Chapter 15

DEF Systems and Aftertreatment Architecture Considerations

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As emissions regulations become more stringent, new aftertreatment technologies are necessary. To assist in the reduction of NO_x emissions, liquid-based SCR technologies have been adopted globally. The most common technique used to introduce ammonia (NH_3) into the exhaust stream is via a dosing system metering diesel exhaust fluid (DEF). SCR system efficiency relies heavily on how uniformly the NH_3 is distributed across the catalyst face. The challenge of preparing uniform NH_3 mixture includes the following (see Fig. 15.1):

- Spraying atomized urea/water solution (DEF) into a mixing section.
- Interaction between liquid drops and exhaust gas, as influenced by varying gas velocity and temperature, dosed urea quantity, droplet size, and quantity control method (pulse width or pulse frequency).
- Decomposition of urea and formation of NH_3 and HNCO gaseous compounds.
- Evaporation of water from droplet surfaces and corresponding increase in urea concentration inside the droplets.
- Uniform mixing of NH_3, HNCO, and the remainder of nondecomposed high-concentration urea particles.

Complete decomposition of urea into NH_3 is not possible given insufficient residence time inside typical mixing spaces found in automotive applications. But as long as a uniform mix is available at the SCR entry, urea decomposition will continue in uniform manner inside the SCR. Thus, most attention in developing the mixing section is devoted to achieving a uniform concentration of gases at the SCR entry.

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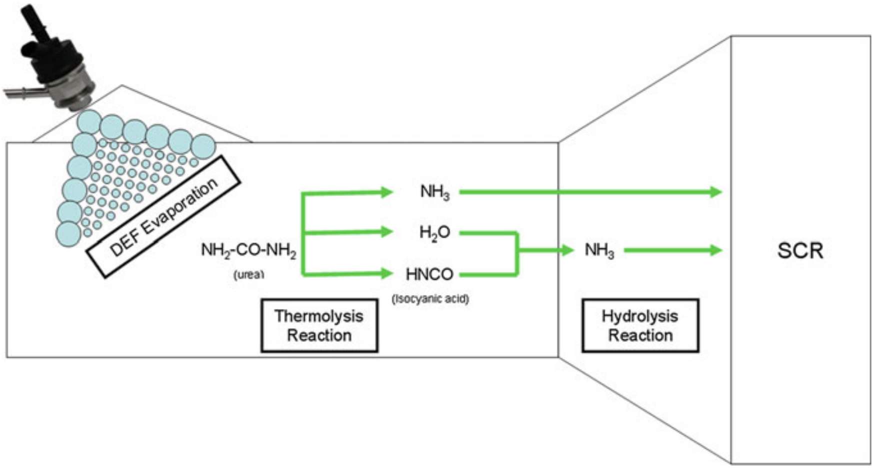


Fig. 15.1 High-level overview of DEF decomposition mechanism

The mixing uniformity challenge has to be met throughout the wide and continuously varying range of exhaust flow and temperature, which produces variability of spray dispersion and deflection from its injection angle, resulting in variability of spray interaction with mixing elements. These phenomena are influenced by injector performance characteristics that include droplet size, spray cone-type (filled, hollow, or individual jets), injection angle, as well as injector tip recess relative to the pipe ID, and gas flow pattern near the spray entry.

The complexity associated with implementing a liquid-based SCR system increases with more stringent NO_x reduction targets. In general, the more stringent the emissions, the more efficient the SCR system must be. To achieve an efficient system, aftertreatment geometry, injector technology, dosing rates, and engine calibration all need to be considered and optimized as a system. Due to their interactive dependencies, taking a component-level approach to integration will prove difficult to meet EPA 2010, Euro VI, and Tier IV Final emission regulations. Because the NO_x reduction targets for these regulations are so aggressive (0.27, 0.4 and 0.4 g/kWh respectively), the implementation of SCR technology should be understood at a system level for maximum efficiency. Having a system level understanding means that all of the necessary inputs and their interactions have been considered and will be implemented in a way where they work together to achieve the NO_x reduction goals of the system. Figure 15.2 provides a pictorial description of the points mentioned above. Understanding the role that each of the inputs plays with respect to achieving NO_x reduction leads to the creation of an optimized system.

After each input has been identified, the engineering process of creating the system begins. The best way to optimize the NO_x abatement system is to follow a defined development process. Figure 15.3 outlines a typical systematic NO_x abatement development process. This process requires an in-depth understanding

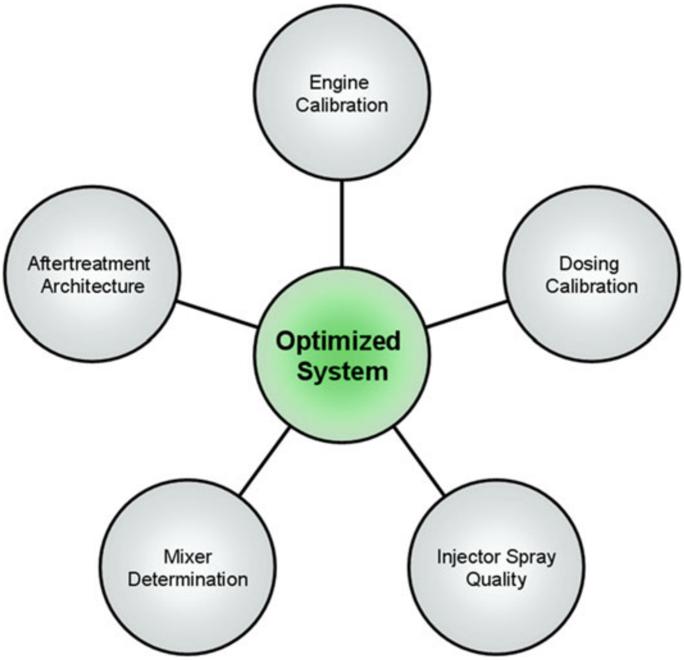
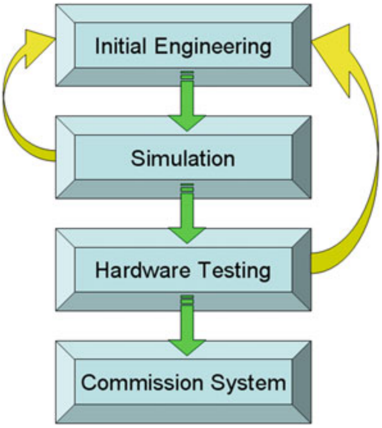


Fig. 15.2 Requirements for an optimized NO_x abatement system

Fig. 15.3 NO_x abatement system development process flow



of the application being targeted for the NO_x abatement system. From this information, simulation and hardware testing can occur. Both 1D and 3D simulations can provide valuable information relative to creating and optimizing a NO_x abatement system. Although significant benefit can come from simulation work, if the input values are not accurate and the simulation work is not correlated with hardware testing, it can lead to wasted time and effort. Once proper correlation has occurred between hardware and simulation, the simulation tools can be used in an iterative process to improve a design before hardware is built. This correlation may be necessary for each targeted application. It is not guaranteed that once the simulation tool correlates to an aftertreatment hardware set, that it will always correlate to all applications. Simulation programs provide an opportunity to quickly evaluate designs without the additional costs associated with building hardware and running engine dynamometer test cells. After the NO_x abatement system has been thoroughly analyzed in simulation, hardware needs to be created and tested. Hardware testing should be performed in a way that evaluates the NO_x reduction efficiency, deposit formation concerns, and overall system robustness. If during this process it is shown that the system will not achieve the intended performance, iterations of the overall design of the system must occur. The subsequent design iterations should begin in the simulation step, with the actual hardware results being fed back into the models for more accurate simulation results in the future.

The most critical piece of the development process flow is the initial engineering step. Figure 15.4 outlines the steps associated with the initial engineering step. Without proper effort during this stage, the project can start down the wrong path, which can ultimately lead to on-application performance issues. The two most common performance issues are NO_x reduction efficiency and urea deposit concerns. The three primary steps to initial engineering are defining system goals, quantifying inputs, and designing the system. The first step related of defining system goals relates to determining what emission regulation the application needs to adhere to, what type of DEF delivery system will be targeted, what the NO_x reduction and backpressure targets will be, and others that define the boundary conditions of the project. The second step, quantifying inputs, relates to retrieving information specific to the application including but not limited to engine emission data, allowable packaging space claim for the NO_x abatement system and typical duty cycle usage. The final step related to initial engineering is the creation of the initial design. The initial design will incorporate the information gained while defining goals for the system and quantifying the inputs. Incorporating this information into the design will provide a good starting point for the design prior to beginning the simulation phase. The more accurate the information feeding the design, the more robust and representative the design will be.

Following a defined development process will help reduce the amount of time necessary to complete a full NO_x abatement system design and system implementation. Successfully completing each step will also reduce the risk associated with in-field failures or issues related to meeting emission certification. Not following a defined process can lead to wasted resources (time, effort, and money) pursuing designs that will not be able to achieve the desired performance requirements. The remainder of this chapter will be focused on describing the primary inputs to an SCR aftertreatment system outlined in Fig. 15.2.

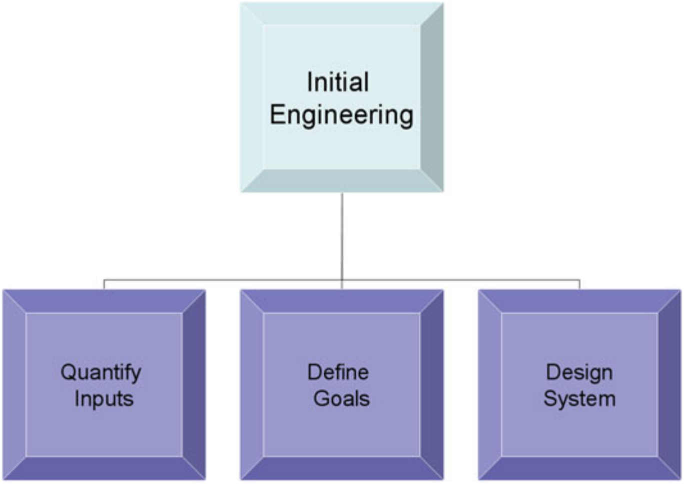


Fig. 15.4 Overview of the initial engineering step

15.1 Role of Engine and Dosing Calibration

As mentioned previously, DEF is metered into the aftertreatment system to reduce tailpipe NO_x emissions. The amount of DEF that needs to be metered into the aftertreatment system is part of the dosing calibration. This dosing calibration is directly linked to the engine calibration. The amount of NO_x created during the combustion process is driven by the engine calibration. Through proper tuning, the dosing calibration is created in a way to meter the proper amount of DEF into the system to reduce the tailipipe NO_x to meet the targeted NO_x level. Figure 15.5 shows how engine calibration and dosing calibration are related to the systemic approach to designing a robust SCR system.

Determining steady-state dosing quantity is a straightforward process. Although this process is straightforward, it does not necessarily reflect the dosing quantity that will be used in the application's final dosing calibration. The reason for the difference is that the final dosing calibration will also consider the SCR catalyst storage characteristics, exhaust gas temperature and targeted reduction to meet the emission regulation. For the purposes of this section, only the chemistry will be considered. Equation 15.1 outlines the equation used to determine the ammonia (NH_3) concentration from a given amount of injected DEF. This equation can also be used to determine the necessary amount of DEF that needs to be injected to create a certain amount of NH_3. Within the equation, $M_{H_4N_2CO}$ is the molecular mass of urea, which is equal to 60.0 g/mol. The average exhaust molecular mass is assumed to be 28.8 g/mol and is denoted as M_{exh}. Lastly, $\dot{m}_{exh}$ represents that mass flow rate of the exhaust in kg/h.

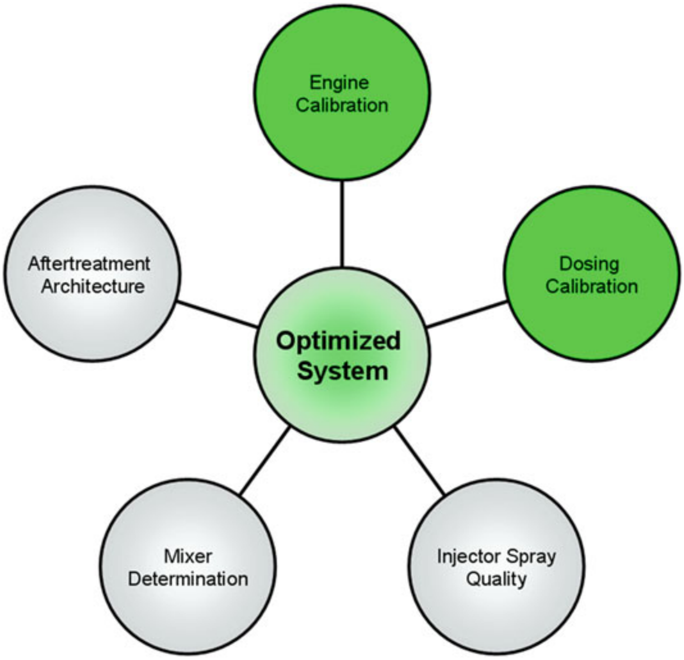


Fig. 15.5 Role of engine and dosing calibration in SCR system optimization

$$\mathrm{NH}_3\,[\mathrm{ppm}] = \frac{\frac{\mathrm{DEF}_{[g/h]} * 0.325}{M_{\mathrm{H_4N_2CO}}} * 2}{\frac{\dot{m}_{exh} * 1000}{M_{exh}}} * 10^6 \qquad (15.1)$$

The amount of NH_3 that needs to be injected under a given condition relates to the targeted ammonia to NO_x ratio (ANR). If the ANR is equal to one, then the amount of NH_3 (ppm) should be equal to the NO_x concentration (ppm) measured during the targeted steady-state condition. As mentioned previously, the ANR term will vary based on engine condition and the chosen catalyst washcoat technology. Figure 15.6 shows an example of an ANR sweep. An ANR sweep is a steady-state test where the amount of DEF injected is increased and the NO_x reduction and ammonia slip is measured at the outlet of the SCR. Ammonia slip represents the ammonia concentration measured that passed through the catalyst without reacting with the NO_x. An ANR sweep is a good tool that can be used to evaluate the steady-state performance of the system. As shown in Fig. 15.6, as the ANR ratio is increased, more NO_x is reduced while ammonia slip increases.

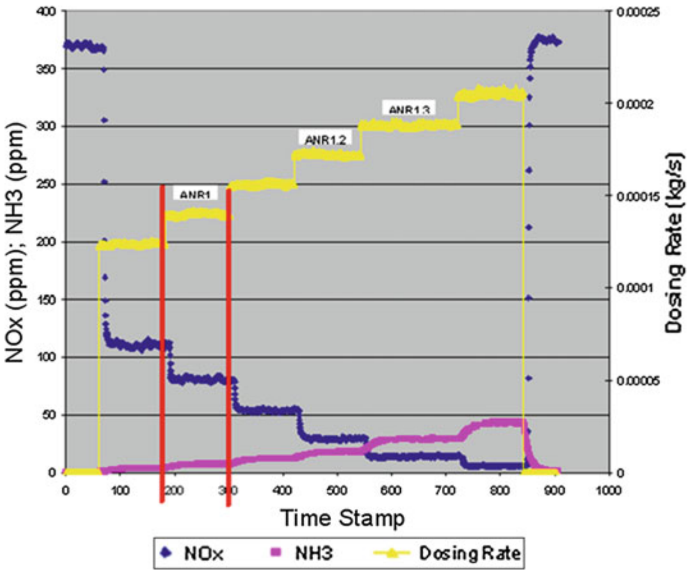


Fig. 15.6 ANR sweep example

15.2 Overview of Injection Technology and Spray Quality

For systems that utilize DEF injection, there are two primary technologies utilized. One type of doser mixes air with the liquid DEF to create the spray that is introduced into the aftertreatment system. This type of system is called an air-assisted system and it utilizes a metering pump and a dumb nozzle. The second type of system is called an airless system, which utilizes an injector to meter liquid DEF directly into the exhaust. The focus of this section will be on airless technology, specifically, two different styles of metering injectors, pressure swirl and liquid jet. Regardless of the injection technology, two main inputs need to be understood when implementing it into the system. The two inputs are dosing quantity and spray quality. Dosing quantity relates to the amount of DEF that needs to be introduced into the exhaust to reduce the targeted amount of NO_x for a given condition and was covered in Sect. 15.1. Spray quality is associated with the evaporation and decomposition of the DEF spray droplet as well as how the spray interacts with the exhaust flow. Figure 15.7 highlights the role of injector spray quality in an optimized SCR system design.

While spray quantity is important to achieving NO_x reduction performance, it is independent of the type of injector technology chosen. Instead, spray quality is a primary metric used in determining the injector and mixing technology that is used. Spray quality is a measure of the size, speed, and pattern of the DEF droplets that enter the exhaust stream. Two types of test equipment used to quantify spray quality are shown in Fig. 15.8. The piece of equipment shown on the left of the

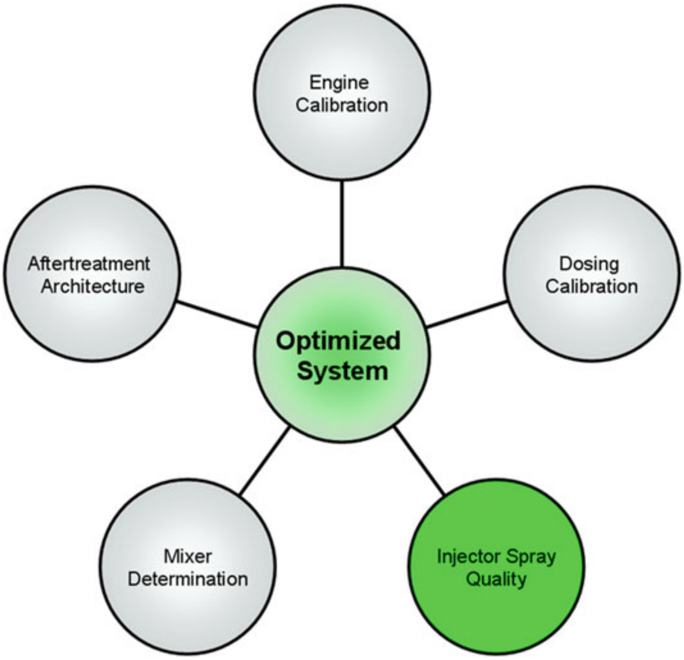
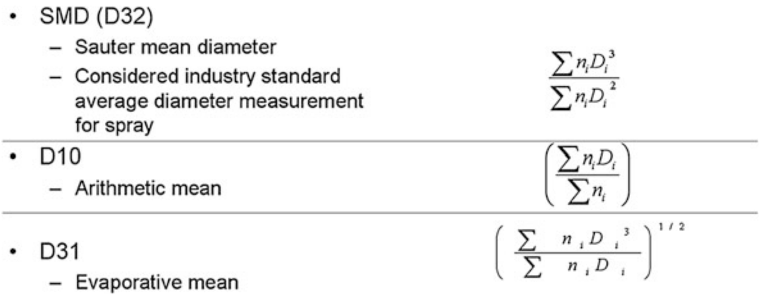


Fig. 15.7 Role of injector spray quality in SCR system optimization

Fig. 15.8 Spray quality measurements equipment. *Left* PDPA. *Right* Patternator

picture is a Phase Doppler Particle Analyzer (PDPA) and the piece of equipment on the right is called a patternator. The PDPA is able to provide droplet size, spray angle, particle concentration, droplet distribution, droplet measurement count, and velocity values. These values are measured using light refraction of the droplets that pass through an intersecting laser probe volume during a set period of time. A patternator is used to identify the spray pattern created by an injector as well as



- SMD (D32)
  - Sauter mean diameter
  - Considered industry standard average diameter measurement for spray

$$\frac{\sum n_i D_i^3}{\sum n_i D_i^2}$$

- D10
  - Arithmetic mean

$$\left(\frac{\sum n_i D_i}{\sum n_i}\right)$$

- D31
  - Evaporative mean

$$\left(\frac{\sum n_i D_i^3}{\sum n_i D_i}\right)^{1/2}$$

Fig. 15.9 Spray quality calculations—SMD, D10 and D31

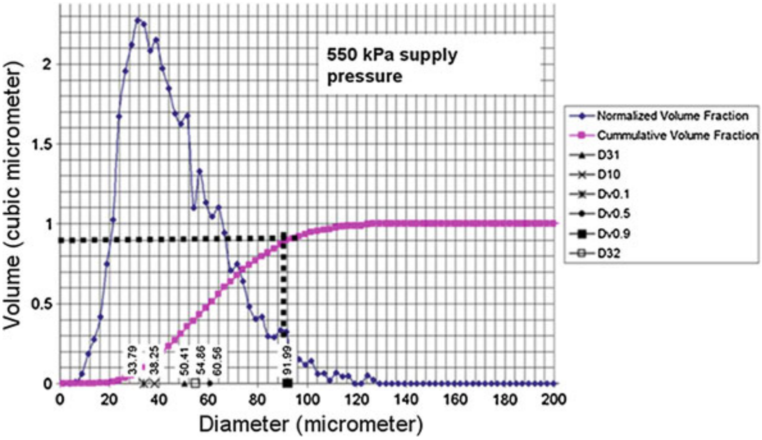


Fig. 15.10 Spray quality calculations—droplet distribution curve and Dv0.9

identifying the spray angle, roundness of the spray pattern, and skewness associated with the spray. Each piece of equipment provides valuable information needed to describe the spray quality of a given injector.

Not only are these tools important for injector development, they also provide critical information used as inputs for computational fluid dynamics (CFD) analysis. As mentioned previously, simulation plays a critical role in SCR system development. The more accurate the measurements are while quantifying an injector's spray quality, the more accurate the simulated spray quality will be which will in turn give better correlation between simulation and hardware testing.

There are multiple spray measurements used to quantify an injectors spray quality. Some of these measurements include D10 (arithmetic mean), D32 (Sauter mean diameter), D31 (evaporative mean diameter), Dv0.9, and droplet distribution curve. Figure 15.9 provides a description and equation used to calculate SMD, D10, and D31. Figure 15.10 shows a typical droplet distribution curve with an overlay to show the Dv0.9 calculation. The Dv0.9 value represents the point where

Table 15.1 Sample spray quality measurement

Diameter measured (μm)	Count
25	12
45	50
65	150
85	32
105	40

90 % of the measured spray has less than the measurement reported for the Dv0.9 value. This description also applies to Dv0.1 (10 %) and Dv0.5 (50 %) measurements.

To provide clarity when calculating Sauter mean diameter (D32), an example has been provided below. The SMD measurement represents a one number descriptor used to compare different sprays and is considered industry standard for comparing spray quality. Table 15.1 provides a truncated sampling of a hypothetical spray. For this example, whole numbers are used to signify the number of droplets counted for a given diameter measurement. This data can be used to calculate the SMD for the example outlined below. Equations 15.2–15.4 show an example of how to calculate SMD based on the data provided in Table 15.1.

$$\frac{\sum n_i D_i^3}{\sum n_i D_i^2} \tag{15.2}$$

$$\frac{[12 * 25^3] + [50 * 45^3] + [150 * 65^3] + [32 * 85^3] + [40 * 105^3]}{[12 * 25^2] + [50 * 45^2] + [150 * 65^2] + [32 * 85^2] + [40 * 105^2]} \tag{15.3}$$

$$\text{SMD} = 79\,\mu\text{m} \tag{15.4}$$

The information provided during the spray characterization process can be used to evaluate different injector technologies. The following examples are a comparison between a commercially available liquid jet style injector and to a pressure swirl style injector. Both injectors fall into the category of an airless injector. The liquid jet injector has three holes that the DEF is injected through whereas the pressure swirl injector only has one hole that the spray flows through. Figure 15.11 shows a side-by-side comparison of the patternator measurements collected. These measurements were made 49 mm from the exit of the injector. The plot for the pressure swirl injector shows that the spray created is a uniform circle with the highest concentration of droplets measured at the center of the spray. The liquid jet injector shows that the highest concentrations of the droplets are measured within the three jets.

Along with the patternator data, the PDPA was used to measure the droplet sizes and velocities. Like the patternator measurements, PDPA measurements were made 49 mm from the outlet of the injector. Figure 15.12 shows the velocity measurement as the measurement probe volume of the PDPA traversed axially through the spray cone. This means that the left side of plot represents the left side

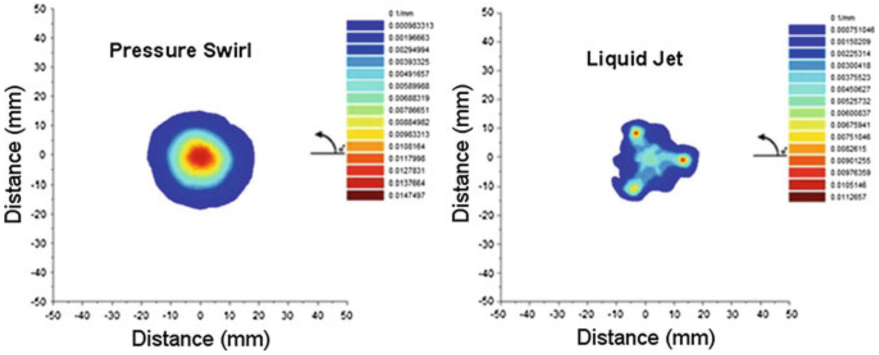


Fig. 15.11 Spray quality comparison—Patternator

of the spray and the right edge of the plot represents the right edge of the spray. For the pressure swirl style injector, the average velocity measured 49 mm from the injector exit is relatively consistent across the entire spray cone. For the liquid jet injector, the measurement probe volume was intentionally traversed through two of the three jet streams. For this injector, it was found that the individual jet streams had the highest concentration of drops (Fig. 15.11) and that these drops have a higher velocity than the other drops in the spray. The penetration of the droplets into the exhaust stream is based on the relationship between the droplet velocity and the exhaust gas velocity. This relationship quantifies whether or not the spray will impact the exhaust pipe walls (or the mixing element) and will be addressed further in the mixer determination section below.

Lastly, droplet distribution curves and droplet size characteristic measurements were made for each of the sprays. Figure 15.13 shows the droplet size characteristics for the pressure swirl injector and Fig. 15.14 shows the droplet size characteristics for the liquid jet injector. The droplet size distribution is shown in both a cumulative and normalized sense. The cumulative volume fraction is used to determine Dv0.1, Dv0.5, and Dv0.9 measurements. The calculated values for D10, D31, and SMD are also shown on each plot. In general, the pressure swirl injector analyzed had a tighter distribution of injected droplets. The tighter distribution means that there are fewer larger droplets measured, which create smaller values for all of the key droplet characteristics, measured (D31, D10, Dv0.1, Dv05, Dv0.9, and D32).

Spray quality plays a critical role in system level performance. Regardless of the doser technology chosen, a thorough understanding of the developed spray characteristics is required to begin to model system level interactions. The spray interaction with the exhaust gas flow is the first portion of the DEF system performance described earlier in Fig. 15.1. Integrating good spray quality into an optimized SCR system design reduces the risk that the overall system will have issues related to droplet impingement, incomplete decomposition, or deposit formation.

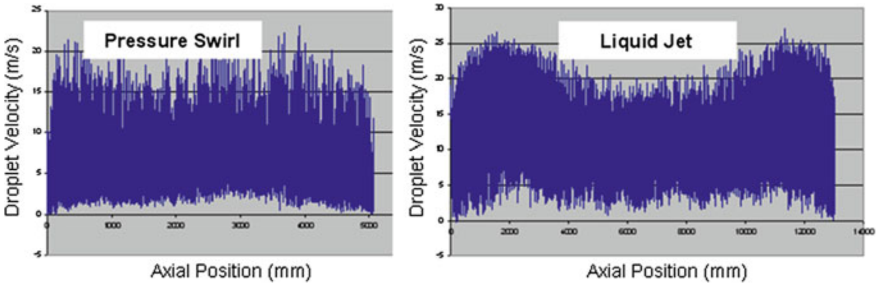


Fig. 15.12 Spray quality comparison—droplet velocity

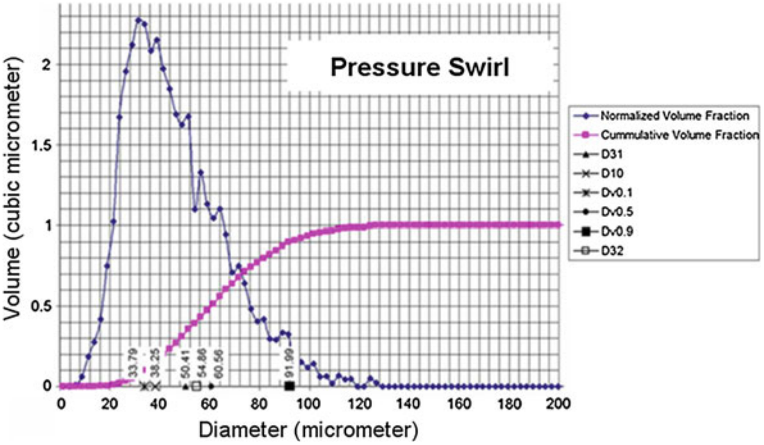


Fig. 15.13 Spray quality comparison—droplet size (pressure swirl injector)

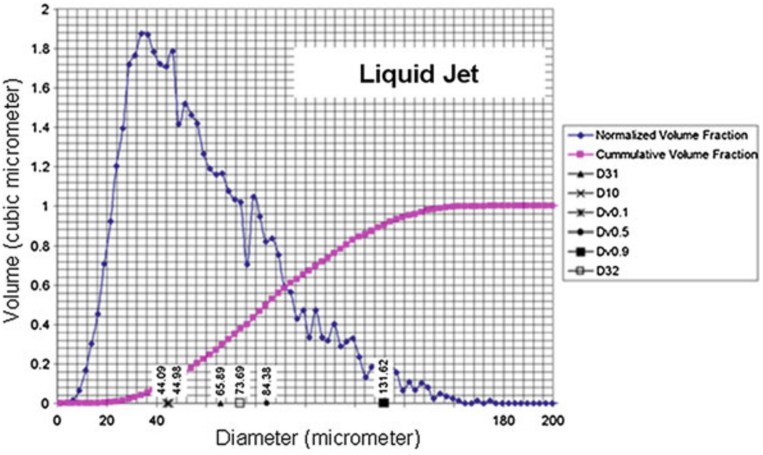


Fig. 15.14 Spray quality comparison—droplet size (liquid jet injector)

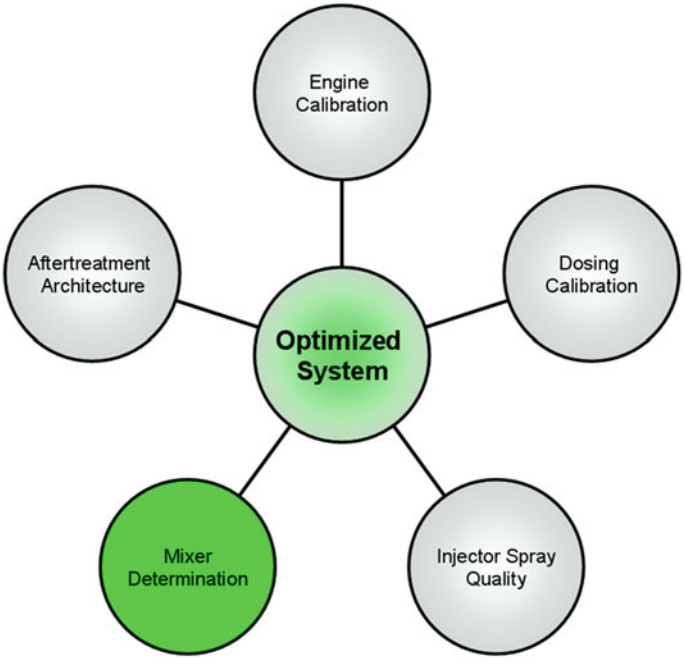


Fig. 15.15 Role of mixer determination in SCR system optimization

15.3 Overview of SCR System Mixing Devices

Mixing devices are used in SCR aftertreatment systems to improve system performance. Figure 15.15 shows the role of mixer determination in the SCR system design process. The type of mixer chosen, and how it is integrated into the aftertreatment system, can help improve system performance by improving SCR uniformity and reducing the risk of deposit formation due to incomplete DEF decomposition. Improper integration of a mixing element can hinder system performance and introduce deposit formation concerns.

There are multiple types of mixing devices used in current production SCR systems globally. For the purposes of this section, the focus will be spent on three different types of mixers; a 2-stage mixer, an in-pipe style mixer, and a swirl style mixer (Fig. 15.16). Each of these styles performs well under certain applications and operational duty cycles, and not so well in others. Along with mixer type, injector placement and injector mount geometry also needs to be considered when designing the mixing portion of the decomposition tube. The decomposition tube is considered as the portion of the aftertreatment system from the injector to the mixer outlet. Although decomposition continues to occur after the mixing unit, the section immediately following the mixing unit will be called the mixing tube.

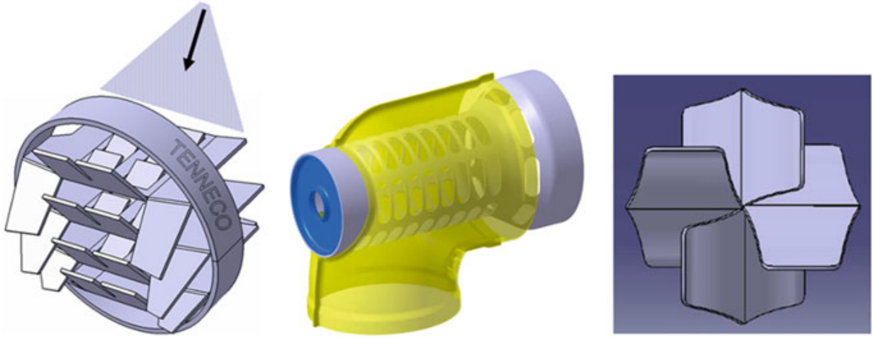


Fig. 15.16 Mixer designs, 2-stage (*left*), in-pipe (*center*) and swirl style (*right*)

Attributes of a well-designed mixing/decomp tube include shortening allowable decomposition/mixing length, reducing DEF consumption and managing lower temperature applications. Figure 15.17 shows an example of how the proper use of a mixing device can help reduce DEF consumption and improve NO_x reduction efficiency. The original system had a nonoptimized mixing solution present. Following the defined process outlined in Fig. 15.3, the system now required a lower dosing rate (under the steady state test point tested) to achieve the same amount of NO_x reduction. It is important to understand that from a chemical perspective, the mixing device chosen will not help create additional ammonia. Instead, this example is highlighting the fact that optimizing the mixer selection and location will improve the velocity and species uniformity on the inlet of the catalyst, thereby increasing the amount of catalyst used.

The primary goal of system optimization is to achieve high velocity and species uniformity at the inlet of the SCR. Having high velocity uniformity means that the gas flowing through the SCR catalyst is well distributed. A high species uniformity means that the concentration of the species (ammonia and isocyanic acid) are evenly distributed across the SCR inlet. Equation 15.5 provides how to calculate uniformity where X is the variable being measured, A is the total area of the catalyst sampled and A_i is the area of each individual node measured within the overall area.

$$\gamma = 1 - \frac{1}{2}\sum_{i=1}^{n} \frac{|X_i - X_{\text{mean}}|A_i}{AX_{\text{mean}}} \tag{15.5}$$

Without good distribution, the SCR system will be prone to increased DEF consumption, decreased NO_x reduction, and increased NH_3 slip (Fig. 15.18). Although Fig. 15.18 shows a comparison between a no mixer scenario and to an SCR system with a mixer, the trend will remain true for a system with an optimized mixing solution compared to one without an optimized mixing solution. Therefore, it is important that care is taken when determining a mixer for an application as well as how the mixer is implemented.

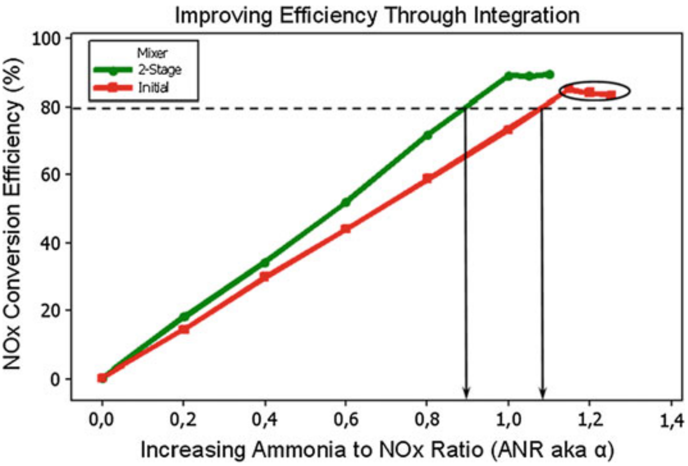


Fig. 15.17 System optimization through mixer integration

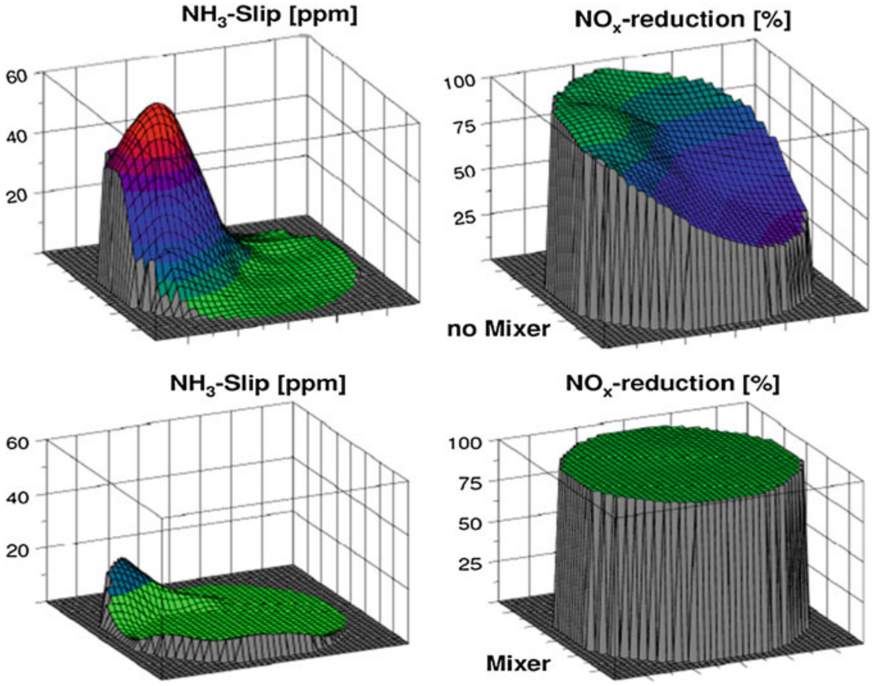


Fig. 15.18 The role of efficient mixing in SCR systems

A primary concern with mixing devices is the increase in backpressure associated with implementing a mixing device. The trade-off between mixing efficiency and backpressure are key factors in designing the decomposition tube.

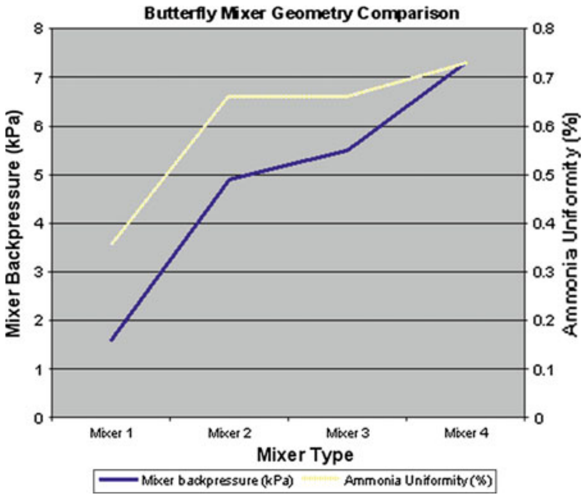


Fig. 15.19 Backpressure versus mixing performance trade-off *curve*—butterfly mixer

In general, higher mixing efficiency (turbulence after the mixer) produces higher backpressure. Figure 15.19 provides a backpressure versus mixing performance (NO_x reduction efficiency uniformity) for the butterfly mixer shown in Fig. 15.16. The aggressiveness of the angles of the blades has been adjusted to improve species uniformity at the SCR inlet. As shown in Fig. 15.19, the steeper the angle of the blades, the greater the backpressure as well as the greater the mixing efficiency.

After the type of mixer has been determined and the applications backpressure requirements are understood, the mixer placement needs to be determined. For this step, a CFD program can be used to determine the ideal position for the mixer. Using a CFD program will require having accurate information related to the duty cycle of the application as well as the injector that will be used. The interaction between the energy of the injected DEF spray and the energy of the exhaust will determine the penetration distance of the spray. Figure 15.20 shows an example of spray droplet penetration and the mixer position. As observed in the picture on the left, without a mixer, the droplets would penetrate through the exhaust flow and impede on the exhaust pipe wall on the opposing side of the injector. Doing this, can lead to issues caused by the DEF impinging on the exhaust pipe wall and locally cooling the surface. Once the exhaust pipe is cooled, the system has the potential to form urea-based deposits. For this reason, a picture on the right shows the position of the mixer placement to ensure that the injected DEF does not impinge on the exhaust pipe wall and instead properly impinges on the 2-stage mixing device.

Mixer placement is not only limited to reducing the potential for impingement on the exhaust pipe, but it also needs to meet the backpressure, velocity, and species uniformity targets. To do this effectively, the engine conditions need to be understood. The primary engine outputs that need to be considered are exhaust mass flow

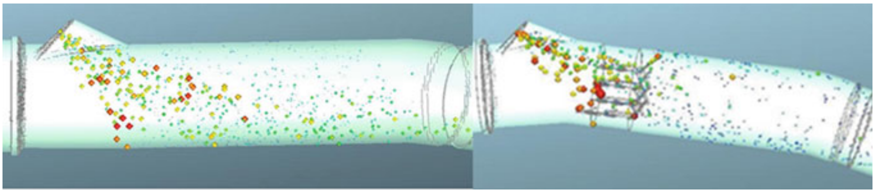


Fig. 15.20 Mixer placement example—2-stage mixer

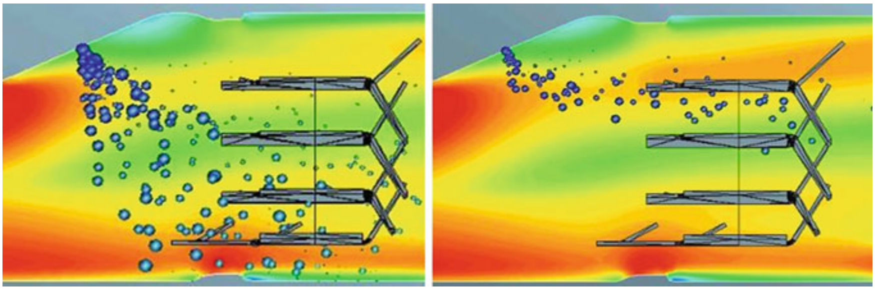


Fig. 15.21 Mixer placement example—2-stage mixer impingement: Low flow (*left*), high flow (*right*)

rate, exhaust gas temperature, and NO_x concentration. Using this information, the CFD model will be accurate and the dosing quantity can be calculated. Additionally, mixer placement cannot be based only on one engine condition. Multiple conditions need to be evaluated in order to fully understand mixer impingement and system performance. Evaluating the system at both low and high mass flow, rate conditions provides valuable information relating to how the injected spray will impinge on the mixer. Figure 15.21 shows the proper configuration for the 2-stage mixer. Under the low flow rate condition (left), the droplets penetrate through the gas stream and impinge on the bottom layers of the mixer. During high flow rate conditions (right), the droplets still impinge on the mixer. Moving the mixer too far away from the injector increases the risk of the injected spray penetrating through the exhaust and creating the increased potential for DEF pooling on the inside of the exhaust pipe causing urea deposit formation.

15.4 SCR System Mixing Devices: Ford Practical Example

Mixing space limitations in exhaust systems of Ford diesel trucks imposed a difficult set of design constraints. At the same time, fixed injector design parameters (injection pressure, spray angle, droplet size, etc.) and some combinations of exhaust flow and temperature resulted in very short residence times (below 20 ms) for droplet evaporation and urea decomposition.

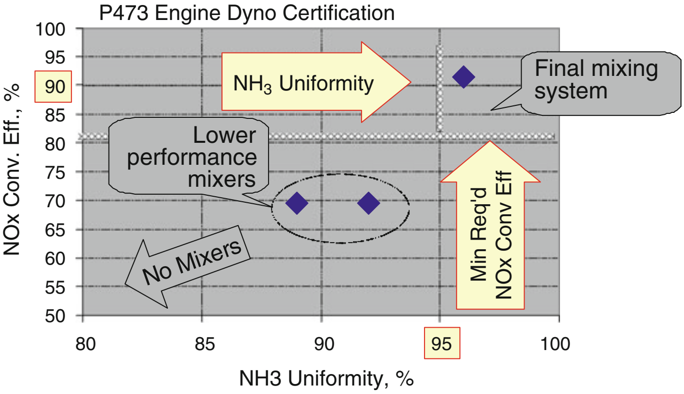


Fig. 15.22 The NO_x conversion efficiency as a function of NH_3 uniformity

To achieve the required NO_x conversion efficiency with these constraints, a single uniformity target for all operating conditions was needed. A series of engine tests was run to determine an effect of mixing uniformity on NO_x emissions. Various mixer designs were tried and produced the data summarized in Fig. 15.22. Here the NO_x conversion efficiency is plotted as a function of mixing uniformity. As the result of the mixer selection process it became possible to meet the NO_x conversion target of 90 % only when uniformity levels were greater than 95 %. To achieve this high level of uniformity, new NH_3 sampling and data analysis methods were developed, as described in the following sections.

To evaluate urea mixing quality, a new test rig was designed and built. The rig allowed collection of 37 ammonia concentration values in about 1 h. The values were collected at the end of the mixing section followed by a short flow-straightening element (Fig. 15.23). A rotating sample probe was designed with a minimal resistance to the gas flow. The data was organized to produce a circular pattern that showed sensitivity to an interaction between the atomized liquid and the gas flow.

The new sampling technique reduced reliance on CFD modeling that, with numerous hardware changes, became more time-consuming and not sufficiently accurate in predicting local gas concentrations. The high-cost engine dynamometer testing was reserved for the rig data validation.

Initial analysis of uniformity was based on the industry-wide uniformity index known as the gamma value. The index is generally expected to take into account local concentration values anywhere within the studied gas flow area. However, when compared to changes in uniformity pattern produced by various mixers, the index was not sufficiently sensitive to certain types of nonuniform distribution resulting in overly optimistic values.

This led to the need to describe uniformity patterns produced by various mixers, and to characterize these patterns in some way. The rotating probe produced data that could be grouped according to the three diameters resulting from rotation of

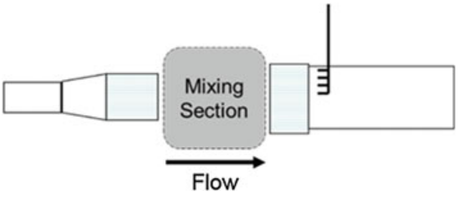


Fig. 15.23 Rotating sampling probe

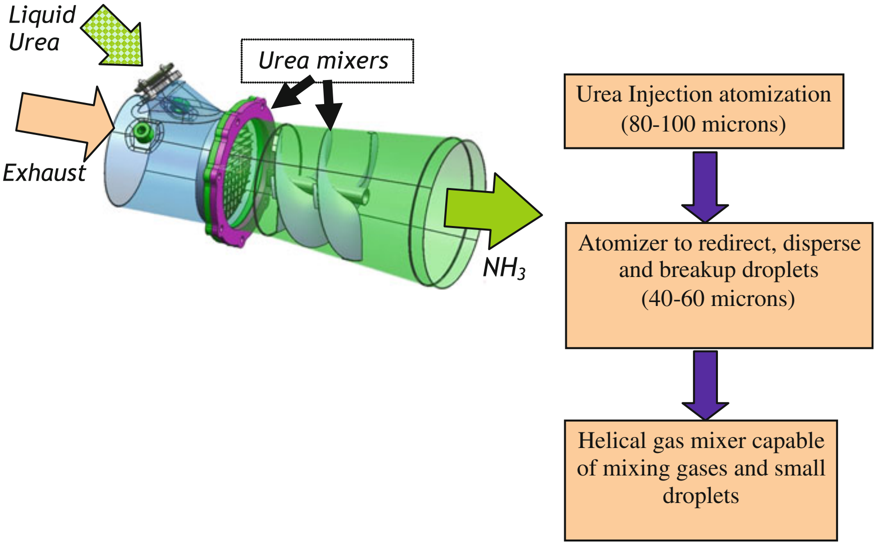


Fig. 15.24 Ford 2-mixer system

probe cell centers. This made it easier to relate uniformity patterns to the round cross-section of the SCR inlet.

The technique was sufficiently sensitive to small changes in uniformity and became a useful tool for continuous improvement of mixing hardware. It allowed:

- Faster comparison of mixing hardware designs and selection of best configurations.
- Fine tuning of mixing hardware within particular mixing section packaging constraints.
- Good correlation of rig uniformity data with engine and vehicle NO_x reduction data.

The uniform mixing (with 95 % gamma or better) was achieved with a 2-mixer approach, using a pre-mixer and a gas mixer, both located downstream of the dosing injector. The spray direction was chosen to form a 45° angle with exhaust flow (Fig. 15.24). The functions of the two mixers were as follows.

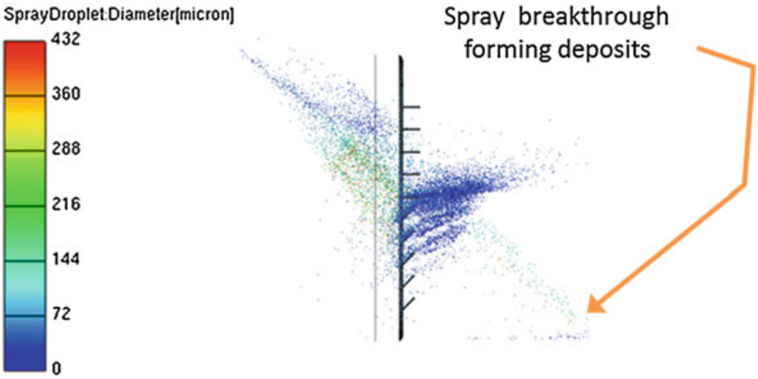


Fig. 15.25 Spray impingement, re-direction and breakthrough

The pre-mixer contained a multitude of spray impingement plates to enable the following:

(a) Redirect spray to align it with exhaust flow,
(b) Disperse liquid drops, and
(c) Facilitate a breakup of urea droplets (secondary atomization).

The width, spacing, and angle of impingement plates were optimized to improve these functions. The angle was adjusted to make the droplets arrive at the center of the main mixer within the variability of the impingement footprint at the mixer entry. The spacing and the width prevented spray breakthrough, so that none of the droplets could pass through the atomizer without being deflected and land at the bottom of the pipe (Fig. 15.25).

The main helically shaped gas mixer (auger mixer) was placed downstream of the atomizer to mix the gaseous fractions and the remaining small drops with exhaust gas. Avoiding reduction in the pipe diameter, allowed achieving the target uniformity levels without exceeding backpressure targets. The helix pitch and the location of the mixer were optimized as a compromise between the space constraints, the uniformity and the backpressure targets.

15.5 Aftertreatment Architecture

The aftertreatment architecture describes the geometry of the decomposition tube, the aftertreatment configuration upstream of the dosing unit, the aftertreatment configuration after the dosing unit (including the mixer), and the catalyst. Figure 15.26 shows the role of aftertreatment architecture in an optimized system design. Like the mixer, the overall geometry of the aftertreatment architecture can either improve system performance or cause system level problems.

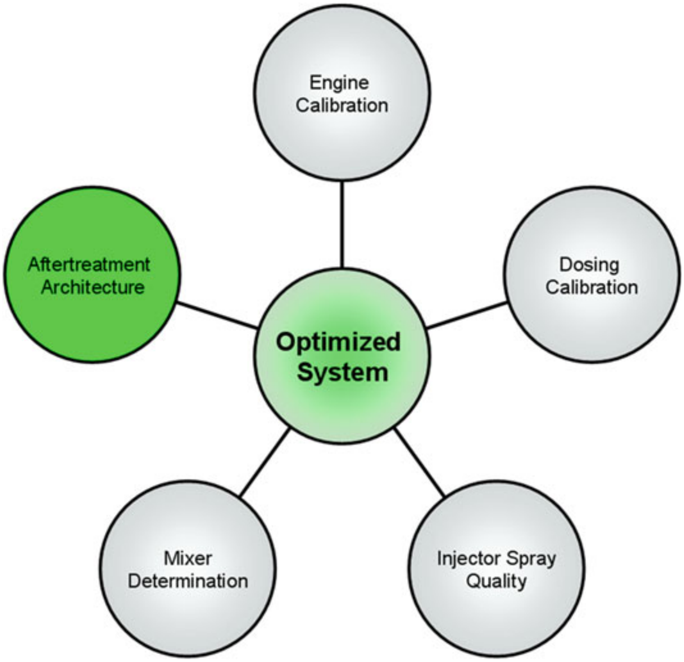


Fig. 15.26 Role of aftertreatment architecture in SCR system optimization

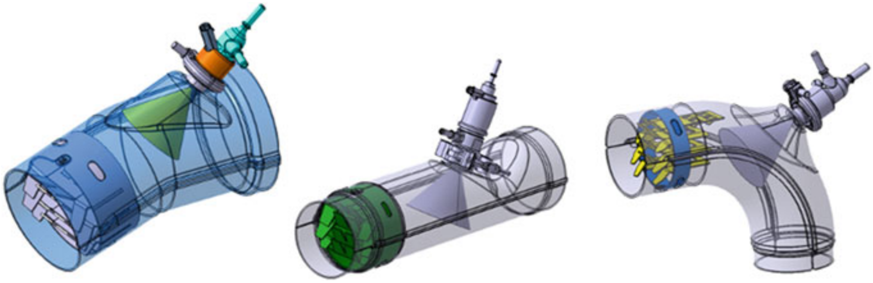


Fig. 15.27 Potential injector mount designs

Because available packaging space and representative duty cycles are not identical between applications, injector mount geometry needs to be optimized based on the targeted application. Figure 15.27 highlights three potential injector mount configurations. The mount on the left is a two-piece stamped design where the injector is recessed from the centerline of the exhaust. This type of configuration has been traditionally utilized in many on-road EPA 2010 compliant applications. Benefits of this configuration include reduced temperature at the outlet of the injector as well as increased distance from the injector to the mixer.

A potential disadvantage of this configuration is an increased potential for exhaust gas recirculation leading to urea deposits in the injector mount housing. The mount geometry in the center is called the inverted mount. The inverted mount moves the injector closer to the centerline of the exhaust gas by placing a V-shape in the exhaust pipe. This type of configuration helps to create flow separation and reduces the potential for deposits in the exhaust mount. Some potential disadvantages include a decreased distance from the injector to the exhaust pipe wall on the opposite side of the injector as well as an increased injector temperature and increased exhaust backpressure. The final design layout is considered an elbow style design. This type of design is prevalent on nonroad applications as well as heavy-duty on-road vehicles. The advantage of an elbow style mount is that the injected DEF is sprayed co-axially into the exhaust stream. This reduces the risk of droplet impingement on the exhaust pipe wall opposing the injector.

After an injector mount geometry and mixer has been determined for an application, the interaction between the pieces needs to be considered and understood. As mentioned in Sect. 15.4, the mixer needs to be placed in a location to achieve the greatest performance at all of the potential operating conditions. Figure 15.28 provides a cross-section of an elbow design with a 2-stage style mixer.

The point of injection defines the distance from the injector outlet to the mixer face (also called the decomposition portion). The distance from the outlet of the mixer to the face of the substrate is called the mixing pipe. Both of these dimensions, as well as the injector mount geometry chosen, has to be evaluated based on the available packaging space for the given application.

For most applications, the ideal aftertreatment geometry and routing will not fit. Because of this, an applications available packaging space needs to be considered when designing the aftertreatment system and integrating the dosing system. Packaging space refers to the allowable area that the aftertreatment fits in. Figure 15.29 provides an example of incorporating aftertreatment design into the available application packaging space for an on-road heavy-duty truck. For this application, there was limited space to incorporate an aftertreatment system consisting of a DOC, dosing system and SCR. To achieve this configuration, an elbow style system was configured to meet the packaging space and performance requirements. A trade-off analysis was performed between temperature loss against system complexity. This trade-off analysis is required in system design because of the chemistry constraints related to temperature. At lower temperatures, reduced DEF decomposition occurs, there is reduced NO_x reduction efficiency due to SCR catalyst washcoat inefficiencies and there is an increased probability of urea deposit formation.

Incomplete decomposition of DEF can lead to deposits within the aftertreatment system. These deposits can have a negative effect on the overall performance of the system as well as the longevity of the application. Figure 15.30 shows the DEF decomposition reactions that occur in the exhaust stream. Along with the primary reactions that produce the NH_3 necessary for reducing NO_x, there is potential for incomplete decomposition leading to deposit formation. The chemical

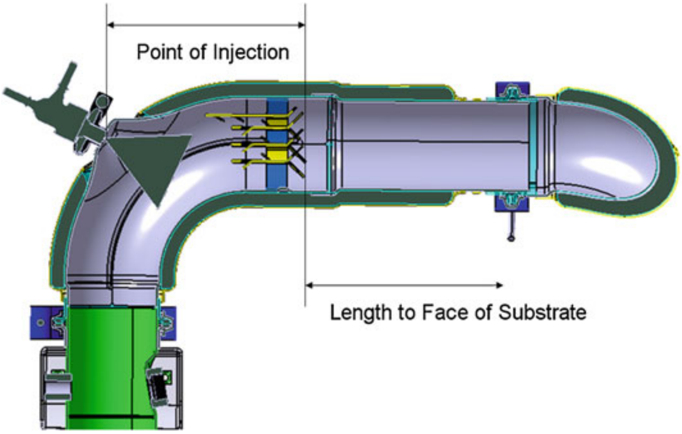


Fig. 15.28 Cross section of elbow style injector mount decomposition tube

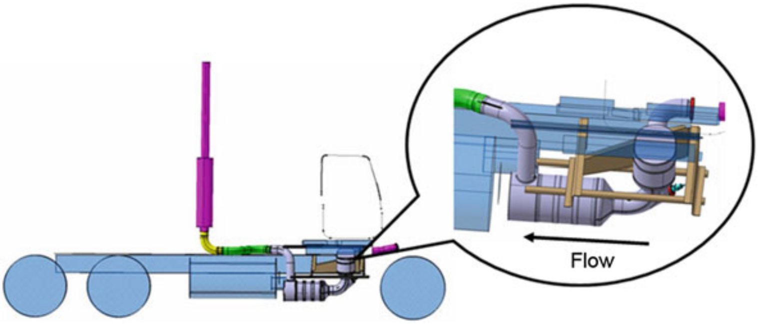


Fig. 15.29 Packaging space considerations

composition of the deposit depends on exhaust conditions and the amount of DEF decomposition that occurs. These deposits can be urea-based or isocyanic acid-based. Urea-based deposits include biuret and ammeline. If the urea makes it through the thermolysis reaction, the isocyanic acid that is created can also form unintended deposit byproducts. Examples of isocyanic acid-based deposits include cyanuric acid, ammelide, and melamine. These deposit formations occur under different conditions and can be mitigated in different ways.

Incomplete DEF decomposition leading to deposit formation is a condition that needs to be avoided and mitigated whenever possible. Multiple approaches can be taken in order to identify and address deposit formation concerns. In the early stages of SCR system development, it is critical that deposit risk is understood. To do this, an applications typical operating conditions and duty cycles need to be understood. For some applications, understanding the typical duty cycle is straightforward. On-road vehicles would fall into this category because

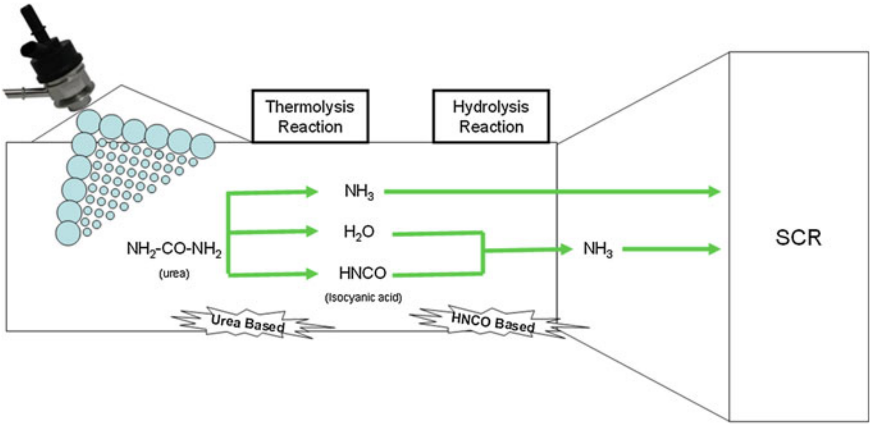


Fig. 15.30 Incomplete DEF decomposition leading to deposit formation

aftertreatment systems typically are designed for one application and that application has a similar daily duty cycle. Complexity comes for nonroad applications. This complexity exists because oftentimes for nonroad applications, there is an engine manufacturer that either provides engines to various machine groups or has loose engine sales. The aftertreatment is then sold with these engines and installed into many different machines. For this reason, nonroad aftertreatment systems traditionally need to be modular in order to adhere to the requirements of the various applications. These applications not only vary by packaging space but also relative duty cycles. With each machine operating differently, the type of deposit mitigation cycle chosen needs to be robust enough to encompass all of the potential uses.

Once a deposit mitigation test cycle has been established and deposit mapping occurs, a deposit mitigation strategy can be implemented. Figure 15.31 shows an example of a reversible deposit and the effect the deposit has on system level backpressure. The test was performed at a steady state test condition where the temperature was held constant at approximately 450 °C over a 3.6 day period. During the test, depositing was monitored, and it was found that the deposits would meet a point of equilibrium and then decompose. This was observed with an increase in backpressure measured. Because of the adverse effect of backpressure on system performance, an active mitigation strategy would be needed to manage the risk of deposits within the application.

One type of deposit mitigation technique is active deposit sublimation. An active sublimation strategy increases the exhaust gas temperature so that the solid urea deposits turn back into the gaseous phase. Doing this reduces the performance impact caused by the deposits that had occurred in the aftertreatment. Along with an active sublimation strategy, adjusting engine and dosing calibration can also provide a viable deposit mitigation solution. Table 15.2 shows four potential test conditions. Test condition 3 had a 25 °C increase in temperature and a 20 %

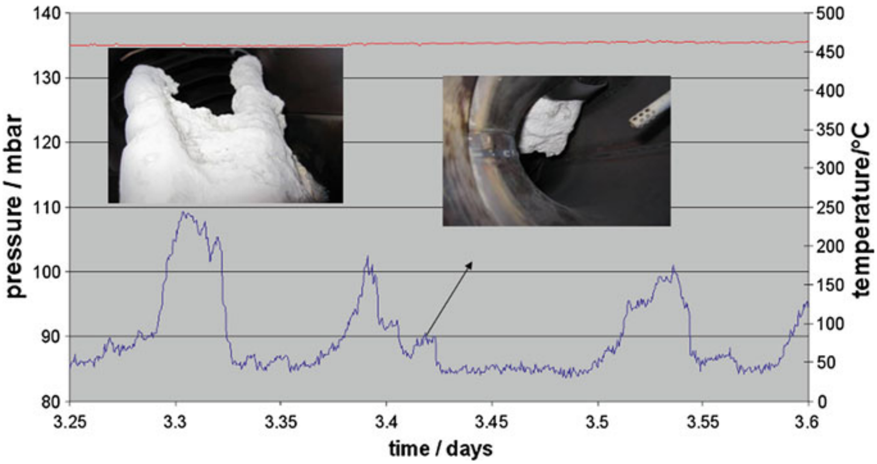


Fig. 15.31 Role of deposit formation on aftertreatment system backpressure

Table 15.2 Deposit mitigation test conditions

Test condition	Exhaust mass flow rate (kg/h)	Temperature (°C)	Dosing rate (g/h)	Decomp tube deposits (g)
1	250	200	150	12.2
2	700	200	1200	19
3	700	225	960	7.3
4	400	500	0	0

reduction in dosing rate in comparison to test condition 2. Figure 15.32 shows a side-by-side comparison of the two mixers after test conditions 2 and 3. The minor calibration modifications between test conditions 2 and 3 reduced the deposit accumulation by 62 %. The fourth test condition increased the exhaust gas temperature, similar to the active sublimation strategy outlined above, which removed all of the deposits that had accumulated.

A systematic approach is necessary for successful implementation of a liquid-based SCR system. Without a systematic approach, the application runs the risk of exceeding established budgets, missing timing, forming deposits, and not meeting NO_x reduction targets. Through these predefined steps, an SCR integration exercise will create a robust system.

15.6 Deposit Mitigation: Practical Example

Ideally the injected liquid should not come in contact with any surfaces and remain airborne until a complete decomposition of urea into ammonia. However, mixing space constraints and injection design parameters make that impossible.

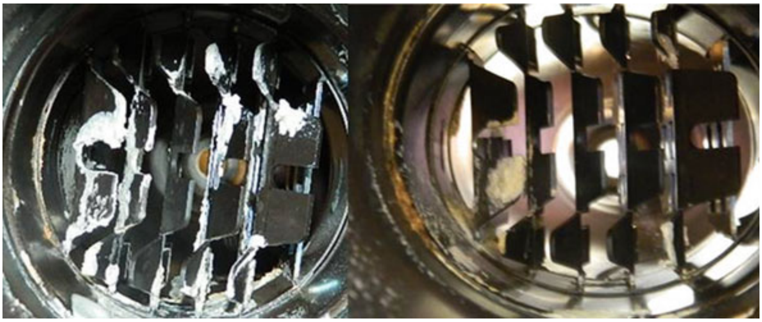


Fig. 15.32 Impact of calibration modifications on mixer depositing

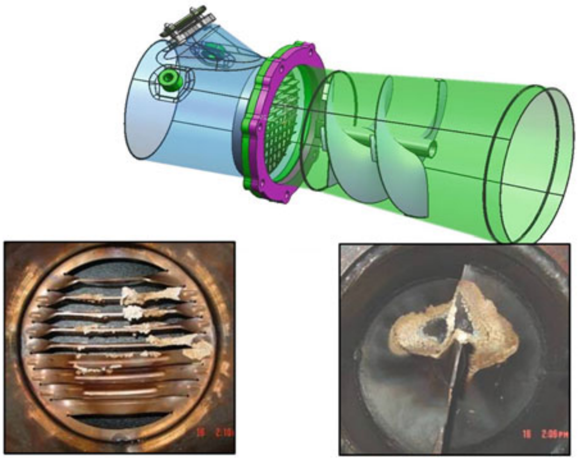


Fig. 15.33 Deposits formed on both mixers

Pre-mixer exit
(viewed upstream)

Mixer entry
(viewed downstream)

Nevertheless, the contact could be limited to mixer surfaces near the center of the pipe having the highest temperatures. The onset of deposits formation will then be determined by surface temperature, exhaust gas enthalpy, and the dosed quantity [1].

The quantitative measurement of deposits can be based on weighting the mixing section parts before and after a test to record the deposits mass growth rate. Figure 15.33 shows typical deposits formation patterns on the surfaces of both mixers.

The dosing rate restrictions protect the aftertreatment from an excessive deposit accumulation inside the urea mixing section. If remained unchecked, an excessive deposit growth may lead to an increase in the exhaust back pressure and a deterioration of urea mixing quality. Higher back pressures would negatively impact engine performance, and poor mixing would reduce NO_x conversion efficiency of the SCR catalyst.

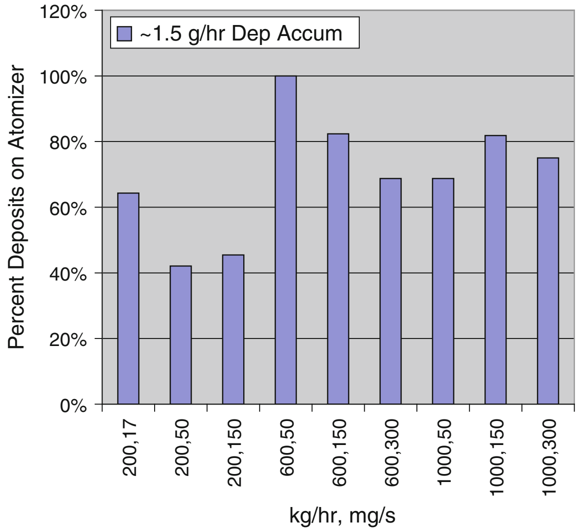


Fig. 15.34 Deposits collected on the atomizer

At lower exhaust temperatures typical for city driving, deposits could be forming in excess of 2 g/h rate. As exhaust gas and surface temperatures increase, the formation rate drops below 2 g/h, and most deposits form on the pre-mixer (Fig. 15.34). This is preferred, as these surfaces have higher average temperatures, which slows down the deposits growth and makes it easier to burn them off during DPF regeneration events.

In addition to measurements of exhaust gas temperature at various locations, knowing exhaust wall temperatures allows to gain better understanding of deposits formation pattern. For each cross-section of interest the wall temperatures were recorded at four rotational positions, 90° apart.

The wall temperature reduction relative to the gas centerline temperatures at the SCR entry are summarized in Fig. 15.35. The data were collected at deposits rate of 1 g/h for 200, 600, and 1000 kg/h air flow. The wall temperature reduction is much higher (lower wall temperatures) at lower exhaust flows that allow for more droplet residence time resulting in more evaporation of the liquid fraction. The evaporation is also helped by smaller amount of liquid in the mixing section to form the same amount of deposits. The delta_T is increasing with gas temperature at all exhaust flows. The magnitude of the delta_T and the rate of rise as a function of exhaust temperature diminish at higher exhaust flows, where heat content is greater.

All tests described here were conducted at room-temperature ambient conditions. The wall temperatures are lower at cold ambient conditions leading to higher deposits formation rate.

In addition to deposits formation on mixer surfaces, deposits can also form on the injector tip [2]. For recessed injector mounts the gas temperature near the tip is much lower compared to the exhaust centerline temperature, thus the tip deposits

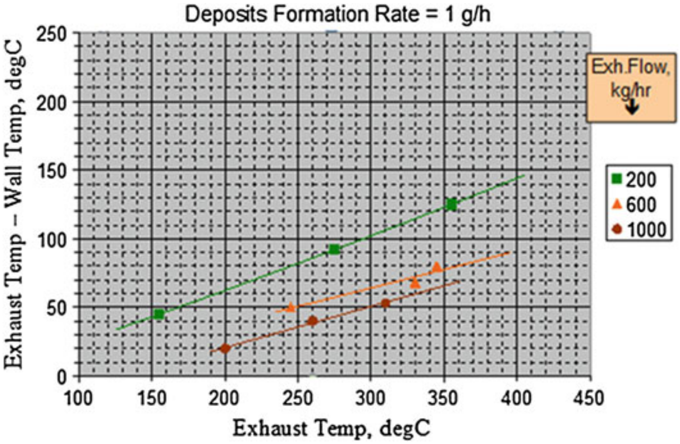
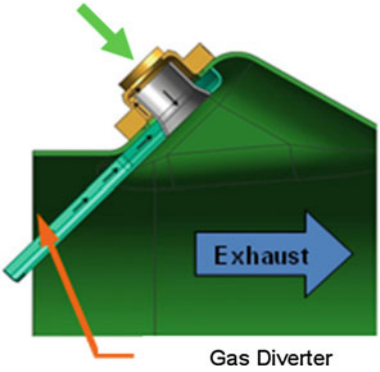


Fig. 15.35 Wall temperature reduction at SCR entry

Fig. 15.36 Deposits tip protection



composition is mostly urea crystals. Consequently, the burn-off temperature for deposits removal does not have to approach DPF regeneration temperature. Still excessive accumulation at the tip threatens to degrade the spray quality and partially block the spray orifices.

To avoid excessive deposits a tip protector can be used (Fig. 15.36). It consists of a gas diverter that directs a small part of exhaust flow to the vicinity of the tip and toward a sleeve. The gas flows around the sleeve outer diameter toward the tip and turns around to create a cylindrical gas shield around the spray. The shield prevents gas recirculation into the recessed area, which would cause the smallest droplets to land on the tip and other surfaces inside the recess cavity. The green arrow represents the location where the injector would be mounted.

The effectiveness of the tip deposits protection is evident from Fig. 15.37. For the case on the left the near-tip temperature (NTT) is 86.6 °C, with the DOC_out temperature at 300 °C (for the gas flow of 200 kg/h and urea dosing at 150 mg/s).

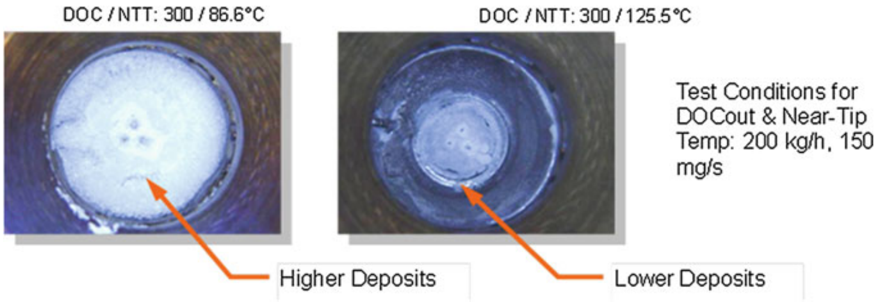


Fig. 15.37 Tip deposits without (*left*) and with (*right*) tip protector

The white deposits are threatening to cover three spray orifices. The photo on the right shows a substantial reduction of deposits, and a higher NTT of 125.5 °C. The higher NTT did not increase the tip internal temperature above the manufacturer specified limit.

15.7 Concluding Remarks

Based on its early adoption into the European market, DEF metered SCR has become the preeminent global NO_x reduction technology. Lessons learned from on-road applications should be incorporated into nonroad applications as well as future high efficiency SCR systems. In order to meet these new system requirements, a structured approach to SCR integration should be taken (as outlined above), which has been proven through many applications that are in production globally and supported by the practical examples provided by Ford Motor Company. By following a structured approach, superior NO_x reduction performance and robust deposit response can be achieved.

References

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2. "Bypass purge for protecting against formation of reductant deposits", US Patent #2010/0107614 A1