Close coupled DOC-mixer-SCR for Tier 4 final

Dr. Korneel De Rudder, Dr. Corine Chauvin
DONALDSON Europe

ABSTRACT

This paper discusses the development of a compact close-coupled DOC+mixer+SCR system, complying with the Tier 4 non-road emission legislation.

Early on, it was assumed that Tier 4 final non-road engines would need aftertreatment, combining SCR and DPF. With recent advancement in boosting, fuel injection equipment and SCR aftertreatment, it is now clear that the Tier 4 final particulate limit can be reached without a DPF, when a high efficiency SCR system is used. The resulting engine-aftertreatment combination leads to a good fuel efficiency and low cost-of-ownership.

To achieve high efficiencies in an SCR system, one needs a DOC for NO to NO_2 conversion, to prepare the exhaust gas for the fast SCR reaction. Downstream of this DOC, AdBlue (Diesel Exhaust Fluid) is injected, evaporated and mixed with the exhaust gas, prior to entering the SCR substrates. The DOC, doser, mixer and SCR are large parts. Especially when they are designed as separate units, the complete aftertreatment system becomes large with several separate bulky units. The present paper discloses an aftertreatment system where the DOC and SCR are close-coupled in one compact unit, with integrated doser and swirl mixer.

This system uses an annular/ring shaped (donut) DOC substrate. At the outlet of this ring shaped donut DOC, the AdBlue is injected along the axis of the inner tube. At the same location, swirling flow is generated. This bulk swirl with AdBlue then flows to the SCR inlet.

The performance of this system in terms of (lack of) deposit formation, mixing and emission reduction is studied. The effect of various parameters such as swirl ratio, residence time, turbulence and geometry is described. This is done by a combination of CFD results, engine dynamometer lab results and natural gas burner results. The T4f actual emission performance cannot be disclosed; however, relative comparisons of different design iterations will be shown, together with actual results of an undersized (too small) T4 system.

INTRODUCTION

This paper focuses on SCR aftertreatment for diesel engines, intended for non-road machinery with a power rating of 56-560kW. These diesel engines are popular in large agricultural machinery, such as tractors, combine harvesters, sprayers and many others.

For the many of these applications, minimizing total operation costs is essential. There is a trade-off between fuel efficiency and NO_x emission. With the help of an SCR system, the engine can run with excellent fuel efficiency and high raw NO_x, but low tailpipe NO_x levels.

For smaller machinery the cost of acquisition is more important than the cost of ownership. For these applications, the cost of the emission reduction systems becomes very important and there is a strong pressure to avoid using a combination of EGR (Exhaust Gas Recirculation), DPF and SCR. Hence SCR-only (or DPF-only) is an attractive solution. For these small engines (56-130kW), high efficiency SCR without EGR might be the preferred solution.

year	Stage	Tier	NOx	PM
2006	3A	3	4.0	0.2
2011	3B	4i	2.0	0.025
2014	4	4f	0.4	0.025

Table 1 Off-highway emission limit >130kW [g/kWh]

Exhaust gas emissions of non-road mobile machinery have been regulated already for many years. **Table 1** gives an overview of the relevant EU and US legislations for diesel engines (130-560kW). Unlike automotive and on-road heavy duty diesel legislation, there is no particulate number limit for non-road engines.

Diesel engine tailpipe emissions can be reduced by a combination of combustion control methods and aftertreatment strategies. Depending on the chosen approach, the engine raw emissions and fuel economy can be altered significantly. Furthermore, due to different base engine calibration (injection settings) and engine configuration (cooled EGR, intercooling), the cooling requirements can increase dramatically.

Compared to previous non-aftertreatment engines, the new generation of engines with aftertreatment, are more complex and comprise more components. Aftertreatment systems are often more bulky than the exhaust mufflers they replace. These extra/larger components have to be integrated on the machine without negative impact on operator visibility, heat rejection, skin temperatures, fuel capacity and many other factors. Diesel engines, complying with the Tier 4 Interim legislation, using aftertreatment can be divided into two families: A) using diesel particulate filters (DPF), and B) using selective catalytic reduction (SCR).

Diesel particulate filters need to be serviced and thus incorporate large clamps and flanges. Furthermore, an additional fuel injector is needed on the exhaust system. DPF engines typically need cooled EGR to be able to control/reduce the NO_x emissions. This EGR cooler adds extra heat to the cooling system, requiring a larger cooling package. During DPF regeneration, high exhaust gas temperatures are generated for which sometimes, special diffusers and venturi systems are installed.

Besides the SCR substrate canning, SCR systems need a pump and injection module, often combined with a purpose designed mixer. In addition to this, a separate tank with AdBlue (DEF) is needed on the vehicle.

Initially, it was assumed that Tier 4 final engines would need aftertreatment that combined DPF and SCR. With the latest developments in SCR technology, it now seems feasible that a diesel engine can meet the T4f emission limit by SCR-only, avoiding DPF technology. Such a system needs exceptional high efficiencies from the SCR system, especially when no EGR is used. These efficiency levels (>95%) can only be reached by a very good evaporation, decomposition and mixing of the AdBlue with the exhaust gas **[1, 2, 3, 4]**.

EXPERIMENTAL INSTALLATION

Aftertreatment performance is evaluated with a diesel engine test installation, consisting of a 600 kW AC dynamometer, using conditioned air (23ºC-50% humidity) for the engine air supply. The engine exhaust mass flow is calculated from intake air flow (hot film sensor) and a wide range exhaust gas O_2 sensor. Gaseous emissions are measured with a Horiba MEXA 7000-series analyzer (chemiluminescence for NO_x). In addition, commercially available Smart NO_x Sensors are used to measure NO_x and to control AdBlue dosing. NH_3 is measured with a Horiba 6000 FTIR analyzer and a NEO LaserGas based on a tunable laser diode for optical absorption spectroscopy.

All results presented in this paper are obtained with AGCO Power diesel engines. Specifically, three different engines with a displacement of 4.4, 6.6 and 8.4 liter were used. These state-of-the art four and six cylinder engines use turbocharging, common rail injection and 4 valves per cylinder.

In addition to the engine test results, some data is obtained on a natural gas burner. This gas burner is able to replicate the transient exhaust flow and temperature of a 350 kW diesel engine. Flow is generated by a 30 kW electric roots blower with a frequency controller; this air flow is then heated by a 300kW natural gas burner. This equipment is used for accelerated thermal aging of full size aftertreatment systems. Furthermore, this installation can evaluate the long term effects of AdBlue spraying in exhaust systems. With this hardware, it is cost-efficient to run deposit formation tests for hundreds of hours. The burner is switched off at predetermined intervals for inspections of the exhaust systems (and deposits) using a digital camera and a digital flexible boroscope.

Ansys-Fluent 14 is used for computational fluid dynamics (CFD) calculations **[5]**. Tetra and Hex mesh are used and the solver is a realizable k-eps model. Typical conditions used for CFD calculations include rated power, but also low temperature (200-220ºC) conditions with different mass flow values.

SWIRL MIXING

In previous papers, it has been demonstrated that swirling gas flow can be a very good way to mix and evaporate AdBlue effectively **[1, 2, 6]**. Bulk swirl is a type of large scale turbulence, being a single large vortex. In a swirling flow, the tangential gas velocity is lowest in the center and rises progressively towards the edge. By using swirl, it is possible to add a lot of turbulent energy to the flow. Compared to small scale turbulence, bulk swirl can be maintained for a long time/distance in the exhaust system.

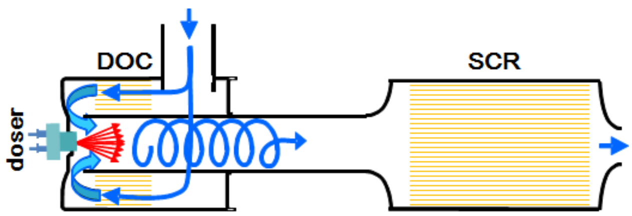

Figure 1 Schematic overview of donut DOC with swirl mixer followed by SCR

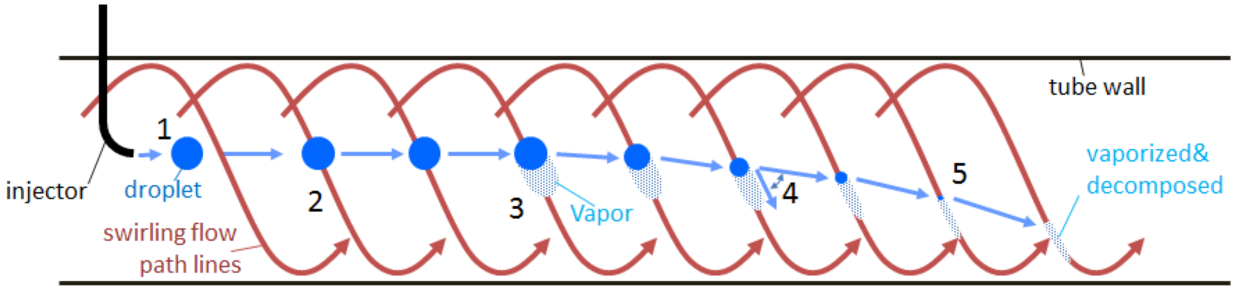

Figure 2 Theoretical model of droplet evaporation/decomposition in swirling flow

One example of a swirl mixing system for AdBlue injection is depicted in **Figure 1**. In this layout, the exhaust gas flows from the turbocharger to the inlet chamber of the DOC. The metallic DOC has an annular shape (donut), with the outlet tube in the middle. At the outlet face of the DOC, a tangential component is added to the flow (swirl). This swirl is generated on a large diameter (same as the DOC), the swirling flow then has to turn 180º to enter into the inner tube of the donut DOC. At the point where the flow turns 180º, the AdBlue injector sprays the reductant (AdBlue) into the exhaust gas. The swirling exhaust gas with the evaporating and decomposing AdBlue then flows towards the SCR inlet, the swirl momentum can be maintained for several meters **[1]**.

Swirling gas flow leads to a very good mixing and evaporation of the injected AdBlue. The trajectory of a single droplet in a tube with swirling gas flow is schematized in **Figure 2**. The AdBlue is injected at a pressure of 5-10 bar, therefore, each individual droplet has significant kinetic energy (1). Due to this high kinetic energy, the individual droplets tend to move relatively independent of the gas flow (2). This leads to a higher heat exchange at the droplet surface, and the droplet tends to heat up faster than when it would move with the same velocity and in the same direction as the gas flow. Once evaporation starts (3), the vapor tends to be swept away by the surrounding gas and is thus moved effectively away from the droplet surface (4). Due to evaporation and decomposition, the droplet loses mass; due to friction with the gas, it loses kinetic energy (relatively to the gas). Both factors (reducing mass and kinetic energy) lead to the fact that the droplet will get entrained in the flow (5).

In reality, a wide range of droplets sizes exist after the spray break up. The above described processes (evaporation, decomposition, reduction of droplet mass and kinetic energy) occur differently for different sized droplets. In general, one can assume that large droplets have more kinetic energy and take more advantage of the swirling flow than smaller droplets.

Once all droplets are evaporated there are still zones with high and low concentration of urea decomposition products (mainly NH_3 and HNCO). The bulk swirling motion leads to large shear effects and effectively mixes the decomposition gases with the exhaust gas.

When the AdBlue is injected along the center axis of the tube, the free spray path length can be maximized. In fact, the spray should be directed in such a way that under all flow conditions, the free spray path length is as long as possible. This reduces the chance that larger droplets impinge on the walls while still being in liquid phase. Under certain conditions, this liquid impingement can lead to the formation of solid deposits **[7]**.

Similar mixing challenges can also be found outside the world of exhaust aftertreatment. Specifically, mixing a liquid reactant with a gas can be found in combustion chambers of diesel engines, gas turbines and industrial burners. In many of these systems, swirling flow is used.

Swirl mixing has been applied in the previously described donut DOC **[8]**. Specifically this type of donut mixer has been used on an agricultural tractor application, as discussed in **[1, 2, 3]**. Another application of this system is in combine harvesters. Typically harvesters have more space available for the exhaust system, compared to tractors. For several applications, this donut mixer DOC is followed directly by the SCR unit. The connection between both components is relatively short. Often, the DOC outlet tube is connected directly to the inlet tube of the SCR. Such a short system is demonstrated in **Figure 3**, this combine harvester uses a 7 cylinder AGCO Power engine (former SISU diesel) of 9.8L-350kW.

During the design process for the Tier 4 final exhaust aftertreatment system, it became clear that it would be advantageous to combine the donut DOC/mixer and SCR in one body. At a minimum, this would eliminate two end baffles, a tube and a V-clamp connection. Further advantages can be found in the assembly procedure and support bracket structure.

On combine harvesters, there is typically enough space available for the aftertreatment system. However on tractors and other non-road machines, packaging space is at a premium and there is significant pressure to reduce the space claim of the aftertreatment system. From this point of view, combining all aftertreatment components into one unit can be advantageous.

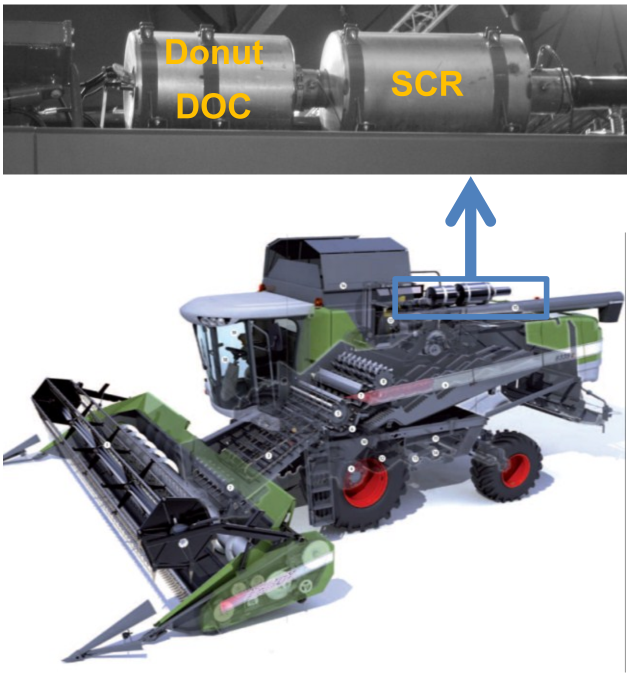

Figure 3 T4i combine harvester with donut DOC and SCR

EFFECT OF SWIRL RATE IN A DONUT SETUP

As described in previous sections, swirl can be a major factor in improving evaporation, decomposition and mixing the injected AdBlue. By using CFD tools, the effect of swirl and a donut layout has been evaluated. It is possible to model many details of the AdBlue injection, chemical decomposition and the following SCR reactions. However, this whole process can be simplified and accelerated by using water instead of AdBlue and evaluating water evaporation, wall film formation and distribution of water in dry exhaust gas. In this specific study, the uniformity index of water (liquid and vapor), the instantaneous evaporation rate and the turbulence intensity are compared. Three different configurations have been evaluated with the AdBlue injection location 250mm before the SCR substrate:

1. A layout where the Adblue is injected into the center of a straight tube.
2. A layout where a donut DOC is used and the flow has to change 180º at the point of AdBlue injection.
3. A Donut layout where a swirling component is added to the flow by means of a swirl baffle.

These three configurations are summarized in **Figure 4**.

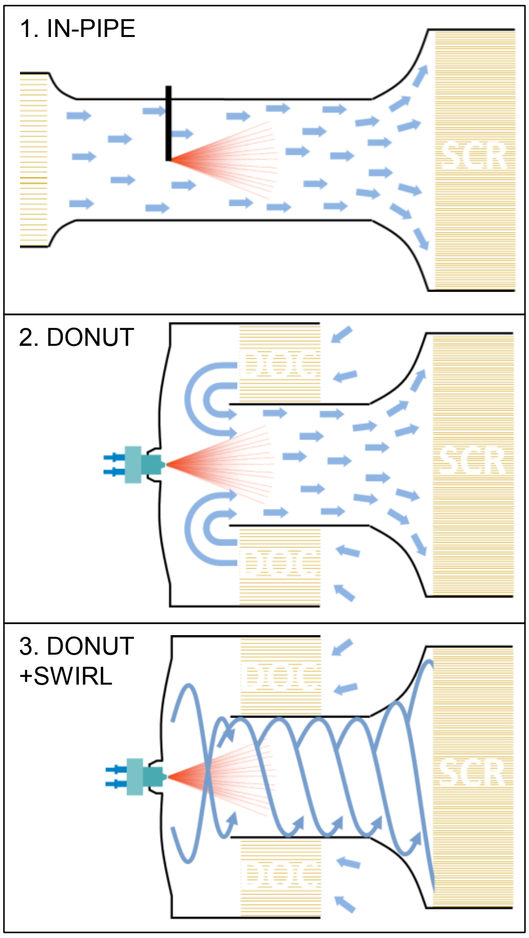

Figure 4 Three different exhaust line layouts

Figure 5 and 7 shows the results of this CFD study. A relatively small system, designed for a 100 kW engine was modeled in CFD. A low exhaust flow rate at a low temperature of 230ºC was combined with an AdBlue injection rate of 150g/h. The injection occurs at 0cm, the SCR substrate face is located at 25cm. Along this distance, three different parameters are plotted in **Figure 5**:

γ H_2O

The first Y-axis represent the γ H_2O, this is the uniformity index of water. H_2O is used instead of NH_3, because this speeds up the calculation time and gives very similar results. The γ H_2O value indicates how efficient the mixing process is; a similar approach can be found in **[9]**.

One can see that for configuration 1, where the injection occurs in a straight pipe, the gamma linearly increases up to the point of the cone expansion, the final gamma value reaches 0.35. One can assume that this leads to low and inefficient NO_x conversion performance. For configuration 2, where a donut (without swirl) is used, the gamma increases more rapidly and reaches a value of 0.91 at the SCR substrate. In configuration 3, a swirling flow component is added; the mixing is much more rapid. At the midpoint of 15cm, a gamma of 0.85 is found and at the SCR substrate, 0.97 is reached.

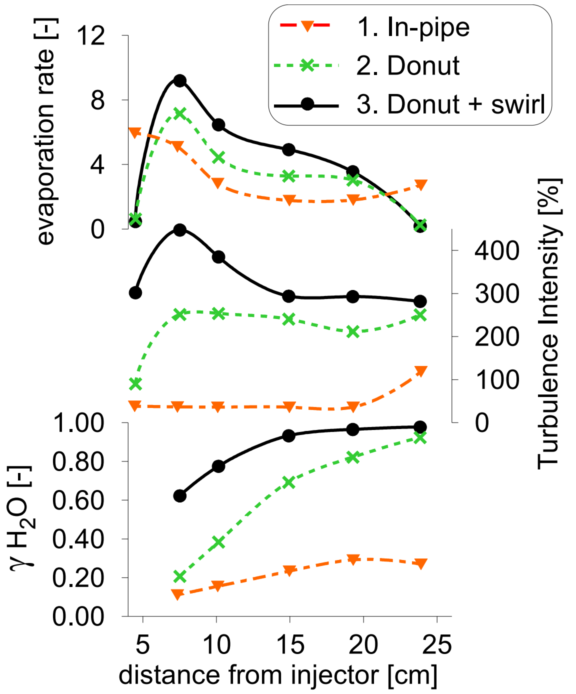

Figure 5 CFD parameters evolution between dosing point and SCR substrate

Turbulence Intensity

The second Y-axis in **Figure 5** represents the Turbulence Intensity (TI). This TI is the ratio of the magnitude of the root mean square of the turbulent fluctuations to the reference velocity. The turbulent fluctuations are related to the Turbulent Kinetic Energy. The typical TI in exhaust pipes is 10-50%. Configuration 1 represents such a case, with ‘normal’ straight tube flow, the TI increases slightly at the flow expansion in the inlet chamber of the SCR. In configuration 2, the TI is much higher, around 200%. This higher TI is originating in the layout of this donut system. The flow has to turn 180º, leading to high turbulence levels. The effect of this higher TI can be seen in the γ H_2O values. In configuration 3, a swirling flow component is added, initially the TI is around 400%, further downstream, this drops to 300%. The much higher TI leads to better mixing and is reflected in the γ H_2O values for configuration 3.

Instantaneous Evaporation Rate

The third Y-axis represents the Instantaneous Evaporation Rate. A similar trend as with the turbulence intensity can be seen. The lowest evaporation rate can be seen for configuration 1, an in-tube injection. When extra turbulence is added by using the donut flow reversal and swirl; the evaporation rate increases.

Mixing and emission performance

Figure 6 shows the corresponding emission results of these three conditions. The exhaust aftertreatment consists of DOC+SCR. The SCR has a vanadium coating with a space velocity of 100.000/h including a zone coating of NH_3 oxidation catalyst. The evaluated condition is rated speed with an exhaust temperature of 260ºC. The layout configurations were the same as in the previously described section, with exception of the in-pipe layout. With this layout, the injection point was not located at the center of the pipe, but the injection occurred from the side of the pipe (because a center-injection airless doser was not available).

Both NO_x conversion and NH_3 slip are plotted as a function of alpha ratio (AdBlue dosing). The start point is a low alpha ratio, as alpha ratio is increased, the NO_x conversion increases, but at a certain point, NH_3 slip starts to appear. The (interpolated) point of 10 ppm NH_3 slip is used as reference point.

The in-pipe layout reaches a NO_x conversion of 45% at 10 ppm NH_3 slip. When a donut configuration is used, the NO_x conversion reaches 71%. By combing swirling flow with the donut layout, the NO_x conversion could be raised to 84%. This ranking in NO_x conversion correlates well with the results on γ

H_2O , Turbulence Intensity and Evaporation Rate, found in the CFD study.

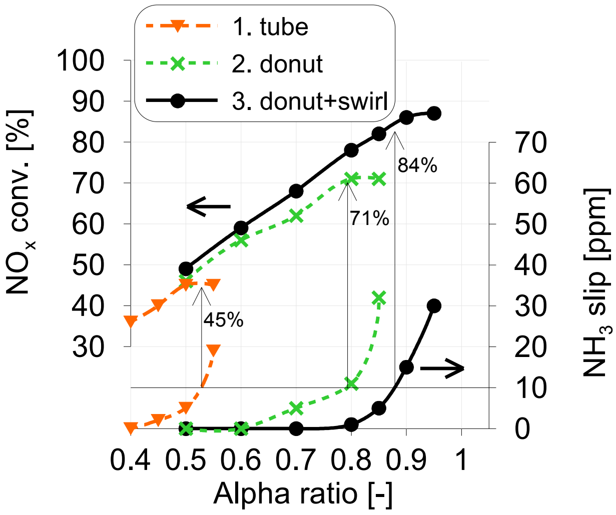

Figure 6 Trade-off between NO_x conversion, alpha ratio and NH_3 slip

Figure 7 is a graphical representation of the CFD results for configuration 3 (donut + swirl). The local gas velocity and turbulence intensity are depicted. In the velocity plot, it can be seen that at the centerline of the tube, the velocity is lower than near the tube walls. This can be attributed to the properties of the swirling flow: due to the rotating motion of the bulk gas, there appears a centripetal force which leads to higher gas velocities near the pipe walls. As a result, wall film formation phenomena are suppressed, contributing to a deposit free system.

An additional advantage of using swirl can be found in expanding sections. With normal, non-swirling flow, tube diameter expansion rates need to be moderate, in the order of 6-12° to avoid flow delamination near the wall. However, with swirling flow, the diameter expansion can be much more abrupt without leading to flow delamination or zones with recirculating flow. This can be seen in the top of **Figure 7**; due to the swirl, the highest flow velocities occur near the wall, and this zone nicely expands in the cone section.

Pressure drop

CFD tools were used to optimize the swirl rate and the swirl baffle geometry. It was found that the higher the swirl rate, the better the mixing and evaporation. However there is a cost in terms of backpressure, more swirl means more backpressure, this backpressure originates both from the swirl baffle, but also from the flow restriction of the downstream tubing (increases with swirl).

The backpressure of the complete exhaust line (donut+swirl configuration) is in the range of 13-17 kPa at rated conditions. The combined backpressure penalty of using this donut configuration (180° turn) and swirl is in the range of 3-6kPa. At these backpressure levels, the influence on fuel efficiency is small in theory, and difficult to measure in practice.

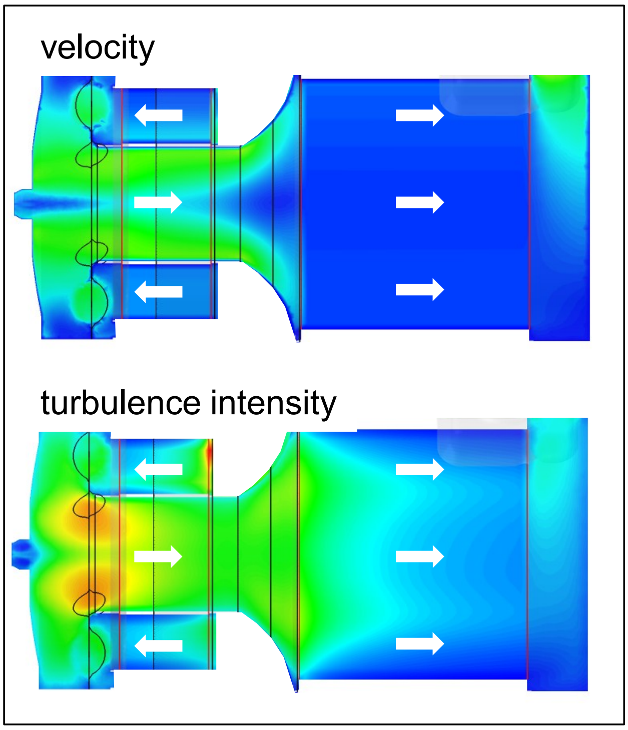

Figure 7 Color plots of parameters that indication mixing

EFFECT OF MIXING VOLUME AND DROPLET SIZE

Every single AdBlue droplet needs to evaporate and mix. As described in previous sections, the local flow/turbulence plays a major role in this process. However, one can assume that the residence time of this droplet also influences this process. If a droplet gets more time before reaching the SCR catalyst, the evaporation and mixing can be improved. At a fixed exhaust gas flow and temperature conditions, the residence time of a droplet can only be increased by enlarging the volume between the injection point and the SCR substrate. The longer a droplet resides in this volume, the more complete the whole evaporation, decomposition and mixing process can be.

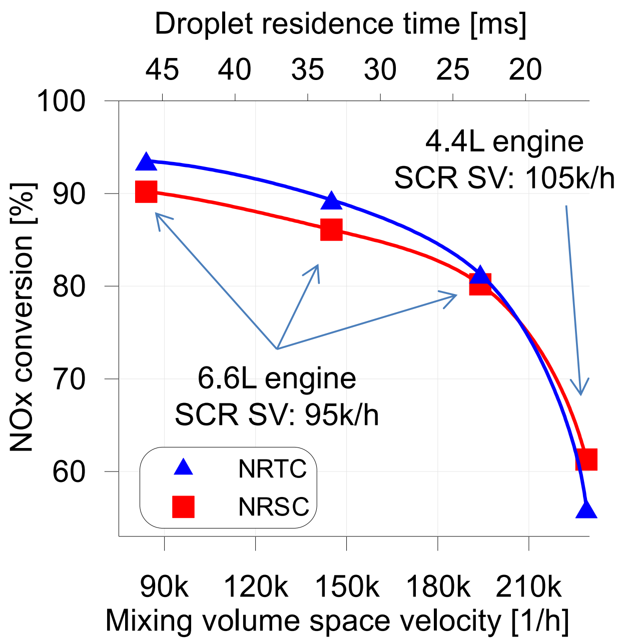

Figure 8 Performance of close-coupled DOC-SCR

Figure 8 shows the result of such an experiment. Two different engines are compared, a 4 cylinder 4.4L and a 6 cylinder 6.6L, both engines have similar SCR and DOC space velocities, the raw NOx emissions are the same. The performance is measured with a Vanadium based SCR with a volume of 1.7 times the engine displacement, an airless AdBlue doser and a DOC of 0.4 times the engine displacement. In this study, the volume between the doser and the SCR catalyst has been made variable. This mixing volume can be seen as the volume that is available for the injected droplets to evaporate. At a fixed exhaust flow condition (e.g. rated power), the mixing volume can be divided by the volumetric flow (at standard conditions), the result is the residence time of the droplets in the exhaust before entering the SCR catalyst. The inverse of the residence time is the space velocity. This scale is plotted on the bottom of the graph in **Figure 8**.

The plot shows the performance of the complete NRSC (Non Road Stationary cycle), and for the hot start NRTC (Non Road Transient Cycle). The residence time has an influence on the maximum NO_x reduction performance (defined at optimal alpha ratio or 10ppm NH_3 slip). At very short residence time values (e.g. 20ms), there is not enough time for the droplets to evaporate and mix with the exhaust gas. At higher residence times, the NO_x reduction improves; above ±35ms, the improvements are rather small.

By using a very compact system, with a small mixing volume, the effect of droplet size is remarkable. With one specific T4i system, the baseline dosing system gives a NO_x reduction is 61/56% over NRSC/NRTC. By upgrading the dosing system, and thus reducing the droplets size, the optimized NO_x reduction becomes 74/70% over NRSC/NRTC. In fact, this performance gain is in the same order of magnitude of what can be achieved by increasing the turbulence/swirl. Unfortunately, both effects do not add up.

On systems with relatively large mixing volumes, as foreseen for T4f, this effect of droplet size on emission performance is not seen. Nevertheless, there might be other reasons to upgrade the doser/injector (e.g. deposit formation). The advantage of having smaller droplets is only found with systems using a very small mixing volume. In other words, systems that have to be very compact can benefit from smaller droplets, but larger systems do not need very small droplets.

TIER 4 FINAL SIZING

The size of the DOC+SCR unit, discussed in this paper is dependent of the actual power rating of the engine and of the emission legislation (T4i or T4f). The range of sizes for engines between 100-350 kW is depicted in **Figure 9**. Due to the good mixing concept, the complete exhaust aftertreatment is compact enough to fit on non-road machinery, ranging from combine harvesters to small tractors.

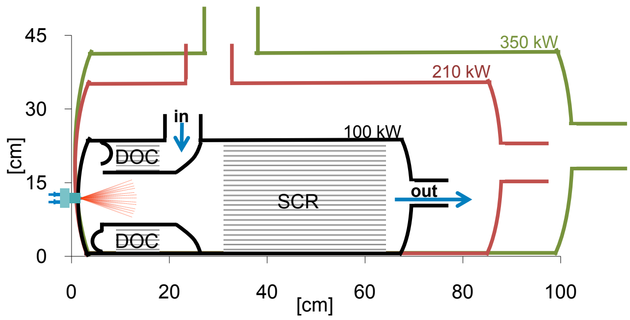

Figure 9 Size range for close coupled DOC+SCR

Because all aftertreatment components are combined in a close-coupled configuration, the thermal losses are minimized. As an example, a half insulated unit for a 210kW engine, loses around 7ºC between inlet and outlet at rated power conditions. Also, the cold-start behavior is optimized as there is very little thermal mass or inertia between DOC and SCR.

DEPOSIT FORMATION

In AdBlue based SCR system, deposit formation is a well-known challenge **[6, 10, 11, 12, 15]**. Under certain exhaust flow and temperature conditions, the liquid AdBlue and its decomposition products can impinge on the wall and cause wall wetting. This wall wetting reduces the local temperature of the wall and can lead to a growth of this wall film. Solid urea and solid by-products of the urea can then be formed and over time these can block the exhaust system **[12]**. Accurate modeling of this complete process is prohibitive because there are many interacting factors, and the real physical process can take many minutes to stabilize. For practical use, CFD models can predict where a wall film will form **[13]**, but the actual prediction of wall temperatures and deposit formation is highly complex **[10, 14]**. Instead, actual hardware test on a vehicle or engine dynamometer are still needed. To reduce the cost and complexity of this process, the actual test can also be done on a natural gas burner. Some results of such natural gas burner testing can be found in **Figure 10**.

A deposit evaluation test consist of an 8h run at the minimum dosing temperature. The exhaust gas flow varies slowly (30min) between the idle speed flow and the rated speed flow. The gas temperature is maintained constant at the minimum dosing temperature of 230 or 200ºC, while the dosing rate is at a realistic value for a T4 engine.

Picture 1 and 2 in **Figure 10** show the exhaust system internals after such and 8h test at 230ºC. The point of view is from the doser seat, looking towards the SCR substrate. In picture 1, one can see the start of deposit formation on the SCR substrate face. For picture 2, the turbulence level was increased using more swirl, and it was possible to completely eliminate this source of deposit formation on the substrate face. The other elements of this system (tube, expanding cone) remain free of deposits.

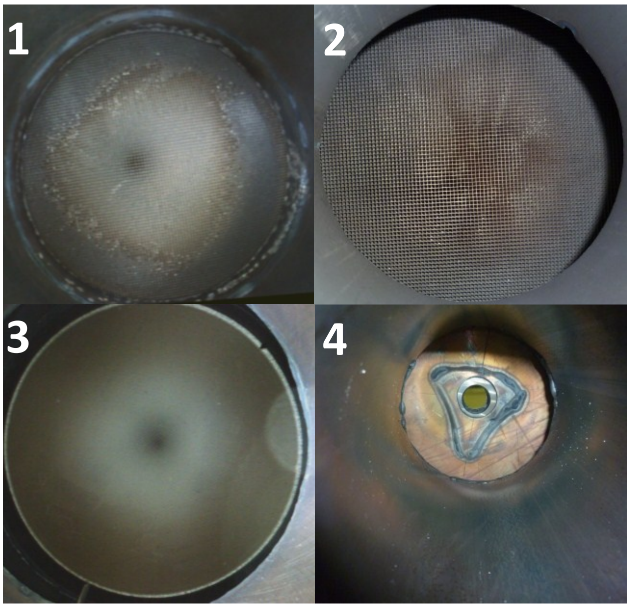

Figure 10 Results of 8h deposit test at minimum dosing temperature

Picture 3 and 4 in **Figure 10** are from a larger system, tested for 8h at 200ºC. Picture 3 demonstrates that the SCR substrate face remains completely clean. In picture 4, the doser seat area shows to be free of deposits.

Picture 4 also demonstrates that the tube walls in between injection and SCR remain completely free of deposits. This can be attributed to the specific velocity distribution in a swirling flow. Gas velocities near the wall are higher than at the center of the tube, leading to good heat transfer and high shear forces on any liquid wall film.

Figure 11 shows the limits of this donut mixing system in terms of deposit formation. This information comes from DOC+SCR, sized for a 350kW engine, using a commercially available airless AdBlue doser. For each specific exhaust condition (e.g. 950kg/h @ 230 degC), the AdBlue quantity is increased in steps of 50g/h. This is done until the point is reached where in a one hour test a deposit initiation is observed. This map can then be used as a limiter for the AdBlue dosing algorithm in steady state conditions.

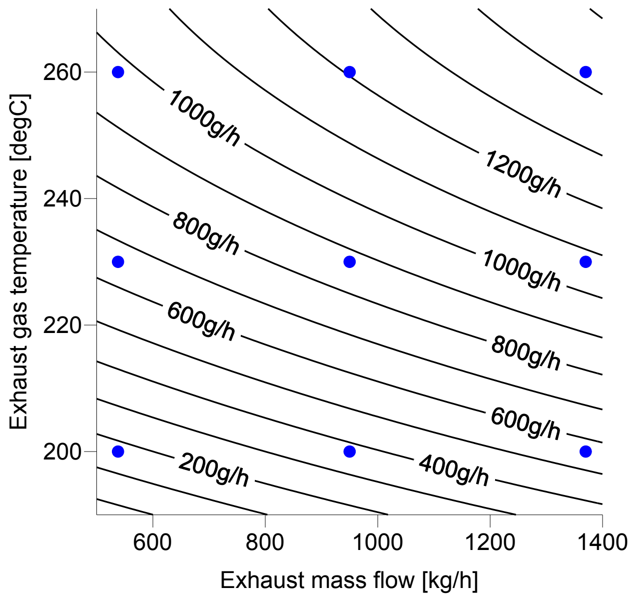

Figure 11 Maximum AdBlue dosing rate for deposit free operation, in function of exhaust gas flow and temperature

CONCLUSION

The presented exhaust aftertreatment system combines a close-coupled and compact DOC+SCR utilizing a swirl mixing system. Due to the specific donut layout, and swirling flow rate, a high amount of turbulence can be created in the injection area. With this violently turbulent flow, the evaporation and mixing of the injected AdBlue is enhanced remarkably. This can be seen, both in the results of the CFD study and in the actual maximum NO_x conversion efficiency. Furthermore, the system can remain free of deposits, even when operating for extended times at low exhaust gas temperatures.

Due to this efficient mixing and evaporation system, the volume between the DOC and SCR can be minimized. The actual distance between the doser and SCR inlet face is in the range of 25-50 cm, while the total length of the full aftertreatment system is 70-100 cm for an engine power range of 100-350kW. With this specific layout, the heat losses are minimized and thermal inertia is minimized, leading to good cold start behavior.

High efficiency SCR systems are feasible for T4f. Although not explicitly shown in this paper, it is expected that the presented systems will function well on a T4f engine, allowing the engine to have high raw NO_x emission and avoiding the use of EGR.

REFERENCES

[1] De Rudder K., "High efficiency SCR for non-road applications", THIESEL 2012 Conference on Thermo- and Fluid Dynamic Processes in Direct Injection Engines

[2] De Rudder K., "Tier 4 high efficiency SCR for agricultural applications", SAE Technical Paper 2012-01-1087

[3] Ratia J., "The Road to Tier 4 Final in the Agricultural Sector - Challenges and Solutions", SAE 2012 Heavy-Duty Diesel Emissions Control Symposium, Gothenburg, 12-sept-2012

[4] Keuper A., Unger H., Huang J., Bressler H., Albrecht W., "Investigations to achieve highest efficiencies in exhaust gas aftertreatment for commercial vehicles using and SCR system", SAE Technical Paper 2011-01-2201

[5] ANSYS Fluent 14.0 users guide, 2011

[6] Birkhold F., Meingast U., Wassermann P., Deutschmann O., "Modeling and simulation of the injection of urea-water-solution for automotive SCR $DeNO_x$-systems", Applied Catalysis B: Environmental 70 (2007) 119-127

[7] Xu. L., Watkins W., Snow R., Graham G., McCabe R., Lambert C., Carter R.O., "Laboratory and engine study of urea-related deposits in diesel urea-SCR after-treatment systems", SAE Technical Paper 2007-01-1582.

[8] De Rudder, K., Schellens, B., Gil, A., Degelin, N., "Flow device for an exhaust system," World Patent Application 2010078052

[9] Zhang X., Romzek M., "Computational Fluid Dynamics (CFD) applications in vehicle exhaust systems", SAE Technical Paper 2008-01-0612

[10] Echtle H., Schoeffel S., Wenninger G., Fischer S., Lauer T., Moeltner L., "Optimization of the selective catalytic reductions by means of numerical methods", Motor Technische Zeitung, 10-2010, Volume 71, pg 54-59

[11] Birkhold, F., Meingast, U., Wassermann, P., Deutschmann, O., "Analysis of the Injection of Urea-water-solution for automotive SCR $DeNO_x$-Systems: Modeling of Two-phase Flow and Spray/Wall-Interaction," SAE Technical Paper 2006-01-0643

[12] Dong H., Shuai S., Wang J., "Effect of urea thermal decomposition on diesel NO_x-SCR aftertreatment systems", SAE Technical Paper 2008-01-1544

[13] Yong Yi, "Development of a 3D numerical model for predicting spray, urea decomposition and mixing in SCR systems", SAE Technical Paper 2007-01-3985

[14] Strom H., Lundstrom A., Andersson B., "Choice of urea-spray models in CFD simulations of urea-SCR systems", Chemical Engineering Journal 150 (2009) 69-82

[15] Blaisdell, J., Gilb, A., Preethi, P., Sweeney, J., Viswanathan, K., Way, P., Zambon, N., “SCR Performance Optimization Through Advancements in Aftertreatment Packaging,” presented at DEER conference 2008

CONTACT INFORMATION

korneel.derudder@donaldson.com

ACKNOWLEDGMENTS

The authors wish to express special thanks to the people from AGCO Beauvais, France and the people from AGCO POWER in Linnavuori, Finland. In addition, the contribution from Bart Schellens, Jeff Gillen, Nic Degelin and Jos Symons from Donaldson is highly appreciated.

DEFINITIONS/ABBREVIATIONS

CFD	Computational Fluid Dynamics
DEF	Diesel Exhaust Fluid, Adblue
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
FTIR	Fourier Transform Infrared Spectroscopy
NO_x	Nitrogen oxides, NO and NO2
NRSC	Non Road Steady-state Cycle, 8-mode test
NRTC	Non Road Transient Cycle
PM	Particulate matter
SCR	Selective Catalytic Reduction
SCRF	DPF with SCR coating
T4	Tier 4 emission regulation
T4f	Tier 4 final emission regulation
T4i	Tier 4 interim emission regulation