International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 1 (2018) pp. 5-9


# A Review on Selective Catalytic Reduction (SCR)-A Promising Technology to mitigate $NO_x$ of Modern Automobiles

**Sadashiva Prabhu S**

*Asst. Professor, Mechanical Engineering Department, School of Engineering, Presidency University Itgalpura, Rajanakunte, Yelahanka, Bengaluru, Karnataka- 560064*

## Abstract

Diesel engine exhaust emissions like nitrogen oxides ($NO_x$) should be effectively removed by the suitable De-$NO_x$ techniques to meet the stringent emission norms. This can be accomplished by a technique called Selective Catalytic Reduction (SCR) effectively. In SCR, the reducing agent ammonia ($NH_3$) which is required for the reduction of $NO_x$ is obtained by the addition of Urea Water Solution (UWS) (32.5% aqueous urea solution) into high temperature exhaust gases in the form of an atomized spray. Even though this technique is more promising, there are many drawbacks associated within it like $NH_3$ slip, incomplete conversion of NOx, deposit formation, etc. To overcome these drawbacks and also to optimize $NH_3$ generation, research work is underway worldwide in different wings. The paper deals with the overview of SCR, construction, advantages, technology developments, drawbacks etc. The alternate solution for ammonia formation by solid reactants were also highlighted.

**Keywords:** SCR, $NO_x$, Urea, Diesel Engines

## INTRODUCTION

The highly efficient aftertreatment technology to tackle $NO_x$ is SCR. In SCR, ammonia ($NH_3$) or urea ($NH_2$-CO-$NH_2$) is used as reducing agent if nitrogen oxides ($NO_x$) have to be eliminated from the exhaust gases of diesel engines. The method is most efficient for the $NO_x$ removal from stationary power plants. SCR technology was initially implemented in Japan in the 1970s and employed in fossil fuel power plants all over the major Japanese cities [1]. Stationary engines and power plants have been using $NH_3$ and urea based SCR systems since many decades. In the last 10 years, automobile manufactures focused their attention towards the further improvement of the technique to make it suitable for automobiles having diesel engines.

The major challenge involved with SCR systems is the reduction of catalytic converter volume at low temperatures and the suitable dosing strategy for $NH_3$ at frequently varying load conditions of the diesel engines. Additionally, the risk associated concerning storing and handling of gaseous $NH_3$ is significant and consequentially it is not commonly used as a reducing agent directly. For reasons of toxic nature of $NH_3$ and handling and storing problems, urea is the preferred substitute for $NH_3$ as a reducing agent in automotive applications. The best procedure is injecting Urea Water Solution (UWS) in the form of spray to hot exhaust stream before the entry to the SCR catalyst.

Urea is an environmentally benign chemical which makes it more suitable for application to the SCR process. Urea is a fertilizer used in agriculture and available in a number of quality grades at a lower cost. Development of Urea-SCR over $NH_3$-SCR has gained momentum due to various problems involved with the use of $NH_3$. $NH_3$ is corrosive, toxic in nature and also a secondary pollutant. Handling of $NH_3$ to be accurate and it is required store at high pressure. In order to introduce $NH_3$ into the exhaust gas stream, proper dosage control mechanism is required [2].

The main advantage with this SCR system is high De-$NO_x$ efficiency (90% or higher). The disadvantages involve the space required for the catalyst, high capital- and operating costs, formation of other emissions ($NH_3$ slip) and formation of undesirable species which may lead to catalyst poisoning and deactivation. The $NH_3$ slip can be controlled by installing an oxidation catalyst after the SCR system. Although the SCR system has some drawbacks the technology has been chosen by the majority of the diesel engine manufactures due to absence of better technology to meet the stringent emission standards.

## SELECTIVE CATALYTIC REDUCTION (SCR)

### Reducing agents

There are different possible ways to introduce the reducing agent to the system; anhydrous $NH_3$, aqueous $NH_3$ or an aqueous urea solution that decomposes to $NH_3$. In order to avoid direct handling of both anhydrous and aqueous $NH_3$, urea is often used as $NH_3$ source [3]. It has been shown that best SCR performance is obtained by gaseous $NH_3$, followed by injection of $NH_3$ solution. The performance with solid urea and urea solution is comparatively poor due to incomplete evaporation and decomposition of urea [4]. Injecting a UWS is more convenient than any other form of urea injection.

The major components of SCR system are 1) Catalyst where the conversion of $NO_x$ into $N_2$ takes place 2) UWS injection system 3) UWS storage tank 4) Data acquisition system. Fig.1 gives the complete details of SCR system of modern automobile.

The UWS decomposition is as given below

1)Evaporation of water from UWS

$$(NH_2)_2CO_{(l)} \rightarrow (NH_2)_2CO_{(s)} + H_2O_{(g)}$$

2) Urea decomposition (Thermolysis) urea into $NH_3$ and

HNCO,

$$(NH_2)_2CO_{(l)} \rightarrow NH_{3(g)} + HNCO_{(g)}$$

(3) Conversion of Isocyanic acid to $NH_3$(Hydrolysis of HNCO)

$$HNCO_{(g)} + H_2O \rightarrow CO_{2(g)} + NH_{3(g)}$$

The SCR process makes use of various catalysts, mostly in the form of oxides of metals such as titanium, vanadium or molybdenum, impregnated onto a metallic or ceramic substrate. The present study is based on the SCR of $NO_x$ with a commercially available vanadium based catalyst, $V_2O_5$-$WO_3/TiO_2$ commonly known as VWT. Typical operating temperatures for an SCR application ranges from 200-500$^0$C [5].

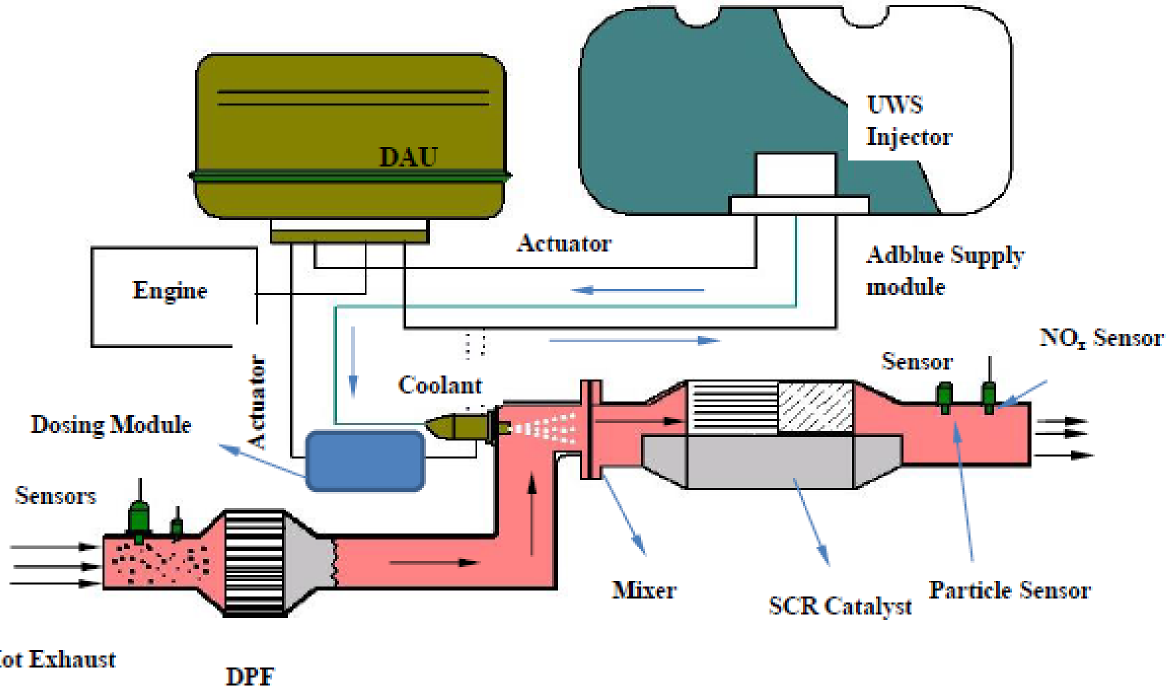


**Fig.2.Components and Working of SCR System**

$NO_x$ reacts with $NH_3$ over catalyst and reduces to $N_2$. $NO_x$ can be successfully removed from lean diesel exhaust gases by using selective and catalytically supported reduction technique. Ammonia($NH_3$) reacts selectively with $NO_x$, along with oxygen to generate harmless products like nitrogen and water vapor. The following three overall SCR reactions are considered [7, 8].

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NH_3 + NO + NO_2 \rightarrow 2N_2 + 3H_2O$$

$$4NH_3 + 3NO_2 \rightarrow \frac{7}{2}N_2 + 6H_2O$$

The first reaction is known as *standard- SCR reaction* involves reduction of NO in equi-molar ratio with $NH_3$. The second reaction includes both the reduction of NO and $NO_2$ and this reaction is called *fast SCR reaction* which shows increased reaction rates in the presence of $NO_2$. The third reaction is *slow-SCR reaction* i.e., at $NO_2$/ $NO_x$ ratios higher than 50%, the De-$NO_x$ behavior is lowered because of stronger involvement of slow SCR reactions reducing $NO_2$ only.

Despite this technology which was implemented by the some of the automobile companies there are some problems still exist like wall deposition, lower urea conversion efficiency, lower $NO_x$ conversion efficiency, $NH_3$ slip, poisoning of catalysts etc. The problems associated with SCR systems can be reduced substantially by optimizing some parameters related to i) exhaust pipe dimensions at the upstream of the catalyst ii) UWS injection system iii) Dosage of UWS iv) mixer and iv) catalyst.

**UWS Sprays and UWS Spray Techniques**

The UWS spray is a major process in SCR system and it has to be generated to suit flow conditions, size and shape of mixing pipe, and dosage is based on $NO_x$ content in exhaust gas. If any error occurs in the injection of UWS (trade name: Ad Blue) results errors in flow at the upstream of the catalyst. The main intention with atomization processes is to maximize the gas-liquid interface since all transport processes are directly dependent upon this surface area and the exchange between the phases will improve with an increased surface area. The exchange between the phases in a spray system increases by several times compared to the case where the liquid is not disintegrated through atomization process [9].

The sizes of the droplets in a spray are usually described by 1) A suitable droplet size distribution function 2) The (mean) size parameter 3) The relative width of the distribution [10].

The different types of spray produced: hollow cone, solid cone and flat sprays. The droplet sizes ranging from 20-150μm with an injection velocity of 5-25m/sec with injection pressure of 10 bar. The exact design and principle of the spray nozzles used for the Euro 6 trucks is known by individual provider. The principles of two types of spray nozzles might be of interest to try to understand the atomization mechanisms in these types of nozzles. Varieties of spray nozzles are available for SCR UWS injection [11]. Among them pressure nozzles and two fluid nozzles are mostly used.

The important feature for the atomization is the dimension of the orifice. The finest disintegration is reached when the orifice is small. But the constraint is, it is more difficult to keep the opening free from foreign particles. So, the minimum size of the orifice is usually limited to approximately to 0.3 mm [12]. The drawback with the pressure atomizer is naturally the need of a pressurized liquid but also that the droplets size produced is relatively uneven and practicable when mass flow rate is low [9].

**UWS Sprays and UWS Spray Techniques**

The UWS spray is a major process in SCR system and it has to be generated to suit flow conditions, size and shape of mixing pipe, and dosage is based on $NO_x$ content in exhaust gas. If any error occurs in the injection of UWS (trade name: Ad Blue) results errors in flow at the upstream of the catalyst. The main intention with atomization processes is to maximize the gas-liquid interface since all transport processes are directly dependent upon this surface area and the exchange between the phases will improve with an increased surface area. The exchange between the phases in a spray system increases by several times compared to the case where the liquid is not disintegrated through atomization process [9].

The sizes of the droplets in a spray are usually described by 1) A suitable droplet size distribution function 2) The (mean) size parameter 3) The relative width of the distribution [10].

The different types of spray produced: hollow cone, solid cone and flat sprays. The droplet sizes ranging from 20-150μm with an injection velocity of 5-25m/sec with injection pressure of 10 bar. The exact design and principle of the spray nozzles used for the Euro 6 trucks is known by individual provider. The principles of two types of spray nozzles might be of interest to try to understand the atomization mechanisms in these types of nozzles. Varieties of spray nozzles are available for SCR UWS injection [11]. Among them pressure nozzles and two fluid nozzles are mostly used.

The important feature for the atomization is the dimension of the orifice. The finest disintegration is reached when the orifice is small. But the constraint is, it is more difficult to keep the opening free from foreign particles. So, the minimum size of the orifice is usually limited to approximately to 0.3 mm [12]. The drawback with the pressure atomizer is naturally the need of a pressurized liquid but also that the droplets size produced is relatively uneven and practicable when mass flow rate is low [9].

**Injector Mountings**

Straight pipe with angular injection is preferred when mixing length is not sufficient. Here spray impaction takes place on wall, thereby the solid hot surface of the pipe enhances evaporation. On the other hand at lower temperature of exhaust gas the wall increases evaporation.

The S-pipe is intended to test the advantage of spraying co axially to enhance the distribution of droplets. In both cases the injector is targeting at the bottom of the mixer; in S-bent pipe, the injector is further shifted downward because of additional lifting effect from flow deflection of S-bent design. The both the designs are shown in Fig. 2.

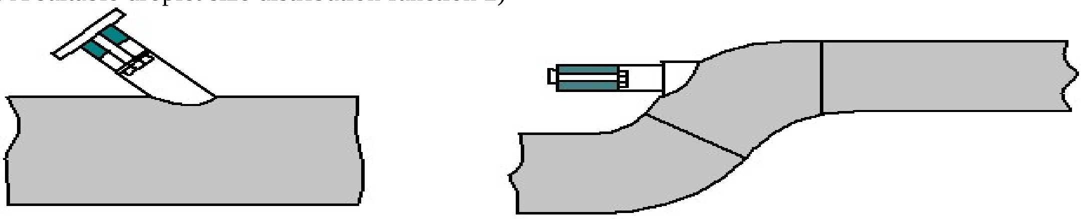

**Fig.2. Angular injection mounting on a straight pipe (left) coaxial injection mounting on S- pipe**

**Spray-wall Interaction**

Based on the flow conditions of exhaust gas, spray condition of UWS, type of fluid and wall temperature, the different phenomena may result when droplets impinge on wall. Chen et al. [13] have shown impinging droplets of UWS in six types of flow regimes. i) Adhesion-the droplet retains at the wall in a spherical form, ii) Rebound- the droplet bounces and hits back to the wall, iii) Spread- the droplet spreads out and forms a liquid film with increased fluidity, iv) Splash- some of the droplets break up and come out as smaller droplets while the rest remains in the wall, v) Rebound with break-up- the droplet bounces back and breaks up into multiple droplets and vi) Break-up-the droplet bounces back and breaks up into a number of small droplets.

**Deposit Formation**

The gaseous products of urea and their compounds at low temperature operation may result in health problems by inhaling exhaust gas of engines. The major drawback of the SCR system is incomplete evaporation and thermolysis where the injection parameters play a major role. The impingement of droplets over the walls of SCR mixing pipe and catalyst setup because of slow evaporation and thermolysis as well as the inertia of the droplets. However, if the evaporation and conversion do not take place fast enough, non-decomposed urea and other byproducts may form crystals and become deposit inside the exhaust system. In addition to this, many factors affect the formation of urea deposits. If conversion does not happen quickly and efficiently, it can form liquid pool resulting in solid urea and other solid byproducts that attach to the inner pipe wall or mixers. The worst case scenario is the deposit formation for lower exhaust gas temperature and high $NO_x$ levels. In this situation, there is low heat to decompose the large flow rate of urea.

The factors affecting deposit formation are categorized as 1) Geometrical factors: i) Injector mounting geometry ii) Pre injector exhaust pipe design iii) Pipe design after injector iv) Mixer type v) Mixer orientation and location vi) Insulation 2) Engine exhaust temperature and weather conditions outside the exhaust pipe 3) Dosing conditions: type of injection system, injector pulse width, frequency,etc.

Back pressure is another problem created due to deposit formation over SCR components such as UWS injector, mixing pipe and mixer. This back pressure reduces engine performance. The deposit formation on the SCR catalyst can reduce $NO_x$ conversion efficiency. Decomposition of urea by heating in an open vessel at different temperatures showed that a variety of byproducts by undesirable ways can form at different decomposition temperatures.

### Urea and alternative $NH_3$ generation from the solid reductants

However, the UWS which is used has a number of drawbacks. It is a corrosive liquid with that freezes below -11 $^0$C, decomposes slowly in the tank at temperatures above 50-60$^0$C, crystallizes easily and has to be made from rather pure urea and distilled water to avoid a buildup of impurities on the SCR catalyst and DEF injection system. Another drawback is spray of UWS into the exhaust line, decreases the temperature of exhaust gas 10-15$^0$C[1]. SCR catalyst itself show different performance with different catalyst types and space velocity[14].Moreover, there is solid deposit formation in the exhaust, and difficulties in dosing at exhaust temperatures below 200$^0$C[15]. Additionally, creating a uniform $NH_3$ by UWS spray most challenging. Gaseous $NH_3$ can be generated from various solid reductants, each associated with various decomposition characteristics. The ammonium salts such as ammonium carbamate and ammonium carbonate are generally liberate ammonia. Similarly Magnesium ammine chloride, Calcium ammine chloride Strontium ammine chloride can also liberate ammonia by multiple reaction steps.

### Mixer Adaptation

Compact system could be designed using both mixing units and reducing the length of the chamber and the connecting pipe. It was assumed that the design would be applicable if it showed a better NOx reduction efficiency than that of the reference case [16]. The influence of static mixer on the evaporation of urea droplet increases of turbulent intensity caused by mixers results in the increase of droplet evaporation rate. For the droplets in the spray, the improvement of the evaporation rate will be affected by the enhancement of droplets distribution in the pipe and the increase of turbulent intensity. The droplet diameters distribution with different configurations without mixers, with one mixer and two mixers have been studied base on the spray wall interaction model [17].

## CONCLUSION

Selective Catalytic Reduction (SCR) technique of reduction of $NO_x$ is most suitable for automobile diesel engines to meet the upcoming stringent emission norms. Although the technology is more efficient, there are several drawbacks like ammonia slip, deposit formation, etc. that are associated with it. It requires up gradation of technology. In order to avoid these problems mixers are most commonly used in SCR systems. Alternately, some of the reducing agents find their suitability as substitute for urea to generate $NH_3$.

## References

[1] A. B. Jensen, H. Topsøe, Scandinavian Shipping Gazette 3 (2000), 37-38.

[2] Selective Catalytic Reduction, The most promising technology to comply with the imminent Euro IV and Euro V emissions standards for HD engines, final report, European Automobile Manufacturer’s Association (ACEA), June 2003.

[3] R. Salib, R.K., Optimization of Ammonia Source for SCR Applications, in 2003 Mega Conference 2003.

[4] Koebel, M., Elsener, M., and Madia, G., "Recent Advances in the Development of Urea-SCR for Automotive Applications," SAE Technical Paper 2001-01-3625, 2001, doi: 10.4271/2001-01-3625.

[5] Johnson Matthey Technol. Rev., 2015, 59, (3), 221 doi:10.1595/205651315x688280.

[6] M. Radojevic, Environmental Pollution 102, Sl (1998) 685-689.

[7] M. Koebel, M. Elsener, M. Kleemann, Urea-SCR: a promising technique to reduce $NO_x$ emissions from automotive diesel engines, Catalysis Today, 59(3-4), 2000, 335-345. doi: 10.1016/S0920-5861(00)00299-6.

[8] D S Yim, S J Kim, J H Bai K I Nam, Y S Mok, J W.Lee, B K Cho, S H Oh, Decomposition of Urea into $NH_3$ for SCR process Ind. Eng.Chem. Res 43(1) (2004), 4856-4863 doi:10.1021/ie034052j.

[9] Udo, F., Spray Systems, in Multiphase Flow Handbook 2005, CRC Press. p. 8-1-8-100.

[10] Fritsching U. Spray Systems. In Crowe CT. Multiphase flows handbook. Boca Ranton, FL: Taylor & Francis; 2006.

[11] Omer K, Ashgriz N. Spray Nozzles. In Ashgriz N. Handbook of Atomization and Sprays. New York: Springer; 2011

[12] Lefebvre, A.H., Atomization and Sprays. Combustion: An International Series, ed. N. Chigier1989, United States of America: Hemisphere Publishing Corporation.

[13] Chen, C., Amlee, D., Johns, R., and Zeng, Y., "Detailed Modeling of Liquid Fuel Sprays in One-Dimensional Gas Flow Simulation," SAE Technical Paper 2004-01-3000, 2004, doi:10.4271/2004-01-3000.

[14] J.R. Theis, SCR Catalyst Systems Optimized for Light-off and Steady-state Performance, 2009. Available at: http://papers.sae.org/2009-01-0901/.
[15] T. Maunula, Intensification of Catalytic Aftertreatments Systems for Mobile Application, 2013. Available at: http://papers.sae.org/2013-01-0530/.
[16] Numerical analysis of $NO_x$ reduction for compact design in marine urea-SCR system CFD studies on effects of SCR mixers on the performance of urea conversion and mixing of the reducing agent Ligang Tana,□, Pengfei Fenga, Shubao Yangb, Yage Guoa, Shaochun Liua, Ziwen Lia Chemical Engineering & Processing: Process Intensification 123 (2018) 82–88.
[17] CFD studies on effects of SCR mixers on the performance of urea conversion and mixing of the reducing agentLigang Tana,□, Pengfei Fenga, Shubao Yangb, Yage Guoa, Shaochun Liua, Ziwen Lia Chemical Engineering & Processing: Process Intensification 123 (2018) 82–88.