



A New Electrically Heated Mixer (EHM) for Efficient SCR of NOx in Low Load Cycles

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Abstract

Low temperature Diesel exhaust operations such as during low-load cycles are some of the most difficult conditions for SCR of NOx. This, along with newer regulations targeting substantial reduction of the tailpipe NOx such as California-2024/2027 NOx regulations, adds to challenges of high efficiency SCR of NOx in low temperature operations. A novel design, low-cost, low-energy Electrically Heated Mixer (EHM™), energized via the 12, 24 or 48 V vehicle

electrical system, is used to accelerate formation of reductants (ammonia, isocyanic acid) in low temperature exhaust (low load cycles), so to enable high efficiency SCR of NOx in most challenging SCR conditions, while also mitigating urea deposit formation. EHM™ is also used to heat the cooler exhaust flow during engine cold-start. It easily fits common exhaust configurations and can be utilized on light, medium or heavy duty Diesel aftertreatment systems, on- or non-road or in stationary systems.

Introduction

Diesel engines and their emission control systems have advanced substantially. Since the implementation of 2010 US EPA regulations for Diesel engines, modern Diesel systems produce substantially less emissions both in particulate matter and in nitrogen oxides (NOx) [1, 2, 3, 4].

One of the great advances in reducing Diesel nitrogen oxides has been due to widespread use of Selective Catalytic Reduction (SCR) [5], a robust catalyst technology effectively lowering the engine-out NOx by more than 90%, often in the range of 95%+ and in as high as 99% [1, 2, 3, 4, 5]. SCR operation demands reductants (ammonia, isocyanic acid) for efficient NOx reduction. Reductants are produced in Diesel systems via injecting a fixed-ratio mixture of urea-water solution (32.5%, 67.5%, respectively), commonly known as Diesel Exhaust Fluid (DEF) in North America and AdBlue™ in Europe and most regions around the world.

Urea water solution, when injected in lower temperature exhaust operations (typically below 200 °C), forms urea deposits, inhibiting an effective SCR of NOx and has also shown to damage exhaust systems [6]. Urea deposits, when sublimating at high rates in high exhaust temperatures, form plenty of gaseous ammonia which may slip through the SCR system and into the environment, an undesirable outcome. Hence, any efforts to (a) avoid urea deposits while (b) accelerate forming gaseous reductants out of urea-water solutions, would add to increased SCR of NOx and hence, overall lower tailpipe NOx emissions.

Since 2010, nearly all Diesel emission control systems utilizing DEF injectors incorporate DEF mixers; (Figure 1). All DEF mixers are not created equal. A quality mixer produces an effective dispersion of injected urea droplets in the exhaust pipe, accelerates droplet heating and evaporation, hence faster ammonia formation, while also avoiding contact between the injected droplets and the pipe exhaust to prevent deposit formation. (Exhaust pipes comprise the lowest temperature in the exhaust systems, making them prone to urea deposit formation.)

These challenges, however, become even worse when the vehicle/ engine operates mainly in low-load duty cycles; examples include stop-and-go, city driving, local delivery, low-idle and more. Here, the exhaust temperature drops dramatically, often well below 200 °C, making it substantially challenging for the urea droplets to form reductants. According to several studies such as the one in Ref.[7] (see Figure 2), SCR systems in Diesel vehicles operating in city drive cycles do not provide an effective reduction of NOx, chiefly due to poor concentration of gaseous ammonia formed in the cold exhaust operation.

Technical Discussions

Here, we discuss an Electrically Heated Mixer (EHM™) capable of being energized (heated) by the vehicle electrical

FIGURE 1 Schematic of a standard DEF mixer in a Diesel exhaust system: DEF injector, mixer, decomposition pipe and SCR catalyst.

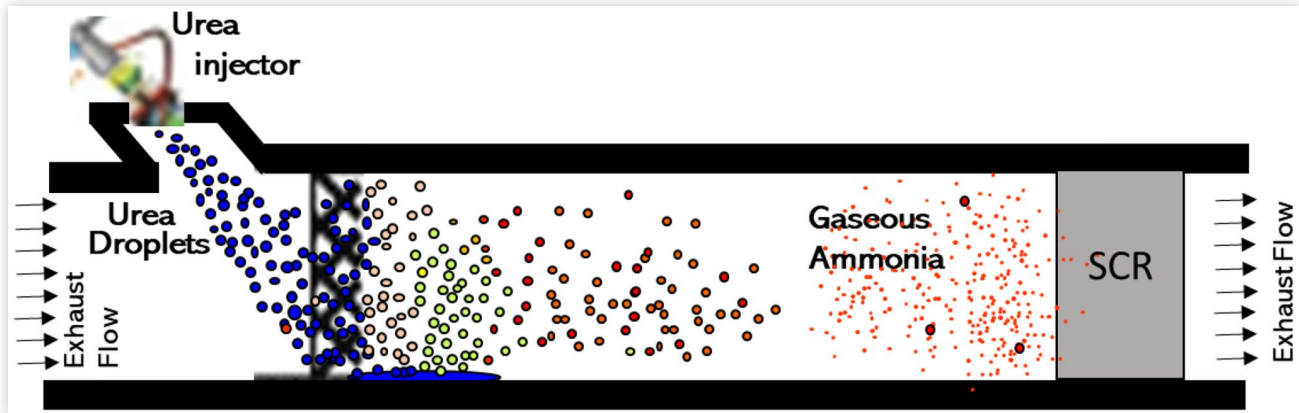
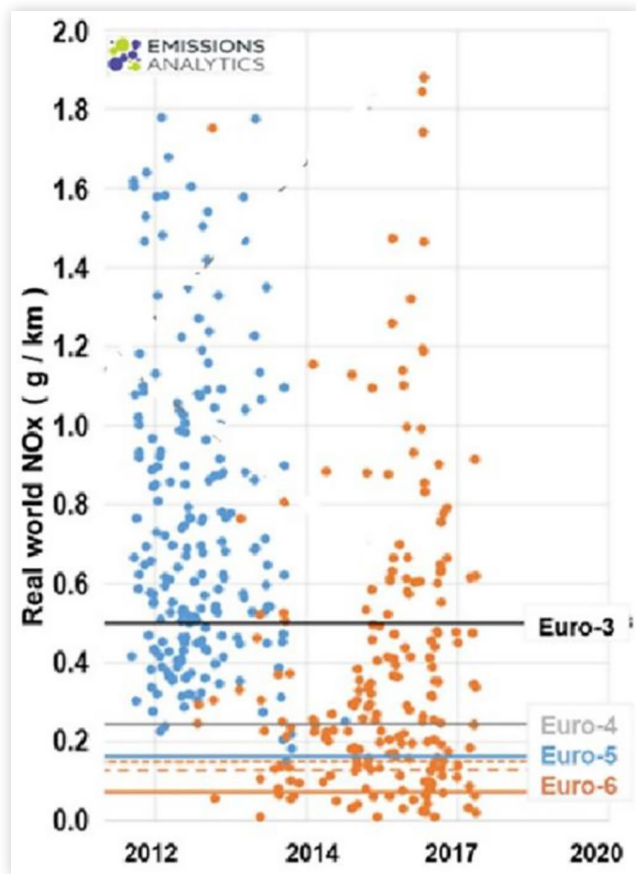
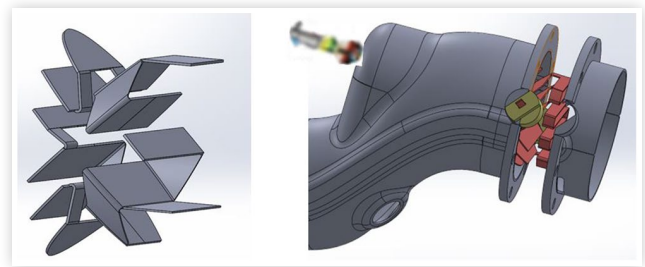


FIGURE 2 Actual tailpipe NO_x measurements of Diesel vehicles (dots) exceeding the regulatory limits. (Emissions Analytics)



system, resulting in thermal energy. Such mixer energy compensates for the lack of thermal energy in Diesel exhaust during low-load cycles, enabling rapid processing of DEF droplets injected in low exhaust temperatures, forming gaseous reductants while also inhibiting deposit formation. EHM is shown in Figure 3, stand-alone and installed downstream of a DEF injector.

FIGURE 3 LEFT: Electrically Heated Mixer (EHM™). RIGHT: EHM installed in exhaust pipe; (geometry is cut to display EHM™ in the decomposition pipe).



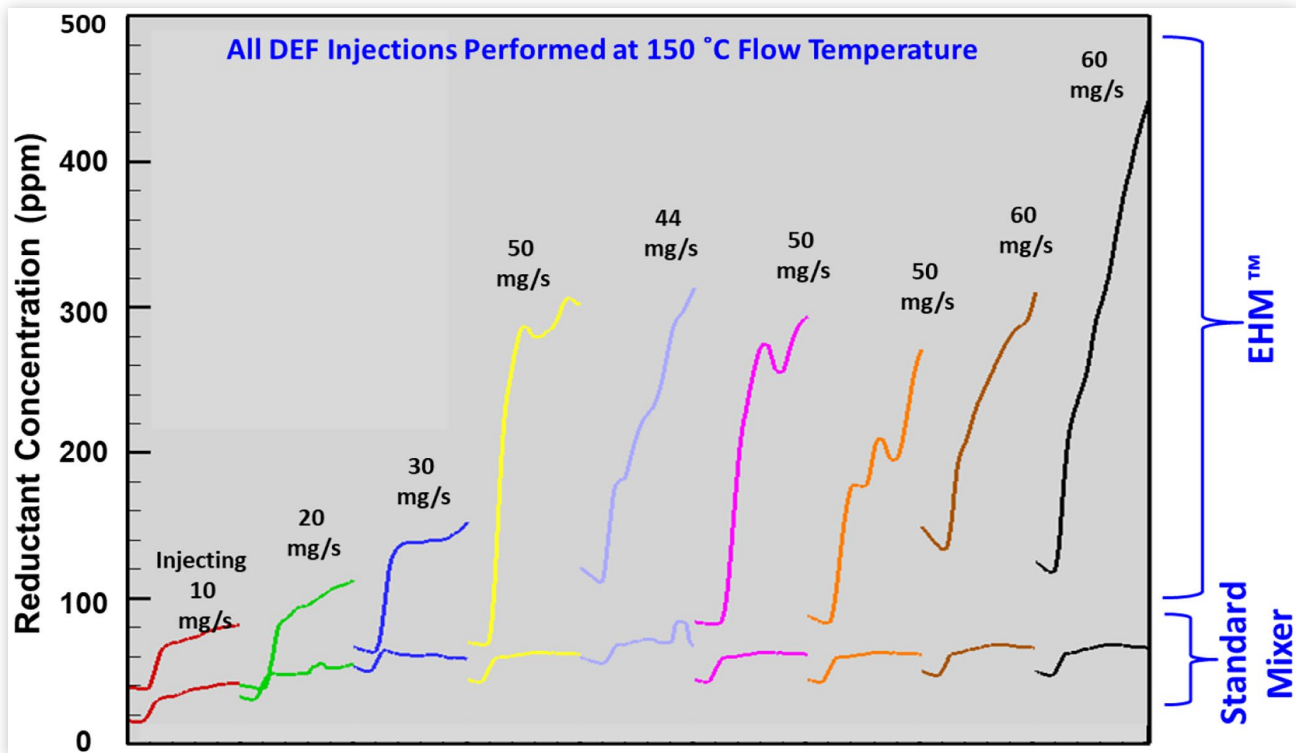
EHM™ developed and tested in this study provides various favorable performance metrics. They are discussed herein, including impact on DEF conversion in low-load (low-temperature exhaust) cycles, deposit mitigation, reductant uniformity, pressure drop and so on, while maintaining very low power consumption.

Converting DEF to Reductants

Impact of EHM on injected DEF in low temperature exhaust is shown in Figure 4. Various DEF injection flow rates, from 20 to 60 mg/s, are injected onto EHM while energized; (for higher DEF injection rates near 320 mg/s in an actual low-load cycle, see the section “SCR Efficiency”.) Inlet flow temperature is maintained steady at 150 C at 100 kg/hr flow rate. The injector is Bosch Denoxtronic 5.2 PC/LD (not air-assisted) having a 3-hole configuration producing an array of droplets with Sauter Mean Diameter of about 100 microns. In principle, EHM can be utilized with any DEF injector.

Figure 4 demonstrates that, with a standard mixer, increase in DEF injection in low temperature exhaust does not yield any increase in reductants concentration (concentration stays fixed at about 50 ppm, nearly independent of the DEF injection rate). This is a known observation, and the prime reason DEF is not injected below 200 C.

FIGURE 4 DEF injection in 150 °C flow onto EHM™. Below: EHM not energized (mimicking a standard mixer) subjected to 20 - 60 mg/s DEF injection. Top: EHMS energized, subjected to the same DEF injection rates, producing up to 10 folds more reductants.



However, when DEF is injected onto EHM in low exhaust temperatures (150 °C in this case, or below 200 °C in general), EHM can dramatically increase the reductants concentration, by nearly 10-fold (see [figure 4](#)) relative to the standard mixer. This is since in low temperature flows (e.g., 150 °C), EHM's thermal energy compensates for lack of heat in the exhaust flow, accelerating DEF droplet's heating, vaporization and their thermolysis. Likewise, in the presence of EHM, higher DEF injection rate could produce higher reductant concentration in low temperatures. Expectedly, EHM's heating mechanism promotes formation of both ammonia (NH₃) and isocyanic acid (HNCO). HNCO is an NH₃ precursor [2], readily converting to ammonia in SCR.

Another observation in [Figure 4](#) is that the same DEF injection rate (for instance 60 mg/s) may produce a somewhat higher, or lower, reductant concentration. This is a 'calibration point' and depends on how much energy is supplied to EHM. This flexibility (reductant concentration dependence on the energy level supplied) leaves room for calibrating the urea injection rate depending on one's preferred SCR strategy, i.e., to form reductants (concentration) for storage in SCR, or for NO_x reduction reactions, or for a balance between the two, both significant for high efficiency SCR of NO_x in lower temperatures. Indeed, further experimentation with EHM on Diesel engine on low-load duty cycles reveals it is possible to gain excellent SCR efficiency well below 200 °C using EHM with a SCR fully purged of its stored ammonia, and sustaining that for long drive cycles [8]. See the next section 'SCR Efficiency'.

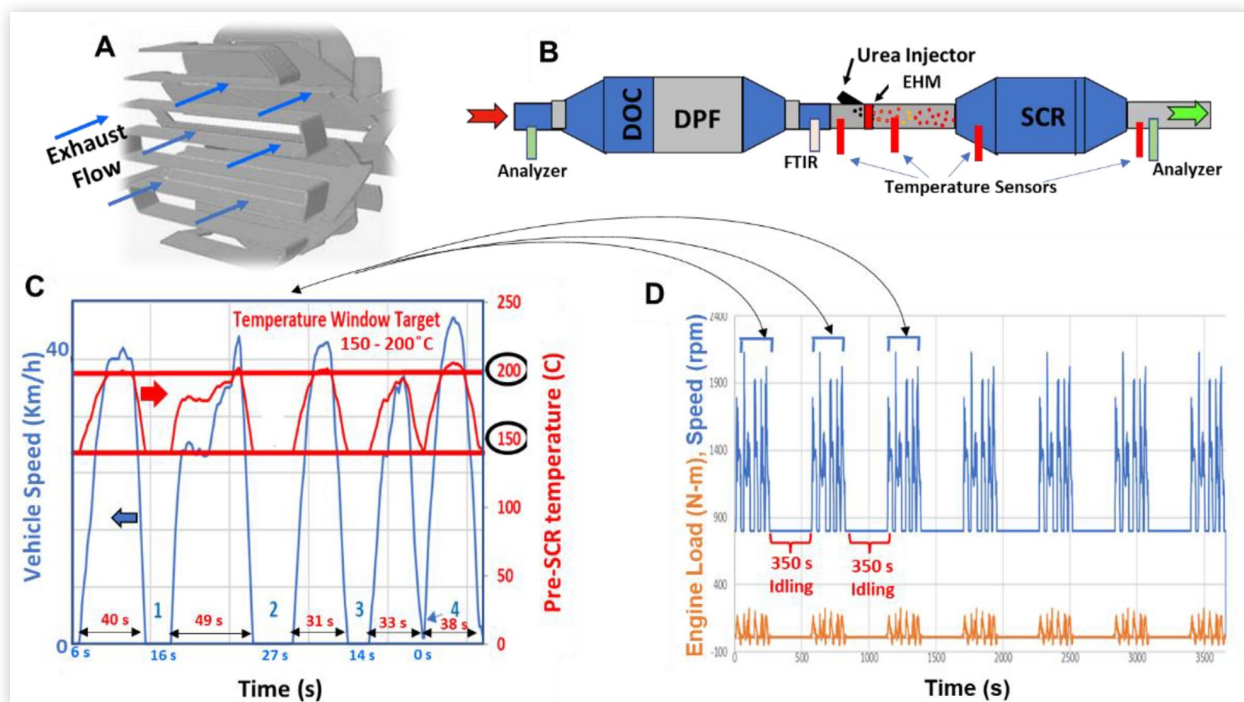
SCR Efficiency

EHM impact on enabling SCR of NO_x in prolong, low temperature exhaust operations was explored in a low-load cycle temperatures consistently maintained below 200 °C on a 3.0 lit. FCA EcoDiesel™ engine using a DOC-DPF-SCR after-treatment system ([Figure 5](#)) equipped with EHM in lieu of a standard mixer. A drive cycle was used to simulate typical stop-and-go, local delivery, city or Real-Driving Emission (RDE)-type cycles, with speeds below 40 km/hour, including plenty of fast transients and long idles (350 seconds each) in between, shown in [Figure 5](#) (C-D) [8]. A Umicore production-grade, Cu-zeolite SCR catalyst was used in the aftertreatment system. Two demonstration tests were conducted using this cycle.

EHM™ Enabling Low-Temperature SCR of NO_x in a SCR without Stored Ammonia In the first test, the more severe one (worst scenario case), the SCR catalyst was entirely purged (deprived) of its stored ammonia prior to the test start. The idea was to explore how flexibly DEF could be injected for long periods of time in a low-temperature (< 200 °C) drive cycle (see [Figure 5](#), C-D) with the SCR catalyst severely and constantly needing ammonia generously in such challenging temperatures, without concerns for deposit formation.

With test cycle starting, DEF injection commenced at 130 °C exhaust temperature. To make plenty of ammonia available to the purged SCR, a substantially higher Ammonia-to-NO_x

FIGURE 5 (A) Electrically Heated Mixer (EHM) evaluated on a (B) DOC-DPF-SCR system in a (C) transient, city cycle with exhaust temperature below 200 °C, with (D) long idles (350 seconds) in between, and repeating [8].



Ratio (ANR), up to 15, was injected in the first 2 to 3 minutes of the cycle, providing ample storage to the purged catalyst. (This is not to suggest such a high ANR is always needed; this would need to be further studied, tuned.)

Figure 6 shows the cycle results, including the SCR inlet temperature, NO_x concentrations pre- and post-SCR and the DEF injection rate throughout the cycle. Note the pre-SCR exhaust flow temperature consistently remains below 200 °C throughout the entire cycle, and pre-SCR NO_x rapidly fluctuates during the cycle's fast transients (see Figure 5, C-D). Comparing pre- and post-SCR NO_x concentrations, Figure 6 shows that EHM greatly enables high efficiency SCR of NO_x in such challenging, low exhaust temperatures, at times producing near-zero tailpipe NO_x.

It is noteworthy that, as the cycle continued, in sustained driving in such challenging (low) exhaust temperatures, EHM increasingly tamped down large fluctuation in SCR-out NO_x (initially created due to cycle's fast transients), and yielded high NO_x efficiency in the range 80 - 95% (see Table 1 below and Ref.[8]). During such transients, DEF droplets' residence time in the decomposition pipe (mixing length) is shorter, making thermolysis/ hydrolysis reactions more challenging. This challenge is however managed by EHM controller [8].

It is once again emphasized the SCR catalyst in this demonstration is a production-level catalyst.

Of considerable importance also was whether urea deposit was formed during such high DEF injection rates (up to 320 mg/s, shown in Figure 6) for one hour in such low temperature

exhaust operations. Figure 7 shows the mixing length (decomposition pipe) post the mixer (i.e., just before the SCR inlet) before and after the described cycle [8]. After one hour of abundant DEF injection, no concerning amount of deposit could be seen in the exhaust pipe; only minor 'staining' was observed.

EHM™ Enabling Low-Temperature SCR of NO_x

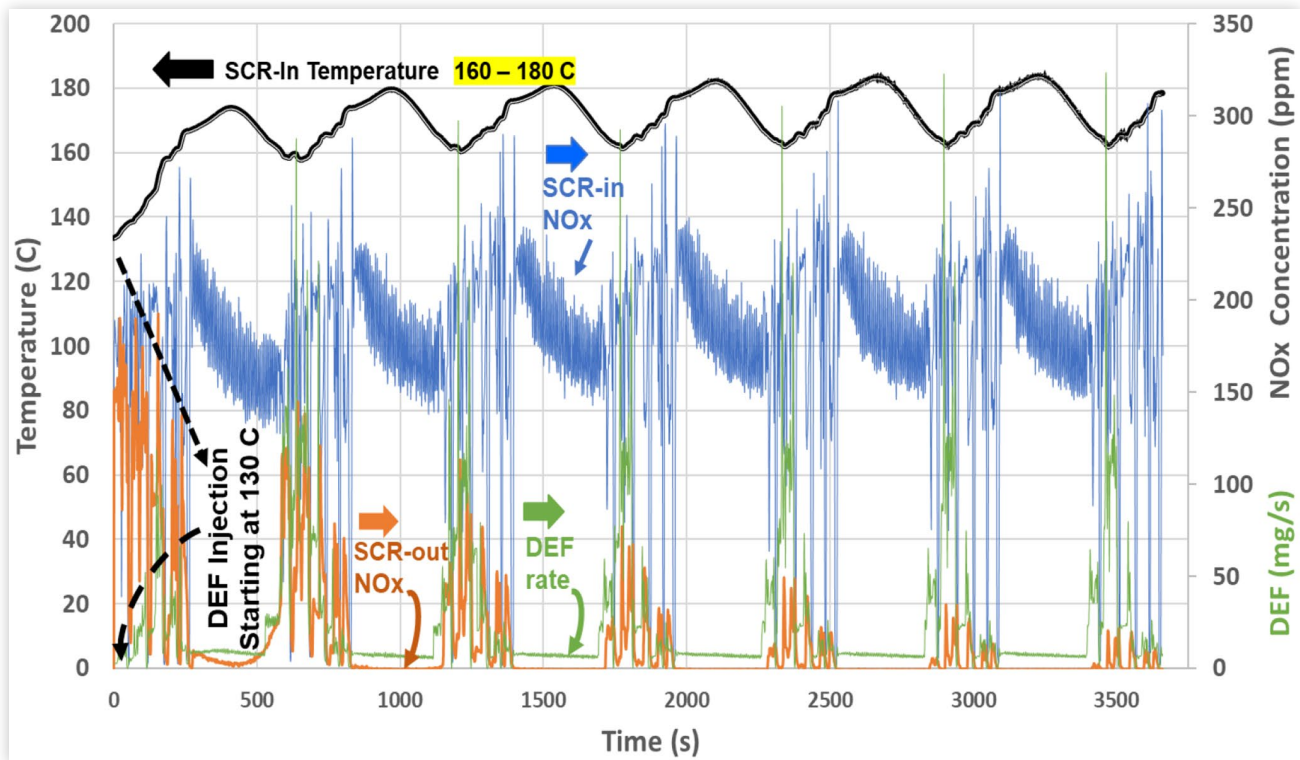
The second test was identical with the first one, used the same cycle (see Figure 5, C-D), aftertreatment system and SCR catalyst, except that, unlike the earlier test, the SCR catalyst was first 'prepped' with stored ammonia according to industry standards. Thus, a lower ANR of 1.2 was used throughout the cycle.

Test results are shown in Figure 8, displaying major reduction of tailpipe NO_x during both fast transients and stop modes (engine idling). The SCR catalyst increasingly demonstrated 95 - 99% NO_x reduction efficiency during 'stops' (idling) at 180 °C, and enabled up to 90% efficiency during fast transients at 160 °C [8], while inhibiting deposit formation [8].

Table 1 summarizes the two SCR of NO_x studies in the low-temperature cycle described above. Further details of these two low-temperature cycles are communicated in a separate publication [8]. In the interest of brevity, that information is not repeated here.

It is interesting that, in both cases, as evident from Figures 6 and 8, despite the low exhaust temperature continually remaining below 200 °C, the longer the cycle continued, the more the SCR efficiency improved in time. A plausible

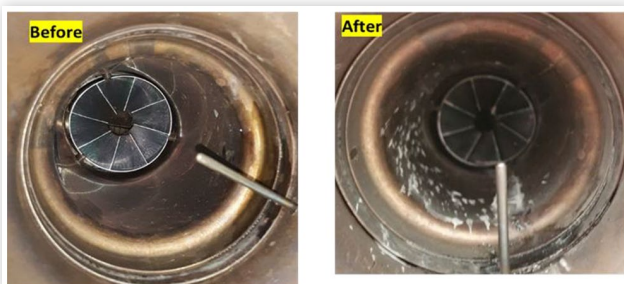
FIGURE 6 EHM enabling SCR of NO_x in a low exhaust temperature (< 200 °C) stop-and-go drive cycle with SCR catalyst initially free of ammonia storage, but subjected to high-ANR DEF injection to replenish storage sites ‘on demand’ throughout the entire cycle. DEF injection started at 130C. EHM markedly lowered tailpipe NO_x, dropping to near-zero ppm during stops (engine idling), while tamping down NO_x fast transients considerably.



explanation is that, in both cases, this may be due to continued ammonia storage in the SCR catalyst.

Finally, it is emphasized these results were achieved by installing the EHM, next proceeding to testing without any engine calibration efforts. Therefore, further improvement to these results could be made via synergizing engine-aftertreatment calibrations.

FIGURE 7 Mixing pipe section post EHM before and after injecting 10- 320 mg/s urea for about one hour, shows no concerning amount of deposit formation. Left: Before. Right: After, [8].



EHM for Deposit Mitigation: DEF Injection in Low Temperature Exhaust

Figure 9, displaying the SCR inlet cone, further demonstrates EHM capability to mitigate urea deposit formation in low temperature operations. Test conditions are similar to those described in Figure 4. DEF is injected onto EHM, first with EHM energized, next without energizing EHM closely mimicking a standard (unheated) mixer. DEF injection took place for 30 minutes continuously with no interruptions. With EHM energized, no major deposit was observed in the mixer vicinity or in the mixing length at the termination of the testing. Thus, while EHM is capable of converting the injected DEF to gaseous reductants in lower flow temperature (generally below 200 C, see Figure 4), it is also capable of mitigating urea deposits in such challenging temperatures.

Generally speaking, as described earlier, EHM is energized in lower exhaust operations (low-load cycles) to facilitate thermolysis and hydrolysis, forming an abundance of reductants for efficient SCR of NO_x. As for utilizing EHM to eliminate higher temperature urea byproducts (melamine, biuret, etc.), further investigation needs to be carried out.

FIGURE 8 EHM enabling SCR of NO_x in a low exhaust temperature (< 200 °C) stop-and-go drive cycle. During stops (engine idling), tailpipe NO_x drops to near zero ppm, while reduced considerably during fast transients.

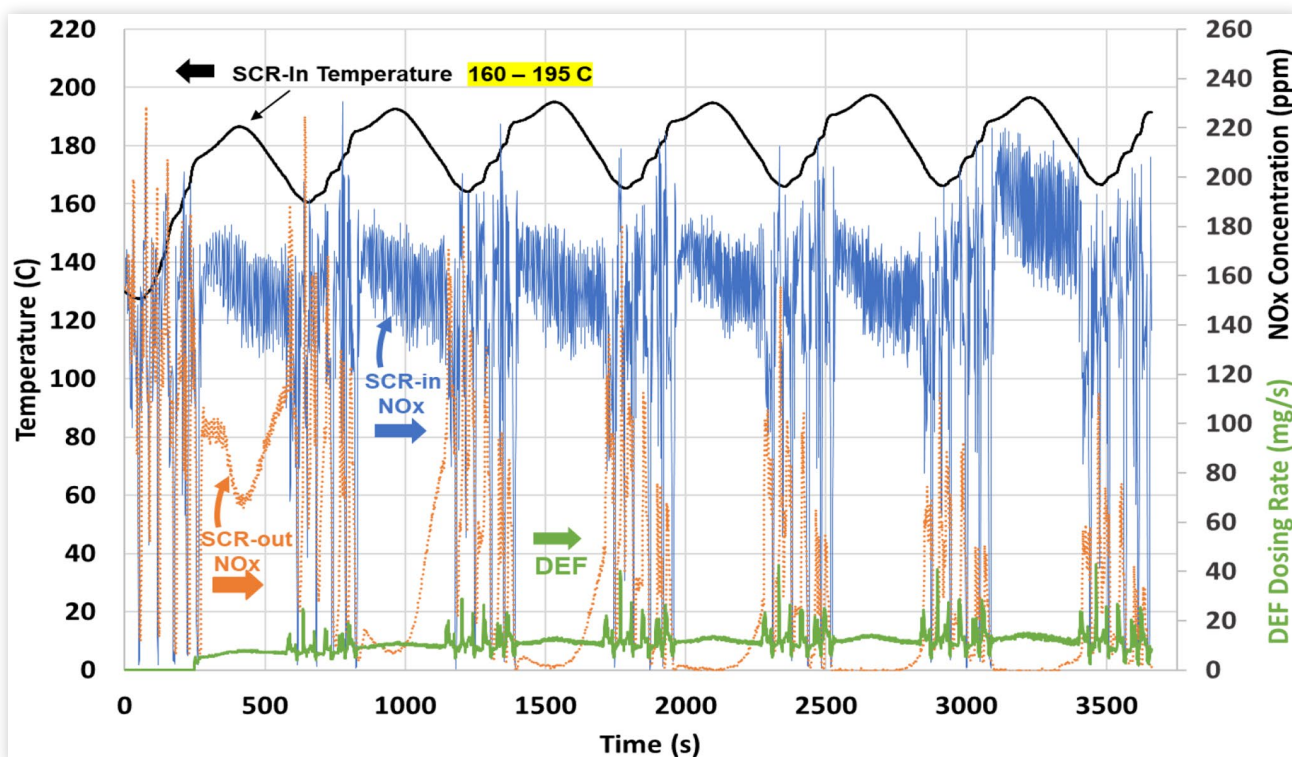


TABLE 1 Summary of EHM impact on SCR of NO_x in a low-temperature cycle (below 200 °C) SCR efficiency up to 100% during stops (idling) and as high as 96% during fast transients was observed.

CYCLE RESULTS	SCR Has Pre-Stored Ammonia (Low ANR)			SCR without Pre-Stored Ammonia (High ANR)		
	SCR-In Temperature	Efficiency (%)	Deposit (Y/N)	SCR-In Temperature	Efficiency (%)	Deposit (Y/N)
During Stops (Idling)	~190°C	Up to 99%	No	~180°C	Up to 100%	No
During Fast Transients	~160°C	60 - 80%+	No	~160°C	85 - 96%+	No

Uniformity

Quality of reductants distribution severely impacts the efficiency of the SCR catalyst. It is commonly known that highly uniform distribution of reductants at the SCR catalyst inlet is paramount for high NO_x reduction in the catalyst.

Figure 10 shows the reductant distribution (uniformity) evaluated experimentally at the SCR inlet downstream of EHM in this study. To ease experimentally measuring reductant uniformity, the SCR catalyst was removed. The measured Uniformity Index (UI) is 0.96, slightly lower than typically desired; however, it is emphasized that the SCR catalyst was removed for this measurement. It is known (and is commonly observed in CFD simulations) that the pressure drop buildup due to the SCR catalyst itself (i.e., when the SCR is *not* removed) improves (increases) the reductant uniformity at the SCR inlet. Further, in our newer EHM design, UI has been

measured to be in the range 0.98 - 0.99 with the SCR removed. It is finally emphasized that uniformity is a system attribute, not a mixer's attribute: While uniformity it is affected by the mixer, it is strongly influenced by the urea pipe mixing length, pipe architecture, upstream bend(s), flow rate and even flow temperature (impacting the flow density and hence flow mixing). Indeed, it is possible to create favorable uniformity in a sufficiently long mixing pipe equipped with a poorly-designed mixer. EHM structure is designed to impose a swirling flow enhancing flow mixing downstream of EHM.

Pressure Drop

Low pressure drop is a must for any component placed in an exhaust automotive system, as high pressure drop is synonymous with increased fuel penalty. Figure 11 shows EHM pressure drop is very low, posing no concerning contribution

FIGURE 9 Deposit test using EHM™ vs. standard mixer: Injecting DEF at 25 mg/s in 150 C flow. LEFT: EHM is not energized; deposit is abundantly formed. RIGHT: EHM™ is energized. No deposit observed. Section shown is end of decomp pipe, inlet cone of SCR.

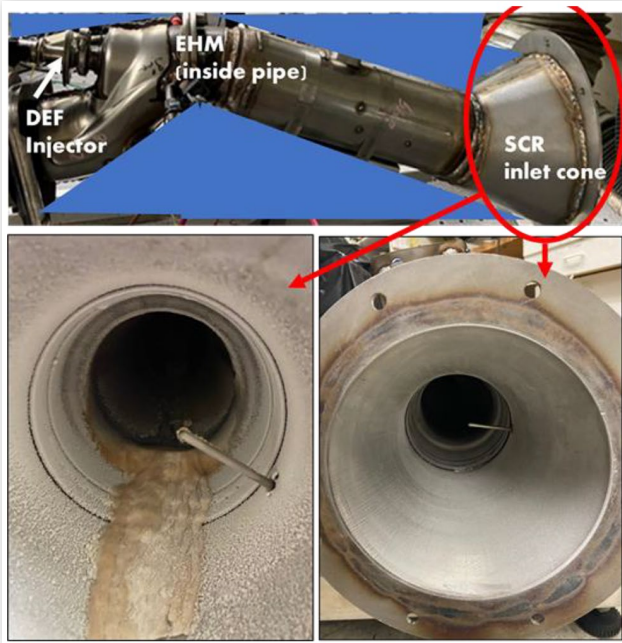


FIGURE 10 Reductant uniformity measured downstream of EHM and at the SCR inlet.

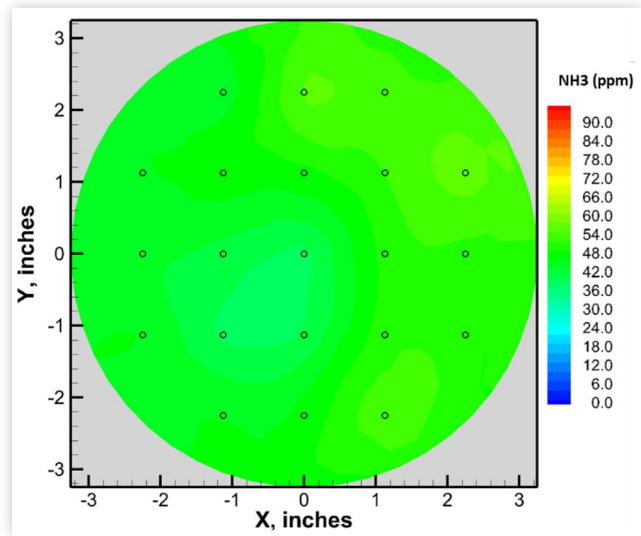


FIGURE 11 EHM™ Pressure drop across a range of flow rates. (Example: light duty engine application).

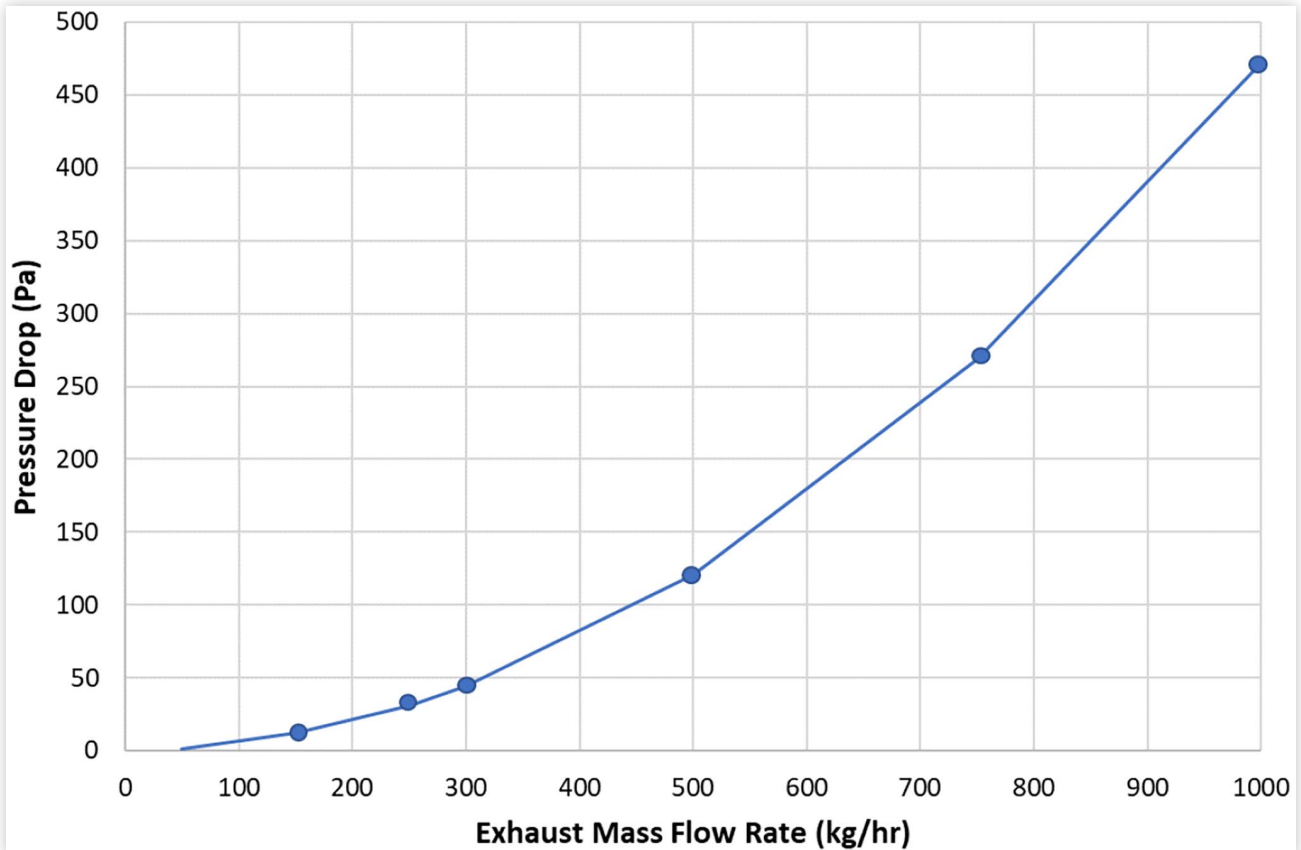
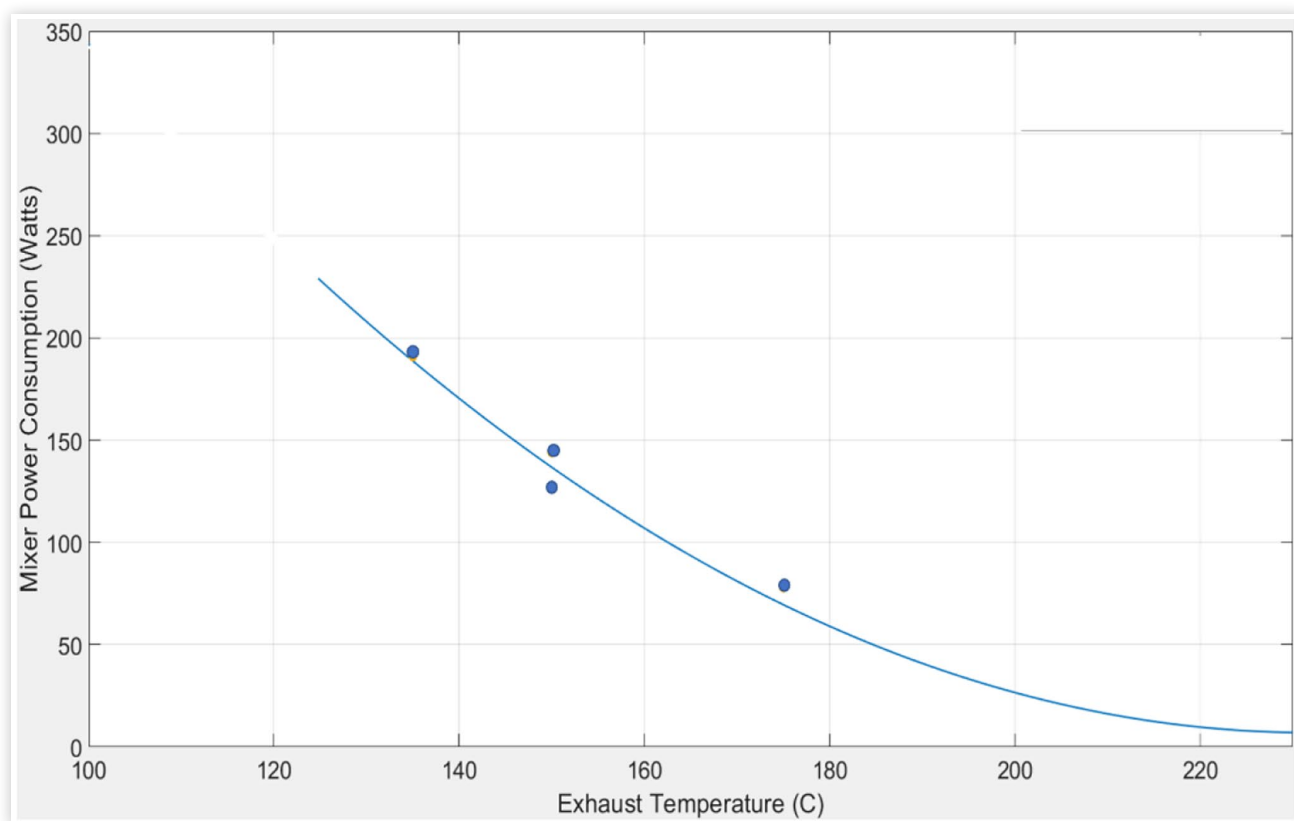


FIGURE 12 EHM™ power consumption decreases with increased exhaust temperature. (Condition shown : 25 mg/s DEF injection in 150 C flow, 100 kg/hr.) Dots are test data (experimental measurements). Line is modeling prediction.



to the overall system pressure drop or an adverse impact on the engine power loss or fuel penalty.

Power Consumption

Generally speaking, the more the heat consumption of an electrical component in a vehicle, the more the load on the engine, resulting in an increase in tailpipe CO₂, a potent, regulated greenhouse gas. Thus, it is prudent that EHM would use minimal energy, so to minimize any adverse impact on the vehicle tailpipe CO₂. EHM designed in this development is often seen to require only about 140 - 170 Watts to operate, shown in Figure 12. Such power consumption is generally considered trivial and comparable to parasitic losses in vehicular systems.

The reason for this very low power consumption is that the controller algorithm manages and minimizes the amount of power supplied to EHM, while also minimizing the deposit risk and simultaneously maximizing the kinetics of reductant formation (thermolysis and hydrolysis reactions.)

Our experience indicates EHM is conveniently scalable to a variety of engine sizes: Light, medium and heavy duty. Recent scale-up of EHM to a 48-V heavy duty diesel engine system [9] shows that, while EHM power consumption expectedly varies with DEF injection rate, it requires energy about 500 Watts for a heavy duty system.

Manufacturing

Evident from its design displayed in Figure 3, EHM can be made using low cost manufacturing processes in high production volumes, much like those used to manufacture standard mixers.

EHM for Meeting Ultra-Low Diesel NOx Regulations: California 2027 and Euro-7

It is fair to say that the new California heavy duty tailpipe NO_x mandate (2027) targeting 0.02 gr/bhp.hr is one of the world's most stringent NO_x regulations, if not the most stringent. A recent EHM study on a heavy duty engine demonstrated that EHM enables meeting such ultra-low NO_x targets. Details will be soon made available to interested readers [9].

Conclusions

A low-cost, low-energy, low backpressure Electrically Heated Mixer (EHM™) has been designed for low-load cycles to promote rapid transition of injected DEF droplets to

reductants (ammonia, isocyanic acid) and to increase SCR of NO_x specifically in challenging, low temperature exhaust operations, while also mitigating deposit risks. Its various performance features have been tested and described here. When tested in sustained, low temperature exhaust flows such as in 150 °C exhaust temperature, EHM™ yields almost 10-fold higher concentration of reductants than a standard mixer. It effectively inhibits deposit formation while producing high uniformity of reductants at the SCR inlet. Due to its heating mechanism, EHM™ can also be used to assist with rapid heat-up during engine cold start. EHM design allows for its rapid production and ease in manufacturability.

Amongst its other benefits, subsequent publications [8, 9] and upcoming investigations will reveal other EHM capabilities and potentials, including

- For accelerated heat-up during cold-start
- For DEF injection in as low as 70 - 80 °C for ammonia storage targets
- For eliminating the 'prep-cycle' (for storage) typically performed prior to regulatory cycles
- For broader DEF injection in 130 °C for SCR of NO_x in various regulatory cycles
- For its flexibility to function across a variety of power systems (12-, 24- or 48-volt)
- For injecting very high Ammonia-to-NO_x Ratio (ANR) for continuous 'on-demand' ammonia presence in most challenging, long, low-temperature duty cycles, and finally
- For enabling meeting most stringent NO_x regulations such as California 2027, EPA-proposed 2031 and Euro-7 targets.

Acknowledgements

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