



Optical Investigation on the Ability of a Cordierite Substrate Mixing Device to Combat Deposits in SCR Dosing Systems

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Abstract

Selective catalytic reduction (SCR) has become the mainstream approach for removing heavy-duty (HD) diesel engine NO_x emissions. Highly efficient SCR systems are a key enabling technology allowing engines to be calibrated for very high NO_x output with a resultant gain in fuel consumption while still maintaining NO_x emissions compliance. One key to the successful implementation of high efficiency SCR at elevated engine out NO_x levels is the ability to introduce significantly more AdBlue into the exhaust flow while still ensuring complete ammonia production and avoiding the formation of deposits.

This paper presents a body of experimental work conducted on an exhaust test bench using optical techniques including high-speed imaging and phase Doppler interferometry (PDI), applied under representative exhaust conditions to a HD diesel engine after-treatment system with optical access inside the mixer tube.

Two different sprays were used to dose AdBlue onto the mixing device. A three-hole injector and a single-hole pressure-swirl injector were characterised in ambient and heated exhaust flow conditions. A metallic two-stage mixer and an uncoated cordierite ceramic substrate mixer were compared and demonstrated the ability of the substrate mixer to reduce deposit formation at higher dosing rates inside the mixer tube when used with the correct spray type. High-speed imaging revealed the ability of the substrate to absorb injected AdBlue spray at cooler exhaust temperatures. However, using the incorrect spray can lead to liquid saturation inside the substrate channels, which is detrimental due to the formation of deposits on the rear face of the substrate.

Introduction

Selective catalytic reduction has become the established exhaust after-treatment technology for combating the NO_x emissions of modern heavy-duty diesel engines. Today's SCR systems are capable of achieving a cycle averaged NO_x reduction efficiency up to 96 % [1] which enables full compliance with the most stringent current

emissions legislation. These systems use a urea water solution, commercially known as AdBlue, to provide the ammonia required for the SCR reaction into the exhaust stream. Many of these systems have been optimised to operate in conjunction with engines using an EGR strategy of around 15-25 % to maintain typical engine out NO_x values up to 3 g/kWh [2]. The continued push from regulators for HD diesel engines to reduce fuel consumption and CO₂ emissions and realising engines with brake thermal efficiencies nearing 50 % will require engine calibrations and a combustion strategy which generate high engine out NO_x at levels of 8 to 12 g/kWh [3]. These engines will require SCR systems capable of over 98 % NO_x reduction efficiency and due to the increased NO_x levels will require significantly increased AdBlue injection rates into the exhaust flow in order to provide enough ammonia for the SCR reactions, but ultimately could deliver a fuel consumption improvement of nearly 3 % compared to a 2010 baseline engine [1].

While there are several aspects key to a highly efficient SCR system, including catalyst formulations and control strategies, the ability to generate and distribute the required ammonia from AdBlue is critical and often presents a number of problems. AdBlue, a fluid consisting of 32.5 % urea in purified water, is sprayed into the exhaust flow upstream of the SCR catalyst. The transfer of thermal energy from the exhaust stream into the spray evaporates the majority of the water content before thermally decomposing the remaining urea by thermolysis and hydrolysis resulting in the release of gaseous ammonia. In many cases, mixing devices located downstream of the injection point are used to provide a hot surface area for spray impingement and heat transfer into the spray, and to uniformly distribute the spray and generated gases within the exhaust flow. The formation of deposits inside the SCR mixer tube, generated from undesirable reaction pathways during the thermal decomposition of the urea are a known and continual problem in SCR dosing systems. Deposit formation is a complex function of exhaust geometry, spray and exhaust flow structures, exhaust gas and wall temperatures and chemistry. Despite a significant body of work published around these subject areas [4, 5, 6, 7, 8, 9, 10, 11, 12], a complete understanding of controlling and avoiding deposit formation is still not available.

One practice implemented to mitigate against deposit formation is to create a deposit-limited dosing map for a specific SCR system [4]. This map defines the maximum amount of AdBlue that can be sprayed into the exhaust at a given exhaust flow rate and temperature without forming deposits over a set period of time. Ultimately, these maps can put a limitation on the NO_x conversion efficiency of an SCR system. If the engine NO_x level requires more ammonia than the deposit map allows, which becomes very significant at high engine out NO_x levels, then insufficient ammonia will be available to conduct the SCR reactions. Therefore, being able to make step performance increases to the dosing map is critical in realising the next generation of ultra-high efficiency SCR systems.

Scope of the Study

The objective of this study was to experimentally assess the ability of a high-surface area mixing device to prevent the formation of urea derived deposits at high AdBlue dosing rates. This was achieved by modifying an after-treatment system to provide full optical access to the mixer and mixer tube. This paper describes the spray characteristics of two different AdBlue injection systems. These sprays were then used to dose AdBlue onto a ceramic substrate mixing device while a combination of time-lapse photography and high-speed shadow imaging have been used to observe and quantify the spray-mixer interactions for each system under representative exhaust flow conditions. The amount of any deposits formed has been evaluated and compared against a benchmark of a two-stage mixer commonly found in current SCR dosing systems.

Experimental Setup

Exhaust Flow Test Facility

In order to gather the experimental data, two identical bespoke exhaust test beds were designed and built within the Mechanical Engineering department at Loughborough University. These test beds were able to operate independently of each other and generate air flows representative of exhaust flows from a HD diesel engine. A schematic of one of the test beds is shown in [Figure 1](#).

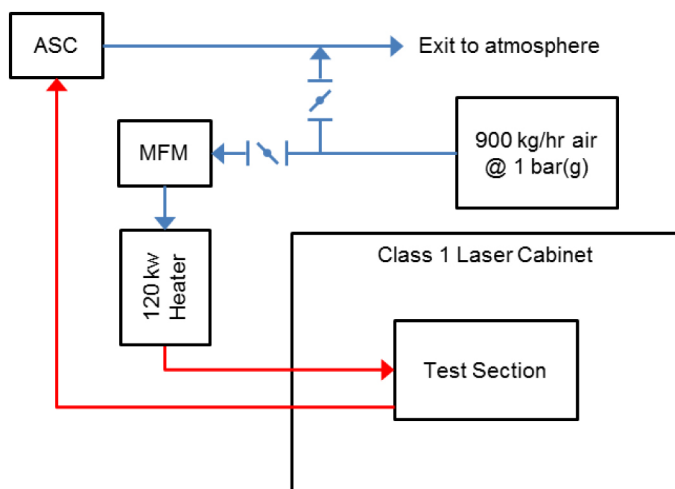


Figure 1. Schematic diagram of exhaust test bench

Each test bed comprised of a 30 kW air blower which supplied up to 900 kg/hr of ambient air at a maximum pressure of 1 bar(g). Air mass flow rate was modulated by splitting the flow between the main supply and a bypass line controlled by butterfly valves and measured by an in-line thermal mass flow meter (MFM). Each air supply was fed through a 120 kW in-line electric heater capable of heating the air to a maximum temperature of 600 °C.

Due to the risks associated with the operation of Class 4 lasers for the experimental work, the test sections were contained inside a Class 1 interlocked laser-safe cabinet. The heated air supply was fed in and out of the cabinet. An ammonia slip catalyst (ASC) was installed downstream of the test sections to remove any ammonia generated before discharging to atmosphere. Atmospheric air was used throughout the entirety of the testing rather than combustion products.

Optical Test Section

All experimental work described in this paper was conducted on a HD diesel engine after-treatment module in which the standard mixer tube was replaced with an optical 97 × 97 mm square profile mixer tube. The optical mixer tube was mounted immediately downstream of a sharp 90° elbow and a two-stage mixing device, similar to those in [8, 10, 14-16], was located at the inlet of the mixer tube. For some of the testing, the two-stage mixer was replaced by a 400 cells per square inch (cpsi) ceramic substrate structure, acting as a high-surface area mixing device for the AdBlue spray to impact on. The AdBlue injector was located on the outside the 90° elbow mounted such that the spray was discharged into the exhaust flow parallel to the centreline of the mixer tube. The distance between the injector nozzle and the leading edges of the mixing device was approximately 100 mm. A simplified representation of the injector and mixer flow path is presented in [Figure 2](#). A DPF located upstream of the test section ensured a consistent flow profile into the mixing device.

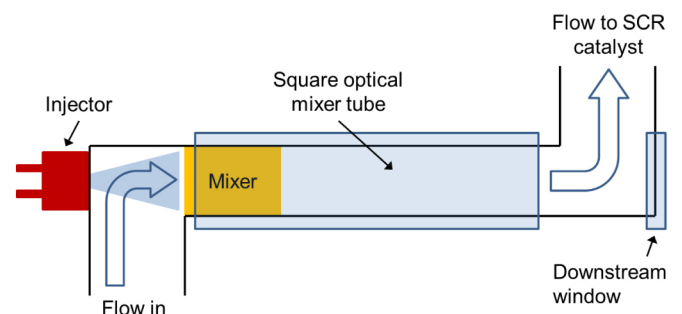


Figure 2. Schematic diagram of SCR injector and mixer location

The optical mixer tube provided visual access to the trailing edge of the mixing device and the downstream region. The two flat windows of the mixer tube were made of 5 mm thick quartz glass. A 3 mm thick flat quartz window was installed downstream of the mixer tube on a 90° bend. This window allowed light to be introduced axially down the length of the mixer tube or for upstream images inside the mixer tube to be acquired. All joining surfaces were sealed with high temperature gaskets to prevent leakages. In this configuration, the optical mixer tube was able to safely operate at exhaust gas temperatures in excess of 500 °C. [Figure 3](#) shows the optical mixer tube and downstream window.

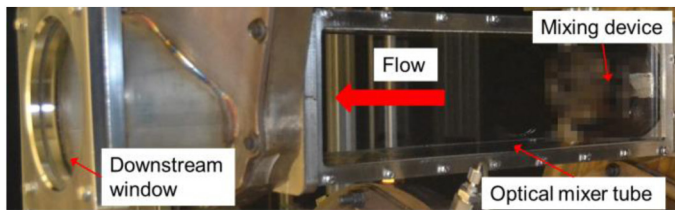


Figure 3. Optical square mixer tube and downstream window

AdBlue Sprays

This study focuses on the use of two different AdBlue dosing systems, each with their own spray characteristics, and how they interact with mixers to influence deposit formation. Both injection systems were airless, single-fluid systems using pulse width modulation at a fixed frequency of 1 Hz to control and vary the rate of AdBlue injection. Both systems consisted of a pumping unit connected via a pressurised line to a separate injection unit which contained a solenoid valve for injection activation. One system featured a three-hole injector and operated at a system pressure of 9 bar(a). The three orifices of the injector were arranged into an equilateral triangle and relied on the turbulent break-up of the AdBlue streams to promote spray atomisation. The second system employed a single orifice pressure-swirl injector, running at an injection pressure of 10 bar(a) to produce its spray. Both systems could achieve a range of AdBlue dosing rates from 50 to 5000 g/hr.

Spray Structures

High-speed shadowgraphy images of the two sprays in ambient conditions (Figure 4 and Figure 5) highlight the differences between their structures. The three-hole injector produced three distinct jets of fluid with long breakup lengths. In comparison the pressure-swirl injector generated a spray that atomised in a very short breakup distance resulting in a solid cone spray structure with a much more uniform distribution of spray across its cross-section. The atomisation of spray from both the injectors was seen to be consistent across the duration of each dosing event and unaffected by dosing rate.

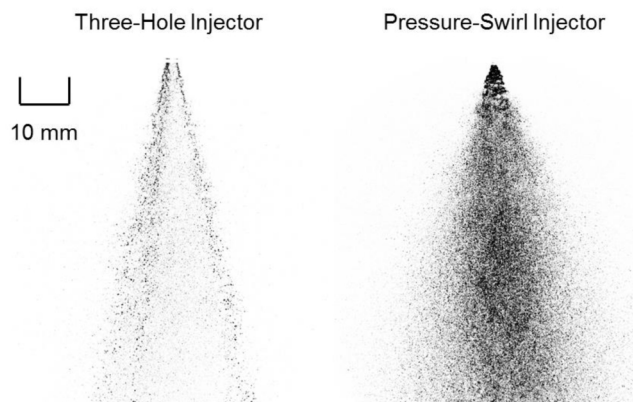


Figure 4. Comparison of sprays in ambient conditions. AdBlue dosing rate = 1000 g/hr

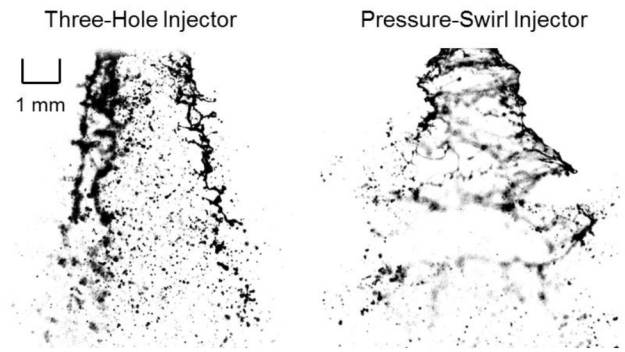


Figure 5. High-speed shadowgraphy images of spray breakup near nozzle in ambient conditions

The cone angle, the angle made by the intersection of the two outside edges of the spray at the nozzle, was determined to be 28° for the three-hole injector while the pressure-swirl injector generated a spray with a wider cone angle of 40° . Figure 6 presents cross sections showing the distributions of the two sprays captured with laser sheet imaging at a plane 100 mm downstream from the point of injection. The injectors were mounted on the outside of a 90° bend and injected into an airflow of 200 kg/hr at a temperature of 350°C . Both spray structures were insensitive to deflection from the cross flow over a range of exhaust flows. It can be seen that the pressure-swirl injector generated a very distributed spray profile across the entire cross section in comparison to the concentrated spots of spray from the three-hole injector.

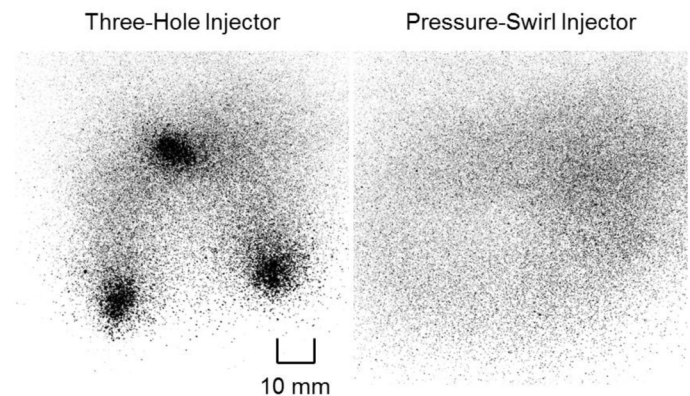


Figure 6. Comparison of spray cross-sections 100 mm from point of injection in an exhaust flow of 200 kg/hr and temperature of 350°C

Spray Droplet Measurement

Droplet diameters and velocities were measured throughout both sprays in ambient conditions using an Artium Technologies PDI-200 Phase Doppler Interferometer system. Figure 7 displays the distribution of droplet diameters across a plane 100 mm from the point of injection at an AdBlue dosing rate of 1000 g/hr for both injectors. Droplets up to $395\ \mu\text{m}$ in diameter were measured in the spray of the three-hole injector although the majority of the droplets measured below 150 microns with a Sauter mean diameter (SMD) of $95.5\ \mu\text{m}$. The spray from the pressure-swirl injector was much finer with an SMD of $33.5\ \mu\text{m}$ and no droplets greater than $100\ \mu\text{m}$ measured, with most of the droplets less than 50 microns in diameter.

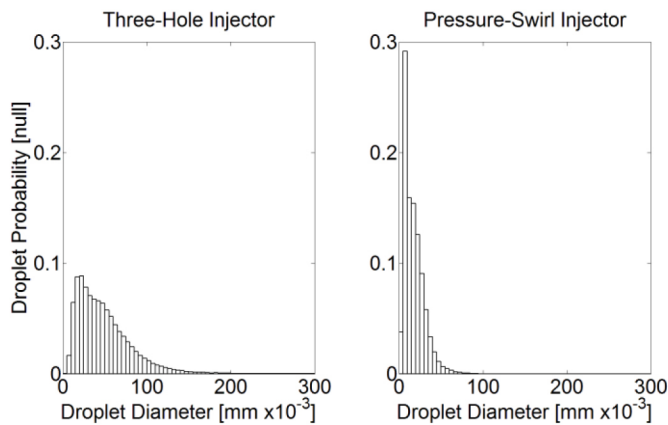


Figure 7. Histogram of droplet diameters measured across a plane 100 mm from point of injection. Dosing rate = 1000 g/hr

Droplet velocities measured at the same 100 mm plane are shown in Figure 8. In both sprays, modal droplet velocities ranged between 6 to 12 m/s. Droplet velocities up to 30 m/s were recorded for both sprays, although the pressure-swirl spray had very few droplets with velocities over 15 m/s. Figure 9 and Figure 10 present the spread of droplet velocities and momentum respectively as a function of diameter for the two sprays.

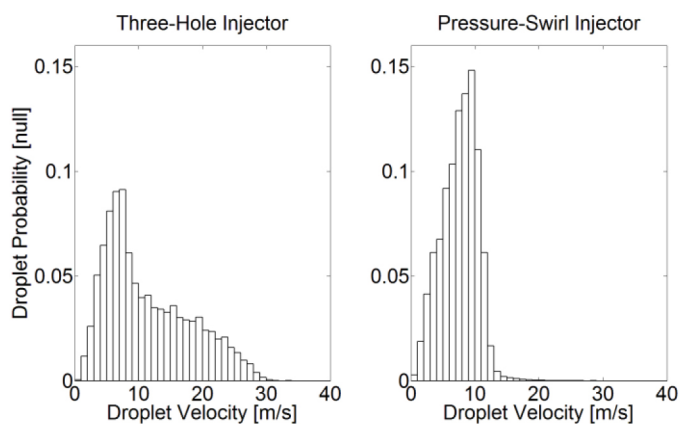


Figure 8. Histogram of droplet velocities measured across a plane 100 mm from point of injection. Dosing rate = 1000 g/hr

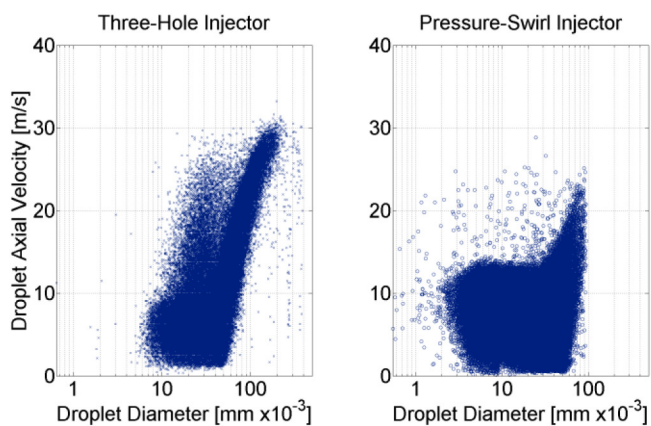


Figure 9. Droplet diameter vs velocity measured 100 mm from point of injection. Dosing rate = 1000 g/hr

For droplets measuring between 10 and 100 μm , droplet momentum was comparable between the two sprays, although the three-hole injector produced droplets above 100 microns with increased momentum whereas the pressure-swirl spray contained a greater quantity of sub 10 micron droplets with very low momentum.

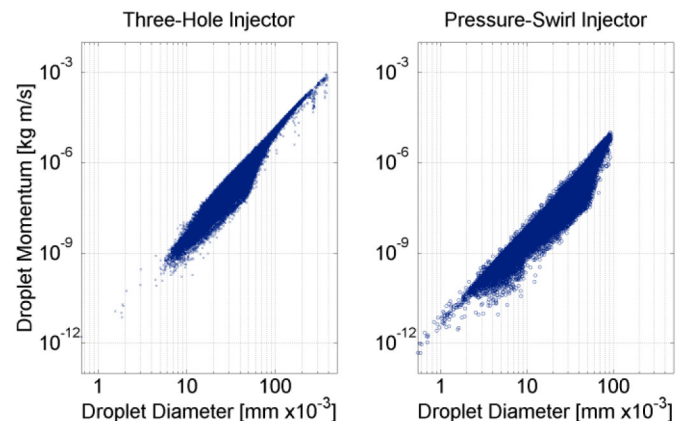


Figure 10. Droplet diameter vs momentum measured 100 mm from point of injection. Dosing rate = 1000 g/hr

Imaging Techniques and Testing Methodology

Throughout the testing, six steady-state exhaust flow conditions were used; three temperatures and two mass flow rates, as listed in Table 1. These conditions represented typical exhaust flows of a HD diesel engine.

Table 1. Exhaust operating conditions used during testing

Exhaust Condition	Exhaust Gas Temperature [°C]	Exhaust Gas Mass Flow [kg/hr]
EC1	250	250
EC2	250	750
EC3	350	250
EC4	350	750
EC5	450	250
EC6	450	750

At each exhaust condition testing was conducted across a range of AdBlue dosing rates ranging from 500 to 2000 g/hr, substantially higher than those operated at to achieve Tier 4 final levels of NO_x reduction on current engines. However, at future engine out NO_x levels of 8 - 12 g/kWh, these higher dosing rates will be required to generate enough ammonia for the SCR reactions.

Two imaging techniques were used throughout this study in order to gather experimental data on the interaction between the sprays and mixing devices.

Deposit Time-Lapse Imaging

Time-lapse photography was used to image the rear face of the mixer and downstream inside the mixer tube over a period of constant AdBlue dosing, allowing the formation and progression of any deposits to be captured. A Nikon D800E DSLR camera fitted with a

60 mm macro lens was positioned to image upstream through the downstream optical window (Figure 11). The camera was set with an ISO of 800, a shutter speed of 1/20 s and at an aperture of $f/16$. The camera was triggered remotely to capture an image every 4 seconds over a 10 minute dosing period resulting in a total of 151 images per test condition. Illumination of the imaging region through the optical mixer tube windows was provided by a 900 lumen LED light.

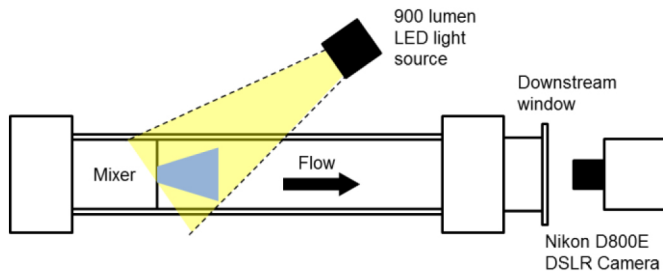


Figure 11. Mixer tube deposit time-lapse imaging setup schematic

At each steady-state exhaust condition, dosing was maintained at a constant rate over the 10 minute period, with the mixer and mixer tube initially free from deposits. After a test, any deposits present were either removed by increasing the exhaust temperature to 450 °C until the deposits fully decomposed or by cooling the rig and manually remove the deposits.

In order to allow a quantitative comparison of the amount of deposits formed at different exhaust conditions, dosing rates and hardware configurations, a subjective ranking was used to assign a value to the final image of each time-lapse series. The severity of any deposits observed on the mixer and throughout the mixer tube was scored between zero and five. A ranking of zero represented no deposits anywhere within the mixer tube while a ranking of five correlated to a significant presence of deposits distributed throughout the mixer tube, with increasing integer values in-between correlating to an increasing presence of deposits.

High-Speed Imaging of Spray at the Mixer Outlet

High-speed shadowgraphy imaging was conducted at the outlet of the mixer to understand how the spray interacted with the mixer over the duration of an injection event. A LaVision Imager Pro HS4M 12-bit digital high-speed CMOS camera fitted with a 105mm lens was positioned to image through the optical mixer tube focussed at the trailing edge of the mixer. The camera was operated at a frame rate of 2000 Hz at a resolution of 1440×1700 pixels. A LaVision high-speed laser diffuser placed on the opposite side of the mixer tube provided a uniform background illumination to generate the shadowgraphy images. The beam from a Litron LDY304 Nd:YLF high-speed pulsed laser, with a maximum energy output of 30 mJ per pulse at a rate of 2 kHz and pulse duration of 150 ns was mirrored into the diffuser. The camera and laser were synchronised through a LaVision high speed controller. A schematic of the high-speed shadowgraphy arrangement is shown in Figure 12. At each test condition, the mixer and mixer tube were initially free from any deposits prior to AdBlue injection. High-speed imaging was typically captured within the first 10 seconds of dosing.

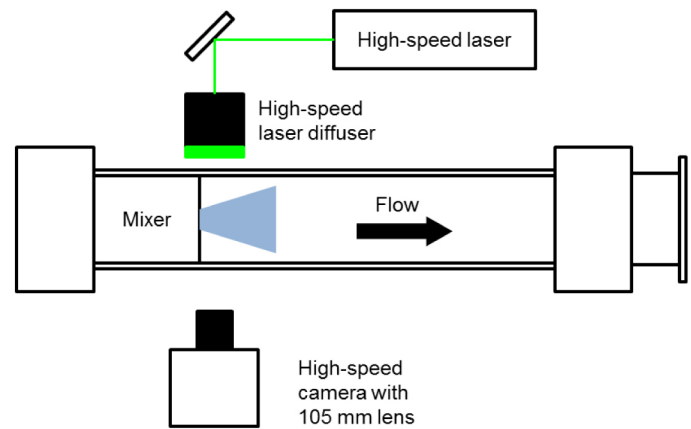


Figure 12. Mixer high-speed imaging experimental setup schematic

Results and Discussion

Two-Stage Mixer Baseline

The original mixing device was based around a metallic two-stage plate mixer, optimised to work with the high-momentum spray generated by the three-hole injector. The plates of the mixer provided a hot surface on which the larger droplets produced by the three-hole injector could impact upon and breakup into smaller droplets with increased evaporation and decomposition rates.

A significant amount of experimental testing was initially conducted using the two-stage mixer with both sprays. A combination of high-speed imaging at the trailing edge of the mixer and deposit time-lapse imaging at the back face revealed the formation of liquid films on the surfaces of the mixer as a result of spray impaction when dosing AdBlue at rates up to six times higher than those seen during normal operation. Previous studies have also experienced the formation of liquid films on the surfaces of two-stage plate mixers [7]. The formation of liquid films had two consequences. The first was a direct formation of deposits on the mixer vane surfaces where the liquid films accumulated and occurred at all temperatures tested. The second was the stripping of the liquid films due to aerodynamic interactions during which large droplets were ejected from the liquid film and impacted further downstream on surfaces of the mixer tube where they formed further deposits at exhaust temperatures below 450 °C. At low exhaust flow rates, once the liquid film had become fully developed one or two droplets ranging from 1-5 mm in diameter would be ejected per injection event. At high exhaust flow rates a smaller liquid film would eject many more droplets between 0.5 and 2 mm in diameter at a high frequency. This mechanism of deposit formation occurred with both injection systems, although the initial onset of the initial liquid film occurred at a higher dosing rate with the pressure-swirl spray.

Table 2 presents the deposit severity rankings at all six exhaust conditions for a range of dosing rates when the pressure-swirl injector was used with the original two-stage mixer. The values in brackets indicate the score given at the same exhaust condition and dosing rate but with the three-hole injector. With both injectors, the amount of deposits increased with an increase in dosing rate, and a reduction in both exhaust gas temperature and mass flow rate.

Table 2. Ranking of deposit severity based on time-lapse images with two-stage mixer and pressure-swirl injector

Deposit Severity Ranking	AdBlue Dosing Rate [g/hr]			
	500	1000	1500	2000
Exhaust Condition				
EC1	2 (3)	5 (5)	No Data (5)	No Data (-)
EC2	0 (2)	3 (3)	No Data (4)	No Data (-)
EC3	1 (2)	1 (4)	4 (5)	No Data (-)
EC4	0 (0)	0 (1)	1 (2)	2 (3)
EC5	0 (0)	0 (2)	No Data (3)	1 (4)
EC6	0 (0)	0 (0)	No Data (1)	0 (1)

It can be seen from Table 2 that the pressure-swirl injector offered a benefit in reducing the amount of deposits when compared to the three-hole injector at many of the conditions tested, with significant reductions at EC3 with a dosing rate of 1000 g/hr and at EC5 at a dosing rate of 2000 g/hr. At these conditions significant amounts of deposits remained after 10 minutes of dosing with the three-hole injector but switching to the pressure swirl reduced these deposits to negligible amounts. At other exhaust conditions such as EC1 and EC2, the pressure-swirl injector reduced deposits at a dosing rate of 500 g/hr but once the dosing rate was doubled to 1000 g/hr, the severity of the deposits with both injectors were comparable.

The improvement seen with the pressure-swirl injector was attributed to the wider spray angle, smaller SMD and more uniform distribution of spray which resulted in better utilisation of the available surface area of the two-stage mixer compared to the three-hole injector. The targeted jets of the three-hole injector and larger droplet size had the effect of locally cooling the impaction sites on the mixer. The pressure-swirl spray reduced localised heat flux from spray impaction on the surfaces of the mixer and the subsequent formation of liquid films that was the starting point for deposit formation was also reduced. However, at higher dosing rates the fact that the deposit severity became insensitive to the spray type suggests that the capacity of the mixer began limiting the capability of the system to extract thermal energy from the exhaust stream and transfer it into the spray mass to enable successful urea decomposition.

A mixer with a much greater surface area should therefore be able to further reduce deposit formation at a given exhaust condition by being able to collect more heat from the exhaust flow through increased convection, and simultaneously impart more of that energy into the AdBlue spray during impaction.

High-Surface Area Substrate Mixer

A 400 cpsi uncoated cordierite ceramic substrate, typically used in automotive catalysts, was employed as a high-surface area mixing device. Each extruded square profile channel measured 1.15 mm × 1.15 mm. Figure 13 shows the front face of the substrate mixer along with an image of the channels when viewed through a microscope.

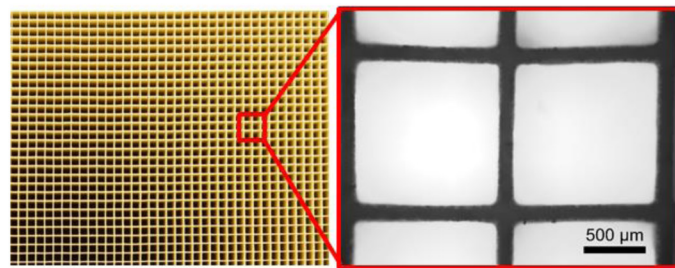


Figure 13. 400 cpsi uncoated ceramic substrate used for a high-surface area mixing device

An 80 mm long section of substrate was cut to shape and fitted inside the optical mixer tube replacing the original metallic two-stage mixer. The total surface area of the substrate mixer channels was approximately 2500 % greater than that of the two-stage mixer.

Substrate Mixer with Three-Hole Injector

The substrate mixer was initially used in conjunction with the three-hole injector to assess whether or not the increased surface area in comparison to the two-stage mixer would lead to a reduction in deposit formation. Deposit formation over a 10 minute period was captured with time-lapse photography and the severity ranked for all six exhaust conditions at a range of AdBlue dosing rates from 250 to 2000 g/hr.

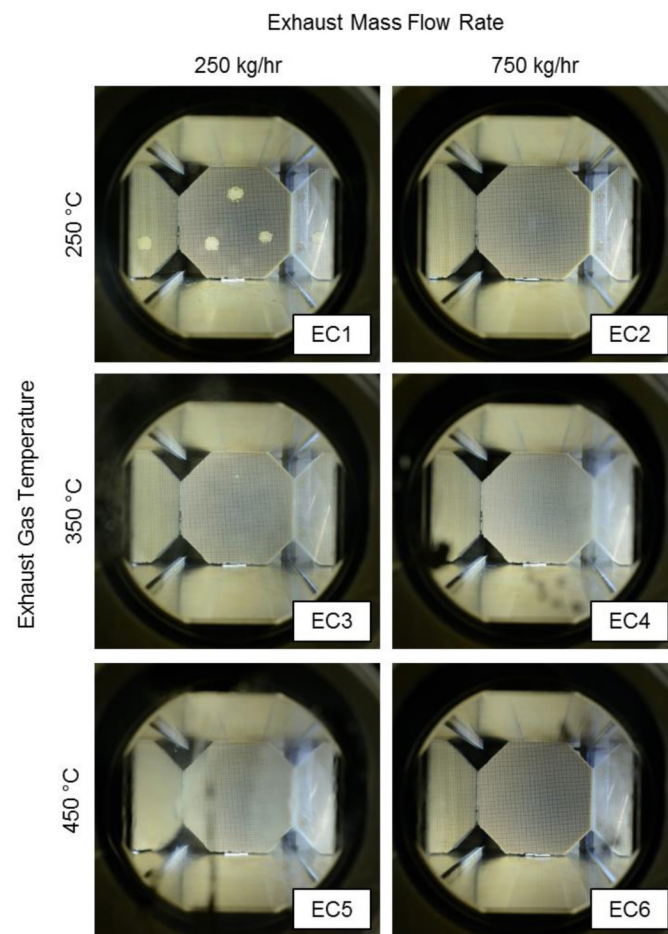
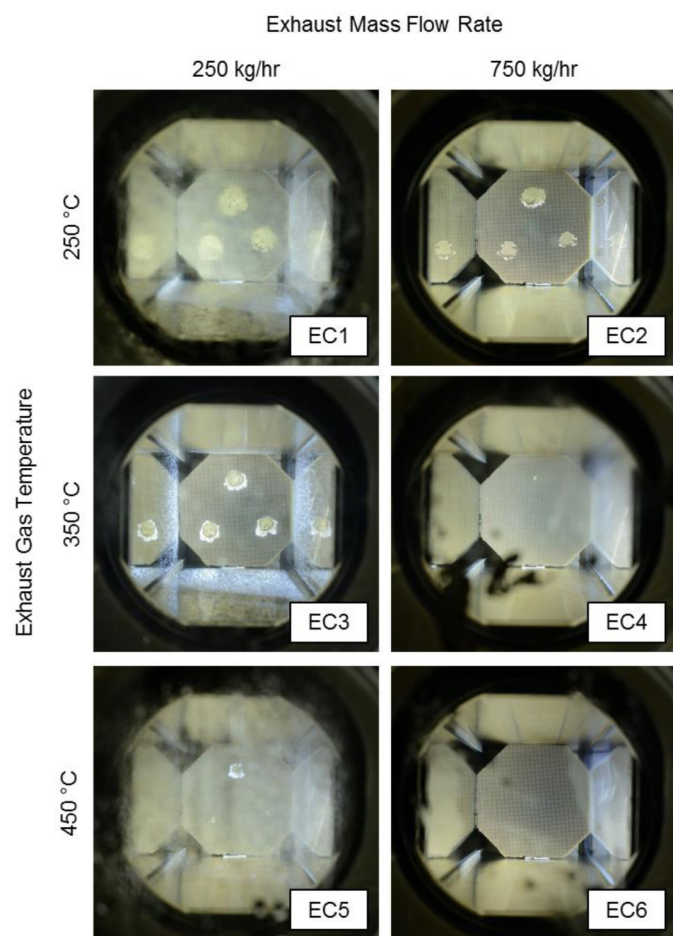


Figure 14. Time-lapse images of the substrate mixer and mixer tube after 10 minutes of dosing AdBlue at rate of 500 g/hr with three-hole injector

Time-lapse images captured observing the downstream face of the substrate mixer taken after dosing AdBlue at a rate of 500 g/hr over a 10 minute period are shown in [Figure 14](#) for all six exhaust conditions. The back of the substrate mixer and inside the mixer tube remained free from deposits at four of the conditions. However, at EC3 and more noticeably at EC1, lighter spots were present on the downstream face of the substrate. At EC1, three spots, each approximately 10 mm in diameter were formed. The spots indicated the presence of liquid AdBlue and that the channel had become fully saturated with spray. At EC1, the first signs of saturation began after approximately 200 seconds of dosing and then continued to grow over the remaining dosing period. The arrangement of the three spots corresponded to the jets produced by the three-hole injector. At EC3, a very small spot could be identified towards the top of the substrate as some of the channels became saturated.



[Figure 15](#). Time-lapse images of the substrate mixer and mixer tube after 10 minutes of dosing AdBlue at rate of 1000 g/hr with three-hole injector

Images shown in [Figure 15](#) were taken at a dosing rate of 1000 g/hr. Doubling the dosing rate led to some level of saturation at all conditions with the exception of EC6. At EC1, the onset of saturation began after 1 minute. After 2 minutes, spitting emanating from the saturated regions began leading to significant wall wetting on the downstream surfaces of the mixer tube. The size of the saturation regions increased to approximately 20 mm in diameter after 5 minute of dosing. At EC3, initial saturation could be seen after the first 80 s of dosing with spitting and wall wetting again occurring after 2 minutes leaving a coating of white deposits distributed over the walls

of the mixer tube. After 6 minutes, white rings started to form and develop around each saturation spot on the back of the mixer. The same white rings were also formed at EC2 and at EC4, 5 and 6 at higher dosing rates.

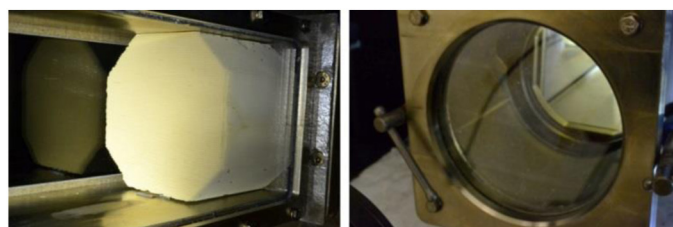
As seen with the formation of liquid films on the two-stage mixer, saturation of the substrate channels occurred the quickest and most readily at low exhaust temperatures, low mass flow rates and at high dosing rates.

Also observed with the substrate mixer was a tendency for deposits to form on the rear imaging window downstream of the mixer tube, even when there was no evidence of channel saturation or deposit formation on the substrate mixer, as displayed in [Figure 16](#).



[Figure 16](#). Urea deposits on rear window at EC6 with no mixer or mixer tube deposits after 10 minutes of dosing at 1000 g/hr

Deposits in this location were not seen to form when the two-stage mixer was fitted. However, with the substrate mixer they occurred at all conditions tested with two exceptions; at EC1 with a dosing rate of 250 g/hr and at EC2 at a dosing rate of 500 g/hr. At both of these low temperature (250 °C) operating points, the substrate mixer did not become saturated ([Figure 17](#)).



[Figure 17](#). No substrate saturation or rear window deposits after 10 minutes of dosing at EC2, dosing rate = 500 g/hr

Two processes have been identified to explain the formation of the deposits seen on the rear window due to the substrate mixer. The extruded profile of the substrate mixer allowed a straight flow path through which the injected spray could pass unimpeded, with no mixer surface directly in the trajectory of the spray. The extruded profile also acted as a flow straightener creating a uniform flow profile downstream of the mixer with very little cross-stream mixing that allowed the droplets to continue until their momentum resulted in them impacting on the downstream window. This could be seen to occur from the time-lapse images and occurred at EC3, 4, 5 and 6 at all dosing rates and consistently over the 10 minute dosing period. This attribute of the substrate mixer was responsible for the deposits seen in [Figure 16](#) where there was no mixer saturation or deposit formation at the mixer. It should also be noted that no spray was seen passing through the substrate mixer when the exhaust gas temperature was 250 °C at both flow rates (EC1 and EC2).

The other process which led to the formation of deposits on the rear window only occurred once the channels of the substrate became saturated. Liquid films present on the downstream face of the substrate were stripped by the air flow discharging through nearby channels and the droplets entrained in the flow eventually impacted on the rear window. Examples of this are shown in [Figure 18](#) and [Figure 19](#). The ejected droplets also impacted on the walls of the mixer tube forming further deposits.



Figure 18. Urea deposits on rear window due to substrate saturation after 10 minutes of dosing at EC2, dosing rate = 1500 g/hr



Figure 19. Urea deposits on rear window due to substrate saturation after 10 minutes of dosing at EC5, dosing rate = 2000 g/hr

The angled surfaces and vanes of the two-stage mixer presented obstructions to the trajectory of the spray resulting in droplet impingement and also created a strong mixing flow inside the mixing tube to disperse the droplets, both of which prevented the formation of deposits on the rear window. Deposit severity rankings are summarised in [Table 3](#) for all the conditions and dosing rates tested at with the three-hole injector and substrate mixer. Corresponding values for the three-hole injector with the two-stage mixer are shown in brackets.

Table 3. Ranking of deposit severity based on time-lapse images with 400 cps substrate mixer and three-hole injector

Deposit Severity Ranking	AdBlue Dosing Rate [g/hr]			
	500	1000	1500	2000
Exhaust Condition				
EC1	2 (3)	5 (5)	No Data (5)	No Data (-)
EC2	1 (2)	2 (3)	4 (4)	No Data (-)
EC3	1 (2)	5 (4)	5 (5)	No Data (-)
EC4	1 (0)	2 (1)	No Data (2)	5 (3)
EC5	1 (0)	3 (2)	5 (3)	No Data (4)
EC6	1 (0)	1 (0)	No Data (1)	4 (1)

Compared to the two-stage mixer, the substrate mixer only marginally reduced deposits at EC1, 2, and 3 at dosing rate of 500 g/hr (and also at 1000 g/hr at EC2). At all other exhaust conditions and

dosing rates, the same or an increased coverage of deposits occurred when using the substrate mixer. In some cases, such as at EC4, 5, and 6 at low dosing rates, this was due to the small amount of deposits formed on the rear window from direct spray impingement despite a deposit free mixer and mixer tube. In other cases saturation of the substrate and associated deposits were responsible for the higher deposit severity rankings.

Spray High-Speed Imaging at Substrate Outlet

To further examine and assess the amount of spray droplets passing through the substrate mixer high-speed shadowgraphy imaging was conducted at the outlet of the substrate mixer at all six exhaust conditions. At each condition, data was collected within the first 10 seconds of dosing, before any potential channel saturation occurred. The images were then processed using LaVision DaVis software to quantify the amount of droplets over an injection event. The steps used to process a series of spray images to extract a measure of spray droplets is listed below.

1. Background removal by subtracting first image from all subsequent images
2. Convert to binary image using fixed pixel intensity threshold. Binary image; spray = 0, background = 1
3. Define fixed pixel area within each image that spray passes through
4. Count all pixels inside defined area with intensity value = 0 (spray)
5. Plot pixel count against image number (time)

Plots of all six exhaust conditions at a dosing rate of 500 g/hr and at 1000 g/hr are presented in [Figure 20](#) and [Figure 21](#) respectively. Both plots indicate at EC1 and EC2 (250 °C) that no droplets were detected at both dosing rates across the full spray events. At all other conditions some quantity of spray droplets were measured across the entirety of the spray event. At both dosing rates the most spray downstream of the substrate mixer occurs at EC5 followed by EC6, both at 450 °C. Less spray was detected at the two 350 °C conditions.

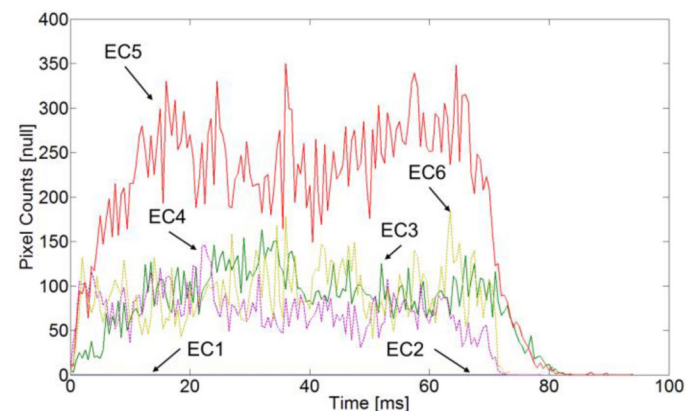
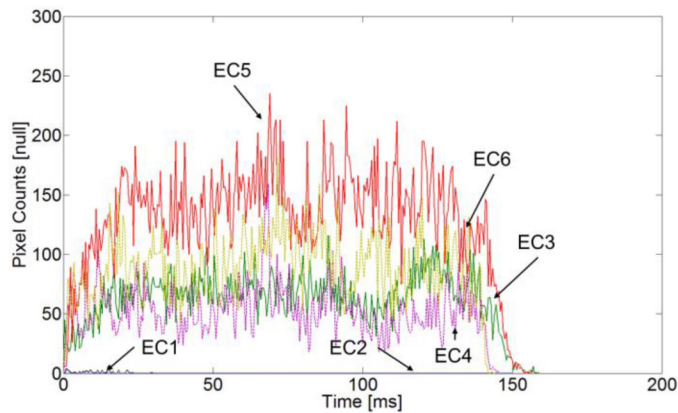


Figure 20. Quantitative analysis of high-speed imaging of spray discharging from substrate mixer with three-hole injector at a dosing rate = 500 g/hr

This analysis indicates that at 250 °C, the substrate mixer was capturing all the injected droplets which promoted quick saturation of the channels. At hotter temperatures, the ability of the substrate to

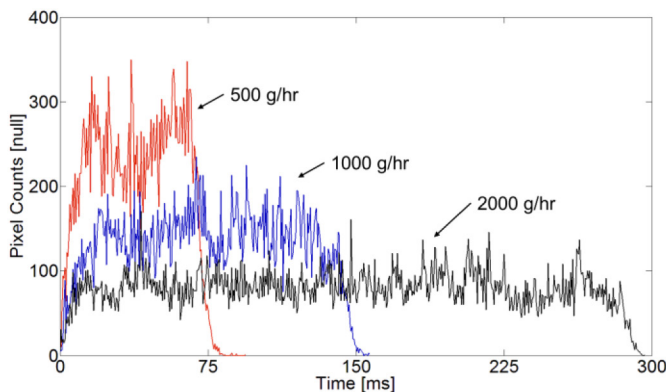
retain all the spray mass was reduced, therefore some of the droplets passed through the mixer leaving less fluid to be captured requiring more time or a higher dosing rate for any saturation to occur.

Comparing [Figure 20](#) and [Figure 21](#) a decrease in the spray quantity detected at EC3, EC4, EC5 and EC6 can be seen as dosing rate was increased.



[Figure 21](#). Quantitative analysis of high-speed imaging of spray discharging from substrate mixer with three-hole injector at a dosing rate = 1000 g/hr

This trend of decreasing amount of spray discharged from the substrate mixer with an increase in dosing rate is highlighted in [Figure 22](#) which shows plots of spray count at EC5 at dosing rates of 500 g/hr, 1000 g/hr and 2000g/hr.



[Figure 22](#). Quantitative analysis of high-speed imaging of spray discharging from substrate mixer with three-hole injector at EC5 at 3 dosing rates

As dosing rate was increased, the surface temperature of the substrate mixer decreased as more heat was transferred to the droplets. As seen in [Figure 20](#) and [Figure 21](#), lower temperatures resulted in less spray discharged and the substrate mixer absorbing a greater percentage of the initial spray.

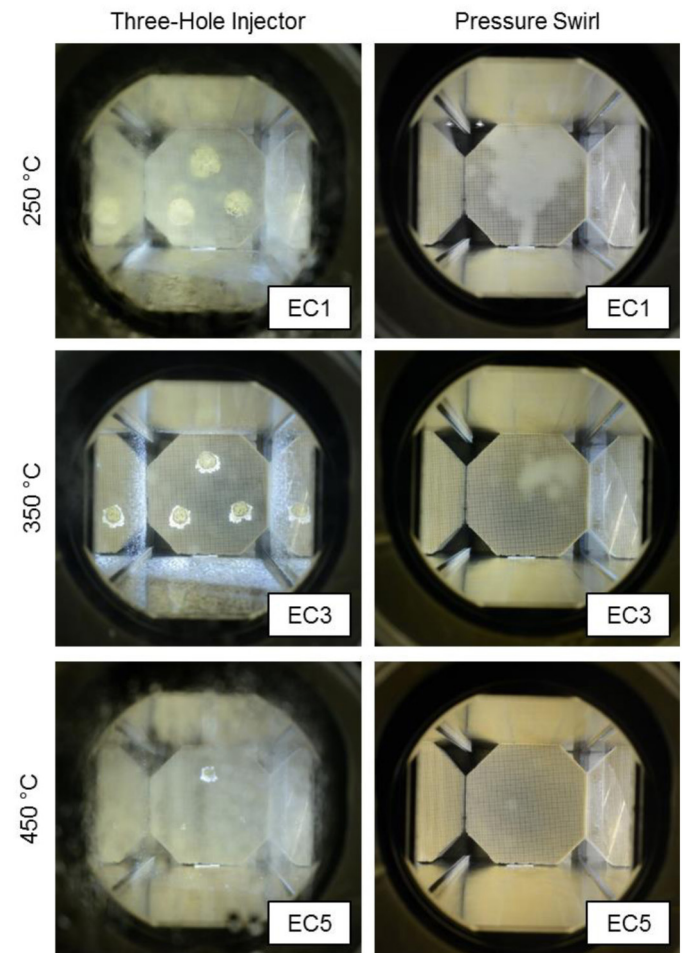
Substrate Mixer with Pressure-Swirl Injector

The substrate mixer with the three-hole injector did not demonstrate a significant performance gain in being able to increase dosing rates while avoiding deposit formations compared to the two-stage mixer. This was in part due to liquid saturation of the channels of the substrate where the jets of the spray hit. The pressure-swirl mixer had already shown to reduce deposits on the two-stage mixer due to its more distributed and finer spray. Therefore, this spray should also be better suited to maximising the high-surface area of the substrate

mixer and yield higher dosing rates without the presence of deposits. Time-lapse imaging of deposit formation and high-speed imaging of the spray were both repeated with the same substrate mixer and the pressure-swirl injector over the same range of high dosing rates.

With the pressure-swirl injector, minimal localised saturation of the substrate only occurred at one condition; at EC1 with a dosing rate of 1500 g/hr. At a dosing rate of 1000 g/hr at EC1 there was no indication of substrate saturation or deposits in the mixer tube. In comparison with the three-hole injector, significant saturation and spitting occurred at this condition and with the two-stage mixer significant deposits formed on the mixer and inside the mixer tube with both injectors.

However, as seen with the substrate mixer and three-hole injector, spray droplets consistently impacted on the rear imaging window resulting in small deposits. This occurred continually across the 10 minute dosing period at all conditions, even at exhaust temperatures of 250 °C which did not happen with the three-hole injector.



[Figure 23](#). Three-hole injector and pressure-swirl injector with substrate mixer after 10 minutes dosing at a rate of 1000 g/hr at EC1, EC3 and EC5

[Figure 23](#) compares images after 10 minutes of dosing at a rate of 1000 g/hr with both injectors onto the substrate mixer at an exhaust flow rate of 250 kg/hr. At all three exhaust temperatures the substrate mixer became saturated with the three-hole spray with deposits on the walls of the mixer tube at 250 and 350 °C and significant wetting on the rear window at 450 °C. At all three conditions some minor spray

impaction on the rear window was evident with the pressure-swirl spray but no deposits on the substrate mixer or the walls of the mixer tube occurred.

Deposit severity rankings from the time-lapse images for the substrate mixer with the pressure-swirl injector are summarised in [Table 4](#). Corresponding values for the pressure-swirl injector with the metallic two-stage mixer are shown in brackets.

Table 4. Ranking of deposit severity based on time-lapse images with 400 cps substrate mixer and pressure-swirl injector

Deposit Severity Ranking	AdBlue Dosing Rate [g/hr]			
	500	1000	1500	2000
Exhaust Condition				
EC1	1 (2)	1 (5)	2 (-)	No Data (-)
EC2	0 (0)	1 (3)	1 (-)	No Data (-)
EC3	1 (1)	1 (1)	No Data (4)	2 (-)
EC4	0 (0)	2 (0)	No Data (1)	3 (2)
EC5	1 (0)	1 (0)	No Data (-)	1 (1)
EC6	0 (0)	1 (0)	No Data (-)	1 (0)

At an exhaust gas temperature of 250 °C deposit severity was significantly reduced by switching to the substrate mixer at both exhaust flow rates (EC1 and EC2). A ranking value of one, indicating negligible amounts of deposits was applied in many cases due to a small amount of spray impaction on the rear window. In some cases such as EC3 and EC4 at a dosing rate of 2000 g/hr deposits on the rear window were more prevalent resulting in a ranking of two or three.

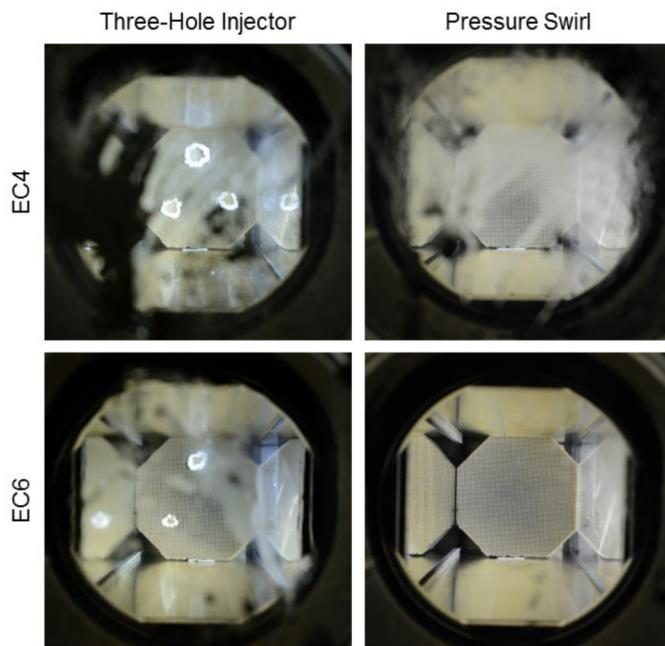


Figure 24. Three-hole injector and pressure-swirl injector with substrate mixer after 10 minutes dosing at a rate of 2000 g/hr at EC4 and EC6

A comparison of deposits with the two injectors at a dosing rate of 2000 g/hr at an exhaust flow of 750 kg/hr is presented in [Figure 24](#). Again, with the three-hole injector saturation resulted in the formation of deposit rings on the back of the substrate and spitting onto the rear window. However, with the pressure-swirl injector, the substrate remained deposit free and direct spray impingement on the rear window was responsible for a small amount of deposit formation.

Analysis of high-speed imaging to quantitatively evaluate the spray discharging from the substrate mixer was carried out with the pressure-swirl spray. [Figure 25](#) shows the spray measured downstream of the substrate at an exhaust flow rate of 250 kg/hr at temperatures of 250 °C (EC1), 350 °C (EC3) and 450 °C (EC5) at a constant dosing rate of 1500 g/hr. As seen with the three-hole injector, the amount of spray detected increased with an increase in exhaust gas temperature. Very small amounts of spray were consistently observed at 250 °C with the pressure-swirl injector, but with the three-hole injector no droplets were detected at this temperature. This might be due to the fact that the droplets of the pressure-swirl spray were smaller in diameter in comparison to the three-hole spray. Over 60 % of the droplets in the pressure-swirl spray measured between less than 20 microns 100 mm from the injection point. Therefore these droplets were more likely to be entrained in the flow passing through the channels of the mixer and had a higher probability of avoiding contact with the channel walls resulting in an increased likelihood of downstream spray. However, this minor amount of spray still resulted in the presence small deposits on the rear window.

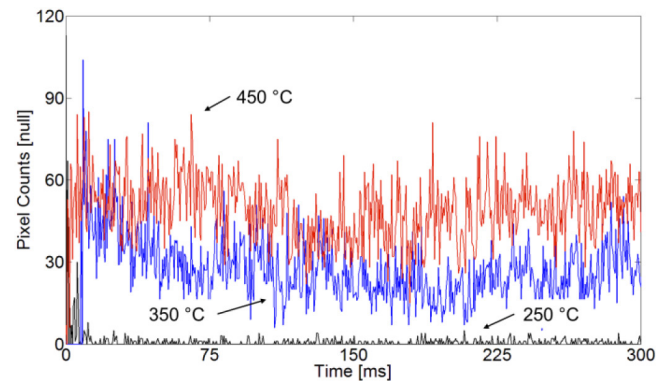


Figure 25. Quantitative analysis of high-speed imaging of spray discharging from substrate mixer with pressure-swirl injector at a dosing rate = 1500 g/hr

The effect of increasing dosing rate on the amount of spray observed downstream of the substrate at EC3 is shown in [Figure 26](#). As seen with the other injector, spray decreased with an increase in dosing rate.

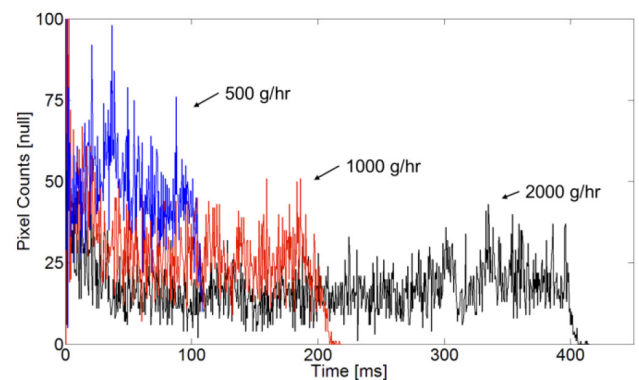


Figure 26. Quantitative analysis of high-speed imaging of spray discharging from substrate mixer with pressure-swirl injector at EC3 at 3 dosing rates

Conclusions

An optical investigation into the interactions between two different AdBlue sprays and a high-surface area mixing device based on a 400 cpsi ceramic cordierite substrate has been carried out on a hot exhaust flow test bench under exhaust flow rates and temperatures typical of a HD diesel engine. The sprays of two injectors have been studied and measured in both ambient conditions and a heated cross-flow to develop a detailed understanding on their behaviours and characteristics.

Imaging inside the mixer tube over a sustained period of dosing with the two different injection systems has revealed the importance of correctly coupling the characteristics of the injector spray and a mixing device. The substrate mixer provided a very high-surface area through which heat could be extracted from the convecting exhaust flow and transferred into the impacting AdBlue spray. The pressure-swirl injector generated a spray with a cone angle which enabled good coverage on the front of the substrate mixer. Within this solid-cone of spray, droplets with diameters no greater than 100 microns were well distributed and therefore the entire area of the substrate mixer was uniformly utilised by the spray. As a result, the formation of liquid films was generally avoided and deposit formation minimised even at high dosing rates in comparison to the two-stage mixer. This injector and mixer partnership has been demonstrated to raise the dosing limits without forming deposits which should result in NO_x conversion efficiency gains.

However, the high-surface area mixer only delivered this improvement with the correct spray type. When using the three-hole injector, which produced much larger droplets up to 395 microns in size, concentrated in three jets of fluid, the available surface area of the substrate mixer could not be exploited. Instead, the spray jets resulted in liquid saturation of the channels. The saturation led to the formation of deposit rings on the rear face of the substrate at several of the conditions tested along with spitting of urea in solution onto downstream surfaces where deposits formed. In general, the substrate mixer offered little to no improvement in reducing deposits compared to the two-stage mixer when the three-hole injector was used, and in some cases actually performed worse.

The extruded profile of the substrate mixer did present the problem of allowing some of the injected spray to pass directly through the substrate resulting in the formation of small deposits at the site where spray impaction occurred downstream. The amount of spray which passed through was related to gas, and therefore substrate wall, temperature. It was shown that at 250 °C the substrate mixer was able to absorb nearly all of the spray which could be advantageous to controlling deposit formation. However as temperature increased, either through a direct increase in exhaust temperature or indirectly through reduced cooling at lower dosing rates, the amount of spray which passed through the substrate mixer increased.

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Definitions/Abbreviations

AdBlue - A fluid consisting of 32.5 % urea by mass in ultra-pure water

ASC - Ammonia Slip Catalyst

CPSI - Cells Per Square Inch

DPF - Diesel Particulate Filter

DSLRL - Digital Single-Lens Reflex

HD - Heavy-Duty

MFM - Mass Flow Meter

NO_x - Nitrogen Oxides

PDI - Phase Doppler Interferometry

SCR - Selective Catalytic Reduction

SMD - Sauter Mean Diameter

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