



## GASOLINE PARTICULATE FILTER (GPF)

How can the GPF cut emissions of ultrafine particles from gasoline engines?

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#### Sasoline Direct Injection (GDI) engine and particles emissions

Over the last years, the Gasoline Direct Injection (GDI) technology has been boosted as a result of EU climate policy and regulatory drivers towards reducing CO<sub>2</sub> emissions from passenger cars. 40% of new non-diesel passenger car registrations in the EU were GDIs in 2015 as indicated by the International Council on Clean Transportation (ICCT) [Fig. 1]. The CO<sub>2</sub> legislation promotes fuel-efficient GDI vehicles in the EU but particles emitted by GDI vehicles have been reported higher than the Euro 6c limit of  $6 \times 10^{11}$  #/km, especially under real driving conditions [Fig. 2].





Figure 1: Share of GDI registrations in new non-diesel passenger car in the EU, ICCT pocketbook 2016/17

Figure 2: PMP Inter-Laboratory Correlation Exercise Final Report

Gasoline Particulate Filters (GPF) have been developed and offer an effective route to reduce the number of ultrafine particles under all driving conditions [Fig. 3].



Figure 3: AECC Member data on GDI PN on RTS95 and RDE test, without and with GPF

#### S Gasoline particles' morphology and composition

Diesel and petrol particle morphology are similar. Scanning electron micrograph of traditional diesel exhaust particulate matter show 80-100 nm (median) aggregate of primary particles of <10 nm diameter [Fig. 4]. Transmission electron micrograph of GDI particulates shows nanoparticle aggregates with fractal-like morphology similar to diesel



soot, but the average primary particle diameter per aggregate had a much wider range that spanned from 7 to 60 nm [Fig. 5].



Figure 4: diesel exhaust particulates, Tschoeke and Mollenhauer (2010)



Figure 5: GDI exhaust particulates, Barone, et al. (2012)

Regarding Elemental and Organic Carbon in particulates from GDI vehicles, the California Air Resources Board (CARB) commented that total carbon is highest for phase 1 of the FTP test cycle, and 70-90% of that total carbon is elemental carbon. For phases 2 and 3 of FTP, total carbon decreases substantially, and 50-80% of the total carbon is organic carbon [Fig. 6]. Gasoline engines particle size distribution has been described by CARB. Particles from LEV II Port-Fuel Injection (PFI) vehicles are generally smaller in size with particle sizes less than 30 nm during engine cold-start, in the FTP cycle. Particles from GDI vehicles are usually larger in size; mean particle diameters at peak concentration are 70-80 nm, and range from 50 to 90 nm during phase 1 of engine cold-start [Fig. 7].



9 300E+05 9 300E+05 8 00E+05 8 00E+05 9 00E+05 1 00

Figure 6: Particulate Emissions from California LEV II Certified Gasoline Direct Injection Vehicles; CARB, 20<sup>th</sup> CRC On-Road Vehicle Emissions Workshop, San Diego, March 2010

#### OFF trapping mechanism

Figure 7: Particulate Emissions from California LEV II Certified Gasoline Direct Injection Vehicles; CARB, 20<sup>th</sup> CRC On-Road Vehicle Emissions Workshop, San Diego, March 2010

For GPFs, like for wall-flow Diesel Particulate Filters, there are three particulate trapping mechanisms: interception, impaction, and diffusion. The trapping mechanisms depend on the particle size. The smaller particles are trapped by diffusion, the larger particles are trapped by interception and impaction. As a consequence, the initial filtration efficiency of the new GPF varies for different particle sizes. The smaller and bigger particles are all trapped; the lower filtration efficiency is observed for particles of around 200 nm in diameter [Fig. 8].



Figure 8: Trapping mechanisms as a function of particle size, Aerosol Technology, William C. Hinds



#### ODI exhaust characteristics for GPF

Gasoline engines emit lower masses of soot than diesels under typical driving conditions. Therefore less frequent regenerations are required and this allows lower thermal mass wall-flow filters than DPFs. Also GPF systems operate at higher temperatures than DPFs which entails that passive soot regeneration occurs more readily; this improves the scope for three-way catalyst conversion activity. Particulate Matter (PM) will accumulate less on the filter under gasoline exhaust conditions than in diesel; low pressure loss and high filtration efficiency are thus required already without PM. Higher porosity filters allow higher washcoat loadings for three-way catalyst coated GPF. The coating also contributes to increase filtration efficiency. GPF design requirements can be summarized as follows:



#### Possible exhaust system architectures

There are a number of possible system architectures [Fig. 9] in which elements may be close-coupled or underfloor.



Figure 9: Possible system architectures

#### Back-pressure and filtration efficiency considerations

The requirement for low  $\Delta P$  (to minimise effect on fuel efficiency) has to be considered in relation to the filtration efficiency required for the application. Key factors are the Open Frontal Area, wall thickness, cell density, pore size and porosity, and length/diameter ratio. Because of the lower amount of PM as described above, the pore size of a GPF must be optimised for sufficiently high filtration without a soot cake. The resulting filtration efficiency depends on the flow rate.

The PN filtration efficiency of a 65% material porosity GPF varies as a function of wall thickness and to some extent also as a function of cell density [Fig. 10].





Figure 10: PN filtration efficiency as a function of wall thickness and cell density, SAE 2015-01-1073

The optimization of the GPF length / diameter ratio with increasing the cross sectional area significantly reduces the pressure drop [Fig. 11]. The filtration efficiency of the GPF will also depend on the GPF volume itself. Due to lower space velocity, bigger GPF shows benefit in PN filtration efficiency [Fig. 12].



Figure 11: Reducing back-pressure by optimizing the GPF length/diameter ratio

Figure 12: PN filtration efficiency as a function of GPF volume, NGK, SIA Powertrain 2017

#### • GPF filtration efficiency in different driving conditions

The filtration efficiency of the GPF varies depending on the drive cycle [Fig. 13]. Lower filtration efficiency can be encountered on the NEDC due to low engine-out PN but also on the very dynamic RTS-95 cycle when it is most likely due to the absence of a soot cake.



Figure 13: PN filtration efficiency of a retrofitted GPF tested on various cycles and on the road (RDE trip), 'Performance of advanced Gasoline Particulate Filter Material for Real Driving Conditions', SIA Powertrain Conference, 2017.

Interestingly, the RTS95 cycle is actually outside of RDE v\*apos boundary conditions [Fig. 14] and therefore too aggressive to represent normal driving conditions under RDE legislation.





Figure 14: Comparison of test cycles and RDE dynamic boundary conditions

#### Coated GPF

Coating the GPF with the three-way catalyst (TWC) allows some substitution of the TWC volume. It reduces packaging space and cost. However, many Euro 6 systems are expected to be twin-substrate for On-Board Diagnostics (OBD) requirements. There is thus some potential to optimise the Platinum Group Metal (PGM) usage.

Specific requirements for coated GPFs include higher porosity substrate material because of the pressure drop increase due to coating [Fig. 15]. Also, higher porosity filters enable higher wash-coat loading [Fig. 16].





Low porosity filter

-High porosity filter

Figure 15: Coating impact on back-pressure of GPFs of various porosities, SAE 2015-01-1073

Figure 16: Coating impact on back-pressure for low and high porosity filters

With a coated GPF, there is potential for OBD diagnosis of thermal events using  $\lambda$  sensors.

#### • GPF regeneration

The exhaust temperature and engine combustion stoichiometry affect the soot combustion in the GPF. At stoichiometric conditions, the GPF core temperature which ignites soot is 650°C but with a leaner mixture (higher oxygen content), the pressure drop reduction is quicker and the GPF core temperature which ignites soot drops to 500°C [Fig. 17]. Coating the GPF can also enhances soot regeneration.



Figure 17: Soot combustion profile at stoichiometric (left) and in lean (right) conditions, SAE 2015-01-1073



#### OF durability

Several publications have demonstrated that the GPF is a durable technology. GPF allows to control PN well below the regulatory limit, and filtration efficiency actually increases over the lifetime of the GPF as ash builds up. No impact on CO<sub>2</sub> is measured when the GPF is optimized for the vehicle.

This is demonstrated below [Fig. 18], where the vehicle and exhaust aftertreatment system travelled a distance of 160 000 km with a mixed drive pattern: 9% urban (within city limits up to 50 km/h), 10% extra-urban (outside city limits up to 100 km/h), 80% motorway (up to 220 km/h), and 1% transit (trips to and from the measurement labs including mileage gained on the chassis dyno).



Figure 18: Tailpipe PN (*left*) and CO<sub>2</sub> (*right*) emissions during NEDC, WLTC and Artemis160 with and without GPF measured at each milestone, 'Novel GPF Concepts with Integrated Catalyst for Low Backpressure and Low CO<sub>2</sub> Emissions', Aachen Colloquium (2014).

#### AECC GDI and GPF test programme results

AECC<sup>1</sup> has been evaluating a GDI car without and with a retrofitted GPF. With the GPF, PN emissions stayed below the Euro 6c limit on regulatory cycles NEDC and WLTP. This was not the case without the GPF when the vehicle was operated with market fuels instead of reference fuel [Fig. 19].



Figure 19: PN emissions of GDI car without and with GPF tested on regulatory cycles

When the car was driven on the road, PN results with the GPF were well below the Euro 6d Not-To-Exceed limit (Conformity Factor of 1.5) both for the total RDE trip and for the urban part [Fig. 20]. Again, no CO<sub>2</sub> penalty was measured.





Figure 20: PN emissions of GDI car without and with GPF tested on the road

Even when the car was driven on a severitzed RDE trip, close to the RDE boundary conditions on dynamicity and at low ambient temperature, PN emissions were still controlled below the Euro 6d NTE limit. This was not the case for the car without GPF which exceeded the NTE limit in severitized RDE test conditions [Fig. 21].



Figure 21: PN emissions of a GDI car without and with GPF tested towards the boundary of RDE

#### Sub-23 nm particles

The current PMP regulatory procedure for measuring PN counts solid particles down to 23 nm. Some measurement methods are investigated for particles smaller than 23 nm. An AECC GDI test programme<sup>2</sup> included such measurements of sub-23 nm particles. The measurements were performed on the chassis dyno, with modified PMP instrument to count solid particles down to 7 nm.



In these tests, PN emissions on NEDC, WLTC and severitized RDE tests at 23°C showed a linear relation between >23 nm PN and >7 nm PN [Fig. 22]. All GPF tests had PN emissions below 6x10<sup>11</sup>/km even with sub-23 nm particles included, with the measurement method used. Only two non-GPF tests met the 6x10<sup>11</sup>/km PN when considering only >23 nm particles. No non-GPF tests was below this Euro 6c level when sub-23 nm particles were included.



Figure 22: sub-23 nm PN emissions of a GDI car without and with GPF

The data collected during that test programme shows that for >23 nm, the GPF filtration efficiency range between 60 and 80% [Fig. 23]. With the modified PMP measurement method used, filtration efficiency increased up to 70-95% for >7 nm particles.



Figure 23: GPF efficiencies for >23 nm and for >7 nm particles on various severitized RDE (SRDE) tests run on a chassis dyno (L/M/H stands for low/medium/high load, 0/-7 for 0 and -7°C ambient temperature tests)

#### Oconclusion: GPF is an efficient and reliable technology

The Gasoline Particulate Filter is an efficient and durable technology to control ultrafine particles emissions from Gasoline Direct Injection engine without negative impact on fuel consumption and  $CO_2$  emissions. The filtration efficiency is not a design criteria for the GPF, the PN Not-To-Exceed limit is. The GPF filtration efficiency increases throughout its lifetime thanks to ash accumulation.

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2 Ricardo/AECC/Concawe 2016 GPF RDE PN Test Programme: PN measurement above and below 23 nm, 21<sup>st</sup> ETH conference (2017), <u>www.aecc.eu/wp-content/uploads/2017/06/170621-Ricardo-AECC-Concawe-ETH-conference-GPF-and-sub-23-nm-PN.pdf</u>.



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