Development of Selective Catalytic Reductant (SCR) controller and Diagnostic requirement of Aftertreatment System for mid-range CPCB-IV Genset Engine

THESIS SUBMITTED FOR PARTIAL FULFILMENT OF THE REQUIREMENTS FOR AWARDING THE DEGREE OF MASTER OF ENGINEERING IN FACULTY OF ENGINEERING AND TECHNOLOGY

Submitted by

Sourav Das

Registration Number: 154342 of 2020-21
Examination Roll Number: M4AUT22009

Under the Guidance of

Dr. Prokash Chandra Roy
Professor
Department of Mechanical Engineering
Jadavpur University

Ashwyn V Parambath
Thermal and Fluid Science Engineer
EBU-ATI
Cummins Technical Centre India

DEPARTMENT OF MECHANICAL ENGINEERING
JADAVPUR UNIVERSITY
KOLKATA-700032
INDIA

FACULTY OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF MECHANICAL ENINEERING
JADAVPUR UNIVERSITY
KOLKATA

DECLARATION OF ORIGINALITY
AND
COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis contains literature survey and original research work, by the Undersigned candidate, as part of his ***Master of Engineering*** *studies.*

All information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name : Sourav Das
Examination Roll No :
Thesis Title : Development of Selective Catalytic Reductant (SCR) controller and Diagnostic requirement for Aftertreatment System of mid-range CPCB-IV Genset Engine

Signature :

Date :

FACULTY OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF MECHANICAL ENINEERING
JADAVPUR UNIVERSITY
KOLKATA

CERTIFICATE OF RECOMMENDATION

We hereby recommend that this thesis under our supervision by **Sourav Das**, entitled, "**Development of Selective Catalytic Reductant (SCR) controller and Diagnostic Requirement for Aftertreatment System of mid-range CPCB-IV Genset Engine**" be accepted in partial fulfillment of the requirements for awarding the degree of Master of Engineering in Automobile Engineering under Department of Mechanical Engineering of Jadavpur University.

………………………………………………..

Dr. Prokash Chandra Roy

Thesis Advisor

Dept. of Mechanical Engineering
Jadavpur University, Kolkata

…..…………………………………………

Dr. Amit Karmakar

Professor and Head
Department of Mechanical Engineering

Jadavpur University, Kolkata

…..…………………………………………..

Prof. Chandan Mazumder

Dean

Faculty Council of Engineering & Technology
Jadavpur University, Kolkata

FACULTY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF MECHANICAL ENINEERING JADAVPUR UNIVERSITY

KOLKATA

CERTICATE OF APPROVAL

The foregoing thesis entitled "**Development of Selective Catalytic Reductant (SCR) controller and Diagnostic Requirement for Aftertreatment System of mid-range CPCB-IV Genset Engine**" ishereby approved as a creditable study of an engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is notified to be understood that by this approval, the undersigned do not necessarily endorse or approved any statement made, opinion expressed and conclusion drawn therein but approve the thesis only for the purpose for which it hasbeen submitted.

Committee of final examination for evaluation of thesis:

…………………………………	………………………………..
Signature of Examiners	Signature of Examiners

ACKNOWLEDGEMENT

This acknowledgement is to express gratitude of the author to all those individuals who guided him in every aspect to make the thesis work successful.

The author would like to express his sincere gratitude and indebtedness to his Thesis Advisor ***Dr. Prokash Chandra Roy****, Professor, Department of Mechanical Engineering, Jadavpur University, Kolkata for his valuable suggestion and requisite guidance in various aspects of this project work. It was a great pleasure for me to work underhis supervision.*

The author is thankful to ***Ashwyn V Parambath ,*** *Thermal and Fluid Science Engineer, Cummins India Limited, .for his support in academic matters. Also* ***Utkarsh Verma****, ATI team leader, Cummins India Limited, was a great support and helped me in learning and understanding the research project in Cummins.*

The author would also like to pay his sensible appreciation to my family members for their constant supports. Lastly the author would like to thank all who have assisted him directly or indirectly to accomplish this work.

Sourav Das

Dated:

Jadavpur University

Kolkata

Abstract

For decades, air pollution has been a global concern amongst industrial practices. One of the major pollutants is Nitrous oxides (NOx) from engine exhaust emissions. Due to this, companies globally have been developing technologies to reduce the NOx output as much as possible. One of the technologies available is the application of a **Selective Catalytic Reductant (SCR)** in the exhaust stream of the IC engine. It is basically a ceramic substrate material, generally zeolite with a catalyst coating. To the exhaust gases, a urea solution is added to react with the exhaust to reduce NOx to water and nitrogen gas. This work deals with the development of a engine controller calibration to reduce maximum NOx particle from exhaust gases of a mid range generator diesel engine. The controller is developed as such that optimum level of urea is sprayed into the exhaust stream not only to reduce maximum NOx but also no amount of ammonia is slipped out, which is a by product of aqueous urea. The controller settings are run to produce three different experimental setups to check the NOx emissions obtained from the exhaust. D2 emission test cycle shows that a reduction of average 95 % of NOx has been seen throughout the cycle using SCR with controller settings. Ammonia slip has been noticed to be around 10 % of permissible legislative limit. Optimum temperature for working of SCR catalyst was observed around 250 degC. The output has been observed well below the emission norm of the upcoming CPCB norm, which is effective from July, 2022. The controller is capable of being installed in ECM calibration for genset engine.

CONTENT

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 General Background

Diesel generators have been in use in industries for decades. A diesel generator is basically a diesel engine, which is a prime mover, connected to an alternator or ac generator. Diesel gensets have uses in industrial sectors as well as marine and mining uses. More than 70 % of power in mining sectors is produced by diesel generators. Due to the vast use of diesel generators, emissions are strictly regulated by manufacturers to meet the norms laid by government of different countries. In India, the governing body for regulating the emission norms of diesel gensets is **Central Pollution Control Board (CPCB).** Diesel engines are one of the most thermally efficient IC engines built. Hence they are used for producing power for large commercial or industrial areas. Diesel engine can be categorised into 2 stroke and 4 stroke engines based on power cycles. In a cyclic 4 stroke engine, the four stages are mainly: Intake, Compression, Power and Exhaust in that order. The combustion of fuel takes place at the end of compression stroke, by injection of highly atomized diesel fuel into compressed air [1]. The air intake into the chamber can be naturally aspirated or forced suction by use of turbocharger or supercharger. With increasing number of diesel engines on roads and industrial applications, concerns are being raised for its emissions of CO, HC, NOx and PM into the atmosphere. New techniques are being used to lower these emissions such as use of advanced after-treatment system consisting of DOC, DPF and SCR in the downstream of engine [2].

1.2 Emission Norms of Generator Sets in India

Just like automotive vehicles have government for legal limit of emissions, like BS-V and BS-VI (Bharat Stage), generators also have emission norms. The regulating body for emission of gensets in India, Central Pollution Control Board (CPCB) has laid the first emission norm for generators in 2004, known as CPCB-I. In 2002, emission norms for generators above capacity 800kW were laid down. In 2003 and 2004, other power ratings were given emission norms.

Table 1.1 CPCB-I emission norms [3]

Engine Power (P)	Date	CO	HC	NOx	PM
		g/kWh			
P ≤ 19 kW	2004.01	5.0	1.3	9.2	0.6
	2005.07	3.5	1.3	9.2	0.3
19 kW < P ≤ 50 kW	2004.01	5.0	1.3	9.2	0.5
	2004.07	3.5	1.3	9.2	0.3
50 kW < P ≤ 176 kW	2004.01	3.5	1.3	9.2	0.3
176 kW < P ≤ 800 kW	2004.11	3.5	1.3	9.2	0.3

The main components of emission gases which were legislated were Carbon-monoxide (CO), unburnt Hydrocarbons (HC), various Nitrous Oxides (NOx) and Particulate matter (PM). The legislative limits are as in Fig 1.1

In 2014, the emission norms were made more stringent and CPCB-II came into effect. Currently all generators available in market are of CPCB-II norms.

Table 1.2 CPCB-II emission norms [3]

Engine Power (P)	Date	CO	NOx+HC	PM
		g/kWh		
P ≤ 19 kW	2014.04	3.5	7.5	0.3
19 kW < P ≤ 75 kW	2014.04	3.5	4.7	0.3
75 kW < P ≤ 800 kW	2014.04	3.5	4.0	0.2

In 2022, a new set of norms were laid down, with no official naming. These are considered to be the upcoming CPCB norms and will be effective from 2023 onwards. In these norms, legislative limit for ammonia (NH3) has been implemented with engines using SCR systems.

Table 1.3 Upcoming CPCB-IV emission norms [3]

Power, P, kW	NOx	HC*	NOx+HC*	CO	PM†	NH3
	g/kWh					ppm
P ≤ 8	-	-	7.5	3.5	0.30	25
8 < P ≤ 19	-	-	4.7	3.5	0.30	25
19 < P ≤ 56	-	-	4.7	3.5	0.03	25
56 < P ≤ 560	0.40	0.19	-	3.5	0.02	10
560 < P ≤ 800	0.67	0.19	-	3.5	0.03	10

Hence various Original Equipment Manufacturers (OEMs) are researching on different technologies to meet the new standards. So far in India, generators were mainly manual engines with no ECU built into them. Also most manufacturers so far has only used a basic catalytic converter in the exhaust tailpipe to reduce the emissions. However with the advent of the new CPCB norms, we can notice that the legislative limit for NOx+HC has been reduced very much, from 4.0 to 0.59 g/kWh for a mid range engine. Also PM has been reduced from 0.2 to 0.02. Conventional single bodied catalytic converter will not be able to cope with reducing emission without alteration in engine output.

This thesis deals with the development of a generator set that will be able to meet the new norms of emissions. The test was conducted in the development phase in Cummins Technical Centre India (CTCI). The engine used was a 4 cylinder mid range 4-stroke engine, with ECM technology. The tests were carried out in engine test cells. A number of test cycles were carried out. The major test cycle for checking emissions of a genset engine in India is a 5-mode D2 cycle.

1.3 D2 cycle

The legislative cycle for running emission tests for gensets in India is the 5 mode ISO 8178 D2 cycle shown in Table 1.4. It is a constant speed test cycle with 5 operating modes at various torque points of the engine, namely 100, 75, 50, 25 and 10 % respectively. Testing is done at ambient air pressure and air temperature [4].

Table 1.4 5-mode D2 emission cycle [4]

Mode No.	Engine speed	% Load	Weighting Factor
1	Rated speed	100	0.05
2	Rated speed	75	0.25
3	Rated speed	50	0.30
4	Rated speed	25	0.30
5	Rated speed	10	0.10

1.4 Aftertreatment System

An aftertreatment system is basically a unit of two or three individual parts which is installed in the tailpipe of a diesel engine. The major components of an aftertreatment system are Diesel Oxidization Catalyst (DOC) , Diesel Particulate Filtrate (DPF) and Selective Catalyst Reductant (SCR). Each part has a different working principle and collectively helps in reducing the amount of harmful gasses.
An after-treatment system is installed in the exhaust tailpipe of a diesel engine to reduce the amount of unburnt HC, CO, Particulate Matter(PM) or soot, and NOx emitted by it. These pollutants are converted into less hazardous components (H2O, CO2 and N2) on a 'reactor bed'. Reactor bed is a catalyst bed which helps in increasing the rate of reaction for the conversion processes. The catalyst used provides a low energy pathway for the reaction to proceed. As the reaction temperature is decreased, it becomes possible for these reactions to occur at tailpipe exhaust temperature. [5]

Initial after-treatment system consisted of only Diesel Oxidation Catalyst (DOC). It took care of HC and CO coming out in exhaust stream. The reaction for these conversions is as shown below:

Oxidation of HCs to water and carbon dioxide,

$$C_xH_y + O_2 \longrightarrow xCO_2 + \frac{y}{2}H_2O$$

Oxidation of CO to carbon dioxide,

$$CO + ½ O_2 \longrightarrow CO_2$$

To address the emissions of PM, vehicle manufacturers are starting to use DPF after DOC. The PM is filtered in DPF, which is finally burned out during regeneration of DPF. The NOx reduction is done in SCR, which selectively reduce the NOx into N_2 by the help of Diesel Exhaust Fluid (DEF) dosed into SCR. The DEF is mainly reducing agent such as NH_3 or its derivative, *e.g.* Urea. The conversion occurs as one the following reactions:

$$4NO + 4NH_3(g) + O_2 \longrightarrow 4N_2 + 6H_2O$$

$$NO + NO2 + 2NH_3\,(g) \longrightarrow 2N_2 + 3H_2O$$

$$6NO + 8NH_3\,(g) \longrightarrow 7N_2 + 12H_2O$$

1.5 After-treatment System Components

An aftertreatment system mainly comprise of three individual components, namely:

1. Diesel Oxidization Catalyst (DOC)

2. Diesel Particle Filter (DPF)

3. Selective Catalytic Reductant (SCR)

The assembly of these are shown in Fig 1.1 below:

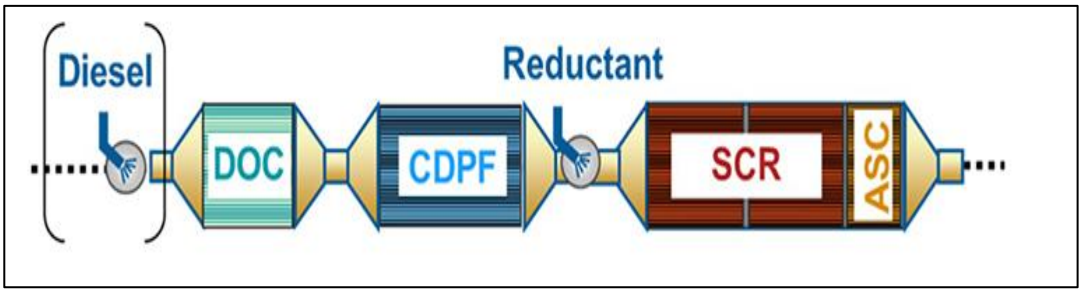

Fig 1.1 Assembly of Aftertreatment System

DOC is basically a ceramic substrate packed in a metal container. Earlier the substrate was made out of metals such as ferrites, iron-chromium-aluminium. The disadvantage was high cost and heavier components. This lead to the rise of ceramic materials such as magnesium-aluminium silicate called cordierite [6,7]. The monolithic is in the structure of a honeycomb, with "flow channels" running parallel across the catalyst. The exhaust gasses when passing through the channels come in contact with the catalysts deposit in wall. The monolithic substrate structure is advantageous as it provides compactness in catalyst with high geometric surface area (GSA) per unit volume, low pressure drop and very low loss of catalysts. The number of cell per square inch (cpsi) can vary from 10 to 1000, with diesel engine application ranging from 300 to 400 cpsi [8].

Diesel Particulate Filter (DPF) is used for filtration of Particulate matter (PM) in engine exhaust. Filtration mechanisms include diffusional deposition, inertial deposition, and flow-line interception. Due to low bulk density, DPF can accumulate large volumes of ash and soot. The particles can be solid, liquid or gases [9]. Filter materials are mainly Silicon-carbide (SiC) or Cordierite. General filter efficiency can be from 70-95%. Lower efficiency is seen for more soluble organic fraction (SOF) and goes higher when metal particles and elemental carbon particles are more in concentration [10,11].

As amount of soot increases, need for "regeneration" comes into picture. This cleaning of accumulated soot is done by combustion of NO_2, which leads to excessive heat [12]. This heat is supplied by the DOC by converting NO_2 to NO. Moreover during "active regeneration", heat is added to exhaust by oxidation of excessive HC in exhaust stream [13]. A schematic diagram of regeneration in DPF is shown in Fig 1.2 below.

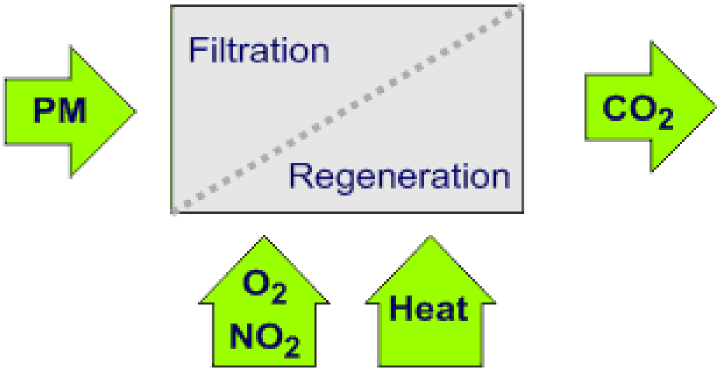

Fig 1.2: Schematics of thermal regeneration in DPF [14]

Selective catalytic Reductant (SCR) systems are catalytic reactors whose purpose is to reduce NOx in the exhaust stream by chemical reduction using a reducing agent such as ammonia (NH_3). Ammonia is introduced into the exhaust stream of gases just before the SCR reactor bed by injecting Diesel Exhaust Fluid (DEF). The DEF used is generally automotive grade (CH_4N_2O) which decomposes into ammonia in a decomposition tank placed before the SCR. The ammonia sets off a reduction reaction which selectively reduces NOx to nitrogen molecule (N_2), water and tiny amounts of carbon dioxide (CO_2) [15]. Schematic setup of an SCR system is shown in Fig 1.3 below.

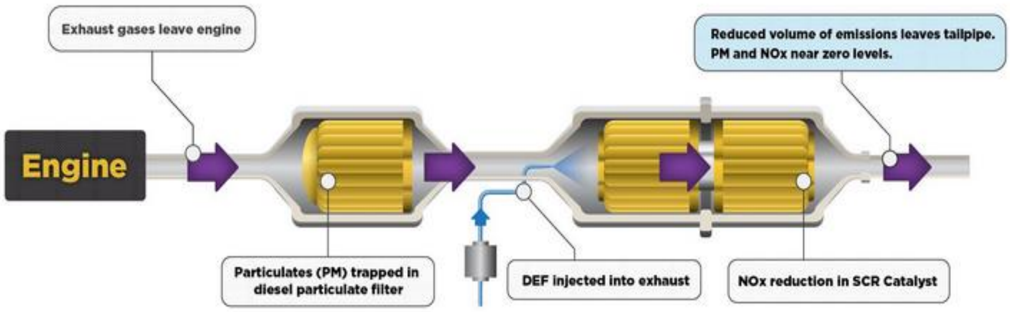

Fig 1.3: Schematics of SCR [15]

The SCR is made up of a ceramic monolithic structure in the shape of an honeycomb structure. Since the ceramic walls have low specific surface area and metal surfaces lack porosity, materials with high porosity and high specific surface area are coated above the wall. This coating is called “washcoat”. Catalyst is coated on to this highly porous washcoat, so that pores carry the catalyst deposits, which provide active sites for reaction as shown in Fig 1.4. Exhaust gas components gets absorbed into the washcoat and they get in contact with the catalyst. Additionally the washcoat prevents undesired reactions between components of a complex catalytic system.

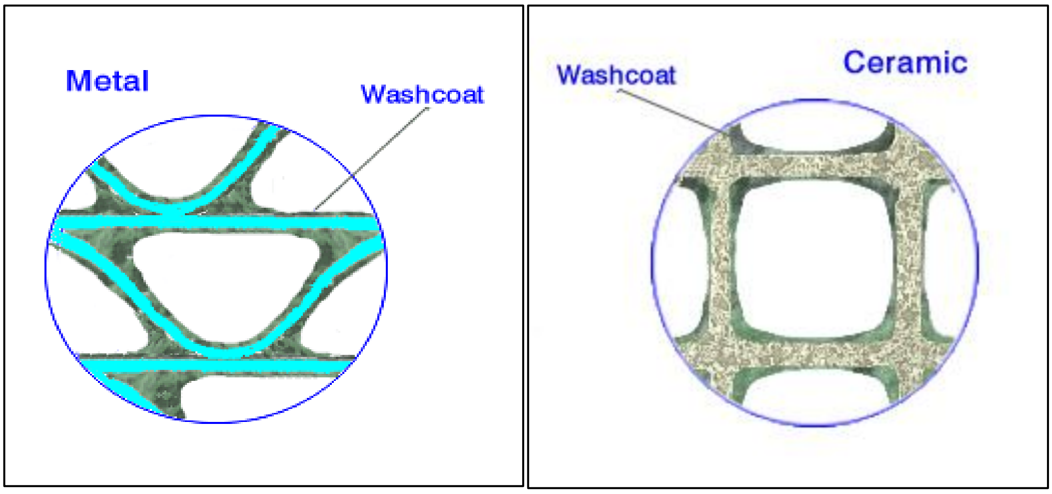

Fig 1.4: Washcoat deposition on substrate [16]

Primary materials used as washcoat are inorganic base metal oxides such as Al_2O_3, SiO_2, TiO_2, CeO_2, ZrO_2, V_2O_5 and zeolites. Washcoat is used as catalyst carrier and some even show catalytic activity of their own [8].

Precious metal catalyst deposits are applied on washcoat directly by impregnation. Impregnation is the process in which the washcoated monolith is exposed to water based catalyst precursors, which is later dried and calcined to get the catalyst monolith. There are two major groups of catalyst, known as Platinum group metals (PGM) and non PGM groups. PGM consist of metals like Platinum (Pl), Palladium (Pd) and Rhodium (Rh). Non PGM groups consist mainly Iron (Fe) and Copper (Cu) [8, 17].

This work deals with the use of an SCR system that has a ceramic monolith structure with a zeolite based washcoat and catalyst used is Copper (Cu).

1.6 Issues and Challenges

Emission from any Internal Combustion engine is a concern for causing air pollution. However, development of techniques which overcome pollution has their own problems.

- Application of aftertreatment system in both automotive and industrial application is fairly new.
- Much research is still going on regarding aftertreatment applications and as such has not reached the peak of its performance
- Application of aftertreatment is fairly new compared to automotive applications and in India, the initiative is being taken for the first time to develop such technology.
- Application of SCR in genset or any automotive engines has to be dealt with high amount of capital cost. Development of such technology is fairly expensive, since it is new in the market.
- SCR catalysts are high maintenance and require sophisticated development to cope with damage and repair costs.
- Installation of SCR induces the problem of ammonia slip, thus introducing NH_3 into the atmosphere. Traditional methods ensured no such gases were produced, and hence is one of the most significant problems.
- Urea injected in SCR breaks down into ammonia through thermolysis and hydrolysis. During these events, production of iso-cyanic acid (HNCO) is possible and itself is very harmful for the environment and also damages the catalyst bed.
- Controller development for SCR model or any other models in such is solely based on the usage of microchips and microprocessors. Although these are newer and far better technology, coming across malfunctions and electrical short-circuiting is fairly common and thus, does not provide the reliability of manual technology

1.7 Objective of present work

- To develop SCR controller module for a genset engine, which has the application of an SCR system along with DOC.
- Modelling of SCR reactions to be integrated into the controller module, that will determine the values of various output signal based on reaction rates.
- Integrating module into ECM calibration and running system to validate SCR functioning.
- Check output data to validate the emission, which is the sole purpose of this development, which is to meet the upcoming CPCB-IV norms.
- Alter gain settings for controller to increase and reduce urea dosing input, to simulate real life situations, where urea pray injector may malfunction.

1.8 Organization of the thesis

Chapter 1	General background of study, history of emission norms of gensets, legislative cycle for testing genset engine emissions, aftertreatment system
Chapter 2	Literature Review and Scope of current work
Chapter 3	Experimental setup , use of test cell and various instruments used , layout of engine and dynamometer, setup of test cycles
Chapter 4	SCR kinematics, requirements for development of SCR system and development of controller module
Chapter 5	Results and discussions after pulling test cycle data
Chapter 6	General conclusion and scope for future work

Chapter 2

LITERATURE REVIEW AND OBJECTIVE

2.1 Literature Survey

The purpose of this thesis is to develop the SCR controller tuning for the engine ECM of a genset engine. Controller tuning should be such that optimum performance is gained in experimental phase of development of calibration. To conduct the experiments, a literature review was done. Based on the key learning, a scope of the work has been identified.

Aderibigbe *et al* [18] performed a study to analyze genset emissions by retrofitting a 15 kVA Diesel Engine Generator (DEG) using Retrofitted Diesel Fuel (RDF) and Pure Diesel Fuel (PDF). Results were analyzed sequentially using simple percentage and graphical methods, which showed that by using retrofitting there was a 71 % reduction in PM, 4 % reduction in NOx emissions and 29 % reduction in fuel consumption. This led to cleaner environment and reduced possibilities of ozone depletion. In this study, the exhaust gases from engine were measured and no emission treatment unit like catalytic convertor or aftertreatment system was used. This study was purely based on the enhancement in the fuel retrofitting and results were compared with baseline pure diesel fuel.

Nishant Tyagi *et al* [19] performed a study for optimization technique of a genset engine to develop from CPCB-I to CPCB-II norms. The experiment was carried out on a 2.86 litre turbocharged engine giving output power of 44 kW @1500 rpm. The experiment used Exhaust Gas Recirculation (EGR) technology combined with change in injection timing and optimized fuel injection pump in a cost effective manner. Also an intercooler was used along with LLR FIP. This experiment showed that using EGR technology, there is a reduction of NOx+HC by 56 % . EGR is basically recirculating part of the exhaust gas into the intake manifold, thus burning unburnt HC along with breaking down larger NOx molecules into nitrogen and water. This also shows that reduction in emissions is possible in engine level only in a cost effective way, as measurement was done in engine out gases only

Brajmohan *et al* [20] conducted a study to assess contribution of emission pollutants from genset engines running in Jamia Millia Islamia University campus . They implemented ISCST3 air dispersion model to simulate air quality for 24 hours average and check ground level SOx, NOx, PM and * hourly average for CO at various locations in campus. Based on the surveys, an inventory was formulated for various gensets of different ratings and their characteristics. The ISCST3 model was based on a steady state Gaussean plume algorithm. Development has been carried out by USEPA for assessing air quality index from point, area and volume sources. Emission rates for different pollutants have been calculated using formulas for gensets on their capacity basis.

Prashant Ghogare *et al* [21] performed a study to develop cost effective techniques for meeting emission norms of genset engine. The development was to meet the emission of CPCB_II norms by implementing techniques on CPCB-I engine. The task was achieved by using EGR technology and intercooler with appropriate injection timing and optimizing fuel pump. Experiment was carried ou in a 3.8 litre turbocharged engine giving power output of 67 kW @1500 rpm. A2000 FIP was used to meet NOx emission norms and EGR is further used to reduce NOx emission and BSFC.

Satashiva Prabhu *et al* [22] performed a review on SCR technology as NOx reduction techniques. The major challenge faced with SCR systems is the reduction of catalytic converter volume at low temperatures, where suitable dosing strategy is required for optimum NH_3 at frequently varying load conditions of the diesel engines. Additionally the risk associated with storing and handling of gaseous ammonia is significant and as a result is not commonly used a reducing agent directly. For this toxic nature of ammonia and handling issues, urea is preferred as a substitute. The best method for this is injecting urea water solution (UWS) in the form of spray to hot exhaust stream before the entry into the catalyst chamber. Urea is environmentally stable chemical which makes it suitable for diesel engine application. Urea is available commercially as fertilizing agents and is available in different grades at lower cost. Urea-SCR over gaseous ammonia SCR gained momentum due to various problems involved with the use of NH_3. Ammonia is corrosive and also a secondary pollutant. In order to introduce ammonia, proper dosing strategies were not established. The main advantage of using an SCR system as means of NOx reduction is De-Nox efficiency (90% or higher). Disadvantages include large volume of SCR system, high capital and operating costs, formation of ammonia deposit as a by-product of SCR working and ammonia slip into atmosphere. Ammonia slip can be avoided by installation of an oxidation catalyst after the SCR. However despite all these drawbacks, SCR system is overall pretty advantageous for reduction of NOx. In order to avoid all the drawbacks, new mixer technologies were introduced, which is basically a decomposition chamber fitted before the SCR to disintegrate urea into ammonia.

Yunhua Zhang *et al* [23] performed studies of an SCR system by reducing the size of catalyst to compare changes in NOx reduction. A combination of DOC,DPF and SCR was used in study , in which, effects of system on CO , HC , NOx and PM outputs from a heavy duty vehicle were evaluated. In addition, influences of ammonia slip catalyst (ASC) coating, SCR catalyst downsizing on NOx conversion efficiency and ammonia slip were investigated. The conclusions from these studies were that installation of an aftertreatment system had negligible effect on fuel consumption of vehicle. Reduction of pollutants were: 97% CO and 67.5% THC in Oxidization catalyst, further an additional fraction was reduced in DPF. PM emissions were reduced by 98% in DPF. The SCR system was effective in reducing NOx emissions but resulted in higher N_2O emission by more than 3 times, meanwhile lead to an average ammonia slip of 3.80 ppm. Downsizing the SCR length by 1/3 could still ensure 91% conversion of NOx and produced less N_2O but also led to increase in ammonia slip by almost 2 times, reaching upto 7.63 ppm. By coating platinum based ASC on the back of SCR, ammonia slip was eliminated.

Börnhorst *et al* [24] studied the challenges faced by urea delivering systems on SCR. The found that efficient NOx removal by urea SCR systems demands a complete renewal of adequately dosed urea to ammonia and its homogenous distribution over the catalyst cross section without degradation of catalyst by formation of solid by-products. Over the last few decades, serious efforts have been made to analyze and understand the chemical processes of mixer in SCR systems, which enable today the development of aftertreatment systems. Detailed knowledge of injections systems were required to enable complete evaporation. One major concern while handling with SCR systems is formation of iso-cyanic acid, which affects catalyst health and is a potential harmful deposit to be dealt with. Gas phase composition as well as droplet evaporation has been handled little in urea SCR related research. Low reactivity of is-cyanic acid reduces conversion of NOx and bears risk of HNCO emissions. Although sophisticated injector designs and system level operations, incomplete evaporation and impingement of droplets need to be accepted and controlled as part of urea conversion process. Based on droplet impingement experiments, new classifications and several models of spray techniques and wall interactions of UWS were developed, which are continuously applied in computational design tools for development of SCR technologies. Recent studies show strong influence of thermal and kinetic parameters on surface properties, particularly roughness, wetability on hydro-dynamic as well as thermal effects during droplet impact and also memory effects and hysteresis are observed. Studies show that existing CFD models with integrated urea decomposition kinetics did not bring about detailed comparison and validation with quantative experimental data on deposit formation, as experiment time was much longer than simulated physical time. Overall, it is observed that several decades of research and development in academics prove that urea based SCR system is state of the art aftertreatment technique for removal of NOx from emissions of IC engines. The challenge of complete NOx removal will remain as long as air is used as oxidizer in combustion systems.

Monorom Rith *et al* [25] conducted a study to emission characteristics of a genset engine with dual producer diesel. The study shows that a biomass downdraft gasifier coupled to a diesel electric generator increases capacity of biomass utilization for production of electric power wit the biomass partially replacing diesel fuel. Three biomass types were used as feedstock for gasifier-genset system to run in producer gas diesel dual fuel mode: Jatropha seeds and Jatropha press cake, and 1:1 ratio of the seeds and press cake on volumetric basis were taken. Constant mass flow rate of 10 kg/h was maintained. Rotational speed of engine was kept constant at 3000 rpm, while load was varied from 0.5 to 2 kW. Press cake derived gaseous fuel was used to replace diesel by 52.7%. Observations were made that poorer emission performance occurred while running on dual fuel mode as compared to diesel mode only. This was due to relation with fuel displacement of air, and the combustion characteristics of producer gas. The electric thermal efficiency was reduced by a factor of 2 in dual fuel modes, as the efficiency at 2 kWh decreased by 10 %.

Rakshith Ramchandra *et al* [26] conducted a study to develop SCR controller strategy for automotive diesel engine application. The experiment focuses on model based feedforward control system for urea dosing function. The SCR model used was a continuously stirred tank reactor, with the main SCR chemical kinetics like ammonia adsorption, desorption, fast SCR, slow SCR reactions and ammonia oxidation. The model is simplified to analyze important dynamics and be quick response at the same time. Two control strategies were implemented, one being a constant ammonia slip condition, and the other being constant feedback ammonia to NOx ratio at outlet of SCR. The catalyst was a vanadium based catalyst, volume was 11.4 litre . Engine used was a 6 cylinder in-line 12.8 litre engine. Observations show that performance of controller was very good compared to flat urea dosing and is successful in achieving higher NOx conversion, less ammonia slip and less urea for injection. Results show that for various ammonia to NOx ratios, NOx conversion were different. For 100 PPM_3 catalyst model, NOx conversion was 27.5 percent higher in 1.4 ANR than flat 1.2 ANR whereas for $100PPM_1$ model, NOx conversion was 22.8 % higher in 1.4 than 1.2 ANR. Ratio controller of ANR does not change NOx conversion. It was observed that increase in NOx conversion using slip control strategy is quite significant.

Schmitt *et al* [27] conducted a study to develop strategies for SCR controller tuning and numeric modelling of SCR. The test was done using a Cooper Bessemer GMV-4 natural gas engine. Test cycle was used as transient cycle, which was used to quantify SCR catalyst response. Variation in space velocity, catalyst temperature, inlet NOx concentration and ammonia to NOx molar feed ratio were made while running test cycles. A numeric model in Simulink was made to analyze SCR transient conditions. The model showed in-catalyst ammonia and NOx concentration as functions of length in multiple directions of exhaust gas flow. Observations also showed 15 minute delay in response time for NOx conversion overall. Ammonia slips occurred 30 minutes before ammonia transition. Modelling showed that the causes for such delays are due to large quantities of ammonia stored in catalysts. Due to this, ammonia waves propagate through the catalyst from front to end and hence emission of these constituent are delayed. This study also made observations on ammonia feed rate control testing to improve NOx emissions. The controls used were feed forward control using a pre ammonia injection ceramic NOx sensor, a feed forward plus feedback control, using same type of sensor. The feed forward controller use ammonia to NOx ratio as control variable and the feedback system used a technique that minimized post catalytic ceramic NOx sensor signal. Ammonia to NOx ratio was stepped every 15 minutes and the algorithm made steps based on decision made by controller by evaluating catalyst response. Feed forward testing showed that lack of pressure compensation on NOx sensors caused errors in feed forward NOx readings and hence sub-optimal ammonia feed. Feedback testing showed that minimization technique was successful if a feedback step of one per fifteen minutes and step size of % ammonia to NOx ratio was implemented.

2.2 Objective and Scope of work

The literature review was done primarily on SCR working techniques, modelling of SCR controller for feed forward and feedback settings and reduction of emissions of NOx for genset engines. The installation of an aftertreatment system in a genset engine is a very new process and manufacturers are mostly in development phase of such techniques. In Cummins, various ratings of gensets are being developed to meet the new emission standards of CPCB-IV norms. This paper deals with the development of a mid range genset engine by production and development of an SCR controller. The controller use both feed forward and feedback controls and development is made to make a urea dosing control, which runs on the feedback loop of the circuit. This not only reduces amount of urea used but also optimizes NOx conversion rate and reduces ammonia slip. The controller is then implemented on the engine ECM and emission test cycles are run to get emission data from engine. The results are then compared to data where no SCR system was installed. This showed the percentage of NOx conversion happening and what are the various factors that controls the rate of NOx conversion. The tests were carried out in a state of the art test cell facilities, and data collected was mostly of emission performance. The emission is checked by installing various sensors at the exit of the turbo exhaust and exit of aftertreatment system to check the emissions produced by the engine itself and the reduction of pollutatants after exhaust gases pass through the aftertreatment systems. Urea water solution is being used in this experiment, as it is the most commercially available product and is already in use in market for automotive applications. The results derived leads to the development of further tuning the calibration of the ECM.

Chapter 3

EXPERIMENTAL SETUP

3.1 Test Cell

The experiments were conducted in a engine test cell. Test cells are necessary for development of engines and components and various manufacturers use it to test and develop their products. Test cells are built in a way that all the necessary devices and components for testing are provided. Typically they include a built in air conditioning system, test bench for placing the engine and components, control circuit for measuring input and output signals and electric lines. Legislative test cycles are fed into the test cell software, which runs the engine according to preferred signals. The engine can also be run manually by controlling the dynamometer attached to the engine. Typical layout of a test cell is shown in Fig 3.1 below.

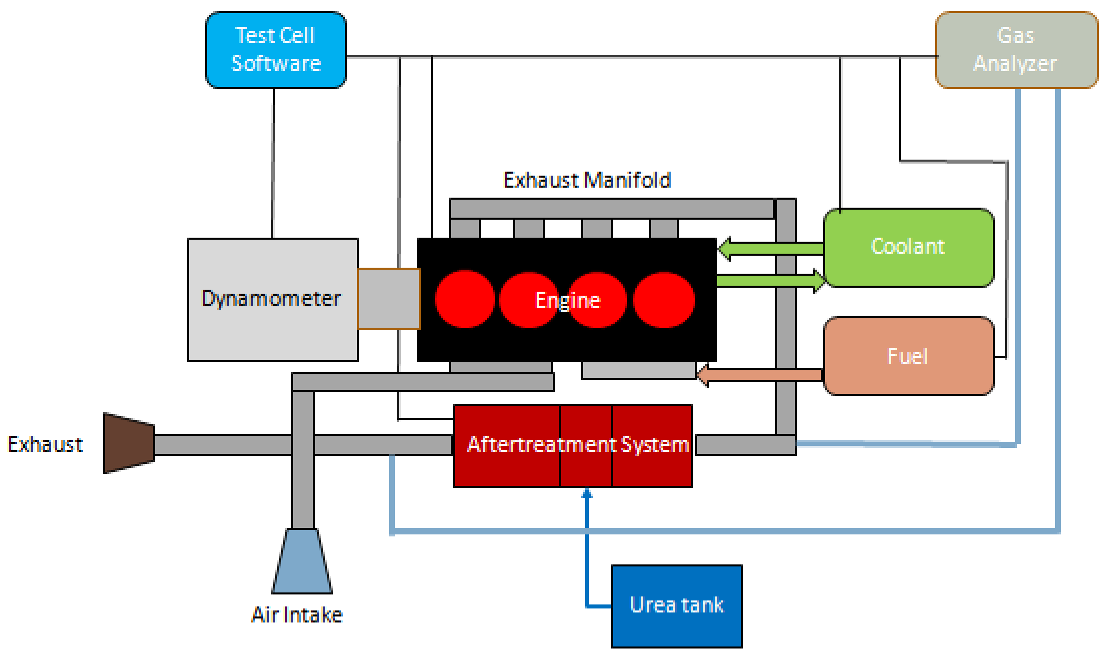

Fig 3.1: Layout of Test Cell

There are different components associated with the use of a test cell. The different purposes of test cell equipments are as follows:

- Dynamometer

  The dynamometer plays an important part in running engine test cells. One of its functions is to run the engine as unlike in automobiles, where a motor starter is used to run the engine, testing facilities do not use that. However the main function of the dyno in test cell is to provide resistive load to the engine as torque input. Dynamometers are of different types, base on its working principle. Engine test cells mainly use brake dynamometer and motoring dynamometer.

- Test cell Software

  Test cell software is a control unit that basically controls the entire working of the cell via input and output signals as shown in Fig 3.2. The computer sends various signals to the system lie input torque, input air temperature etc and reads output signals from engine and other components like feedback torque, which is the actual torque with which the engine is running.

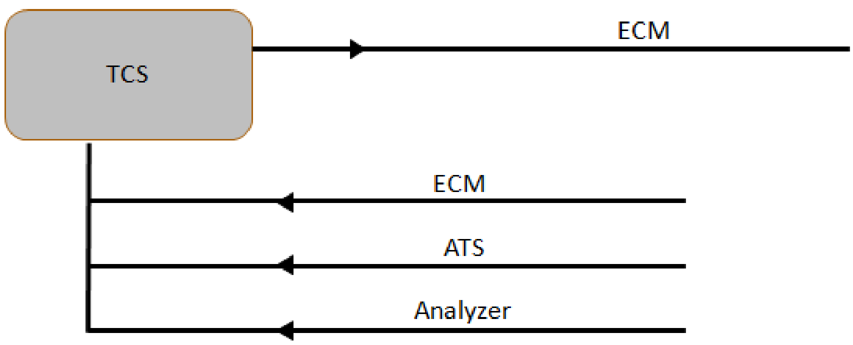

Fig 3.2: Schematic of a TCS working

- Smoke meters

  Smoke meters are used to measure smoke coming out from the engine and aftertreatment system. The working of smoke meters is based on the principle that light is passed through the exhaust gases, and is absorbed into the soot. The concentration of soot is measured from the absorbed light using the Beer-Lambert law of light absorption.

- Gas Analyzers

Gas analyzers are essential for quality control when process involves packaging under protective atmosphere. In continuous gas analysis, an analyzer module is integrated into the gas mixing system. The analyzer the continuously monitors the composition of gas mixtures. Below shows the different principles used in gas analysis:

Table 3.1: Different principles for gas analysis

Principle	Name	Measures	Description
FID	Flame Ionization Detector	Hydrocarbons	A hydrogen helium mixture flame is burning in an electrical field and when sample gases containing hydrocarbons are passed, it gets split and ionized into several fractions, which in turn increase ionic current between anode and cathode of the detector
NDIR	Non Dispersive Infrared Radiation	CO,CO2	An infrared ray is directed through sample chamber towards detector. Gases in chamber causes absorption of specific wavelengths and attenuation of these is measure by detector to measure concentration of gases
CLD	Chemiluminescence Detector	NOx	A sample amount of gas is passed to a reaction chamber. NO2 is produced at excited state, which emits light. This light is measured by a photon counter and the amount of light is directly proportional to the NOx concentration

Gas analyzers are kept at engine out and system out of the whole setup. A number of gas molecules can be measured using gas analyzers, all using different principles. The list of gases measured by gas analyzers are tabulated in table 3.2.

Table 3.2: List of gases and their ranges in gas analyzers

Components	Range		Principle
	Min	Max	
CO	0~50ppm	5000ppm	NDIR
CO_2	0~0.5%	20%	NDIR
O_2	0%	25%	MPA
THC	0~2000ppmc	6000ppmc	H.FID
THC/CH_4	0~2000ppmc	25000ppmc	H.FID
NO_x	0~2000ppm	10000ppm	H.CLD/Calc.NO_2
R-EGR-02H	0~10%	20%	H.NDIR

- FTIR Analyzer

Apart from gas analyzers, Fourier Transform Infrared Radiation (FTIR) analyzers were also used. The advantages of FTIR analyzer is that it can measure a larger group of molecules. FTIR is mainly used for measurement of NOx emission, as it is the most reliable method of measuring. FTIR technology works on the principle that when light is passed through a gas molecule, and the refracted ray is passed through a grit, then different molecules impart different bands of wavelength. This wavelength can be used to determine what molecule it is, when passed through an absorber.

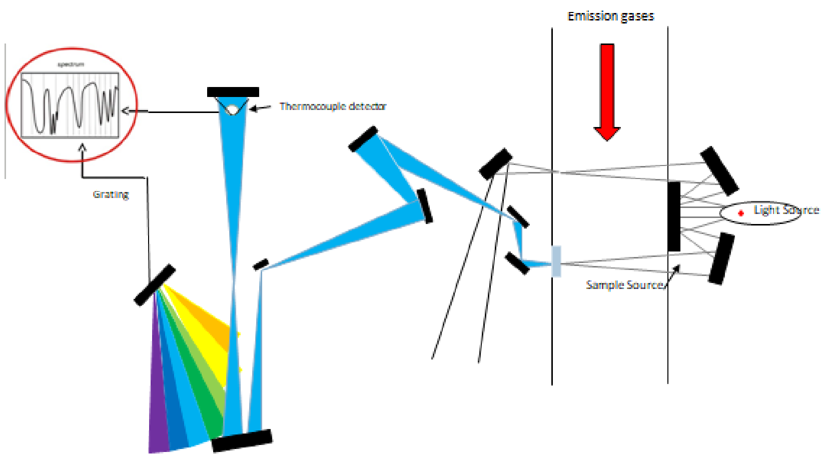

Fig 3.3: FTIR technology used in gas spectroscopy

There is a broad range of research going on in FTIR research itself. Gas chromatography is the basis of such research. This helps in development of gas measuring technologies, which in turn inputs in development in the automotive industry. The range of gas molecules that it can measure is tabulated in table 3.3.

Table 3.3: Range of molecules detected by FTIR

CO2	Carbon dioxide	**C3H6**	Propylene	**C2H5OH**	Ethanol
CO	Carbon monoxide	**C4H6**	1,3 Butadiene	**CH3OH**	Methanol
NO	Nitrogen monoxide	**NC5**	n-Pentane	**HCOOH**	Formic Acid
NO2	Nitrogen dioxide	**IC5**	iso-Pentane	**CH3COOH**	Acetic Acid
NOx	Total Nitrogen oxides	**AHC**	Aromatic-	**C3H8**	Propane
H2O	Water		hydrocarbons	**C7H8**	Toluol
NH3	Ammonia	**NC8**	n-Octane	**C8H10**	p-Xylol
N2O	Nitrous oxide	**HCHO**	Formaldehyde	**TALC**	Sum Alcohols
CH4	Methane	**CH3CHO**	Acetaldehyde	**TCARB**	Sum Carbonyls
HC	Sum Hydrocarbons	**COS**	Carbonyl sulfid	**THC-G**	Total Hydrocarbon
C2H2	Acetylene	**SO2**	Sulfur dioxide		from Gasoline
C2H4	Ethene	**HNCO**	Isocyanic Acid	**THC-D**	Total Hydrocarbon
C2H6	Ethane	**HCN**	Hydrogen Cyanide		from Diesel

Span gas is used for all gas analyzers. The idea is that the refracted wavelength of light is compared to that of the refracted light from a neutral gas. This helps in determining the difference in wavelengths.

In this experiment, the major components that were measured are mainly all N0x molecules. This includes N_2O, NO_2, N_2O_3 and other traces of nitrogen compounds.

3.2 Engine and Dynamometer setup

All the tests were carried out in a Cummins mid range diesel engine. Tests were carried out in a testing facility. The engine used was a mule type engine and has turbocharged aspiration. Air charge is cooled to 25 degC before entering engine. Exhaust piping was adjusted to fit aftertreatment system. The engine is 4 cylinder in-line. Peak torque and power ratings are not disclosed due to confidentiality related to product. Injection System used is a high pressure common rail system. The dynamometer is Scorch build with 225 kW asynchronous drive. The engine and dynamometer is cooled by shop water. Tables 3.4 and 3.5 show the engine and dynamometer specifications.

Table 3.4: Engine Specification

Model	Cummins Mid-range DE
Type	4 stroke
Cylinder	4, in-line
Aspiration	Turbocharged, Charge-cooled
Displacement	4.5 litres
Rated power	Confidential
Peak torque	Confidential
Timing	Variable (Electronic)
Injection system	High Pressure Common rail

Table 3.5: Dynamometer specification

Parameters	Values
Manufacturer	Schorch
Rated Power (kW)	255
Rated Torque (Nm)	1220
Max. Speed (rpm)	1997
Polarity frequency (Hz)	34
Power factor at 34 Hz	0.84

Engine exhaust line was attached to aftertreatment system which was attached to an aftertreatment system comprising of Diesel Oxidation Catalyst (DOC) and Selective Catalyst Reductant (SCR) system in the downpipe as shown in Fig 3.4. For this work , the research focus is mainly on SCR development and not the engine as per say. Engine provides feed gas to the aftetreatment system to work on.

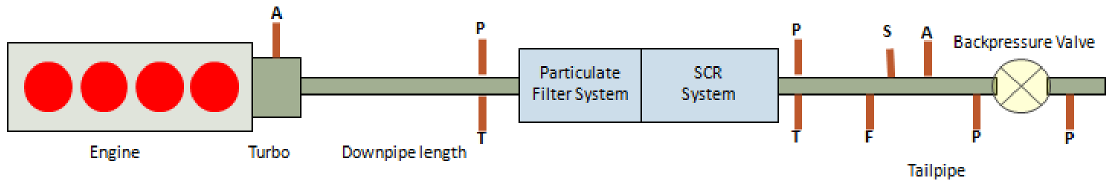

Fig 3.4: Layout of Engine and Aftertreatment system used

For development of this genset engine, no DPF was used as this is a steady speed engine and at 1500 rpm, production of particulate matter is very less. Also engine is non-smokey type engine, which means almost no smoke is produced from engine end.

Chapter 4

SCR CONTROLLER DEVELOPMENT

4.1 SCR Kinematics

Here we discuss about the various working principles and terminology associated with SCR working. The catalyst used was a zeolite based monolithic structure and catalyst used was Copper. Since SCR works in high temperatures, Copper was used as it is not easily damaged and Copper is a better reductant than Platinum group metals, which are mostly oxidization catalysts. Here are some of the chemical kinetics involved in an SCR system.

- Adsorption and desorption of NH_3 onto the surface of the catalytic converter

  The reaction which takes places is as follows

  $$NH3\ (g) + T \longleftrightarrow NH3$$

  T in the equation denotes the free site on catalyst bed where ammonia is adsorbed onto the surface. It is an empty void and is occurred due to other adsorbent atoms not completely surrounding it. The forward reaction is the adsorption event while the reverse is the desorption event. The favourable temperature for this is around 200 degC and the temperature provided by the exhaust gas passing from the DOC is generally above that.

- SCR reactions

  SCR is basically a reactor bed where ammonia is used as a reducing agent to break down NOx into smaller atoms, mainly nitrogen and water molecules. There are three reactions which occur in the SCR, depending on the temperature of the catalyst bed. These are known as slow, fast, and standard reactions.

  The first reaction is the standard reaction, and it around 90% of the conversion occurs here, as most of the NOx particles emitted are NO molecules

  $$4\ NH_3 + 4\ NO + O_2 \rightarrow 4\ N_2 + 6\ H_2O$$

The next reaction that occurs is the fast reaction. The reaction is called so because it happens very rapidly. The DOC changes the concentration of NO_2 as some amount if it is broken down in the DOC itself. The fast reaction is dominant when the NO/NO_2 ratio is close to 1.

$$4\ NH_3 + 2\ NO + 2\ NO_2 \rightarrow 4\ N_2 + 6\ H_2O$$

The last reaction is the slow reaction an is the least dominant. It occurs when almost no NO is left in the catalyst

$$4\ NH_3 + 3\ NO_2 \rightarrow 7/2\ N_2 + 6$$

- Ammonia oxidation reactions

  Ammonia is oxidised into N_2 and water. This reaction is important as it occurs above 300 degC and may also lead to the formation of N_2O molecules, which is undesirable.

$$4\ NH_3 + 3\ O_2 \rightarrow 2\ N_2 + 6\ H_2O$$

$$2\ NH_3 + 2\ O_2 \rightarrow N_2O + 3\ H_2O$$

Other reactions also occur in trace amounts and are not subject to study in this report. The reaction rates of all of these are used to calculate amount of ammonia that is used in catalyst.

Temperature model of SCR is not studied in the present work as development of controller is mainly focused on urea dosing and it is independent of temperature profile of catalyst bed.

4.2 SCR controller development

The first criteria for development of an SCR controller is meeting the requirements laid down by the customer. In this case, it is to meet the emission norms of the CPCB-IV annexure. Hence to develop controller, the primary things which should be know are applicable NOx emission limit, concentration of urea, target NOx conversion and SCR controller model. The process flow is shown in Fig 4.1.

Fig 4.1: Process flow for controller development

There are six basic equations modelled for the development of urea doser controller

The reaction rates for adsorption and desorption are as follows

$$R_{ad}= k_{ad} . C_{NH3} . C_s . (1 - \Theta)$$

$$R_{ds}= k_{ds} . e^{-(E/R.T)} . C_s . \Theta$$

In the above equation, Θ is the surface coverage of catalyst, k is the adsorption and desorption constant, E is the activation energy and R and T is universal gas constant and temperature of bed respectively.

The activation energy is described as follows

$$E = \Delta HNH3.(1 - \alpha.\theta)$$

The rate of standard reaction is as follows

$$R_s= k_s . e^{-(E/R.T)} . C_s . C_{NO} . \Theta$$

The rate of fast reaction is as follows

$$R_f= k_f . e^{-(E/R.T)} . C_s . C_{NO} . C_{NO2} . \Theta$$

Oxidation reaction rate are as same as desorption rate reaction

$$R_{ox}= k_{ox} . e^{-(E/R.T)} . C_s . \Theta$$

Once the reaction rates were modelled, they were implemented onto the controller module, which is made through the help of Simulink.

Here is the basic block diagram of the controller model shown in Fig 4.2 which has been implemented.

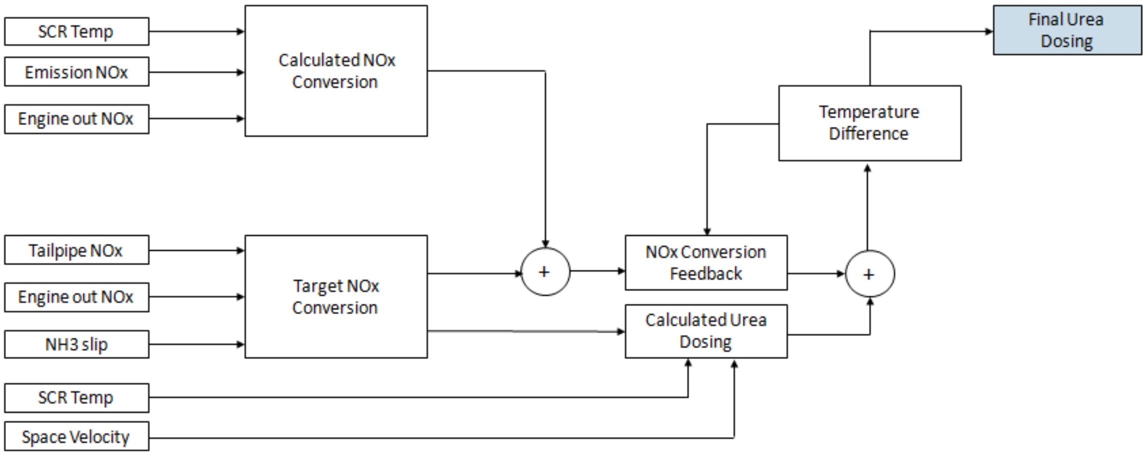

Fig 4.2: Controller model

After the model was made, a selection matrix was made which will be the input of all the parameters responsible for altering the urea dosing system as shown in Fig 4.3. Since it is an active system, both feedback and feed forward loops were added.

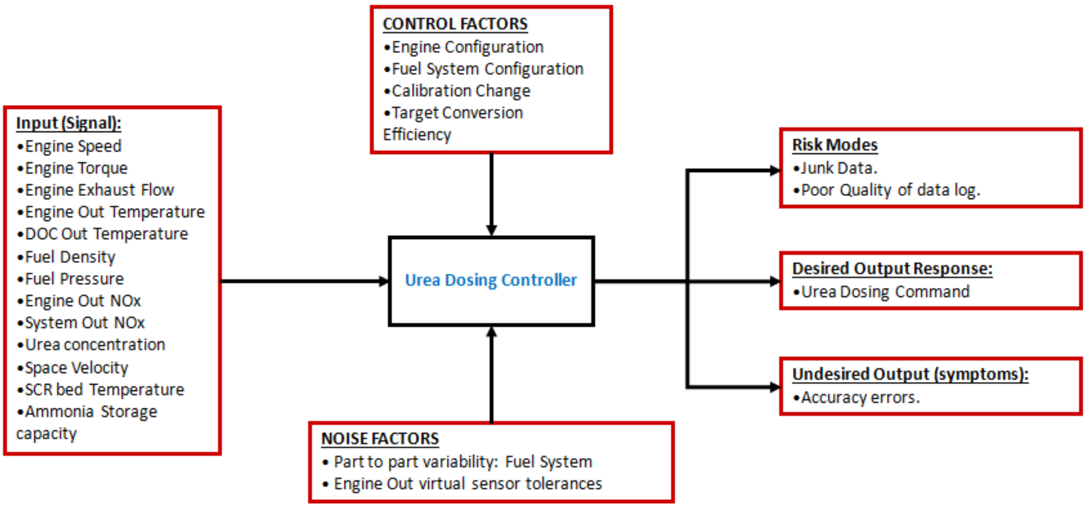

Fig 4.3: P-matrix for input and output signals of controller

4.3 Test cycles

After development of controller, it was installed in the ECM of the engine via a Cummins software, which is connected from a computer to the engine via a P-CAN adapter. After the development of the calibration, test cycles were carried out. Before the actual emission test cycle, some preliminary tests were conducted.

4.3.1. Engine health check

In this process the engine is run at boundary conditions for 15 minutes. This is a standard procedure before running each cycle. The objective of this is to check engine performance.

For air inlet temperature and pressure:

$$f_a = (99/P_s) * (T_a/298)^{0.7}$$

Where T_a is atmospheric temperature 302 K and P_s is dry inlet absolute pressure, which is maintained at 101 kPa.

Exhaust back-pressure is maintained at rated and is not disclosed due to confidential purposes

Fuel inlet temperature is 40 degC average with tolerance of 3 degC on either side.

Results showed that engine showed stable performance on all runs and all output temperature and pressure was matching with baseline data.

4.3.2. Full Throttle Performance (FTP) and Part Throttle Performance (PTP)

Full throttle performance is when an engine is run at 100% rated torque and output is measured. Part throttle performance is when only a percentage of the torque is applied. For example if an engine is rated at 1000 Nm torque, then 10 % PTP of that engine is 100 Nm. PTP cycles are taken because they show the overall mapping of the engine. At each torque load, all input parameters are measured for base mapping of the engine .

PTP cycles also provide data for running custom test cycles like Aftertreatment health check. PTP curve for this engine is shown below.

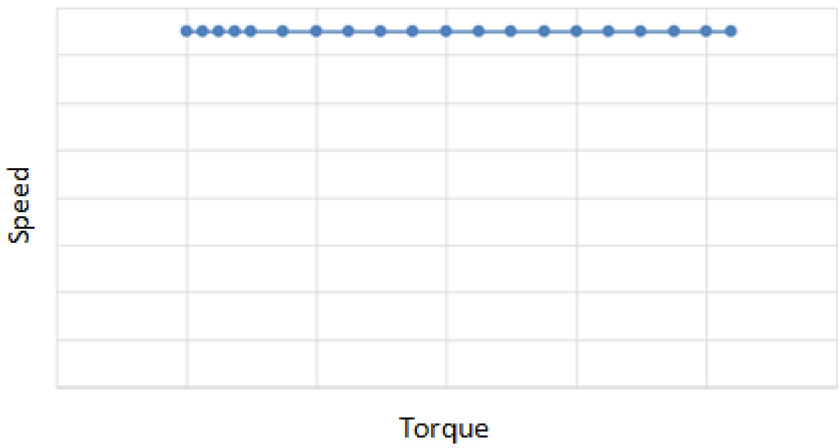

Fig 4.4: PTP for genset engine

In genset engine , speed is always constant. In India, gensets are run at 1500 rpm. This is due to the reason that electricity provide in India is 50 Hz. In a 4 pole generator setting, engine rpm require is hence 1500.

$$\text{Speed} = \frac{(Frequency * 120)}{No\ of\ Poles}$$

Fig 4.5: Empirical formula for Speed setting

4.3.3. SCR Health Check

SCR health check is performed to establish proper functioning of catalyst bed. To do this, a torque point is found where optimum temperature for SCR catalyst working is found. This depends on the size of the SCR. For this instance, temperature was found to be 250 degC. At this point, constant urea is dosed and run for 5 minutes, and after each run, urea dosing is increased. This is to see where NOx conversion is optimum and whether data collected is synonymous with previous runs.

SCR health check data analysis is shown in the next chapter.

4. 5 mode D2 cycle

The legislative cycle for running emissions test on a genset engine is the D2 cycle. It is a constant speed cycle and is established by the government of India ISO-8178. There are 5 modes and each mode is run for 10 minutes. The modes are different torque ratings and weightage of emission responsible.

The test cycle procedure is as follows and is taken from the government of India [4]

- Any other facility that has been approved by these certifying authorities may be used as a test facility. The certification authorities will oversee the testing procedures.
- Test equipment, setup, procedure, calculation method and other relevant technical details to be used shall be as per following standards, except where it is mentioned, specifically, in this document. (a) ISO 8178 – 1 Reciprocating internal combustion engines – Exhaust emission measurement Part –1 : Test bed measurement of gaseous and particulate exhaust emissions (b) ISO 8178 – 3 Reciprocating internal combustion engines – Exhaust emission measurement Part –3 :Definitions & methods of measurement of exhaust gas smoke under steady state conditions. The smoke shall be measured at all specified mode points of the test cycle.
- Engine dynamometers must be used for the testing on the engines. When importing a complete generator set, the engine must be decoupled in order to be tested on an engine dynamometer. The testing must be carried out according to the subsequent 5-mode cycle. Type No. Engine speed% Weighting Factor for Load 100 0.05 rated speed, 75 0.25 rated speed, and 50 0.30 rated speed Rated speed 4 is 25.30, and Rated speed 5 is 10.10Testing shall be done with reference diesel fuel as per the specification. The fuel inlet temperature shall be maintained at 38±5Deg C throughout the test.
- Engine air intake systems for single- and dual-cylinder engines must be checked. All other engines must either use the maximum reported air intake depression or an air intake system during testing.Running in of the engine, for COP, shall be as per clause 7.13 of part II of this document.

- The standard for adjusting dynamometer load and determining specified emission values shall be gross observed power.The declared rated gross power shall be verified and corrected as mentioned below.

  Power Corrections Factors: The coefficient by which the measured power must be multiplied to determine the engine power under the reference atmospheric conditions listed below is referred to as the power correction factor.

  Po = α P

  Where:

  Po is the corrected power (i.e. power under reference atmospheric conditions); α is the correction factor P is the measured power (test power) Reference atmospheric conditions:

  Temperature (T): 298^0K

  Dry pressure (Pso): 99kPa

  Note: The dry pressure is based on a total pressure of 100 kPa and a water vapour pressure of 1kPa.

  Test atmospheric conditions: The atmospheric conditions during the test shall be the following:

  Temperature (T) : Between 283 K and 313 K

  Pressure (P) : Between 80 kPa and 110 kPa

  (The tests may be carried out in air -conditioned tests rooms where the atmospheric conditions may be controlled.)

In the next chapter data collected from cycles has been shown.

Chapter 5

RESULTS AND DISCUSSIONS

Data has been collected and analyzed in MATLAB. Various scripts were made for checking data. Since data collected is part of Cummins proprietary, only normalized data has been shown.

5.1 SCR health check data

In SCR health check, a constant speed and torque has been maintained. The data is collected and the following observations were made as shown in Fig 5.1.

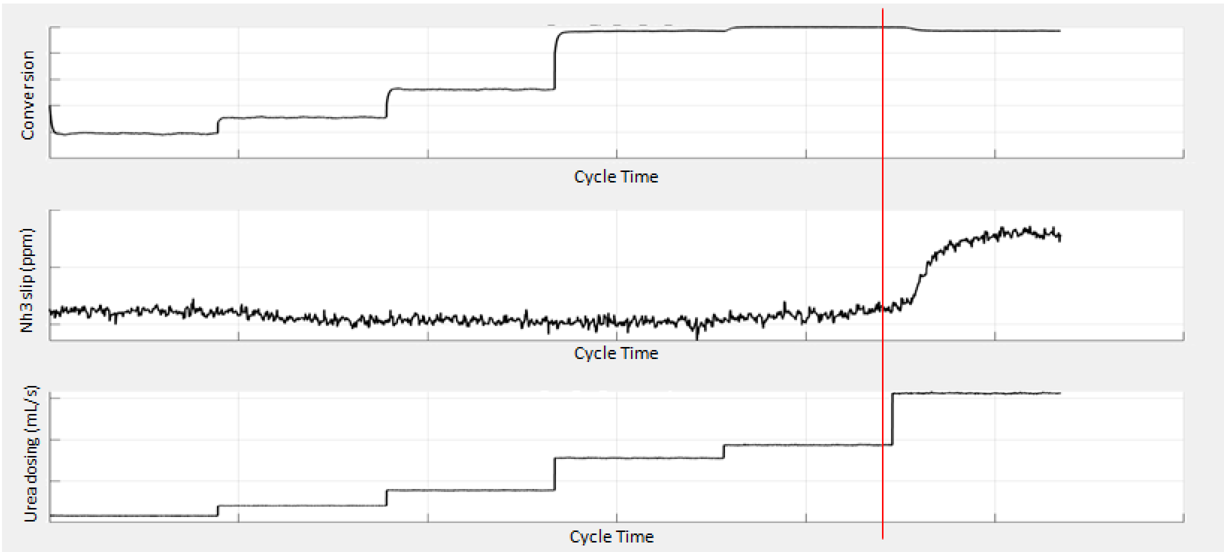

Fig 5.1: SCR health check

We can see that urea is dosed in a constant rate and 6 steps of dosing has occurred. The primary observations were as follows:

- As urea dosing increases, conversion rate increase. Since engine is run at constant speed and torque, engine out NOx emission is constant.
- NH_3 slip gradually decreases as conversion rate increase. This is because at higher performance of controller, ammonia slip occurs less .

- After a certain limit of urea dosing, the NOx conversion decreases. This is shown by the red line. Here it is also observed that ammonia slip increase rapidly during this period.
- This is due to the fact that after optimum ratio of NH_3/NOx is reached, excess dosing of urea leads to overcompensation and as a result excess ammonia is un-reacted and leaves the tailpipe. Also NOx conversion is hampered at this point.

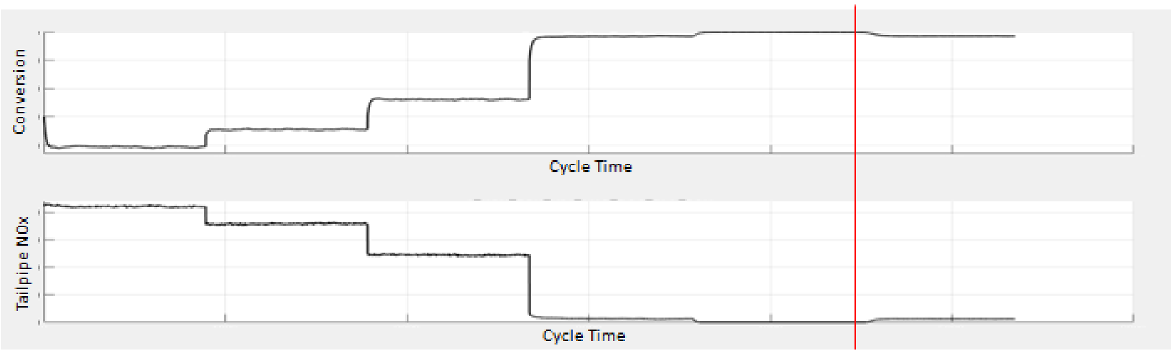

Fig 5.2: Tailpipe NOx

- We can also see the tailpipe NOx behaviour as depicted in Fig 5.2. As urea dosing is increased, NOx conversion increase and tailpipe emission reduces.
- Similarly as above, after a certain period, the tailpipe NOx increase slightly, due to hampering of performance by urea overdosing
- Hence it is concluded that optimum dosing of urea is to be maintained. This occurs when NH_3/NOx is near about 1. Hence overdosing or under dosing both affects performance.

Thus working of an SCR catalyst under constant speed and torque is observed. The temperature of 250 degC is taken since in this particular SCR, it is the optimal working conditions for conversion of NOx. The data also shows in steady state conditions there are no major deviations in emission performance. The only time that occurs is if there is change in boundary conditions or the system is compromised.

5.2 Emission Cycle Data

In the first part of running D2 cycle, an empty can of SCR has been fitted with no catalyst inside. The idea of this experiment was to show how much of NOx is reduced by DOC and simulate a no SCR condition.

The results of NOx emissions without the use of SCR are shown in Fig 5.3 below.

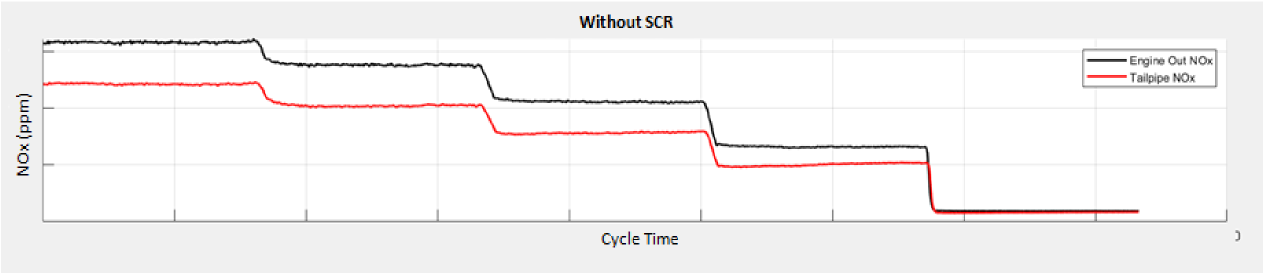

Fig 5.3: NOx emissions without using SCR

Here it is observed that almost 15-20 % of the NOx is converted in DOC, in the absence of an SCR system. The black line represents the NOx emission from the engine and red line is emission observed at tailpipe sensor. The 5 modes of the D2 cycle can be clearly seen in the graph. It is also observed that at 100 % torque rating , the emission of NOx is highest, and lowest at 10 % torque rating. Also almost no conversion takes place in the 5th mode of the cycle as engine out NOx is pretty low.

In comparison to that, when an SCR is attached, the data collected for NOx emissions with SCR is shown in Fig 5.4

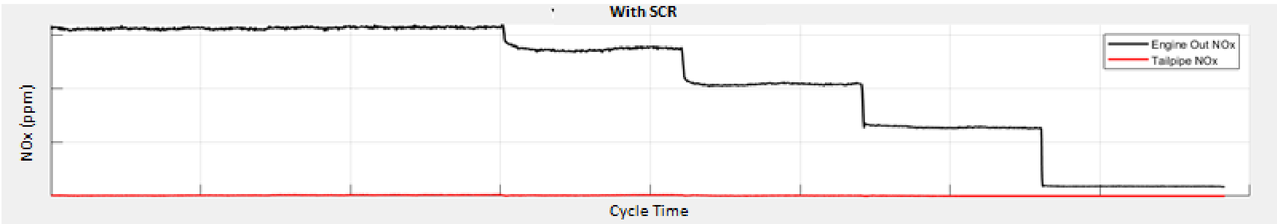

Fig 5.4: NOx emissions with SCR

This is the standard operation of a D2 cycle with SCR system. As observed, application of an SCR vastly changes the emission performance. More than 95 % of the NOx is converted . A closer look at the tailpipe NOx is shown in Fig 5.5

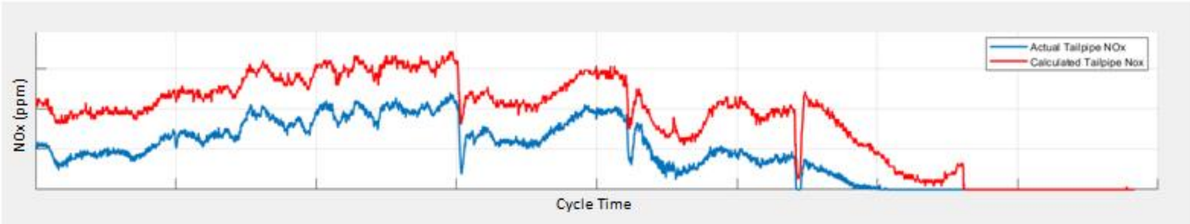

Fig 5.5: Close-up of tailpipe NOx

The data shown in blue line is calculated in the controller with the help of the models implemented on it.

The following observations are made:

- Estimated tailpipe NOx is found to be higher than actual NOx. This shows that controller over predicted the NOx values from engine out. A part of this reason is also due to varying engine performance parameters like changein temperatures etc.
- Although NOx emission is almost same throughout , after the 3rd mode of the cycle, NOx reduces. This is due to change in BSFC and low load conditions.

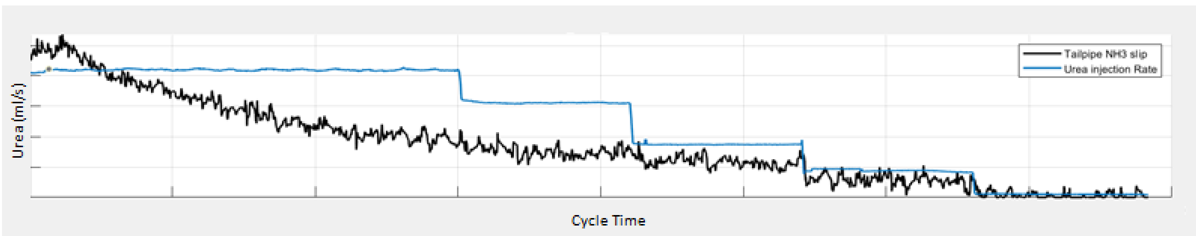

Fig 5.6: Ammonia slip with respect to urea dosing

- Ammonia slip is observed to be higher during the initial mode as shown in Gig 5.6. This is due to catalyst being cold initially.
- Urea dosing is also changing with respect to change in load. Hence we conclude that dosing controller is working independently.

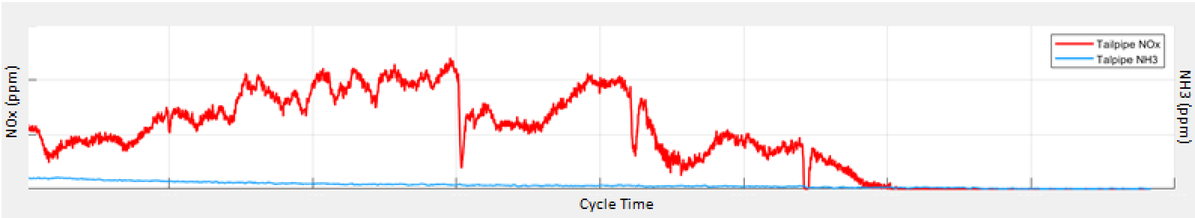

Fig 5.7: Comparison of NOx vs NH_3 slip

- Ammonia slip is much lower than tailpipe NOx. Legislative limit for NOx is 100 ppm and that of urea is 10 ppm for this rating of engine.
- All NOx and NH_3 slip from tailpipes are well below legislative limit as shown in Fig 5.7

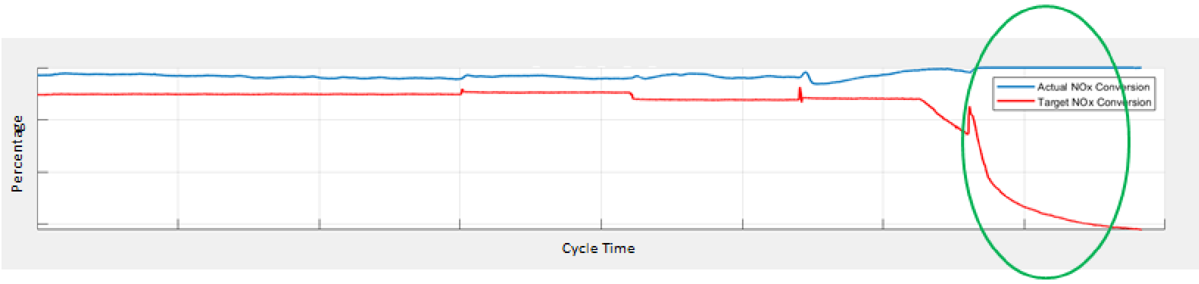

Fig 5.8: Target NOx conversion vs. Actual conversion

- In Fig 5.8, we can see the difference between the predicidted NOx conversion by controller and the actual NOx conversion.
- Controller also over predicted conversion rate. In the last mode we can see that controller shows almost no conversion , while actual conversion increases. This is due to controller reading very low engine out NOx and as a result dosing very less urea.
- In low NOx areas, dosing of low urea gives better conversion

In the next part, we show data collect for change in controller gain. This is done by tampering with the controller such that step size of changing dosing is increased. As a result for every change in step of NOx , injector either under-doses or over-doses. The idea is to simulate real life circumstances where either the ECM or injector doser is malfunctioning and if SCR still can maintain legislative limits of NOx emissions.

5.3 Change in Dosing Gain

The controller for urea doser uses a PID setting. Hence change in gain is done by increasing step size as shown in Fig 5.9. In the first case, we increase dosing gain by 15 % and in the second case we reduce by 15 %.

Case-I: Overdosing

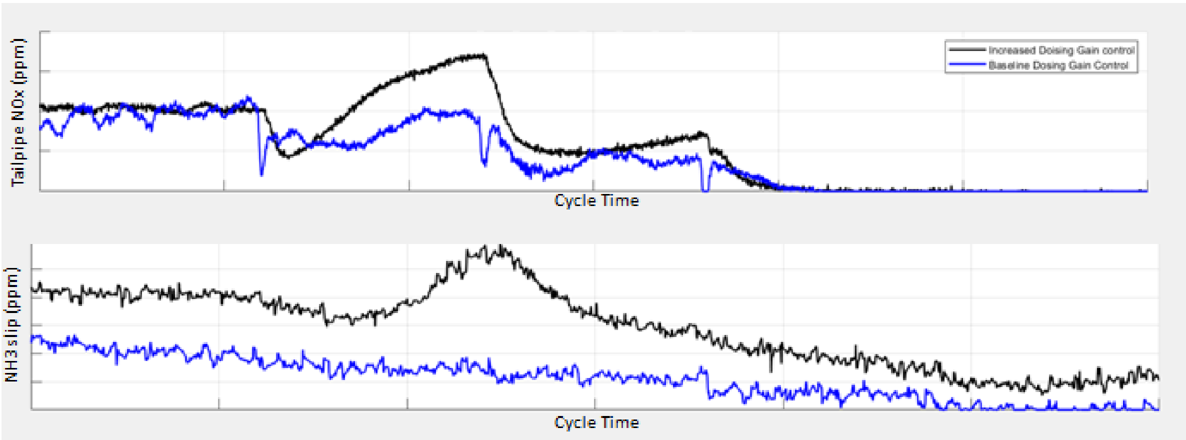

Fig 5.9: Increased Gain control

The data in black line shows the data while change in gain. It is compared to baseline emission data , The following observations were made:

- Tailpipe NOx emission is almost similar, although in mode 3 , it went higher than usual.
- Ammonia slip is almost as twice than baseline data.
- This shows that increasing gain will increase urea dosing.

Case- II: Under-dosing

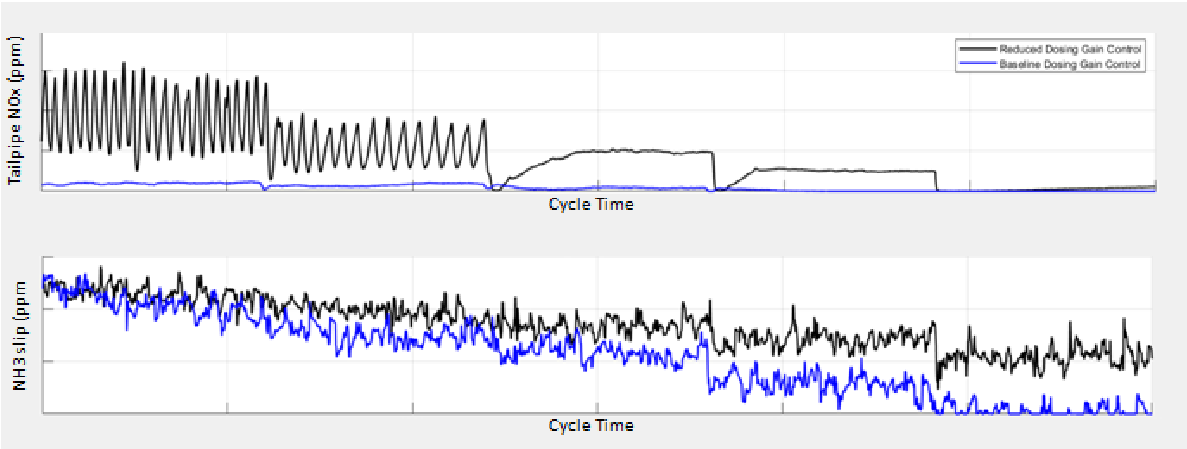

Fig 5.10: Reduced Gain Control

The data in black line shows actual data, compared to baseline data which is in blue as represented in Fig 5.10

- We can see large increase in output NOx as compared to baseline.
- Ammonia slip is almost similar to baseline data.
- This shows that reducing gain also reduces urea dosing and ammonia slip almost remains same.
- In reduced dosing gain, NOx emissions are just below legislative limits in 1st and 2nd modes.

Hence total working of SCR controller is established. This controller was made for research purposes only and was part of internship project for author. The inputs made by making this controller is used in the development of actual product, where many more modules are integrated in SCR controller like temperature model, catalyst health model etc.

Chapter 6

CONCLUSION

6.1 Conclusion and remarks

This thesis discusses SCR catalyst operation, testing, modeling, and controls development. Knowledge of SCR catalyst operation has the potential to improve catalyst performance by improving ammonia feed controls. In addition, NOx emissions from engines can be reduced and ammonia slip minimized. The use of internal combustion engines will continue to enrich human lives, as they have in the past century. Here are the general observations:

- DOC reduces about 15-20 % of NOx even without application of SCR system. The major component that gets broken down here is NO_2 and trace amounts of NO.
- The optimum temperature for working of this particular SCR system is around 250 degC. Here reaction of ammonia with NOx is most effective.
- Application of SCR system reduces NOx on an average of 95 %. Unlike DOC, which maintains a fixed ratio of NOx conversion, SCR gives linear output NOx, no matter what the engine out NOx is.
- Ammonia slip occurs when urea is overdosed. This overdosing generally occurs when NH_3/NOx ratio goes over 1.
- In emission cycle, NOx conversion is almost linear throughout and controller over-predicts output NOx of engine.
- Validation of controller is successful, since urea dosing is actively changed according to controller command.

- This implies the controller is working and implementation or further development of it can be done in original product.

6.2 Future Scope of Work

- The controller can be installed in ECU and field testing can be done to view long term effects of SCR controller. Field data collected from previous generation of gensets show huge difference in performance, especially after a long term of use has occurred. However in India, field data of gensets are not collected as ECM technology in gensets is pretty new
- SCR controller technology can be advanced by adding more modules into the controller.
- Application of this controller module can be installed in automotive application and investigation can be carried out between steady state and transient conditions
- This controller can be used to perform diagnostic work and diagnostic settings can be applied in this module to check if it hampers urea dosing.

Various OEMs will now work on the development of such technology in India, as this is a brand new research is. Such technology has been implemented in the automotive industries for quite some time, but the genset market is quickly adapting to such methods and this will be the future of generators in India.

References

[1] V. Ganesan, (2012) Internal Combustion Engines, McGraw Hill Education (India) Pvt Ltd

[2] Johnson, T. V. (2012). Vehicular emissions in review. *SAE International Journal of Engines*, *5*(2012-01-0368), 216-234.

[3] https://dieselnet.com/standards/in/genset.php accessed on 15th April 2022

[4] "System & Procedure for Compliance to Emission Limit for Genset Application (Up to gross mechanical power 800kWm)", published by Central Pollution Control Board, Ministry of Environment & Forests, Govt. of India

[5] Engel, T., &Ertl, G. (1979). Elementary steps in the catalytic oxidation of carbon monoxide on platinum metals. In *Advances in Catalysis* (Vol. 28, pp. 1-78). Academic Press.

[6] Majewski, W. A., &Khair, M. K. (2006). *Diesel Catalysts, Diesel emissions and their control* (Vol. 303). SAE Technical Paper.

[7] https://eic.rsc.org/feature/the-evolution-of-catalytic-converters/2020252.article accessed on 26th April 2022

[8] https://www.dieselnet.com/tech/cat_mat.php accessed on 15th April 2022.

[9] Stamatellou, A. M., & Stamatelos, A. (2017). Overview of Diesel particulate filter systems sizing approaches. *Applied Thermal Engineering*, *121*, 537-546.

[10] Stratakis, G. A., Konstantas, G. S., & Stamatelos, A. M. (2003). Experimental investigation of the role of soot volatile organic fraction in the regeneration of diesel filters. *Proceedings of the Institution of*

Mechanical Engineers, Part D: Journal of Automobile Engineering, *217*(4), 307-317.

[11] W.A. Majewski, Wall-Flow Monoliths, <www.dieselnet.com>. accessed on April 2016.

[12] Johansen, K., Widd, A., Zuther, F., &Viecenz, H. (2016). *Passive NO 2 Regeneration and NOx Conversion for DPF with an Integrated Vanadium SCR Catalyst* (No. 2016-01-0915). SAE Technical Paper.

[13] Triana, A. P., Johnson, J. H., Yang, S. L., &Baumgard, K. J. (2003). *An experimental and numerical study of the performance characteristics of the diesel oxidation catalyst in a continuously regenerating particulate filter* (No. 2003-01-3176). SAE Technical Paper

[14] Majewski, W. A. (2001). Diesel particulate filters. *DieselNet.< https://www. dieselnet. com/tech/dpf. php*.

[15] Lee, C. (2017). Numerical and experimental investigation of evaporation and mixture uniformity of urea–water solution in selective catalytic reduction system. *Transportation Research Part D: Transport and Environment*. Volume 111, pp 11-13

[16] Mohiuddin, A. & Nurhafez, Muhammad. (2007). Experimental analysis and comparison of performance characteristics of catalytic converters including simulation. 2.

[17] Majewski, W. A., &Khair, M. K. (2006). *Diesel Catalysts*, *Diesel emissions and their control* (Vol. 303). SAE Technical Paper. Pp5-9

[18] Aderibigbe M.A, Wara, S.T, Airoboman A.E. (2017) Diesel Engine Generators Consumption/Emission Controls by Retrofitting for Sustainable Environment. Volume 121, pp-11-12

[19] Tyagi, Nishant & gupta, Shobhit & Bhardwaj, Punit & Gayen, Hirak & Thulasi, Vijayakumar. (2013). Optimization of GENSET engine for CPCB- II norms using cost effective techniques. 12. 10.4271/2013-01-2838.

[20] Brajmohan , Adil Masood, Kafeel Ahmed. (2018) Air Pollution Dispersion Modeling for Diesel Generators at Jamia University Campus, New Delhi, India.

[21] Ghogare Prashant,. Patil S.R, Kajale J.N. (2014) Genset Engine Development to Meet Current Emission Norms" (Conversion from CPCB-I to CPCB-II)

[22] Prabhu S Sadashiva,(2018) A Review on Selective Catalytic Reduction (SCR)-A Promising Technology to mitigate NOx of Modern Automobiles, Volume 13, Number 1 (2018) pp. 5-9

[23] Yunhua Zhang, Diming Lou , Piqiang Tan, Zhiyuan Hu, Liang Fang ,(2022) Effect of SCR downsizing and ammonia slip catalyst coating on the emissions from a heavy-duty diesel engine, Energy Reports,Volume 8

[24] Börnhorst M., Deutschmann O., (2021) Advances and challenges of ammonia delivery by urea-water sprays in SCR systems,Progress in Energy and Combustion Science,Volume 87, pp 54

[25] Monorom Rith, Jose Bienvenido M. Biona , H. W. Gitano–Briggs , Piseth Sok , Jeremias A. Gonzaga , Nechoh Arbon and Archie B. Maglaya (2016) , Performance and Emission Characteristics of the Genset Fuelled with Dual Producer Gas–Diesel

[26] RAMACHANDRA RAKSHITH & RAMESH SUDARSHAN (2014), Master's Thesis in Ammonia Dosing Control Strategy for heavy duty automotive SCR, pp. 11-14

[27] Schmitt Joshua C. (2010), SELECTIVE CATALYTIC REDUCTION: TESTING, NUMERIC MODELING, AND CONTROL STRATEGIES, Volume 18, pp. 13-16