Energy Proceedings
Vol 29, 2022
ISSN 2004-2965

The Effect of Urea Injectors to Optimize Ammonia Uniformity and NOx Conversion in SCR System

Muhammad Khristamto Aditya Wardana [1*], and Ocktaeck Lim [2]

1 Research Centre of Smart Mechatronic, National Research and Innovation Agency of the Republic of Indonesia (BRIN), Jl Sangkuriang Komplek BRIN Gd 20 Cisitu, Bandung, Indonesia. (Corresponding Author)

2 School of Mechanical Engineering, University of Ulsan, 44610, South Korea

ABSTRACT

The Euro 3 Koreans heavy-duty diesel engines produce the high NOx pollutant and harmful for human body. The effective method to reduce nitrogen oxide (NOx) pollutions is the selective catalytic reduction (SCR) system. This study deals with problems in the urea evaporation and decomposition process in heavy duty diesel engine with 12.000cc. The ammonia quantity and quality were sampled at the catalyst inlet using a 18 gas sensor, and samples of NOx from each urea injector were compared by experiments and simulations using STAR-CCM+ software. The results elucidate the saturation phenomena, vaporization phenomena, urea distribution patterns, and NOx reduction efficiency value urea injectors.

Keywords: Ammonia Value, Solid deposit, Evaporate, selective catalytic reduction, Heavy-duty diesel engine, Urea Water Solution (UWS)

NONMENCLATURE

Abbreviations	
NOx	Nitride Oxide
PM	Particular Matters
HC	Hydrocarbon
CO_2	Carbon Dioxide
CO	Carbon Monoxide
SCR	Selective Catalytic Reduction

1. INTRODUCTION

Diesel engines are widely used because of having several advantages like, high thermal efficiency, better fuel economy and low greenhouse gases emissions. Regarding heavy duty transportation there are no effective alternatives to diesel engine vehicles. In new generation diesel engine, fuel economy is improved as well as the NOx emission also increased. This harmful NOx is the most detrimental environmental pollutants induced by the transportation sector. An efficient after-treatment solution is mandatory to decrease the NOx emissions, by maintaining a better fuel economy. Current emission limits for heavy-duty diesel vehicles set by EURO 3 can be met by engine tuning. Various in-engine technologies have been applied to meet legislation requirements, such as combustion system optimization, intercooling, turbocharging, injection pressure increases, injection timing retardation, development of smart electronic controllers, shaping of injection rates, and exhaust gas recirculation (EGR). Although some of these technologies are still not fully developed and others are still emerging, such as homogenous charge compression ignition (HCCI), indications are that the emission limits that will be defined by future legislation will require an after-treatment system in order to reduce NOx and/or to abate PM emissions to the required levels. The reasons are limitations set by the combustion process itself, development costs, or a high fuel penalty caused by the in-engine emission abatement technologies.

Diesel particulate filters (DPF) appear to be very effective in PM removal. They have to be regenerated, which is done either by fuel injection or catalytically. Their drawbacks are an increase in back pressure and a fuel penalty, and they still have a limited lifetime due to the accumulation of ash. While DPF do not affect the NOx concentration, The SCR converters reduce PM. Additionally, DPF require a certain amount of NOx to work properly. The meeting the progressive compact emission legislation, like Euro 6, engine manufacturers are being forced to install exhaust after-treatment devices to meet the rising challenge. The selective catalytic reduction (SCR) is the most felicitated automotive exhaust gas after treatment solution for nitrogen oxides (NOx) emissions reduction which is capable of meeting most of the emission standards [1]. Ammonia (NH3) gas reacts with the flowing exhaust gas into the SCR device and converts the NOx element into nitrogen (N2) gas and water (H2O) [2]. Though NH3 is a noxious chemical component and harmful for human health, urea is used as the precursor of NH3 gas, which can be easily handled and transported [3]. Urea-water solution (32.5% urea by weight) known as AdBlue is injected into the exhaust gas stream by means of an injector, and then urea is decomposed to ammonia (NH3) gas [4]. However, the ammonia was difficult to produce because solidification of urea water solution [4]–[7]. For this reason, this study presents a simulation and a systematic study of the effects super-hydrophobic pattern material to improve the urea decomposition process and prevent occurrence of solid deposited in SCR system. The temperature used for process of ammonia uniformity in diesel SCR systems have been investigated with ambient temperature (298 K) and inlet gas temperature 648 K. Data were obtained on the actual conditions in the SCR system.

2. NUMERICAL

The CFD simulation was performed with the commercial software package STAR CCM+ version 11.04. Among various existing methods, the direct numerical simulation (DNS), the Eulerian-Eulerian model and the Eulerian-Lagrangian model are the most common approaches for multiphase flow modeling having better accuracy. The interphase existing between continuous phase and dispersed phase is only modeled in DNS approach. Though DNS predict much perfect results, but it is very heavy computational process. DNS computation may take several weeks to finish a calculation, so for a very high computational cost, it is not recommended for industrial use. The advantages of Eulerian-Lagrangian modeling over Eulerian-Eulerian framework are more detailed information on discrete behavior of particle rather than continuum dynamics and Eulerian-Eulerian framework become computationally expensive when multiple sets of equations are used. Eulerian-Lagrangian framework acts in two separate concepts, the particles are modeled either individual droplets or together as a bundle. Individual particle modeling predicts more accurate results than bundle or parcels but computationally expensive. The particle's dynamic properties (e.g size, velocity) are similar within the same parcel. The interaction between each particle or parcel and with the continuous phases are modeled in Eulerian-Lagrangian approach using the incompressible and un-steady Reynolds-averaged Navier Stokes (RANS) equations for energy, mass, momentum and species. The realizable k-ε model is applied for the modeling of the turbulent flow because it has improved ability over standard k-ε model in case of turbulence quantities estimation. The urea injector had 3 holes to spray and 120 micrometers of diameter. Each hole had a cone angle of 7° and could produce 8.05-E5 kg/s of urea mass flow rate. The urea injection mechanism process is shown in Figure 1 [7].

The primary spray atomization for the thin liquid sheet produced at the nozzle tip, created by the pressure-swirl atomizer is modeled by Linearized Instability Sheet Atomization (LISA) model [52]. Liquid film surrounded by an air core is produced by the centrifugal motion and sheet breakup of the injected liquid, LISA model can calculate the thickness and velocity for the fluid film formed. For modeling the droplet size distribution an empirical function known as Rosin-Rammler distribution is used and it is expressed as:

$$1 - Q = \exp(-(\frac{D_p}{X})^q) \tag{1}$$

Here, Q is the portion of total holding drops volume with a diameter smaller than Dp. The exponent value q is the measure of spread and higher value denotes more uniform spray. X denotes the reference droplet diameter. The collision between the droplets are estimated by the NTC (No Time Counter) collision detection algorithm.

If a cell comprises N droplets, the probable number of collisions in the cell over a time interval is expressed by summing the probability of all possible collisions:

$$M_{col} = \frac{1}{2}\sum_{i=1}^{N_p} q_i \sum_{j=1}^{N_p} q_j \frac{v_{i,j}\sigma_{i,j}\Delta t}{v} \tag{2}$$

Where, $v_{i,j}$ denotes the relative velocity between two colliding particles, σ_{ij} denotes the collision cross section of the two drops and defined as

$$\sigma_{i,j} = \pi(r_i + r_j)^2 \tag{3}$$

Δt represents the time-step size, V denotes the cell volume, Np is the number of parcels in a cell, qi is the number of droplets in parcel i.

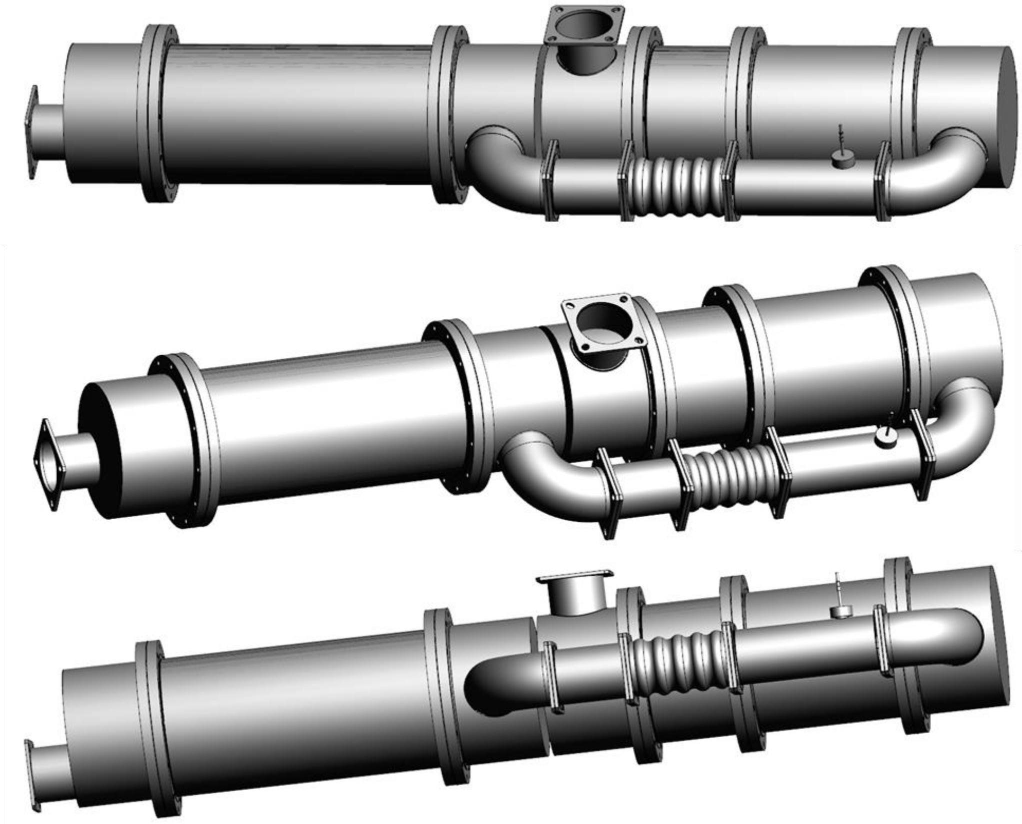

Fig. 1. The CFD simulation geometry model of the commercial SCR system by HYUNDAI D6CC

3. EXPERIMENT CONDITION

The experiment used optical access based on a six-cylinder water-cooled, naturally aspirated, 4-cycle diesel engine condition. The air temperature was heated by the air heater in the experiment based on Engine operating condition 1000 rpm and 1700 rpm [1], [3] were fed into SCR system. A schematic diagram of the test engine and measurement setup can be seen in Figure 3. The UWS injector temperature were 263 °C, adblue flow rate (1319 ml/h) and ambient temperature (298 K) and inlet gas temperature 313 K and 453 K [8]. This study was conducted in an experiment multiple times of consecutive collecting data to obtain the best visualization to shows the superhydrophobic pattern performance to decrease the solidification urea water solution

Fig. 2. Experiment setup and engine measurement.

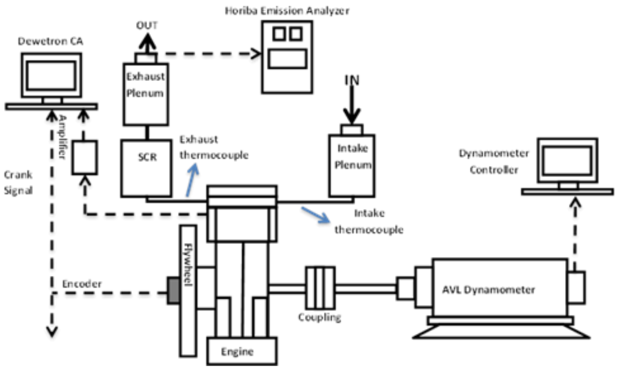

Fig. 3. Schematic diagram of the test engine and measurement setup [7]

4. RESULT

Figure 4 shows the NOx conversion from L-type urea injector in the experiment system by the gas analyzer. In this result, we can understand the conversion value from L-type injector in heavy-duty diesel engine; the urea decomposes and become ammonia gas. The equal quantity between ammonia gas and NOx gas is the important indicator to reduce NOx from diesel engine. M. Khristamto, et.al. [7] analyze the impact of ammonia gas to reduce NOx gas emission from diesel engine. Figure 5 showing the NOx conversion value from I-type urea injector with the engine condition 1000rpm. In that engine operation, the heavy-duty diesel engine can produce high temperature to assist the vaporization urea process in SCR system. However, that high temperature also can easily produce solid deposit inside the injector.

In this experiment result, showing that I-type of urea injector can produce higher value of NOx conversion that L-type urea injector in SCR system. That phenomena also occur in the simulation result by the Starccm+. The I-type of urea injector better than L-type of urea injector to distribute the urea into the SCR system. This process can be showing in the ammonia uniformity result in figure 6. The ammonia uniformity value shows that I-type produce higher value of ammonia distribution in the inlet catalyst. And that result was match with the experiment result in the SCR system; that the I-type of urea injector produces higher value of NOx conversion efficiency in the system. This data approving because the urea easily generates become ammonia and minimizer the solid deposit in the system. With the higher quantity of ammonia gas in the system can assist the chemical process to generate ammonia and NOx gas to become steam and nitrogen in outlet of SCR system.

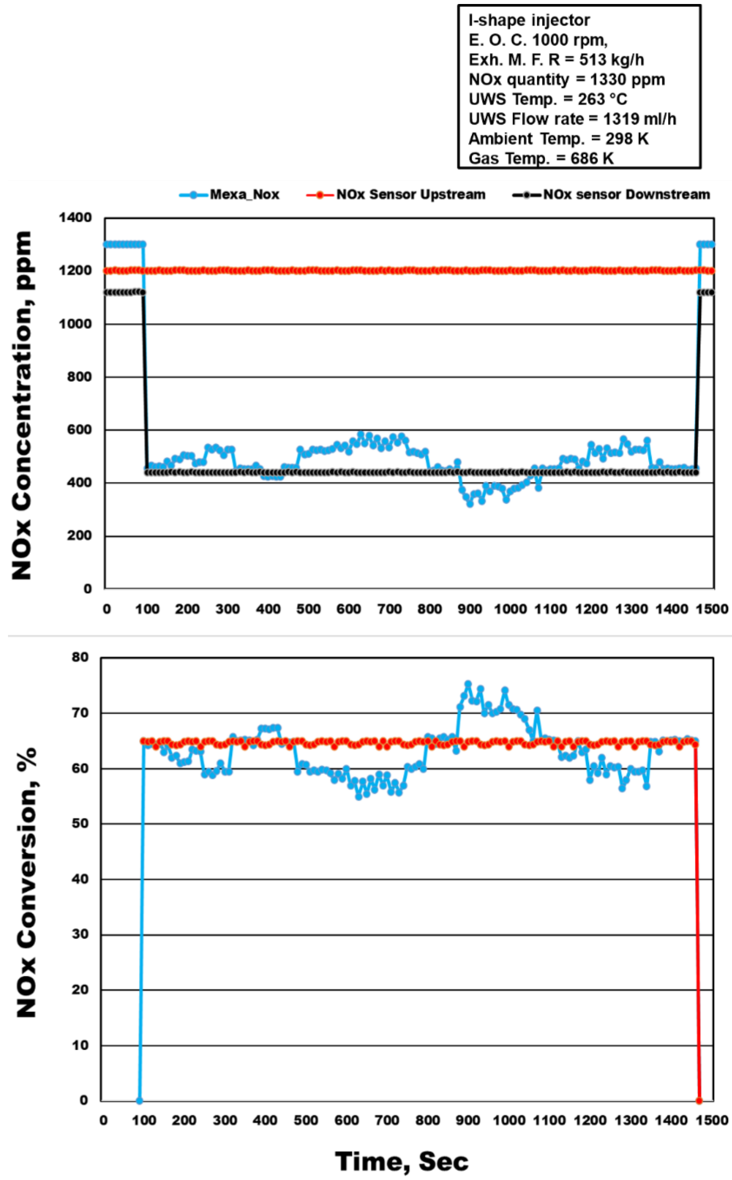

Fig. 4. NOx conversion from L-type Injector in 1000rpm engine operation.

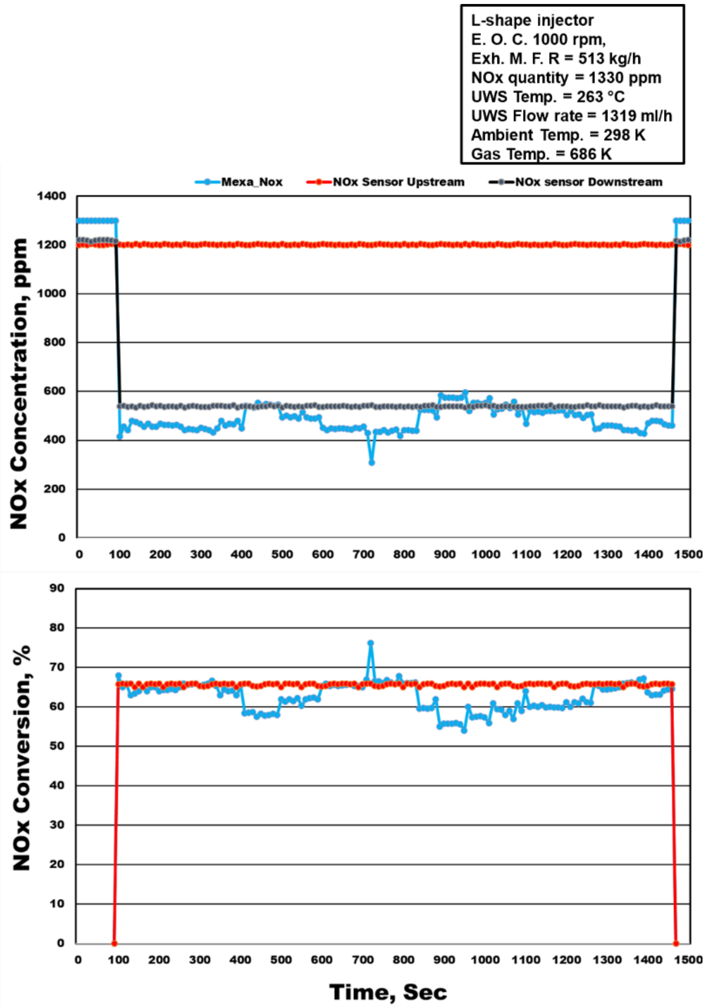

Fig.5. NOx conversion from I-type Injector in 1000rpm engine operation

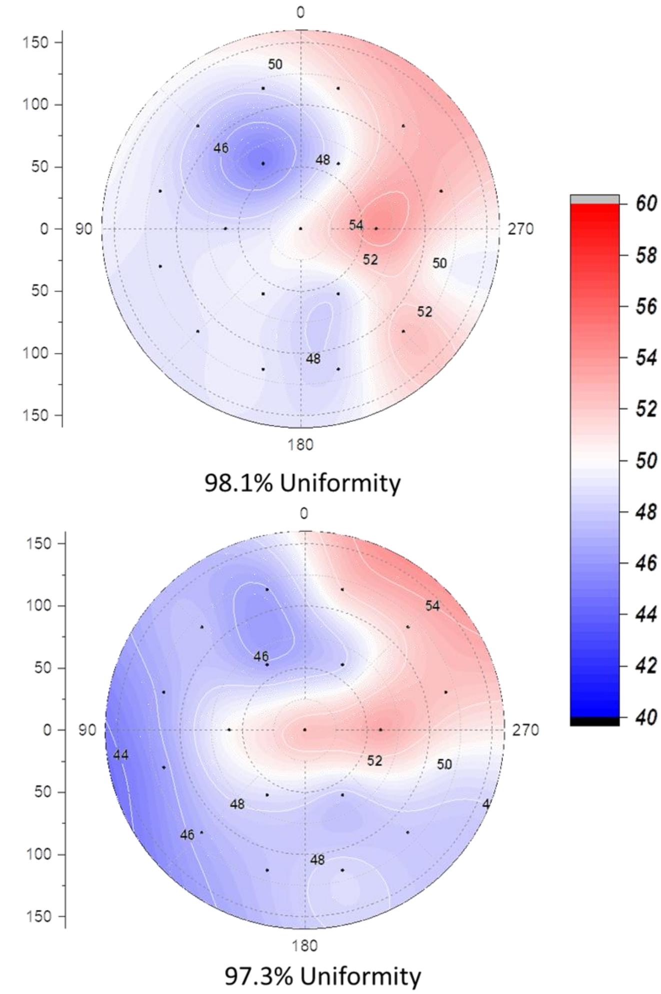

Fig. 6. Ammonia Uniformity from I-type of urea injector and L-type of urea injector.

5. CONCLUSION

A study on the effects of urea injector to increase the ammonia uniformity and NOx conversion in the heavy-duty diesel engine with the experiment and simulation using STARCCM+ was conducted. The experiment and simulation studies were performed used 2 type of urea injector that in the simulation (CFD) was designed based on the commercial SCR, the first CFD using L-type urea injector and second CFD using I-type urea injector. The suggestion of I-type of urea injector was produces the higher NOx conversion value in the experiment and simulation than the original injector (L-type of urea injector). Those phenomena can show in the simulation with the ammonia uniformity and that phenomenon also can be proved by the NOx conversion result in the experiment condition. The appropriate of urea injector can manage the urea generation process to produce the high ammonia gas and minimizer the solid deposit in the system.

ACKNOWLEDGEMENT

This work was supported by a research program supported by the Department of Mechanical of Engineering (Generation Fuel and Smart Power Train Laboratory), University of Ulsan, Re-public of Korea.

REFERENCE

H. L. Fang and H. F. M. DaCosta, “Urea thermolysis and NOx reduction with and without SCR catalysts,” Appl. Catal. B Environ., vol. 46, no. 1, pp. 17–34, 2003.

[2] S. Hua et al., “Atmospheric Emission Inventory of Hazardous Air Pollutants from China’s Cement Plants: Temporal Trends, Spatial Variation Characteristics and Scenario Projections,” Atmos. Environ., vol. 128, no. 19, pp. 1–9, 2016.

[3] A. Varna, K. Boulouchos, A. C. Spiteri, P. Dimopoulos Eggenschwiler, and Y. M. Wright, “Numerical Modelling and Experimental Characterization of a Pressure-Assisted Multi-Stream Injector for SCR Exhaust Gas After-Treatment,” SAE Int. J. Engines, vol. 7, no. 4, pp. 2012–2021, 2014.

[4] P. Iodice and A. Senatore, “Air Pollution and Air Quality State in an Italian National Interest Priority Site. Part 2: The Pollutant Dispersion,” Energy Procedia, vol. 81, pp. 637–643, 2015.
[5] H. Smith, T. Lauer, M. Mayer, and S. Pierson, “Optical and Numerical Investigations on the Mechanisms of Deposit Formation in SCR Systems,” SAE Int. J. Fuels Lubr., vol. 7, no. 2, pp. 2014-01–1563, 2014.
[6] Y. Yi, “Development of a 3D Numerical Model for Predicting Spray, Urea Decomposition and Mixing in SCR Systems,” SAE Tech. Pap., no. 724, 2007.
[7] M. Khristamto, A. Wardana, G. M. H. Shahariar, K. Oh, and O. Lim, “AMMONIA UNIFORMITY TO PREDICT NOX REDUCTION EFFICIENCY IN AN SCR SYSTEM,” Int. J. Automot. Technol., vol. 20, no. 2, pp. 313–325, 2019.
[8] H. Smith, T. Lauer, V. Schimik, and K. Gabel, “Evaluation and Prediction of Deposit Severity in SCR Systems,” SAE Int. J. Engines, vol. 9, no. 3, pp. 2016-01–0970, 2016.
[9] X. Zhang and M. Romzek, “3-D Numerical Study of Mixing Characteristics of NH3 in Front of SCR,” no. 724, 2011.
[10] M. Koebel and E. O. Strutz, “Thermal and Hydrolytic Decomposition of Urea for Automotive Selective Catalytic Reduction Systems: Thermochemical and Practical Aspects,” Ind. Eng. Chem. Res., vol. 42, no. 10, pp. 2093–2100, 2003