Potential of PM Reduction with Diesel Particulate Filter-less System for Off-Road Engine Applications*

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This paper describes that it applies to off-road engine by tandem DOCs system with metal LS-design (Longitudinal Structure design) substrates which have special shovel on corrugated foil regularly. At first, it confirmed the advantages of DOC with LS-design substrate (LS-DOC) for the tandem DOCs system. Then, it also confirmed that new PM reduction process hypothesized by turbulent flow at a gap of between first LS-DOC and second LS-DOC. As a result, for difficulties of conventional Diesel Particulate Filter system applied to off-road engine applications, it confirmed that the tandem LS-DOCs system has the advantages compared to conventional other types of substrates in tandem DOCs systems.

KEY WORDS: Heat engine, Post treatment system, Emissions gas, Tandem DOCs, Metal substrate, PM Filter-less system (A1)

1. Introduction

Diesel engines have been extensively used as a primary power source not only in motor vehicles, but also in off-road engine applications, including construction machines, agricultural machines, power generators, boats and ships, and cogeneration systems, by virtue of various advantages, including the general versatility of diesel fuel, high heat efficiency, robustness, and low running costs. Stringent emission standards, or Stage 3B/Tier 4 Interim emission standards for off-road engines, were phased in beginning in 2011 in Japan, the U.S., and Europe, with similar emission standards scheduled to take effect in other emerging countries. Particulate matter (PM) emissions from off-road diesel engines are reduced to meet these emission standards, using aftertreatment systems consisting of a diesel oxidation catalyst (DOC) and diesel particulate filter (DPF), as is the case with trucks, buses, and passenger cars subject to the stringent standards.

However, the operating environments of off-road engine applications are greatly different from those of passenger cars and trucks. These engines also experience accumulation of PM and ash due to continuous and extended periods of operation under heavy or light loads, limitations on loading conditions, unexpected usage of improper fuels, extended periods of operation under poor maintenance conditions, and higher engine costs, which may make it difficult to apply the DPF system to all such applications.

This paper verifies the effectiveness of a DPF-less system consisting of tandem DOCs with metal LS-design substrates (LS-DOC), that has been reported with regard to off-road engines(1) to support off-road applications that are difficult to address with a DPF system only, in which the collision of exhaust gas with the catalyst is changed by changing its flow via shovels formed inside channels in the substrates to allow lateral diffusion of the exhaust gas.

The potential of a DOC having LS substrates to reduce PM emission and prevent local accumulation of PM is confirmed, and there is predicted a new PM emission reduction process that utilizes several effects occurring in the first and second catalysts and turbulent flow of gas generated at the gap between the two. Consequently, a DPF-less system to reduce PM emissions from diesel engines for off-road applications is found to be feasible.

2. Problems Unique to Off-Road Applications

Diesel engines used in off-road applications face various challenges, including severe operating environments (e.g., operation in mucky water and extended periods of exposure to the outdoor environment), extended periods of operation under extremely high/low loads at rated power and idling speeds associated with stand-by, spatial limitations for enhanced work safety, expectations for higher endurance and reliability over an extended period of time, fuel properties that vary between regions, and space and cost limitations on engines from body manufacturers. Consequently, some off-road engines suffer from:

- Excessive engine oil consumption, which results in over-accumulation of ash, etc., in the DPF;
- PM, ash, etc., arising from low-load operation, causing clogging of DOC and DPF front surfaces;
- Over-accumulation of ash, etc., at the front surfaces, despite operation under proper operating conditions;
- The requirement of frequent cleaning or other maintenance inside the DPF due to the accumulation of ash, etc.;
- Restrictions on the installation of aftertreatment systems, including engine management systems and other devices; and,
- The possibility of melting arising from the over-accumulation of PM in the DPF under various operating conditions.

In particular, unlike passenger cars and trucks, off-road small diesel engines may present difficulties in hosting a provided DPF system.

3. DPF-less System for Off-Road Engines

As described above, diesel engines for off-road applications are required by regulation to reduce a significant amount of PM emission. Agricultural machines, etc., that cannot meet the standards through the use of conventional DPF systems have been equipped with DPF-less systems, including those utilize engine management only, single DOC only, and utilize SCR systems. This paper evaluates the potential of a tandem DOC system that employs multiple DOCs to reduce PM emission.

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3.1 PM Components Emitted from Off-Road Diesel Engines

Figure 1 shows the composition of PM emitted from diesel engines(2). In order to reduce PM levels in exhaust emissions using DOCs exclusively, it is generally important to oxidize the hydrocarbons adhering to soot, as well as other unburned hydrocarbons, such as the solid liquid soluble organic fraction (SOF) around the soot. In the process of this oxidation, adsorption and diffusion are repeated in the channels of the catalytic converter, thereby accelerating the oxidation reaction, as illustrated in Fig. 2(2).

Figure 3 shows the typical composition of PM emitted from small diesel engines (less than 56 kW) for off-road applications in exhaust gas certification mode (C1 mode). Due to continued operation at rated power or other operations in off-road applications, these engines are considered to consume an excessive amount of engine oil and fuel, from which relatively larger amounts of SOFs are derived. For this reason, SOF that can be reduced by DOC in some cases account for up to half of PM emission, which is large compared to the PM emissions from passenger cars and trucks. If these SOFs could be eliminated completely, the PM reduction rate would rise to at least 50 percent.

However, off-road engines, which are often operated under high-load conditions, including operation at their rated point, when operated under practical use or in certification mode, necessarily have a higher gas flow rate, and as a result, a greater space velocity (SV), making it impossible to perform repeated adsorption and diffusion on a catalyst. Furthermore, unlike a catalytic reaction in a gas, it is difficult for minute oil droplets, SOF, and the other solid liquid components derived from engine oil shown in Fig. 2 to undergo a complete oxidation reaction in a short period of time. For these reasons, the following measures are effective in improving the SOF and HC reduction rate in PM through the use of DOC:

- Catalyst capacity is increased as much as possible (in particular, the SV is reduced);
- Either the amount of precious metal is increased or a catalyst is added to accelerate oxidation;
- The number of cells is increased to achieve a larger geometric surface area (GSA);

- Catalysts are installed at a location where the gas flow is constant and slow.

However, application of the above measures to off-road applications is more difficult than application to passenger cars and trucks, due to limited mounting spaces, cost limitations, maintenance of catalyst durability under severe conditions, restrictions on pressure loss at the rated point, and differences between engine and body OEMs; therefore, a new approach is needed to obtain improved performance.

3.2. Potential for Reduced PM Emission through Tandem DOCs

Since conventional DOCs encounter difficulties in reducing PM emission, as described above, we will now consider a tandem system that in the past has yielded good results when applied to passenger cars(3), which employs multiple substrates where exhaust gas energy and flow are utilized. Figure 4 shows a metal supported tandem catalyst system for use in gasoline engines(4)(5). In the days when the tandem catalyst system was first developed, various metal-supported tandem catalyst systems, which assisted in improving catalyst performance, were developed to meet the stringent emission standards in effect in the U.S. and European countries. These systems feature improvements such as rapid catalytic activity from lower temperatures resulting from the reduced heat capacity due to use of a two-piece catalyst, enhanced gas-catalyst contact via the turbulent gas flow occurring at the gap resulting from use of a divided substrate, the effective use of the rear portion of the first catalyst by making gas flow concentrated to the center portion flow back from the gap, and, prevention of precious metal deterioration caused by unnecessary heating through the further division of low-heat-capacity metal substrates.

These features, if applied to off-road diesel engines, would conceivably be very effective in reducing SOF and hydrocarbons in PM emission. The tandem DOC system designed for PM reduction is expected to have the following positive and negative effects.

Positive effects:

- An increase in the area of contact with the catalyst, which has the potential to reduce SOF and HC emissions;
- A maintenance-free catalyst, as well as a significant reduction in the amount of accumulated ash, compared with DPF;
- Improved purification performance arising from the use of turbulent flow at the gap generated by the use of divided DOCs;
- Lower pressure loss and costs than DPF; and,
- Prevention of precious metal deterioration caused by heat under high loads through the use of metal substrates with divided DOCs.
Negative effects:

• Due to difficulties in eliminating all PM, a reduction of engine-out PM is needed;
• A solid oxidation reaction will require a larger DOC capacity than usual (=greater geometric surface areas (GSA));
• Smaller molecular movement than in the gas case will require measures to move PM to the catalyst surfaces;
• Ash accumulation resulting from the engine oil consumption associated with high-load operation will rise with an increase in GSA;
• Front surfaces will become clogged with PM and ash due to the increased front surface area to which PM attaches in association with high/low-load operation;
• Installation of a catalyst in mufflers may result in exhaust gas drift, causing local accumulation of PM; and,
• Particulate number (PN) must be taken into consideration in the future.

Unlike gasoline engines for passenger cars, off-road diesel engines are not viable unless the problems described above are solved. For this reason, in using a metal LS-design substrate for tandem DOC systems for off-road diesel engines, a reduction of engine-out PM is needed; a reduction of engine-out PM is needed; the following points are evaluated to verify the possibility of resolution of the problems faced by tandem DOC systems and an improvement in PM purification efficiency:

1. Whether or not improvements can be made, regarding uneven gas flow and local PM accumulation, and whether or not more frequent contact between the exhaust gas including PM and catalysts can be made to occur over a large area.

4.1. Approaches for Substrates to Assist in Improving Catalyst Performance

The following equation was reported to determine emission conversion efficiency for parameters that contribute to the performance of catalytic converters:

\[
\ln \frac{C_{\text{in}}}{C_{\text{out}}} = -\frac{P_{\text{gas}}}{N_{\text{gas}} R T_{\text{gas}}} \frac{A}{\epsilon} k \frac{1}{1 + \frac{k}{\beta}}
\]  

(1)

Here, \(C_{\text{in}}\) is the pre-catalytic converter emission level (%), and \(C_{\text{out}}\) is the post-catalytic converter emission level (%). \(N_{\text{gas}}\) is the catalytic converter efficiency), \(N_{\text{gas}} R T_{\text{gas}}\) is the molar mass flow rate (mol/s), \(P_{\text{gas}}\) is the exhaust gas pressure (Pa), \(R\) is the universal gas constant (J/molK), \(T_{\text{gas}}\) is the exhaust gas temperature (K), \(A\) is the catalytic converter inner geometric surface area (m²), and \(k\) is the catalytic reaction rate constant (m/s). This equation may be transformed to yield the mass transfer coefficient, \(\beta\), for the final catalytic converter, as shown below:

\[
\beta = \frac{V \cdot \epsilon \cdot \omega_{\text{channel}}}{L} \frac{1}{A} \ln \frac{C_{\text{in}}}{C_{\text{out}}}
\]  

(2)

Here, \(V\) is the catalytic converter capacity (m³), \(L\) is the catalytic converter length (m), \(\epsilon\) is the open frontal area of catalytic converter (%), and \(\omega_{\text{channel}}\) is the exhaust gas speed for the channels (m/s). These equations indicate that if the mass transfer coefficient \(\beta\) can be increased, an overall PM reduction rate can be maintained, despite a decrease in GSA caused by a lower cell density. For example, provided that the HC (= in C₃H₈) conversion efficiency is 90% when exhaust gas flows in a 1.4 liter DOC (length of 5 inches, 300 cpsi/5 mil, GSA 3.1 m²/p., aperture ratio is 72.3%) at a rate of 16.7 m/s, Equation (2) shows that the mass transfer coefficient \(\beta\) is 0.098 m/s. Equation (2), however, theoretically indicates that, provided that the mass transfer coefficient \(\beta\) can be increased up to 0.14 m/s, performance could be maintained even if GSA is reduced 30 percent. The mass transfer coefficient \(\beta\) can also be expressed by the following equation:
to the mass transfer coefficient 

gas (m²/s), higher exhaust gas velocity, substrates, it is best to reduce the diameter of the substrate to obtain a 

addition, they reduce the channel hydraulic diameter, shovels, thereby improving the mass transfer coefficient \( \beta \). To change the parameters for the substrates, it is best to reduce the diameter of the substrate to obtain a higher exhaust gas velocity, \( \omega \), and also to reduce the aperture ratio to obtain a smaller hydraulic diameter \( d_{h,channel} \) of the channels. However, these measures may pose challenges for off-road diesel engines, such as increased pressure loss under high-load conditions, clogged front surfaces, insufficient catalytic reaction time, and over-accumulation of ash and PM arising from a biased gas flow. These shortcomings become worse in the case of tandem DOC systems with typical substrates, making these systems non-viable. These shortcomings become worse in the case of tandem DOC systems with typical substrates, making these systems non-viable.

4.2. Structure and Characteristics of Metal LS-Design Substrates

Although ceramic and metal substrates are widely used as substrates for DOCs, the metal LS-design substrate has shovels formed by reverse stamping of the corrugated foils of conventional metal substrates at regular intervals. Figure 6 shows a metal LS-design substrate and its foils (flat and corrugated foils). This structure:

1. Doubles the number of inner cells and allows exhaust gas to come into direct contact with the shovels;
2. Causes turbulent flow to occur in each substrate channel; and,
3. Causes the exhaust gas to be divided into right and left cells, to some extent.

These effects instantly increase the channel exhaust gas speeds \( \omega_{ch,channel} \) at shovels, and can thereby achieve a greater \( Re_{channel} \). In addition, they reduce the channel hydraulic diameter, \( d_{h,channel} \) at shovels, thereby improving the mass transfer coefficient \( \beta \), which represents the probability of exhaust gas contacting the catalyst supported by substrates in a catalytic converter. Furthermore, they make an improvement towards gas uniformity due to exhaust gas diffusion, thereby helping enhance catalyst performance for improved emission conversion efficiencies. Possible solutions to the following challenges faced by the tandem DOC system through the use of this special metal LS-design substrate will be explored below.

- Lower cell density and thinner foils are implemented, while the front surfaces are prevented from clogging, to maintain performance; and,
- Diffusion of uneven gas flow is accelerated, to remedy the local accumulation of ash and PM.

4.3 Confirmation of Correlation between HC Purification Efficiency and Re Number using Gas Rig Tester

The actual HC conversion efficiency provided by the lower cell density type (200 cpsi) was evaluated using a gas rig tester under conditions in which the above-mentioned \( Re_{channel} \) parameters were varied. Based on these results, a correlation with the Re number was confirmed for the lower cell density type (200 cpsi), and the results verify the possibility of enhancing catalyst performance by using LS-design substrates, under the low/high temperature and greater gas flow rate conditions unique to off-road engines.

4.3.1. Test Setup, Test Methods, and Test Results

Figure 7 outlines the employed gas rig test setup. In each test, plant air is fed by a compressor to yield a gas flow rate of 5 to 55 kg/h, with the flow rate measured by a flow meter. Subsequently, the air is heated to a temperature of 200 to 400°C, and injected with HC gas from an HC \((C_3H_6)\) gas bottle. The air is conditioned to provide an HC level of 250 ppm, and passed through a catalytic converter (amount of precious metal supported: Pt 1.77 g/L) containing a 40 mm diameter by 50.8 mm long (0.064 liter) standard metal substrate (200 cpsi) or metal LS-design substrate (200/400 cpsi). HC level is measured at points before and after the catalytic converter, using a flame ionization detector (FID). The difference between these measurements is then determined to yield HC conversion efficiency for each substrate.

Figure 8 shows the HC conversion efficiency results obtained from tests conducted on a catalytic converter containing a standard metal substrate and an LS-design substrate. As demonstrated in our aforementioned work, the LS-design substrate presents an advantage in HC conversion efficiency within the temperature range of 200 and 400°C, to which off-road engines are frequently exposed. In particular, a greater difference in conversion rate is found over the gas flow rate range that approximates the SV in high-load range unique to off-road engines.
Because the substrates have the same inlet cell density (200 cpsi), the gas flow may raise concerns regarding increased pressure loss and melting due to the local over-accumulation of PM and ash. As shown in Fig. 9, the use of DOCs employing the LS-design substrate, when used under typical off-road operating conditions, is estimated to provide catalyst performance 10 to 20 percent higher in terms of HC conversion efficiency, so long as the gas flow remains constant.

4.4 Gas Diffusion Efficiency through Restrictions on Gas Flow Rate at the Inlet

In most off-road engines, catalytic converters are typically integrated into the muffler above the engine due to the limited mounting area. This arrangement may cause the exhaust gas to enter the catalytic converter with considerably uneven flow, while at the outlet, use of a bent exhaust tube will cause the exhaust gas flow to be even more uneven. The tandem DOC system, if mounted to such converters, may raise concerns regarding increased pressure loss and melting due to the further over-accumulation of PM and ash. In order to address these concerns, an evaluation has been conducted on the possibility of dividing the exhaust gas that is subjected to direct contact into right and left cells at shovels, a feature of the metal LS-design substrate, and thereby diffuse the gas. Although the aforementioned paper has also confirmed an improvement in the gas uniformity index (UI) with regard to the contribution of the LS-design substrate to an improvement in gas flow distribution, in this work, the degree to which gas diffusion is possible is evaluated experimentally, with an emphasis on gas diffusion.

4.4.1. Test Setup, Test Methods, and Test Results

Test samples include a metal LS-design substrate (200/400 cpsi) considering the possibility of reduction of cell density and a 400 cpsi standard metal substrate, whose cell density is that of the typical DOC used as a DPF system for off-road diesel engines (both substrates have dimensions of 98.4 mm diameter x 113 mm length). In each test, the plant air is heated to approximately 50°C and fed to a substrate at a constant rate of approximately 350 kg/h to simulate the high-load operating conditions of off-road engines. The gas velocity distribution is then measured using a gas flow sensor (grid size: 5 mm; effective measuring points: 293). Figure 10 shows an image of the gas distribution flow velocity test and results. The image indicates that, due to its ordinary gas passage channels, the standard metal substrate (400 cpsi) has a gas flow that remains unchanged from the inlet to the outlet of the substrate. In contrast, the metal LS-design substrate (200/400 cpsi) has a gas velocity distribution which spreads at the outlet. These results confirm, under the above test conditions, that the 200 cpsi based lower-cell density metal LS-design substrate has roughly 1.7 times greater diffusion in terms of area than the 400 cpsi standard substrate. Based on these results, use of the tandem DOC system in off-road engine applications is considered to be effective in avoiding pressure rise and melting caused by the local over-accumulation of PM and ash, as compared to the standard substrate. In addition, its improved gas diffusion ability is estimated to accelerate the effective use of the catalyst, greatly contributing to a reduction of PM emission, in addition to an increase in the mass transfer coefficient resulting from the increased channel flow velocity.

4.5. Estimated SOF Reduction by LS-DOC

From the results obtained thus far, HC in the exhaust gas as well as the solid-liquid-state SOF in PM, which has thus far been considered to be difficult to purify by DOCs, can be reduced by optimizing the mass transfer coefficient of DOCs containing metal LS-design substrates. Figure 11 shows the calculation results of off-road diesel engine SOF reduction rates achievable through the use of catalytic converters with metal LS-design substrates, based on the PM test results conducted on various engine outputs (37 to 75 kW) and SOF/soot rate. The findings from these tests demonstrate that even DOCs containing LS-design substrates effective for SOF reduction will require a size nearly equal to the engine capacity.

5. SOF and Soot Reduction Achievable through Tandem LS-DOC

To this point, the discussion has focused on the possibility of employing an LS-DOC with a metal LS-design substrate for reducing SOF. In this final section, tandem DOC systems possessing the LS-DOC are evaluated. As shown in Fig. 12, results from the tests conducted thus far on LS-DOCs regarding the PM reduction rate show that this rate often falls within the
range from 60 to 70%, although SOF accounts for only half of PM. In consideration of the operating conditions, including high-load operation unique to off-road engines, the following combined processes may be considered.

Preconditions:
In the first LS-DOC, solid and liquid HC including SOF come into contact with a catalyst more frequently by collision and diffusion, thereby causing exposure of soot surfaces in the process of the oxidation reaction.

(1) When HC containing SOF is burned, soot surface temperature rises, and the temperature for oxidation reaction through collision and diffusion is reached in the second LS-DOC.

\[ \text{O}_2 + \text{C} \rightarrow \text{CO}_2 \ (\text{>550°C, w/several PGM >420°C}) \]

These phenomena occur in conventional DPF systems and are considered to occur in the above-described temperature range when SOF acts as an ignition agent.

(2) NO in the exhaust gas is oxidized to NO2 in the first LS-DOC, and soot oxidation is accelerated in the second LS-DOC through collision and diffusion.

\[ \text{NO}_2 + \text{C} \rightarrow 2\text{CO}_2 + \text{NO} \quad \text{(w/ Pt 280-420°C)} \]

As described in the report of the flow-through DPF (7), these phenomena are considered to occur during retention time achieved by utilizing the shovels or gas diffusion when excited NO2 is used, and when considering continuous regeneration through fast oxidation reaction.

(3) Ceria (Ce) metal in the catalyst adsorbs O2, and NO in the exhaust gas accelerates soot oxidation in the second LS-DOC in the vicinity of O2 adsorbed by collision and diffusion (or, soot is oxidized with adsorbed O2 only.).

\[ 2\text{NO} + 2\text{C} + \text{O}_2 \rightarrow 2\text{CO}_2 + \text{N}_2 \quad \text{(w/ Pt+Ce 280-600°C)} \]

As described in the report of catalysts for DPF (6), these phenomena are considered to occur during retention time achieved by utilizing the shovels or gas diffusion when considering fast oxidation reaction that occurs in the vicinity of CeO2 in the catalyst coat.

That is, most of SOF is burned in the first LS-DOC, and exposed soot with increased temperature is decomposed and partly adheres to the catalyst surface at the nano-level in the second LS-DOC through collision and diffusion. Soot oxidation is then considered to be accelerated through combination of processes (1) - (3). In particular, the oxidation reaction through a Ceria catalyst in process (3) is very fast under the conditions where more frequent contact with soot occurs, and is therefore very effective in SOF reduction, as previously reported in connection with FBC (Fuel-Borne Catalysts) (9), as shown in Fig. 13.

6. Conclusion

This paper addresses the problems unique to off-road applications which are difficult to solve only by DPF systems. Provided below are findings from the verification that has been conducted on tandem DOC systems possessing a metal LS-design substrate in which the substrate inside the catalytic converter has a special structure.

(1) From the results of tests conducted thus far, the conditions for reducing PM resulting from SOF and HC adsorbed on soot in LS-DOCs have been clarified, whereby theoretical PM reduction methods have been proposed.

(2) Hypotheses for using tandem LS-DOC systems to reduce soot, which has thus far been considered to be difficult to reduce by DOC, have been constructed, whereby the potential for total PM reduction combined with the aforementioned SOF reduction has been presented.

(3) The positive and negative effects of the tandem DOC system have been clarified, and the viability of the tandem LS-DOC system has been demonstrated.

Challenges that the tandem LS-DOC system will address in the future include:

- Accurate characterization of the SOF/soot reduction rate achievable through the use of actual engines;
- Breakdown of soot reductions by NO2 and Ce catalyst on coating layers; and,
- Verification of the PN reduction achievable through the use of tandem LS-DOC systems.

References