

Development of Meshwork DPF Catalyst for Fuel Economy Improvement

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ABSTRACT

Diesel particulate filters (DPFs) are an essential aftertreatment component for reducing the PM emissions of diesel engine vehicles. Installation of a DPF can achieve high filtration efficiency, but PM filtration also causes a high pressure drop due to deep bed filtration. Consequently, periodic PM regeneration is necessary to keep a low pressure drop, but this causes significant deterioration in fuel efficiency. Improving the efficiency of PM regeneration and keeping the pressure drop low are major challenges faced by DPF manufacturers in meeting future CO₂ emissions regulations. This paper presents a novel morphological catalyst layer for DPFs, which is located in the surface of the inlet DPF channels and has been formed into a highly porous and three-dimensional meshwork shape. These features enhanced not only the prevention of deep bed filtration to reduce the pressure drop, but also the soot-catalyst contact for a faster PM regeneration rate. Cold flow and transient tests were used to evaluate the pressure drop, while passive and active regeneration conditions were used to investigate PM regeneration. The improvement in fuel economy was also estimated. This novel catalyst showed significant low transient pressure drop. The meshwork catalyst provided almost the same pressure drop compared to a bare substrate without PM loading, as well as a low pressure drop with PM loading. Moreover, the achievement of a higher PM regeneration rate was confirmed when measured under active regeneration conditions. Additionally, this catalyst improved fuel economy remarkably compared to a conventional DPF under PM loading and regeneration cycles.

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INTRODUCTION

Given its high torque at low speeds, high reliability, and good fuel economy, the diesel engine is a promising technology not only for on-road utilities like passenger cars and trucks, but also for off-road utilities in the construction and agricultural sectors. On the other hand, diesel exhaust contains PM and NO_x, which are recognized as one of major causes of air pollution. However, to satisfy the newer more stringent emissions regulations, such as Euro 6 in Europe, Tier3 in the U.S., and the post new long-term regulation in Japan, advanced exhaust aftertreatment systems such as DPF for PM, SCR, and LNT for NO_x are required. These catalytic converters are being used successfully and have decreased harmful emissions drastically.

The DPF is an essential aftertreatment component for diesel engine vehicles because of its high PM filtration efficiency. However, PM filtration causes a high pressure drop, so periodic regeneration is needed. Periodic regeneration consists of an increase in the exhaust gas temperature via post injections and/or exhaust fuel injection in order to combust the loaded PM and keep pressure drop low. For that reason, repeated PM loading and regeneration are indispensable to characteristic of DPF operation.

Fuel economy standards and emissions regulations are also becoming more stringent. CO₂ emissions standards for passenger vehicles were initially introduced in Europe in 2009, with a 120 g/km fleet average CO₂ standard stipulated by 2012. A 95 g/km CO₂ standard is now

targeted to go into effect by 2020. The U.S. is also targeting a 97 g/km CO₂ standard for passenger cars by 2025 [1]. These regulatory trends indicate that the fuel economy of vehicles has clearly become an important point for future emissions regulations.

DPFs have two main problems when it comes to fuel economy: the pressure drop during soot loading, and regeneration. Filtration during soot loading is divided into two modes: deep bed mode and cake mode. At the beginning of soot loading, deep bed filtration mode occurs due to penetration of soot particles into the DPF substrate pores. After initial soot loading, additional soot particles are deposited on the soot layer that was already loaded on the surface of substrate channels. This deposited soot layer then acts as a filtration layer and becomes thicker. This phenomenon is called the cake filtration mode. The pressure drop increases rapidly during deep bed filtration mode due to the decrease in substrate wall permeability [2]. Various membrane approaches have already been proposed to overcome this rapid increase in pressure drop during deep bed filtration [3, 4, 5, 6, 7, 8, 9, 10]. For example, a membrane which has a different pore structure than the DPF substrate is located in the inlet channel surface and has small pores. This membrane provides low transient pressure drop and good filtration efficiency. It also improves pressure drop hysteresis because of accelerated soot cake formation. However, applying a coating catalyst on the DPF substrate with this membrane is relatively difficult because the membrane pores become clogged with catalyst particles, causing a high pressure drop.

In addition, there are two soot regeneration methods: active and passive regeneration. In the active regeneration process, soot is regenerated by oxygen predominantly at a temperature of over approximate 500 degrees Celsius. Active regeneration needs fuel injection in order to elevate the exhaust gas to a high temperature. However, it also causes a remarkable deterioration in fuel economy. Passive regeneration requires large amounts of NO_2 in relation to the soot mass to promote the chemical reaction between carbon and NO_2 at a relatively low exhaust temperature. Catalyst technology also plays an important role in the soot burning process. A catalyst washcoat deposited in or on the DPF substrate promotes active and passive PM regeneration. Many factors affect PM regeneration performance because of the complexity of PM regeneration as a solid-solid-gas reaction. One of the critical factors is catalyst-soot contact. While the tight contact mode generally provides effective catalytic performance, in practical use the majority of the contact mode is loose contact. In order to address the poor soot-catalyst contact problem, the morphology of the catalytic particles was studied by many researchers [11, 12, 13, 14, 15, 16]. Catalysts with special morphology, such as fibers, nanometrics, and core-shells, have been described and they enhanced the catalytic performance because of an increase in the number of contact points. Despite these positive results, most studies remained pure laboratory work and did not note the relation to comprehensive DPF performance.

The demand for improvement of both transient pressure drop and PM regeneration efficiency led to the development of this meshwork DPF catalyst, which simultaneously unites the functions of decreased deep bed filtration and increased soot-catalyst contact to improve the fuel economy performance of the DPF. Furthermore, this meshwork catalyst also provides superior filtration efficiency. In this paper, evaluation results from both the laboratory and the engine-bench will be presented to describe the basic catalyst performance and to demonstrate its advantages compared to conventional catalysts. In addition, the improvement in fuel economy under PM loading and the regeneration cycle will also be estimated.

Concept

The sharp increase in pressure drop during the initial soot loading period is a well-known fact. This behavior is called deep bed filtration, and is caused by soot particles penetrating into the DPF substrate and clogging the wall pores. In order to solve this problem, a small pore structure and a high porosity structure is an effective means of achieving both a low pressure drop and good mechanical strength. Consequently, dual-layer membrane substrate approaches were proposed. A surface layer that has small pore diameters and high porosity provides high filtration efficiency and a lower pressure drop during soot loading, while also providing DPF substrate functions that maintain the structural strength and ensure heat capacity. Although this surface layer achieved good suppression of the sharp increase in the pressure drop during the initial period of soot loading, the majority of the soot remained on the surface layer. Conventional DPF catalysts were coated inside the substrate, and catalytic soot regeneration performance might therefore have decreased due to the lack of soot-catalyst contact.

The soot-catalyst contact is a very important factor in catalytic soot regeneration. In general, the soot oxidation rate of tight contact that is prepared by mixing soot together with the catalyst in a ball mill is much higher than that of loose contact that is prepared by mixing it with a spatula. The soot-catalyst contact that occurs during practical use is most similar to the loose contact condition making it difficult to apply the results from tight contact to real conditions. Catalyst morphology control is one of the most effective methods for overcoming this problem. Some researchers reported that catalyst morphology enhanced soot oxidation under the loose contact condition because of the increased amount of soot-catalyst contact.

The meshwork catalyst achieves both a low pressure drop and high soot oxidation performance, improving the total fuel efficiency of DPF operation. This meshwork structure consists of a catalyzed three-dimensional network positioned on the inlet channel surface. These unique features enhance not only the inhibition of deep bed filtration, but also the soot oxidation by surrounding the soot particles three dimensionally and increasing the amount of soot-catalyst contact.

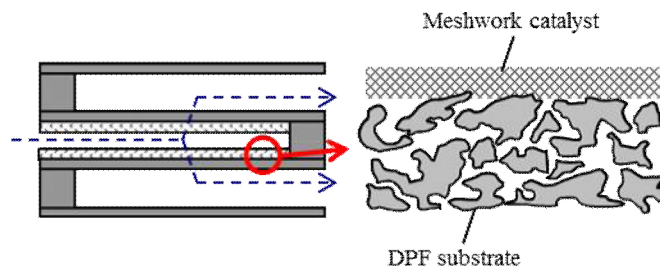


Figure 1. Meshwork catalyst concept.

EXPERIMENTAL

Catalysts

This meshwork catalyst was then compared to a conventional DPF catalyst to demonstrate how this new type of catalyst improves the vehicle fuel economy. All samples were prepared with SiC-DPF filters. Detailed DPF specifications are summarized in Table 1. Both samples were prepared using the same DPF specifications. In the engine bench test a DOC was used in front of the DPF samples. The DOC was a conventional one with PGM loading of Pt = 56.6 g/ft³ and Pd = 28.3 g/ft³.

The amount of PGM loading for both the meshwork and conventional catalysts was the same. Pt loading was 17 g/ft³ and Pd loading was 8.5 g/ft³. Table 2 shows the detailed catalyst specifications.

Table 1. DPF substrate specifications.

Substrate material	Silicon Carbide
Size	160 mmD × 135 mmL (2.7 L)
Cell structure	12 mil / 300 cpsi
Cell symmetry	asymmetry
Mean pore size	11 μm
Porosity	42%

Table 2. DPF catalyst specifications.

Pt load amount	17 g/ft ³
Pd load amount	8.5 g/ft ³

Table 3. DOC catalyst specifications

Pt load amount	56.6 g/ft ³
Pd load amount	28.3 g/ft ³

Laboratory Evaluation

Cold flow tests were performed using a flow bench in order to evaluate the increase in the pressure drop due to the catalyst coating. The pressure drop of the catalyzed DPF was evaluated at various flow rates. The flow temperature was maintained at 25 degrees Celsius and humidity was maintained at 65%.

Engine Bench Evaluation

Test Cell Setup

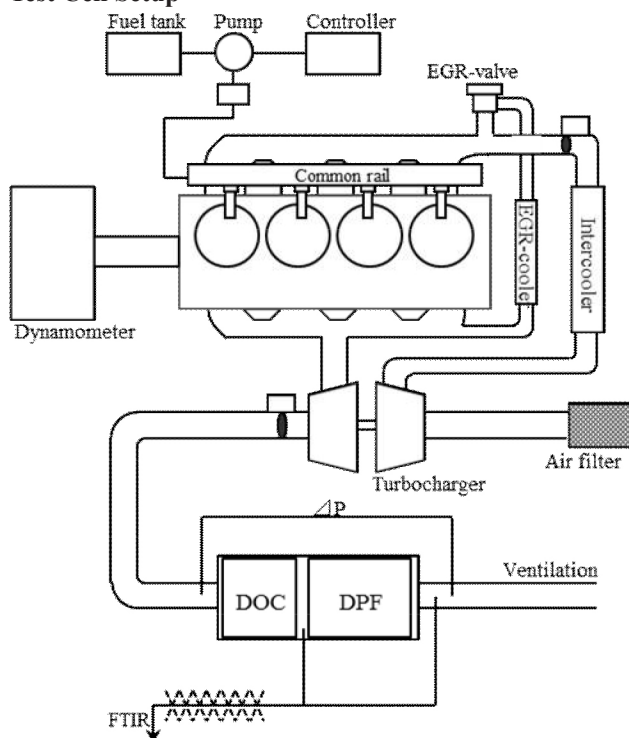


Figure 2. Test cell schematic.

Figure 2 illustrates the test cell layout, which shows the engine, dynamometer, and instrumentation, and other details. The engine used for this test was an in-line 4-cylinder 2.9 L common rail direct-injection turbocharged diesel engine. The base engine has a rated power of 106 kW. Engine-out NO_x in WLTC was about 0.21 g/km. A smoke meter (GSM-10EA, from Sokken) was used for accurate estimation of the soot loading amount. A gas analyzer (Horiba MEXA-7100D) was used to measure CO, HC, NO/NO_x, O₂ and CO₂. The measuring points were set at the inlet and outlet of the DPF. A manometer (PZ-77, from Sokken) was used to measure the

pressure drop behavior during soot loading and regeneration. The measuring points of the differential pressure before and after the aftertreatment system included the DOC and DPF.

Soot Loading

Soot loading was performed under steady state conditions. Table 4 shows these test conditions in detail. The DOC was located in front of the DPF during soot loading in order to reproduce practical soot properties. In the soot regeneration test, soot was loaded up to 5 g/L. After loading, the amount of soot was weighed under dry conditions at 250 degrees Celsius. Soot loading rate were accelerated in order to reduce test time.

Table 4. Soot loading conditions.

Engine speed	2000 rpm
Torque	50 Nm
Intake air mass	30 g/s
Temperature	300 deg. C
Soot loading rate	6.5 g/h

Soot Regeneration

Active and passive regeneration tests were performed to evaluate the soot regeneration rate under different modes. The active regeneration evaluation was performed by exposing the catalysts to a steady state at 300 degrees Celsius and then applying a temperature ramp from 300 to 580 degrees Celsius. After ramping up, the inlet DPF temperature was held steady for 5 minutes. The passive regeneration evaluation was performed by using a temperature ramp from 300 to 400 degrees Celsius and then holding the temperature steady for 1 hour. In these experiments, the regeneration rate was calculated as the total amount of soot burn divided by the regeneration time.

Table 5. Active regeneration conditions.

Engine speed	2200 rpm
Torque	65 Nm
Intake air mass	60 g/s
DPF inlet temperature	580 deg. C

Table 6. Passive regeneration conditions

Engine speed	2000 rpm
Torque	80 Nm
Intake air mass	50 g/s
DPF inlet temperature	400 deg. C

Drop to Idle

A drop-to-idle test was performed to evaluate the thermal shock durability of the meshwork catalyst. Thermocouples were placed in certain locations on the DPF substrate as shown in Figure 3. The sample inlet temperature was ramped up from 300 to 700 degrees Celsius in 30 seconds before dropping back to idle. Figure 4 shows these test conditions in more detail. A repeated cold flow test and regeneration test were performed to evaluate the thermal durability.