New Particulate Filter Concept for Gasoline Engines

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Introduction

Environmental protection and saving of resources have become a global challenge in recent years. With a share of 77% in 2004 CO_2 can be seen as the most important anthropogenic greenhouse gas. As the transportation sector highly contributes to CO_2 emissions [Ref. 1], CO_2 reduction and therefore further improvements on fuel economy is a key issue for the automobile industry. To establish general conditions the European Union will introduce a CO_2 limit from 2012 on and will reduce it further in 2020 [Ref. 2].

Gasoline vehicles have a big potential to reduce the fuel consumption and therefore CO_2 emissions. Engine concepts like Gasoline Direct Injection (GDI) are in focus and partially already adapted to current vehicles [Ref. 3].

The turbocharged GDI engine can be used effectively for downsizing while keeping the same driving performance. In addition a significant reduction in fuel consumption can be realized [Ref. 3]. But as a drawback the GDI engine raises the issue of Particulate Matter (PM) emissions.

The European legislation currently regulates Particulate Mass and will limit Particle Number (PN) for diesel engines from Euro 5b in 2011 as well. The PN regulation limit was set to 6.0×10^{11} #/km and a discussion to introduce a PN limit for gasoline engines for Euro 6 in 2014 is ongoing. As a result of this potential limitation, additional emission control devices for GDI engines may become necessary.

For reducing PM from a diesel engine, a Diesel Particulate Filter (DPF) is an established emission control device. It is expected that a Gasoline Particulate Filter (GPF) could be an effective device to reduce particle emissions from a gasoline engine as well. The objective of this study is to investigate new filter concepts for GDI applications and the impact on Filtration Efficiency, Pressure Drop, CO_2, Fuel Consumption and Soot Combustion performance.

Test Conditions

For this evaluation a Cordierite GPF with 48% porosity and a Mean Pore Size ≤15 µm was chosen. As a basis the standard cell structure 12/300 [mil/cpsi] was used. In order to optimize the filters for applying to GDI engines, 8/360 and 5/360 cell structures were added. Except the Soot Combustion test, only uncoated filters were evaluated.

For all tests a 1.4L GDI λ=1 vehicle was used. To see the impact of raw PN emissions a 1.8L GDI lean burn vehicle was included in addition. The serial exhaust layout of the 1.4L vehicle contained a Three-Way-Catalyst (TWC) in closed coupled (CC) position. For testing a GPF was installed in underfloor (UF) position.

As test cycle the NEDC consisting of four urban driving cycles (ECE-15) and one extra-urban driving cycle (EUDC) was used. Before testing a pre-conditioning of three EUDC followed by a soaking time of six hours was conducted. The pre-conditioning for compression-ignition vehicles was chosen, because this procedure is already mandatory for measuring PM [Ref. 6, 7]. PN emissions were measured according to the requirements of the PMP (Particulate Measurement Programme) protocol [Ref. 7].

Results

Filtration Efficiency: Effect of Raw PN Emission

To see the impact of raw PN emissions on tailpipe emissions and Filtration Efficiency, one GPF (12/300) was tested in two vehicles with different PN raw emissions at UF position. In general, PN Filtration Efficiency is defined as tailpipe PN emissions related to engine-out PN emissions.

By adding a GPF the PN was reduced more than 70% on both engines. The test showed that Filtration Efficiency decreases with lower raw emissions. A reason for higher Filtration Efficiency could be a faster PM accumulation in case of high engine out emissions. In addition it can be seen that even having lower Filtration Efficiency due to low engine raw PN emissions, the tailpipe PN emissions can be brought down to the same level because less PN has to be filtered by the GPF.

It can be concluded that installation of a GPF is effective to reduce PN under a wide range of PN engine raw emissions. In addition, the PN emissions were reduced below the Diesel Regulation limit of 6.0×10^{11} #/km in both tests.

Filtration Efficiency: Effect of GPF Volume (Impact of wall flow velocity)

In order to confirm the impact of GPF volume and cell structure on PN filtration performance two GPF with different cell structures (5/360, 12/300) were tested.

One main filtration mechanism is Brownian Diffusion which is linked to the flow velocity [Ref. 5]. As the wall flow velocity change by different filter volumes, the correlation of filter volume, corresponding wall flow velocity and Filtration Efficiency was investigated. The filter with 12/300 cell structure and 1.0L filter volume was set as the basis for the relative wall flow velocity.

The testing showed an effect of wall flow velocity on Filtration Efficiency. In addition the sensitivity of the wall flow velocity on the Filtration Efficiency varied according to different cell structures. Considering the 12/300 cell structure the 2.5L GPF had approximately 4% higher Filtration Efficiency than the 1.0L GPF. At the same time the relative wall flow velocity decreased by 60% caused by the larger volume. The same trend could be observed with the 5/360 cell structure. Nevertheless the impact of the wall gas flow velocity on Filtration Efficiency was three times higher compared to the 12/300 GPF. When the flow velocity was reduced by 50%, the PN Filtration Efficiency was increased from 83.5% to 87.5% with 12/300, but it was increased from 62.5% to 75% with 5/360.

Originally it was assumed that smaller filter volumes support Filtration Efficiency due to a higher PM accumulation per specific area but the results showed the opposite. As GDI engines have too less PM emissions the filtration by PM accumulation (soot cake) has less influence and the main factor is wall flow velocity. Based on the results a slower wall flow velocity and therefore greater GPF volume to improve the filtration is preferred.

Effect of Pressure Drop on Fuel Consumption

The backpressure of the emission control system affects fuel consumption and therefore CO_2 emissions. As the GPF is an important component of the emission control system, optimizing the GPF in regards to Pressure Drop highly contributes to decrease the total system backpressure.

For diesel engines with high PM emissions the filter development mainly focuses on the Pressure Drop performance with PM loading. On the contrary, GDI engines emit less PM. Therefore the Pressure Drop performance without PM accumulation (initial Pressure Drop) is in focus. The initial Pressure Drop is greatly affected by gas constriction at the inlet side and gas flow expansion at the outlet side. To reduce initial Pressure Drop due to gas constriction and the expansion the open frontal area (OFA) of the GPF has to be increased [Ref. 4]. The related design parameters are wall thickness and cell density. To investigate the impact of these parameters on Pressure Drop and fuel consumption, three different GPF were evaluated (12/300, 8/360, 5/360).

The tests showed, that a change from 12/300 to 5/360 reduces the Pressure Drop during NEDC by 40%. Nevertheless the impact on fuel consumption during NEDC was not significant and only within measurement variation.

Soot Combustion

Even GDI engines emit low amounts of particle mass, it is necessary to investigate the potential for soot combustion without active regeneration.

Before the evaluation 1.4 g soot was accumulated in the GPF and the soot amount was weight before and after testing. Only for this evaluation coated samples were used in CC position. It is expected that due to the high temperatures at the last hill of the EUDC and the increase of Oxygen due to the fuel cut during deceleration a regeneration of soot is occurring.

The test confirmed this theory as all of the accumulated soot was regenerated during the testing. The GPF temperature raised up to 900 degC even the GPF inlet gas temperature decreased. Based on these data it can be expected that soot regeneration occurs already during NEDC.

Off-Cycle-Tests

All previous tests were conducted with the NEDC as the official EU certification cycle. The filtration performance of a ceramic wall flow filter was evaluated during off-cycle conditions as well. In addition the impact of a GPF on fuel consumption and CO_2 was determined.

To cover various engine conditions and to test in a repeatable way, the ADAC and the Artemis Cycle were chosen to complete typical driving profiles. The ADAC Cycle comprises a highway profile with full load accelerations and decelerations between 80 and 130 km/h. The Artemis Cycle is a highly transient cycle containing phases for City-, Extra-Urban- and Highway-driving up to 160 km/h.

For all evaluations a GPF with 5/360 cell structure was used.

Off-Cycle-Test: Particle Number Emissions

To ensure comparable and repeatable results, all evaluations were done with the same GPF and the same measurement protocol.

The results showed that the GPF could reduce PN emissions significantly during all three tested cycles. Therefore it can be stated that a GPF can reduce particles during a wide engine mapping area. Furthermore, all tailpipe emissions were well below the Diesel Regulation limit of 6.0×10^{11} #/km.

Off-Cycle Test: CO_2 and Fuel Consumption

The results showed no significant difference in CO_2 and fuel consumption not only during NEDC, but also during ADAC and Artemis Cycle. It can be stated that the installation of a GPF is CO_2 neutral based on these testing conditions.

Conclusion

Particle Number

- √ Potential EU6 PN Regulation Limit could be met by GPF
  - independent of PN Raw Emissions
  - over a wide Engine Mapping (NEDC, ADAC & Artemis Cycle)
- √ Larger GPF Volume shows higher Filtration Efficiency
- √ Thin Wall GPF shows a high Increase of Filtration Efficiency by Reduction of Wall Flow Velocity

CO_2 and Fuel Consumption

- √ 5 mil / 360 cpsi Thin Wall Filter reduces Pressure Drop by 40%
- √ No significant difference in CO2 and Fuel Consumption was observed during NEDC, ADAC & Artemis Cycle by GPF Installation

References

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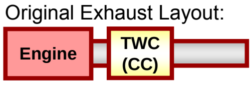
Definition

Background: Engine Technology
Due to the Global Warming CO_2 reduction is in main focus. Gasoline Direct Injection (GDI) Engines cope with this requirement, but have the drawback of increased Particle Number (PN) Raw Emissions.

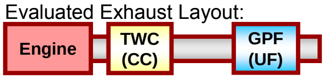
Background: Regulation
The European Commission introduced a PN limit of 6E+11/km for Diesel Vehicles for Euro 5b and 6. The introduction of a PN Regulation for Gasoline Vehicles for Euro 6 is currently under discussion.

Objective of this study:
As ceramic Wall Flow Filters are well introduced for Diesel engines, it is expected to be effective for gasoline particle reduction as well. The objective of this study is to investigate new filter concepts for GDI applications and the impact on Filtration Efficiency, Pressure Drop, CO_2, Fuel Consumption and regeneration performance.

Test Vehicle:
1.4L GDI, λ=1
Original Exhaust Layout:



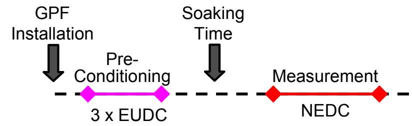
Evaluated Exhaust Layout:



GPF Properties:
Cordierite Material
Porosity: 48%
Mean Pore Size: ≤15 μm
Cell Structures [mil/cpsi]:
12/300, 8/360, 5/360
uncoated

Test Procedure:

[Changes of Test Conditions are mentioned separately]

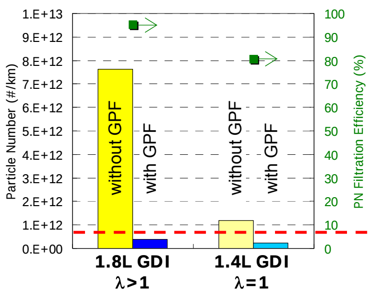


GPF is treated by Electrical Furnace before installation.

Measurement System:
Following PMP Protocol

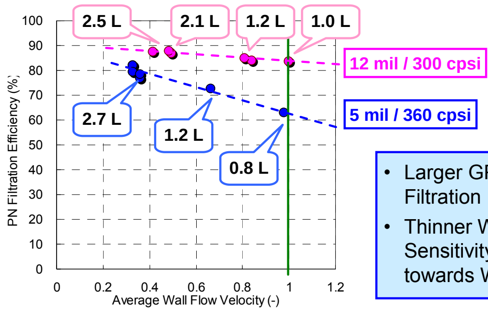
Results

Filtration Efficiency: Effect of Raw PN Emission



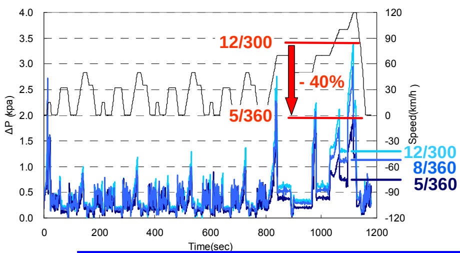
- Higher PN Raw Emissions cause higher Filtration Efficiency
- Independent of the Raw Emissions, PN can be reduced below the EU6 PN Regulation for Diesel Vehicles

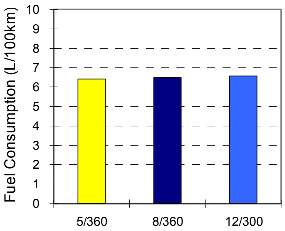
Filtration Efficiency: Effect of GPF Volume



- Larger GPF Volume shows higher Filtration Efficiency
- Thinner Wall GPF shows higher Sensitivity of Filtration Efficiency towards Wall Flow Velocity

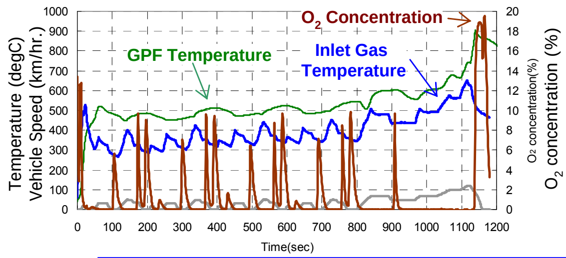
Effect of Pressure Drop on Fuel Consumption





5/360 has approx. 40% lower Pressure Drop than 12/300 during NEDC but the difference of fuel consumption is not significant.

Soot Combustion



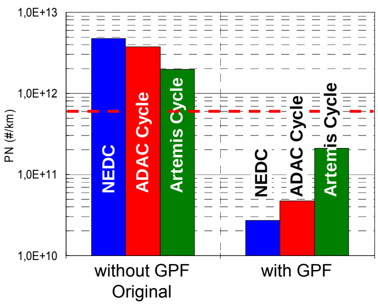
Layout:
Coated GPF at **Closed Coupled Position (CC)**

GPF Soot Loading:

Before NEDC (g)
1.4
After NEDC (g)
0

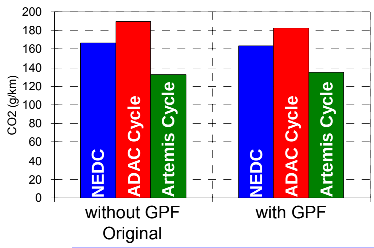
Soot Combustion can be expected during EUDC.

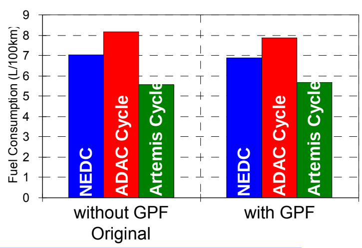
Off-Cycle Test: Particle Number Emissions



- A GPF can significantly reduce PN during NEDC, ADAC cycle and Artemis Cycle
- PN can be reduced over a wide engine mapping by GPF below the EU6 PN Regulation for Diesel Vehicles

Off-Cycle Test: CO_2 and Fuel Consumption





No significant difference in CO2 emissions and fuel consumption was observed during NEDC, ADAC cycle and Artemis Cycle.

Conclusion

Particle Number

√ Potential EU6 PN Regulation Limit could be met by GPF
- independent of PN Raw Emissions
- over a wide Engine Mapping (NEDC, ADAC & Artemis Cycle)

√ Larger GPF Volume shows higher Filtration Efficiency
√ Thin Wall GPF shows a high Increase of Filtration Efficiency by Reduction of Wall Flow Velocity

CO_2 and Fuel Consumption

√ 5 mil / 360 cpsi Thin Wall Filter reduces Pressure Drop by 40%
√ No significant difference in CO2 and Fuel Consumption was observed during NEDC, ADAC & Artemis Cycle by GPF Installation

GPF: Gasoline Particulate Filter

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