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Platinum Group Metal and Washcoat Chemistry Effects on Coated Gasoline Particulate Filter Design

Development of gasoline particulate filters to meet Euro 6c

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Gasoline particulate filters (GPFs) are being developed to enable compliance with future particulate number (PN) limits for passenger cars equipped with gasoline direct injection (GDI) engines. A PN emissions limit of 6 × 10^{11} km^{-1} over the New European Drive Cycle (NEDC) will apply for new GDI vehicles from September 2017. (A three year derogation allowing a higher PN limit of 6 × 10^{12} km^{-1} is currently in force.) Real-world Driving Emissions (RDE) legislation is being finalised by the European Commission, which is expected to impose additional restrictions on particle number emissions in typical driving conditions. Legislation proposed for Beijing, China, (commonly known as Beijing 6) is also expected to set a limit on PN emissions from GDI vehicles.

This paper, based on a presentation given to the Society of Automotive Engineers (SAE) Light Duty Emissions Symposium in Detroit, USA, in December 2014, discusses the results from Johnson Matthey test programmes to understand the effects of different driving conditions on engine out PN emissions, the benefits obtained from applying a platinum group metal (pgm)-containing coating onto a GPF and the impact of such a coating on soot combustion properties.

Effect of Driving Conditions on Particle Number Emissions

Almost all GDI vehicles can meet the current 6 × 10^{12} km^{-1} PN target over the NEDC. It has been reported that a limit of 6 × 10^{11} km^{-1} can be achieved through engine design measures such as the use of high pressure fuel injectors, injection and combustion timing and careful design of spray patterns and piston heads to improve mixture formation and to avoid wall wetting (1–3). However, the NEDC is characterised as having moderate acceleration and deceleration rates and extended cruises at constant speed, which are generally unrepresentative of typical real-world driving. Harder acceleration rates and more transient driving are observed to give higher PN emissions. For example a Euro 5 GDI vehicle equipped with a flow through three-way catalyst (TWC) system emitted 2.8 × 10^{12} particles km^{-1} over the NEDC. PN emissions from the same vehicle increased almost fourfold to 9.6 × 10^{12} km^{-1} when a transient drive cycle with harsh acceleration rates was used. Similarly, experiments on multiple GDI vehicles indicated 30–85% higher PN emissions from testing using the more transient US Federal Test Procedure (FTP)-75 drive cycle compared to NEDC data. Driver to driver variability has also been observed. Therefore, it is likely that real-world PN emissions from GDI vehicles are significantly higher than NEDC test data indicate.

Furthermore, ambient temperature has a significant effect on PN emissions. NEDC testing is conducted at a temperature of 23ºC, significantly above the average temperature in the UK and many other European countries. A Euro 6 GDI vehicle equipped with a flow through TWC system was measured to emit <4 × 10^{11} particles km^{-1} over the NEDC when tested at 23ºC (**Figure 1**). When the test car was cooled to 10ºC before the start of the test, PN emissions increased threefold to 1.1 × 10^{12} km^{-1}. Cooling the car to 0ºC before the start of the test doubled PN emissions again to 2.3 × 10^{12} km^{-1}. Therefore, even vehicles designed to give low PN emissions during the certified test at 23ºC are likely to emit significantly more in the ambient conditions many drivers experience daily.

Benefits of a Coated Gasoline Particulate Filter

GPFs have been shown to be very effective at attenuating PN emissions (4, 5). Cordierite wall flow filters are most commonly used in development programmes and at least one series application employing uncoated cordierite GPFs is on sale today. Adding an uncoated filter downstream of the existing aftertreatment system allows PN control without requiring significant changes to engine calibration or on-board diagnostic (OBD) strategies. However, the addition of an extra unit adds canning cost and the space required can be problematic on smaller vehicles. Applying a suitable TWC coating onto the GPF allows it to be substituted for flow through TWC volume in the existing aftertreatment system, resulting in a more compact architecture. Johnson Matthey and other coaters (6–8) have demonstrated such technologies previously.

However, expected RDE limits on nitrogen oxides (NOx) emissions will add further demands on the gasoline aftertreatment system. Many European exhaust systems have their catalyst volume and precious metal content optimised to meet current NEDC emissions targets. It is well known that conversion of NOx requires more catalyst volume than conversion of CO or hydrocarbons. NEDC-optimised catalyst systems may not provide sufficient NOx conversion activity under more demanding conditions with higher space velocities. Adding effective catalyst volume by applying a pgm-containing coating onto the GPF can increase the conversion of gaseous pollutants under such conditions. For example, a Euro 5 1.0 l GDI application was tested over the NEDC and World-Harmonised Light-Duty Test Cycle (WLTC) with uncoated or coated GPFs fitted downstream of the series TWC. With the uncoated filter system NOx emissions over the NEDC were 56 mg km^{-1}, increasing to 82 mg km^{-1} over the more transient WLTC for which the TWC was undersized. With a coated GPF NEDC emissions were ~10% lower than with the uncoated filter, at 50 mg km^{-1}. Furthermore, the coated GPF gave good control over the WLTC with emissions of 47 mg km^{-1}. The coated GPF is particularly effective in avoiding NOx slip during the higher speed, higher space velocity conditions experienced in the final 600 s of the WLTC (**Figure 2**).

The benefits of a coated GPF can be further enhanced by optimising the precious metal content of the coating. For example, **Figure 3** shows NOx emissions from testing of a TWC plus coated GPF system on a Euro 5 2.0 l GDI vehicle over the transient Artemis test cycle. Thrifting precious metal from the close-coupled TWC resulted in a *ca*. 20% increase in NOx emissions. However, increasing the rhodium loading on the

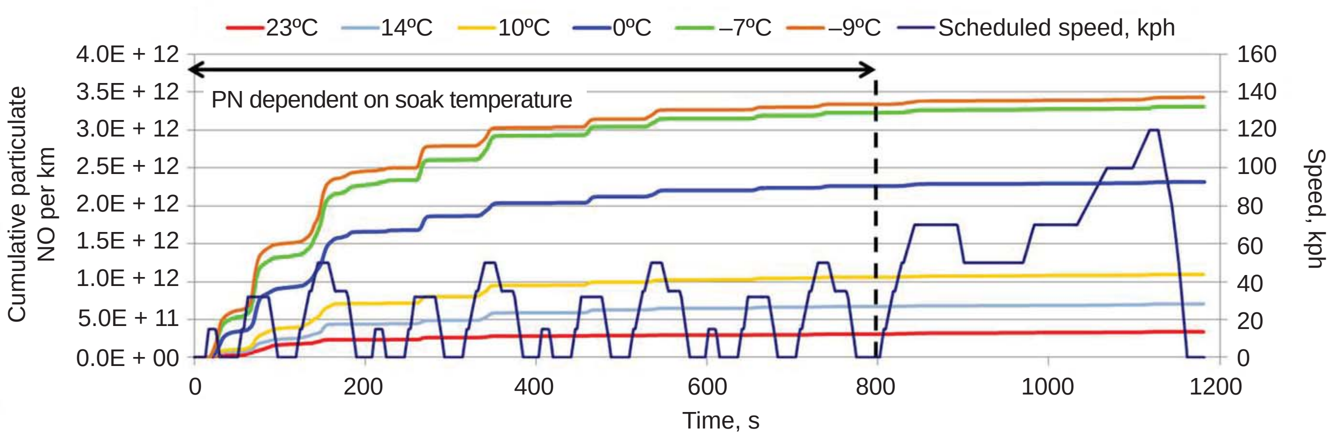

Fig. 1. Impact of vehicle soak temperature on PN emissions over the NEDC

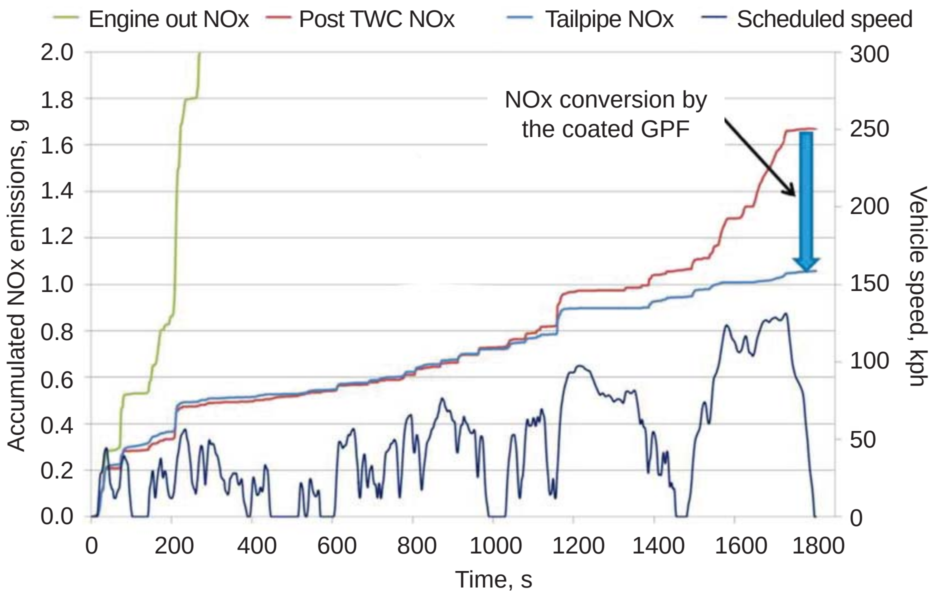

Fig. 2. Comparison of TWC plus coated or uncoated GPF over the WLTC

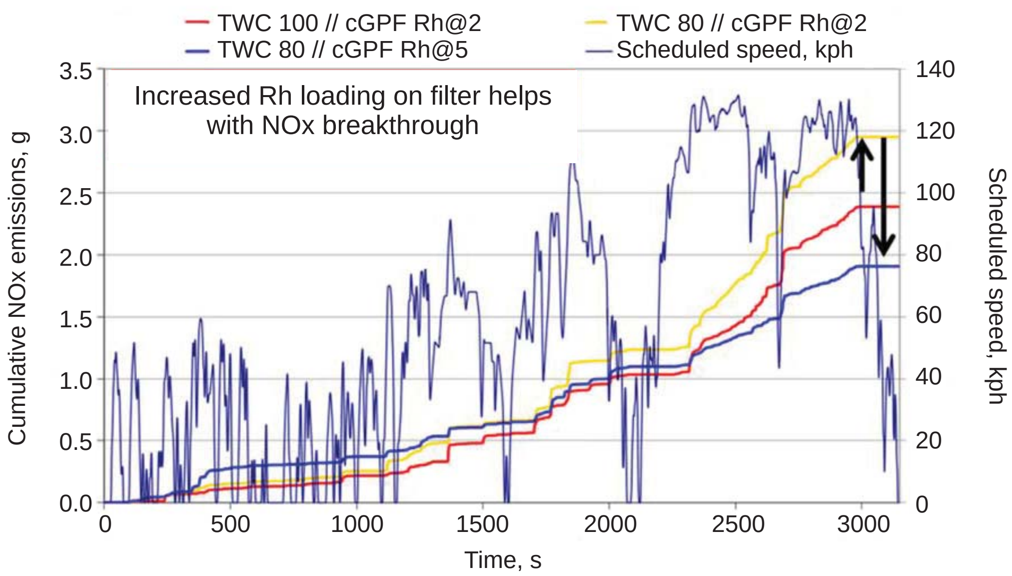

Fig. 3. Effect of GPF Rh loading in compensating for emissions breakthroughs from pgm thrifting of the upstream TWC

downstream coated GPF from 2 g ft^{-3} to 5 g ft^{-3} more than compensated for this effect, with significantly improved conversion at higher speeds.

Therefore, as well as controlling PN emissions, coated GPFs offer advantages over uncoated GPFs in conversion of gaseous pollutants for RDE and more transient drive cycles. Additional pgm and oxygen storage capacity (OSC) on the coated filter help to control emissions breakthroughs during harsh accelerations and high speed driving.

Soot Combustion

A concern about the use of uncoated GPFs, particularly when located in remote underfloor locations, is whether they will regularly reach sufficient temperatures to regenerate collected soot without the use of extreme engine operating conditions to artificially increase the filter temperature. It was hypothesised that the presence of an active coating on the GPF would enhance soot combustion. To investigate this soot-loaded coated and uncoated GPFs were fitted to a Euro 5 1.4 l GDI vehicle and tested over a cycle comprising the NEDC with the final, higher speed, Extra-Urban Drive Cycle (EUDC) repeated ten times. The final EUDC deceleration from 120 kph triggers a fuel cut-off and the resulting oxygen-rich environment can lead to soot combustion at suitable filter temperatures. Peak filter inlet temperatures during the NEDC were controlled to values between 520ºC and 650ºC by varying the dynamometer gradient from 0 to 3%. Soot combustion was monitored through measurement of pressure drop over the aftertreatment system and by weighing the filter before and after each test to measure the mass of soot removed.

In the uncoated filter only 50% of the soot was removed at a peak temperature of 600ºC, increasing to 90% at 650ºC (**Figure 4**). In contrast, soot combustion in the coated filter increased rapidly at temperatures above 550ºC, with complete removal of the soot at *ca.* 570ºC. Therefore, the presence of a pgm-containing TWC coating reduced soot combustion temperatures by approximately 100ºC, delivering significant benefits for vehicle strategies to control soot build up in a GPF. Detailed analysis of the differential pressure data showed that at 570ºC the backpressure reduced to a stable level after the first EUDC, indicating rapid promotion of soot combustion.

The chemistry of the TWC coating can also be optimised to enhance soot combustion properties. Powder reactor studies confirmed that the presence of pgm and ceria-containing OSC materials significantly reduce soot combustion temperatures and that the choice of OSC material can influence peak soot combustion temperatures by more than 50ºC.

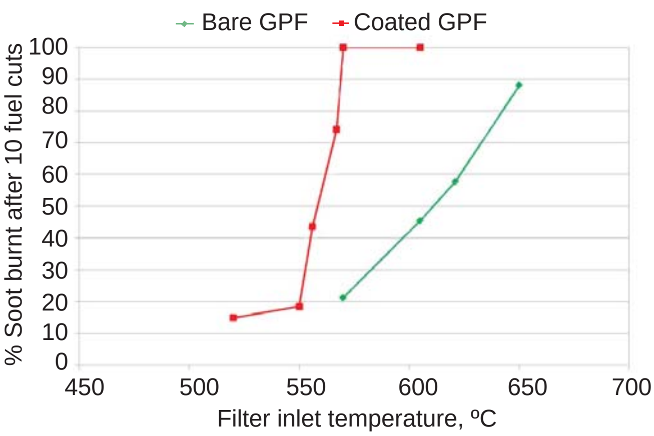

Fig. 4. Effect of a pgm-containing GPF coating on soot combustion under vehicle deceleration fuel cut-off conditions

Conclusions

Control of PN emissions from GDI engines is of increasing importance to meet Euro 6c and proposed RDE and Beijing 6 emissions standards and GPFs are effective in reducing tailpipe PN emissions. However, emissions of particulates and gaseous pollutants can be significantly higher in real-world conditions, with more transient driving, higher maximum speeds and lower ambient temperatures all shown to have a detrimental effect. Use of a pgm-containing coated GPF offers benefits over an uncoated GPF, including the abilities to control emissions breakthroughs from upstream TWC components, to enable regeneration of collected soot at lower temperatures and at a faster rate and to allow substitution for TWC volume for system compactness. These benefits can be enhanced through careful design of the washcoat chemistry and precious metal content.

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