

A Metal Fibrous Filter for Diesel Hybrid Vehicles

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ABSTRACT

Trends towards lower vehicle fuel consumption and smaller environmental impact will increase the share of Diesel hybrids and Diesel Range Extended Vehicles (REV). Because of the Diesel engine presence and the ever tightening soot particle emissions, these vehicles will still require soot particle emissions control systems. Ceramic wall-flow monoliths are currently the key players in the Diesel Particulate Filter (DPF) market, offering certain advantages compared to other DPF technologies such as the metal based DPFs. The latter had, in the past, issues with respect to filtration efficiency, available filtration area and, sometimes, their manufacturing cost, the latter factor making them less attractive for most of the conventional Diesel engine powered vehicles. Nevertheless, metal substrate DPFs may find a better position in vehicles like Diesel hybrids and REV in which high instant power consumption is readily offered enabling electrical filter regeneration. Electrical filter regeneration is more easily applied to metal filters as the filter substrate itself can act as the resistance heater element. In this work, a metallic substrate filter is presented. The filter was assessed with respect to its filtration efficiency, soot loading behavior under constant and transient engine conditions and its electrical regeneration performance. Its emissions control performance has been evaluated against future particle emission limits. The application of electrical filter regeneration revealed a significant advantage in fuel consumption associated with filter regeneration compared to conventional ceramic filters.

INTRODUCTION

Among hybrid vehicle powertrains, the Diesel hybrid offers advantages with respect to CO₂ emissions or fuel consumption and NO_x emissions due to cutting off peak loads by electrical boosting [1,2]. Figure 1 shows an example comparing the fuel consumption and NO_x-emissions of classical Direct Injection (DI) Diesel with a hybrid DI-Diesel powertrain both operated in a passenger car in the New European Driving Cycle (NEDC). In the urban part of the NEDC a start/stop strategy was applied. In Figure 1 it becomes obvious how the electric motor assists and thus lowers the torque to be provided by the internal combustion engine (ICE) at higher load requirements. Both measures together with a corresponding recuperation of deceleration energy give fuel consumption benefits of ~ 9% together with a NO_x reduction by ~ 15% in this specific example.

However, hybridization of the Diesel powertrain is not expected to make the Diesel Particulate Filter (DPF) obsolete in the future since engine operation at higher loads cannot be avoided especially if down-sizing is applied where the reduced engine displacement will lead to higher specific loads at full load operation. In addition to making more likely the necessity of DPF use for emissions homologation, the hybrid platform also poses certain restrictions on the suitable DPF management modalities. Particularly during start-stop operation - e.g. during the Urban Driving Cycle (UDC), the average exhaust gas temperature of Diesel hybrids will be lower due to partly electric operation of the powertrain.

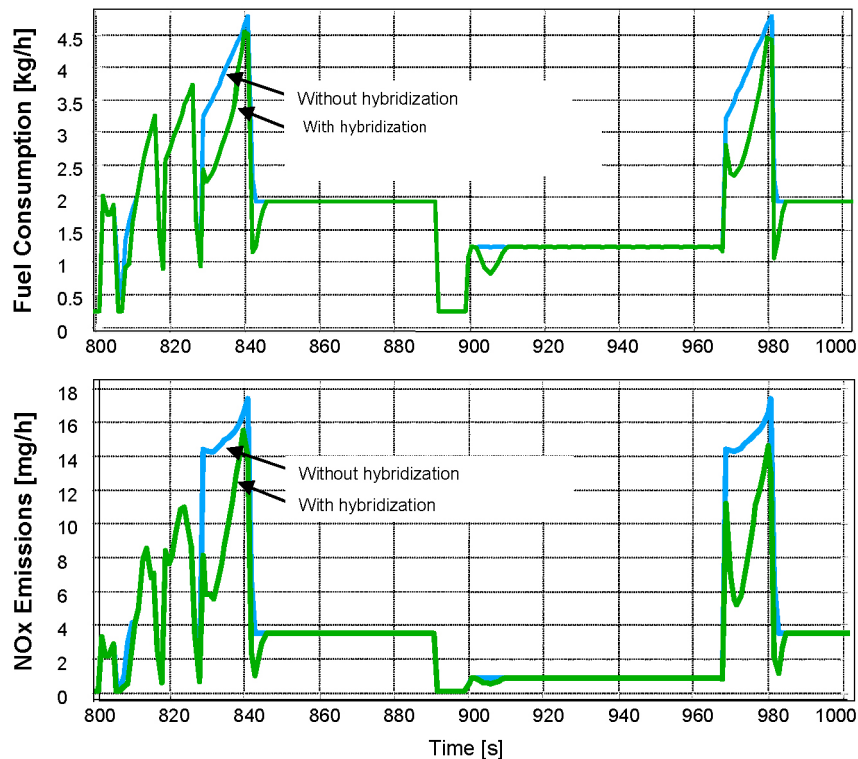


Figure 1. Fuel consumption and NOx emissions benefits of a hybrid drive train in the extra urban part of the NEDC.

Consequently, the average temperature of components such as the DPF can drop below levels which are needed for continuous filter regeneration (CRT). Hence, alternative strategies or technologies are needed to guarantee the proper performance of the particle filter system since fuel consumption will suffer if engine measures are employed to provide extra exhaust gas temperature for the after-treatment components. The injection of species which reduce the light-off temperature for the DPF regeneration, while having been widely applied [3,4,5], is generally not a problem-free practice. On the other hand, electrical filter regeneration is a strategy that matches very well with the Diesel-hybrid. Electrical heating as a means of filter regeneration offers significant advantages when the filter serves as the electrical heater itself, when it is applied at low exhaust flow conditions and when there is already sufficient availability of electrical power on-board. In hybrid applications, where there is no need for 100% of full-load ICE operation during vehicle driving, electrical heating can be applied during low load, idling or engine-off conditions, when electrical power is available and exhaust flow conditions also tend to be most favorable. Moreover, hybrid powertrains invariably host a high power on-board electrical network, enabling a straightforward integration of an electrically heated DPF system.

Porous materials made of high-temperature resistance metals, usually in the form of sintered metal particles or fibers, present an alternative to ceramics for constructing the DPF

wall. Metal filters, serving as electrical heaters themselves, are suitable for electrical filter regeneration with very good energy conversion efficiency. Electrical regeneration has also been utilized with other filter materials (such as silicon carbide) but with poor energy conversion efficiency [6,7] resulting mainly due to inefficient coupling of the heat source with the trapped soot. The first metal DPF designs have been presented since the 1990s [4,5,8]. These developments consisted of a wire mesh support, coated with sintered Fe-Cr-Ni metal particles. Further developments concerned a metal fiber medium, which is a non-woven, pleatable sheet with a felt-like microstructure made of sintered Fe-Cr-Al alloy metal fibers [9,10]. Another design considered bladed corrugated metal foils separated by porous sinter metal fleece layers resulting in a partial flow filter [11]. In general, metal filters have shown low exhaust-gas back pressure and high ash storage capacity while offering a high degree of flexibility in forming different DPF designs. On the other hand ceramic honeycomb filters demonstrate on average increased filtration efficiency compared to metal filters, higher available filtration area and often an advantage with respect to the manufacturing cost. However, when considering cost issues, one has to take into account that most metal filter concepts remain in the product development phase while ceramic honeycombs nowadays are mass produced.

This paper describes the study of a metallic fiber full-flow filter operated on the exhaust line of an experimental Diesel engine able to simulate different degrees of hybridization,

Table 1. Characteristics of the experimental AVL engine.

Engine configuration	L4 with 4V/Cyl
Displacement	1.91 L
Compression ratio	16 : 1
Swirl	Variable Swirl System (VSS via continuous port deactivation)
Charge system	Variable Nozzle Turbo (VNT)
EGR system	Low Pressure Exhaust Gas Recirculation (EGR) combined with High Pressure EGR
Fuel system	Solenoid Common Rail (CR) with 1600 bar maximum pressure, Nozzle flow = 360 ml/30s, number of nozzle holes = 7.
After treatment	Close Coupled (cc)-Oxidation catalyst + DPF in uf-position

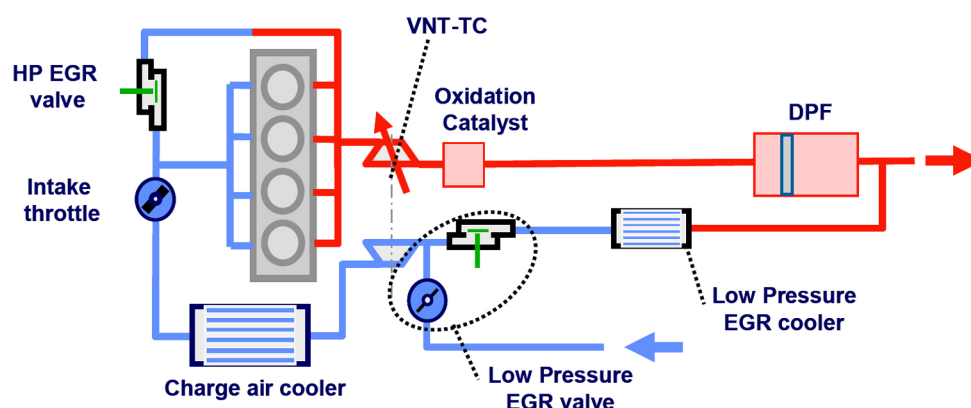


Figure 2. The AVL experimental engine.

from start/stop to full hybrid operation (Edrive). First, the experimental engine is described and the effect of different levels of hybridization is discussed with respect to the gaseous and particulate emissions as well as the CO₂ emissions and the fuel consumption over the NEDC. Second, the evaluation of the metal filter is presented with respect to pressure drop behavior, filtration efficiency and electrical regeneration performance. The latter study was performed over conventional Diesel engine operation and the filter evaluation results were extrapolated to the hybrid operation of the experimental Diesel engine to establish the potential advantage with respect to the fuel economy provided by the utilization of the metal filter and also whether the hybrid-Diesel vehicle equipped with such a filter could comply with Euro6 emissions limits.

THE EXPERIMENTAL ENGINE SETUP

BASE ENGINE CONFIGURATION

The experimental base engine used is a four cylinder turbocharged, intercooled, direct injection Diesel engine compliant with EU4 emission levels.. The specification of the engine is shown in [Table 1](#). The engine, described

schematically in [Figure 2](#), was operated on test bed facilities of AVL List GmbH. located in Graz, Austria.

The base engine combustion bowl is modified to achieve a geometric compression ratio of 16:1. The experimental engine is equipped with a VSS which deactivates one intake port continuously. A fixed swirl was simulated by fixing the duty cycle of the variable swirl actuator to a certain value within the whole emissions relevant operating area. For the engine Hardware (HW) simulation of a fixed geometry turbo charger, it was decided to stay with a variable nozzle turbine (VNT) Turbo Charger (TC) but to fix the duty cycle to a certain value within the emission relevant map area. In this way, the following three different engine HW complexity stages were simulated:

- variable Swirl and VNT-TC VAR - VAR
- fixed swirl actuator and VNT-TC FIX - VAR
- fixed swirl actuator and fixed duty cycle for VNT-TC FIX - FIX

For each of these engine HW configurations, individual ECU-datasets were created.

THE EGR SYSTEM

Based on the NO_x emission target values (Euro6: 80 mg/km), it was decided to use a combination of Low Pressure EGR (LP-EGR) and High Pressure EGR (HP-EGR). AVL experience has shown a potential for improvement of NO_x -Brake Specific Fuel Consumption, BSFC - Particulate Matter, PM trade-off for such a low pressure EGR concept. The air and exhaust system setup is shown schematically in Figure 2. In the map area at lower load, a combination of LP-EGR and HP-EGR is applied to keep the intake manifold temperature above a certain level. With increasing load the HP-EGR line is closed completely and only the LP-EGR route is used. The maximum cooling power of the low pressure EGR cooler is below 5kW and there is no cooler installed in the HP-EGR route. Additionally, a throttle valve in the exhaust line is used to guarantee sufficient EGR rates in light load operation.

THE ENGINE CONTROL SYSTEM

The engine uses the original Engine Control Unit (ECU) with two independent Proportional-Integral-Derivative (PID) controllers to control the EGR rate and intake manifold pressure. Additionally the AVL approach to cylinder pressure control was implemented. The system uses series production glow plug pressure sensors to measure the cylinder pressure. From the cylinder pressure signal, several combustion relevant parameters can be calculated: the start/center/end of combustion, the rate of cylinder pressure rise during combustion/compression and the maximum pressure. These values were used for control or monitoring. Demand values were set for the center of combustion value. The Start of Injection (SOI) is closed loop controlled in order to achieve the demanded values. The cylinder pressure combustion control is necessary in order to apply the fully and partly premixed low NO_x combustion concepts in stationary and transient operation.

SETUP OF THE TEST CYCLES

Four different hybridization strategies were used:

ICE

Internal combustion engine only (Reference)

S/S

Start/Stop Simulation

RECU

Recuperation and Peak Shaving (Including S/S)

Edrive

Electrical driving with recuperation, Peak shaving and S/S

The engine control strategies were implemented on a dynamic test bed set up for NEDC operation of a powertrain architecture shown in Figure 3.

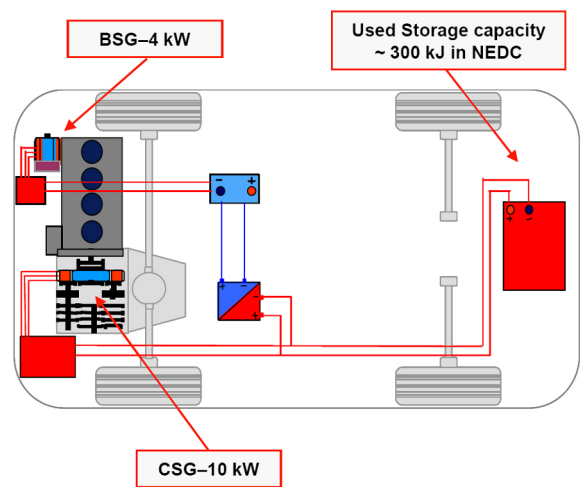


Figure 3. The hybrid architecture.

For the urban part (UDC) and the extra-urban part (EUDC) of the NEDC, engine speed and torque values were defined for the different levels of hybridization as shown in Figure 4 and Figure 5. The three different strategies of hybridization are described below:

ICE - Conventional Cycle Operation with Internal Combustion Engine Only

For baseline testing, the NEDC has been simulated with AVL-CRUISE to create appropriate demand values for engine speed and engine torque to be used on the dynamic test bed.

S/S - Start/Stop Simulation

A conventional start with the engine starter was simulated. Accordingly, emission peaks were expected to occur. Assuming a sophisticated alternator strategy the required electric energy for cranking etc. is available from motoring phases. However, some fuel is needed for starting and acceleration to idle condition.

RECU - Recuperation and Peak Shaving

Recuperation during the motoring phases is assumed to use this energy for peak shaving to improve especially NO_x emissions and CO_2 . In the NEDC, the energy storage device can be filled to its maximum capacity in the final phase of the cycle (electric storage capacity ~ 300 kJ in NEDC). An operating strategy was defined involving the use of electric power (max 10 kW - CSG) during the EUDC acceleration from 100 to 120 km/hr.

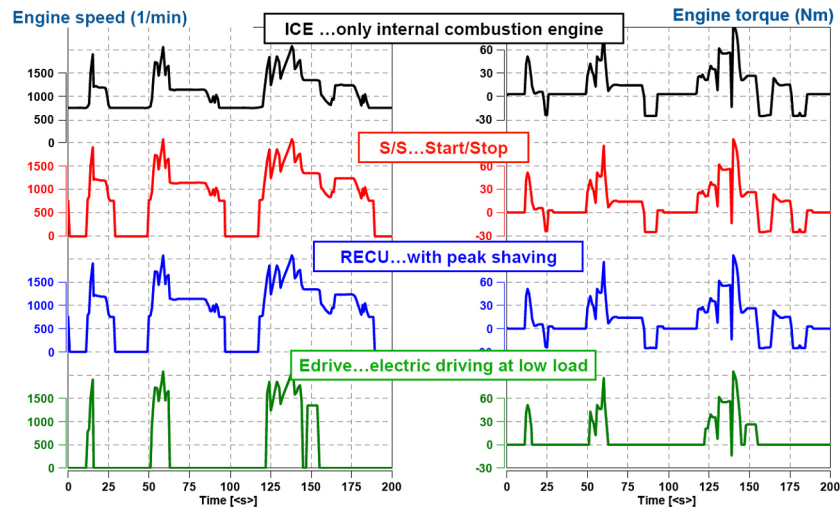


Figure 4. UDC engine speed and torque demand values for different levels of hybridization.

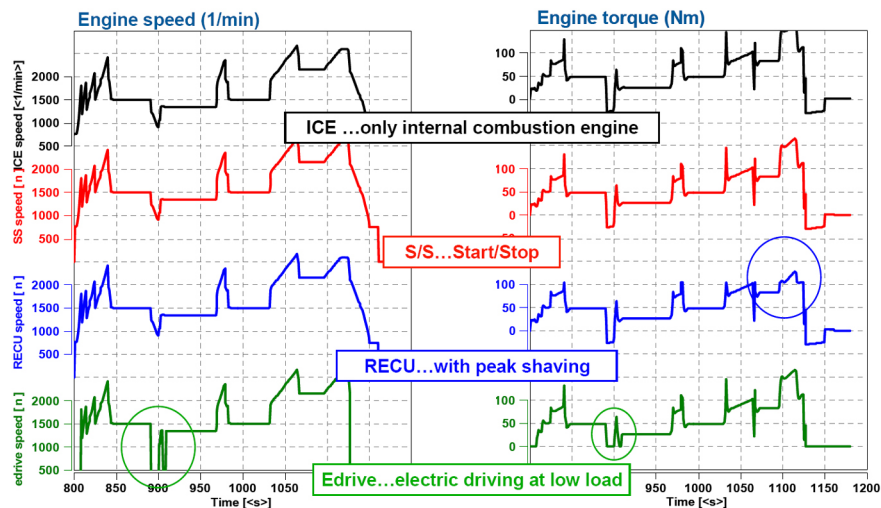


Figure 5. EUDC ICE speed and torque demand values for different levels of hybridization.

Edrive - Electric-Only Driving at Low Vehicle Power Requirement

The aim of the Edrive strategy is to avoid low load (and thus inefficient) operation of the ICE. Thus, in the UDC, the phases with low and constant velocity can be covered with the electric motor (~ 10 kW CSG). Naturally, the overall energy balance was considered within the test cycle and the electric storage capacity employed is again ~ 300 kJ in the whole NEDC.

EFFECT OF HYBRIDIZATION LEVEL

From the tests with different HW configuration it was found out that the FIX-FIX configuration is the best compromise between the Brake Specific Fuel Consumption (BSFC) and emissions. However, the advantages of the FIX-FIX

configuration disappear with increasing engine speed. The Euro6 NO_x target was achieved during the NEDC under all three hardware configurations. The minimum CO_2 emission in both cold (114.8 g/km) and hot NEDC (104.7 g/km) cycles is also achieved with the FIX-FIX hardware. A fixed geometry TC is superior due to lower exhaust back pressure levels and to a CO_2 improvement of $\sim 5\%$ at rather similar NO_x cycle results. Table 2 summarizes the overall cycle results for CO_2 and NO_x .

Since the FIX-FIX hardware configuration demonstrated the highest potential for CO_2 emission reduction, it was the configuration adopted to study the effect of the level of hybridization on the emissions and the fuel consumption. It was found that the CO_2 emissions decrease significantly with the level of hybridization. This improvement is a sum of the cycle work reduction due to recuperation and the increase of