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A Multi-Function, Heated Mixer for Rapid Heat-up, Low-Temperature Ammonia Demand, Deposit Prevention and to Meet Ultra-Low NOx Regulations

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Abstract

Selective Catalytic Reduction (SCR) operation depends strongly on both heat and ammonia availability (stored or incoming). These requirements make high efficiency SCR challenging in lower temperature cycles where SCR is relatively cold, and Diesel Exhaust Fluid (DEF) injection is largely absent due to deposit risks. Examples include low temperature cycles such as low-idling, stop-and-go or low-load cycles such as city driving or local delivery cycles.

An Electrically Heated Mixer/ EHM™ is utilized to address these challenges in a single component. EHM simultaneously provides heat for rapid SCR heat-up during the cold phase or in other low-temperature operations, steady or transient. Second, its heating mechanism makes deposit risks nearly non-existent. Third, EHM enables DEF injection at 130 °C, markedly enhancing the low temperature SCR impact. It is shown that these capabilities collectively make EHM a promising pathway for meeting ultra-stringent NOx targets including California 2027 (0.02 gr/hp.hr). Via rapidly heating the SCR catalyst during cold-start, EHM enables substantially lowering the cold-phase NOx. For instance, it is shown this lowers the cold FTP and cold WHTC NOx emission by 2 – 2.5 fold and in Low-Load Cycle by 22-fold.

EHM also allows DEF injection in low exhaust temperatures such as in 70 - 80 °C, for instance for rapidly filling the SCR catalyst with ammonia, if needed.

Unlike adding other exhaust flow heating devices where an additional component is ultimately integrated in the aftertreatment architecture, EHM is a mixer, already present in emission control systems. These flexibilities, along with its lower cost and ease in fitting, make EHM an enabling pathway for Diesel emission control systems meeting very low NOx regulations.

Introduction

Diesel engines are known for their high efficiency and long durability. Also, owing to their higher compression ratio (longer stroke and turbocharging), they produce more torque and power, becoming the powertrain of choice for high power applications such as in long-haul heavy vehicles, farming and construction powertrain, mining machineries and marine propulsion, amongst others. Their fuel efficiency has also made them the prime choice when considering lower cost of ownership.

For the last two decades, various regulatory mandates in the US and abroad have considerably lowered Diesel tailpipe emissions. As such, modern Diesel powertrain systems are equipped with state-of-the-art emission control systems including sophisticated particulate filters and robust Selective Catalytic Reaction (SCR) catalysts, producing near zero tailpipe emissions. In only a few years, California will require heavy Diesel vehicles to meet the ultra-low 0.02 gr/hp-hr NOx target [1], considerably below the current federal limit [2], possibly on track to become a federal mandate itself [3].

While meeting particulate matter tailpipe emission targets has reached a relatively stable point [4, 5], meeting ultra-low Diesel NOx has been challenging, especially in the face of new regulatory developments demanding ever-most stringent NOx targets [2, 6]. Meeting lower NOx targets is also a mixed bag of challenges needing deposit-free DEF injection especially in low-load cycles (low exhaust temperatures), no-slip ammonia, N_2O inhibition, lowered total cost of ownership and more. Most remain open challenges to date.

It is generally agreed that ultra-low NOx emission targets could be best met via reducing the SCR catalyst heat-up (light-off) time during the engine cold-start, i.e., the so-called SCR light-off time. For this reason, some newer aftertreatment architectures include a closed-coupled SCR to do exactly that.

In this work, we introduce an Electrically Heated Mixer (EHM™), a DEF mixer with embedded heating capability, that helps meet all the challenges noted above: (i) During engine cold-start, EHM functions like a heater (if desired so) for rapidly heating the SCR catalyst, substantially lowering the tailpipe NOx; (ii) EHM heating can be utilized to largely prevent urea deposits, especially in low-load duty cycles (lower

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exhaust temperatures) when DEF needs to be injected for SCR operations. (iii) In exhaust temperatures as low as 70 – 80 °C (including during cold-start), EHM enables DEF injection for rapidly filling the SCR catalyst with ammonia; this could assure that the SCR catalyst would gain additional stored ammonia, no matter how low the exhaust temperature, or how long. (iv) EHM enables DEF injection from a standard DEF injector at 130 °C exhaust temperature, rather than the common DEF injection at ~ 180 °C

These features, along with its substantial flexibility for its application in short or long durations, in low, moderate or high exhaust temperatures, in low or high DEF dosing (low or high ANR (Ammonia-to-NOx ratio)), along with ease in its architecture, integration and lower cost, make EHM an ideal candidate for meeting world's most stringent NOx targets.

EHM™ Description

The novel Electrically Heated Mixer can be designed in two variations (models). The first, designed for systems needing modest heating, such as during cold-start, is a stand-alone heated mixer, energized via the vehicle electrical system, capable of providing ~ 3 kW of heat (extendable to ~ 5 kW). In the second model, the mixer includes an embedded heater, likewise connected to the vehicle electrical system, capable of providing ~ 7 kW of heat (extendable to ~ 10 kW). Either model provides heat for rapid heat-up, for low-load (low temperature) cycles, or for other applications.

EHM, along with its optional E-Heater (if needed, and for greater heat supply), is shown in Figure 1. Its functionality and energy (heat) rating is in Table 1. A sample concept of its integration in cold-start heating, cold-start ammonia making for storage in SCR and DEF injection starting at ~ 130 °C for SCR of NOx is depicted in Figure 2.

FIGURE 1 Schematic of EHM and its E-Heater (optional, for greater heat supply) [7]. Functions and power ratings are in Table 1. EHM can be also used stand-alone [10, 11] shown in Figure 6.

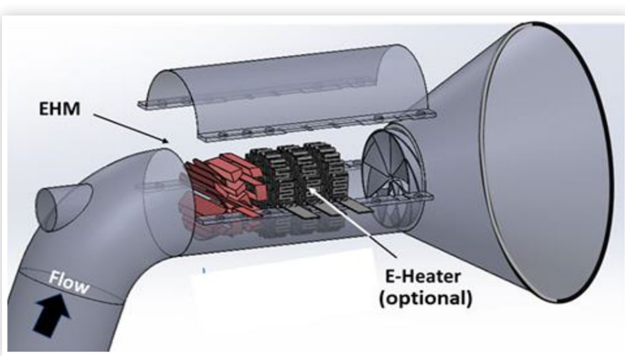


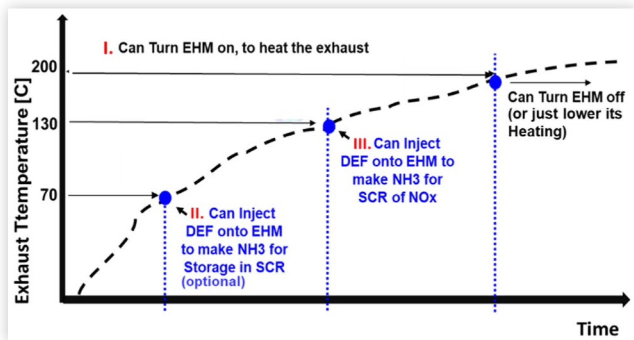
TABLE 1 EHM without, and with E-Heater for greater heat supply.

EHM Models I& II	Includes	Energy Supply * for DEF Processing**	Energy Supply * for Rapid Heat-Up/ Exhaust Flow Heating
Model 1: EHM™	Heated Mixer	~0.2 - 0.3 kW	~1 - 3 kW
Model II: EHM™ + E-Heater	Heated Mixer & E-Heater	~0.2 - 0.5 kW	~1 - 7 kW

*Approximate values.

**Varies with DEF inejction rate, other system variables

FIGURE 2 Examples of EHM flexibility/ strategy for rapidly heating up the SCR catalyst, ammonia making during rapid heat-up, or both, and start of DEF injection at 130 °C exhaust temperature. Suggested values shown are approximate.



EHM for Rapid Heat-up

It has been reported that EHM can *rapidly* heat the SCR catalyst while supplying it with reductants via DEF injection, shown to markedly lower the tailpipe NOx by several folds, both in regulatory and vocational cycles [7]: 3.3-fold in FTP, 22.5-fold in Low Load Cycle (LLC) and 10-fold in World Harmonized Transient Cycle (WHTC). EHM also enables meeting ultra-stringent NOx targets such as California 2027 (0.02 gr/hp.hr) [7].

In this section, we squarely focus on EHM for rapidly heating the catalyst system chiefly the SCR catalyst, showing this significantly reduces the tailpipe NOx. This is a combination of EHM's capabilities to both heat and to enable early DEF injection. The SCR NOx reduction activities start earlier, rapidly lowering the untreated NOx and hence the overall tailpipe NOx.

The demonstration in this section regards EHM+E-Heater (Figure 1) installed in an aftertreatment system shown in Figure 3: An in-line, DOC-DPF-SCR system including a closed-coupled SCR [7]. The entire aftertreatment system was aged to meet full useful life (FUL) aging equivalent to 435,000 miles per a known aging protocol [8, 9] used frequently.

The E-Heater embedded within the EHM (Figure 1) is not always necessary: EHM may be also installed stand-alone

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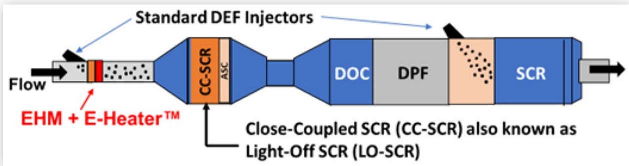
FIGURE 3 EHM+E-Heater [7] used for simultaneous rapid heat-up and DEF injection during engine cold phase, substantially lowering tailpipe NOx. EHM could also rapidly heat the primary SCR.



[10, 11]. The choice between EHM vs. EHM+E-Heater exclusively depends on the desired heating power and heating strategy; i.e., how aggressive one wishes to engineer the rapid heat-up in cold start. Approximate heating power of EHM vs, EHM+E-Heater is shown in Table 1. The displayed values are directional guidance: Design flexibility and system requirements allow designing each for other heating values not displayed in Table 1.

The aftertreatment system in Figure 3 was utilized on a Cummins X15 (2018 model year, 15-lit., inline six-cylinder calibrated for 500 hp) [7].

EHM impact on cold-start NOx are next discussed. Next, EHM application for urea deposit minimization (potentially its elimination) in low temperature conditions is demonstrated. Finally, EHM is shown to enable DEF injection in as low as 70 – 80 °C for rapidly storing ammonia in SCR catalyst during cold-start.

A. Lowering Cold-Start NOx via EHM

It is commonly agreed that rapid SCR heat-up during engine cold-start is an effective strategy for reducing the overall tailpipe NOx.

In this section, we therefore discuss and demonstrate EHM rapidly heating the CC-SCR and its impact on the overall cold-phase NOx emission. For demonstration purposes, we focus on the cold portion of two common cycles: FTP and WHTC. The aftertreatment system shown earlier (Figure 3) is utilized for this demonstration, and is tested on the Cummins X15 engine described earlier.

During this demonstration, engine base calibration may allow the engine-out NOx to vary according to the change in the SCR catalyst temperature [7]. No change was made in the engine base calibration when executing the runs with EHM such as changing engine-out species concentrations, catalyst performance, DEF dosing rate, NH_3 storage, coverage or such. To the extent possible, the two (baseline vs. with EHM) were allowed to run on engine default calibration.

A.1. Lowering NOx in Cold FTP We focus here on Cold FTP [7], especially on its first 400 seconds, the most determining part of such cold cycle. NOx emissions both at 400 seconds and for entire Cold FTP are summarized in Table 2. and in Figure 4. It is demonstrated that, in the first 400 seconds, EHM increases the CC-SCR temperature from 150 to 184 °C (time-averaged temperature over 400 seconds). This reduces Cold FTP NOx emission in half (from 0.14 to 0.07 gr/hp.hr). This is mainly because, owing to its rapid heat-up in the first 400 seconds by EHM, CC-SCR NOx emission can have twice as much NOx reduction efficiency: 0.09 gr/hp.hr NOx-out instead of 0.19. At the termination of Cold FTP, tailpipe NOx is lowered from 0.159 to 0.078 g/hp.hr, nearly precisely cut in half. The profound impact of this reduction is discussed in Ref. [7] enabling meeting California 2027 NOx target.

Full FTP NOx emission was reduced by 3.3 fold when using EHM, meeting California 2027 tailpipe NOx threshold of 0.02 gr/hp.hr. Details are available in Ref [7].

The CO_2 penalty due to EHM+E-Heater for the full FTP cycle was 2% [7]. No attempt was made in this study to reduce the CO_2 impact. Lowering CO_2 will be investigated in a subsequent study.

A.2. Lowering NOx in Cold WHTC Same approach is next taken to investigate impact of rapid heat-up impact due to EHM+E-Heater on NOx emission in cold phase of the World Harmonized Transient Cycle (WHTC), including on the first 400 seconds of the Cold WHTC, its most significant segment.

FIGURE 4 Impact of early heating and DEF injection using EHM+E-Heater on Cold FTP. NOx emission is reduced in half.

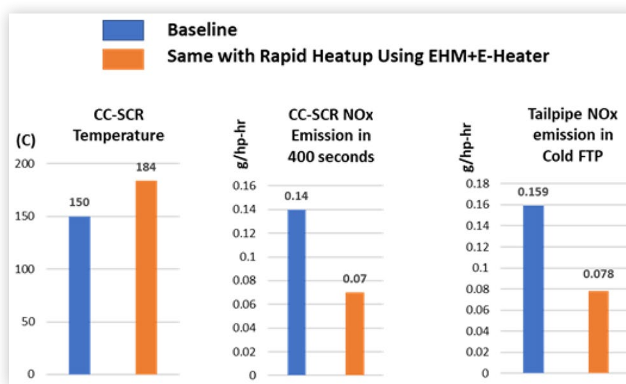


TABLE 2 NOx emission in cold FTP in its first 400 seconds, is reduced in half using rapid heat-up provided by EHM+E-Heater.

	Engine-Out	CC-SCR		Tailpipe NOx		
	BS NOx in Cold FTP	Avg. Temp. in 400 sec	BS NOx in 400 sec	BS NOx in 400 sec	BS NOx in Cold FTP	Cummulative Power EHM+E-Heater in 400 s
	(g/hp.hr)	(C)	(g/hp.hr)	(g/hp.hr)	(g/hp.h r)	(kW-hr)
Baseline	2.00	150	0.19	0.14	0.159	0
" with EHM+E-Heater	1.921	184	0.09	0.07	0.078	0.41

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TABLE 3 NOx emission in cold WHTC and its first 400 seconds, reduced markedly due to rapid heat-up by EHM+E-Heater. Cold WHTC NOx is lowered by 2.5-fold.

	Engine-Out	CC-SCR		Tailpipe NOx		
	BS NOx in Cold WHTC	Avg. Temp. in 400 sec	BS NOx in 400 sec	BS NOx in 400 sec	BS NOx in Cold WHTC	Cummulative Power EHM+E-Heater in 400 s
	(g/hp.hr)	(C)	(g/hp.hr)	(g/hp.hr)	(g/hp.hr)	(kW-hr)
Baseline	3.98	120	0.16	0.13	0.245	0
" with EHM+E-Heater	4.28	176	0.10	0.07	0.091	0.5

FIGURE 5 Impact of heating via EHM+E-Heater on Cold WHTC. NOx emission is reduced by almost 3-fold.

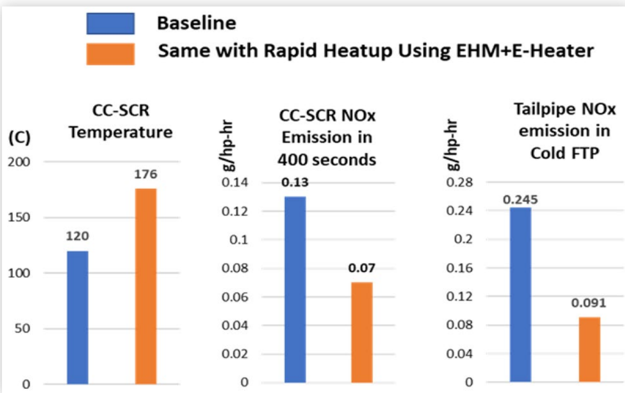
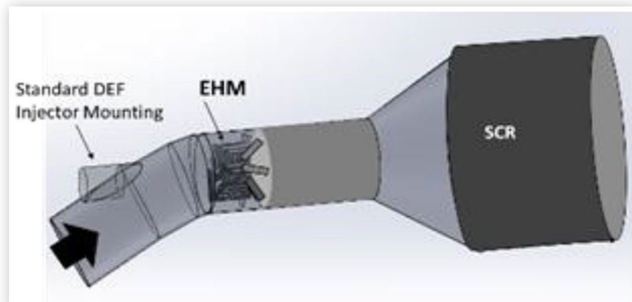


FIGURE 6 Standalone EHM (without E-Heater) positioned pre-SCR, demonstrating deposit prevention.



Cold WHTC NOx emission at 400 seconds and also for the full cold cycle are summarized in Table 3 and in Figure 5. In the first 400 seconds, EHM raises the CC-SCR average temperature by about 50 °C (from 120 to 176 °C), cutting its NOx emission in half. Cold WHTC tailpipe NOx emission is lowered from 0.245 to 0.091 g/hp.hr. or roughly by 3-fold. Full (Composite) WHTC cycle NOx emission was reduced by 10-fold via utilizing EHM system. Details are presented in Re*f*. [7].

The CO_2 penalty due to EHM+E-Heater for the full WHTC cycle was only 0.6% [7]. No attempt was made in this study to reduce the CO_2 impact. Lowering CO_2 will be investigated in a subsequent study.

B. EHM for Deposit Prevention

In this section, we demonstrate EHM substantially lowering deposit risks during extended DEF injection in lower temperatures exhaust

(~ 130 – 150 °C). The test setup is on a bench test closely mimicking low temperature exhaust in an aftertreatment system. The test unit is shown in Figure 6; test condition is given in Table 4.

Figure 7.A displays the condition with EHM not energized (turned off), closely mimicking a standard mixer in the given conditions. Not surprisingly, deposit is readily formed, especially considering the flow temperature is only 150 °C. Figure 7.B. displays the same flow and DEF injection condition as in Table 4, with EHM energized. The mixing section is virtually deposit free after 5400 second (1.5 hours) of constant DEF injection.

TABLE 4 Demonstrating EHM preventing urea deposit. Note DEF injection is prolonged, taking place in very low exhaust temperature.

Operating Conditions		(unit)
Mass Flow Rate	250	Kg/hr
Flow Temperature	150	C
Mixer Power Use	350	Watts
DEF Injection Rate	75	mg/s
DEF Injection Total Time	5400	sec.

In a recent publication, EHM's deposit prevention capability has been also demonstrated in engine runs lasting 10 to 20 hours [12].

There is a specific reason for the flow temperature set to 150 °C. Newer, production-level SCR catalysts demonstrate satisfactory activity near 150 °C and good activity near 180 °C [10]. Capitalizing on this SCR activity, EHM allows DEF injection starting at 130 °C exhaust temperature, yielding SCR efficiency ~ 80 – 100% in sustained temperatures near ~ 160 - 180 °C in highly transient, prolonged, low- load, stop-and-go operations [10, 11] (such as in city driving), with EHM needing only ~ 150 - 200 Watts on smaller engine aftertreatment systems and ~ 400 -500 Watts on heavy ones [10, 11, 12].

C. DEF Injection in Ultra-Low Exhaust Temperatures (70 - 80 °C)

Ammonia storage in SCR is a low-temperature phenomenon. Hence, to store ammonia in SCR, DEF injection in very low

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FIGURE 7.A EHM not energized ('off'), mimicking a standard mixer, subject to flow and DEF injection conditions shown in Table 4. Urea deposit is readily formed.

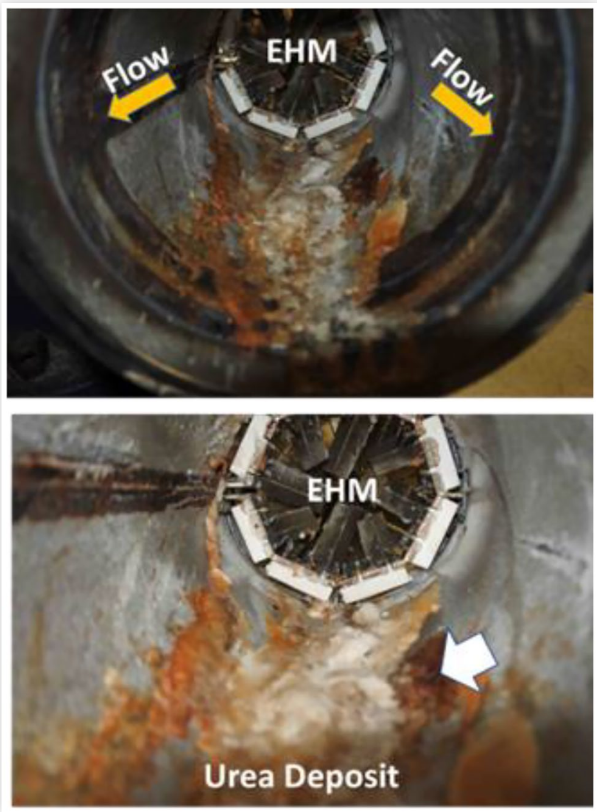
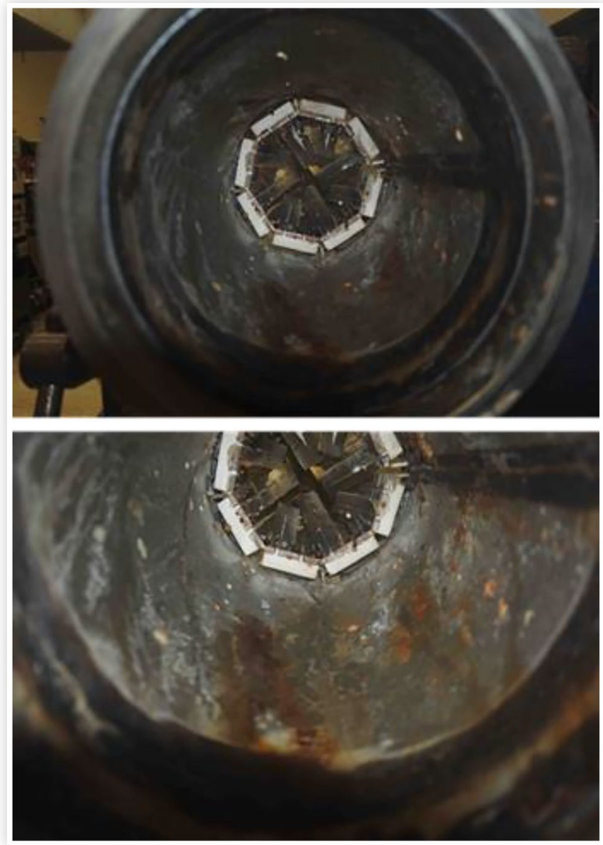


FIGURE 7.B EHM energized, in flow and DEF injection conditions given in Table 4. Urea deposit is non-existent after 5400 seconds of constant injection.



temperature exhaust would be helpful. This is however not available due to risks of forming urea deposit.

Since EHM is an effective means of preventing urea deposit (see the prior section, also Refs. [10, 11, 12]), EHM enables injecting DEF in very low temperatures, in as low as 70 – 80 °C, aimed at ammonia storage in the SCR catalyst. This provides several advantages:

a. Generally, low temperature DEF injection makes available a new operational window for ammonia storage.
b. Low temperature DEF injection is especially helpful when, during engine cold-start, the SCR catalyst may not have sufficiently stored ammonia. In such cases, DEF could be readily injected during cold-start onto the EHM (with exhaust flow temperature below 100 °C), forming reductants for rapid storage in the SCR catalyst.

This is especially helpful for improving in-use compliance, with no need to resort to fuel post-injection to keep the exhaust flow hot in low temperature operations to enable DEF injection / NH_3 making; i.e., EHM enables DEF injection in such stringent low temperatures while saving both fuel and CO_2.

c. Low temperature DEF injection: It was have demonstrated that a *purged* SCR catalyst (i.e., free of stored ammonia prior to its operation), when subjected to DEF dosing below 100 °C to allow rapid storage during heat-up, could yield excellent NOx reduction efficiencies as high as ~ 80 – 100% in temperatures well below 200 °C [10] .

These additional flexibilities for DEF injection during engine cold-starts, enabled by EHM, provide strong potentials for more efficient NOx reduction in most severe conditions, enhanced regulatory observance and especially for in-use compliance.

Generally, how and when cold flow heating (such as with EHM or E-Heater) is used, is a matter of one's choice of heating strategy. In this demonstration, EHM heating during Hot FTP was still used, though this heating was less than that used in Cold FTP [7].

Enabling DEF Injection at 70 - 80 °C Exhaust Temperature (or, Generally, Below 130 °C)

The key idea in this section is to demonstrate EHM enabling NH_3 storage in SCR catalysts below 130 °C. While such temperatures are too low for NOx reduction activities, they are ideal for NH_3 storage purposes. Injecting DEF in lower temperatures could be helpful not only for more robust regulatory compliance (such as in certification cycles [13]), but especially helpful for improved in-use compliance.

The aftertreatment system displayed in Figure 3 was utilized for this demonstration. It is emphasized that, even though that system has a CC-SCR, using EHM for

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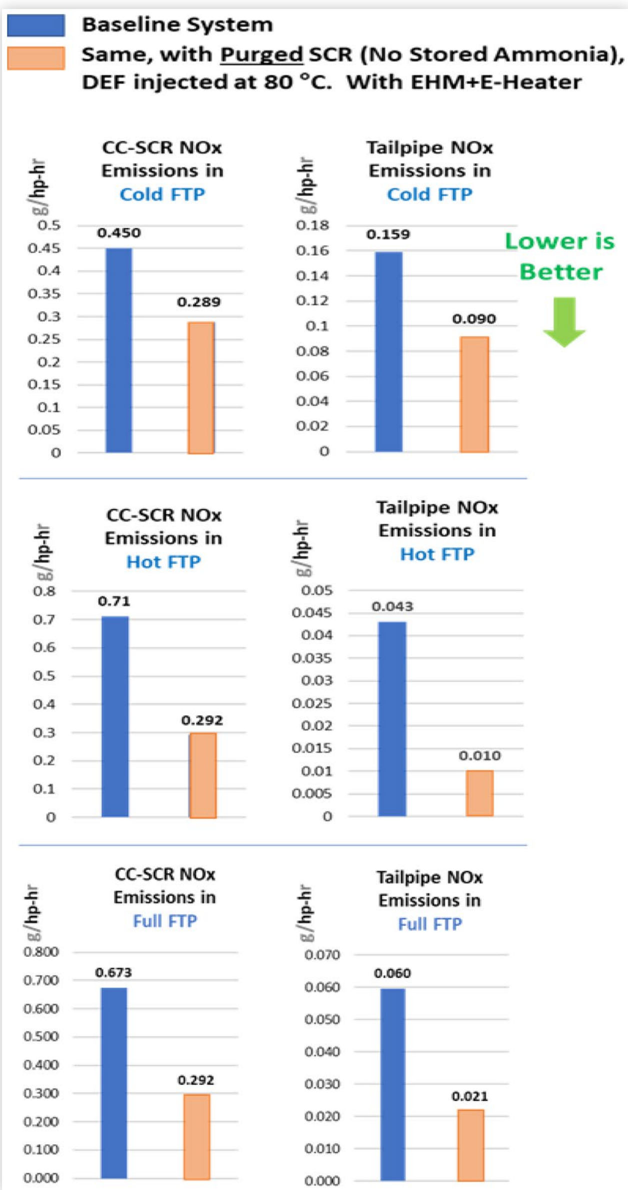
low-temperature DEF dosing is equally applicable to aftertreatment systems without CC-SCR. (See for instance Refs. [10, 11] demonstration on an aftertreatment system without a CC-SCR, in a highly transient vocational cycle, yielding excellent results, yielding tailpipe SCR efficiency in ~80 - 100% in exhaust temperatures well below 200 °C.)

In this testing demonstration, the aftertreatment system was subjected to DPF regeneration the night prior to the test, thus fully purging the SCR catalysts of its stored NH_3. Equipped with EHM, the aftertreatment system was then cycled through the cold and hot heavy duty transient FTP cycle. The results were then compared to the baseline performance (one with an ammonia-loaded SCR and no EHM.)

Figure 8 compares the baseline aftertreatment system performance in FTP cycle with the same system next free of

FIGURE 8 Cold, Hot and Full FTP in the baseline system compared with same system with no stored ammonia, with DEF injection starting in 70 - 80 °C onto EHM.



stored ammonia, subjected to early (~ 80 °C) DEF injection. During both cold and hot FTP, EHM+E-Heater enabled CC- and primary SCR to have higher temperatures lowering the tailpipe NOx.

Despite having a SCR purged of its stored ammonia, the configuration equipped with EHM+E-Heater markedly outperformed the baseline in tailpipe NOx during Cold FTP, Hot FTP and Full (composite) FTP. This demonstrates additional flexibility enabled by EHM, especially helpful for robust in-use compliance in low-temperature cycles needing continuous supply of DEF, and thus NH_3, to SCR.

Let's recall California 2027 NOx target, world's most stringent tailpipe NOx limit, is 0.02 gr/hp.hr. Despite having a SCR fully purged of its stored NOx, EHM-equipped aftertreatment system achieved Full FTP tailpipe NOx of 0.021 g/hp.hr, not far from meeting California 2027. That is, modest system optimization would likely enable meeting such ultra-stringent regulations with EHM even in the absence of ammonia storage. (In the presence of stored ammonia, prior EHM demonstrations have established enabling meeting 0.02 gr/hp.hr [7].)

Conclusions

A new technology, an Electrically Heated Mixer (EHM), has been demonstrated for its multi-functionality, markedly reducing Diesel NOx tailpipe emissions, demonstrating

1. EHM can rapidly heat up the SCR catalyst, useful in cold cycles and in low temperature operations. Demonstrations show this reduced the tailpipe NOx in FTP cycle by at least 2-fold, in low-load cycles by 22-fold [7]
2. EHM enables DEF injection in as low as 70 - 80 °C producing an abundance of gaseous reductants (ammonia, isocyanic acid) for storage in SCR (i.e., well before SCR NOx reactions start.)
    - This could assure the SCR catalyst would never run out of stored ammonia. This is unambiguously useful in prolonged, low-temperature exhaust operations where DEF injection is still needed to maintaining high efficiency SCR operations [10].
    - It enables an aftertreatment system with SCRs without stored ammonia to outperform those with stored ammonia. This has been shown to produce high SCR efficiencies, ~ 80 – 100%, in highly transient, low-load (low-temperature exhaust), vocational (non-regulatory) cycles [10, 11].
3. EHM enables DEF injection at 130 °C for ammonia storage and for rapid, early NOx reduction in the SCR catalyst
4. EHM noticeably reduces deposit risks [12].
5. In low-load drive cycles (exhaust temperatures below 200 °C), EHM constantly makes reductants available on-demand for the SCR catalyst [10].

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6. Unlike other exhaust heating devices, integrating EHM in the aftertreatment system does not add one more component to the architecture; this is because mixers are already present in aftertreatment systems.
7. EHM's multi-functionality for low-temperature DEF injection, deposit inhibition and SCR heating renders it a dependable technology to meet ultra-low NOx regulations such as California 2027 [7] and EU-7/VII.

EHM could be incorporated in 12-, 24- or 48-Volt systems [7, 10, 11, 12].

Along with prior publications, this work forms a trilogy demonstrating EHM enabling rapid system heat-up making available several fold reductions in tailpipe NOx enabling meeting ultra-stringent NOx regulations [7] while enabling high efficiency SCR of NOx in low-load and in fast transient cycles [10].

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Abbreviations

CC-SCR - Close-Coupled SCR. A smaller SCR catalyst positioned closer to the engine; (also known as Light-Off SCR LO-SCR)

E-Heater - Electric Heater

EHM - Electrically Heated Mixer

FTP - Federal Test Protocol; a regulatory cycle

HNCO - Isocyanic acid; an ammonia precursor

LLC - Low-Load Cycle, a regulatory cycle

LO-SCR - Light-Off SCR; (same as CC-SCR)

NH_3 - Ammonia

NO_x - Nitrogen Oxides (NO and NO_2) Reductants Ammonia (NH_3) and Isocyanic acid (HNCO)

SCR - Selective Catalytic Reduction

WHTC - World Harmonized Transient Cycle

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