Paper ID APEN-MIT-2022_4294
Applied Energy Symposium: MIT A+B
July 5-8, 2022 • Cambridge, USA

The Optimization of Urea Injectors to Reduce the NOx Emission in Heavy-Duty Diesel Engine

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Abstract—The heavy-duty diesel engines have created effective method to reduce nitrogen oxide (NOx) pollutions with selective catalytic reduction (SCR) system. This study deals with problems in the urea evaporation and decomposition process, the ammonia gas distribution in SCR system and ammonia pattern at inlet of catalyst. The test system used two types of urea injectors, an L-type and an I-type. The ammonia gas value was sampled at the catalyst inlet using a gas sensor. The results elucidate the saturation phenomena, ammonia distribution phenomena, and ammonia value from the two types of urea injectors. The study of effect urea injector was shown at the catalyst inlet by the different chemical mechanisms governing of ammonia concentration distribution in the SCR system.

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

I. Introduction

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 (NH_3) gas reacts with the flowing exhaust gas into the SCR device and converts the NOx element into nitrogen (N_2) gas and water (H_2O) [2]. Though NH_3 is a noxious chemical component and harmful for human health, urea is used as the precursor of NH_3 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 (NH_3) gas [4].

Urea water solution droplets decomposition is a thermally activated phenomenon, it begins by water evaporation from the solution, separating the urea components. Then urea molecules are decomposed into ammonia gas. Urea decomposition is not always uniform. During the decomposition process intermediate phases can react with undecomposed urea and produce various unwanted complex polymer [5,6]. These by products (urea deposits) are accumulated on the injector tip, exhaust pipe wall, catalyst surface, mixing element and reduce the catalyst activity, increase engine backpressure, thus lower the NOx conversion rate and gradually make the system ineffective. Urea deposits are decomposed at very high exhaust temperature, however maintaining a high exhaust temperature may increase the fuel consumption.

The most challenging part to execute urea SCR systems is the uniform distribution of urea, also the mitigation of solid deposit formation. Though modern urea-SCR systems require compact design of exhaust pipe and thermal decomposition of urea is comparatively lengthy process, droplet spray impingement on the exhaust pipe wall or on the mixer is hard to be avoided [4]–[7]. For this reason, this study presents a simulation and a systematic study of the effects of urea injector to reduce NOx quantity in the system using STARCCM+. Simulation studies were performed at 2 models of CFD based on the commercial SCR, the first CFD using L-type urea injector and second CFD using I-type urea injector. The temperature used in diesel SCR systems have been investigated with ambient temperature (298 K) and inlet gas temperature (648 K) operation.

II. Numerical modeling and goemetri condition

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 modelling having better accuracy. The interphase existing between continuous phase and dispersed phase is only modelled 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 [6]. The advantages of Eulerian-Lagrangian modelling over Eulerian-Eulerian framework are more detailed information on discrete behaviour 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 modelled either individual droplets or together as a bundle.

Individual particle modelling 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 modelled 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 modelling of the turbulent flow because it has improved ability over standard k-ε model in case of turbulence quantities estimation [7].

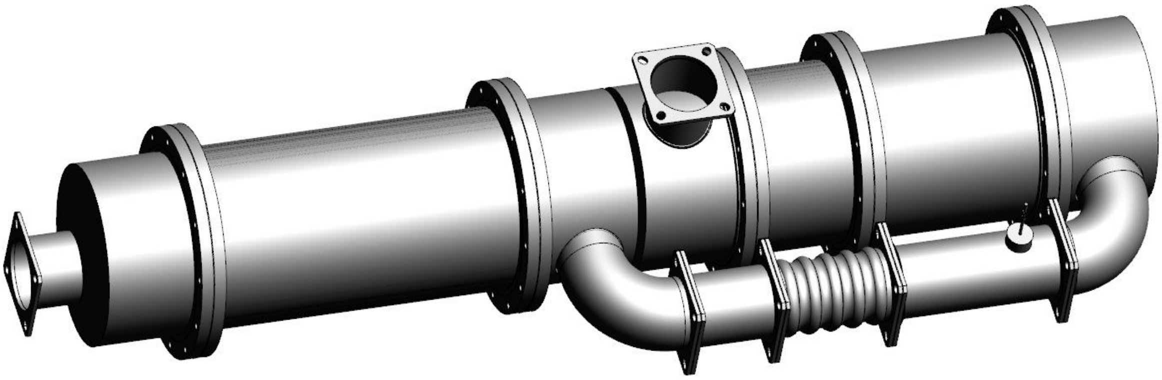

Fig. 1. The simulation geometry model of the commercial SCR system by HYUNDAI D6CC.

The primary spray atomization for the thin liquid sheet produced at the nozzle tip, created by the pressure-swirl atomizer is modelled 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 modelling 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 D_p. 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 is estimated by the NTC (No Time Counter) collision detection algorithm.

III. EXPERIMENT CONDITION

The experiment setup was based on a six-cylinder water-cooled with naturally aspirated. Engine operating condition 1000 rpm, the engine can produce a mass flow of 513 kg/h, yielding NOx of 1,330 ppm [1], [3] were fed into SCR system. The UWS injector temperature were 263 °C, AdBlue flow rate (1319 ml/h) and ambient temperature (298 K) and inlet gas temperature (686 K) [8] The mixing process between NOx and ammonia occurred from pipe until catalytic converter. The outlet catalyst was connected with pipe into a Horiba MEXA-7100DEGR and back pressure valve for measurements pressure outlet and to reduce emissions (hydrocarbon and NOx). This study was conducted in an experiment with ten (10) times of consecutive collecting data to obtain the effect of urea injection timing and exhaust temperature on the NOx reduction efficiency in SCR system.

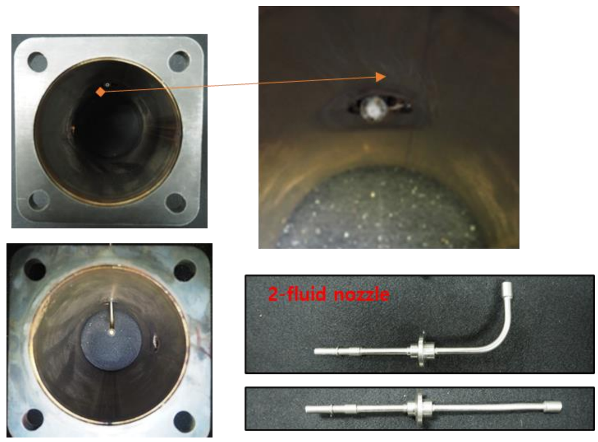

Fig. 2. The urea injector; (A) L-type of urea injector (original type) and (B) I-type of urea injector (Improvement injector).

Fig. 3. Experiment system and measurement setup.

IV. RESULT

The simulation using the 3D was the best for showing the clearly phenomena in SCR system. Figure 4 shows the simulation of saturation phenomena in SCR system. The I-type urea injector result simulation was showing the higher value than L-type urea injector. Zhang et. al. [9] analyze by the minimizing the solid deposit in the system the ammonia gas can easily produce by the saturation process in the systems. The effect of urea injector also can assist the quantity of ammonia gas in the system. Figure 5 showing the simulation of I-type urea injector to distribute the ammonia gas in the SCR system: the heavy-duty diesel engine with operation condition 1000rpm produce higher flow mass to assist the distribution ammonia gas in the system.

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In these studies, shows that I-type of urea injector produce higher saturation value of urea water solution process in SCR system. That phenomena can proved in by the ammonia value in the catalyst inlet as captured by gas analyzer. Based on the experiment, the I-type of urea injector produce higher value of ammonia uniformity than L-type of urea injector in the SCR system; This value was showing in the figure 6. This data can be achieve based on the previous research by M. Khristamto et.al [7], they show that in the L-type urea injector was hampered by the solid deposit; that's situation can decrease the urea distribution and reduce the ammonia gas generation process. However, the I-type can be solved, because the urea easily to distributed to the system and prevent the solid deposit inside the urea injector.

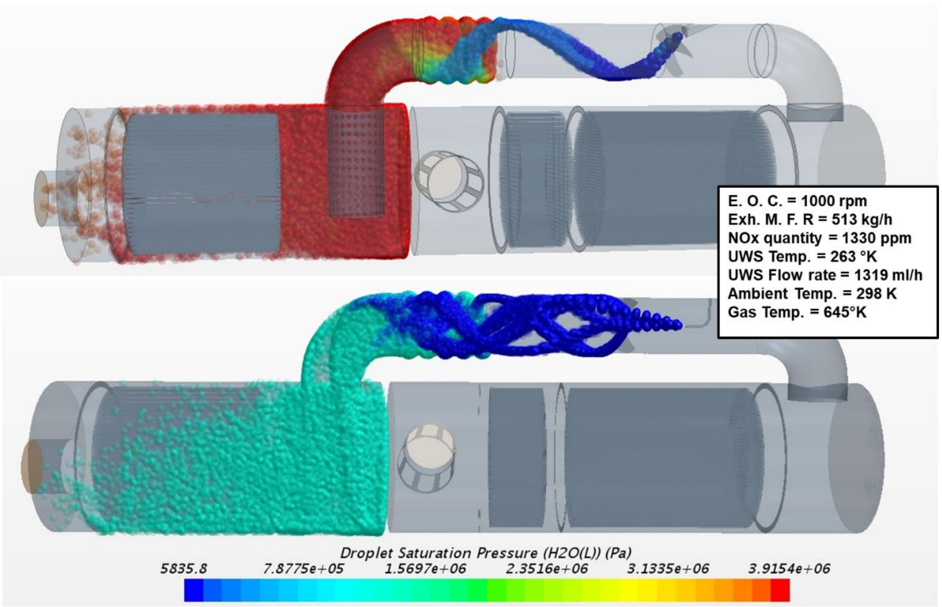

Fig. 4. The simulation of saturation phenomena of I-type and L-type urea injector

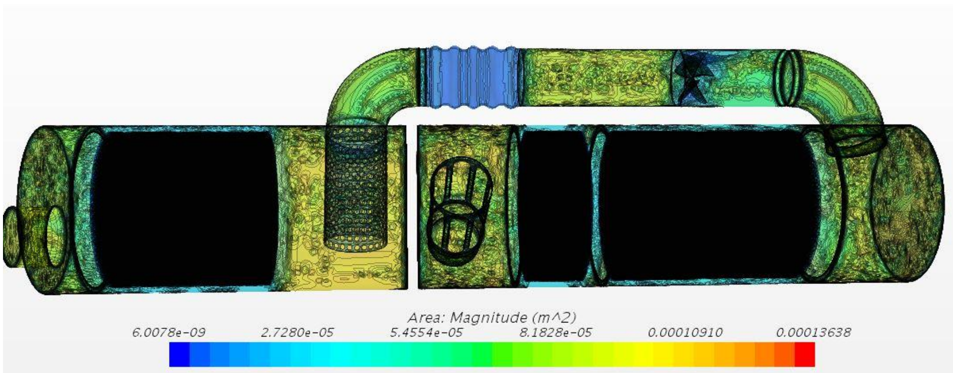

Fig. 5. The simulation of I-type urea injector to distribute the ammonia gas in SCR system

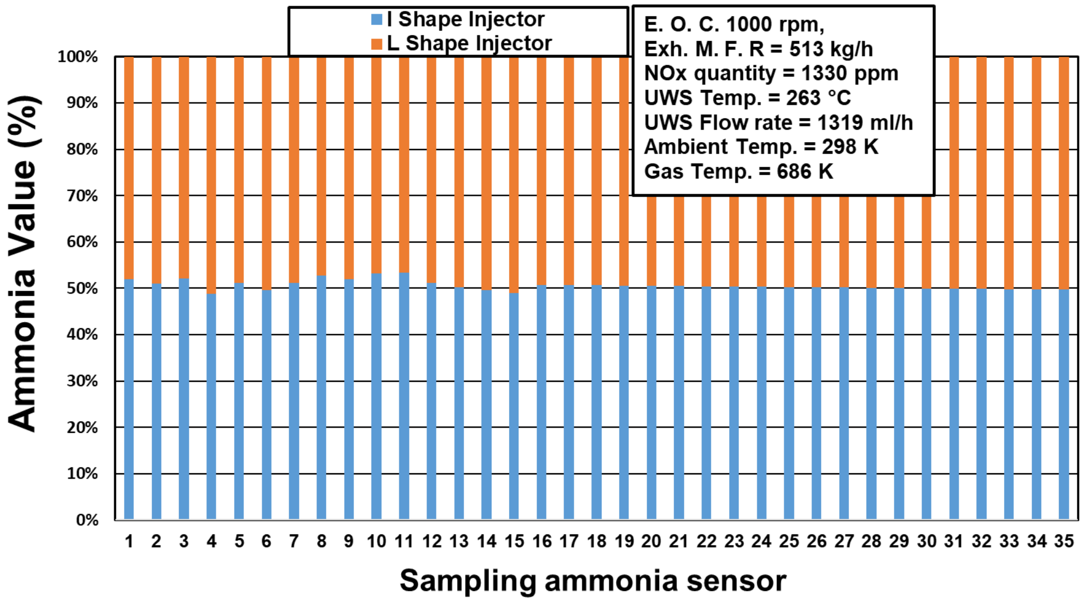

Fig. 6. The Ammonia value from I-type and L-type of urea injector.

V. Conclusion

A Study of optimization urea injector showed that the I-shaped injector produced the highest amount of ammonia during saturation in the system using STARCCM+. The lowest ammonia quantity affected by the hampered distribution urea inside the injector. The urea easily become solid when effected by the temperature in main flow gaseous; that reaction only occurred in L-shaped injector, because that injector directly blocked the exhaust main flow gaseous. That phenomena can proved in by the ammonia value in the catalyst inlet as captured by gas analyzer. Based on the experiment, the I-type of urea injector produce higher value of ammonia uniformity than L-type of urea injector in the SCR system. The ammonia distribution value for I-shaped injector can reach to all side of system; the increasing the velocity gaseous or changing the mixer position is the required solution for future study to improve ammonia quality and NOx reduction quantity.

Acknowledgment

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.

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