

The Study of Exhaust Heating to Improve SCR Cold Start Performance

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ABSTRACT

SCR cold-start effects are increasingly important for meeting today's emission requirements [1]. A significant challenge toward quickly achieving NO_x abatement is the presence of moisture in the catalyst at lower temperatures [1]. This paper describes the ability of an electric heater to effectively raise the temperature of the exhaust and overcome the effect of moisture and low exhaust temperature, allowing NO_x conversion to begin sooner. A model of the moisture storage and removal is presented, along with results from engine tests. Results show that it is possible to achieve high NO_x conversion temperatures quickly with robust heater technology that is suited for diesel applications.

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INTRODUCTION

Overview

Heavy-duty engine manufacturers in the US have already achieved excellent levels of performance and fuel economy while meeting extremely low nitric oxides and particulate matter (NO_x/PM) limits. This superior engine performance was made possible through combustion system improvement, including high boost pressure ratios, high EGR rates, alternative combustion schemes, and advances in injection systems, as well as advanced lubricant formulations that enabled catalytic exhaust treatment of criteria pollutants. While these in-cylinder technologies are very impressive in their positive impact on engine performance and low emissions profile, engine-out emissions of NO_x and PM remained above the regulated low limits thus requiring the adoption of catalytic exhaust emissions controls. Diesel particulate filters (DPF) were introduced in production in 2007 to meet PM limits while NO_x emissions were met using in-cylinder technologies.

In 2010 urea selective catalytic reduction (SCR) for NO_x aftertreatment was commercially introduced for heavy-duty applications. This technology has already demonstrated over 90 percent NO_x conversion efficiency under ideal conditions. However, urban driving conditions proved to be a challenge for this technology due to low exhaust temperatures that resulted in low SCR NO_x conversion efficiencies. SCR catalysts low temperature inefficiency for three major SCR catalyst formulations (see Figure 1) extended to light load operation as well [2]. SCR NO_x conversion inefficiency at low exhaust

temperatures is further exacerbated when condensate builds up on the catalyst as it cools down. Reference (SAE 2013-01-1064) shows that exhaust-heating energy is consumed first in ridding the catalyst from moisture. This process retards the effectiveness of the catalyst and reduces the overall SCR catalyst conversion efficiency.

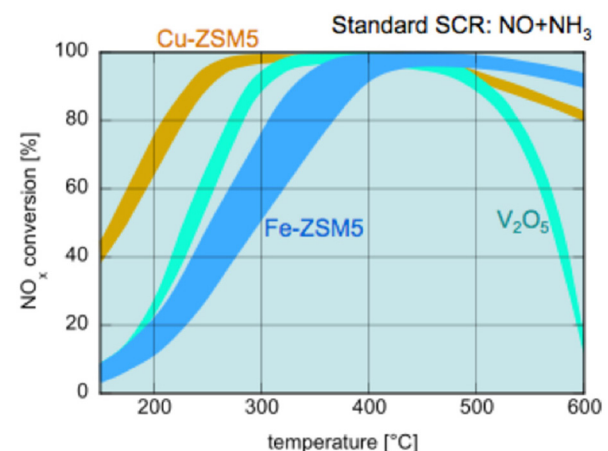


Figure 1. SCR NO_x conversion characteristics.

This paper will discuss the application of exhaust heating and its impact on SCR catalyst efficiency during cold-start, as well as idle and light-load operation. The impact of moisture and its elimination is modeled and verified on a test stand as well as in a test engine.

Moisture

Bench reactor testing with zeolite SCR catalysts has demonstrated an exotherm when the catalyst adsorbs H_2O and an endotherm when the H_2O desorbs [1]. These thermal events are offered as explanations of the initial cold start behavior of SCR catalysts in which the SCR outlet temperature exceeds the inlet temperature and is followed by a slow decrease in SCR outlet temperature while the inlet temperature increases [1]. Since this cold temperature phenomenon occurs below 150°C and delays the heating of the catalyst to effective NOx conversion temperatures, it presents an important challenge for improving higher NOx conversion efficiency.

Electric Exhaust Heater

The concept of using electric heat to warm a catalyst within an exhaust system is not new and dates back at least to the 1980's [3, 4, 5]. At that time it was thought that an electrically heated catalyst might be needed for the purpose of automotive cold-start emissions [5]

Energy Efficiency

The use of an electric heater to increase exhaust temperature has been shown to consume on the order of three times less fuel than engine-based heating methods [3]. This stands to reason based on an energy balance for the engine. Figure 2 shows a schematic for the purpose of describing the energy balance. A portion of the energy introduced to the engine (with the fuel and inlet air) is converted to effective power; another part is transferred to the coolant, and yet another to the exhaust gases that exit the engine [6]. At idle and low load conditions, where exhaust heating would be required, the engine thermal efficiency drops significantly. The drop in thermal efficiency renders most if not all engine-based exhaust heating means rather energy inefficient.

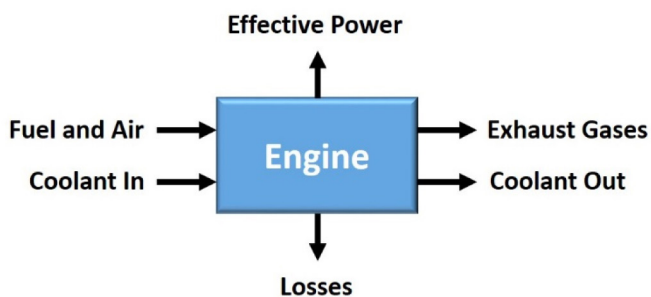


Figure 2. Schematic to describe the engine energy balance [6].

Figure 3 shows the average energy balance during a New European Driving Cycle (NEDC) as described in Reference [6]. The miscellaneous category included in the graph includes energy used to raise the temperature of the engine block and losses to ambient air. During the cycle, on average, 23.8% of the input energy resulted in effective work and 13.7% was lost through exhaust gases [6]. This means that, on average, the addition of an incremental amount of fuel for engine-based heating would have resulted in 13.7% conversion of energy to the exhaust. If an electric heater was placed directly in the exhaust stream and powered by the diesel engine, the addition of an incremental amount of fuel would add heat to the exhaust by converting the increase in effective power to heat and by increasing exhaust gas losses. This would raise the conversion of incremental

energy to the exhaust to be nearly the sum of the effective power and the exhaust losses (about 35%). The comparative advantage of electric heat would be even greater during the initial portion of the NEDC cycle when the temperatures are lower and the miscellaneous losses are greater.

Electric heat would also improve fuel economy by increasing the NOx conversion efficiency of the SCR system and enabling a timing advance for the engine that normally improves energy efficiency.

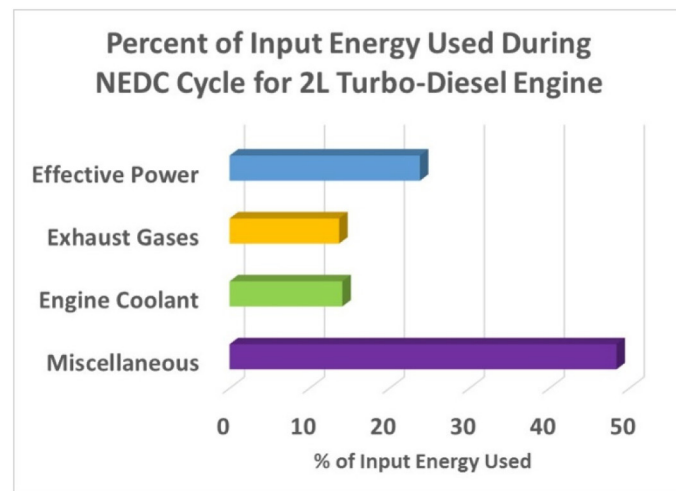


Figure 3. Energy balance of 2 liter turbo-diesel during NEDC driving cycle [6].

Heater Robustness

In order to be a viable candidate for heavy-duty diesel applications, it is important for the heater be designed to withstand the vibration environment. For this reason, a tubular heater construction was selected. A cross-section drawing of an individual tubular heating element is shown in Figure 4. With this tubular construction, the electrical resistance wire is not directly exposed to exhaust. The wire is surrounded by MgO (magnesium oxide) powder and positioned within a metal sheath. The diameter of the metal sheath is mechanically reduced, compacting the MgO and protecting the resistance wire. The heater is then annealed and formed into the desired shape. Figure 5 shows a vibration test in progress. Vibration testing with a heavy-duty diesel power spectral density (PSD) having a root mean square acceleration (G_{RMS}) of 4.6 was used to verify robustness of the tubular heater. The tubular heater construction has already demonstrated a life of over 10,000 hours in this vibration environment and is expected to improve further with future designs. Additional durability information will be included in future papers updating this work.

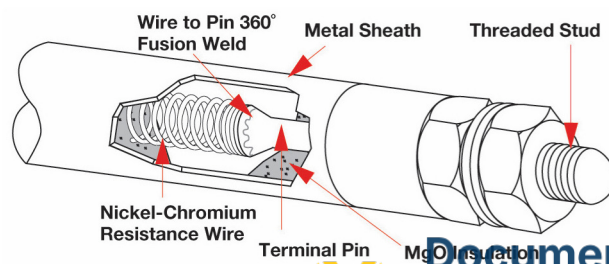


Figure 4. Construction of tubular heater.



Figure 5. Vibration test of tubular heater.

METHODS

In order to explore the ability of a tubular construction heater to improve SCR cold-start performance, engine testing and flow testing was completed. Both tests included production aftertreatment components with actual thermal masses. Both test configurations had urea injection hardware but urea was not dosed. A comparison of thermal data was used to determine the effect of the electric heater.

Engine Testing

Test Schematic

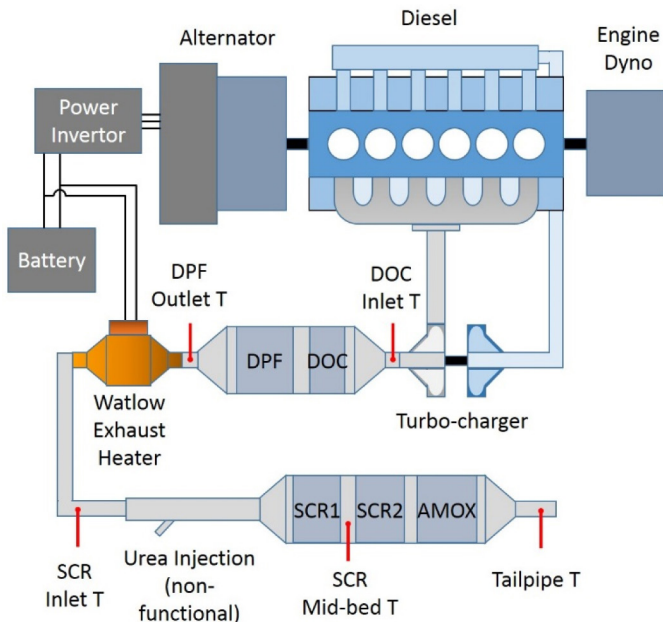


Figure 6. Engine test configuration diagram.

A diesel-electric hybrid test stand was used for the engine tests. Figure 6 illustrates key aspects of the test system. A Cummins ISDe 6.7 liter engine was connected to both an engine dynamometer and an alternator, allowing the engine to be independently loaded by either of the devices. A power inverter was used to convert ac power from the alternator to dc power that was provided to both the battery and the electric heater. The nominal voltage was 330Vdc. The

aftertreatment system consisted of a diesel oxidation catalyst (DOC), diesel particulate filter (DPF), selective catalytic reduction (SCR) and ammonia oxidation catalyst (AMOX), as shown in Figure 6.

Test Description

SCR

The SCR was comprised of two monolith substrates (referred to as SCR 1 and SCR 2), each of which was cordierite with 400 cells per square inch (cpsi) and a copper zeolite catalyst. The size of each substrate was 267mm diameter and 152mm long. A thermocouple was positioned between the two SCR catalysts and is referred to as SCR mid-bed temperature.

Heater



Figure 7. Exhaust heater without inlet and outlet cones.

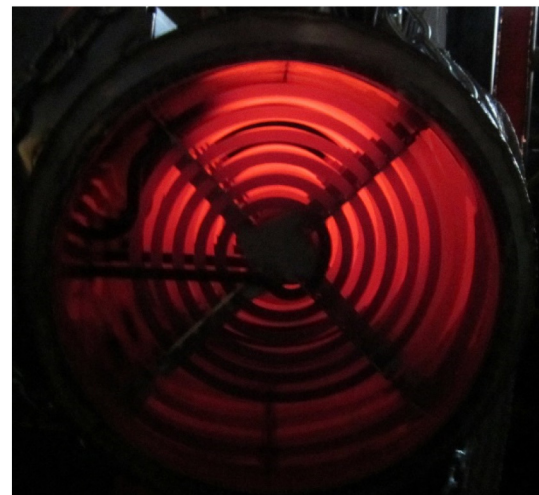


Figure 8. Internal view of heater when powered (no flow condition).

The heater was comprised of 5 spiral wound heating elements, each rated nominally at 6kW. Figure 7 shows the heater with the inlet and outlet cones removed. The configuration of the heater allowed any number from two to five of the elements to be powered, providing nominal values of 12, 18, 24 or 30kW. A temperature sensor measured the internal temperature of the heater and was used in combination with a solid state switching system and a microprocessor based control to limit power to the heater when the desired