

Diesel Particulate Filter System – Effect of Critical Variables on the Regeneration Strategy Development and Optimization

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ABSTRACT

Regeneration of diesel particulate filters poses major challenges in developing the particulate matter emission control technology to meet EPA 2007/2010 emissions regulations. The problem areas are multifold due to the complexity involved in designing the filter system, developing regeneration strategies and controlling the regeneration process. This paper discusses the need for active regeneration systems. It also addresses several key limitations and trade-offs between the regeneration strategy, chemical kinetics, exhaust gas temperature and the regeneration efficiency.

Passive regeneration of diesel particulate filter systems is known to be highly dependent on the engine-out [NO_x/PM] ratio as well as exhaust temperature over the duty cycle. Using catalytic oxidation of auxiliary fuel injected into the system, the exhaust gas temperature can be successfully enhanced for filter regeneration. However, as demonstrated in this work, such active temperature increase may be either beneficial or detrimental to the efficiency of regeneration, depending on the mechanism of particulate matter oxidation. Engine tests and bench reactor results were used to understand this effect. This information should help provide tools for developing optimum regeneration strategies for different applications based on the engine emission characteristics, duty cycle and type of the filter system.

INTRODUCTION

Diesel particulate filter (DPF) is a promising aftertreatment technology for meeting the 2007/2010 EPA particulate matter regulations. However with the need for 2010 engine-out NO_x emissions to be lower than 2007 levels, regeneration of particulate filters has been a major challenge area and is continuing to form the basis for several technological improvements in the application of diesel particulate filters on diesel engines. With the development of catalyst formulation by the catalyst companies in the recent years, significant improvements have been made in the DPF technology

on applications that meet the regeneration requirements. Typically, these applications are referred to as passive regeneration systems where the filters will regenerate without a need for additional energy source to increase the duty cycle temperature. Such systems are highly dependent on the engine-out NO_x and particulate matter (PM) emission levels in addition to the duty cycle exhaust temperature. These limitations restrict the passive technology to select engine duty cycle applications.

To overcome this limitation, active regeneration is essential for developing a robust filter technology suitable to all applications. Several active regeneration concepts like the electric, burner, catalytic oxidation and microwave systems are being considered and each system has its own pros and cons depending on the performance, cost, application and durability requirements. This paper highlights the key features and technology limitations of the concept of catalytic combustion as an example.

In active regeneration using hydrocarbon injection, the theoretical concept is that the injected hydrocarbons (primarily diesel fuel) are vaporized in the exhaust at a certain temperature and oxidized over the catalytic surface thus producing the heat to increase the exhaust temperature (catalytic oxidation). The increase in temperature is then utilized to enhance oxidation of the diesel soot trapped in a soot filter. Without a catalyst, exhaust temperatures close to 600°C are required to oxidize the diesel soot trapped in a filter. In normal applications of diesel engines on the highway, such high temperatures are rarely seen. Application of a catalyst is known to shift oxidation of soot to substantially lower temperatures, due to:

- Changes to the exhaust gas composition: conversion of NO into the very active soot oxidant NO₂, and/or
- Oxidation of soot with the direct participation of the catalyst, if they are located in the close proximity.

In this paper, a brief discussion on the experimental setup will be followed by the concept of catalytic oxidation using active strategies, regeneration performance evaluation of different configurations under steady-state and transient duty cycle conditions, regeneration analysis, optimization challenges and conclusions.

EXPERIMENTAL SETUP

The engine laboratory consisted of a 5.9 liter ISB 270HP engine coupled to an eddy current dynamometer. The exhaust system was designed to have the diesel particulate filter systems in different configurations. Figure 1 shows the schematic of active regeneration using the concept of catalytic combustion.

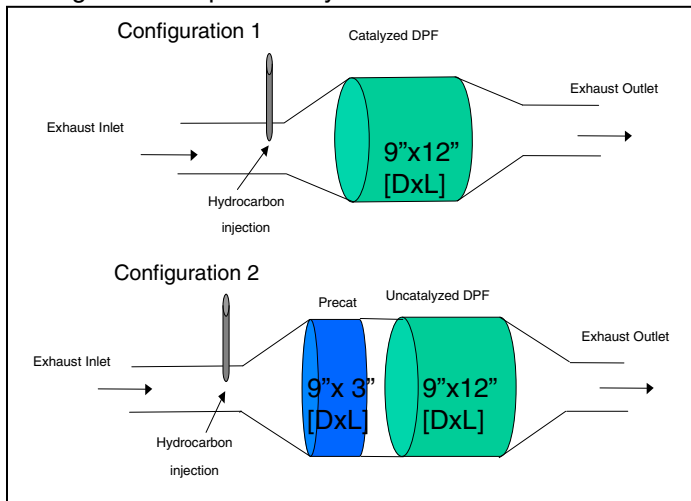


Figure 1: Schematic of Catalytic Combustion Setup

In configuration 1, diesel fuel is injected upstream of a catalyzed soot filter [DxL=9"x12"] and the vaporized hydrocarbons are converted into heat energy on the catalytic surface thereby increasing the exhaust temperature. In configuration 2, the diesel fuel is injected upstream of a flow-through oxidation catalyst [DxL=9"x3"] to increase the exhaust temperature by oxidizing hydrocarbons and to favorably change the exhaust gas composition before the filter. Thus the soot oxidation process in configuration 2 is de-coupled from the fuel and NO oxidation process.

A gasoline direct injector (GDI) was used as a prototype for evaluation purposes. The injector was placed at a constant distance upstream of the catalyst during all the experiments. The injector was calibrated periodically to ensure proper fuel delivery rates. Fuel injection pressure was held constant for all the experiments and supply pressure was set to ensure adequate flow distribution characteristics based on previous experience. Low sulfur diesel fuel [< 30ppm sulfur content] was used during this study. Cordierite ceramic was used for both precatlyst and DPF materials. The DPF in both configurations had 17mil wall thickness and 100 cells/sq.in cell density. The precatlyst had 6.5 mil wall thickness and 400 cells/sq.in

cell density. Both precatlyst and catalyzed DPF had high platinum loading formulations in respective configurations.

DESCRIPTION

The filter and precatlyst were instrumented with internal thermocouples during the entire study and the schematic of thermocouple locations is shown below in Figure 2.

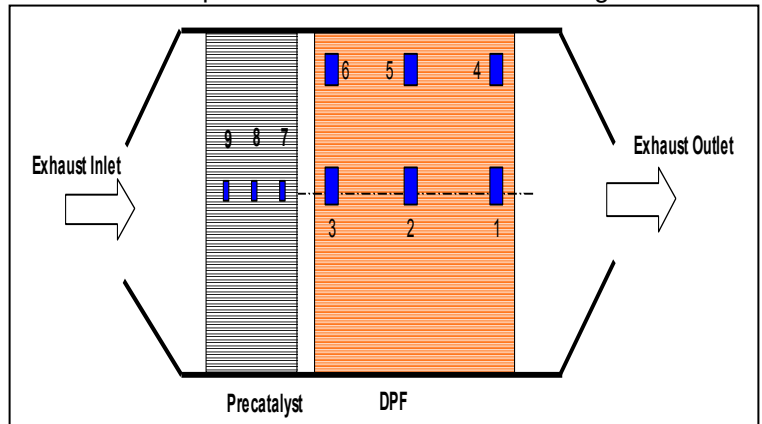


Figure 2: Schematic of Thermocouple Locations

RESULTS AND DISCUSSION

Minimum HC light-off Temperature

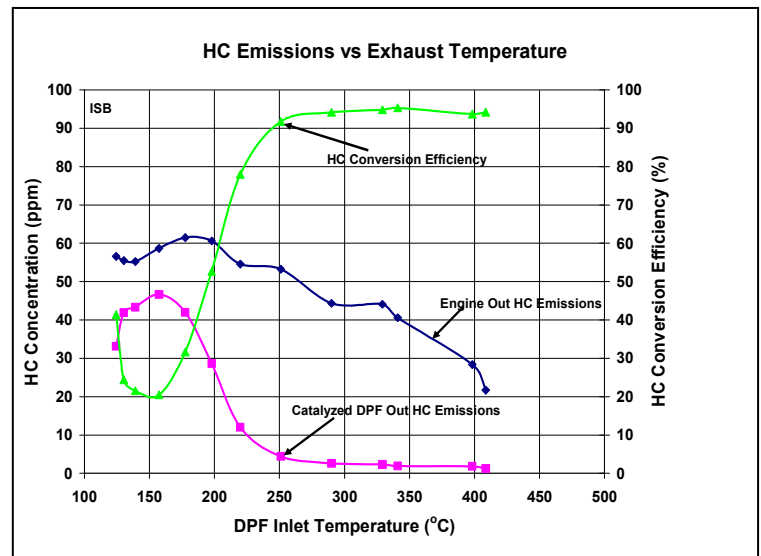


Figure 3: Oxidation of Engine-Out Hydrocarbons

Oxidation of Engine-Out Hydrocarbons

Figure 3 shows the hydrocarbon (HC) emissions and HC conversion efficiency vs exhaust gas temperature at the catalyzed DPF inlet at 1000 rpm engine speed. No auxiliary HC's were injected into the exhaust during this experiment and the DPF had less than 25 gms of soot. The HC conversion efficiency reaches 90% at 250°C and maximizes at 95% for temperatures greater than 250°C.

The behavior of HC conversion efficiency curve between 100-150°C could be attributed to the HC storage and release process. At 100°C, conversion efficiency turns out to be 40% which could be due to HC storage and as the temperature increases to 150°C, conversion efficiency drops to 20% which can be explained by release of HCs. Above 150°C, the actual conversion of HCs begin through light-off and gradually increases with temperature from there onwards.

Oxidation of injected fuel: When diesel fuel was injected into the exhaust at 200°C upstream of a catalyzed soot filter, noticeable hydrocarbon slip was observed even with very low injection quantities due to incomplete oxidation and no increase in catalyst outlet temperature was observed. However, when the injection was done at 250°C upstream of a Catalyzed Soot Filter (CSF), the exhaust gas temperature at the CSF outlet increased and no HC slip was seen. Thus the concept of active regeneration using exhaust HC injection requires a minimum exhaust temperature between 250°C – 350°C depending on the catalyst system design and applications.

Steady-State Test

Active Regeneration

Figure 4 compares the regeneration performance between a catalyzed Diesel Particulate Filter [DPF] or CSF (Configuration 1) and a precatalyst + Uncatalyzed DPF (Configuration 2) systems with active HC injection. In both the experiments, the DPF was preloaded with 45 gms of soot at steady state engine operating mode. The soot loading level was determined by weighing the filter before and after loading.

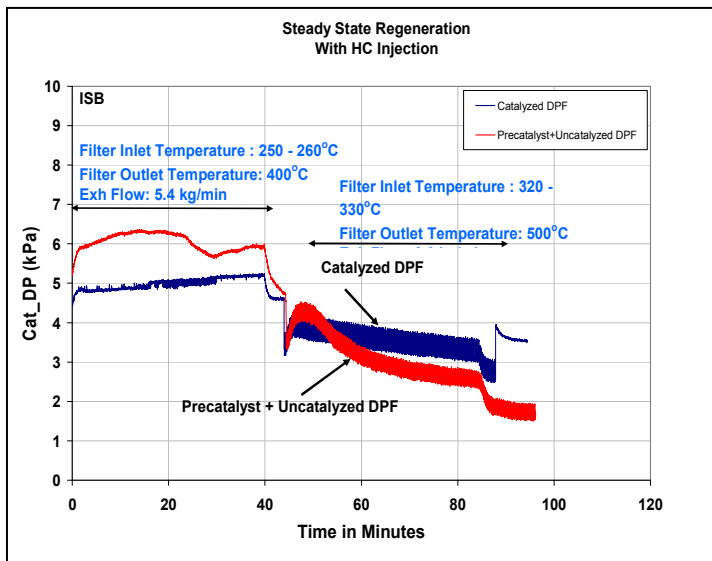


Figure 4: Steady-State Active Regeneration Performance

During the first regeneration step, the engine was at a high speed/low load condition with an exhaust temperature of 250°C at the catalyst inlet. Diesel fuel was injected upstream of the precatalyst for a period of 40 minutes and the filter outlet temperature increased to 400°C without any

HC slip. After 40 minutes, the engine operating conditions were changed to a low speed/high load with low exhaust flow rate and an exhaust temperature of 325°C at the precatalyst inlet. Using active HC injection, filter outlet temperature was increased to 500°C without any HC slip. By weighing the systems after the regeneration experiment, 7 gms of soot oxidation from 47 gms of initial soot loading was noticed in Configuration 1, while in Configuration 2, a decrease in 15 gms of soot from the initial weight of 45 gms was observed. At time $t=0$, the pressure drop between the two configurations are different and this could be attributed towards variations in soot loading level, soot distribution and pressure drop measurement variability due to location of static pressure taps. The behavior of pressure drop curves with respect to time during regeneration qualitatively agrees with weight measurements in explaining the regeneration performance during active regeneration.

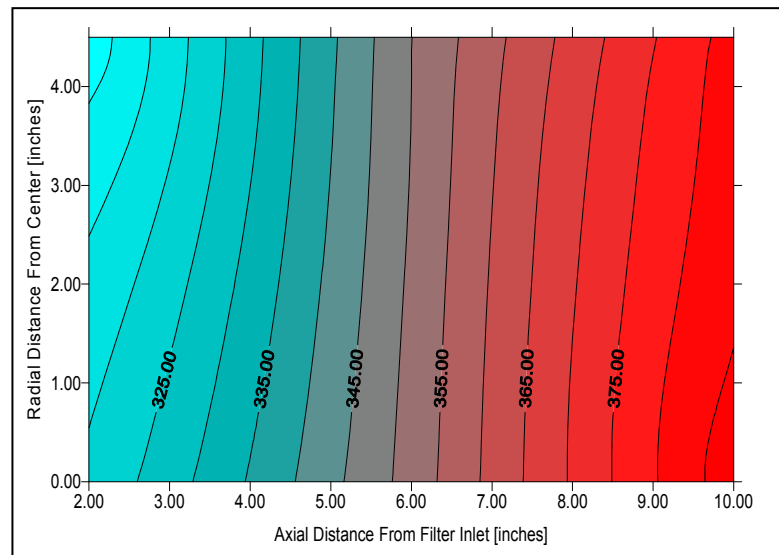


Figure 5: Temperature Distribution in a Catalyzed DPF without Precatalyst

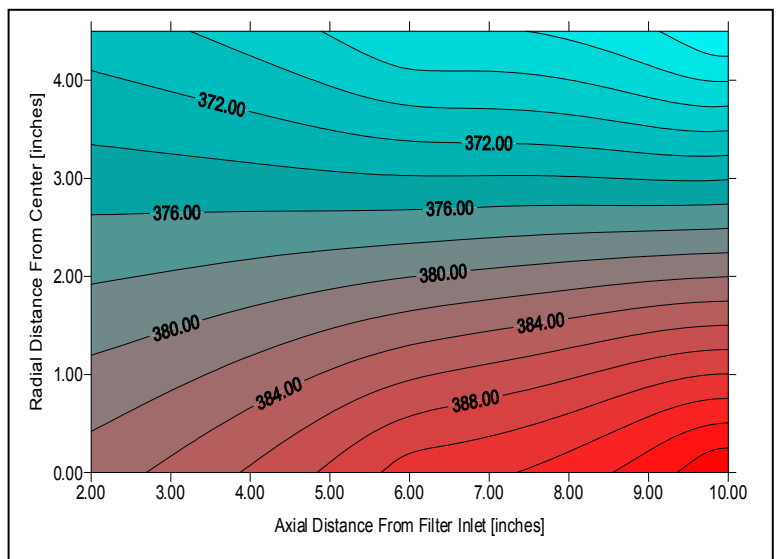


Figure 6: Temperature Distribution in a DPF with Precatalyst

Figure 5 shows the temperature distribution across the DPF with and without a precatalyst. The contours were developed using an interpolation scheme based on six temperature measurements at different locations inside the DPF. Without a precatalyst in Configuration 1, axial temperature gradients are more prominent during HC injection. This makes the outlet portion of the filter hotter than the inlet by more than 80°C. Major portion of the HCs burn towards the outlet portion of the filter, thus generating heat at the outlet. This could possibly result in poor soot oxidation towards the inlet of the filter compared to the outlet. The presence of precatalyst upstream of a DPF yielded better results with less variation in axial temperature distribution [Figure 6] as well as improved soot oxidation during the regeneration experiments. Thus, configuration of the catalyst system is a key factor in active regeneration using the concept of catalytic combustion.

Passive Regeneration

Figure 7 shows the regeneration performance between the two configurations during passive regeneration without any HC injection in the exhaust. At 350°C exhaust temperature, Configuration 2 shows better performance than Configuration 1, since the soot oxidation is mainly dominated by NO₂ mechanism. The precatalyst in Configuration 2 converts engine out NO to NO₂ and NO₂ is critical to soot oxidation. This mechanism plays a significant role in Configuration 2 thus resulting in better regeneration performance. At 505°C, the soot oxidation mechanism is mainly dominated by the presence of O₂ since NO₂ availability is thermodynamically limited. Configuration 1 shows better regeneration performance at 505°C with a significant decrease in pressure drop. This could be possibly attributed to the presence of catalyst on the filter and the contact between the soot and catalyst layer under those conditions [8].

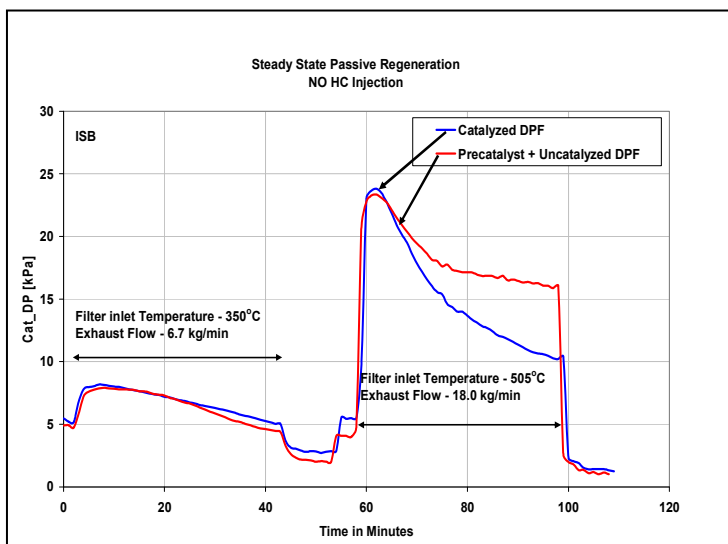


Figure 7: Steady-State Passive Regeneration Performance

Transient Test

A transient duty cycle representative of transit city bus operation was developed to have low duty cycle temperature, which would prevent passive regeneration of DPF during the cycle operation. This duty cycle was tested with Configuration 2. Figure 8 shows the cumulative temperature distribution for the duty cycle which has an exhaust temperature > 270°C for 10% of the time at the precatalyst inlet. Figure 9 shows the cumulative exhaust temperature distribution at the precatalyst inlet, precatalyst outlet and DPF outlet during active regeneration using HC injection. The cycle averaged HC conversion efficiency during active regeneration was 94%.

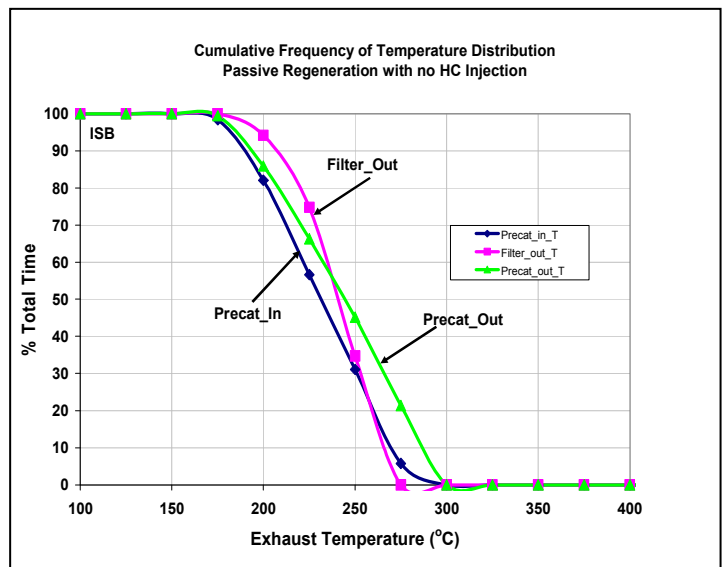


Figure 8: Temperature Distribution without HC Injection

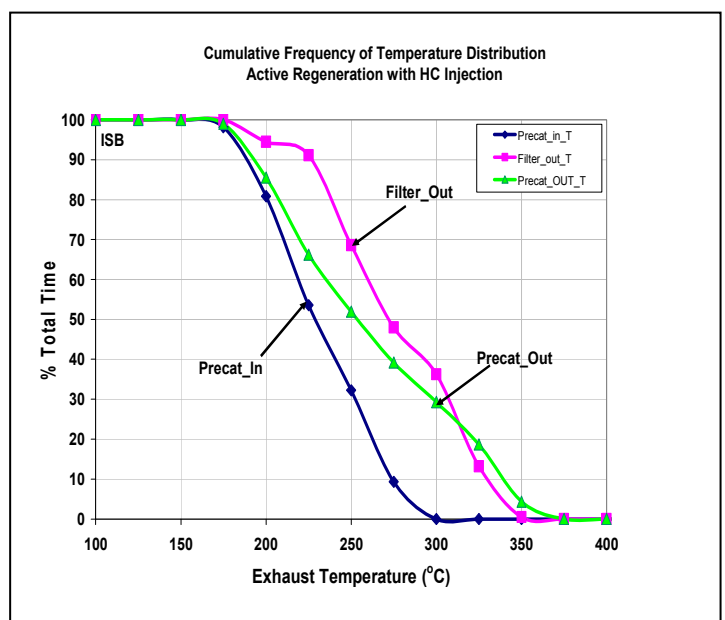


Figure 9: Temperature Distribution with HC Injection