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Research Article

Experimental Analysis for Nitrogen Oxide Reduction in a Diesel Engine by the Hydrogen-Assisted Selective Catalytic Reduction Technique

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Diesel engine emissions pose a serious threat to the environment and cause inevitable hazards to the atmosphere. The technique that is used to control and combat nitrogen oxide (NO_X) emissions is selective catalytic reduction. However, the various experimental conditions in the SCR technique will reduce NO_X emissions. Former studies experimentally discovered the decrease of NOx discharges at a higher temperature. In this study, a two-cylinder diesel engine with a 34 kW rated power at 3750 rpm under low-temperature operating conditions underwent hydrogen-assisted selective catalytic reduction of NO_x. The experiment was performed by differing the hydrogen injection duration (0–40°CA) and NO_X emissions were studied. Variation in emissions with H_2 injection was investigated. On varying the hydrogen injection duration, NO_X, HC, CO_2, CO, and smoke emissions are reduced (mention the % of reduction) and it can be applied in real time to reduce global warming.

1. Introduction

Nitrogen oxide emissions are significantly rising day by day due to the extensive use of diesel engines. Diesel engines are extensively used in transport due to their low fuel consumption, high durability, and efficiency which increases the emission of NOx in the environment. Though technologies are available to reduce NO_x emissions, the demand for an effective and efficient technology is still persisting [1].

At present, selective catalytic reduction technology is adopted as the best method to reduce NO_x emissions. In the SCR method, reductants such as ammonia, urea, alcohol, and hydrogen are used to reduce NO_x emissions. Especially, in heavy-duty diesel engines, ammonia-assisted selective catalytic reduction techniques are widely used. Ammonia slip, ammonia storage, ash odor, etc., are profane issues that arise during the adoption at lower exhaust temperatures [2].

The urea (reductant) in the urea-SCR system does not undergo reaction at low temperatures; instead, it generates poisonous byproducts such as biurea, cyanide, ammonia, and melamine. Currently, H_2-SCR technology was used, and it was found to be more beneficial than urea-SCR. There are a few literature papers on the H_2-SCR Technology employing different catalysts stated as follows.Resitoglu and Keskin's[3] research demonstrated that H_2 has a positive impact on SCR activity, especially at low temperatures and when no pollutants are formed. The most practical catalysts for H_2-SCR are Pt and Pd-based. In order to selectively catalyse the reduction of NOx by H_2 (H_2-SCR) in the presence of oxygen, Pt/TiO_2 and WO_3-modified Pt/TiO_2 catalysts were studied by Liu et al. in 2016. With the addition of WO_3, the effectiveness of the NOx conversion at low temperatures (100–150°C) increased to up to 90% [4]. Zirconia was used as the primary substrate by [5] in H_2 -SCR systems in place of the readily accessible alumina and silica.

The findings showed that zirconia performed better than alumina and silica in terms of conversion efficiency. To increase efficiency, zirconia is used as a substrate for Pt/WO_3 systems. Resitoglu and Keskin (2015) investigated the effects of various parameters on the activities of the metal ion-exchanged zeolites and discovered that the active selective catalyst for HC-SCR requires some acidity [3].

Zhang et al. [6, 7] investigated the impact of H_2 and CO injection in HC-SCR activity in the presence of 1% Pt/Al_2O_3 catalyst and noted the improvement in the conversion rate at lower temperature by H_2 addition. HC-SCR was superior, although it also decreases the catalyst's activity. As a result, scientists used H_2 as a reductant in SCR technology [2]. Because it produces H_2O and improves NO_x conversion efficiency, an H_2 reductant is sometimes known as a "green reductant." H_2 is a less processed reductant than others and is not poisonous or caustic. Scientists investigating H_2-SCR systems started paying attention to these aspects [3].

Noble metal catalysts are intensively investigated in the H_2-SCR system because they operate more effectively at low temperatures [5]. Li et al. investigated the effectiveness of H_2 on reducing NO_x utilising a Pt catalyst over four distinct substrates: Pt/Al_2O_3, Pt/MgO, Pt/HZSM-5, and Pt/ZrO_2. The property of the substrate affects catalytic efficiency. To support it, Park et al. [5] examined at zirconia-incorporated silica with platinum catalyst support, which showed a considerable improvement in the reduction of NO_x when compared to other substrates like alumina and silica [8].

In addition to Pt catalysts, Sadokhina et al. [9] and Zhang et al. also employed Ag/Al_2O_3 catalysts in the H_2-SCR systems (2007). Theinnoi et al. [4] and Stakheev et al. [10] investigated the reduction of NO_x in an H_2-assisted HC-SCR system employing an alumina-supported silver catalyst, and their results revealed a considerable improvement in the low-temperature range [3].

According to the literature, numerous catalysts have been used in the H_2-SCR system to lower NO_X emissions from diesel engines. The chromium-plated V_2O_5 catalyst has not yet been explored in an H_2-aided SCR system to reduce NO_X emission. Controlling the H_2 infusions helps lower the NOx emissions.

Our research aims to analyse the NOx reduction in a novel internal combustion engine model using hydrogen injection and a V_2O_5 catalyst with chromium plating in the SCR system.

2. Experimental Setup

The equipment used for experimental determinations includes an engine, an analyzer of exhaust gases, and a smoke meter.

2.1. Engine. The experiment was carried out on a four-stroke, turbocharged, and direct-injection diesel engine, and the specifications of the engine are summarized in Table 1.

The modified CI engine is shown in Figure 1 along with a hydrogen injector and a massive SCR structure in the exhaust. The injection was performed as a result of the injector controller's programming to coordinate with engine speed. According to the engine's valve diagram, the injection timing was estimated. Initially, a small delay was added to the entire exhaust time. To calibrate the injection, the compression TDC was used as a reference signal. An air surge tank, which enables for continuous volume, provided air to the engine. A U-tube manometer and a burette with a timer were used to measure the flow rate of the gasoline and air. For loading, the engine was connected to a dynamometer that resembled an alternator. The most used thermocouple, with a range of −270°C to 1260°C, is type K.

Table 1: Engine specifications.

Cooling system	Oil cooled
Displacement	909 cc
Bore	83 mm
Stroke	84 mm
Compression ratio	16.5 : 1
Rated power	33.57 kW @ 3750 rpm
Rated torque	98 Nm @ 1600–3000 rpm
No. of cylinders	2

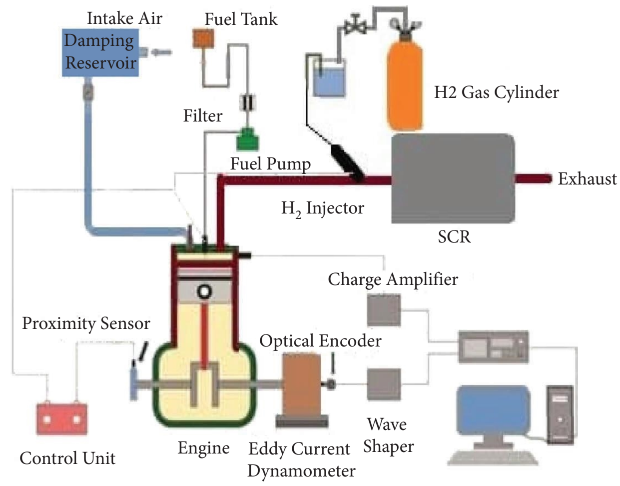

Figure 1: Engine setup with SCR.

2.2. Five Gas Analyzer. The five-gas analyzer is a system for determining the composition of the exhaust waste following a combustion event. This is accomplished by putting a probe, more formally known as a detector, into the engine tailpipe [11].

2.3. Gas Analyzer. A calibrated AVL gas analyzer (DIGAS 444N model, Figure 2) that could assess lambda (λ) and the concentrations of CO, CO_2, O_2, HC, and NOx was used to quantify the exhaust gas emissions. Table 2 displays the AVL gas analyzer's emission measuring range and accuracy.

2.4. Smoke Meter. Smoke meters are used to detect and measure the amount of light blocked in the smoke emitted by diesel engines from cars, trucks, ships, buses, motorcycles, locomotives, and large stacks from industrial operations. A smoke meter is used to determine the smoke density of the

Figure 2: AVL 444N gas analyzer.

Table 2: Emission measurement range of the AVL gas analyzer (DIGAS 444N model).

Emission	Measurement range	Resolution
CO	0–15% vol	0.001% vol
HC	0–20,000 ppm vol	1 ppm/10 ppm (0–2000 ppm)/(>2000 ppm)
CO_2	0–20% vol	0.1% vol
O_2	0–25% vol	0.01% vol
NO_X	0–6000 ppm vol	1 ppm vol

Table 3: AVL smoke meter specification details.

Description	Measurement range	Resolution
Opacity	0–100%	0.1%
Absorption (K value)	0–99.99 m^{-1}	0.01 m^{-1}
Engine speed (RPM)	400–6000 min^{-1}	1 rpm

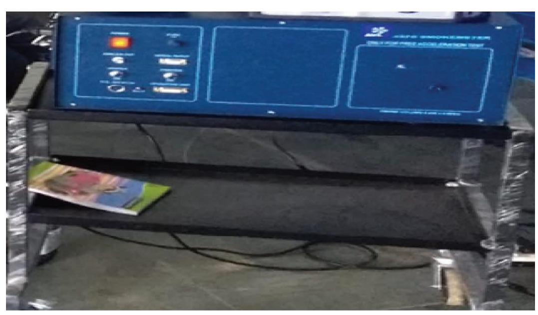

Figure 3: AVL 437C smoke meter.

engine exhaust. The AVL 437C Smoke Meter was used to quantify the exhaust gas emission. Table 3 displays the AVL Smoke Meter (Figure 3) specification details.

2.5. H_2-SCR System. SCR monolith was made up of stainless steel which has four containers out of which two of them were plated with a chromium V_2O_5 catalyst and another two were coated with an ammonia slip catalyst. The catalyst was coated on the honeycomb bed inside the monolith. The reductant (H_2) was injected at an injection pressure of 2 bar through the injector with a 45° inclination angle for better mixing of hydrogen with exhaust gas [10]. To prevent a backfire, a solenoid shut-off valve was used. With the aid of a high-pressure hose, the reductant passes through the flame trap and it was injected by using the hydrogen injector [5].

The hydrogen injector controller precisely quantifies the amount of hydrogen injected. By using the valve timing diagram, the injector time was calculated. Then, the injection duration was calculated based on the operating condition of the engine. The triple injection was performed to get better NO_X reduction. Moreover, the injection duration varies depending on the engine load. It will manipulate and inject according to the engine speed.

3. Result and Discussion

Experiments have been conducted using hydrogen as a reductant to minimize the NO_X emission in a diesel engine by supplying hydrogen through the flashback arrester and flame trap. In addition, a hydrogen leak detector was also used to avoid leakage. The injection durations were 0° CA, 10° CA, 20° CA, 30° CA, and 40° CA. The appropriate quantity of hydrogen needed to convert the NO_X into N_2 and H_2O was determined. The experiments were performed at two different speeds 1800 rpm and 1500 rpm to get better results. Exhaust emission was measured for the concentration of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbon (HC), particulate matter (PM), and oxides of nitrogen (NO_X) by using an emission analyzer and smoke meter.

3.1. Variation of Oxides of Nitrogen Emission with H_2 Injection Duration. Figure 4 infers us that the emission of NOX depends on H_2 injection. The variation of NO_x emission value based on different hydrogen quantities of engine speed is also represented. NOx reduction efficiency indicates a result of load increment and catalyst. At 1800 rpm, 8% NO_x is reduced at 40° CA compared to 10° CA.

On reducing the engine speed to 1500 rpm, 10% NO_x reduction was achieved at 40° CA compared to 10° CA.

When the load is increased the overall fuel-air ratio will increase which in turn increases NO_x formation.

But the obtained experimental results show that there is a 20% NO_x reduction at 100 CA compared to no load. Further on increasing the load, NO_x reduction was greater due to the H_2 injection durations.

Effect of the H_2 and NO feed concentration ratio (H_2/NO ratios) The H_2-SCR activity of the V_2O_5 catalyst at different loads (No load, 10 Nm, 20 Nm, 30 Nm, and 40 Nm) was investigated at a temperature range of 75–230°C, and the results are shown in Figure 5. The four conversion curves indicated the same variation trend, and NO_x decreased by 68.64% at 1500 rpm and 53.62% at 1800 rpm (40 Nm and 40°CA hydrogen injection). Due to the use of V_2O_5 (high-temperature catalyst), the NO conversion rate reached a maximum in higher temperatures. The H_2 concentration influenced the NO conversion in low-temperature conditions. Therefore, H_2-SCR process could appropriately reduce the usage of the reductant to obtain satisfactory treatment efficiency and greatly improve its economic performance in future low-temperatureafter-treatment systems.

3.2. Variation of Hydrocarbon (HC) Emission with Different H_2 Injection Duration. Hydrocarbons are produced generally due to the incomplete combustion of fuels. The obtained experimental result depicts that HC emissions are initially more at 10° CA and decrease slowly when it reaches 40° CA. It is noted that some amount of injected hydrogen is coming out initially as HC which increases in hydrocarbon emissions as well as on increasing the load hydrocarbon emissions are decreased [12].

Figure 6 shows that at 40° CA, the HC emissions reduced to 16% compared to no load. The higher exhaust temperature at higher loads will burn the unburnt hydrocarbons; hence, the emissions are reduced. The variation of HC emission value based on different hydrogen quantities at engine speed is also shown.

The variation of HC emission with load is shown in Figure 6. The HC emission was reduced drastically in high load with the SCR system. The main reason for the reduction in HC emission is that hydrocarbon itself acts as a reduction agent and takes part in NOX reduction. The maximum HC emission reduction was 28.57% at 1500 rpm and 16.18% at 1800 rpm (40 Nm and 40°CA). As the load increases the conversion efficiency of the HC increases due to an increase in combustion temperature. H_2-SCR shows better results in

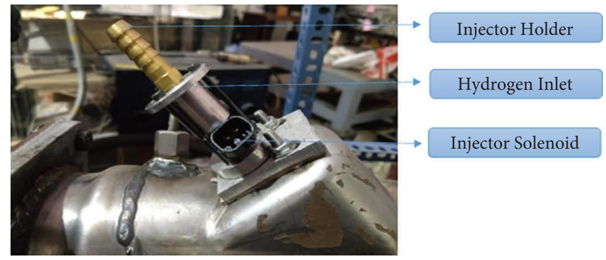

Figure 4: Hydrogen injector with a flame arrester.

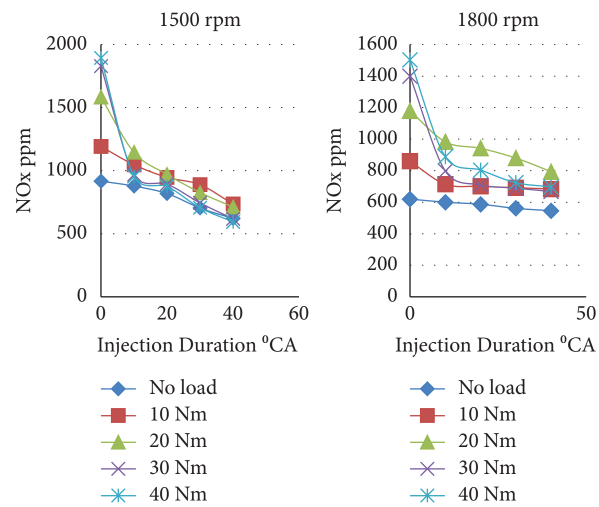

Figure 5: NO_x emission for different H_2 injection of engine speeds of 1800 rpm and 1500 rpm.

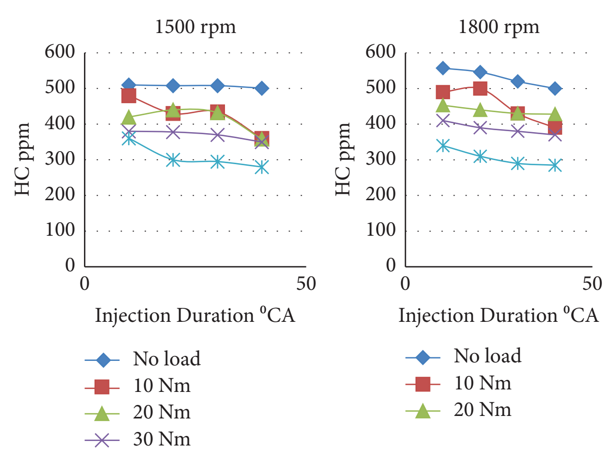

Figure 6: HC emission for different H_2 injection of engine speeds of 1800 rpm and 1500 rpm.

terms of combined HC and NO_X reduction. As H_2 injection duration increases, the utilization of the HC as the reduction agent is increased due to high load conditions and this is evident by a decrease in HC emission with an increase in H_2 injection values.

From all four curves, hydrogen initially increased due to low temperature and it is lowered (45%) while temperature and load increase.

3.3. Variation of Carbon Monoxide and Carbon Dioxide Emission with Different H_2 Injection Duration. CO and CO_2 emission value variation based on engine speed concerning H_2 injection duration using chromium-plated V_2O_5 as shown in Figures 7 and 8. For the no-load condition, the CO emission is more compared to the full-load condition. On increasing the load, the temperature of the exhaust gas increases, which initiates the conversion of CO to CO_2. By escalating the injection duration, CO and CO_2 are reduced at higher rates.

It is observed that as the load increases, the CO_2 emission increases initially. Further on increasing H_2 injection duration, the CO and CO_2 were reduced. While for minimum H_2 injection duration, carbon oxides slightly increase and decrease to the base value. CO_2 emissions decrease substantially with hydrogen addition at all engine speeds. Similar results were observed by the researchers Andre´ Marcelino de Morais, Marco Aure´lio Mendes Justino, Osmano Souza Valente, Se´rgio de MoraisHanriot, and Jose ´ Ricardo Sodre, (International Journal of hydrogen energy, 38, 2013, 6857–6864) when H_2 was used as a reductant in diesel engines. Thus, it confirms us it will be an alternative technology to save the world.

The variation of CO emission at various loads and ANR values is presented in Figure 7. The CO emission is lower than without hydrogen injection in the SCR system and it reduces in the entire load range. HC and CO oxidizes and takes part in NO_X reduction. The CO emission was reduced by 26.67% at 1500 rpm (40 Nm and 40°CA).

Figure 8 shows the variation of CO_2 emission with respect to load. CO_2 emission does not have many changes in different load conditions and variations in the hydrogen durations. There are two reasons for the no major changes in CO_2 emission. One is the lower oxidation of CO and the other one is no impact on hydrogen reductant in the exhaust. But, conventional urea-SCR system decomposition of urea produces some CO_2. This is 15.16% at 1500 rpm (40 Nm and 40°CA) lower than that of the without hydrogen injection in the SCR system.

3.4. Variation of Smoke Emission with Different H_2 Injection Duration. Smoke emission variation with respect to injection duration at different engine speeds using a chromium-plated V_2O_5 catalyst is shown in Figure 9.

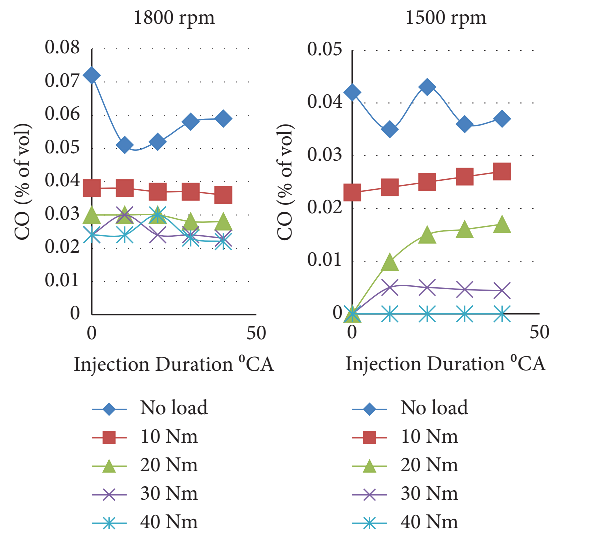

Figure 7: Carbon monoxide emission for different H_2 injection of engine speeds of 1800 rpm and 1500 rpm.

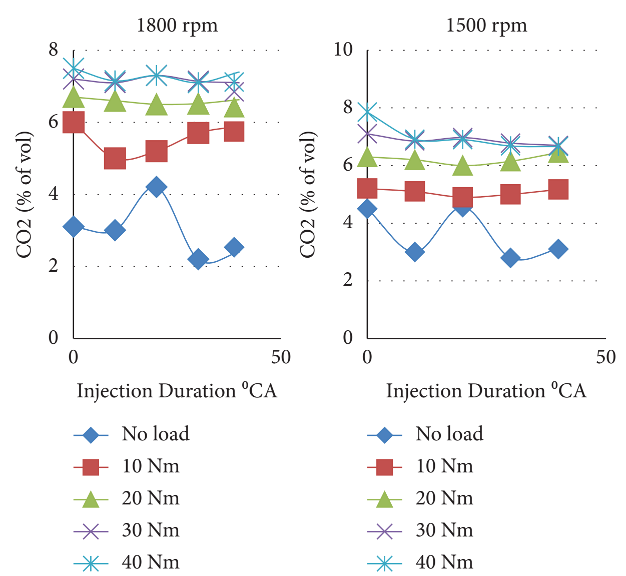

Figure 8: Carbon dioxide for different H_2 injection of engine speeds at 1500 rpm and 1800 rpm.

The obtained result proves the decrease in soot emission values at all engine speeds with hydrogen injection duration.

It is found from results at 40° CA injection duration, NOX and smoke emission were low compared to other injection rates. Similarly, at a 30 Nm load, the smoke level remains a constant value with the increase in injection duration of hydrogen. Better smoke reduction is achieved in high load with an increase in injection duration compared to baseline readings.

The variation of smoke emission at various loads and different hydrogen values is given in Figure 8. The smoke

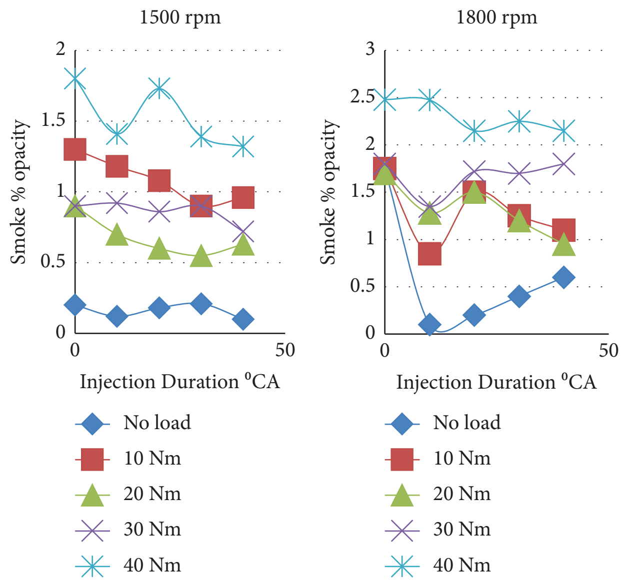

FIGURE 9: Exhaust smoke for different H_2 injection of engine speeds at 1800 rpm and 1500 rpm.

emission from the engine with the H_2-SCR system was reduced by 13.31% at 1800 rpm (40 Nm and 40°CA).

4. Conclusion

An experimental investigation was carried out on a four-stroketwin-cylinder diesel engine using the SCR technique with hydrogen injection in the engine exhaust with along chromium-plated V_2O_5 catalyst. Hydrogen injection has an enhanced efficiency on SCR reactions at low temperatures. From the results studied in this paper, the modified SCR monolith is an essential part of reducing NOx. In conclusion, H_2 is the best reductant for SCR monolith for reducing NO_x without forming any harmful pollutants, H_2 is an effective promoter for reducing NO_x emission in LTC engines, Hybrid catalysts can be used as an effective conversion rate, and also NOx and smoke emission can be reduced simultaneously.

At two different engines, the duration of hydrogen injection was varied (10–40° CA). Experiments were carried out to see how the H_2-SCR system worked with the V2O5 catalyst. The following conclusions are reached from the experimental study: for hydrogen port injection, the best injection pressure and duration were 2 bar with a 40°CA injection duration. In comparison to 0°CA hydrogen injection, NO_x emission was 68.64 percent at 1500 rpm and 53.62 percent at 1800 rpm (40 Nm and 40°CA hydrogen injection). The smoke level variation was lowered by 13.31 percent at 1800 rpm with timed H_2 injection to the exhaust method (40 Nm and 40°CA). Smoke emissions, on the other hand, are observed to be higher than in no-load conditions. At 1500 rpm, the greatest HC emission reduction was 28.57 percent, and at 1800 rpm, it was 16.18 percent (40 Nm and 40°CA). The conversion efficiency of the HC increases as the load increases due to an increase in combustion temperature. Hydrocarbon emissions are significantly reduced as compared to the no-load condition. The amount of CO_2 produced by hydrogen operation is also shown to be lower. When compared to no hydrogen injection, using hydrogen in the timed port injection technique improves efficiency and reduces emissions. In general, H_2-SCR indicates a reduction in emissions in the future once the treatment system is installed.

Abbreviation

SCR:	Selective catalytic reduction
UBHC:	Unburned hydrocarbons
CO:	Carbon monoxide
PM:	Particulate matter
ECU:	Electronic control unit
CO_2:	Carbon dioxide
HC:	Hydrocarbon
EGR:	Exhaust gas recirculation
DEF:	Diesel exhaust fluid
DOC:	Diesel oxidation catalyst
EPA:	Environmental protection agency
SUVs:	Sport utility vehicle
H_2-SCR:	Hydrogen selective catalytic reduction
Pt/TiO_2:	Platinized titanium dioxide
Pt:	Platinum
Pd:	Palladium
WO_3:	Tritungsten oxide
Pt/WO_3:	Platinum over tritungsten oxide
Pt/Al_2O_3:	Platinum over aluminium oxide
V_2O_5:	Vanadium pentoxide.

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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