Selective Catalyst Reduction (SCR) using Zeolite for Reduction of NOx Emissions in C.I. Engines

Ayush Dwivedi, Hemraj Chaudhary, Venkateswarlu Chintala and Ashish Karn*

Department of Mechanical Engineering, School of Engineering, University of Petroleum and Energy Studies, PO – Bidholi, Dehradun, 284007 India.

*Email: akarn@ddn.upes.ac.in

ABSTRACT

The current study is aimed for reduction of NOx emission (oxides of nitrogen) from a direct injection CI engine by SCR (selective catalytic reduction) technology. The SCR system was developed originally at the (CAER) Centre for alternate and renewable energy in which zeolite was used as a catalyst. The developed SCR system was integrated with a single chamber direct injection CI engine of 3.7 kW rated power at 1500 rpm. Experimental tests results revealed the significant reduction of NOx emission with SCR system at all engine loads. Experimental design of the investigation typified obtaining standard behaviour of the engine i.e., without SCR followed by engine's information after the presentation of SCR framework. It is investigated from the exploratory tests results that hydrocarbon (HC) emission was highest about 20ppm at 10kg load yet at 4kg load it decreased to 16ppm. Carbon monoxide (CO) emission was moderately increased with SCR system. NOx emission are minimum with SCR at all engine loading conditions as compared to without SCR system. An experimental time study is also done & readings being taken in the time interval of 5 minutes. A difference of 10ppm hydrocarbon emission has been measured in between 15-20 minutes. In the NOx emissions, a difference of 97 ppm has been observed while using the SCR system. Henceforth, the introduction of SCR to the engine minimizes the emissions & enhance the combustion performance along with the benefit of reduction in NOx emissions. After the complete analysis of the data, the outcomes demonstrate a positive impact on the selective catalyst reduction (SCR) system set up with the engine.

Keywords: Carbon monoxide emission, Direct-injection Compression Ignition Engine, hydrocarbons, Oxides of nitrogen, Selective Catalytic Reduction.

INTRODUCTION

The Diesel-powered (CI) engine is a generally acknowledged main player owing to its load-bearing abilities and high fuel transformation efficiency. However, the high levels of (NOx) and PM (particulate matter) emissions emits due to the utilization of diesel in CI engine [1]. The SCR technology has been widely used with diesel powered compression ignition engine in order to maintain the emission level. In the present work, an endeavor has been made to assess the impact of Selective Catalyst Reduction (SCR) on a single chamber compression ignition engine behavior to address the issue of the powerful decrement in these emissions. The essential principle of the SCR system is that before the SCR catalyst, a solution of urea is injected into the exhaust pipe [2]. The catalyst substrate adsorbed the gaseous ammonia which is formed by the injected liquid urea solution, under a suitable temperature and environment [3]. The adsorbed ammonia (NH3) is active and has the efficient ability to respond with NOx species and converts the NOx into (N2) nitrogen and (H2O) water. Various chemical reactions happen in the ammonia SCR framework, as represented by Eq. (1). To Eq. (5).

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (1)$$

$$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O \quad (2)$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \quad (3)$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \quad (4)$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \quad (5)$$

The "ideal" exhaust gas working temperature is for the most part somewhere in the range of 550F and 750F (288C and 399C). The procedure often requires at least 1% abundance oxygen in the pipe gas for the reaction to proceed to completion. The best possible design of the ammonia injection system is critical for complete mixing in the exhaust gas steam. Meanwhile, the adsorbed NH3 can be desorbed from the substrate or oxidized at a high-temperature condition [3]. It is essential to take note of that, if the urea solution is overdosed and the gaseous ammonia is a lot for the reduction responses, the vaporous ammonia would slip into the tailpipe. This vaporous ammonia is both caustic and perilous for human beings. In this way, the tailpipe ammonia slip ought to be obliged and the control of urea injection is of significance for the system of SCR [4].

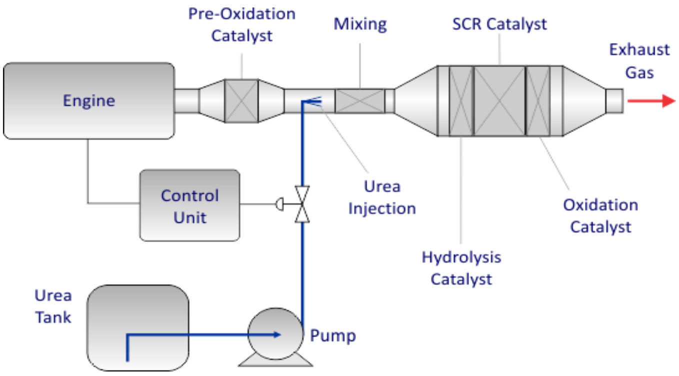

Figure 1. Photographic views of SCR System.

The accompanying factors influence the effectiveness of the SCR procedure:

- The Integration of the SCR unit into the existing exhaust gas system can noticeably affect the general undertaking cost.
- The residence time required for SCR reaction to take place.
- Controlling the permissible ammonia slip.
- The Concentration of SO2/SO3 in the exhaust gas can cause catalyst fouling.
- Early plugging of the catalyst bed with little FCC catalyst particles.

It is well known that to address the problem of NO_x emission the exhaust gas recirculation fitments are commercially accessible. However, the level of EGR is constrained because of its antagonistic consequences for the smoke/PM discharge and engine's performance [5]. Henceforth, in this study the SCR was utilized to target the both improvements, NOx/PM emissions reduction and to improve combustion.

METHODOLOGY

An after-treatment device (SCR) was constituted of a cylindrical substrate coated with thermally treated Zeolite paste [6]. An aqueous solution of Urea decomposes into ammonia gas which has been used for redox catalytic reduction of NOx to nitrogen and water vapor to produce ammonia gas, automotive-grade Diesel exhaust fluid (DEF)/Urea solution was sprayed into the exhaust manifold of the engine using a downdraught nozzle. The Urea solution decomposed into ammonia gas and water vapor facilitating forward reaction with NOx [7]. A comparative assessment of the NOx reduction rate concerning varying concentrations of DEF and reaction temperature was radically implemented [8]. On a single-cylinder D.I. (direct injection) diesel engine, the experimental tests were carried out to achieve BS-VI norms in NOx.
The whole experimentation was done in three phases as represented underneath.

Reactor Fabrication

The Reactor utilized for SCR was manufactured at UPES University, CAER (Center for Alternate Energy Research). The reactor comprises of inlet & outlet passage (reducers) with a cylindrical pipe in between them as shown in "
Figure 2". The material which is used to fabricate the experimental model is galvanized iron & mild steel. The black thermal safe paint was used to paint the cylinder. The right half of the chamber has an exhaust outlet and an inlet on the opposite side. The catalyst was coated on hardened steel mesh and stacked in a steady progression at a specific separation in the channel [9]. When the exhaust gas is being passed through the cylinder where the catalyst is being coated with the substrate, the thermochemical reactions will take place in the appearance of a catalyst.

Figure 2. Reactor fabrication photographic views.

Formulation of Catalyst

Catalyst substrate was picked as mild steel mesh, cutting as a circular shape each to mound then fitted inside the cylinder-shaped catalytic cylinder. A hand press machine was used to cut the mesh cross-sections utilizing a punch-die arranged for the equivalent. The preparation of catalyst paste was finished by mixing demineralized water with zeolite powder and copper sulfate powder (2.5 by weight) as delineated in "
Figure 3". After the arrangement, the catalyst is being coated to the substrate by plunging it into the paste and afterward it is permitted dry for quite a while. The sieve is heated for 2.5 hours at 370o C in the heating furnace and then it allowed to cool down for an hour. The group of zeolite catalysts has been utilized in the application of basic cycle gas turbines for thermal operability benefits yet is once in a while utilized for stationary applications today because of inferior resistance to sulfur species and expensive material [10].
An active business sector use of zeolites is copper-zeolite catalyst utilized in versatile diesel SCR applications for high thermal durability, particularly in situations where the SCR is put downstream of an effectively regenerated DPF (diesel particulate filter) [11].

A slurry mixer of catalyst is formed and applied to the mesh, at that point the substrate is fitted inside the cylinder (pipe) as the particular plan which finishes the arrangement and the experimentation is carried out on the accompanying engine.

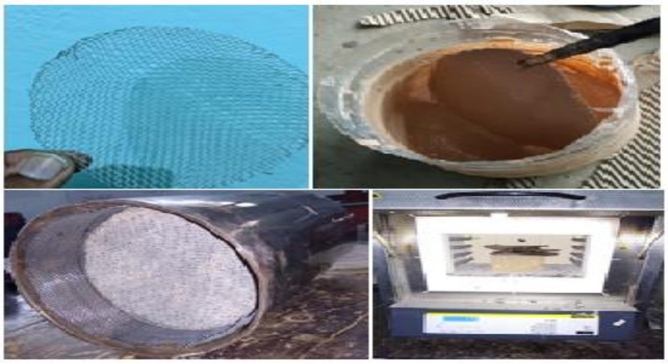

Figure 3. Catalyst formulation photographic views.

ENGINE SPECIFICATION

The SCR system was incorporated with a single chamber compression ignition engine as shown in "
Figure 4". Engine technical specifications are present in "**Error! Reference source not found.**". After completing the arrangement and ensuring for airtight, the engine was operated under idle condition to ensure the system heats up and reliable qualities are acquired through the engine diagnosis programming. When all qualities got become steady, further experimentation has continued. All fuel rate, combustion and discharge readings were taken at the engine load from 4 to 10 kg in the steps of 2 kg.

Table 1. Engine Specification.

Engine type	C.I. Single cylinder engine

Bore	80 mm
Stroke	114 mm
Connecting Rod	211 mm
Compression ratio	16.5:1
Displaced volume	0.53 Liter
Inlet Valve Open	43° Before Top Dead Centre
Exhaust Valve Open	87° Before Bottom Dead Centre
Inlet Valve Close	67° After Top Dead Centre
Exhaust Valve Close	39° After Bottom Dead Centre
Speed	1470 rpm

Figure 4. Experimental test setup of engine.

DISCUSSION AND RESULT

Effect on Engine Performance Characteristics with SCR

The initial parameters has to be maintained as mentioned in “ T” to initialize and properly carried out the experimentation.

Table 2. Initial Parameters Maintained.

Estimated Engine of Combustion Angle	392.22 deg
Max Pressure Crank-Angle	376.11 deg
Max Pressure measured	61.66 bar

Air Flow	22.87 kg/hr
Exhaust Gas Temperature	271.00 degree C
Torque	99.6 Nm
Inlet temperature of Cooling Water	28.58 degree C
Outlet temperature of Cooling Water	42.35 degree C

SFC (Specific fuel consumption) of the Compression ignition diesel engine is 0.23kg/kwh at a heap of 10 kg as mentioned in “

T”. With the increment in load, the in-chamber temperature increases with the mixing getting more extravagant to keep up the engine steady speed rpm [12]. However, the brake thermal efficiency increases with the increment in load. This is a result of the explanation that as the load is increasing, a more-richer fuel mixture is required so as to keep up a steady RPM [13]. Here the brake thermal efficiency at 10 kg load is 36.39 % & the volumetric efficiency is 91.92 % with the specific fuel consumption of 0.23 kg/kwh. The maximum heat release rate per degree is 369.20 J/deg which further converted to a high amount of work output and the maximum heat release rate angle is 369.20 deg. With an increment in load the BMEP (brake mean effective pressure) will increase, as the BMEP is an element of burning temperature. As brake mean effective pressure is 10.31 bar at 10 kg of load. FMEP (Frictional mean effective pressure) stays steady all through the experimentation which is 0.34 bar, as frictional power stays consistent. IMEP (Indicated mean effective pressure) is a hypothetical articulation of frictionless power and equivalents to the total frictional and brake power [14].

Table 3. Calculated Values of the test Engine at Load 10kg.

Brake Power	3.65 kw
Specific Fuel Consumption	0.23 kg/kwh
Brake Thermal Efficiency	36.39 %
Volumetric Efficiency	91.92 %
IMEP	10.65 bar
Fmep	0.34 bar
Bmep	10.31 bar
Indicated Power	7.62 kw
Frictional Power	4.19 kw
Mechanical Efficiency	45.00 %
Max pressure raise rate angle	367.36 deg
Max pressure raise rate	3.02 bar/deg
Max Heat Release Rate Angle	369.20 deg
Max Heat Release Rate	369.20 J/deg

Combustion Duration	49.71 deg

Effect of SCR on Combustion Characteristics

A richer fuel mixture is required to keep up a constant rpm of engine, which will in general increment the chamber pressure [15]. The more the mixture gets richer, higher the temperature will increase with the increment in total heat energy. In-chamber pressure during burning expanded with an expansion in engine load "
Figure 5". As higher load requires higher fuel amounts to keep up a consistent rpm, the maximum pressure accomplished will be lower at lower loads, and higher/more extreme at higher loads. The maximum in-cylinder pressure reaches to 61.66 bar at the crank angle of 376.11 deg. A longer period of time is required to burn the accumulation of higher quantities of fuel, which is why the ignition delay is depicted as between the crank angle of 347.57 deg to 351.25 deg.

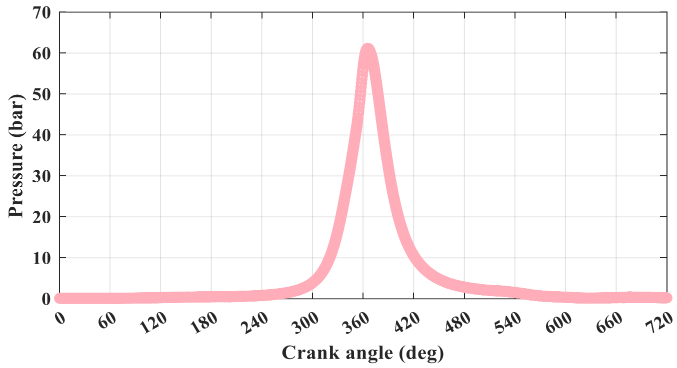

Figure 5. In-cylinder pressure profile with SCR.

The heat release rate with respect to crank angle (degrees) at 10 kg load are illustrates in " Figure 6". It is realized that the peak of heat release expanded with an increment in load. A higher amount of fuel in the chamber add on to ignition delay and a more extreme ascent in heat release toward the beginning of uncontrolled diesel combustion [16]. At 10 kg load, the expansion in the heat release is maximum as it arrives at the most noteworthy exhaust gas temperature.

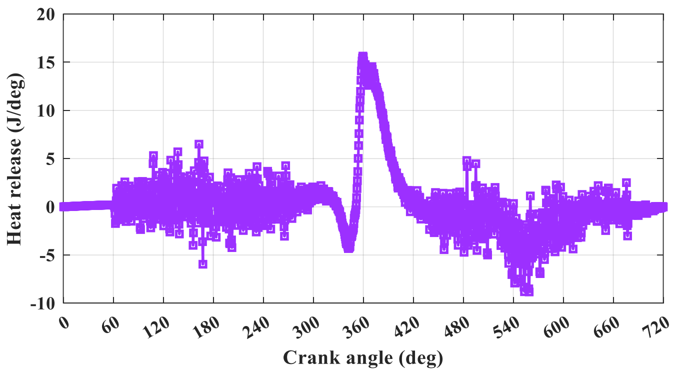

Figure 6. Heat release rate profile with SCR.

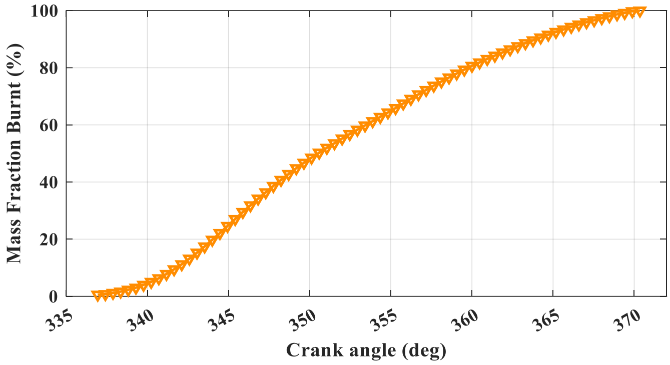

Figure 7. Mass fraction burned variation with SCR.

This mass fraction burnt (MFB) curve is depicted at 10 kg of load, the MFB reaches to 100% at low loads sooner than high loads because at higher loads the accumulation of fuel-air mixture is more [17] "
Figure 7". The flame formation period is (0% to 10% mass-consumed) i.e. from 336.94 deg. to 342.13 deg. crank angle. The bulk mass burned span (10% to almost half burned) from 342.13 deg. to 351.69 deg., and the location of the combustion process with respect to TDC a.k.a combustion phasing (50% mass burned crank angle).

Effect on Engine Emission Characterstics with SCR at varying loads (kg)

Below "
Figure *8*" illustrates the carbon-di-oxide emissions (%Vol) with respect to the various Loads (Kg). The CO2 emissions were measured lowered with the SCR system as compared to without the SCR system at different loads. At load 4 kg the CO2 emission was lowered by (0.8 %Vol) & (0.7 %Vol) at 6 kg to 8 kg load. The difference of 0.4 %Vol is measured at 10 kg load with the scr as compared to without scr system. It shows that the CO2 emissions are also increasing with increasing the load & the difference between the scr & without scr emissions is decreasing.

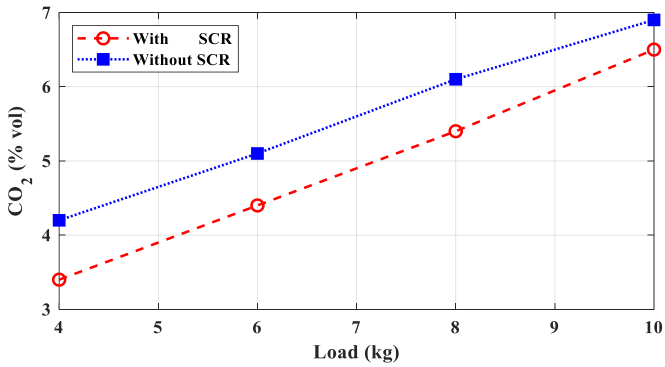

Figure *8*. CO2 emission variation with SCR and without SCR.

The carbon monoxide (CO) emission with SCR is slightly more than without the SCR system. There was a difference of 0.04% measured throughout the different loads while at 6kg it was measured as 0.05kg. At higher loads, the CO emissions are increasing slowly however the difference decreases as shown in "

Figure 9”. Because of the intake charge dilution, and lacking oxygen, the higher emission levels can be seen at lower loads, prompting lower combustion temperature [18].

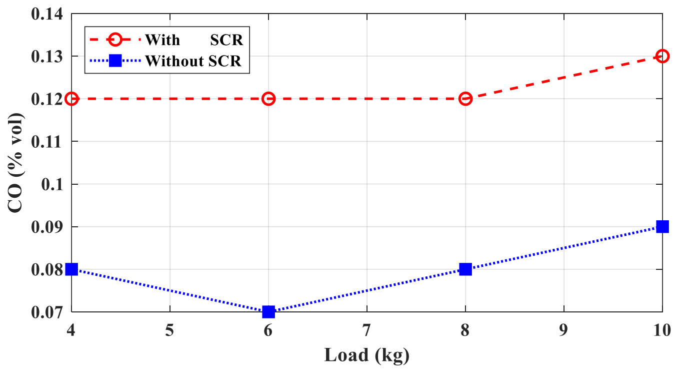

Figure 9. CO emission variation with SCR and without SCR.

Due to the partial combustion of the air-fuel mixture, incomplete combustion occurs which results in the hydrocarbons (HC) emissions [19]. The increased frequency of partial burn cycles turn into misfired cycles [20]. With the SCR system the HC emissions decrease significantly as compared to without SCR system. At lower Load (4kg), the difference between the SCR & without SCR system is low about 1ppm, however, at higher loads, the difference is increasing with respect to Load. It is shown in “

Figure 10" that the HC emissions were decreased by 5ppm at 10kg load with SCR system & keep decreasing at higher loads.

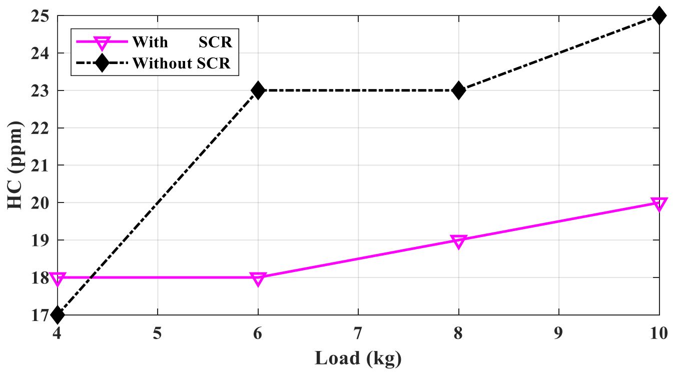

Figure 10. Variation of HC emission with SCR and without SCR.

NO_x emission (oxides of nitrogen) levels with SCR are shown to be lowered as compared to without SCR system. At load 4 kg, 200 ppm NOx emissions were measured with the SCR, almost a difference of 100 ppm NOx emission from without SCR system. It is following the same pattern approximately with the higher loads & it is also shown in graph “

Figure 11”that the NOx emission is increasing with the increment in load. Meanwhile, it is noticeable that a less difference is depicted at 10 kg of load within the SCR line and without SCR line.

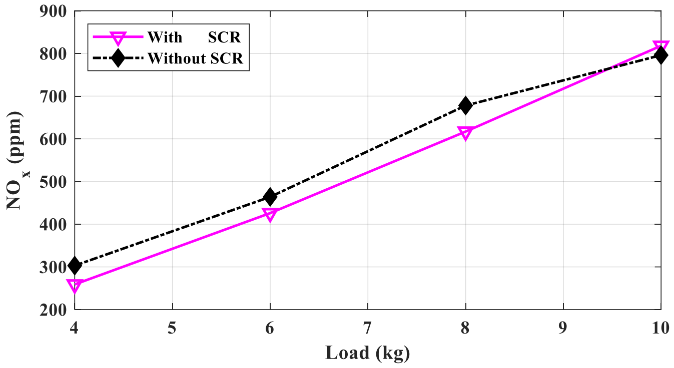

Figure 11. Variation of NOx emission with SCR and without SCR.

Effect on Engine Emission Characteristics with SCR at varying Time (min)

In “
Figure 12”a noticeable difference was shown in CO2 emissions with SCR than without the SCR system concerning the time interval. In the starting phase, the CO2 emissions were (6.3%vol) then slightly increase with the time and again decreases to (6.4%vol) then continues to decrease.

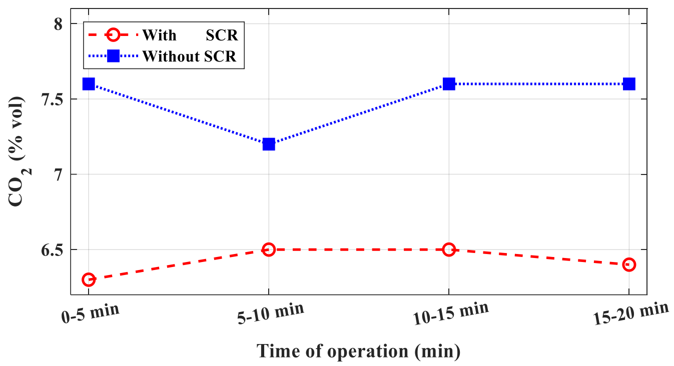

Figure 12. Variation of CO2 emission with SCR and without SCR.

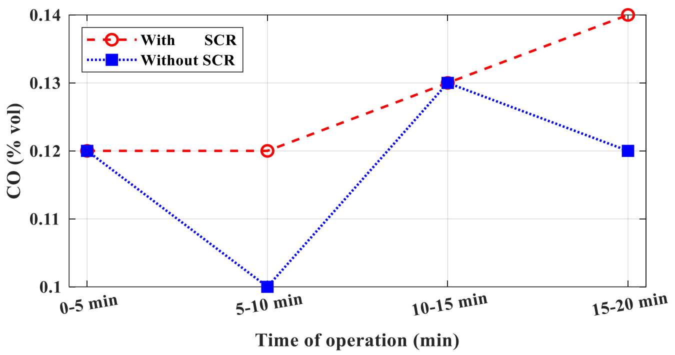

Figure 13. Variation of CO emission with SCR and without SCR.

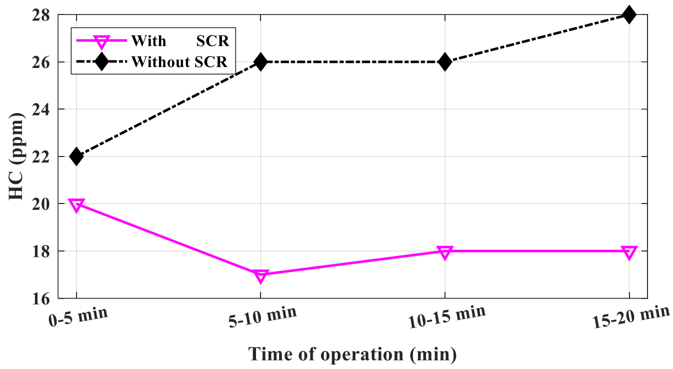

Figure 14. Variation of HC emission with SCR and without SCR

The difference between the NOx emissions with r.p.t. the time interval of SCR system & without SCR system is noticeable as shown below in "
Figure 15". In this graph, the NOx emissions at higher load is shown, in the initial phase of SCR the emissions were 803ppm. After 5 minutes of the interval, the emission was noted as 810 then decrease to 796ppm. The conclusion drawn from this figure is that a difference of 100ppm is maintained between the scr & non-scr system emissions.

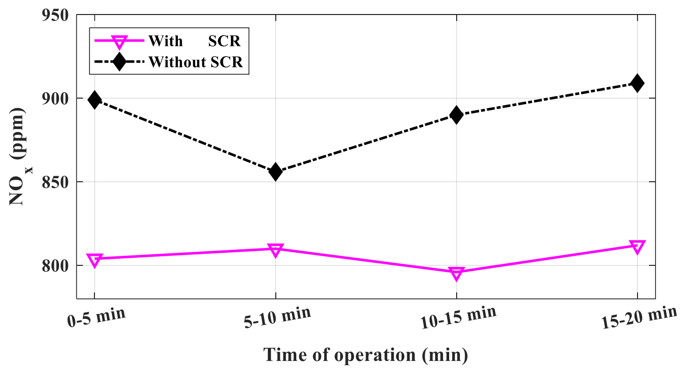

Figure 15. NOx emission variations with SCR and without SCR.

CONCLUSION

On the basis of experimental tests conducted on a single-cylinder C.I. engine with the introduction of the SCR system, the accompanying conclusion was drawn. The brake thermal efficiency was 36.39 % at higher load & the volumetric efficiency was estimated as 91.92 % with the specific fuel consumption of 0.23 kg/kWh at 10 kg of load. The high amount of work output is generating from the maximum heat release rate per degree that is 369.21 J/deg and the maximum heat release rate angle was measured as 369.21 deg. The maximum in-cylinder pressure reaches to 61.66 bar at the crank angle of 376.11 deg. A longer period of time is required to burn the accumulation of higher quantities of fuel, which is why the ignition delay is depicted as between the crank angle of 347.5 deg to 351.2 deg. The CO_2 (%Vol), HC (ppm) & NOx (ppm) emissions were measured lowered with the SCR system. In NOx emissions, the 200 ppm NOx was measured at 4 kg load with SCR, almost a difference of 100 ppm NOx emission from without the SCR system. In the graph of carbon-based emissions with respect to time intervals, initially at lower loads the emissions were higher with SCR, however, they decreased significantly at higher loads.

REFERENCES

1. Mikalsen, R. (2011). Internal combustion and reciprocating engine systems for small and micro combined heat and power (CHP) applications. In *Small and Micro Combined Heat and Power (CHP) Systems* (pp. 125-146). Woodhead Publishing.
2. Schär, C. M., Onder, C. H., Geering, H. P., & Elsener, M. (2003). Control of a urea SCR catalytic converter system for a mobile heavy duty diesel engine. *SAE transactions*, 1180-1188.
3. Lee, K., Ogita, Y., Sato, S., & Kosaka, H. (2015). *NOx Reduction with the HC-SCR System over Cu/Zeolite Based Catalysts* (No. 2015-01-2012). SAE Technical Paper.
4. Sun, K., Ji, F., Yan, X., Jiang, K., & Yang, S. (2018). A particle filter for ammonia coverage ratio and input simultaneous estimations in Diesel-engine SCR system. *PloS one*, *13*(2).
5. De Serio, D., de Oliveira, A., & Sodré, J. R. (2017). Effects of EGR rate on performance and emissions of a diesel power generator fueled by B7. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *39*(6), 1919-1927.
6. Tarabulski, T. J., Knapper, C. J., Peter-Hoblyn, J. D., & Valentine, J. M. (2000). *U.S. Patent No. 6,063,350*. Washington, DC: U.S. Patent and Trademark Office.
7. Yim, S. D., Kim, S. J., Baik, J. H., Nam, I. S., Mok, Y. S., Lee, J. H., ... & Oh, S. H. (2004). Decomposition of Urea into NH3 for the SCR Process. *Industrial & engineering chemistry research*, *43*(16), 4856-4863.
8. Akihama, K., Takatori, Y., Inagaki, K., Sasaki, S., & Dean, A. M. (2001). Mechanism of the smokeless rich diesel combustion by reducing temperature. *Sae Transactions*, 648-662.
9. Parent, Y. O., Caram, H. S., & Coughlin, R. W. (1983). Tube-wall catalytic reactor cooled by an annular heat pipe. *AIChE Journal*, *29*(3), 443-451.
10. Eriksen, V. L. (Ed.). (2017). *Heat Recovery Steam Generator Technology*. Woodhead Publishing.
11. Muthusamy, V., Harkonen, M., Kumar, A., Trigunayat, A., & Rajan, B. (2019). *Thermally Durable Zeolite Based SCR Catalysts for Controlling NOx Emissions in Diesel Exhaust to Meet BS VI Norms* (No. 2019-26-0130). SAE Technical Paper.
12. Singh, A. P., Bajpai, N., & Agarwal, A. K. (2018). Combustion mode switching characteristics of a medium-duty engine operated in compression ignition/PCCI combustion modes. *Journal of Energy Resources Technology*, *140*(9).
13. Reitz, R. D., & Duraisamy, G. (2015). Review of high efficiency and clean reactivity controlled compression ignition (RCCI) combustion in internal combustion engines. *Progress in Energy and Combustion Science*, *46*, 12-71.
14. Gish, R. E., McCullough, J. D., Retzloff, J. B., & Mueller, H. T. (1958). Determination of true engine friction. *SAE transactions*, 649-667.
15. Ceviz, M. A., & Kaymaz, I. (2005). Temperature and air–fuel ratio dependent specific heat ratio functions for lean burned and unburned mixture. *Energy Conversion and Management*, *46*(15-16), 2387-2404.
16. Wong, C. L., & Steere, D. E. (1982). The effects of diesel fuel properties and engine operating conditions on ignition delay. *SAE transactions*, 3873-3892.

17. A. D. Avinash Kumar Agarwal*, "Performance, emissions and combustion characterization of bio-diesel in a generator engine," Indian Institute of Technology Kanpur, Kanpur-208016, India, Kanpur.
18. Kook, S., Bae, C., Miles, P. C., Choi, D., & Pickett, L. M. (2005). The influence of charge dilution and injection timing on low-temperature diesel combustion and emissions. *SAE transactions*, 1575-1595.
19. Wasiu, S. O., Sulaiman, S. A., & Aziz, A. R. A. (2011). An experimental study of different effects of EGR rates on the performance and exhaust emissions of the stratified charge piston direct injection compressed natural gas engine. *Journal of Applied Sciences*, *11*(9), 1479-1490.
20. Maldonado, B. P., & Stefanopoulou, A. G. (2018, November). Non-Equiprobable Statistical Analysis of Misfires and Partial Burns for Cycle-to-Cycle Control of Combustion Variability. In *ASME 2018 Internal Combustion Engine Division Fall Technical Conference*. American Society of Mechanical Engineers Digital Collection.