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ORIGINAL PAPER

A Heated AdBlue/DEF Mixer for High Efficiency NOx Reduction in Low Temperature Drive Cycles, RDE and City Driving

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Abstract

An electrically heated mixer (EHM™) has been developed. It enables injecting urea-water solution in low temperature Diesel exhaust operations, such as in low-load cycles, real-driving-emissions (RDE), stop-and-go, city driving and local delivery cycles, enabling high efficiency (SCR) selective catalytic reduction of NOx in challenging operations. In low temperature exhaust, EHM frees the injected droplets from relying on the heat of the exhaust. It provides thermal energy to swiftly heat and evaporate the droplets, accelerating their thermolysis and hydrolysis reactions. Designed to be compact, low cost and robust, EHM forms plenty of reductants (ammonia, isocyanic acid) while mitigating the deposit risks. It has been tested on an engine in highly transient, low-load cycles exhibiting robust SCR of NOx well below 200 °C in long cycles with urea injection starting in as low as 130 °C. The mixer has been evaluated on a light duty Diesel engine using a purged (no-ammonia-stored) SCR catalyst simulating extended stop-and-go operations, demonstrating 99–100% NOx reduction efficiency during "stops" (idling) at 180 °C, and 80 to 95% during fast transients at 160 °C, while inhibiting deposit formation. These results were achieved without any engine or system calibration. EHM needs less than 200 W to operate on a light duty Diesel engine, and about 500 W on a heavy-duty engine. Given its thermal energy, it can be also used during cold-starts or cold-cycles for rapid-heatup of the SCR catalyst(s). EHM can also enable high engine-out NOx strategy so for fuel economy and reduced CO_2.

Keywords Deposit · NOx · SCR · Ammonia · Mixer · Low-load

1 Introduction

Selective catalytic reduction (SCR) of NOx is a robust technology for NOx mitigation in Diesel exhaust [1] and much literature has been published on the technology and application of SCR catalysts and systems [2–7]. SCR operations require injecting urea-water-solution (here called 'urea' for simplicity) known as AdBlue™, Diesel exhaust fluid™ or by other names around the world. In general, injecting urea below 200 °C specially for longer durations can form a non-negligible amount of urea deposits (crystals) n the emission control system [8–11], an unwanted by-product created due to incomplete evaporation of urea. Deposits can damage exhaust components, yield large ammonia slips and possibly increase N_2O emission, amongst other adverse impacts. As a result, in general urea is not widely injected in Diesel exhaust in temperatures below 200 °C. This allows Diesel NOx to leave the tailpipe largely unabated, ensuing major health, environmental and regulatory concerns. To make up for this shortcoming, evaporation of injected urea spray and formation of gaseous reductants are typically assisted via adding a heat source, such as exhaust heaters [12], electrically heated catalysts (EHCs) [13], burners [14] or post-injection of fuel [15]. Other techniques have included injecting gaseous ammonia [16] or using an electrically heated urea doser (injector) [17]. Each approach has pros and cons on cost, complexity, maturity, durability, fuel penalty, CO_2, regulatory concerns or a mix. Here, we discuss a newly-developed electrically heated mixer (EHM™) providing a low-energy, low-cost, compact, easy-to-integrate and durable solution forming plenty of gaseous reductants in low exhaust temperature operations while simultaneously hindering urea deposit formation. It is shown that EHM enables highly efficient SCR of NOx in challenging low-load Diesel engine operations and fast transients well below 200 °C. EHM could be also used to heat the exhaust components/catalysts during cold start for rapid heatup. EHM draws its

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thermal energy from an electrical source in the vehicle (12, 24 or 48 V system), accelerating heating and evaporation of injected urea spray droplets, i.e., the droplets need not rely on the exhaust thermal energy. Also, since modern Diesel exhaust after treatment architecture already includes a mixer, utilizing EHM avoids adding one more component to the after treatment architecture.

2 Experimental Evaluation

Figure 1A shows the EHM installed on a standard DOC-DPF-SCR system (Fig. 1B). SCR catalyst is commercially available Cu–Zeolite from Umicore. Engine (not shown) is the FCA (2019) GEN III, 3.0 L eco-Diesel. No change was made in its base calibration for the purpose of this study. NOx is measured in various locations, using FTIR and analyzers, so to allow calculating the SCR efficiency. Flow temperature is measured both pre- and post-EHM, as well as pre- and post-SCR. A low-temperature, highly transient stop-and-go city driving cycle with the vehicle speed varying rapidly between 0 and 40 km/h was simulated using first 5 hills in bag-2 FTP cycle (see Fig. 1C). Each transient set is followed by engine idling for 350 s, and the pattern is repeated (see Fig. 1D).

Two identical copper zeolite SCR catalysts were used, one at a time. The first one was called the "prepped" SCR which had stored ammonia, and a pre-SCR temperature of ~ 160–195 °C that was maintained throughout the testing. Next, to demonstrate a worst scenario case, the second (identical) SCR had no stored ammonia, here called the "purged SCR". With injection starting at 130 °C, the purged SCR was subjected to exceedingly high urea injection rate and ammonia-to-NOx ratio (ANR) ≫ 1. Due to this higher injection rates, pre-SCR temperature was lower, ~ 160–180 °C. EHM was energized just at the same time urea injection started, (not earlier).

The two different ANR values were used, shown in Fig. 2. It is emphasized that the higher ANR (1.2–15) for the purged SCR test case was arbitrarily chosen to be a large ratio, much beyond practical numbers used in actual automotive applications. This was deliberate to demonstrate EHM's ability to

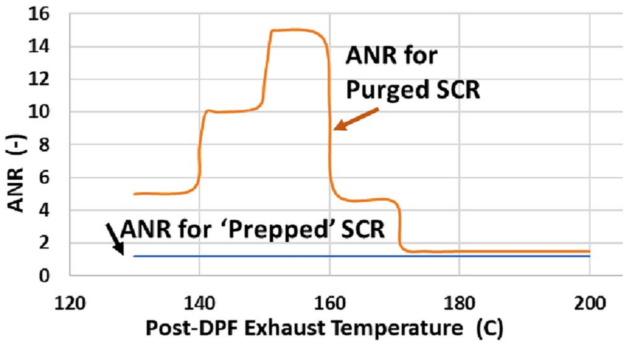


Fig. 2 Ammonia-to-NOx (ANR) ratios used for SCR testing. Purged SCR was supplied a much catalyst higher ANR, between 1.2 and 15. Prepped SCR use a fixed ANR 1.2

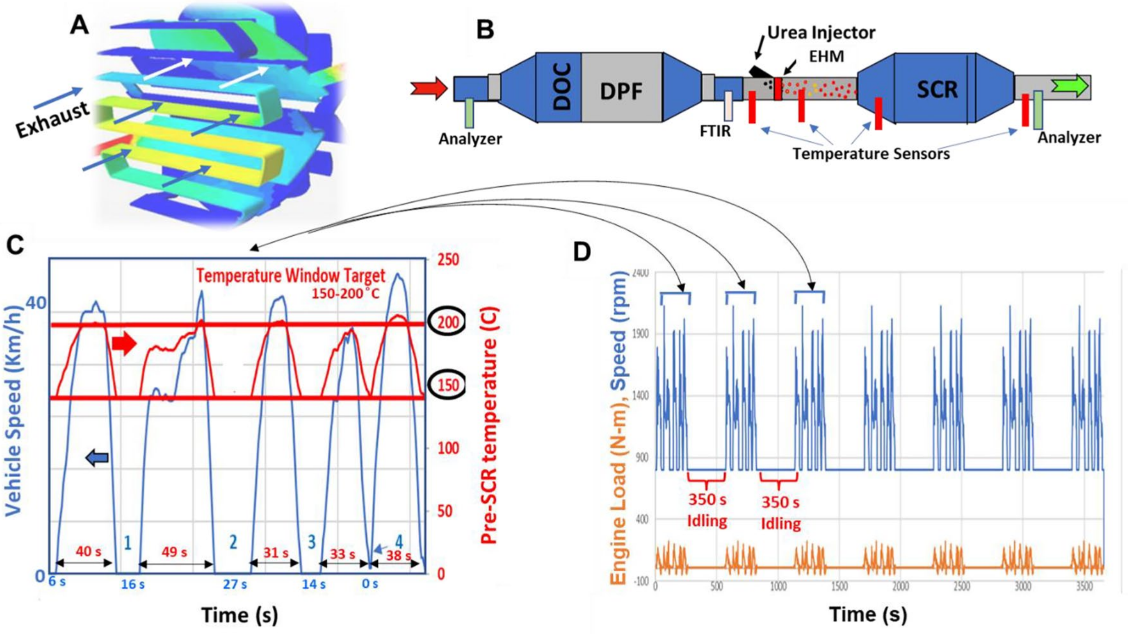


Fig. 1 **A** EHM evaluated on a **B** DOC-DPF-SCR system using a **C** highly transient, low-load cycle (temperatures 150–200 °C) with **D** long idles of 350 s in between and repeating

abate deposit formation even in remarkably ultra-high urea injection rates.

EHM performance, dynamically responding to exhaust conditions and urea injection, is managed by a microcontroller. The microcontroller can be integrated into the After treatment Control Module (ACM) or into the ECU [18].

3 Results and Discussions

Figure 3 shows the test results for the ‘prepped’ SCR catalyst. It displays that EHM improves the SCR efficiency during transients, with SCR of NOx rapidly reaching about 95–99% during “stops” (idling). During fast transients, it initially displayed SCR efficiency in the range 30–50% at 160 °C but rapidly enabled a rising SCR efficiency, reaching about 80% and even higher at temperatures about 160 °C.

The results for the “purged” SCR, shown in Fig. 4, are even more encouraging. Here, the arbitrarily high ANR 15 allowed injecting appreciable amount of urea (10–320 mg/s), to provide rapid ammonia storage in the purged SCR with remarkably low risks of urea deposit due to EHM. During stops (idling), SCR efficiency rapidly reached 100% at 180 °C. During fast transient (rapid stop-and-go), efficiency initially was displayed at an average of 60–80% at 160 °C, gradually increasing to 95%. Time-averaged power consumption of EHM during the entire drive cycle (almost exactly one full hour in stop-and-go with frequent stops in between) was 185 W.

Figure 5 displays the mixing or decomposition pipe past the mixer (just before the SCR) after the last test was competed. It displays no concerning amount of deposit following aggressive urea injection (10–300 mg/s, ANR up to 15) for nearly an hour. We emphasize the exceedingly high ANR 15 was chosen somewhat arbitrarily and for two reasons: one to demonstrate that even with such substantially high urea injection rates, the newly-developed EHM is well capable of mitigating deposit formation. The second reason was to enable the purged SCR to rapidly store sufficient amount of ammonia it needs to deliver high SCR efficiency. Otherwise stated, this high ANR used in this study should not be interpreted that using a heated mixer by any means signals the need for unusually large amount of urea injection. Choice of urea injection ANR is instead a matter of NOx control strategy synergized with engine-out NOx, flow rate, temperature, SCR catalyst volume and technology, regulatory requirements and an overall tailpipe NOx target. Such targets did not fit the demonstration in this study.

It is also emphasized that these results were gained without performing any calibration or optimization before or during the tests were carried out; thus, there is room to improve the observed results even further via proper calibration, consistently enabling 95+% SCR of NOx in challenging exhaust temperatures below 200 °C. During the entire testing on a 3.0 L Diesel engine demonstrated above, EHM energy

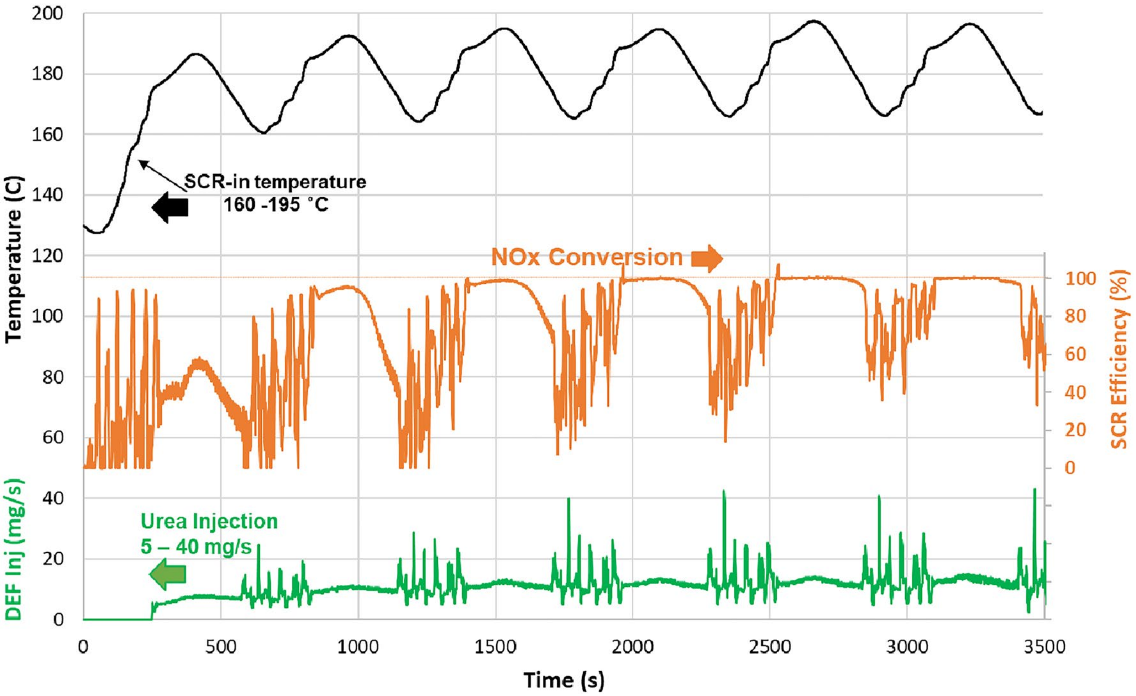


Fig. 3 Test results for prepped SCR (has stored ammonia). Given sufficient ammonia formation due to the heated mixer, SCR reached about 80% efficiency at 160 °C during fast transients and 99–100% efficiency during long stops (idling) at 180–190 °C

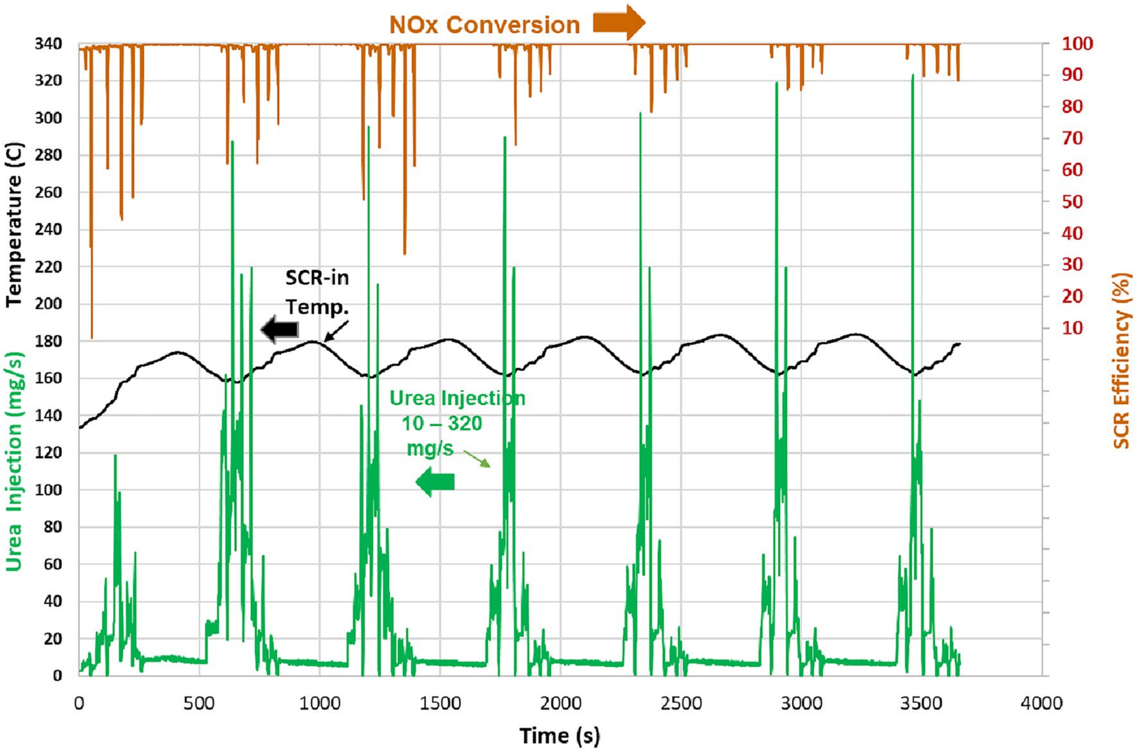
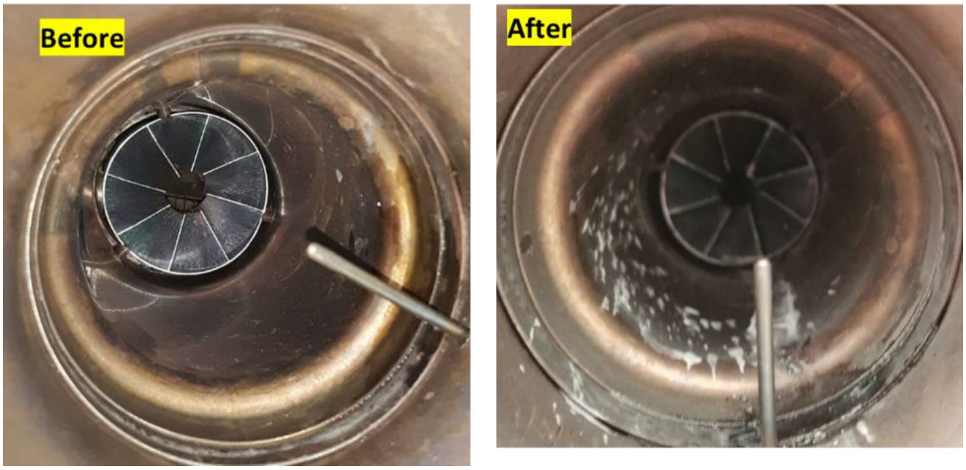


Fig. 4 Test results for purged SCR (has no stored ammonia). Given sufficient ammonia formation due to EHM, SCR reached up to 95% efficiency at 160 °C during fast transients and 100% efficiency during long stops (idling) at 180 °C

Fig. 5 Mixing pipe section post EHM before and after injecting 10–300 mg/s urea for about 1 h, showing no concerning amount of deposit formation



consumption stayed mostly within 140–180 W. EHM, currently in evaluation on a heavy-duty engine, displays requiring approximately 500 W. EGM testing results on a heavy duty engine are to be published in the near future [18].

3.1 Potentials for Fuel Economy and CO_2 Reduction

EHM capability could be utilized to reduce CO_2 in a couple of different, yet compounding ways. First, it is well known that higher NOx reduction efficiency is synonymous with fuel economy. Since EHM enables improved NOx reduction, it could be utilized to increase engine-out NOx and hence fuel economy and its associated CO_2 reduction. This could be easily achieved via proper integration of this mixer in engine fuel injection strategy, hence on the engine-out NOx and thus on reduced CO_2. Second, EHM's thermal energy itself could be used for SCR rapid heatup, saving some of the excess fuel typically used for exhaust heating during lower temperature exhaust operations, providing another layer of

CO_2 reduction. These strategies will be explored in future works.

It is emphasized that EHM use is not limited to light engines/vehicles. EHM can be utilized in any vehicle or system equipped with urea-SCR system. Thus, it can be easily employed in all platforms utilizing Diesel engines with urea-based SCR systems, light, or heavy vehicles, on- or off-road (agriculture, construction, marine, etc.) or in stationary platforms, including those with dual-SCR, with light-off (close-coupled) SCR catalysts or with SCR-on-DPF, as examples.

4 Conclusions

A novel urea mixer, heated electrically, capable of providing thermal energy to the injected urea spray is presented. It enables rapid heating and vaporization of injected urea droplets, forming reductants (ammonia, isocyanic acid) in very low temperature exhaust operations (below 200 °C) for prolonged periods of driving. Such conditions are common in low-load and RDE-type duty cycles. Most importantly

1. The newly-developed electrically-heated mixer enables injecting DEF in as low as 130 °C for SCR of NOx.
2. EHM provides flexibility to inject DEF at virtually any rate (any ammonia-to-NOx ratio) in very low temperature (< 200 °C) exhausts, especially at extremely high injection rates (ANR ratio) when the SCR catalyst may be without stored ammonia, thus replenishing the catalyst “on demand” with the needed stored ammonia.
3. EHM improves SCR of NOx dramatically during prolonged, low temperature exhaust drive cycles while simultaneously abating the deposit risk.
4. EHM, evaluated in stop-and-go duty cycles, shows 100% SCR of NOx during idling (stops) modes. This is achieved regardless of whether the SCR catalyst initially had stored ammonia or whether it did not, or how long the low temperature drive cycle continued.
5. EHM, evaluated in stop-and-go duty cycles, shows that the longer the drive cycle continues, the higher efficiency in the SCR catalyst is achieved. This is due to the abundance of ammonia made available to the SCR catalyst during the low temperature drive cycle.
6. Observations reported here were made without any major engine calibration or adjustment. It is anticipated that, via synergizing calibration of engine-after treatment-EHM, the benefits observed here could be further expanded upon, for instance utilizing EHM for fuel economy and CO_2 reduction.

In the view of the upcoming Euro-7 regulations, meeting high NOx efficiency in low temperature drive cycles remains essential in both light and heavy duty platforms. The low-cost, heated mixer discussed in this communication provides an alternative solution: it avoids adding an additional unit (as existing systems already have mixers). Its low energy consumption is especially noteworthy since as it avoids adverse fuel penalty/CO_2 impacts.

Additional results on testing the heated mixer on a 15 L. Heavy duty Diesel engine with a fully-aged catalyst system demonstrating meeting most stringent tailpipe NOx limits (e.g., 0.02 gr/bhp.h., California 2027) and its impacts on low-load cycles will be soon reported in a separate publication [18].

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