

Secondary Fuel Injection Characterization of a Diesel Vaporizer for Active DPF Regeneration

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ABSTRACT

Secondary fuel injection is applied to facilitate active soot management of the particulate filter within diesel aftertreatment systems, avoiding concerns with fuel delivery via in-cylinder post-injection. System performance is dependent on the thermo-fluid interactions of the injected fuel with the exhaust stream, with the intent of having more fully vaporized fuel and a well-mixed air-fuel mixture at the inlet of the oxidation catalyst for uniform thermal distribution as it exothermically reacts. Pre-heating the fuel with a diesel vaporizer prior to its delivery into the exhaust enables improved system performance, reducing droplet sizes and mixing demands. A diesel vaporizer is applied within the exhaust of a medium duty truck application, and the response of the catalyst is characterized across a variety of conditions. Cross-sectional measurements at the catalyst and filter outlet are described, including gas velocity, temperature, and HC concentration, and the effect of poor fuel vaporization is demonstrated. The system is installed in a medium-duty truck with a 4.8L engine and characterized on a chassis dynamometer across various steady-state and transient conditions. Performance is measured while applying closed loop fuel dosing control algorithms, demonstrating control capabilities similar to injectors. Adequate thermal distribution is achieved with minimal HC slip, and recommendations are offered to further demonstrate system integration benefits and risks of diesel vaporizers.

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INTRODUCTION

Benefits of diesel particulate filters (DPFs) have been discussed much over the recent years as they have become a common aftertreatment solution for particulate matter and particulate number control [1]. Soot load control methodologies and their performance dependencies have also been well described, including both active and passive regeneration [2-3]. There are numerous ways to achieve active regeneration, and a favored approach is to apply diesel fuel to react catalytically with a diesel oxidation catalyst (DOC) to elevate temperatures for a downstream DPF [4, 5, 6, 7, 8, 9]. In-cylinder post-injection of the diesel fuel is of concern due to cylinder wall-wetting and oil dilution, which are offset when the fuel is injected directly into the exhaust [10-11]. Figure 1 illustrates a typical DOC-DPF exhaust system demonstrating options of fuel introduction, including post-injection and secondary fuel injection, which can be applied within the exhaust manifold, at the turbo-outlet, or further downstream closer to the catalyst. However, thermo-fluid dependencies of the injected fuel with the exhaust gas, flow geometry (including mixers), and catalyst must be taken into account to ensure there is appropriate flow distribution of the exhaust and fuel across the catalyst cross-section, otherwise hot spots occur causing control complexities and operational risk for both the DOC and DPF [12].

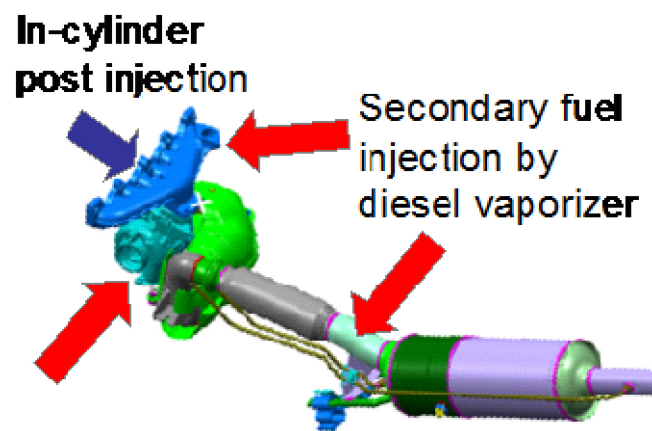


Figure 1. Typical DOC-DPF layout options

Thermal uniformity performance is also dependent on the droplet size of the injected fuel, as well as its spray pattern, velocity, and mount orientation, as evidenced in previous urea dosing studies [13, 14]. Larger droplets require additional effort to break up and vaporize, requiring additional mixing length and/or pressure drop from more aggressive mixers. Packaging restrictions demand systems to be as compact as possible, and since catalytic responses are highly temperature dependent, they are best positioned close to the heat source

(the engine). For these reasons, vaporizers are applied to preheat the fuel, which provides smaller droplets for easier mixing and improved catalytic response, enabling improved packaging and thermal management [15, 16, 17, 18, 19]. And optimizing the vaporizer integration is critical not only for active regeneration systems, but any fuel-based aftertreatment dosing needs, such as for lean NO_x traps or catalysts (LNTs, LNCs) [20–21].

OBJECTIVES

It is of interest to integrate a diesel vaporizer and mixer into a DOC-DPF exhaust system and characterize its fuel distribution performance across a range of steady state operating conditions, quantifying flow and thermal distributions as well as HC slip at the outlet of the DOC and DPF. The operating conditions consist of varying exhaust mass flow rates and temperatures, representing the range expected in the application, particularly to which the DPF regeneration is activated (requires catalyst activity to react with the dosed fuel, necessitating a minimum temperature often greater than 300°C) [12]. Effects of dosing various amounts of fuel are measured, applying thermocouples, infrared imaging, and flame ionization detection (FID). Influences of vaporization are also studied by measuring its response with its electrical power turned off, illustrating response if the vaporizer functionality (heating) is inoperative. The resulting thermal distributions across the DOC and DPF are targeted to be less than 50K from target temperature, achievable with hydrocarbon injectors as long as an acceptable mixer is integrated [12]. The exhaust system is then applied within a medium-duty truck and verified across steady state and transient conditions.

EXPERIMENTAL SETUP

This study involves a particular exhaust layout with a DOC and DPF appropriately sized and packaged for a 4.8L 158kW EUV Deutz engine within a medium-duty truck application. The DOC is 8.5" × 4" and the cordierite DPF is 8.5" × 6", loaded with 60 and 14 g/ft³ of Pd, respectively. A vaporizer (Figure 2) is installed approximately 800mm upstream of the DOC and is supported with adequate electrical energy (24V, 480W maximum) and controlled fuel delivery. The vaporizer applies a glow plug core from Beru and is in commercial production, fully validated for over 1,000 cycles without coking or clogging. The vaporizer is offered in different scales, essentially limited by power and fuel delivery rate, including a low (12V, 140W peak) and high flow (24V, 480W peak). It consists of an electrical connection at its top (1), a bendable inlet fuel tube welded on its side (2), a serviceable fastener (M22×1.5 bolt thread) to mount it to the exhaust pipe (3), a sealing cone (4) to ensure leak-free joint, and an exit tip (5) designed to target fuel dosing near the pipe center. A reciprocating piston pump is applied to deliver fuel (low pressure since vaporizer outlet hole is not restrictive) to the vaporizer at controlled rates. As the DPF requires regeneration, fuel is delivered to the vaporizer, of which its current is regulated based on its thermal response with the varying mass flow rate of the fuel. It is required to

mount the vaporizer vertically on top half of the exhaust pipe circumference with its outlet facing downward to enable the fuel to adequately drain upon shutdown. A simple "flap" mixer (Figure 3) is positioned 50mm downstream of the vaporizer (Figure 4), applying large-scale turbulence to mix the fuel vapor with the exhaust gas. An array of type-K thermocouples (Figure 5) is placed 20mm behind the DOC and DPF outlet, supplemented with an infrared camera image at the DPF outlet.

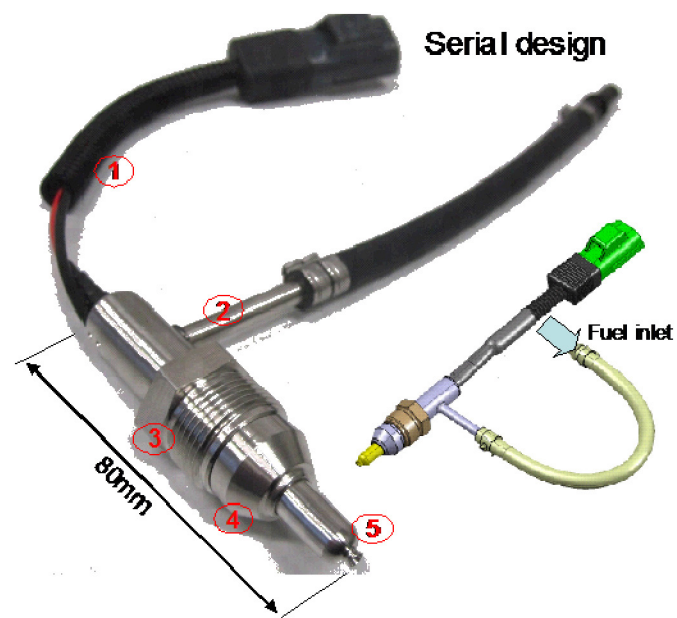


Figure 2. Applied vaporizer



Figure 3. Mixer applied after the vaporizer

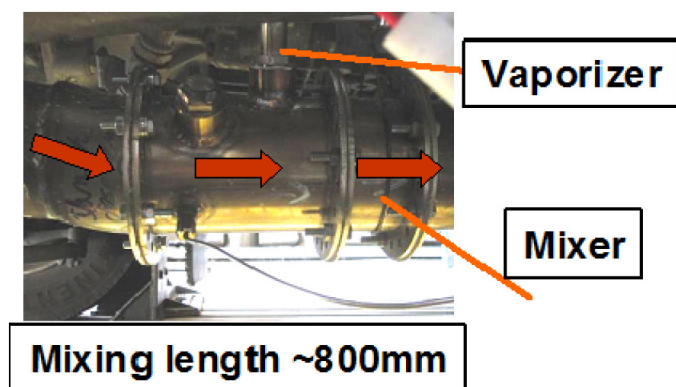


Figure 4. Vaporizer and mixer positioning

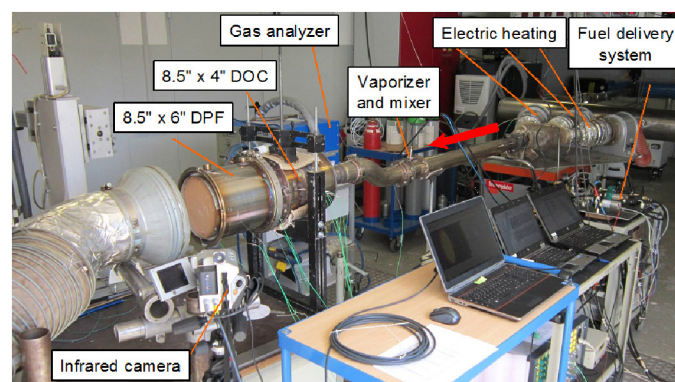


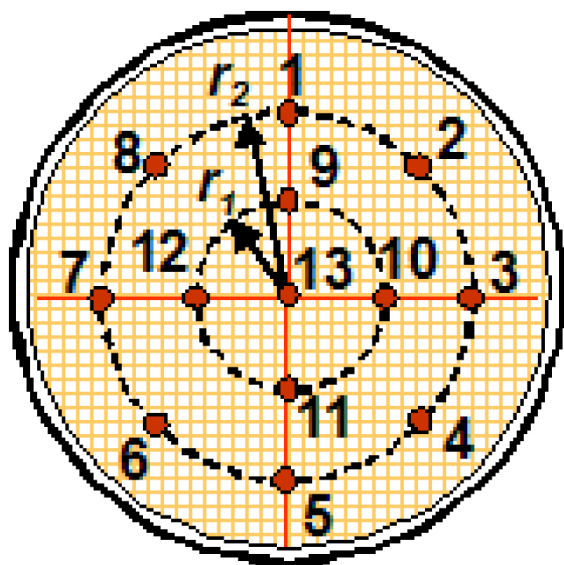
Figure 6. Flow lab experimental setup

Table 1. Flow lab operating points

Operating point	Gas mass flow [kg/h]	Gas temperature [°C]	Target temperature [°C]	HC demand [mg/s]
1	120	430	650	200
2	510	440	650	740
3	740	410	650	1210



Figure 7. Chassis dynamometer experimental setup

Figure 5. Thermocouple array ($r_1 = 30\text{mm}$, $r_2 = 90\text{mm}$)

RESULTS AND DISCUSSION

The flow lab is first applied to characterize system pressure drop and flow uniformity, providing static backpressure values for ambient (20°C) and hot flow conditions across the mass flow rate inputs. The mapped velocities are in Figure 8, including the low (65kg/hr), medium (273kg/hr), and high (407kg/hr) cold flow conditions, noting a slightly better uniformity at lower flows (94%) and stabilized flow uniformity at medium and high flows (93%). And, as expected, peak velocities noted in the scales of the velocity maps increase proportionally with gas mass flow rate, noting 0.9, 3.6, and 5.4m/s for the low, medium, and high flows, respectively. Pressure drop of the system (DPF is clean without soot or ash)