Urea Solution Dosing System for Improved Catalyst Efficiency

Georg Hüthwohl 1) Andreas Müschen 2)
1)-2) Albonair GmbH,
Carlo-Schmid-Allee 1, 44263 Dortmund, Germany (E-Mail: georg.huethwohl@albonair.com)

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ABSTRACT: A urea solution dosing system for Heavy Duty Diesel engines has been developed with improved spray quality of 15 µm droplet size. The system is in production for EURO 6 trucks. This is accomplished by an air assisted dosing system and innovative nozzle design with external mixing.

KEY WORDS: heat engine, selective catalytic reduction, emissions gas/harmful emissions, urea solution dosing system

1. Introduction

Main toxic pollutants emitted by Diesel engines are particulates and NOx. Within the last 20 years, both have been reduced by about 99 percent using turbocharged engine architectures with electronically controlled high pressure injection systems and exhaust gas recirculation (EGR), combined with exhaust aftertreatment like catalysts and Diesel particulate filters (DPF). Comparing today’s heavy duty engines fulfilling the JP 09, US EPA 10 or Euro IV standard with those engines produced in 1990, the current status is already in the range of “zero emission”.

To reduce the NOx emission, selective catalytic reduction (SCR) technology was introduced to fulfil the Euro IV emission legislation in 20051) and it is used in all Euro VI, EPA 10 and JP 09 trucks today. SCR is also used or planned for implementation in most of the heavier passenger cars with diesel engine in order to fulfil current or upcoming future emission regulations. For off-road applications complying with the Tier4 final emission standard SCR is also the favourite technology2).

To meet customer’s expectation and future reliability targets of the powertrain, the aftertreatment systems need to be improved, concerning packaging and cost aspects simultaneously3). Improvement of the SCR system efficiency provides the opportunity to reduce the amount of EGR as a means for optimized fuel economy, reduced coolant requirements, less weight and better engine durability while increased NOx feed gas emission are balanced independently by exhaust gas aftertreatment.

2. The SCR Process

SCR technology uses ammonia (NH3) as a reducing agent to decompose NOx on a catalytic surface as shown in Figure 1. As ammonia is not available in the exhaust gas, it has to be provided in a controlled way.

Due to toxicity of ammonia, any on-board handling in mobile applications would be ruled by health & safety regulations, which create high burden on the aftertreatment concept. The state-of-the-art solution is to produce NH3 in the exhaust system, using non-hazardous ingredients: an aqueous urea solution. Due to specific advantages, a solution of 32.5 percent urea in water is used as a standard.

![Fig. 1 Principle of selective catalytic reaction](image)

Step 1: Thermolysis

\[(\text{NH}_2\text{H})_2\text{CO} \rightarrow \text{NH}_3 + \text{HNCO} \text{ (isocyanuric acid)}\]

Step 2: Hydrolysis

\[\text{HNCO} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2\]

The decomposition of urea solution to ammonia takes place in the gas phase and is favoured by efficient vaporization of urea and especially by avoiding any wall contacts of the spray.

Vaporisation of the urea is depending on temperature, droplet size (at injector outlet), exhaust velocity (flow turbulences) and time. Main aspects for the ammonia supply to achieve a high conversion efficiency of the catalyst are:

- the homogeneity of the urea solution distribution
- good evaporation of the urea solution
- accurate dosing amount
- avoiding wall contact of the urea solution which may form deposits in the exhaust system.

Using the latest level SCR converter technology, light off temperatures of the catalyst (50 percent NOx conversion rate) is in
the range of 175 °C. At 200 °C already 75 percent NO\textsubscript{x} conversion may be achieved\textsuperscript{(4)}. The injection of the urea solution at very low temperatures is challenging. Especially wall-wetting and accumulation of urea solution in the exhaust system will create unstable urea solution dosing and deposit formation.

In the following chapters, the focus shall be on the urea solution injection process and the adjacent evaporation and mixing processes as factors of the catalytic reactor’s performance, with a special view on packaging and design of the dosing system and reliability.

3. Urea Solution Injection and Droplet Formation

Key element to an optimized SCR catalyst performance is the quality of the urea solution distribution in the exhaust gas as well as the rapid evaporation of the droplets. In combination with prompt urea hydrolysis (temperature dependent) this will result in minimized length of mixing/evaporation/hydrolysis zone downstream of the injector and so reduces the risk for undesired wall contact and condensation of urea. This is a pre-requisite for reduced formation of deposits of crystallized urea in the exhaust pipe.

At the nozzle tip the air is accelerated almost up to ultrasonic speed. The high speed air stream adds velocity to the urea injection flow, provides primary droplet formation, supports flow mixture and as a consequence secondary droplet formation\textsuperscript{(5,6)}. The droplet diameter achieved is about 15 µm SMD (Sauter Mean Diameter). Due to the free flow conditions, the spray angle is 20°\textsuperscript{(6)}. Figure 3 shows the spray formation of an injection shot.

Due to the high velocity of the air stream, even the smallest droplets are accelerated to a high speed of about 24 m/s in the outer space up to 34 m/s in the center. Figure 4 shows the droplet velocity at a distance of 30 mm from the nozzle tip, evaluated by simulation.

The specific advantage of this air assisted concept is a very fine spray quality without having small nozzle orifice diameter, high urea supply pressure or moving elements in the injector (passive injector).

In addition, the urea spray is completely insulated by the accompanying air when entering the hot exhaust stream. This insulation, combined with the enforced droplet formation, supports the intent of reducing the mixing / evaporation / hydrolysis zone and hence contributes to reducing the risk for deposit formation.

Due to the small droplet size achieved as shown in Figure 5, there is no need for a mixer to break up big droplets in the exhaust flow upstream the catalyst. Even distribution of the urea solution
in the exhaust may be achieved by optimisation of the injection point and the exhaust flow. Mixing aids may be necessary if the homogeneous distribution of the urea solution cannot be achieved due to package constraints in the exhaust system, adversely affecting nozzle position, orientation and pipe routing. However most of the systems operated with the air assisted dosing system are operated without a mixer.

It is advantageous to adjust the airflow to the urea solution mass flow and the SCR catalyst requirements. At very low exhaust temperatures it is possible to create very small droplets by increasing the air flow thus enabling improved catalytic conversion. However, at high exhaust temperatures and high exhaust mass flows evaporation of urea solution is not the limiting factor to overall system performance and hence air consumption may be reduced without penalty by reducing the air pressure upstream the nozzle.

4. Urea Solution Dosing System Set Up

To supply the required amount of air and urea solution to the described passive dosing nozzle with external mixing, a dosing unit is necessary.

The required air supply is in the range of some 10 l/min, which requires an air supply at a relative pressure of circa 0.5 bar, referred to the actual exhaust system pressure. This supports both the function of internal nozzle cooling and adequate spray formation. Figure 6 shows the air flow depending on the air pressure upstream the nozzle. To adjust the airflow a proportional valve is used for truck applications. The pressure downstream the proportional valve is controlled by the Aftertreatment Control Unit (ACU) using the signal of the pressure sensor. The proportional valve is directly connected to the vehicle air system with a pressure up to 12 bar. Depending on the application, minimum pressure required is 1 bar.

![Fig. 5 Droplet size depending on urea solution and air flow](image)

Increasing air flow rates creates better spray performance with smaller droplets. It is advantageous to adjust the airflow to the urea solution mass flow and the SCR catalyst requirements. At very low exhaust temperatures it is possible to create very small droplets by increasing the air flow thus enabling improved catalytic conversion. However, at high exhaust temperatures and high exhaust mass flows evaporation of urea solution is not the limiting factor to overall system performance and hence air consumption may be reduced without penalty by reducing the air pressure upstream the nozzle.

![Fig. 6 Air flow depending on air pressure](image)
For urea solution delivery and metering, a membrane dosing pump is used. The membrane pump is typically operated with a dosing frequency up to 55 Hz. Max volume flow of the today’s system is 10 kg/h urea solution. The urea solution mass flow is a linear function of the operating frequency and remains nearly unchanged over the lifetime of the system; Figure 7 shows the deviation from nominal over frequency and at different states in component life.

Additional components and functions have to be implemented in the dosing system for extended function, durability and OBD requirements.

- System purge to be frost resistant
- Detection of deviation from “normal operation” / regular urea solution supply including dosing failure
- Detection of leakages and blockages
- Sensor and actuator check routines

Figure 8 shows the schematic of the dosing system for truck applications using pressurized air as provided by the on-board system of the vehicle. The system has 4 main functional components, on the air side an air flow control valve and an air pressure sensor, on the urea solution side a dosing pump and a combined temperature/pressure sensor; all sensors are positioned downstream the actuator. The urea solution pump is self-priming and directly connected with the urea solution tank. The urea solution pressure on the outlet is in the range of 0.5 bar with peaks during the shot up to 3 bar depending on the pump frequency. The function of the pump is monitored by the pressure sensor, so that the Aftertreatment Control Unit (ACU) is in a position to detect a leaky pressure line for instance as part of the OBD function. The temperature sensor is used to monitor and control system defreezing progress during winter operation as a pre-requisite for urea solution dosing, and to compensate the temperature influence of density and viscosity of the urea solution for improved dosing accuracy.

The proportional air valve is directly connected to the vehicle pressure which is normally in the range of 6 - 12 bar. The air pressure in the system is controlled to the application value needed for the spray formation (range of 0.5 - 1 bar), using the pressure sensor downstream the air control valve.

To purge the system, the air pressure line is connected with the urea solution line by a check valve. When the system is stopped the remaining urea solution of the dosing system is delivered into the exhaust system by opening the proportional valve completely for several seconds: by fully opening the air control valve, the pressure downstream the proportional valve increases to higher level that operates and opens the check valve and in consequence the remaining urea solution in the dosing system and feed lines is injected into the exhaust system. To minimize the amount of urea solution purged into the exhaust system, the inner diameter of the lines are limited to 2 mm. Injected amount is in the range less than 10 ml which is not forming deposits as it is spayed in the hot exhaust with a fine spray due to the high pressure both on the urea solution and the air lines of the nozzle.

Table: Application of UREA Dosing System Components

| Application          | EU6 UDS - On-Road (MD/HD) |
|----------------------|--------------------------|
| Emission regulations | EU 4, 5, 6, EPA 10, JPO9 |
| Differences on functional Level | 24V, 12V capable with modifications |
| Power Supply         | 24V 12V capable with modifications |
| Product readiness (year) | SOP 2013 |

Fig. 8 Set up of the urea solution dosing system using vehicle air

If the pressure lines between dosing unit and nozzle are long, as an alternative solution to the purge routine, a collection of the urea solution in a dedicated reservoir governed by a membrane actuator has been designed. The reservoir is operated either by the air pressure or by a solenoid. On engine stop or cut-off of voltage
supply, the urea solution is sucked back into the reservoir by providing additional volume. For the next start, the urea solution is pressed back into the system as to be seen in Figure 9. Besides avoiding the consumption of urea solution for the purge routine, it is an advantage of this concept that it is self-operating at every switch-off of the engine so there is no operated process (“afterrun routine”) necessary when stopping the engine. This is important for the ADR applications. Frost protection of components (during system shut-off) is provided by suitable reservoir design.

As shown in Figure 10, all components are mounted on an alumina bedplate which is designed to route and control air and urea solution flows, to fixture the components and to connect the tubes. The alumina sub plate is heated by coolant water to defrost and keep the system running also at low ambient temperatures; due to this concept, the components mounted on the sub late do not require specific and individual heating but are ideally connected via thermal conductivity to the heat source.

In case, the vehicle has no compressed air available on board, as is the case with most of the off-road applications, the system can be operated with an electric air compressor as shown in Figure 10. To reduce the electric power necessary and achieve the required durability target, the air pump is directly connected to the dosing unit and nozzle. The function is controlled by the air pressure sensor in the dosing unit. The pressure level required from the pump is approx. 1 bar rel., resulting in an air flow rate of ca. 10 l/min depending on the backpressure of the engine.

For future designs, a concept has been worked out to integrate the dosing pump into the urea solution tank as shown in Figure 11, minimizing the number of interfaces. On top, the air path is totally separated from the urea solution path, and heating the urea solution pump and sensors is done via the tank heater. With this design, significant cost optimization can be achieved while taking advantage of higher flexibility in system package.
The air assisted dosing system is in production for EURO 6 trucks\(^9\). Due to the simple design and avoiding any electric components at the dosing nozzle, it is proven to be very robust. Purging the system is leading to a frost resistant design. The compact nozzle allows variable installations in the exhaust system as shown in Figure 12.

5. Conclusion

An air assisted dosing system for EURO 6, US2010 and JP09 emission legislation demonstrates the importance of a good spray formation with an SMD of 15 µm. Injection of the urea solution is possible at temperatures as low as 170 °C without deposit formation on the exhaust walls. The system is also capable of very high exhaust temperatures as there are no measuring/moving mechanical parts in the nozzle due to the “passive nozzle” concept.

The presented dosing principle allows a compact design and can be adapted for different installation requirements, following the ideas of maximum system integration or locally distributed components and functions. The system has been brought into production and proves functionality and reliability at the end customer.

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