

Advanced Diesel Particulate Filter Technology for Cost Effective and Robust BSVI Solutions

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ABSTRACT

With Bharat Stage VI (BSVI) regulations on the horizon [3],[4] tighter particulate matter (PM) regulations will require the use of wall flow diesel particulate filters for on-road heavy duty (HD) diesel engines in India. The Indian HD vehicle market is very cost sensitive, especially with the majority of engine displacement being less than 7L [5] therefore, after treatment cost plays a significant role in design of the system. Robust wall flow diesel particulate filter solutions with the ability to deliver high filtration requirements required for particle number regulations can be designed in a cost-efficient manner. In this paper advanced design for diesel particulate filters with pressure drop, ash capacity, regeneration, and filtration performance are discussed. Corning's asymmetric cell technology (ACT) was created to improve ash capacity and reduce pressure drop and has the potential to downsize up to 45%. This performance aspect can also be attributed to the monolithic design of the ultra-low expansion cordierite material. Other material concepts with high expansion (like SiC) require segmentation for thermo-mechanical robustness and these are not as good for space utilization, despite the thinner walls of the filter. From a regeneration perspective the cordierite diesel particulate filter (DPF) material enables regeneration at lower inlet temperatures (15-20°C) and can regenerate more efficiently at the same DPF inlet temperature compared to the SiC DPF. Finally, sufficient robustness is demonstrated at soot load levels to deliver extended regeneration intervals.

Overall the Corning® DuraTrap® AC 300/9ACT Cordierite DPF solution is a very compact and cost effective solution for the Indian market for the future BSVI regulations.

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INTRODUCTION

Diesel particulate filters have been used for several decades in retrofit and select particulate emissions focused applications.

With the introduction of EPA 2007 regulations, DPFs became the standard choice of technology to meet emissions regulations for on-road vehicles in the US. These systems were implemented with a combination of active and passive regeneration, however, the lack of NOx reduction (DeNOx) after treatment resulted in a reduction of ranges for passive regeneration optimization. To comply with strict NOx emissions limits (0.2 g/bhp•hr) released by EPA in 2010[1], all systems implemented Selective Catalytic Reduction systems (SCR) for DeNOx. A similar after-treatment design was used for Euro VI regulations [2].

In the last few years, the Ministry of Road Transport and Highways in conjunction with the Central Pollution Board of India, introduced new air pollution regulations for on-road vehicles in Bharat Stage IV [3] & VI [4]. These were released to improve air quality. All new light duty, medium-duty, and heavy duty diesel engines would be subject to India's Bharat Stage IV regulations in all cities by April 2017. All new diesel engines manufactured after April of 2020 would be subject to Bharat Stage VI regulations. New guidelines were also

released for fuel quality to reduce the amount of sulfur content from 50 ppm sulfur to 10 ppm [6]. This is necessary to compliment the Euro VI like regulation, which involve after treatment architectures sensitive to sulfur content.

Bharat Stage IV regulations primarily allow low PM or low NOx regulations that would result in diesel oxidation catalysts (DOCs) followed by a partial flow filter (referred to as PF) or architectures for with selective catalytic reduction technology only. As the regulations get stricter from Bharat Stage IV to Bharat Stage VI (in April 2020), the architectures of after treatment systems need to evolve to those with advanced market designs. Most persistent in the industry is the architecture of DOCs followed by a wall flow diesel particulate filter (DPF) with a SCR and an ammonia slip catalyst (ASC). The DPF is a significant contributor on the pressure drop due to the soot and ash accumulation. It is imperative to optimize the DPF pressure drop for soot (organic portion of PM) storage, ash load, and ash cleaning intervals.

Ash is the non-combustible part of PM and occurs primarily from the additive components in lubricant oil, with secondary contributions from fuel (not including Biodiesel), coolant, engine wear, and debris over time from exhaust system components. Low ash oils and advanced engine technology can aid in lowering input rates of

lubricant derived ash in the exhaust, but over time ash is bound to accumulate in the DPF. Average life cycle of a heavy-duty engine in India designed for 5 years would be about 350,000 km - 450,000 km.

A review of current ash cleaning intervals for DPFs, recommended by various engine manufacturers in the US, indicate that most recommend ash service around 200,000 - 500,000 miles for on-road engines based on duty cycle. This equals approximately 50 - 70% of engine useful life. If the ash service intervals could be stretched another 40 - 60%, it would enable engine manufacturers to design in DPF systems that last beyond the emissions durability period or are fit for life. If we extend this to the Indian market for a useful life of 350,000 km it is possible to design for lifetime solutions with advanced DPF designs proposed in this study.

DPFs are also subject to thermal cycling due to controlled and uncontrolled regeneration events. Corning® DuraTrap® AC and AT DPFs with ACT cell geometry are designed to satisfy these requirements. The focus of this paper is to investigate life time pressure drop performance of the DuraTrap® AC and AT and also demonstrate robust thermal cycling performance to survive extreme regeneration conditions.

PRODUCT CONCEPT

Conventional wall flow DPFs used in early days have the same inlet and outlet channel sizes. However, this means that the inlet channels that capture soot and ash from the engine have the same open channel volume as that of the outlet channels. This leads to narrower paths for exhaust to flow through as the DPF accumulates soot equaling a smaller hydraulic diameter for inlet channels. This situation worsens with the accumulation of ash in the inlet channels. This is described in the ash study presented by Aravelli [13]. Figure 1 shows that accumulation of ash and soot in the inlet channels of a DPF with standard technology.

171mm(6.75") from inlet

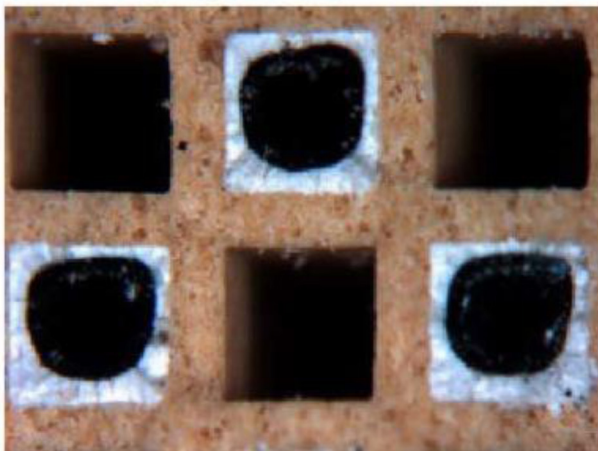


Figure 1. Picture portrays how soot and ash is accumulated in the inlet channels with standard cell technology design 12 x11 DPF. Picture taken from study from SAE Paper Aravelli,K. et Al 2007-01-0920.

To improve the ash holding capacity of a DPF and to lower its impact on pressure drop Corning pioneered an ash storage concept - ACT in heavy-duty applications. Today, more than 1.5 million DPFs with Corning ACT technology are deployed in the heavy-duty/non-road market.

To understand the difference the different contributors of pressure drop in a wall flow DPF needs to be studied. Pressure drop of wall flow is already studied in detail by several publications [7], [7], [9], [10], [11], [12]. Main contributions for pressure drop in a wall flow monolithic DPF are described below and also shown in Figure 2:

1. Contraction and expansion losses - occur when exhaust gases contract when entering a channel and expand while leaving the channels.
2. Channel frictional losses - occur when exhaust gas flows along the channel
3. Wall frictional losses - occur when exhaust gas flows through the wall of the DPF
4. Soot layer losses/ash layer losses - occur when the exhaust gas flows through a soot layer and an ash layer
5. Plug losses - occur due to existence of the DPF plugs.

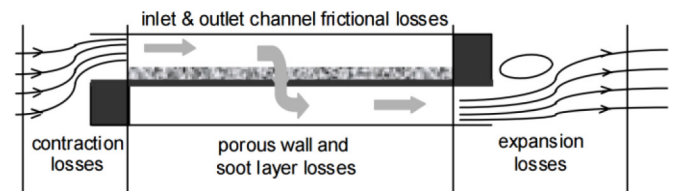


Figure 2. The schematic illustrates the different contributors for pressure drop in a wall-flow DPF [10].

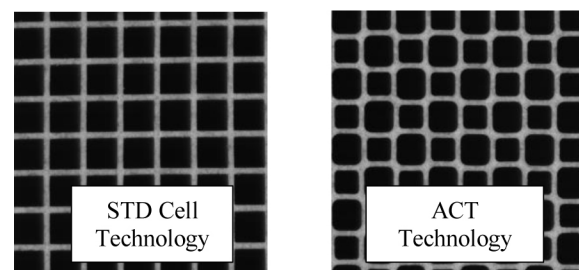


Figure 3. The pictures above illustrate the difference in cell geometry of Standard Cell Technology (STD) and Asymmetric Cell Technology (ACT) used in wall flow DPFs

To provide increased life time pressure drop, a reduction in frictional losses can be achieved by increasing the available hydraulic diameter of the inlet channels. ACT focuses on increasing the hydraulic diameter and filtration surface area (FSA) for the inlet channel and reducing that of the outlet channel. With soot and ash accumulating in the inlet channels, the effective hydraulic diameter is reduced resulting in higher channel velocities.

ACT is designed to mitigate this increase by increasing the hydraulic diameter of the inlet channels. This helps store soot and ash and while keeping the effective hydraulic diameter in good condition for lower pressure drop. Standard cell technology has been in use for the last decade for the North American heavy-duty market. However, ACT

has also been a part of this market since 2007 and has become more attractive as original equipment manufacturers look for improved lifetime pressure drop and to extend service intervals for DPF ash cleaning and to downsize after treatment devices.

To understand the impact of ACT let us consider the following example:

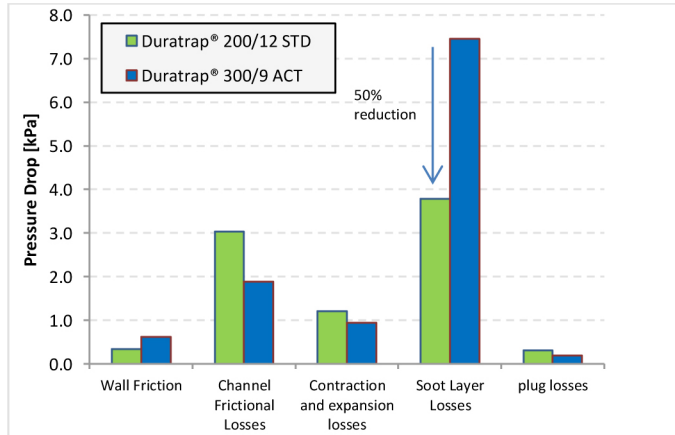


Figure 4. Graph depicts pressure drop contributions of different components to the standard cell technology (STD) & asymmetric cell technology (ACT) for 12" diameter and 7" length DPFs at 1900 kg/hr & 500°C obtained by modeling

The pressure drop comparison shown in Figure 4 depicts the differences between DuraTrap® 200/12 DPF (referred to as AC 200/12 in the remainder of text) and DuraTrap® 300/9 ACT DPF (referred to as AC 300/9 ACT in the remainder of the text). We can see that for the same size DPF, the pressure drop due to soot load is less for ACT by about 50%. This is due to 2 factors.

1. More filtration area for the same volume results in lower soot layer thickness, which in turn results in lower pressure drop. In this case the reduction is about 50% at 5g/L soot compared to standard technology.
2. ACT technology provides higher filtration surface area for the same volume of DPF as compared to that of a standard cell design. There is a slight increase in channel frictional losses which is proportional to the increase in filtration area and higher pressure drop for ACT technology. The contraction and expansion losses are also marginally higher compared to the STD cell technology. This is also dependent on the ACT ratio.

Therefore, it becomes important to design the DPFs with the optimum ACT ratio to minimize pressure drop at both soot loaded and clean conditions.

Table 1. Open Frontal Area Comparison of Corning® DuraTrap® 200/12 standard filters and Corning® DuraTrap® AC 300/9 ACT filters

	Corning® DuraTrap® AC 300/9 ACT	Corning® DuraTrap® AC 200/12 STD
Open Frontal Area – Inlet	45%	34%

PRODUCT PERFORMANCE

Pressure Drop Assessment - On Engine Comparison

Pressure drop assessment of the DPF matrix discussed in Table 1 of DPFs is evaluated on engine dynamometer setup. The engine used for this evaluation is described by the specifications as follows.

Table 2. Specifications of engine used for pressure drop and regeneration testing

Number of Cylinders	6
Cylinder Configuration	Inline
Model Year	2013
Displacement	6.7 Litre
Rated Power	240Hp@ 2400 rpm
Peak Torque	760Nm@ 1600 rpm

The engine testing procedure to obtain pressure drop behavior of the DPFs is described below:

1. The DPF is subjected to a deep clean procedure (above 650°C DPF Inlet temperature for about 30mins) to ensure that no soot remains.
2. The DPF is then subject to a pressure drop "sweep" procedure with increasing steps of mass exhaust flow with a constant temperature of 250°C
3. The DPF is then conditioned at a high speed and load point (C95).
4. The DPF is loaded with soot with accelerated soot loading to achieve the desired soot load.
5. The pressure drop sweeps are performed at the desired load steps to obtain a soot loaded response of the given DPF.

In this paper, we compare the following technologies:

Table 3. DPFs used for pressure drop, ash capacity comparison

	Dimensions	psi	Wall thickness
Duratrap® AC 300/9 ACT	Ø9"×7.25" Len	300	9mil
Duratrap® AC 300/9 ACT	Ø9"×5.5" Len	300	9mil
Duratrap® AC 200/12 STD	Ø9"×7.25" Len	200	12mil
SiC 300/7 Ash storage design	Ø9"×7.25" Len	300	7mil

All DPFs were coated with a typical precious group metal (PGM) based catalyst. The SiC filter was a commercially available DPF from a current US current medium-duty (MD) application. The design incorporated larger inlet channels and smaller outlet channels (high ash storage design). Due to a higher coefficient of thermal expansion the SiC DPF is segmented, whereas the DuraTrap® DPFs are monolithic for optimum volume utilization. The segmentation of the SiC DPF results in a reduction of 8% inlet volume and 15% filtration surface area per unit volume.