

An Experimental Investigation into DEF Dosing Strategies for Heavy Duty Vehicle Applications

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ABSTRACT

In recent years urea selective catalytic reduction (SCR) has become the principal method of NO_x abatement within heavy duty (HD) diesel exhaust systems; however, with upcoming applications demanding NO_x reduction efficiencies of above 96 % on engines producing upwards of 10 g·kWh⁻¹ NO_x, future diesel exhaust fluid (DEF) dosing systems will be required to operate stably at significantly increased dosing rates.

Developing a dosing system capable of meeting the increased performance requirements demands an improved understanding of how DEF sprays interact with changing exhaust flows. This study has investigated four production systems representing a diverse range of dosing strategies in order to determine how performance is influenced by spray structure and identify promising strategies for further development.

The construction of an optically accessible hot-air flow rig has enabled visualisation of DEF injection into flows representative of HD diesel exhaust conditions. High-speed and laser sheet imaging have been applied to capture the injection event and analyse spray development within the flows.

Results from ambient shadowgraphy show the extent of variation in spray structure that exists between the systems; further quantified with droplet size distribution data collected using phase Doppler interferometry (PDI). Imaging within the exhaust section indicates that the structure of a spray has a significant impact on droplet entrainment within the flow, in turn affecting the level of spray-wall impingement seen. This suggests knowledge of dosing strategy will be critical for optimal system design and enabling near future dosing rate demands to be met.

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INTRODUCTION

The treatment of engine out NO_x using selective catalytic reduction has been an area of research interest for over a decade, during which time the technology has been demonstrated as an effective method of reducing tailpipe NO_x and widely adopted for both on- and off-highway applications. There currently exists detailed treatment of the fundamental reaction schemes of the SCR process, from ideal decomposition to proposed pathways that lead to undesirable reaction by-products often found as deposits within exhaust systems.

The fundamental principal of the technology is the promotion of reactions between engine out NO_x and ammonia (NH₃) in the presence of oxygen [1]. The reaction products, nitrogen and water, are then safely emitted at the tailpipe. However, issues with safe on-board storage of ammonia have led to the use of precursors: less hazardous substances such as urea, from which ammonia can be generated [2]. Diesel exhaust fluid (DEF), a mixture of 32.5 % urea

and 67.5 % de-ionised water, is the most widely used of these, with a now mature supply infrastructure established. As DEF is liquid at atmospheric conditions it is injected into the exhaust gas, where first the water content is evaporated off before the urea thermally decomposes to ammonia and isocyanic acid (HNCO). Isocyanic acid is stable in the gas phase, but will hydrolyse to carbon dioxide (CO₂) and ammonia on surfaces within the exhaust system or the SCR catalyst. However, in reality the formation of decomposition by-products through alternative reaction paths is often seen, with deposit formation from injected urea widely reported within SCR studies [3,4,5,6]. A detailed study of the decomposition of urea has shown that the by-products present during decomposition at different temperatures include biuret, cyanuric acid, ammelide, ammeline and melamine [7]. A large number of desirable and undesirable reactions have been proposed [8], with reactions involving the intermediate HNCO attributed to producing common by-products [9], yet despite this knowledge operating free of deposits still poses the most significant challenge for urea SCR systems.

Deposit formation is often seen to occur at low exhaust temperatures, with cooling by the DEF spray causing internal surfaces to fall below a critical temperature and become wetted [4]. To prevent excessive cooling, maps of maximum allowable dosing rate can be generated experimentally; limiting the DEF dose given monitored exhaust flow conditions. This approach enables stable operation of urea SCR; however, the NO_x reduction of such a system is constrained by the ability of the dosing system to operate without forming deposits. Therefore, to maximise the NO_x reduction efficiency that can be achieved approaches to increase this maximum stable dosing rate must be developed.

One reported approach is to improve the atomisation of the DEF spray, reducing droplet residence time and therefore decreasing the quantity of spray impacting on and cooling internal surfaces. Alternative routes to a finely atomised spray can be taken, with high pressure and air-assisted injectors both reported to show reduced droplet size [10, 11]. The approach is supported by modelling results which have suggested that droplet evaporation time can be reduced significantly when atomised to 50 µm [12], although this alone cannot guarantee spray-wall impingement is avoided. With single fluid injectors capable of atomising droplets to below 100 µm, a move towards more advanced single fluid injectors has been reported as a current trend in the industry [13].

The use of mixing devices as an additional component coupled to the dosing system is another strategy to improve system performance now commonplace within SCR systems: providing hot-surfaces within the flow to break-up larger droplets and promote mixing to increase ammonia uniformity. Much work has been done on investigating the design of mixing devices [14,15,16], with experimental and simulation results suggesting that performance gains are achievable when a holistic design approach is taken [11]. Detailed knowledge of the spray structure and exhaust geometry are therefore critical when developing an optimised mixing device. Similar approaches, such as dosing directly onto a hydrolysis catalyst [17], have been proposed, although such systems still require an understanding of spray behaviour within the gas flow to ensure an even coverage across the catalyst face is achieved.

The work dedicated to developing high efficiency urea SCR has so far culminated in systems reportedly capable of NO_x reduction efficiencies of approaching 96 % [6, 18]. In Europe, tailpipe out NO_x limits of 0.4 g·kWh⁻¹ will require NO_x reduction efficiencies approaching 98 % given the engine out NO_x levels upwards of 10 g·kWh⁻¹ possible from proposed high efficiency combustion configurations [19]. Therefore, next generation systems will be required to operate at increased efficiency with DEF dosing loads exceeding current operation while remaining deposit free.

Meeting required performance levels presents a difficult challenge for aftertreatment designers, and a fundamental understanding of the interactions between DEF sprays and exhaust flows is now critical to maximise the NO_x reduction achievable in next generation systems. With a broad range of urea dosing systems commercially available it appears likely that the hardware to meet the challenge exists; however, as yet a clear demonstration of the effect that injection strategy can have on spray development within realistic hot-flow conditions has not been seen.

This study has identified how the structure of a spray affects droplet interaction with bulk exhaust flows, and in turn discusses features of a dosing strategy that could enable stable performance as higher dosing rates are demanded. The study has not set out to assess or rank the dosing systems that have been investigated and no judgement on the quality of the hardware provided has been made.

EXPERIMENTAL SET-UP

Experimental work within this study has focused on analysing the spray structure of four commercial SCR dosing systems, each of which possess distinct design features influencing different operation strategies. Systems were first set-up and tested following manufactures guidelines in order to identify operating principles, and enable a characterisation study of the spray produced in ambient conditions to be performed. Each system was then installed on a hot-flow test facility to allow observation of the injection events in conditions representative of real world application.

Commercial Dosing System Overview

The four dosing systems procured for this study were commercially available production systems, and therefore representative of urea SCR dosing system technology at the time of testing. Key features of system operation for each of the four units are summarised in [Table 1](#). The breadth of injector hardware available gives an indication of the importance of understanding how changing injection strategy can affect the performance of a system.

Table 1. Summary of dosing system key features

System	A	B	C	D
Injection fluid	Air-assist	Single fluid	Single fluid	Air-assist
Dose metering	Frequency modulated	Pulse-width modulated (1 Hz)	Pulse-width modulated (1 Hz)	Continuous (at point of injection)
Metering control	At pump	Injector head (solenoid)	Injector head (solenoid)	At pump
Injector location	Wall	Wall	Wall	Centre-line
Number of orifices	2 (Concentric)	3	1	4 (Radial)

Commercial DEF was used as the injection fluid in all testing performed within this study. Where compressed air was not generated by the dosing system it was supplied from compressed air lines within the laboratory at 5 bar(g). During testing each system was controlled via control area network (CAN) bus communication enabling manual specification of dosing rates.

Hot-Flow Test Facility

To generate hot gas flows representative of a HD diesel exhaust a bespoke facility was designed and built within the Optical Engineering Laboratories at Loughborough University. The facility comprises of two enclosed optical test benches, each supplied with high temperature air-flows for parallel study and development of urea SCR dosing systems. To enable fundamental study of spray-flow interactions the facility was designed to operate with independent control of gas flow rate and temperature, achieved by artificially generating and heating an air flow. Two 30 kW air blowers supply air at flow rates of up to 900 kg·hr⁻¹ to each of the rigs, which is heated to up to 600 °C with 120 kW in-line electric heaters. As the bulk flow

does not contain combustion products, no SCR reactions take place within the facility. Therefore an ammonia slip catalyst (ASC) was installed downstream of the test section to manage emission of ammonia produced from DEF decomposition. All results presented in this paper have been collected using dry air as the hot gas.

Due to the nature of the experimental work, all testing was performed within interlocked enclosures, ensuring the optical benches are Class 1 systems to minimise the risk of exposure to laser emissions. The insulated pipework installed within the enclosed cabinets is shown in Figure 1, illustrating the configuration of the test section used to collect the data presented within this study.

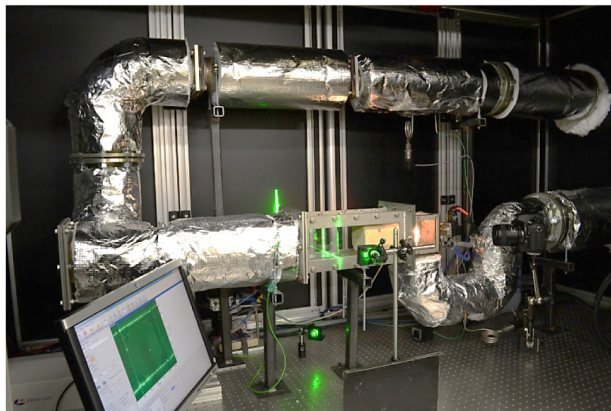


Figure 1. Hot-flow pipework geometry and optical section within laser cabinet

Flow Control

Heater controllers were used to set flow temperatures at the heater outlet, with the temperature at the rig inlet, measured with a K-type thermocouple, used to monitor the test section temperature. The air mass flow rate was set using valve control on main and by-pass flow lines and measured using an insertion probe thermal mass flow meter. Temperatures and pressures across the test section were also monitored and logged during experimental work. A schematic of facility components relevant to this study is included in Figure 2.

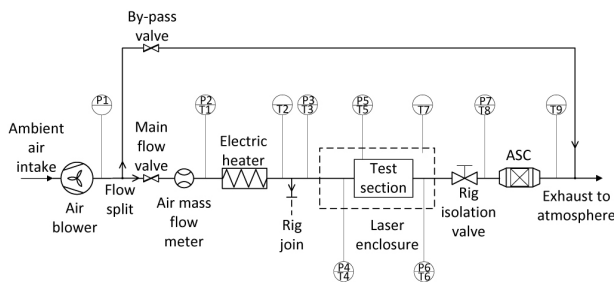


Figure 2. Schematic of hot-flow test facility showing sensor locations

Test Section Geometry

Injection systems were mounted on a sharp 90° bend to imitate s-bend and flow-hood injection configurations. The only exception to this was the centre-line injector, which was mounted immediately downstream of the bend in the straight optical pipe section.

A square profile optical pipe section, 90 × 90 mm in dimension, was designed incorporating quartz windows to give visual access at the point of injection and along the central axis of the injection pipe. Figure 3 illustrates the test section geometry, showing the flow path, injector locations and optical access.

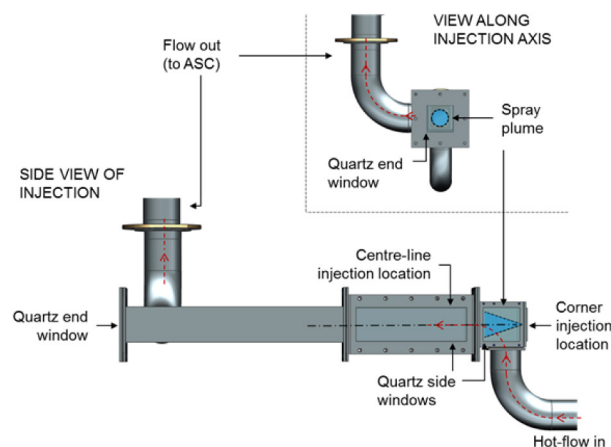


Figure 3. Test section set-up showing optical access at the point of injection and along the injection axis

Side and end quartz windows enable the application of shadowgraphy and laser sheet imaging (LSI) to visualise the spray within the flow up to 400 mm downstream of the point of injection. The experimental set-up of all hot-flow testing is illustrated in Figure 4, including the camera layouts and location of laser sheets.

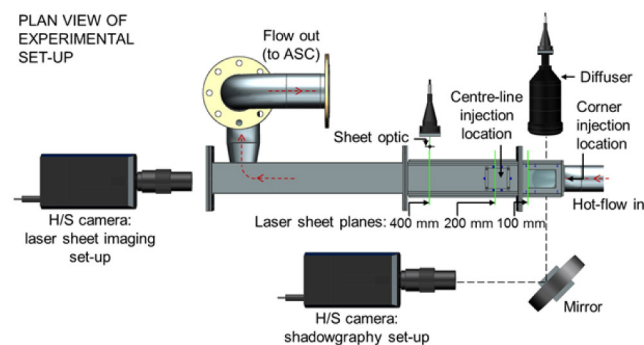


Figure 4. Plan view of optical test section with set-up of imaging tools for shadowgraphy and laser sheet imaging within a hot-flow

Optical Diagnostics

A number of optical diagnostic techniques were used to perform spray analysis within this study. Imaging techniques were used in both ambient and hot-flow conditions, with quantitative phase Doppler interferometry (PDI) data for spray characterisation collected only in ambient conditions.

Spray Visualisation

High-speed shadowgraphy imaging was the primary method of spray visualisation used within this study. An Imager pro HS 4M camera supplied by LaVision UK Ltd. was used to capture the spray formation at a frame rate of 1 kHz and resolution of 2016 × 2016 pixels. An imaged region of approximately 120 × 120 mm was captured using a 105 mm Nikkor lens, giving a scale factor of 0.058 mm/pixel. An aperture setting of f/11 was used to provide adequate depth of field when capturing injection events. Start and end of injection events were manually identified within the series of stored images. Fluorescent light produced by expanding an Nd:YLF (527 nm) laser beam into a Rhodamine 6G dye screen was used to back illuminate all shadowgraphy images. A far field microscope was used to provide more detail on spray break-up at the nozzle.

Laser sheet imaging, another visualisation technique, was used during testing to capture droplet distributions within the spray cross sections. Plano-convex cylinder optics were used to generate 2-dimensional laser sheets aligned perpendicular to the spray axis, enabling the spray footprint to be captured at various distances from the nozzle.

Image Processing

Slight variations in illumination intensity in shadowgraphy images were corrected by capturing a background image of the illumination source at the beginning of each image series and subtracting it from the experimental images. Intensity thresholds dictating image contrast were selected to ensure the spray structure is clearly visible in each image series. The processing has been kept consistent across data sets; however, slight adjustment was required between each spray.

Processing image sets to produce a composite image was also performed within the body of work. Typically an RMS average of a series of LSI images was taken in order to represent an injection event with a single image. Such images will be seen in analysis of spray cross sections in ambient and hot-flow conditions reported in the results section.

Phase Doppler Interferometry

Point measurements of droplet size and velocity were obtained in ambient conditions using phase Doppler interferometry. An Artium Technologies PDI-200 system capable of measurements in two-dimensions was set-up to collect droplet data at a point until either 10000 droplets had been detected or 20 seconds had passed. As droplet size and velocity measurements are made at the waist of interfering beams the system was traversed through the sprays in planes orthogonal to the spray axis, characterising the sprays at 50, 100 and 200 mm from the nozzle.

Experimental Test Conditions

Detailed characterisation of the four sprays was performed in ambient conditions. During PDI measurements sprays were directed into an extraction system in order to prevent buoyant droplets re-entering the measurement volume.

Table 2. Summary of flow conditions and dosing rates used during hot-flow injection event observation

Test point	Mass flow rate (kg·hr ⁻¹)	Flow temperature (°C)	Dosing rate (g·hr ⁻¹)
1	200	200	100
2	200	350	400
3	900	200	900
4	900	350	2000

Observation of injection events within hot-air flows was performed at four conditions for each system. The test points, given in Table 2, were selected to be representative of conditions seen in application and illustrate the effect that flow rate and temperature have on spray propagation within a flow. Dosing rates used during testing were based on maximum deposit free dosing rates achievable at each flow condition at the time of testing.

RESULTS AND DISCUSSION

Detailed characterisation of each spray including visualisation of spray structure and cross section, and quantitative droplet size distribution data will first be presented with discussion of the dosing system operation in ambient conditions. Attention is given to the consistency of the spray produced during an injection event and across the range of system dosing rates in order to identify any features of the spray likely to contribute to unstable performance during application. Visualisation of each spray within hot-gas flows will then be presented to illustrate DEF spray development within real-world application conditions and link spray-flow interactions with spray characterisation data.

Spray Structures in Ambient Conditions

Images typical of the fully developed spray produced by each system are presented in Figure 5. From these images alone the extent of variation in spray structure between production systems can be seen. The spray plumes produced by the air-assisted systems A and D appear well atomised but within tighter cones than the single fluid sprays of B and C. The three distinct jets that can be discerned in spray B correlate to the number of orifices of the system, and are seen to atomise into a coarse, yet well dispersed spray. Spray C appears similar to the air-atomised spray of A in structure, yet the pressure swirl injector atomises the DEF dose without a second fluid. A fundamentally different dosing strategy is seen in the spray produced by system D, whereby a mixture of DEF and compressed air is radially injected through four orifices offering a wide dispersion of the dose.

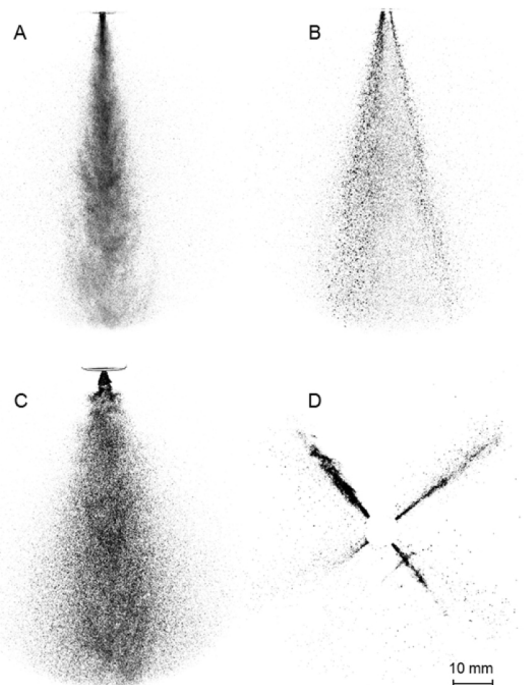


Figure 5. Shadowgraphy images showing variation in spray structure between four production systems: DEF dosing at 1000 g·hr⁻¹ in ambient conditions.