type EGR. This shows that CO with NO_x trade off relations is minimized with the increase in EGR % that is mostly difficult to attain in conventional diesel engines.

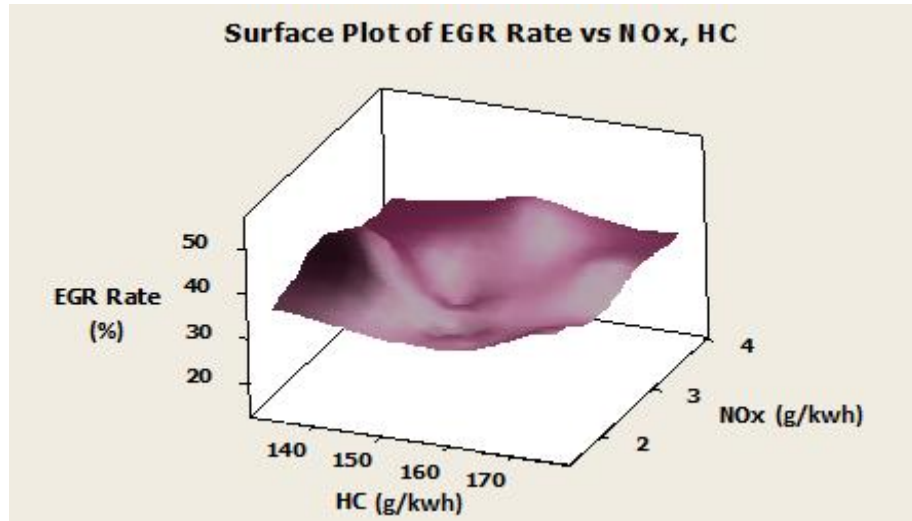


Figure 4.25: Surface plot of EGR % vs NO_x, HC

Similarly HC also indicated a minimized or improved trade-off relations with NO_x that is for the increase in EGR % HC and NO_x 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, NO_x and smoke amounts. From the above results (Figure 4.19 to Figure 4.24) of surface and contour plot figures; CO, HC and smoke results are increasing in relation to the increase in EGR %. In this regard excess EGR application should be avoided to minimize lack 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 NO_x in the PCCI-DI setup.

Affecting the combustion characteristics to enable features of PCCI combustion mode were made effective by utilizing EGR particularly by varying and optimizing EGR %.

In this investigation the EGR % used for the several tests indicated that they affect the combustion stability and emission results. From this finding it was observed that increasing EGR % has the effect of minimizing smoke and NO_x 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 % impacts on engine load conditions and thermal efficiencies. For the chosen experimental engine setup optimized EGR % 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 % applied for the tests as the EGR % 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.

4.4 Effect of Engine Load Conditions on Emissions

In addition to studying the effects on emission results, effect of engine load conditions on emissions were studied. Optimum results of combustion and emissions for the PCCI-DI set up and conventional diesel combustion set up were compared and analyzed under low load and low speed ranges. Specifically the application of this PCCI-DI mode of combustion is optimized to a better low load range for the chosen experimental set ups. Engine load conditions showed impacts on emissions during the experimental study and Minitab analysis as indicated in Figure 4.1 to Figure 4.24.

High load operations indicated increased CO and NO_x for the increased in EGR %. But in high loads there was a decrease in smoke for a decreased in EGR %. There was also a decrease in HC for the increased in EGR % and increased in engine load. At higher diesel ratios in dieseline, increasing engine load indicated increased smoke and NO_x productions

but decreased HC and CO results were observed. Increased in injection timing during high engine loads resulted less production of CO, HC and smoke results but there was increased in NO_x amounts. Increasing the load close to maximum affected the proper operation of the engine including noise and missing of the engine indicating an incomplete combustion of the mixture.

4.5 Emission Analysis Using Interaction Plots

An interaction plots were developed and used to show the relationship between factors and responses depends on each other. This plot presents results using levels of one factor on the x-axis and another line for each level of another factor. The plots showed lines that brief how the interactions affect the relation among the engine operational parameters and responses. These interaction effects designate that a third factor affects the relationship between independent and dependent variable. The strength of the interactions was judged by observing the degree of the non-parallel condition of the lines.

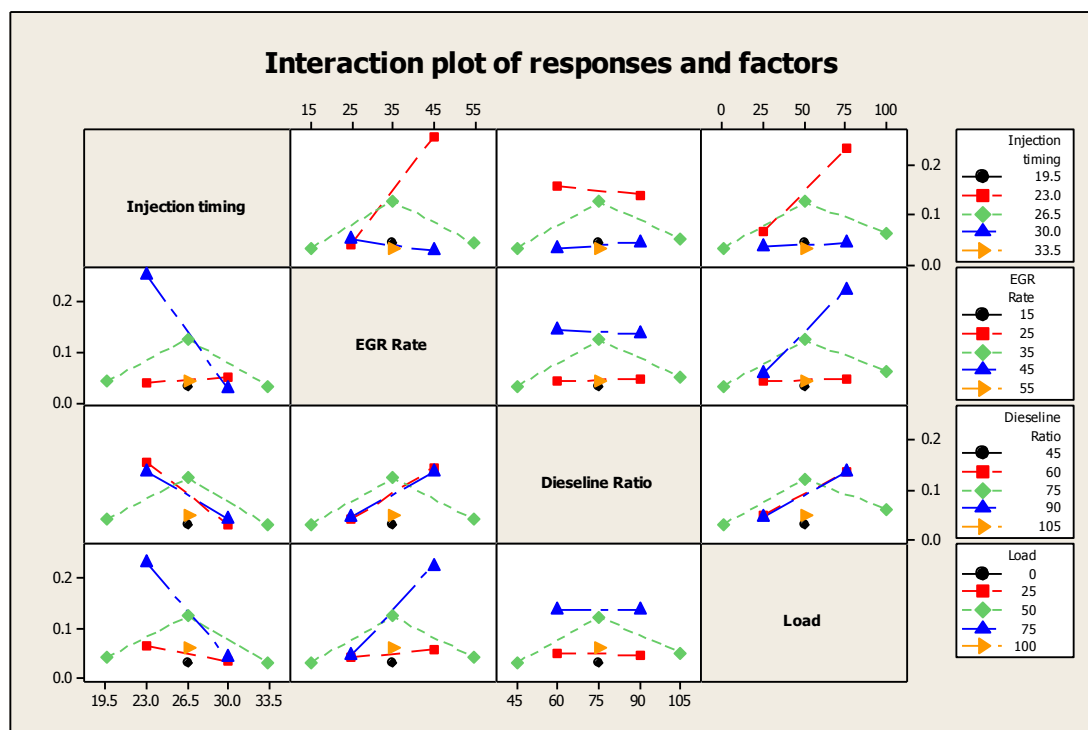


Figure 4.26: Interaction plots for emission and combustion control factors versus Smoke emission (g/kwh) calculated through ANOVA

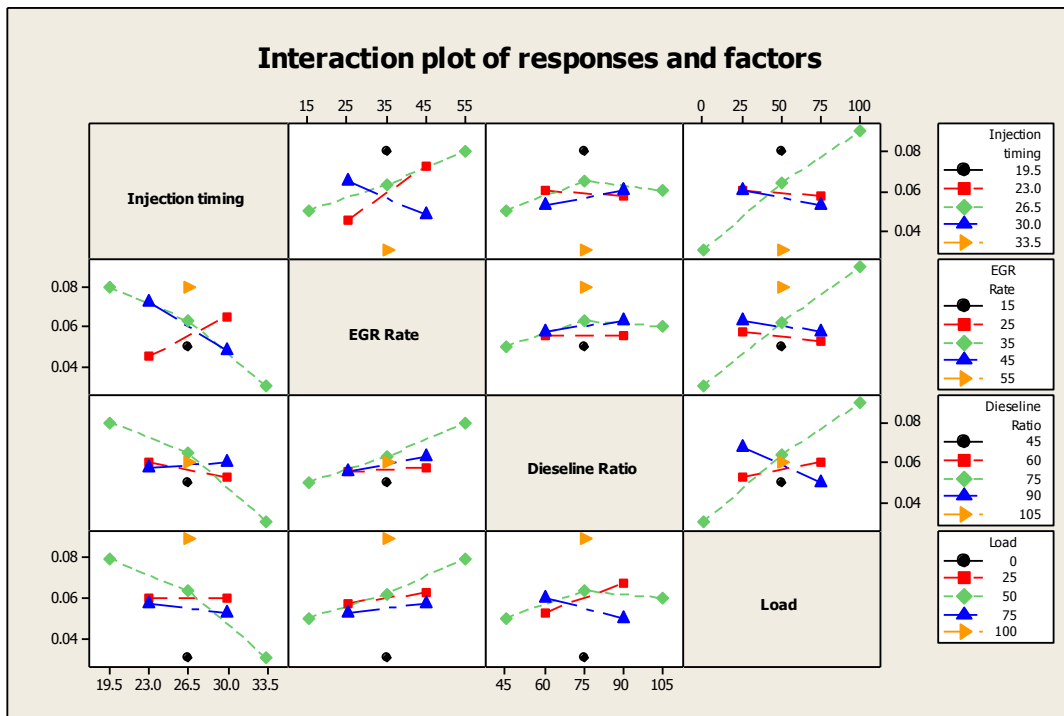


Figure 4.27: Interaction plots for emission and combustion control factors versus CO emission (g/kwh) calculated through ANOVA

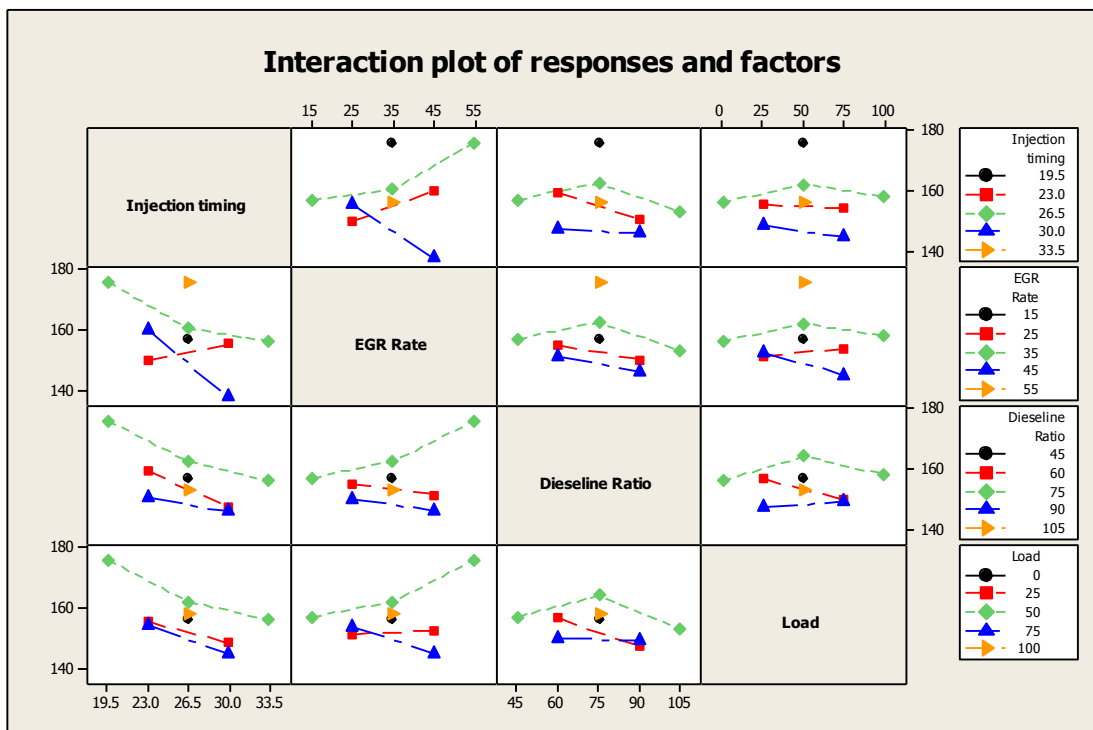


Figure 4.28: Interaction plots for emission and combustion control factors versus HC emission (g/kwh) calculated through ANOVA

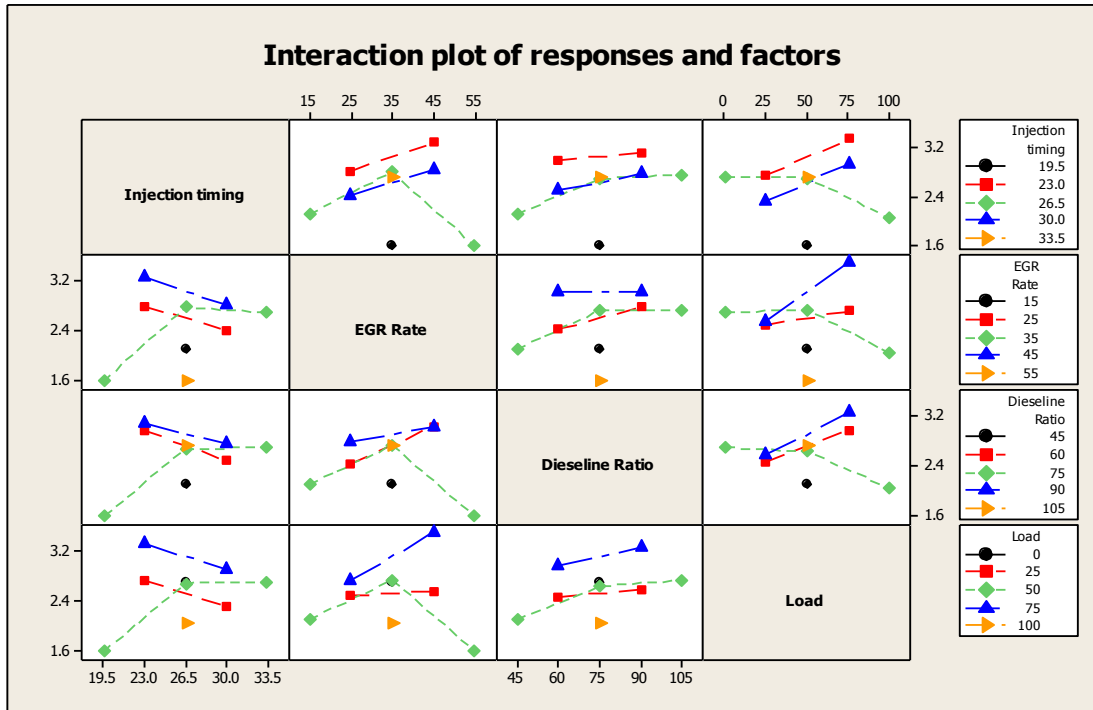


Figure 4.29: Interaction plots for emission and combustion control factors versus NOx emission (g/kwh) calculated through ANOVA

From Figure 4.26 to Figure 4.29 it is shown that higher S/N ratio being better for optimum emission results. They also indicated the main effects plots for each of the operation parameters.

The interaction between the control factors (injection timing with EGR rate, Injection timing with dieseline ratio, Injection timing with load, EGR rate with dieseline ratio, EGR rate with load and dieseline ratio with load) were considered as indicated in Figure 4.26 to Figure 4.29. The optimum configuration depends on the highest S/N ratio values. The control factors interaction plots S/N ratio values are indicated in these figures.

From the interactions of the control factors in Figure 4.26 indicated that there is a considerable interaction between injection timing and EGR rate while moderate interactions with the other control factors which affect smoke productions. From Figure 4.27 there is less interactions between EGR rate and dieseline ratio and also between injection timing and dieseline ratio on HC production effects. There is also a substantial interaction between dieseline ratio and load for CO outputs.

It is shown that these plots of interactions are used to compare the relative degree of impacts or effects among the control factors. Figure 4.28 also showed a significant interaction between injection timing and EGR rate which affect HC production. Control factors EGR rate with dieseline ratio indicated less interaction to affect the HC output. Relatively less interaction of the control parameters injection timing and dieseline ratio were observed in affecting NO_x productions as shown in Figure 4.29. Thus from these interaction plots analysis, the injection timing is most influencing control factor for the emission results.

4.6 Effect on Exhaust Gas Temperature

Characteristics of the exhaust gas temperatures for the PCCI-DI and conventional diesel operations in this experimental study were investigated in relation to speed as shown in Figure 4.30. In PCCI-DI combustion temperature of the exhaust gas showed lower than the conventional diesel combustion conditions due to the decrease in temperature of combustion inside the cylinder.

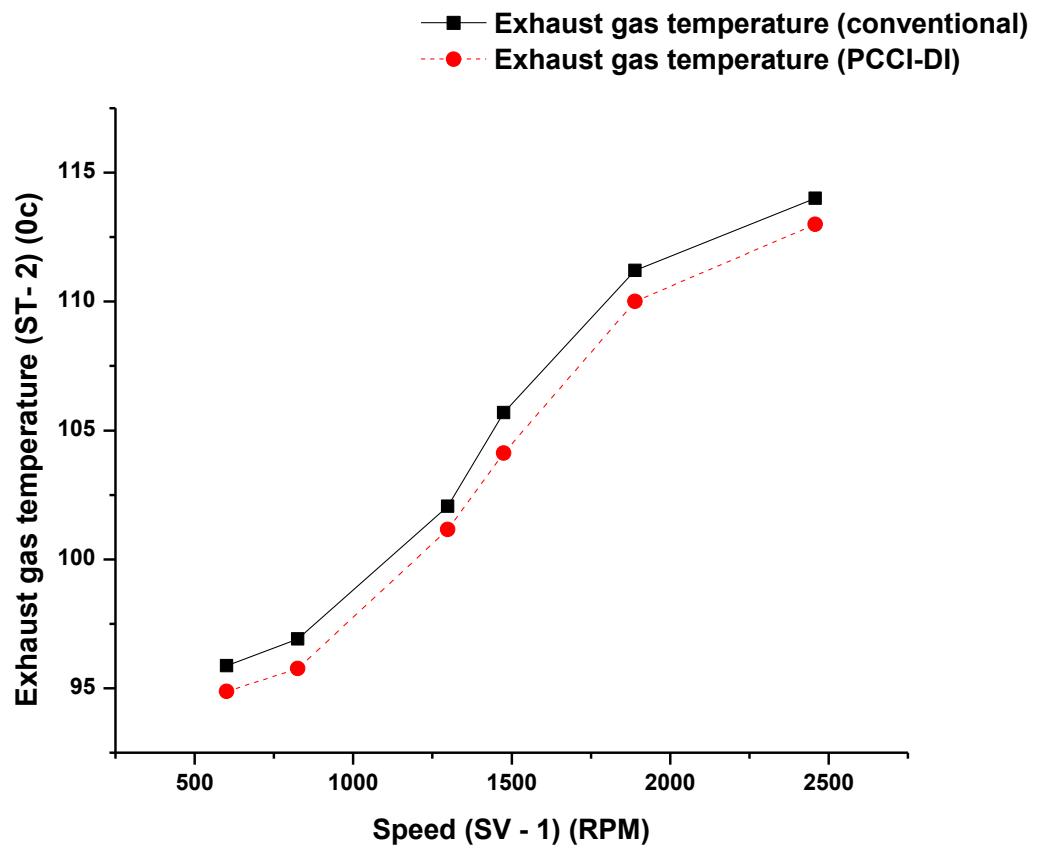


Figure 4.30: Exhaust gas temperature vs speed at conventional and optimized PCCI-DI conditions

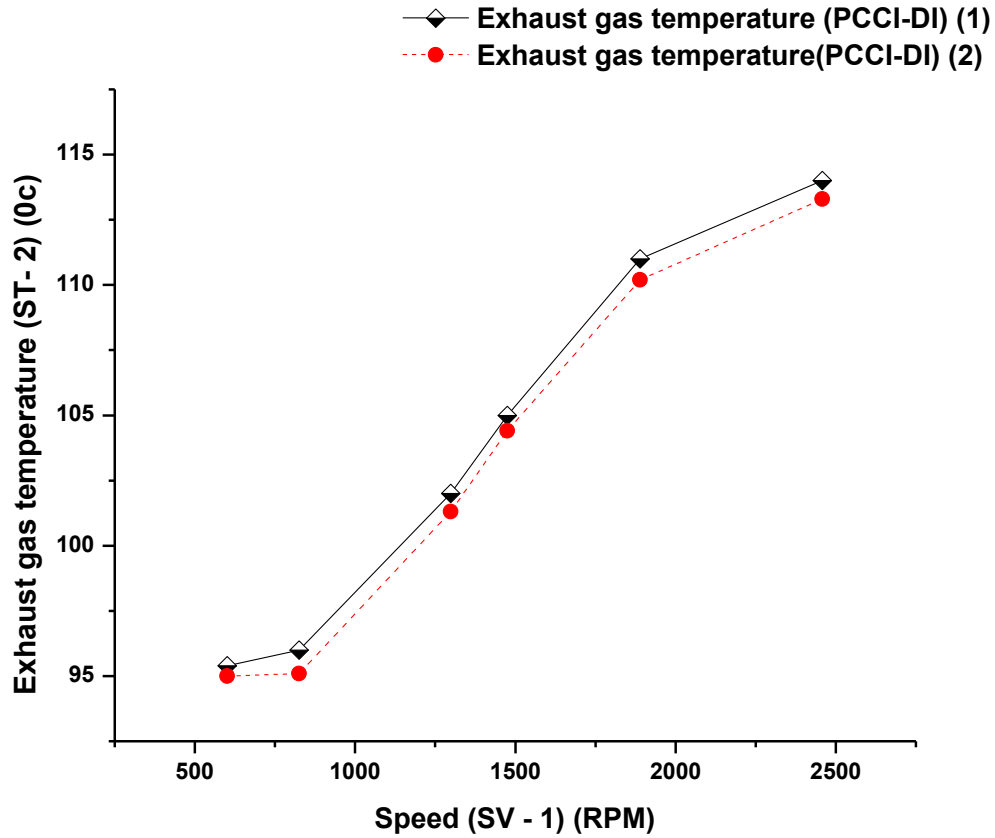


Figure 4.31: Exhaust gas temperature vs speed in PCCI-DI conditions

In Figure 4.31 two PCCI-DI settings (1) and (2) were checked for the exhaust gas temperature. In this designation PCCI-DI (1) has the settings of 23° CA BTDC injection timing, 25 % EGR %, 60% dieseline ratio and 25% engine load whereas the PCCI-DI (2) has operational factors settings of 30° CA BTDC injection timing, 45 % EGR %, 80% dieseline ratio and 25% engine load. From the results indicated in Figure 4.31, the exhaust temperature is affected by the engine operational factors. Advanced injection timing, better EGR % together with higher diesel ratio in dieseline fuel have positive contributions in reducing the exhaust temperature in the PCCI-DI combustion setups.

4.7 Effect of Fuels on Emissions

This study was conducted to expand basic understanding of the effects in performance particularly emissions results by using alcohol fuel methanol and blends of diesel and gasoline in a modified diesel engine. The experimental results obtained from this experiment

could provide a basis to further optimize engine operating points together with methods of methanol and dieseline applications.

Methanol/dieseline fuels combination showed promising combustion features and fuel components which could be a proper candidate for PCCI-DI combustion to minimize emissions without significant effect on performance characteristics. The application of methanol in this PCCI-DI diesel engine experimental set up helped in realizing the benefit of methanol which has the features of no production of smoke, particulates and soot during combustion. It also confirmed its ability to burn at lower temperature that it helped to lower emission of NO_x which will strengthen the idea of methanol to be a potential substitute of diesel fuel for diesel engines. In this study applying the methanol premix together with dieseline direct injection on PCCI-DI diesel engine operation indicated its functionality with slight increase in noise of combustion. Mixing of methanol, diesel and gasoline were used in the experimental setup of PCCI-DI operation, the methanol port injection and dieseline direct injection in this study helped to minimize HC and CO increments relative to the previous attempts on PCCI-DI diesel engines. In cylinder fuel mixing of these fuels through port injection of methanol and direct injection of a pre blend of diesel and gasoline which is dieseline were occurred to form the mixture. This helped to create optimum ignition conditions on the fuels.

4.8 Effect of Methanol Port Premixing on Combustion and Emissions

This study showed positive impacts on the combustion and emission characteristics in compression ignition engines by premixing alcohol particularly methanol. Due to its effective air/fuel mixing nature of methanol, relative decrease in CO was obtained in this experiment. The chemical nature of methanol indicates the oxygen content in it that would be provided into the combustion chamber. This helped in avoiding the shortage of oxygen during combustion that helped to avoid excess increase in CO. The premixing of methanol through port injection improves the degree of premixing which upgrades the effectiveness of the premixed combustion. This improvement rose from the variation in reactivity characteristics of the fuels which affected the combustion efficiency.

Methanol port injection on the inlet manifold showed a beneficial contribution in lowering the cylinder temperature in creating LTC strategy that minimized combustion noise, smoke and NO_x. This effect is due to the higher octane number or lower reactivity nature and greater latent heat of vaporization features of methanol. PCCI-DI combustion mode set up on diesel engine indicated that through increasing the amount of methanol port injection affects the overall oxygen/fuel ratio in the mixture that affects the HC and CO emissions. Methanol port injection helped in lowering the combustion temperature inside the cylinder due to its effect on dropping the pressure. Using the ideal gas law the average cylinder temperature was calculated from the cylinder volume and pressure.

4.9 Effects of EGR configurations on PCCI-DI diesel engine emissions

The main objective of this topic is to analyze experimentally the impact of different EGR configurations (No EGR, Cold EGR and Hot EGR) on exhaust emissions of the optimized PCCI-DI engine from this study. As discussed in previous chapters' methanol port injection, dieseline direct injection, advanced injection timing and different EGR % were adapted and optimized on baseline engine for this different EGR configuration set up. The optimization technique which is the hybrid algorithm of grey relational analysis with Taguchi method was unchanged for this experimental study i.e. the previously discussed optimized engine is used for this experiment. Results were compared among the PCCI-DI combustion strategy with the baseline using cold EGR, hot EGR and with no EGR configurations. Both cold and hot EGR configurations resulted lower emission of NO_x plus smoke at different loads. At low loads hot EGR showed promising results of lower HC and CO than the cold EGR with a difference of 18.33% and 33.3% respectively. NO_x and smoke reductions simultaneously and better trade-offs were obtained using cold EGR configuration.

Cooled water flowing from the radiator is mostly applied in heat exchangers for automotive applications, but in this experimental set up separate water reservoir is designed for the cooling water supply. The recirculated exhaust gas is cooled above its condensation temperature before mixing into the incoming air which prohibits condensed water in the combustion chamber. Similar to most experiments implementing PCCI combustion by using high level of EGR (Wagner, Dam et al. 2018), this experiment also adapted the con-

ventional short-route cooled EGR arrangement having greater EGR level. The system also employs the shell and tube type heat exchanger so that coolant will circulate inside the shell and exhaust gas circulates inside the tube. Port fuel injection (PFI) method were used in this experimental set up in addition to the dieseline direct injection since; considering its simplicity, better fuel delivery and volumetric efficiency by using the high volatile methanol alcohol (Chen Z, Wu Z et al. 2013; Panao, 2007).

For the multi response optimization procedure; DoE and a hybrid of grey relational analysis with Taguchi method were used. This method helped in solving complex interrelationships having multi-objective optimization problems. This by considering the grey-Taguchi based optimization technique is applied and confirmed in several studies to obtain results of optimum emissions, performances, fuel consumptions and fuel types (Natarajan and Mahalakshmi, 2018).

4.9.1 Experimental Scheme and Methodology

As discussed in chapter 3; in this experimental investigation tests were conducted in an engine in the speed ranges of 1500 to 2500 rpm and connected to eddy current type dynamometer for loading and timing measurements. Exhaust emission analyzer for direct reading of NO_x, HC, CO and smoke were used for the study. The engine is single cylinder, four stroke, used air as coolant and also comprising computerized direct injection light-duty compression ignition engine with some modifications to form PCCI-DI combustion. Modifications on the chosen engine include; modification of fuels (port injection of methanol and direct dieseline injection with different ratios), adaptation of EGR % (25, 35 and 45 %) and injection timings (23⁰, 25⁰, 30⁰; advanced) were used for the PCCI-DI mode of combustion. Obtaining a precise EGR % control set up is still unsolved problem in the progress of developing an engine with advanced combustion concept. Increasing the EGR % resulted an increase in HC and CO emissions but by optimizing other operating control factors showed possibility of minimizing the percentage of increase of HC and CO emissions.

In addition this setting was optimized for lower emission results applying the multi-response optimization technique of Grey-Taguchi. Table 3.1 shows the basic specifications of the engine and experimental settings.

Experimental investigation on the modified PCCI-DI combustion of the chosen diesel engine within the possible load ranges were done in making the operation free from engine knocking. Results also indicated the potentials of minimizing NO_x and smoke emissions and also optimized CO and HC results were promising. The experimental investigations and analysis were done between the adopted PCCI-DI combustion and the conventional diesel combustion.

The EGR system and control setup including the EGR cooler used for this experiment is discussed in chapter 3 under the topic 3.2.6.

4.9.2 Results and Discussions

Results were analyzed and argued individually as shown from figure 4.32 to figure 4.35, and from the results conclusions were made. Experimental studies were followed to know and analyze impact from EGR configurations; hot EGR, cold EGR and no EGR configurations on emission results of the optimized PCCI-DI operation following minor and suitable modifications which lower the production of NO_x, HC and CO. The L₉ (3⁴) Orthogonal array matrix in Table 5.1 shows the nine experimental tests conducted with their results or responses obtained during the optimization process.

4.9.2.1 Emissions of NO_x

From the study as shown in Figure 4.32, highest value of NO_x reduction (optimum), with 68.02% from the baseline diesel were obtained from the cold EGR configuration. Least value of NO_x reduction with 33.42% is found from no EGR configuration. The hot EGR configuration resulted 63.87% NO_x reductions for the load indicated. The reduction in NO_x is mainly linked to the lowering of the oxygen amount.

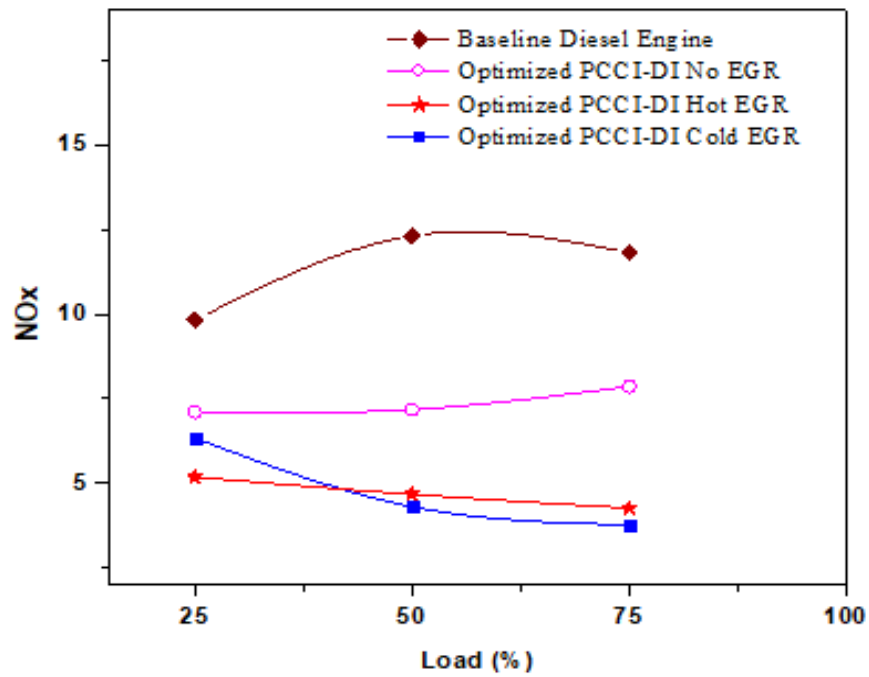


Figure 4.32: Effect of EGR configurations on NOx versus Load

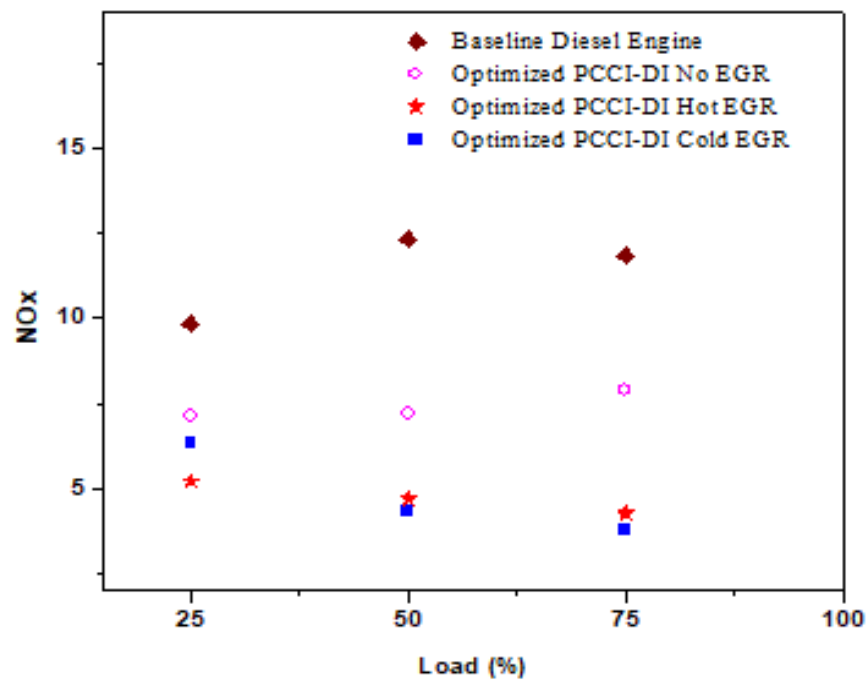


Figure 4.33: Effect of EGR configurations on NOx versus Load (dot lines)

Parallel reduction in NOx and smoke results having better trade-offs were obtained using cold EGR configuration.

4.9.2.2 Emissions of HC

HC is also affected by EGR configurations being cold, hot and no EGR. As indicated in Figure 4.34, results showed that lower HC was found in hot EGR configuration due to improved combustion which validates the previous study by (Boot, Somers et al. 2009; Shim, Park et al. 2018). In this experiment, for the optimized PCCI-DI hot EGR setting with EGR level of 25 %; HC emission results from the optimized PCCI-DI hot EGR is lower by 18.3 % from the Optimized PCCI-DI cold EGR configurations and increased by 9.2% from the Baseline diesel engine.

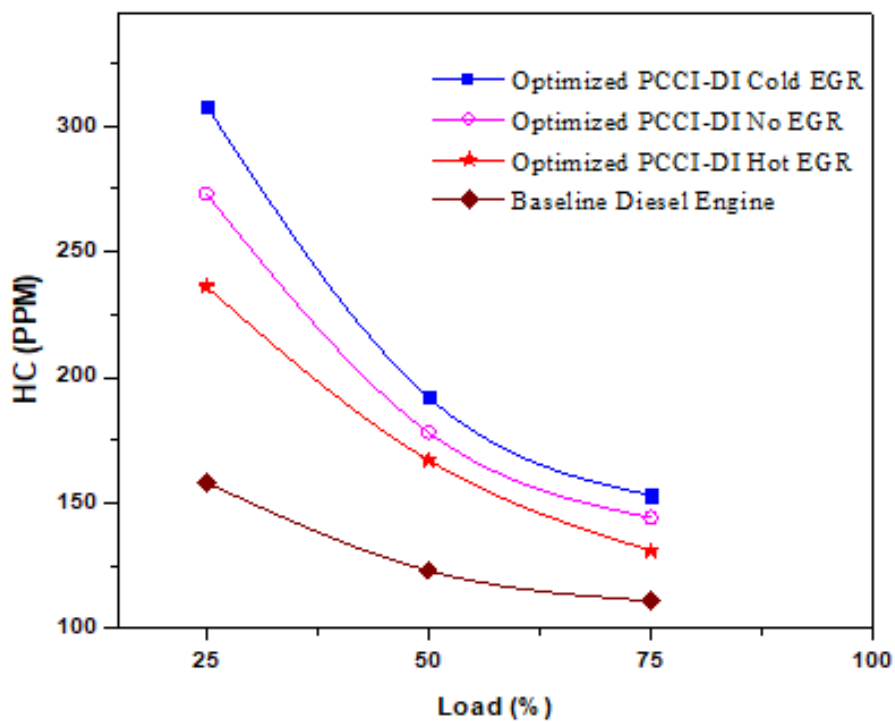


Figure 4.34: Effects of EGR configurations on HC versus Load

4.9.2.3 Emissions of CO

Similar to NO_x and HC emissions there is a difference in the results of CO for the different EGR configurations. As indicated in Figure 4.35 decreased CO was found in cold EGR configuration since relative better oxygen amount than the hot EGR scenario. At low loads, optimized PCCI-DI cold EGR indicated lower CO emissions than the hot EGR.

From medium to higher loads, hot EGR indicates lower CO with a difference of 33.3% than the cold, which could be due to the better efficiency of the hot EGR at higher loads in line with the better intake air temperature for better combustion. Higher emissions of both CO and HC were resulted at low loads.

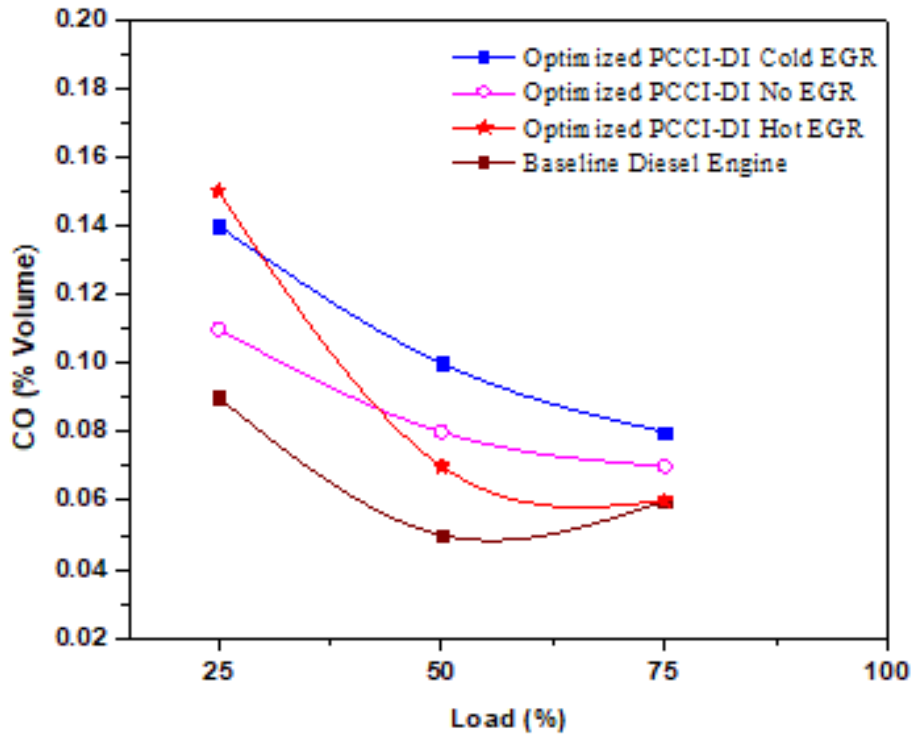


Figure 4.35: Effects of EGR configurations on CO versus Load

4.9.2.4 Emissions of Smoke

The positive effects of applying EGR with different configurations to lower smoke emission at all load ranges is shown in Figure 4.36 comparing with the baseline. Both cold and hot EGR configurations indicate almost similar effects at lower loads. In the ranges medium to higher loads both hot and cold EGR shows higher percentage reduction in smoke which could be due to the better thermal efficiency and soot oxidation from the enhanced combustion temperature.

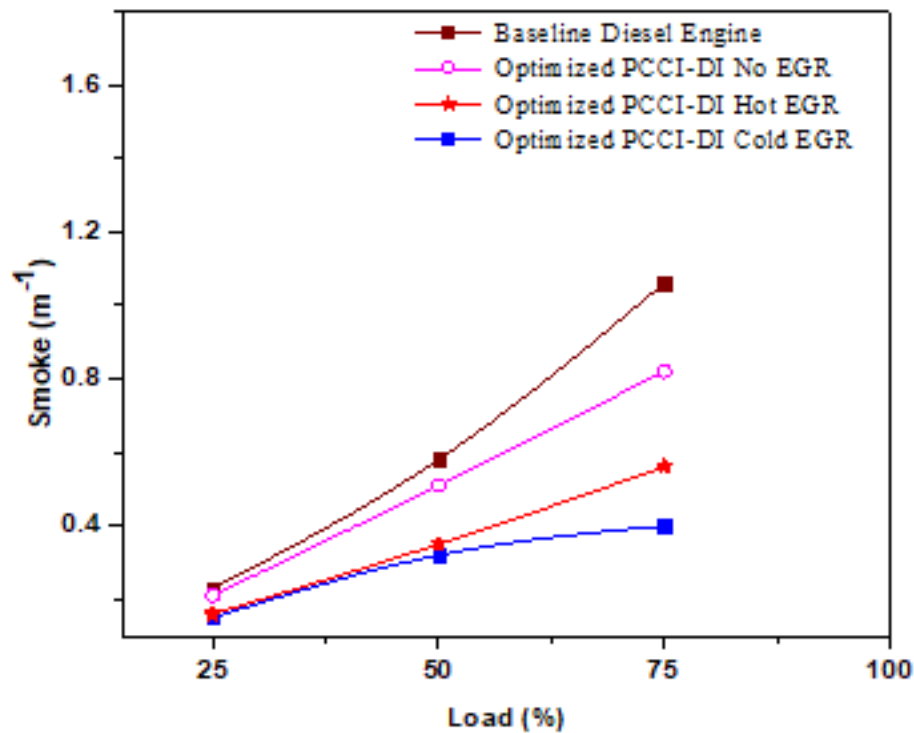


Figure 4.36: Effects of EGR configurations on smoke versus Load

In general, in this investigation applying different EGR configurations of cold, hot and no EGR resulted reduction of NO_x by 68.02%, 63.87% and 33.42% respectively for the optimized operations of PCCI-DI single cylinder diesel engine. Similarly lower smoke emission by 63.2%, 47.16% and 22.64% respectively was registered comparing with the baseline diesel engine. Percentage increments of HC and CO were minimized comparing with the previous studies on PCCI combustion. 27.5%, 9.2% and 20% increase in HC and also 33.33%, 1.7% and 16.67% increase in CO were obtained in the cold, hot and no EGR configurations respectively. The study shows the possibilities of emission reductions by applying different EGR configurations on PCCI-DI diesel engine of the type methanol port injection and dieseline direct injection.

4.9.3 Conclusions

Considering its achievements of low emissions, PCCI mode of combustion becomes a promising technique especially at particular load ranges. This mode of combustion is found to be applied on diesel engines with minor and suitable modifications which lower the production of NO_x, HC and CO. In this study effect of EGR configurations (hot, cold and no EGR) on emissions on this mode of combustion were investigated. Using both EGR configurations (cold and hot) help in reducing exhaust emissions in PCCI-DI diesel

engines. Impacts of using different EGR configurations on emissions on this optimized PCCI-DI diesel engine are summarized below:

- Applying hot EGR helped to minimize the incomplete combustion in the PCCI-DI set up which has positive effect on emissions of HC, CO and smoke. Lower HC and CO results obtained for low loads by using hot EGR than cold EGR configuration with a difference of 18.33% and 33.3% respectively.
- HC and CO emissions are relatively lowered in hot EGR configuration than the others due to the increase in inlet air temperature resulting better thermal efficiency in PCCI-DI combustion.
- Lower specific fuel consumption was also registered in hot EGR configuration than the others comparing with the baseline diesel PCCI-DI operation.
- This study explored the potential of hot EGR configuration in lowering emissions of HC and CO under PCCI-DI combustion modes particularly for methanol port injected and dieseline direct injected compression ignition engines.
- The cooled EGR indicated better NO_x reductions than hot and no EGR configurations. This could be due to the effects on the amount of air mass and oxygen flow in the intake.
- Both cold and hot EGR configurations found affecting the intake air temperature which automatically affects the combustion phenomena inside the cylinder that influences emission results.
- The no EGR configuration also showed lower HC and CO results than cold EGR configuration in PCCI-DI combustion modes.

From the investigation, results indicated the possibility of reducing both NO_x as well as smoke together. Option of minimizing increments in HC and CO emissions by applying different EGR configurations on this PCCI-DI setup which comprises port and direct injection of methanol and dieseline respectively were found. Summary results are shown in table 4.1.

Table 4.1: Results of emissions from different EGR configurations in the optimized PCCI-DI diesel engine experimental setup pertaining to the “optimal” points featuring cold and hot EGR configurations in comparison with previous research attempts.

	Load	Baseline diesel Engine	Optimized PCCI-DI (No EGR)	Reduction (R) or Increment (I) in %	Other previous research works with no EGR	Optimized PCCI-DI (Hot EGR)	Reduction (R) or Increment (I) in %	Optimized PCCI-DI (Cold EGR)	Reduction (R) or Increment (I) in %	Other previous research works on cold/hot EGR.	Other previous research works on PCCI operations
NO _x (g/kWh)	25	9.82	7.11	27.6%d	47%R at lower loads and 55.6%R at higher loads (Bhio-gade, Suryawanshi et al. 2016). 54%R at lower loads and 43%R at higher loads (Girish and Jiwak, 2017)	5.19	47.15%R	6.34	35.4%dR	- Cold EGR is better by 54% than hot EGR (Elkelawy, Shenawy et al. 2022). - Cold EGR is better by 15% than hot EGR in diesel engine at higher loads (Saichaitanya1, Simhadri et al. 2013)	13% reduction Compared to CD (Girish and Jiwak, 2017) 20–90% reduction (Ying, Longbao et al. 2010).
	50	12.31	7.18	41.67%d		4.68	61.98%R	4.31	65%R		
	75	11.82	7.87	33.42%d		4.27	63.87%R	3.78	68%R		
HC (g/kWh)	25	158	273	72.79%I	>120%I at lower loads and 40% I at higher loads (Bhio-gade, Suryawanshi et al. 2016) 62%I at lower loads (Girish and Jiwak, 2017)	236	49.37%I	308	95%I	>100%I. - Hot EGR better by 27% and 3% than cold at high and low loads respectively (Elkelawy, Shenawy et al. 2022)	>125%I (Girish and Jiwak, 2017). 30 times higher than the conventional CI mode (J. T. a. A. D. N, 2007). 400%I (Ambrosio, Iemmolo et al. 2016). >300%I (Ying, Longbao et al. 2010)
	50	123	178	44.72%I		159	29.27%I	192	56%I		
	75	120	144	20%I		131	9.17%I	153	27.5%I		
CO (g/kWh)	25	0.09	0.11	22.22%I	100I at higher loads (Bhio-gade, Suryawanshi et al. 2016). 68%I at higher loads and 20%I at lower loads (Girish and Jiwak, 2017)	0.14	55.55%I	0.15	66.67%I	Cold EGR better by 3.5% at higher and lower loads (Saichaitanya1, Simhadri et al. 2013)	30 times higher than the conventional CI mode (J. T. a. A. D. N, 2007) >100%I (Girish and Jiwak, 2017) 100%I (Ambrosio, Iemmolo et al. 2016).and >150%I (Ying, Longbao et al. 2010)
	50	0.05	0.08	60%I		0.1	100%I	0.07	40%I		
	75	0.06	0.07	16.67%I		0.08	33.33%I	0.06	No change		
Smoke (/m)	25	0.23	0.21	8.7%R	3.9%R at lower loads and 60%R at higher loads. 38.8%R at higher loads (Girish and Jiwak, 2017)	0.16	30.43%R	0.15	34.78%R	Cold EGR resulted 5.3% than hot EGR at lower and higher loads (Saichaitanya1, Simhadri et al. 2013)	78 - 83% reductions (Girish and Jiwak, 2017)
	50	0.58	0.51	12.07%R		0.35	39.66%R	0.32	44.83%R		
	75	1.06	0.82	22.6%R		0.56	47.17%R	0.4	62.26%R		

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1 Experimental Observation for L_9 Orthogonal Array

Different combinations of four operating control parameters; advanced injection timing, EGR %, dieseline ratio and load were considered and four output responses; NO_x, HC, CO and smoke were obtained. As table 5.1 indicates (including results), nine experimental tests were conducted by applying L_9 (3^4) matrix. Impacts of the chosen operating control parameters on emissions were shown on the surface and contour plots (Figure 5.1. to Figure 5.8) and table 5.1. In this study, results indicated that advancing the time of injection increases NO_x as well as smoke but decreases HC and CO results. Increasing EGR level indicated higher HC and CO effects since less amount of oxygen during PCCI condition but it decreases NO_x and smoke. In addition, decreasing the gasoline ratio in dieseline; decreases NO_x, HC and smoke but increases CO emissions. This is due to the impact of dieseline on ignition delay coming from the higher volatility nature of dieseline. Also the improved ignitability and combustion stability of dieseline in this PCCI-DI combustion could contribute for these results. The decrease in ignition delay helps in forming less over mixed regions that oxidation of fuel is challenging. High engine load resulted better HC and CO outputs however it increased NO_x as well as smoke results.

Table 5.1: L_9 (3^4) Orthogonal Array test matrix with factors and responses

Coded Input Parameters												
A		B			C		D		Responses			
Injection timing (CA BTDC)		EGR % (%)			Dieseline Ratio (D:G) (% By Vol.)		Load (%)					
Run No.	code	actual	code	actual	code	actual	code	actual	NOx in g/kWh	HC in g/kWh	CO in g/kWh	Smoke in /m
1	-1	23	-1	25	-1	60	-1	25	2.73	153	0.06	0.05
2	-1	23	0	35	0	80	0	50	2.10	157	0.05	0.03
3	-1	23	1	45	1	90	1	75	1.58	176	0.08	0.04
4	0	25	-1	25	0	80	1	75	3.92	154	0.07	0.42
5	0	25	0	35	1	90	-1	25	3.15	173	0.06	0.12
6	0	25	1	45	-1	60	0	50	2.03	158	0.09	0.06
7	1	30	-1	25	1	90	0	50	2.69	156	0.03	0.03
8	1	30	0	35	-1	60	1	75	3.68	133	0.04	0.04
9	1	30	1	45	0	80	-1	25	2.53	139	0.05	0.02

Premixing methanol on intake port in the experiment has an impact on better combustion since improved oxygen amount which positively affected the emission characteristics by forming leaner combustion. Application of dieseline also contributed in lowering emission results from its characteristics of forming homogeneous mixture which improves the combustion efficiency. The air-blast injection of methanol helped the PCCI-DI combustion by forming a lean combustion features that helped in achieving lower NOx and smoke and also significant lowering on the increments of HC and CO emissions.

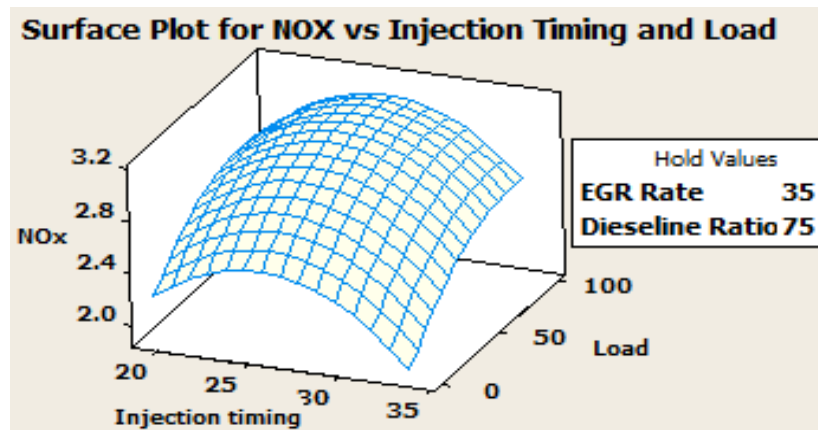


Figure 5.1: 3D surface plot for NOx versus injection timing and Load

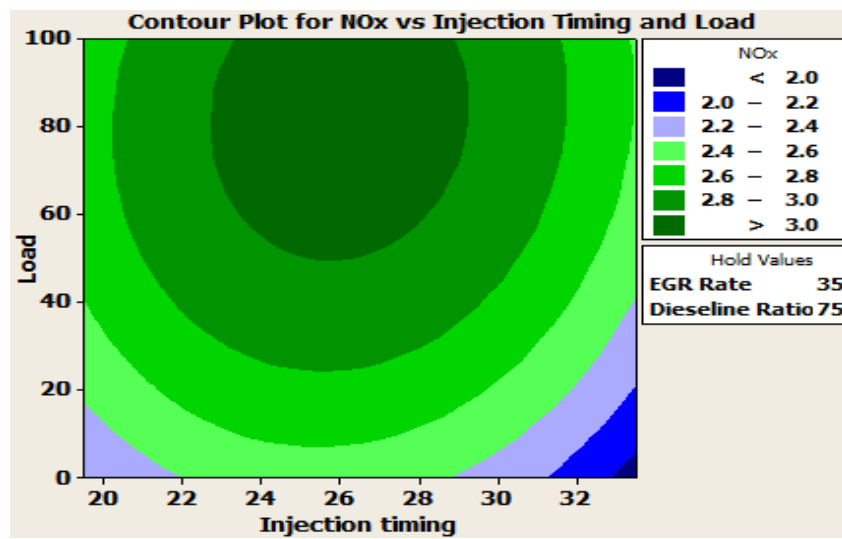


Figure 5.2: 3D contour plot for NOx versus injection timing and Load

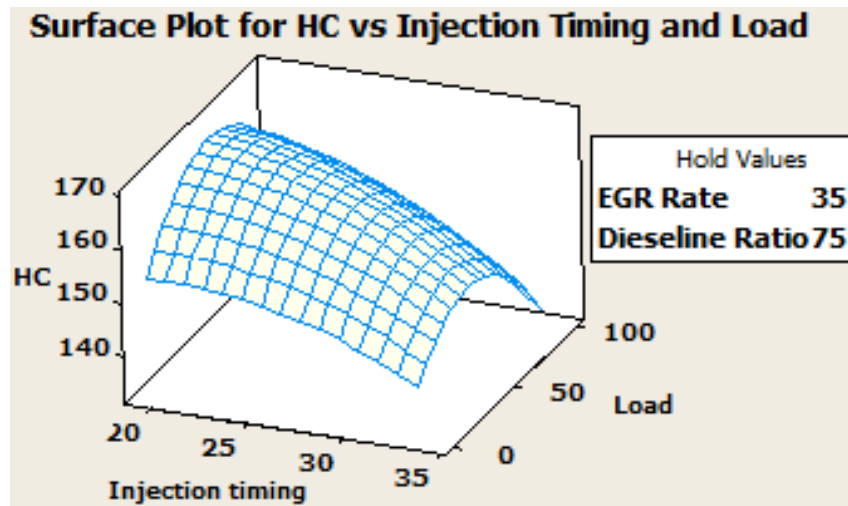


Figure 5.3: Plots of 3D surface for HC versus injection timing and Load

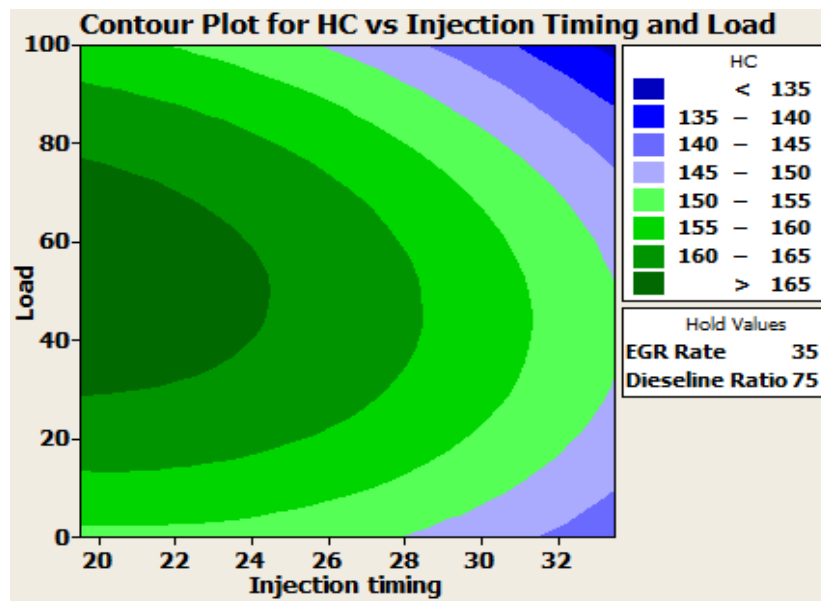


Figure 5.4: Plots of 3D contour for HC versus injection timing and Load

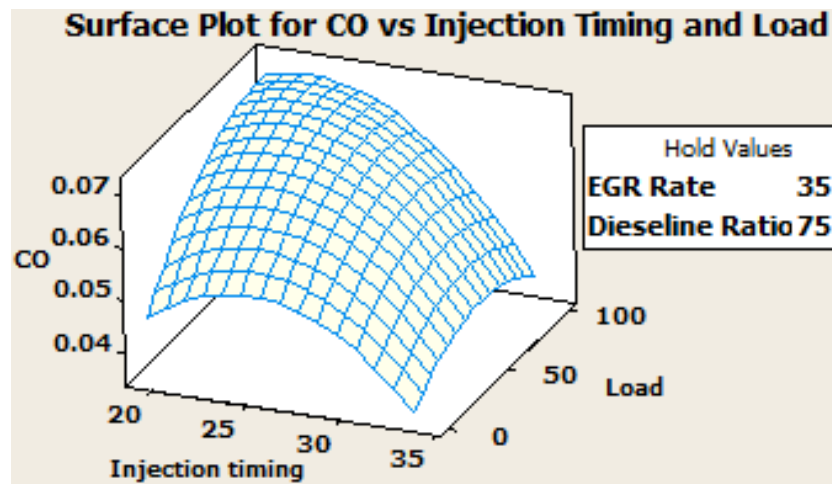


Figure 5.5: Plots of 3D surface for CO versus injection timing and Load

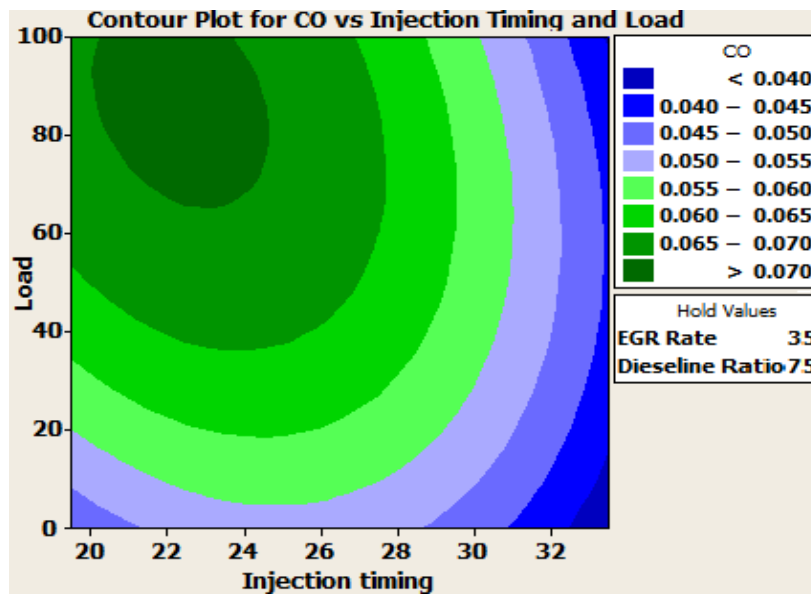


Figure 5.6: Plots of 3D contour for CO versus injection timing and Load

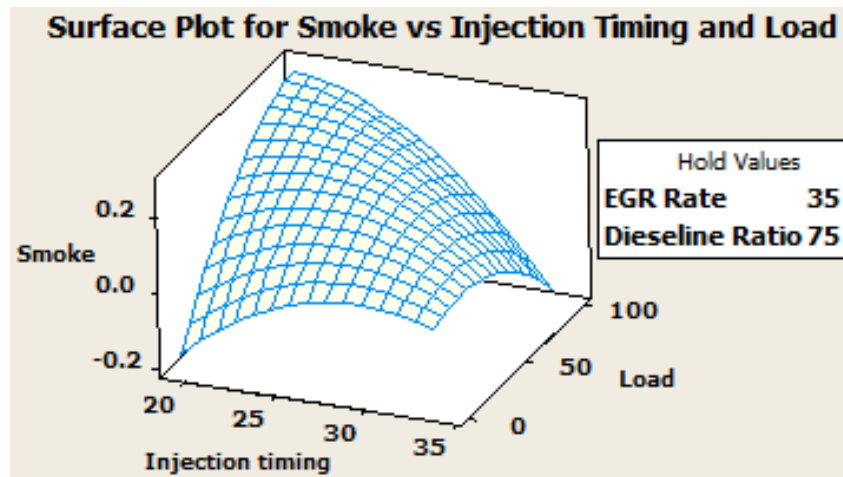


Figure 5.7: Plots of 3D surface for smoke versus injection timing and Load

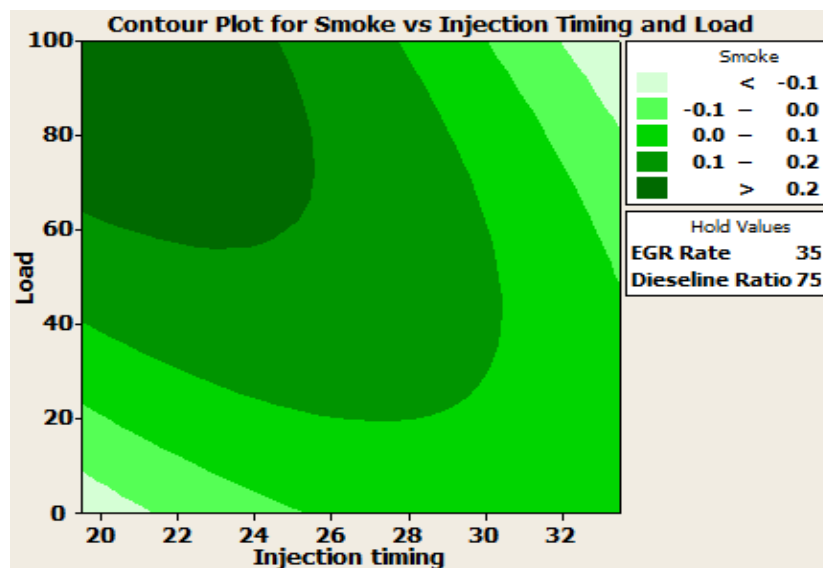


Figure 5.8: Plots of 3D contour for Smoke versus injection timing and Load

As indicated in table 5.2, optimum combination among the control operating factors is obtained by following analysis of grey relational method. During the analysis S/N ratios were calculated for the obtained experimental data, S/N ratios were normalized, coefficients of grey relational including grades of grey relational were computed, and optimum levels combination of the control operating parameters was found.

Table 5.2: Taguchi response table for the grades of the grey relation

Level	Parameters			
	A	B	C	D
1	0.5350	0.5859 *	0.5391	0.5364
2	0.6917 *	0.5432	0.5598	0.5014
3	0.4574	0.5550	0.5852 *	0.6463 *
Delta	0.2342	0.0426	0.0461	0.1450
Rank	1	4	3	2

* Optimum level of factors

Graph for the grade of the grey relational is indicated in Figure 5.9. Larger values of grade shows improved emission results. Therefore, selection of level is depending on its possession of the largest average response value. As shown in Figure 5.9; advanced time of injection with 25° crank angle before TDC, 25 % EGR level, dieseline ratio of 90:10 in percent and 75 % of load arrangement (A₂ B₁ C₃ D₃), is the combination being optimum that achieves minimum emission the engine.

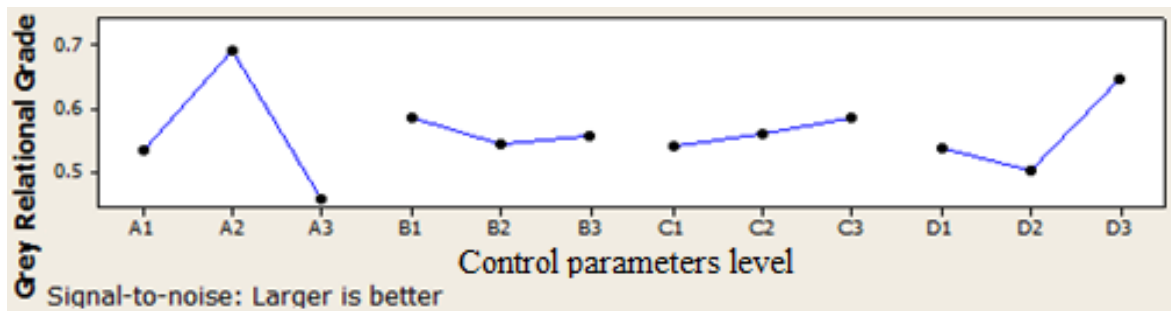


Figure 5.9: Taguchi response graph for the grey relational grade

5.2 S/N Ratio Analysis

The S/N response curves are shown from Figure 5.10 to Figure 5.13. They also indicate the effects of varying the levels of each of the control operating parameters on the responses. Minitab software is applied for S/N ratio calculations, Taguchi design, doing ANOVA and main effects plots.

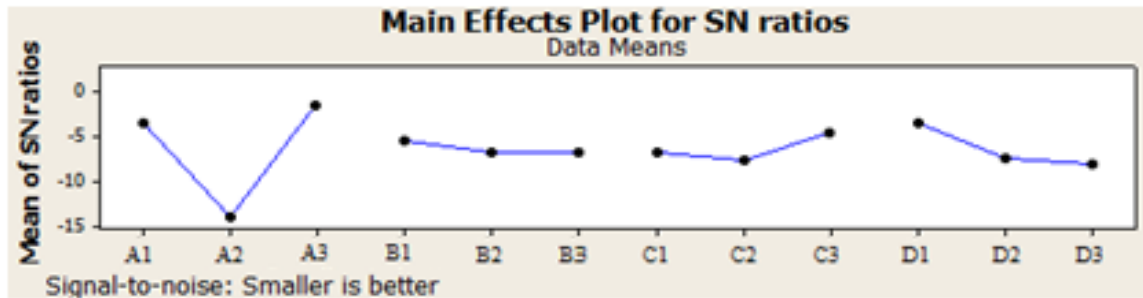


Figure 5.10: S/N response curves of factors for NOx emissions

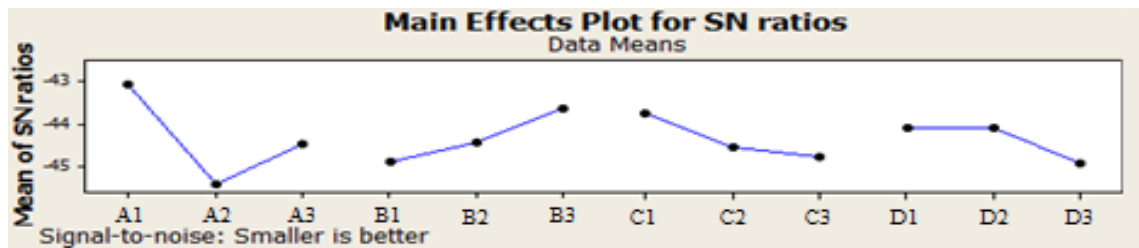


Figure 5.11: S/N response curves of factors for HC emissions

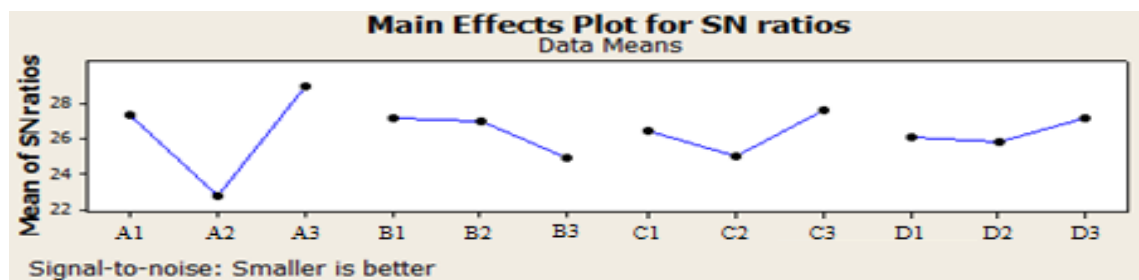


Figure 5.12: CO emissions S/N response curves of factors

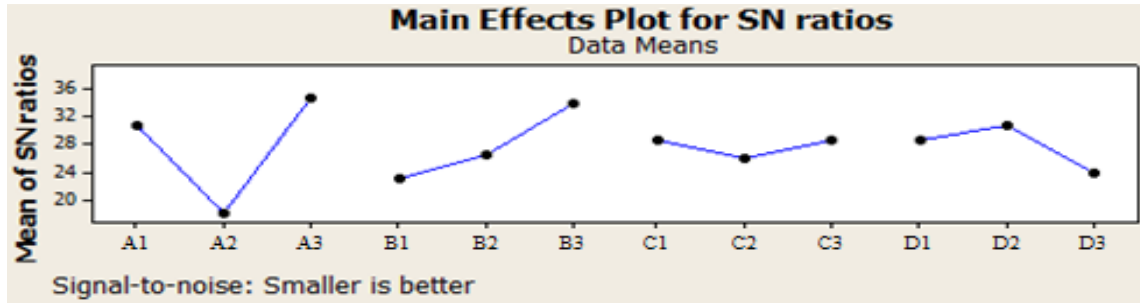


Figure 5.13: S/N response graphs of factors for Smoke emissions

5.3 Optimized Test Results of Emissions Using the Control Factors

Selection of control parameters and levels were done primarily before going to the optimization process. After passing through compressive literature surveys the control parameters; injection timing, EGR and dieseline ratio with three levels were selected and considered as control parameters for the design optimization study since they have influence on the objectives of reduction of emissions with respect to load in LTC engines. Targeting simultaneous low NO_x and smoke emissions together with optimized lower HC and CO emissions; the effects of methanol PI, dieseline DI, EGR % and injection timing were analyzed from the experimental test results of emission characteristics. Lowest value of emission results were taken as quality indicators.

Analyzing the effects of the selected control factors on emissions and combustion targeting to get optimal parameters calibration were done with the help of DoE with grey Taguchi method. Table 5.3 shows the obtained optimized control parameter settings for lower results of NO_x, HC, CO and smoke.

Table 5.3: Optimum parameter settings for optimal lower NO_x, HC, CO and smoke

parameter settings			
Parameters	Unit	(optimum)	
A Injection timing	CA BTDC	25	
B EGR %	%	25	
C Fuel Ratio for DI (D:G)	% By Vol	90	
D Load	%	75	

Following this the exhaust emission values from the optimal operating control parameters of the PCCI-DI setup is indicated in Table 5.4

Table 5.4: Exhaust emission values of the optimized PCCI-DI combustion setup

Optimum experimental results (PCCI-DI)			
CO	HC	NO _x	Smoke
(g/kWh)	(g/kWh)	(g/kWh)	(m ⁻¹)
0.08	153	3.78	0.39

In comparison as it is shown in the above tables (Table 5.3 and Table 5.4); it is generally observed that lowering emission levels are possible through PCCI-DI combustion experimental setups by applying the optimized operating control parameters; injection timing, EGR %, diesel ratio and load.

Data obtained from the baseline engine operation are given in table 5.5

Table 5.5: Experimental data baseline

Experimental Results (baseline)			
CO	HC	NOx	Smoke
(g/kWh)	(g/kWh)	(g/kWh)	(m ⁻¹)
0.06	120	11.82	1.04

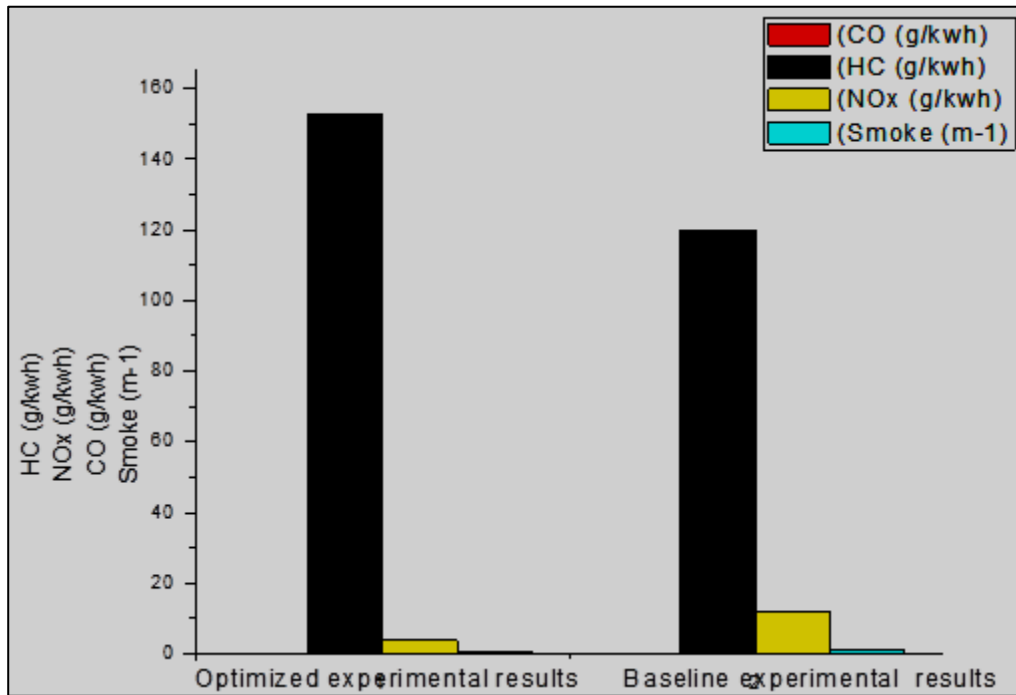


Figure 5.14: Optimized and baseline experimental results from PCCI-DI diesel engine

The average percentage changes of emissions for the optimized PCCI-DI diesel engine including the baseline results are indicated in Figure 5.14. Results indicated that decrease in emissions of NOx and smoke were 68.02% and 62.37% respectively and 27.49% and 33.18% increments of HC and CO respectively

In all load conditions HC is showing higher results than the baseline conventional diesel. This could be based on the facts of flame quenching impacts near the combustion chamber wall coming from greater evaporation of heat.

5.4 Optimized PCCI-DI Combustion Emission Result Analysis

From this study as shown from Figure 5.10 to Figure 5.13; optimum parameter settings for low NO_x are A₃ (30 CA BTDC), B₁ (25 %), C₃ (90:10 %) and D₁ (25%). For low HC; A₁ (23 CA BTDC), B₃ (45%), C₁ (60:40 %) and D₂ (50%) were found optimum settings. For low CO; A₃ (30 CA BTDC), B₁ (25 %), C₃ (90:10 %) and D₃ (75%) were optimum settings. Also for lower smoke; A₃ (30 CA BTDC), B₃ (45 %), C₃ (90:10 %) and D₂ (50%) were found optimum parameter settings. From ANOVA injection timing is found the highest affecting control factor possessing 69.35% contribution followed by load, dieseline ratio and EGR % respectively.

Table 5.6: Data pre-processing for response variables

Run No.	Taguchi design				Normalized values of S/N ratios Z _{ij}				Comparability Sequence				Grey Relational coefficient				Grey grade	Rank
	A	B	C	D	NO _x	HC	CO	Smoke	NO _x	HC	CO	Smoke	NO _x	HC	CO	Smoke		
1	1	1	1	1	0.602	0.500	0.631	0.301	0.398	0.500	0.369	0.699	0.557	0.500	0.575	0.417	0.512	5
2	1	2	2	2	0.313	0.592	0.465	0.133	0.687	0.408	0.535	0.867	0.421	0.551	0.483	0.366	0.455	7
3	1	3	3	3	0.000	1.000	0.893	0.228	1.000	0.000	0.107	0.772	0.333	1.000	0.823	0.393	0.637	3
4	2	1	2	3	1.000	0.523	0.771	1.000	0.000	0.477	0.229	0.000	1.000	0.512	0.686	1.000	0.800	1
5	2	2	3	1	0.759	0.939	0.631	0.589	0.241	0.061	0.369	0.411	0.675	0.891	0.575	0.549	0.672	2
6	2	3	1	2	0.276	0.615	1.000	0.361	0.724	0.385	0.000	0.639	0.408	0.565	1.000	0.439	0.603	4
7	3	1	3	2	0.586	0.569	0.000	0.133	0.414	0.431	1.000	0.867	0.547	0.537	0.333	0.366	0.446	8
8	3	2	1	3	0.930	0.000	0.262	0.228	0.070	1.000	0.738	0.772	0.878	0.333	0.404	0.393	0.502	6
9	3	3	2	1	0.518	0.158	0.465	0.000	0.482	0.842	0.535	1.000	0.509	0.372	0.483	0.333	0.425	9

The computed results for the experimental responses indicated in Table 5.6 are calculated using the formulas (3.1), (3.2), (3.4), (3.5), (3.7) and (3.8) shown in chapter three.

5.5 PCCI-DI Engine Performance Characteristics Test

Engine performance characteristics were tested on the experimental set up which is operated in both PCCI-DI and conventional/baseline modes of operations. Measuring the performance characteristics is not the objective of this study but to know how much it is significantly affected during the engine modification. Parameters and their corresponding relations; Exhaust gas temperature vs Engine speed, power output vs specific fuel consumption and SFC vs Engine load were evaluated. The change in cylinder combustion temperature and chemical property of fuel used affect the performance and emission characteristics.

The amount of power produced from the combustion engine is obtained from the data acquisition and control software of the test stand control unit.

From this experiment it is observed that the experimental setup together with the application of the optimization technique helped for the reduction of emission results of oxides of nitrogen and smoke in PCCI-DI diesel engine with almost the same power output with the baseline conventional diesel engine.

Loading and unloading for the chosen load ranges (0%, 25%, 50% and 75%) on the eddy current type dynamometer brake was done using the computer software. Torque and power measurement results were obtained by ordering the computer on the screen through several menus and buttons of the data management system. Load condition is varied using the computer software to load and unload on the eddy current type dynamometer brake.

Knowing the volume flow rate of the fuel with respect to time from the fuel flow measuring device on the experimental setup and multiplying it by the specific gravity of the fuel used would give us the fuel consumed by the computer controlled single cylinder engine test bench. To measure the fuel consumption in this experimental set up a flow meter is arranged on the fuel flow line. An eddy current electromagnetic brake type dynamometer was used that offers loading torque with a variator that allows control of the supply volt-

age and to vary its torque characteristics. The brake is jointly joined to the combustion engine shaft by a double Cardan joint that transfers power and torque.

The basic performance characteristic measurements were taken during experimental engine operation under the optimized combination of the four control operating parameters. This includes advanced injection timing of 25° CA BTDC, EGR % of 25 %, dieseline ratio of 90:10 in percent and 75 % of load arrangement (A₂B₁C₃D₃). This PCCI engine was expected to perform at higher loads like the conventional diesel engines but due to its limitations being LTC combustion mode it couldn't go to higher load operations.

The power output of the PCCI-DI engine is compared with that of the baseline conventional diesel engine as shown in Figure 5.15.

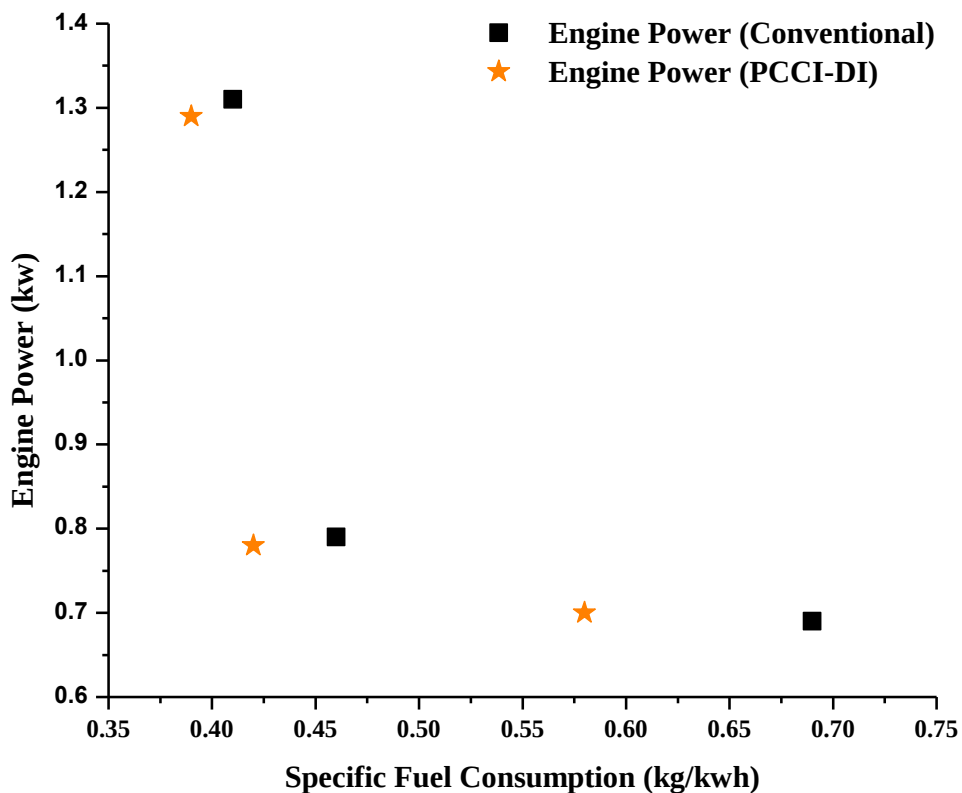


Figure 5.15: Conventional and PCCI-DI diesel engine operations power output vs specific fuel consumption

This Figure indicates that emission reduction in the PCCI-DI operation is possible with insignificant reduction of engine power output. From this experimental setup, the PCCI-DI combustion setup in the test indicated lower specific fuel consumption as shown in

Figure 5.16. Specific fuel consumption (SFC) is the input energy needed to produce unit power output.

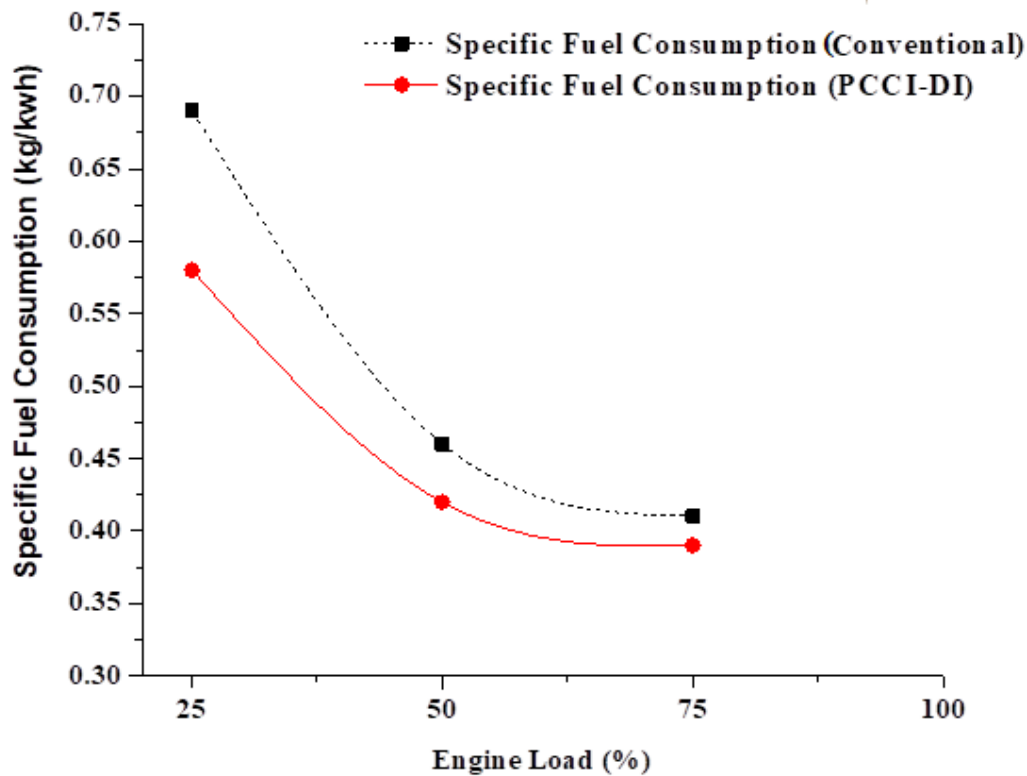


Figure 5.16: SFC vs Engine load in conventional and PCCI-DI diesel engine operations

During increase in load the specific fuel consumption in both the conventional and PCCI-DI operations shows decreasing. This is from the fact that as the load increases the combustion becomes more efficient due to the reason that higher suction pressure is developed mostly up to 90 to 100% of load (Domkundwar, 1710). It is expected that further increase in load from the graph indicated the combustion efficiency drops and more frictional losses will arise and this will result increasing in BSFC from the overloading of the engine. Also from the study the poor fuel atomization and vaporization due to the greater viscosity nature of diesel and methanol, and their blends which resulted late combustion helping for the development of higher exhaust gas temperature in the PCCI-DI engine setup as indicated in Figure 5.17.

In general from this investigation the performance characteristics of conventional and PCCI-DI diesel engines combustion modes resulted the following; exhaust gas temperature is observed to be greater for the conventional or baseline than the PCCI-DI

mode, higher specific fuel consumption is observed in the case of the conventional/baseline diesel mode of operation than the PCCI-DI mode of operation and possibility of minimizing emissions in PCCI-DI operating conditions with insignificant power output differences in the two operating modes.

Temperature of the exhaust gas exiting the cylinder indicates the degree of temperature resulted during the combustion event. Increase in speed of the engine indicated an increase in temperature of exhaust gases for both PCCI-DI and conventional operation conditions. As shown in Figure 5.17 exhaust gas temperature in PCCI-DI is less than the baseline or conventional diesel operation in all speed ranges.

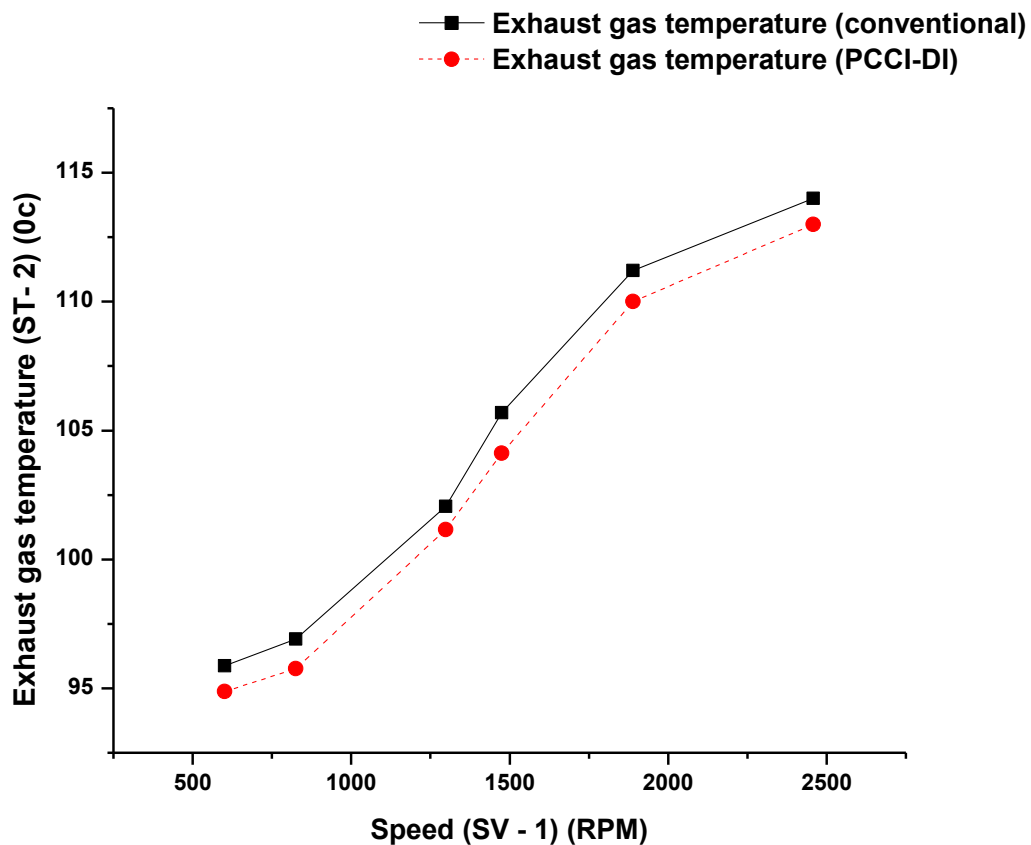


Figure 5.17: Exhaust gas temperature vs Engine speed in conventional and PCCI-DI diesel engine operations

The degree of combustion reaction and the temperature inside the cylinder become less due to the reduction of oxygen due to the EGR which makes a decrease in exhaust gas temperature in PCCI-DI conditions. The less combusted gas temperature is affecting the increased HC and CO amounts in comparison to the conventional diesel combustion. The

ignition delay characteristic which is affected by the addition of dieseline and EGR contributed for the reduction of the exhaust gas temperature in the PCCI-DI diesel engine set up. The other contributing factor for less exhaust gas temperature production is that PCCI engines have features of having combustion inside the cylinder which occurs in large areas of the cylinder not on particular point that brings high temperature concentration points.

Confirmation Test

In validating the results found using Taguchi technique experimental verification was conducted using significant factors arranged at optimal conditions. Values from the verification test under the optimal conditions are; advanced time of injection with 25° crank angle before TDC, 25% of EGR level, dieseline ratio of 90:10 in percent and 75 % of load arrangement ($A_2B_1C_3D_3$). Confirmation test results indicated that in optimizing a multi response challenges, grey-Taguchi is a convenient optimizing tool in predicting the injection timing, EGR %, dieseline ratio, and load arrangement for lower emission characteristics in PCCI-DI diesel engines. Results from the optimized PCCI-DI combustion mode (optimum combination at $A_2 B_1 C_3 D_3$) resulted reduction of 68.01% in NO_x and 62.37% in smoke compared with base-line. Relatively promising lower percentage increments of 27.49% and 33.18% in HC and CO results respectively were found in comparison to the average previous studies on PCCI combustion. Minimized HC and CO percentage increments as indicated under 6.1 Conclusions and these are promising results comparing with most previous studies having more than 30% increments even more than 100% increments (Bhiogade and Suryawanshi, 2017; Girish and Bhiogade, 2017).

5.6 Error and Uncertainty Analysis

Accuracy of measurements leads in getting genuine study results. In determining the uncertainty obtained in this study, defining the sources of error and calibrating the used measuring apparatus were considered. To minimize errors during measurements three readings were taken and averaged for the analysis. Percentage relative uncertainties for emissions of NO_x , HC, CO and smoke were calculated and shown in table 5.7.

Table 5.7: Accuracies and uncertainty levels of the emissions

Accuracy ± 5%			% Uncertainty	
NOx			Min.	Max.
Run No.	Min. - 5%	Max. + 5%	-	+
1	2.68	2.78	1.83	1.83
2	2.06	2.14	1.90	1.90
3	1.56	1.60	1.27	1.27
4	3.88	3.96	1.02	1.02
5	3.09	3.21	1.90	1.90
6	2.01	2.05	0.98	0.98
7	2.66	2.72	1.12	1.12
8	3.62	3.74	1.63	1.63
9	2.50	2.56	1.19	1.19
Uncertainty level of NOx			1.43%	+ 1.43%
Likewise results of others are indicated below				
Uncertainty level of HC			1.06%	+ 1.06%
Uncertainty level of CO			1.53%	+ 1.53%
Uncertainty level of smoke			2 %	+ 2 %

The exhaust gas analyzer was calibrated with clean ambient air in order to get the mentioned specification standards. Emission results of the exhaust gas from the engine were measured using the element computer controlled TBMC-AGE exhaust gas analyzer. Measuring carbon monoxide (CO), unburned hydrocarbon (HC) and oxides of nitrogen (NOx) were made possible through this analyzer. The analyzer needs to make frequently zero the sensors. Once a ZERO has been made the time to the next zero is displayed in minutes assuring there is enough time before beginning the test. The analyzer was calibrated with clean ambient air in order to get the specification standards. Flow sensor is installed to measure the amount of the outlet flow of exhaust gases.

From this uncertainty result it indicated that an uncertainty of less than 5% during measurement of this experimental study was attained. Nine tests were conducted to minimize cost and to avoid excess random errors in the experiments. From the results of these experiments, the average value is reported after conducting three experiments.

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This experimental research work aims to identify the optimum combination of the operating parameters; injection timing, EGR % and Dieseline premixing ratio for better trade-off between NO_x with that of HC and CO productions and also for better load % combinations without penalizing other performance parameters.

In this study an experimental investigation applying the hybrid of grey Taguchi technique of optimization was conducted to obtain optimum lower emission results in diesel engine operating in PCCI-DI combustion mode. For the investigation operating control parameters; injection timing, EGR %, dieseline ratio and load having three levels were selected for optimization of emission characteristics pertaining to NO_x, HC, CO and smoke. In designing of experiments and conducting tests Taguchi's L₉ orthogonal array was applied. Taguchi, Grey relational analysis and Analysis of Variance (ANOVA) were used in finding the optimum combination of the control operating parameters which is applied in several engine operation optimization techniques. For the study an experimental setup or facility was built having feature of PCCI-DI operating mode which is adapted from the conventional diesel engine. Methanol port injection together with direct injection of dieseline was used on the chosen single cylinder diesel engine to evaluate their effects on the emission characteristics on PCCI-DI diesel engine. These optimized injection timing, EGR % and dieseline premixing ratios would be very significant in achieving simultaneous low NO_x, HC, CO emissions with respect to engine load. Validity of the results was verified through the confirmation tests. This study indicated that a hybrid of Taguchi method and grey relational analysis can be successfully used for the study of multi- response optimization of emission characteristics in PCCI-DI diesel engines.

The following main conclusions have been made from the study and computations;

- The study indicated that LTC engine set up in PCCI mode was enabled with dieseline direct injections and methanol port injection from a conventional diesel engine modified and adapted in automotive workshop. The experiment confirmed

that varying the control operating parameters have significant impact on PCCI_DI combustion and emissions.

- For lower emissions of NO_x, HC, CO and smoke; the optimum operational settings of the control parameters are advanced injection timing of 25° CA BTDC, EGR % of 25 %, dieseline ratio of 90:10 in percent and 75 % of load arrangement (A₂B₁C₃D₃).
- Optimized settings of the control parameters for better responses of individual emission results were found as: for low NO_x emissions A₃ (30 CA BTDC), B₁ (25 %), C₃ (90:10 %) and D₁ (25%). For low HC; A₁ (23 CA BTDC), B₃ (45%), C₁ (60:40 %) and D₂ (50%) were found optimum settings. For low CO; A₃ (30 CA BTDC), B₁ (25 %), C₃ (90:10 %) and D₃ (75%) were optimum settings. Also for lower smoke; A₃ (30 CA BTDC), B₃ (45 %), C₃ (90:10 %) and D₂ (50%) were found as optimum parameter settings.
- Based on the rankings and ANOVA results, the order of contribution were injection timing with a contribution of 69.35% followed by load, dieseline ratio and EGR % respectively. Significant sensitivity of the PCCI_DI combustion of this experimental investigation under LTC strategy was seen during varying the injection timing than varying the other control factors.
- From the confirmation test, good agreements between prediction from the grey relational analysis based on Taguchi method and experimental values were obtained.
- Through the help of DoE particularly the L₉ (3⁴) orthogonal array has been employed for experimental design and analysis. By applying the weighting factors of grey relational analysis, multi-response problem was converted into a single one and optimal solution was obtained from the experimental data.
- In this study the modified PCCI-DI operation through port air-blast injection of methanol and dieseline direct injection were compared with the base-line conventional diesel combustion mode. Results indicated that decreases in emissions of NO_x and smoke were 68.02% and 62.37% respectively and 27.49% and 33.18%

increments of HC and CO respectively were found. The HC and CO percentage increments are promising results comparing with most previous studies. This shows methanol port injection together with the optimized control factors helped to minimize HC and CO results. The low reactivity characteristic nature of methanol minimized the premature auto-ignition characteristics of the mixture inside the combustion chamber and also indicated promising LTC set up by maintaining emission standards.

- Low NO_x, smoke and exhaust temperature were obtained in all combinations of; EGR %, diesel:line ratio and advanced injection timings including better tradeoff between the emissions of NO_x and those of HC and CO in this PCCI-DI combustion set up comparing with the conventional diesel combustion.
- Test results from this experiment indicated the possibility of getting more optimized results in LTC engine set up through DoE technique and by incorporating more control factors in combination with alternative fuel additions which facilitate the commercialization of LTC engine technology which is more energy-efficient and environmentally friendly.

In addition, the study investigated the effect of EGR configurations (hot, cold and no EGR) on emissions of the chosen engine operational setup. From the study, applying both EGR configurations (cold and hot) contributed significantly in reducing exhaust emissions in PCCI-DI diesel engines. Impacts of using different EGR configurations on emissions on this optimized PCCI-DI diesel engine are summarized below:

- Applying hot EGR helped to minimize the incomplete combustion in the PCCI-DI set up which has positive effect on emissions of HC, CO and smoke. Lower HC and CO results obtained for low loads by using hot EGR than cold EGR configuration with a difference of 18.33% and 33.3% respectively.
- HC and CO emissions are relatively lowered in hot EGR configuration than the others due to the increase in inlet air temperature resulting better thermal efficiency in PCCI-DI combustion.

- Lower specific fuel consumption was also registered in hot EGR configuration than the others comparing with the baseline diesel PCCI-DI operation.
- This study explored the potential of hot EGR configuration in lowering emissions of HC and CO under PCCI-DI combustion modes particularly for methanol port injected and dieseline direct injected compression ignition engine.
- The cooled EGR indicated better NO_x reductions than hot and no EGR configurations. This could be due to the effects on the amount of air mass and oxygen flow in the intake.
- Both cold and hot EGR configurations found affecting the intake air temperature which automatically affects the combustion phenomena inside the cylinder that influences emission results.
- The no EGR configuration also showed lower HC and CO results than cold EGR configuration in PCCI-DI combustion modes.

From the investigation on effects of EGR configurations on emissions, results indicated the possibility of parallel reductions of both NO_x as well as smoke together. Minimizing the increments of HC and CO emissions by applying different EGR configurations on this PCCI-DI setup by comprising port and direct injection of methanol and dieseline respectively were found from this study.

6.2 Recommendations

The study has shown the feasibility of minimizing emissions of NO_x and smoke in parallel with minimizing the increments of HC and CO in PCCI-DI diesel engines. Since higher HC and CO productions hinders the manufacturing and commercialization of LTC engines which are having a prominent advantages in terms of reducing NO_x and PM.

Below are recommendations for future research work on the PCCI-DI combustion diesel engine of the LTC strategy:

- This study addressed the significance of port air-blast injection of methanol to build PCCI engine setup for better premixing of methanol. But the amount of methanol to be injected in to the inlet port is pre calibrated and fixed. So works should be done in the future by making self-adjusting/automatic as per the engine operating conditions that could make the experimental set up more effective.
- Additional input factors for maximum optimal emission reductions need to be included on the modified or adapted diesel engine. For the current study or optimization work mainly 3 factors were modified; modifying the engine through methanol port injection, varying the fuel through dieseline direct injection and adapting EGR set up together with different EGR configurations. Future works could be addressed by using more alternative fuels with additives including alcohols and including other engine adaptations for best results.
- More optimization work could be done on different EGR configurations to obtain best optimized engine emission results in advanced engine combustion operational setups for clean combustion of IC engines particularly diesel engines.
- Establishing low temperature combustion engine setup for this experiment is the first attempt at national level in Ethiopia thus more attention should be paid and well equipped engine testing facility should be designed and built to conduct advanced researches in the field of clean combustion through LTC approach.
- The challenge of excess emissions of HC and CO in LTC engines including PCCI-DI engines is still unsolved issue that more research works through engine and fuel modifications and also by applying additional optimization techniques should be done targeting cleaner and efficient engine manufacturing.

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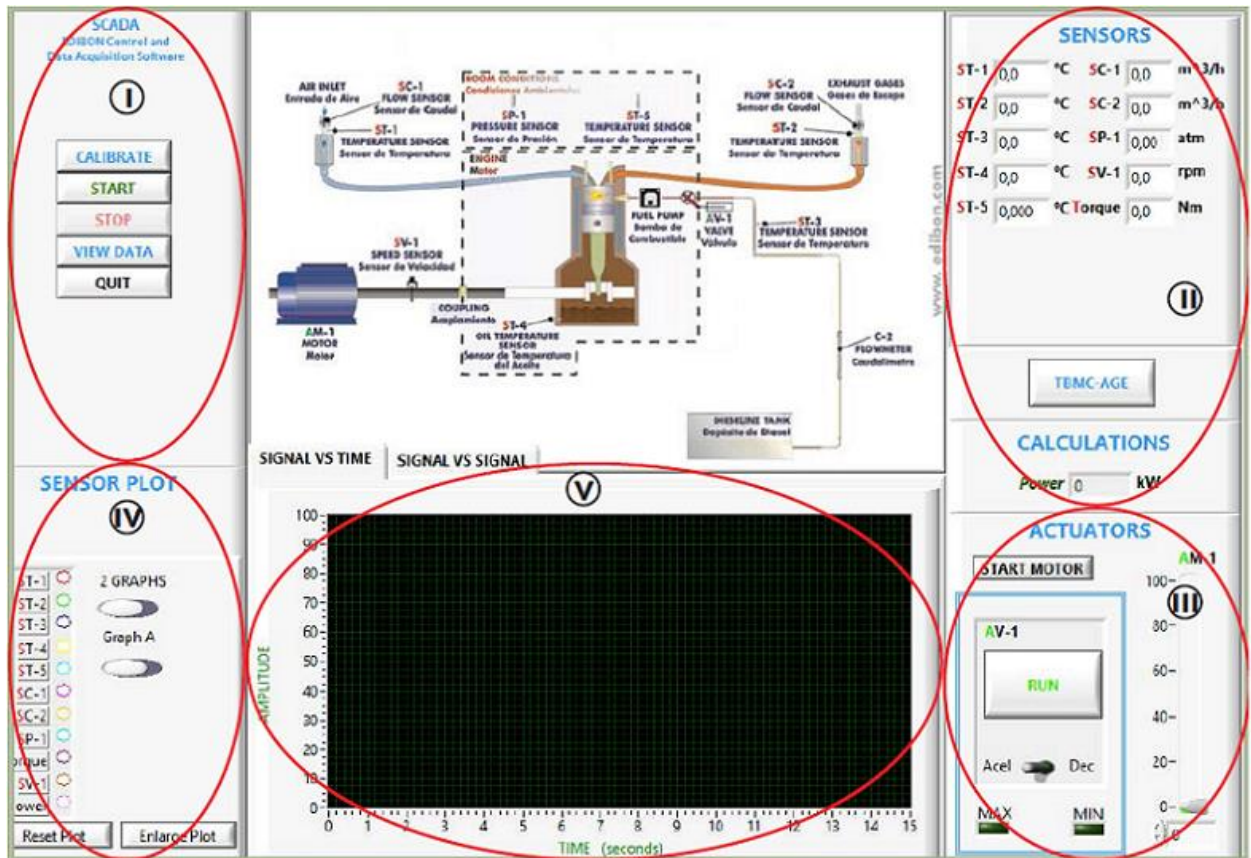
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APPENDICES

Appendix 1: Process diagram and unit elements allocation including software main screens



Appendix 2: Experimental test results on the developed orthogonal array test matrix

Coded Input Parameters													
		A		B		C		D		Results			
		Injection timing (CA BTDC)		EGR % (%)		Dieseline Ratio (D:G) (% By Vol.)		Load (%)					
Run No.		code	actual	code	actual	code	actual	code	actual	NOx in g/kWh	HC in g/kWh	CO in g/kWh	Smoke in /m
1	1 st									2.80	153	0.06	0.04
	2 nd	-1	23	-1	25	-1	60	-1	25	2.61	155	0.05	0.05
	3 rd									2.78	150	0.06	0.05
2	1 st									2.07	152	0.04	0.03
	2 nd	-1	23	0	35	0	80	0	50	2.04	159	0.05	0.03
	3 rd									2.21	161	0.05	0.03
3	1 st									1.47	182	0.08	0.04
	2 nd	-1	23	1	45	1	90	1	75	1.64	174	0.07	0.04
	3 rd									1.63	173	0.08	0.03
4	1 st									4.01	156	0.06	0.43
	2 nd	0	25	-1	25	0	80	1	75	3.86	155	0.07	0.41
	3 rd									3.89	152	0.07	0.42
5	1 st									3.12	168	0.06	0.11
	2 nd	0	25	0	35	1	90	-1	25	3.21	173	0.06	0.12
	3 rd									3.13	178	0.06	0.12
6	1 st									1.98	156	0.08	0.06
	2 nd	0	25	1	45	-1	60	0	50	2.01	163	0.09	0.06
	3 rd									2.09	155	0.09	0.05
7	1 st									2.62	152	0.04	0.03
	2 nd	1	30	-1	25	1	90	0	50	2.67	162	0.03	0.03
	3 rd									2.78	153	0.03	0.03
8	1 st									3.67	133	0.05	0.04
	2 nd	1	30	0	35	-1	60	1	75	3.70	135	0.04	0.03
	3 rd									3.68	137	0.04	0.04
9	1 st									2.47	137	0.05	0.02
	2 nd	1	30	1	45	0	80	-1	25	2.53	137	0.06	0.02
	3 rd									2.60	143	0.05	0.02

Appendix 3: Results of emissions from different EGR configurations in the optimized PCCI-DI diesel engine

	Load	Baseline diesel Engine	Optimized PCCI-DI No EGR	Optimized PCCI-DI Hot EGR	Optimized PCCI-DI Cold EGR
NO _x (g/kWh)	25	9.82	7.11	5.19	6.34
	50	12.31	7.18	4.68	4.31
	75	11.82	7.87	4.27	3.78
HC (g/kWh)	25	158	273	236	308
	50	123	178	159	192
	75	120	144	131	153
CO (g/kWh)	25	0.09	0.11	0.14	0.15
	50	0.05	0.08	0.1	0.07
	75	0.06	0.07	0.08	0.06
Smoke (/m)	25	0.23	0.21	0.16	0.15
	50	0.58	0.51	0.35	0.32
	75	1.06	0.82	0.56	0.4