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A Study on the Effect of Injection Amount on NO_x Emissions in the Selective Catalytic Reduction (SCR) System in a Single Cylinder Diesel Engine

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Abstract

One of the most important exhaust emissions in diesel engines is nitrogen oxides (NO_x). The most effective method for reducing NO_x emissions is Selective Catalytic Reduction (SCR) systems. Although it has been used in light and heavy-duty vehicles in Turkey for about 15 years, it has become used in all diesel motor vehicles including cars as of 2020 due to the changing emission regulations. In the SCR system, nitrogen oxide emissions are reduced to nitrogen and water by injecting of the diesel exhaust fluid (DEF) into the catalytic reactor. In this study, the SCR system was installed in a single-cylinder diesel engine and the DEF injector characteristic was extracted and NO_x conversion efficiency was examined in various injection quantities. The aim of this study was to provide the best NO_x conversion by finding the optimum injection amount and to reduce the accumulation of urea in the system by obtaining minimum DEF consumption. In experimental studies, NO_x conversion was examined according to the DEF consumed in various injection amounts of 40, 80, 160, 240, 320, 400 and 560 mg/s. In order to determine the minimum DEF and maximum NO_x percentage reduction, the reduction % in NO_x emission was proportioned by the DEF injector mass flow rate (mg/s). The highest result was obtained with a value of 0.38 with 40 mg/s injection.

Keywords: Diesel exhaust fluid (DEF); Diesel engine; NO_x emission; SCR

Research Article

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1. Introduction

Nitrogen oxides (NO_x) are air pollutants that have a negative impact on the environment and human health [1]. There are primary measures taken during combustion and secondary measures taken after combustion to reduce NO_x emissions resulting from high combustion temperatures in industrial facilities (such as cement and glass factories) and internal combustion engines used in vehicles. Various methods have been used to reduce harmful exhaust emissions to date. One of them is to carry out chemical reactions in the exhaust gas flow process with catalytic converters after harmful gases are formed [2]. These chemical reactions convert harmful exhaust emissions into acceptable CO_2, N_2 and H_2O [3].

The most effective method applied after combustion is Selective Non-Catalytic Reduction (SCNR), Selective Catalytic Reduction (SCR) or their hybrid systems [4]. These systems are globally recognized and accepted technologies that can reduce NO_x emissions by 90% [5]. In these systems, urea or ammonia solutions are injected into the hot exhaust gas with a special technique. The gases react with the injected solutions and convert NO_x emissions into environmentally friendly nitrogen gas (N_2) and water vapor (H_2O) [6,7].

After the entry into force of the Euro-4 standards, it has become very difficult to ensure that NO_x emissions can only be provided with changes in engine technology [8]. With the entry into force of EURO-5 and EURO-6 standards in 2009 and 2014, it became necessary to improve NO_x emissions in the exhaust line after the engine. SCR has been studied for a long time to reduce NO_x emissions [9].

The SCR catalyst is injected on ammonia or urea to react to NO_x. In addition, it can be injected in CO and H_2 to provide harmless water and nitrogen formation into the exhaust gas. The reduction of NO_x emissions can be achieved with high efficiency (up to 90%). However, although SCR systems have been applied to large vehicles until now due to its cost, difficulty in implementation and control procedures, it has been obliged to apply in all diesel engine vehicles as of 2020 due to emission standards. The urea in Diesel Exhaust Fluid (DEF) (AdBlue) used in SCR systems is also widely used in many industrial activities and especially in agricultural activities.

Due to the installation of the SCR system in passenger cars and the need to purchase DEF at certain times after sales, it creates costs that cannot be accepted by customers. For this reason, alternative choices such as the use of NO_x storage converters are used instead of the SCR system in passenger vehicles. However, efforts to reduce the size and cost for the SCR system to be applied to passenger vehicles are still ongoing [10,11].

1.1 SCR (Selective Catalytic Reduction)

The SCR system was first developed in Japan in the late 1970s. These systems are available in industrial boilers and various power plants such as gas turbines, thus reducing NO_x emissions by 70-95%. In addition, the engines of marine vehicles such as ferries, passenger ships, cargo ships, military ships, tugboats and diesel locomotives are also equipped with the SCR system [12,13].

In the SCR system, the exhaust gas is mixed with ammonia by passing through a special catalyst layer at a temperature of 300-400 °C and NO_x are reduced to N_2 and H_2O [14–16].

Although there is no catalyst cost in SNCR (non -selective catalytic reduction) technology used to reduce NO_x emissions caused by furnaces and boilers, it requires a plus cost due to re -heating of waste gas for the desired high temperature [17].

Storage and transportation of DEF, which is necessary for reducing NO_x emissions, brings extra costs and difficulties. In addition, an extra space in the vehicle is required for the DEF storage.

SCR system is one of the most preferred exhaust emission reduction methods today, due to its advantages such as working at low temperatures and obtaining high efficiency. SCR technology has been successfully used in the reduction of emissions in power plants, marine vehicles, locomotives and stationary diesel engines since 1980 [18,19].

Through SCR technology, nitrogen oxide (NO_x) gases, which are harmful to the atmosphere and life, react with the urea solution and are converted into harmless water (H_2O) and nitrogen (N_2). The reason why the system is called "selective" is that the catalytic reduction reaction of NO_x gas with reducing agents such as ammonia and urea occurs more preferentially than the reaction of reducing agents with oxygen [20]. The working principle of the SCR system and the reactions that take place are shown in Fig. 1.

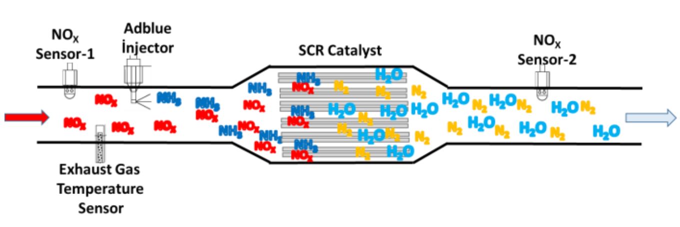

Fig. 1. SCR system working principle diagram.

In the SCR process, when DEF injected into the exhaust gas by injector which is positioned on front of the SCR catalyst urea decomposes into ammonia (NH_3) and isocyanic acid (HNCO) as seen in equation (1) with the effect of high temperature [16,21]

$$CO(NH_2)_2 + heat \rightarrow NH_3 + HNCO \quad (1)$$

After this reaction, isocyanic acid is hydrolyzed as ammonia and carbon dioxide with the reaction in equation (2).

$$HNCO + H_2O \rightarrow NH_3 + CO_2 \quad (2)$$

The ammonia (NH_3) obtained after these reactions reacts with nitrogen oxide emissions in the catalyst. NO_x emissions are reduced to harmless nitrogen (N_2), water (H_2O) and less harmful N_2O. SCR reactions (equation 3-6) to reduce NO_x emissions are shown below [22].

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

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

$$8NH_3 + 6NO_2 \rightarrow 7N_2 + 6H_2O \quad (5)$$

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

Through this technology, NO_x emissions in the exhaust gases can be reduced by 90%, HC and CO emissions by 50-90% and particulate matter (PM) emissions by 30-50%. These rates are further increased by combining the system with systems such as the Diesel Particulate Filter (DPF) and Exhaust Gas Recirculation (EGR) [23].

The efficient and regular operation of the SCR system in diesel engines depends on some parameters. These are the type of catalyst, the surface area of the catalyst in contact with the exhaust gases, the residence time of the exhaust gases in the reactor, the amount of injected urea solution, the injection timing, the mixing degree of ammonia and exhaust gases, the sulfur content of the fuel used in the engine, the amount of dust in the exhaust gases [24].

The aim of this study is to examine the effect of injection amount, which affects SCR efficiency and operation, on NO_x emissions.

2. Material and Method

In this study, SCR system setup was installed on a single-cylinder diesel engine. The experimental setup is shown in Fig. 2. In the experimental setup, the analog signals coming from the sensors were converted into digital signals with the National Instrument USB-4716 data acquisition card and the data were recorded on the computer. Exhaust pressure was not measured during experiments.

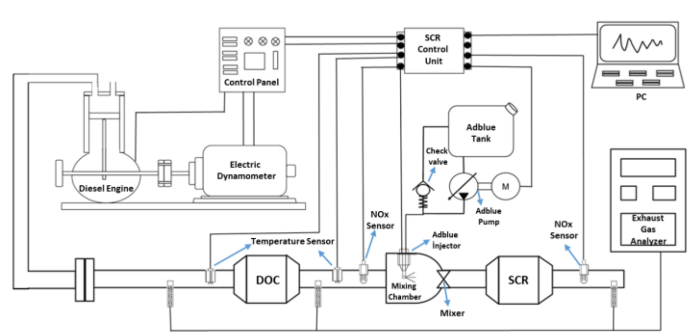

Fig. 2. Schematic view of the experimental setup.

The experiments were carried on Antor 3LD 510 naturally aspirated, single-cylinder direct injection diesel engine. This engine is used in many agricultural practices from anchor machines to motopomps in Turkey. The technical properties of the test engine are shown in Table 1.

Table 1. Technical properties of the test engine [25].

Model	Antor 3LD 510
Engine type	Four-stroke, air-cooled, direct-injection diesel engine
Number of cylinders	1
Displacement (cm^3)	510
Bore (mm) x Stroke (mm)	85 x 90
Compression ratio	17.5:1
Max. speed (rpm)	3000
Max. power (kW)	6.6@3000 rpm
Max. torque (Nm)	32.8 @1800 rpm
Type of cooling	Air-cooled

The engine was loaded by electric dynamo at 2800 rpm. When the temperature measured by the exhaust gas temperature sensor reaches the desired value, the load adjustment of the engine was fixed. Air and fuel consumptions were not measured during experiments. In this study, the experiments were carried out in the temperature range of 320-325 °C. NiCr-Ni type-K Elimko brand thermocouple was used because the exhaust gas temperature measurement was desired to be precise. Exhaust emission measurements were carried with the Bosch BEA060 exhaust gas analyzer. The technical properties of the exhaust emission measuring device are shown in Table 2.

Table 2. Emission measuring device technical properties [26]

Parameters	Measuring range	Resolution
NO (ppm by volume)	0 - 5000	1
CO (% by volume)	0 - 10	0.001
CO_2 (% by volume)	0 - 18	0.01
HC (ppm by volume)	0 - 9999	1
O_2 (% by volume)	0 - 22	0.01
Lambda	0.5 – 9.999	0.001

In the experimental study, a SCR catalyst with a density of 400 cpsi, V_2O_5-WO_3/TiO_2, was used. There was also a standard DOC catalyst made of ceramic material before the SCR catalyst. As a DEF, a nature-compatible water-based urea solution produced in accordance with ISO 22241 standard was used.

Bosch second generation (deNO$_x$ 2.2) DEF injector (Fig. 3) was used in the SCR system to inject the DEF into the exhaust gas.

Fig. 3. Diesel Exhaust Fluid (DEF) injector

It is a solenoid (electro valve) type injector that can be controlled electronically instantaneously, has a very fast opening and closing feature and can be injected gradually. DEF pressurized by the pump is pressurized in the injector and injection is performed when the signal is sent. It can inject from three holes with pressure. The technical properties of the DEF injector are given in Table 3

Table 3. Technical properties of the DEF injector [27,28].

Properties	Value
Dosing Quantity (min.-max.)	36-7,200 g/h @ 9 bar optional 60-12,000 g/h (available in 2013)
Service Life	up to 35,000 hours
Maximum Ambient Temperature	180 °C
Operating Pressure	9 bar
Spray Quality	75 µm SMD (Sauter Mean Diameter)
DEF Inlet Temperature	90 °C
Supply Voltage	12 V
Emission Target	JPNLT, US13, Euro VI, Tier 4 final/Euro Stage 4

3. Results

3.1 Determination the DEF injector injection characteristics

The DEF injector was controlled by a special LabVIEW-based software developed for this study. In order to determine the amount of liquid injected at certain opening durations of the injector, the injection characteristic was extracted.

With the injector opening durations varied between 7-200 ms/s, DEF injected into a beaker, as a result of a 1-minute injector operation, in other words, 60 injections, was measured by a precise balance

SF-400C Plus digital precision balance (with 500 g load and 0,01 g precision) was used for weight measurements. The average of three repetitive measurement was taken. In cases where the difference between the minimum and maximum values of the three repetitive measurements in each step was above 0,08 g, the measurements were repeated. When the difference between the minimum and maximum value was met the criteria, measurement of the next opening duration result was started.

Figure 4 shows the injector control signals used for the time the 100 ms injector remains open in a single injection per second.

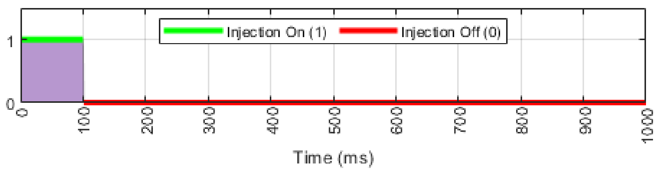

Fig. 4. Example injector control signal.

Injection durations are defined in the LabVIEW block diagram interface is shown Fig. 5. It is shown that the definition of a one-minute injection, with the injector on for 100 ms and off 900 ms in one second (one injection per second) and repeating this process 60 times.

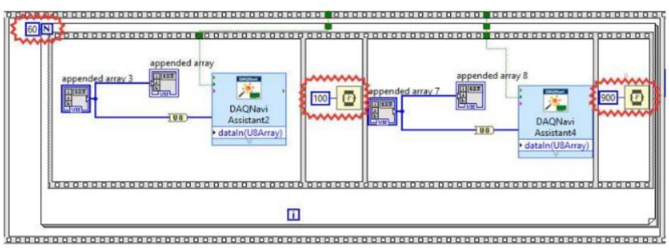

Fig. 5. Definition of injection duration from the LabVIEW block diagram interface

The injector does not inject below 7 ms at the line pressure of approximately 4 bar. Since there was no injection below the specified period, no measurement was performed.

With LabVIEW control software, injector control can be done only in integer values in milliseconds (ms). Control with decimal values in milliseconds is not possible. It had been determined that an average of 0.066667-gram liquid injection (1.11 mg of liquid per second) was injected as a result of 60 seconds (60 injections) measurement with one injection per second in 7 ms which was the minimum injector opening duration.

In each measurement step, the average of three measurements that met the appropriate deviation condition was used in linear regression. The DEF injector mass flow rate was calculated with the mean values of the measurements of an injection with one pulse per second at the end of the total one-minute injector working time.

Fig. 6 shows the variation of the DEF injector mass flow rate depending on the 18 different injector opening durations (which varied between 7-200 ms/s) and the values as a result of linear regression.

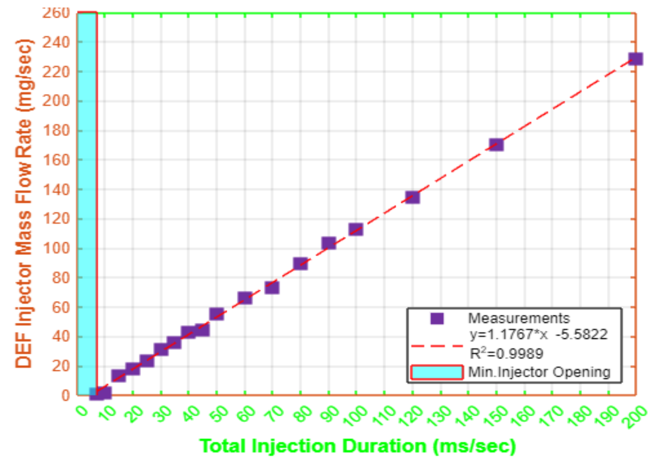

Fig. 6. Determination of DEF injector mass flow rate (mg/s) by linear regression for different injection times (ms/s)

The equation of the trend line obtained with high R^2 values as a result of the linear regression between the measurement data was defined in LabVIEW-based control software to calculate the injector opening duration required for the desired DEF injection amount.

3.2 Effect of injection amount on NO_x Emissions

In Fig. 7, the effect of injected DEF in different amounts on NO_x emissions at constant engine load and exhaust gas temperature in the range of 330-335°C is shown with NO_x values before and after injection.

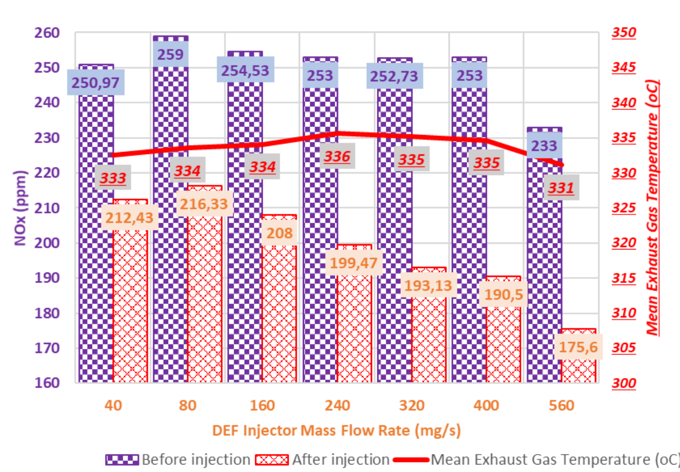

Fig. 7. NOx emissions before and after injection

In the first experiment, NO_x emissions were measured as 250.97 ppm with the emission device. When 40 mg/s DEF was injected for one-minute, the NO_x emission value decreased to 212.43 ppm obtaining a difference of 38.54 ppm. A 15.4% reduction in NO_x emissions was achieved.

The percentage reductions in NO_x emissions according to the 40, 80, 160, 240, 320, 400 and 560 mg/s DEF injector mass flow rates injected into the exhaust line for one minute are shown in Fig. 8.

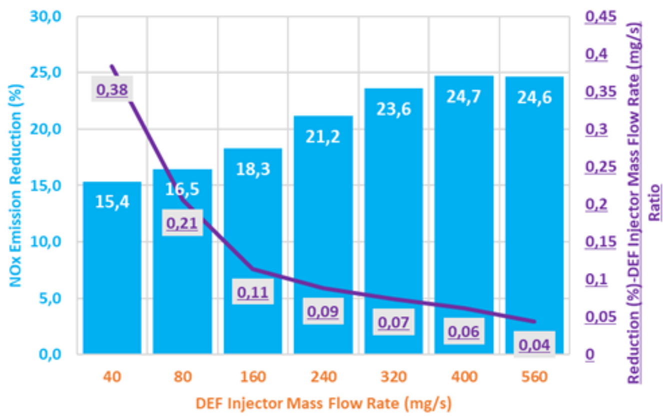

Fig. 8. Variation of NO_X reduction with respect to injector mass flow rate

Thereafter, the NO_x values, which had reduced with the effect of injection, were expected to be restored and the NO_x values came to 259 ppm in this process. While the engine load and exhaust gas temperature conditions were at their previous values, 80 mg/s DEF was injected for one minute this time, and NO_x values decreased to 216.33 ppm and a 16.5% NO_x reduction was observed.

In experiments repeated at the same engine load, the reduction in NO_x emissions was 18.3% at 160 mg/s injection, 21.2% at 240 mg/s injection. While the NO_x variations in 40, 80, 160 mg/s injections were close to each other as 15.4%, 16.5% and 18.3%, respectively, a 21.2% decrease was observed in 240 mg/s.

Similarly, there was a 23.6% decrease in NO_x values at 320 mg/s injection.

In order to observe how much the NO_x variations in the relevant experimental conditions could decrease, a 400 mg/s injection was carried out by increasing the DEF injector flow rate and the NO_x reduction was obtained as 24.7%. A low difference of 0.9% was obtained compared to a change of 320 mg/s. Thereupon, an injection of 560 mg/s was performed and the NO_x reduction was obtained as 24.6%.

As seen in Fig. 8, although the amount of injection was increased, there was no more than a 25% decrease in NO_x emission. In the reactions that take place in the SCR system, ammonia is formed first when DEF is injected. The resulting ammonia reacts with NO_x and turns into harmless and less harmful gases. Here, if DEF is injected less than necessary, enough NO_x conversion does not occur, and if it is too much, ammonia accumulation occurs in the system. As can be understood from here, according to the experimental system used, a significant NO_x reduction could not be obtained at DEF injector flow rates above 240 mg/s according to the relevant exhaust temperature and engine load.

In order to determine the minimum DEF and maximum NO_x percentage reduction, the reduction % in NO_x emission was proportioned by the DEF injector mass flow rate (mg/s). According to these ratios are shown in Fig. 8, the highest result is obtained with a value of 0.38 with 40 mg/s injection.

NO_x variation due to DEF injection with a 40 mg/s is shown in Fig. 9.

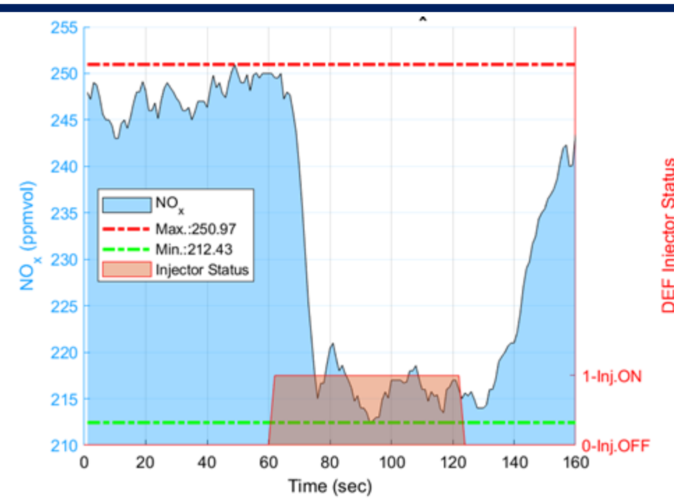

Fig. 9. NO_X variation during 40 mg/s DEF injection

In Fig. 9, NO_x conversion starts shortly after the start of the injection and continues throughout the injection. At the end of the injection, the NO_x decrease continues for a while and starts to increase after a certain period of time.

The exhaust gas temperature variation during the 40 mg/s test is shown in Fig. 10.

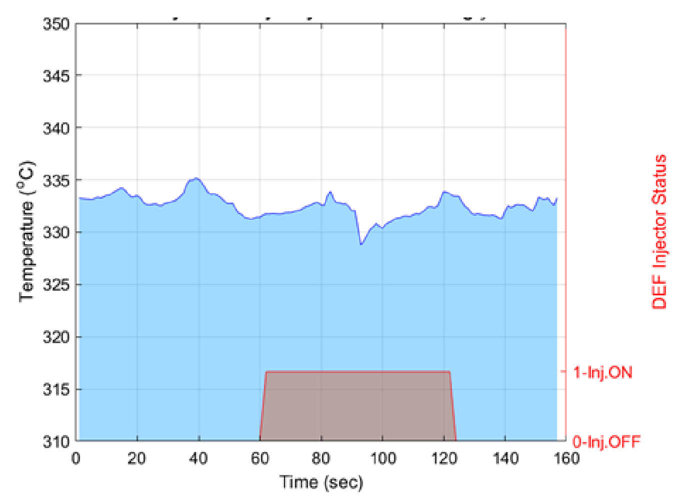

Fig. 10. Temperature variation during 40 mg/s DEF injection

The variations of O_2, CO_2, CO and lambda(λ) in the experiment with 40 mg/s injection are shown in Fig. 11. No visible variation could be detected due to the change in DEF injector mass flow rate in emission values other than NO_x.

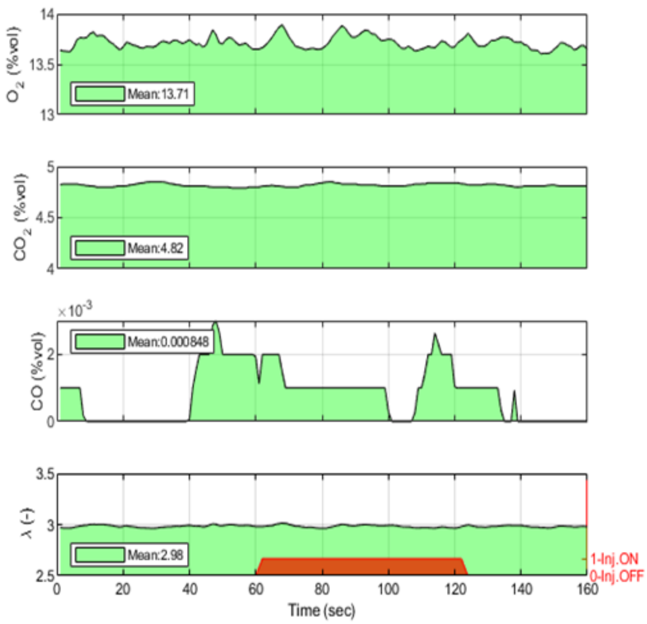

Fig. 11. Variations of other emission values during injection of 40 mg/s DEF

4. Discussion and Conclusion

PM and NO_x emissions are the ones that are risky for the environment and human health because of the pollutants in the exhaust gases of diesel engines. PM and NO_x emissions cannot be reduced to the emission values required to be met in the new Euro 6 and later standards with the studies carried out only within the engine system [29]. Therefore, emission reduction systems such as EGR, DPF, diesel oxidation catalysts (DOC) and SCR continue to be developed by automotive manufacturers [30].

The most widely used of these systems is the SCR system. The use of DEF requires additional costs in the SCR system. In addition, it is necessary to control the SCR system correctly and regularly and to provide the desired emission values. One of the values to be checked is the injection amounts.

In this study, a study was conducted to examine the effect of DEF injection amount on NO_x variations by considering certain parameters on the SCR system.

When the experimental work and academic studies in the literature are examined, the following suggestions should be taken into account in order to increase the efficiency of SCR systems;

- ✓ It is seen that the increase in the amount of injection in SCR technology generally increases the NO_x conversion efficiency, but it stabilizes after a certain amount.
- ✓ In order to prevent ammonia accumulation, which is called ammonia slip, and the clogging of the catalyst in SCR systems, it should be taken into account that the amount to be injected must be determined accurately

In this work, considering the laboratory conditions, the SCR is equipped as an experimental system and is open to new options. In the experimental system, the conditions can be changed since the SCR mechanical and ECU unit are our own design (use in different engines, use of different catalysts, and use of different DEF ratios). Because of these features, the study is different and new work in its field.

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Nomenclature

DEF: Diesel Exhaust Fluid
DOC: Diesel Oxidation Catalysts
DPF: Diesel Particulate Filter
EGR: Exhaust Gas Recirculation
NO_x: Nitrogen oxide
PM: Particulate Matter
SCNR: Selective Non-Catalytic Reduction
SCR: Selective Catalytic Reduction
SMD: Sauter Mean Diameter

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Şükrü Ayhan Baydır: Conceptualization, Supervision, Project administration, Software, Data curation, Resources, Formal analysis, Validation, Visualization, Investigation, Writing - review & editing.
Emrah Erçek: Conceptualization, Writing-original draft, Resources, Data curation, Formal analysis, Validation, Investigation.

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