Durability Study On Diesel Particulate Filter For BS-VI Heavy Commercial Vehicle Applications

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Abstract - *Diesel particulate filters (DPF) are an indispensable after-treatment component for all heavy commercial vehicle diesel engines. For the diesel particulate filters' adaptability in commercial vehicles, there are a few key challenges, including the selection of DPF volume for maximum soot loading capacity. On the other hand, the maximum soot loading durability of DPF material during vehicle drop to idle conditions as well as soot estimation strategies play a major role in meeting the DPF durability requirements. Consequently, if the diesel particulate filters' design and calibration strategies for commercial vehicles are not fine-tuned to the stipulated conditions, then the consequences could be massive and impose a cost impact on customers. Nevertheless, the OBD requirements for DPF are also becoming more meticulously strict starting from the 2023 model year. Accordingly, the DPF durability validations for soot regeneration strategies based on vehicle duty cycles become vital for vehicle performance. Hence, in this paper, significant validations for DPF soot estimation, soot regenerations during drop to idle conditions, accelerated DPF life testing, and WHTC test performance after a systematic understanding of DPF key parameters such as material properties, cell structure, soot loading, and regeneration temperature are deliberated to determine the thermal stress on DPF systems. Based on the validation the during drop to idle condition the maximum DPF out temperature is accomplished within 600oC with hydrocarbon slip of less than 100 ppm to avoid Pt catalyst migration. Furthermore, after 100 hours of WHTC (World Harmonized Testing cycle) cycle testing, no cracks were observed on the DPF faces.*

Key Words: Diesel particulate filter; Durability; Material; Testing; Commercial vehicle.

1. INTRODUCTION

Currently, in the global transportation sector, a significant role is played only by the diesel engine. Compared to other power sources, the diesel engine's fuel economy and thermal efficiency make it more attractive for commercial vehicle (CV) customers as well as for several other purposes, like power generation, construction, and industrial activities [1–2]. Typically, during a diesel engine's combustion process, more particulate matter and NOx are produced, which leads to a rise in health concerns compared to the petrol engine [2–3]. Therefore, to curtail this tailpipe emission, the Indian government has pronounced enforcement of the hardest emission standards norms of BS-VI (April 2023 onwards) from the earlier BS-IV norm. Due to the above-mentioned stringent Indian emission norms, the usage of diesel particulate filter (DPF) systems by vehicle manufacturers has increased.

This DPF product was first introduced in the year 2000 in Europe [3], and the ceramic material for extruded monolithic substrates is cordierite (2 MgO_2 Al_2O_3 $5SiO_2$) [4], which is most extensively used on one hand. This DPF system is recognised as the most effective PM abatement device, with approximately 97% soot filtration efficiency. However, based on the vehicle applications, critical DPF selection parameters should be finalised accordingly, as shown in Figure 6.

Furthermore, on the other hand, silicon carbide (SiC) also has outstanding heat resistance properties and is preferred as the principal material for DPFs. For this SiC DPF material to maintain a higher coefficient of thermal expansion, a "segment" type of design is utilized. However, compared to cordierite DPF, this SiC DPF has a higher pressure drop for the same volume. Regarding the filtration efficiency for this SiC DPF configuration, it ranges from 80% to 92%. However, by reducing the mean pore diameter from 25 to 15 micrometers, this can be improved [5]. The filter's mean pore size of less than 15 micrometres resulted in 100% efficiency [6]. Based on the aforementioned DPF material requirements, SiC DPF is selected for durability validation. Moreover, the critical challenge associated with the modular DPF system design is to regenerate soot effectively throughout various commercial vehicle duty cycle conditions. Figure 2 (a) shows a schematic of the DPF systems. (b) shows soot filtration inside the DPF channels. Though various soot regeneration options for DPF have been demonstrated, the selection of options based on vehicle applications is significant.

Option one is to oxidise NO in the exhaust to NO2, which is then used to oxidise the carbon deposited inside the DPF channels; option two is to add catalyst to the vehicle fuel to regenerate soot at lower DPF inlet temperatures; and option three is to use the engine control system to adjust the inlet boundary conditions entering the DPF so that regeneration can occur [7, 8]. The fourth option is to inject diesel fuel upstream of a gas-phase burner [9] or an oxidation catalyst [10, 11], which burns the fuel and generates the temperature required to regenerate the DPF; e) the fifth option is to inject diesel fuel directly into the catalysed DPF [12].

Material	200/ 300/7 ACT Cordierite	200/ 12ACT 300/9/ 12 ACT Cordierite	300/12 ACT 300/9 ACT Aluminum-Titanate	Monolithic design w/ low CTE approx. 10^{-7}/°C Cordierite & Aluminum Titanate material
Bulk density	Low	Medium	High	
Pressure drop	Very low	Low	Low-Medium	
Soot mass limit	Low	Medium	High	
Filtration	Very high	High	High/Very high	
	Low regen requirement system	↔	Low regen requirement system	ACT: Asymmetric Cell Technology for High Ash Storage

Fig -1: DPF selection parameters

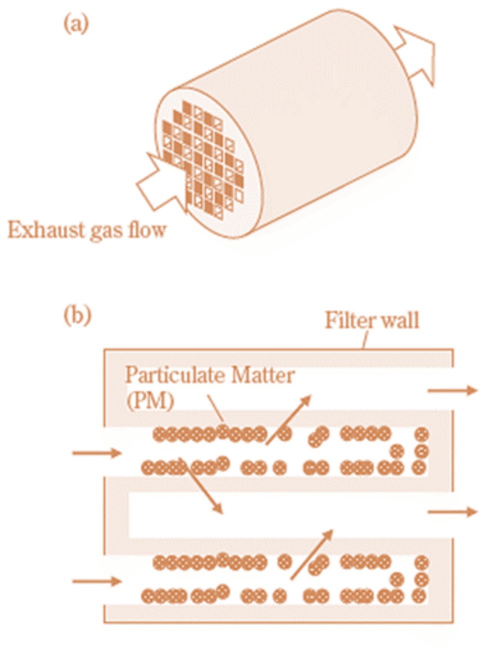

Fig -2: Schematic of the SiC DPF soot filtration

In the above-mentioned first two options for the "passive" regeneration, the engine's mass flow, temperature, and oxygen levels should be maintained consistently to meet the regeneration conditions of the DPF. Consequently, if the DPF inlet temperature gets lower or varies, then the soot will not react with incoming oxygen or NO_2, which will impact the regeneration process. Often these type of not meeting regeneration conditions scenario are frequently observed during low temperature operating duty cycles such as garbage pick-up vehicles and school buses applications. To mitigate the aforementioned scenario, active regeneration is the preferred option for soot regeneration, which was earlier described as option three. However, for the latter two options, the metered fuel is introduced in the exhaust stream, and this fuel gets combusted to raise the temperature of the DPF for soot regeneration. The fuel can be introduced into the exhaust stream either by late-cycle or post-cycle in-cylinder injection or by direct fuel injection into the exhaust stream.

Based on the fuel dosing, soot regeneration strategies are finalised by vehicle manufacturers.

Though the DPF is actively regenerating, the fuel or energy consumption rate is high for the DPF without a catalyst. Hence, an optimised solution like passive regeneration with active regeneration assistance at discrete intervals is required. This will control the amount of soot accumulated on the filter, prevent the incidence of uncontrolled regenerations on the DPF substrate, and avoid damage to the filter. One such system that combines passive regeneration with discrete active regeneration consists of a DOC followed by a catalysed DPF. This DOC is located before the catalysed DPF system and oxidises the fuel as well as generating NO_2. DOC also works as a filter by passively regenerating soot. There will be soot build-up in the DPF when the exhaust temperatures and engine NOx to PM ratios are not high enough. In such a scenario, the filter by injecting fuel upstream of the DOC is actively regenerated. An exothermic reaction across the DOC is produced when the atomized diesel fuel is injected at discrete intervals upstream of the DOC. This increases the exhaust temperature upstream of the DPF and ensures periodic O_2-based soot oxidation in the filter, in addition to normal NO_2-based regeneration. However, such a DPF system should meet two durability requirements, as follows: First is the lower DPF temperature during soot regeneration; this is to maintain the Pt catalyst migration into the downstream system. The maximum temperature inside the DPF is due to the inlet gas temperature due to hydrocarbon fuel oxidation over the diesel oxidation (DOC) system [13]. The second requirements are to have higher thermal resistance for DPF system during the abnormal regeneration event at maximum soot loaded condition.

In this paper, the SiC material durability validation for the maximum soot mass limit is discussed. Accordingly, the DPF material's thermal durability based on the below critical tests is discussed:

1. Soot mass accuracy estimation test; 2. World Harmonized Transient Cycle (WHTC) emission validation for more than 100 hours; 3. Drop to Idle (DTI); and 4. An accelerated DPF life test.

2. EXPERIMENTAL SET-UP

The schematic of the after-treatment used for this DPF durability validation is shown in Figure 3. In this after-treatment system schematic, two sub-systems (a. DOC, DPF, and b. hydrocarbon dozer) are mainly critical for durability validation. Further, this DPF durability validation was carried out for Indian driving conditions. Usually, to increase the DPF regeneration temperature, a calculated amount of fuel is periodically injected into the inlet of the DOC by means of a HC dozer. This injected HC fuel is oxidised further by the DOC system before reaching the DPF inlet. Accordingly, the exhaust gas from the engine is passed through the DOC, followed by the DPF, and then the SCR systems, before exiting into the atmosphere.

Fig -3: Schematic of the after-treatment system

2.1. Diesel Oxidation Catalyst (DOC) and Catalyzed Diesel Particulate Filter (C-DPF) System

For this study, the filter material is typically SiC with a cell density of >200 cells per square inch. It is an adequately sized system with an engine-to-DPF volume ratio of >1.5. Further, the DPF design has alternate channels blocked at each end, forcing exhaust to flow through the walls of the filter where gaseous components pass through the filter as well as the soot that is trapped. The C-DPF (catalysed-DPF) section is a honeycomb substrate coated with highly active precious group metals. The DOC substrate material used for this study is cordierite, with a cell density of 400 cells per square inch. The purpose of this DOC is to oxidise HC, the SOF portion of PM, CO, and also to generate NO_2 by oxidizing NO for passive soot regeneration. At temperatures favourable for NO_2 generation by both DOC and DPF, a portion of soot gets oxidised by NO_2. This is called passive regeneration. However, at low temperatures, NO_2-based soot oxidisation is not possible, and soot accumulates gradually on the filter. In addition, the DOC is also formulated to be highly effective in oxidising the fuel to increase the gas temperature favourable for active regeneration of the DPF. However, during repeated active regeneration conditions, the catalyst and DPF material are subjected to high thermal stress. Accordingly, durability validation for the DPF to withstand higher thermal gradients during extreme operating conditions is significant. If the ECU detects the amount of soot buildup on the filter is exceeding the specified limit or a specified time interval has elapsed, an active regeneration is triggered. This causes the soot on the filter to get oxidised in an O_2-rich environment at temperatures above 500 °C at the inlet to the C-DPF. The C-DPF sub-system also contains two temperature sensors and a pressure sensor. The temperature sensors monitor the upstream and downstream gas temperatures, and the pressure sensor monitors the pressure drop at the DOC inlet. Based on these monitoring conditions, the amount of soot collected in the filter is regenerated according to the regeneration strategies.

2.2. Hydrocarbon Dosing System

The ECU continuously monitors system backpressure upstream of the DOC and monitors temperatures both upstream and downstream of the DOC. The active regeneration kicks in when either (1) the time since the last regeneration exceeds the defined time interval between two regenerations or (2) the system backpressure levels indicate that the maximum allowable soot loading on the filter has been reached. Once the ECU detects a need for regeneration, it waits until temperature criteria are satisfied, when the exhaust temperature exceeds the light-off temperature of the DOC and the entire system is sufficiently warm. Based on reaching the target boundary conditions, it precisely calculates the amount of fuel to be delivered by the injection unit based on engine parameters, including exhaust flow and temperature. The pulse-width modulated fuel injector in the injection over the exhaust outlet pipe delivers this quantity of fuel to the dosing nozzle. To control the exothermic reaction, the DOC outlet temperature is monitored continuously by the ECU. The ECU also monitors various performance and safety-related parameters and, when necessary, sends alarm signals to alert the vehicle's driver. In addition, this ECU system also includes data logging functions.

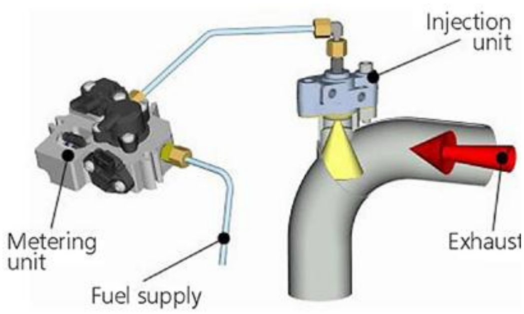

Fig -4: Hydrocarbon dozer system before DOC

2.3. Diesel particulate filter: soot loading condition

C-DPFs were pre-loaded with a target amount of soot before performing the burn-off test. Pre-loading of soot in the C-DPF is attained by operating the test engine at a predetermined duty cycle at high soot formation conditions for specific periods of time. During this soot loading duration, the active regeneration triggering condition is kept disabled to avoid soot regeneration during the soot pre-loading condition. To minimise passive regeneration, the exhaust gas temperature is also maintained below 250 °C before it enters the DOC catalyst. Accordingly, soot accumulation inside the DPF is controlled by altering the engine's operating time. After completing the soot loading duration, the filters were weighed before and after preloading to confirm the amount of soot loaded. To avoid measurement errors due to variations in moisture content, the DPF weight measurements are performed at average filter temperatures of 125 °C. For this testing, ultra-low sulphur diesel (ULSD) fuel is used. The sulphur content of the fuel used is 10 ppm.

3. RESULTS AND DISCUSSION

3.1. Soot estimation accuracy validation

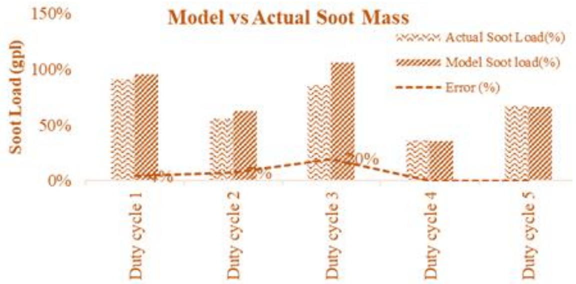

Fig -5: Soot estimation accuracy for various duty cycles

One of the significant portions of soot regeneration is calibration robustness. It is validated based on the DPF soot loading accuracy. The engine is operated on various vehicle duty cycles, taken from different field applications, and at the end of each duty cycle, the actual soot load is measured by weighing the diesel particulate filter (DPF) along with soot. The model-based and actual soot estimations are compared for each duty cycle. Figure 5 shows soot estimation accuracy for various duty cycles. The DPF accuracy is observed to be within ±20%. Accordingly, based on these variations, the conditions for the soot regeneration strategies are finalised and validation for further tests is carried out.

3.2. World Harmonized Transient Cycle (WHTC) validation (test cycle> 100hrs)

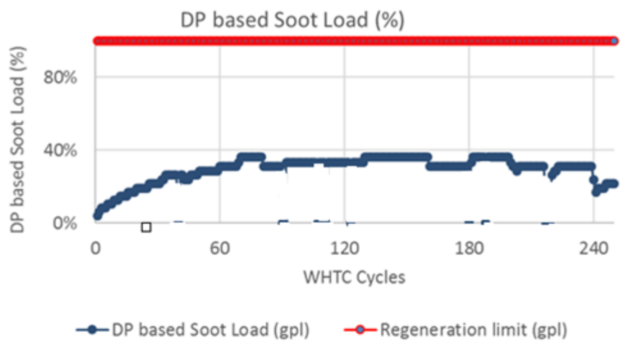

Fig -6: Delta pressure across DPF (DP) and soot estimation

The WHTC (World Harmonized Transient Cycle) test objective is to check the behavior of a DPF system in transient operating conditions for a long duration. This test confirms the soot regeneration interval. Figure 6 shows the delta pressure soot estimation for WHTC test cycle>100hrs. Based on soot accuracy control, the measured soot level is below 40%. Furthermore, passive regeneration of soot is accomplished most of the time due to the favourable catalyst temperature at the DPF inlet.

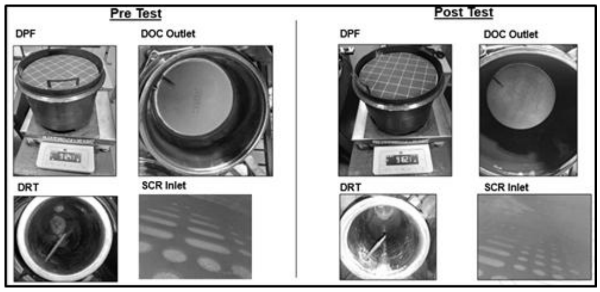

Fig -7: DOC, DPF faces before and after 100hrs of WHTC

Figure 7 shows no abnormal soot traces or deposits on DPF inlet faces after completing the WHTC test cycle. This shows that soot loading on the DPF is less, as well as that no abnormal thermal stress is observed on the DPF during regeneration intervals. This shows that calibration is robust for both soot accuracy and regeneration.

3.3. Drop to Idle (DTI)

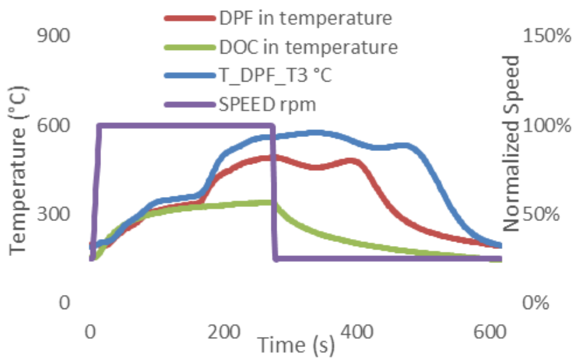

Fig -8: Drop to idle test

The drop-to-idle test is one of the most important tests conducted for DPF validation. Drop to idle is a phenomenon that occurs when the engine is running at maximum power with maximum soot mass and the vehicle stops suddenly. Then, the engine speed drops to idle, and the mass flow rate is reduced. In this scenario, the heat generated due to soot burning will not be carried away from the DPF and the local heating of the DPF will increase. Consequently, thermal shock develops, causes a rapid increase in DPF temperature, and creates thermal stress on the DPF. As a result, cracking can be initiated. However, the DPF material selection should be robust enough to withstand the thermal shock, and there should not be any cracks or any other failure during such a scenario. Hence, to validate the material's robustness, the DTI test is significant. For the selected DPF in this research, the acceptance criteria for the temperature gradient in the DPF is kept < 35°C/cm circumferentially, axially and radially.

Figure 8 shows DTI test, during this test maximum DPF in temperature is maintained less than 600 °C, and the temperature gradient during the test is 35 °C/cm. As result the thermal stress limit is accomplished within the specified limit of DPF material. This shows the DPF material and configuration selected for this vehicle application are robust. Furthermore, across the DPF, 50 (T1 to T50) channel thermocouples are instrumented to measure the temperature gradients. The T3 thermocouple has the highest gradient out of the 50 channels, and this is discussed in this paper.

3.4. Accelerated Life Test (ALT Cycle)

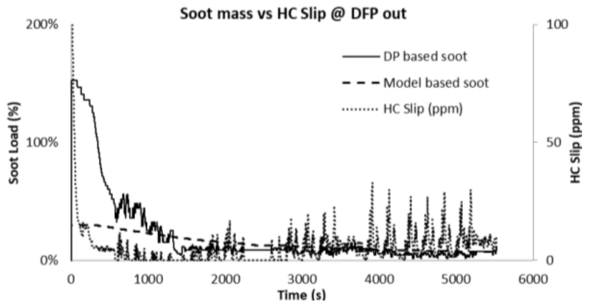

Fig -9.: Soot load % and HC slip during ALT regeneration test

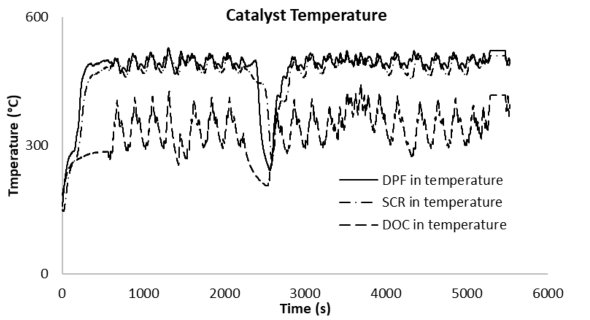

Fig -10.: DOC and DPF temperature during ALT regeneration test

An ALT cycle is a defined duty cycle that consolidates various vehicles' operating conditions to generate a worst-case vehicle operating condition. The accelerated life test is to study DPF durability. For this test, the DPF is loaded with more soot than the target level (soot percentage >100%) using a pre-defined operating soot loading cycle in the testbed. The catalyst temperature and hydrocarbon (HC) slip are measured at the DPF outlet during this test. The soot load percentage and HC slip during ALT regeneration test is shown in figure 9. DOC and DP temperature during ALT regeneration test is shown in figure 10.

Overall test results show the DPF operating conditions are within the allowable DPF out temperature limit (650 °C) during this ALT cycle, which proves the DPF's thermal durability. This temperature limit is pre-defined based on DPF material thermal stress. Typically, if the any abnormal spike in catalyst temperature (>1000 °C) or HC slip (>2500 ppm) above the pre-defined level then the failure of the DPF could be anticipated.

4. CONCLUSION

Therefore, for commercial vehicles, the diesel particulate filter is one of the most critical components of the after-treatment system because it filters out the soot particles from the exhaust gases. In this paper, the significance of DPF material durability and validation methodology based on various vehicle operating duty cycles are discussed. Furthermore, with the calibrated soot estimation accuracy condition of ±20%, the drop to idle test as well as the accelerated life test results show the robustness and durability of the DPF material. The test results show that for the SiC DPF material, the maximum DPF out temperature during soot regeneration during drop to idle conditions is less than 650 °C with a maximum hydrocarbon slip of less than 100 ppm. This could confirm there is no pt catalyst migration from the DPF. In addition, ALT test results also confirms DPF's exhaust temperature is within the specified operating conditions. Furthermore, with the same DPF, after completing WHTC testing for 100 hours the DPF is removed and checked for cracks. Visible face cracks on the DPF after DTI and WHTC testing are not observed. The results and finalised soot mass limit are robust enough to meet on-road vehicle durability with enhanced performance.

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