

Fluid Dynamic Comparison of AdBlue Injectors for SCR Applications

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ABSTRACT

The injection process of urea-water solution (AdBlue) determines initial conditions for reactions and catalysis and is fundamentally responsible for optimal operation of selective catalytic reduction (SCR) systems. The spray characteristics of four, commercially available, injectors (one air-assisted and three pressure-driven with different nozzle-hole configurations) are investigated with non-intrusive measuring techniques.

Injection occurred in the crossflow of a channel blowing preheated air in an exhaust duct similar configuration. The effect of several gas temperatures and flows on the spray propagation and entrainment has been extensively studied by shadow imaging. Shadow images, in addition, show that the spray of the pressure-driven injectors is only marginally affected by the gas crossflow. In contrast, the air assisted spray is strongly deflected by the gas, the effect increasing with increasing gas flow. Phase Doppler Anemometry (PDA) measurements delivered droplet size distributions and droplet velocities. Measurements have been performed in several locations near the opposed channel wall area. Sauter mean diameters of the droplets from the pressure-driven injectors are between 60-80µm while of the air assisted 20µm. Higher velocities have been associated with the larger droplets in the pressure-driven spray after the primary breakup while droplet velocities have been evenly distributed to all droplets sizes in the air-assisted spray.

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INTRODUCTION

Successful NO_x emission abatement from Diesel engines requires further optimization and enhancement of existing urea-SCR systems [1, 2]. The main challenges are maximizing NO_x reduction performance and minimizing ammonia slip as well as formation of deposits [3, 4]. Shortcomings are mainly due to incomplete urea decomposition [5, 6] and substantial non-uniformity of the spatial distribution at the catalyst entrance [7], both attributed to the dosing system. So far, studies have focused on the main reactions and selective catalysis of NO_x with ammonia [2, 8, 9, 10, 11]. Investigations of the urea decomposition process to ammonia [5, 6, 12, 13, 14] have proven invaluable for efficient system design, as urea decomposition greatly determines required mixing lengths and deposit formation. Experimental studies on the injection for SCR purposes are however scarce. The lack of knowledge in this field restricts options to optimize current systems, since initial conditions of the spray and its evaporation are unknown.

Improved mixing not only facilitates NO_x conversion, lowers both NH₃ slip and deposit formation, but inherently leads to smaller sizing of the aftertreatment systems - an intrinsic demand of automotive applications. Attempts have been made to address this issue with the installation of different mixing devices and flow homogenizers - including structured metallic substrates [15], wire-meshes [16], or two step mixers [17]. The comparative effectiveness of different devices has been investigated both experimentally and numerically [18]. To this end, the effect of injection type, location, and pressure on the urea evaporation rate and uniformity of the ammonia distribution within an exhaust duct have been investigated to determine aspects of optimum system design [19, 20, 21].

Attempts at modeling, simulation and optimization of SCR systems have been conducted [19, 20, 21, 22, 23, 24, 25, 26, 27]. Numerical simulations of different urea injection configurations have been performed [19]. High speed photography and particle sizing have been employed to determine urea spray pattern parameters, which

were used as input for a CFD model [27]. A model for urea-injection while taking into account interaction with exhaust tubing has also been developed [22, 23]. Coupling of spray dynamics and turbulence with chemical reactions in vehicle exhaust gases has been reported too [24, 25, 26]. In the above cases, experimental data on aspects of SCR systems was either explicitly not available [19], limited to a few sources or had to be generated specifically for the study in question [22, 23, 27].

Fluid dynamic investigation of urea-water SCR sprays have been conducted in our laboratory in the last years based on a specifically designed test rig having exhaust similar conditions while providing the possibility to set exact mass, temperature and composition of the gas flow. The fluid dynamic behavior of a 6-hole SCR injector spray was extensively investigated [28], characterizing the macro spray properties. The spray morphology and droplet size distributions under exhaust flow conditions have been used to validate numerical simulations [29, 30]. The influence of two different injectors on the NO_x conversion of an SCR catalyst was investigated in [31]. The temperature evolution on the exhaust gas duct being hit by the urea water spray has been also investigated [32].

The present work compares four commercially available injectors experimentally in terms of the bulk spray analysis, droplet size and droplet velocity distributions and predicts the suitability for mobile SCR applications. In addition, the results provide valuable initial boundary conditions for numerical modelling of the SCR system or alternatively enable the validation of SCR spray models.

EXPERIMENTAL SETUP

The experiments were conducted in the flow laboratory at EMPA, Dübendorf. This laboratory was designed for the experimental investigation of urea-water injection into the exhaust channel for SCR application. For the scope of this paper, all experiments were done with dry air as exhaust flow to investigate the fluid dynamic behavior of the injection spray. The air is taken from EMPA pressurized air network and fed into a large dampening volume to get rid of possible oscillations. The air flow is then led through three heating units to reach the target temperature. The prepared gas flow subsequently passes through the injection channel assembly which allows optical access from four directions, two from the sides, one from the top and one from the bottom. Figure 1 shows an overview of the exhaust flow channel. In this work, the chamber with a square cross section of 80mm by 80mm and 150mm in length is used. The gas flow through the measurement chamber can be regulated up to 450kg/h and 500°C, which allows the reproduction of engine exhaust like conditions.

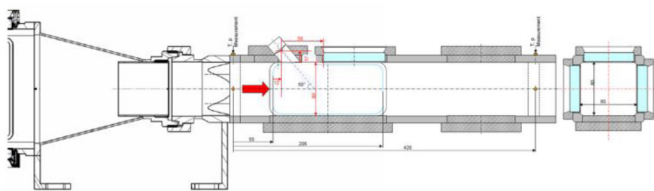


Figure 1. Schematic diagram of the EMPA high temperature flow channel.

Table 1. Characteristics of the four SCR injectors

Injector	A-A	P1-6H	P-3H	P2-6H
Driven mechanism	air-assist	pressure	pressure	pressure
Pressure	-	9bar	9bar	9bar
Air-pressure	1.5bar	-	-	-
Static flow rate	2.64kg/h	15.2kg/h	7.2kg/h	7.3kg/h
Nozzle diameter	970µm	210µm	190µm	130µm
Nozzle number	1	6	3	6
Spacing diameter	-	1.3mm	1.9mm	1.9mm

Table 1 shows the injector characteristics including: driven mechanism, working pressure, static flow rate and nozzle geometries. The injector was mounted on the top of the measurement chamber, 50° inclined to the gas flow direction. The high pressure system of the urea dosing unit can deliver fluid pressure of up to 15bar. The pressure-driven injectors were operated with a back pressure of 9bar during experiments and the air-assisted injector worked with an air pressure of 1.5bar. Figure 2 shows the stereomicroscopic photographs of the nozzle tip configuration of the four commercial SCR injectors investigated. A-A is a single-hole air-assisted injector. The intermediate ring between the injection nozzle and the air nozzle is 310µm thick and the width of the air nozzle is 165µm.

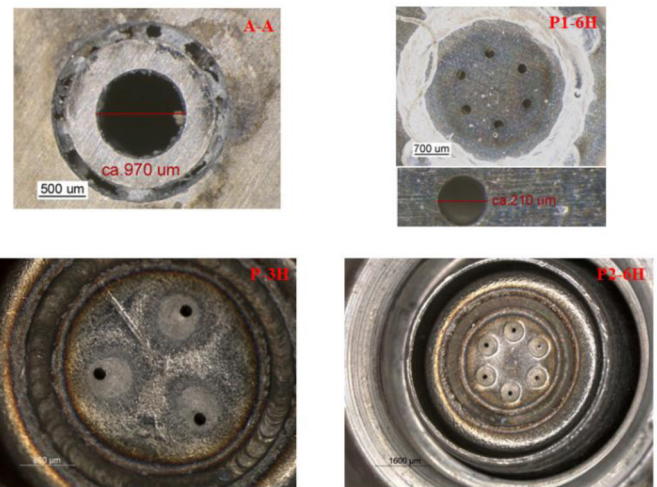


Figure 2. Stereomicroscopic photographs of the nozzle tip configuration of the four commercial SCR injectors investigated.

In this study, shadow imaging and phase Doppler anemometry (PDA) have been applied to investigate the behavior of the spray. For shadow imaging, the optical system was set up according to Figure 3. The laser which sat at the back of the injection chamber was expanded over a hemispherical lens to illuminate the diffusion plate, in which way a uniform bright background was created. And the camera was located on the other side of the injection chamber to take pictures of the spray in front of the illuminated background. On the images captured by the camera there are shadows, where the laser light has been scattered away by the spray droplets, being visible over a bright background as shown in Figure 3. The background illumination was done by using Cavitax CAVILUX smart which is a

pulsed diode laser light source with a wavelength of 690nm. Laser pulses of 40ns and 1Hz synchronized with the injection event were used to avoid significant movement during the laser pulse and overexposure of the camera sensor. The PCO Sensicam camera with a resolution of 1040 by 1376 was used as the recording source.

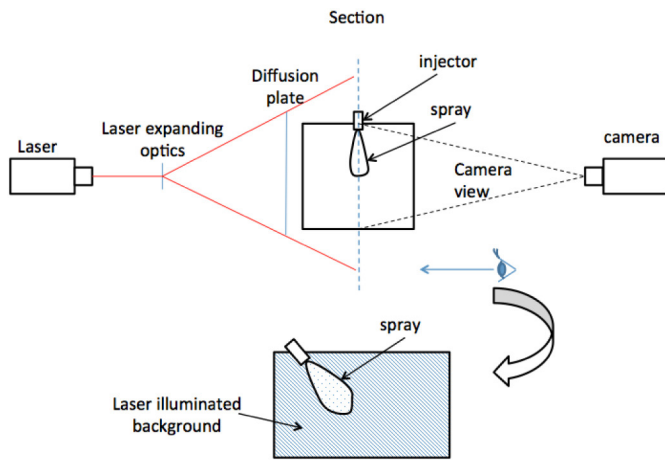


Figure 3. Schematic diagram of shadow imaging setup

PDA optical setup has been described in detail by a previous work [30] which was done on the same test bench.

Figure 4 displays the experimental region of interest of shadow imaging and PDA. The orange box is the shadow imaging region of interest and the green line indicates the plane for PDA measurement.

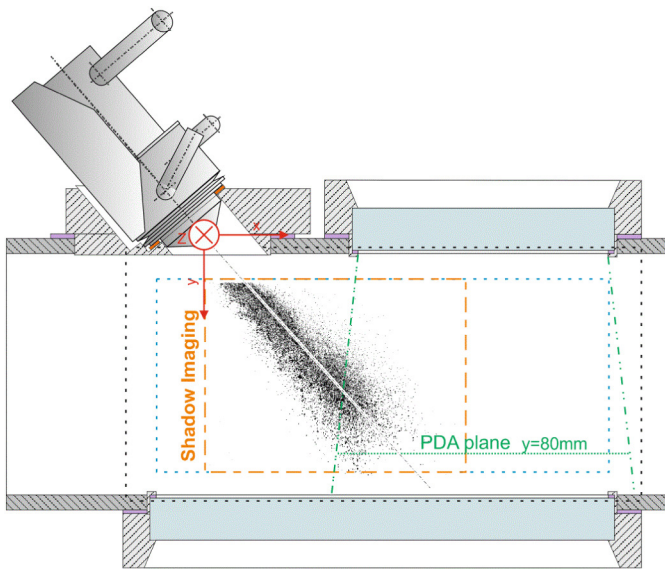


Figure 4. Experimental region of interest of the optical experiments: shadow imaging and PDA.

Previous study [28] proves that the injected fluid water and Adblue show similar behaviors in terms of the bulk spray properties and the droplet size distributions. Thus, water sprays were used in this work.

For both shadow imaging and PDA measurements, relevant flow conditions were chosen. They are similar to exhaust gas conditions at catalyst inlet. Table 2 shows the channel flow conditions at which different optical techniques were applied.

Table 2. Experimental flow conditions

Temperature [°C]	Flow rate [kg/h]	Mean gas velocity [m/s]	Re [-]
200	100	5.8	13441
200	200	11.6	26881
200	300	17.5	40322
300	100	7.0	11780
300	200	14.1	23560
300	300	21.1	35340

RESULTS AND DISCUSSIONS

This section is organized in the following way. Firstly, shadow imaging shows the overall shape of sprays from different SCR injectors and also the influence of the exhaust flow conditions on the overall spray outline. Comparative analysis of droplet size distributions from PDA measurements on the near-wall plane provides a good indication of the atomization efficiency of the different injectors studied and gives the initial conditions of the spray-wall interaction together with the droplet velocities. Finally the study is completed by the determination of droplet volume flow rates at different locations for different droplet sizes.

Spray Contours Analysis

Shadow imaging is employed to visualize the overall shape of the sprays from the four injectors. Figure 5 shows the spray contours at the same exhaust flow temperature of 300°C but at different exhaust mass flow rates 100kg/h, 200kg/h and 300kg/h. The images are obtained through binarizing the averaged image of 120 raw images which were taken at 16ms after the electronic start of injection.

Fundamentally different to the other three injectors, the air-assisted injector spray features increasing deflection of propagation with increasing exhaust mass flow rate. With increasing exhaust flow velocity the spray tends to propagate along the axial flow direction. As the spray moves coaxially with the exhaust flow, the droplets mix better with the exhaust flow and wall impingement is minimized. This behavior is favorable for the SCR application.