

メタルLS担体によるオフロードエンジンへの適用*

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Applications to the Off-Road Engines by LS Metal Substrate

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This paper describes the applications to off-road engine of metal LS (Longitudinal Structure design) substrate which improves emission conversion efficiency in catalytic converter. From a hydrodynamic and heat transfer of viewpoints, metal LS substrate is firstly calculated for optimization of off-road applications. Then, the hypothesis was evaluated by gas rig and actual engine tests for HC conversion efficiency and catalytic converter volume reduction (=PGM reduction) considering the cost and space limitation. In summary for off-road engine applications, it was confirmed LS substrates have advantages compared to conventional substrates in catalytic converter.

KEY WORDS: Heat engine, Emissions gas/ Aftertreatment system, Metal substrate, Mass transfer coefficient [A1]

1. Introduction

A diesel engine is one of the most efficient sources of powers with lower CO₂ emission, which have been considered for prevention of global warming and saving of fossil fuel as well as alternatives to electric motors and hybrid engine. The advantages of diesel engines have already been proven by multiple trucks/buses around the world as well as over half of passenger cars in Europe. Furthermore, off-road applications (construction machinery, agriculture motor, marine vessel, generator and co-generation system, etc.) do also applied use engines for high heat efficiency, fuel versatility, robustness and running cost.

However, the diesel engines emit PM(Particulate Matter) and NO_x (Nitrogen Oxide), which are well known to affect the environment and biogeocenosis. For these countermeasures and strict emission legislations, trucks/buses and passenger cars have introduced DOC (Diesel Oxidation Catalyst), DPF (Diesel Particulate Filter) and urea SCR(Selective Catalytic Reaction) system for years.

By the same token, emission legislations for off-road applications have been introduced step by step around the world. Especially, Japan, U.S. and Europe play a leading role for full-scale emission legislations, which Stage3B/Tier4 Interim from 2011 and Stage4/Tier4 final from 2014~2015. For that reason, this paper describes the catalytic converter containing a metal LS-design^① (Longitudinal Structure design) substrate was applied to off-road engine for improvements of exhaust emission reduction efficiency.

Firstly from off-road engine application viewpoint, metal LS substrate was investigated for theoretical catalyst activation

improvement by optimized calculation. The hypothesis was evaluated and demonstrated by gas rig reactor and actual engines. Moreover, feasibility of catalytic converter volume reduction (=PGM reduction) have been investigated by optimization of metal LS substrate due to specific space and cost limitations for off-road engine applications. As a result these investigations have shown that catalytic converter with metal LS substrate had significant higher HC (HydroCarbons) and PM in SOF (Soluble Organic Fraction) reduction compared to standard substrate.

2. Countermeasure of Off-road engine exhaust emission

2.1 Compared to Passenger car / Truck by different usage situation

Off-road diesel engine applications are pointed out several differences compared to diesel engine passenger car/ truck. These differences are as follows⁽²⁾:

- a. Severe usage conditions (e.g. in muddy water, outdoor exposure).
- b. Continuous long duty by high-load.
- c. Large vibration with work.
- d. Inferior heat release due to lack of cooling wind.
- e. Severe limitation space for securement of safety.
- f. Requests of high durability and reliability by long life period.
- g. Limited aftertreatment costs due to multi-small-lot production
- h. Possibility of improper fuels usage.

Therefore, the exhaust emission reduction method would be difficult to apply conventional diesel passenger cars / trucks engine technologies (e.g. latest combustion chamber improvement, fuel

injection system modification and optimization of combustion control). Also, aftertreatment systems such as DOC, DPF (Diesel Particulate Filter), and Urea-SCR (Selective Catalytic Reduction) might be applied if above a-h. conditions could be overcome, and engine improvements achievement. For that reasons, it is very difficult to build up the exhaust emission reduction system for off-road engine application compared to diesel passenger car/truck.

2.2. Exhaust gas emission test procedure

Current off-road diesel emission test procedures are several steady state modes (e.g. C1 mode) including measurement of rated power. However, it has been considered for condition of actual usage and consolidation of worldwide emission control. On that account, NRTC (Non Road Transient Cycle) mode will be introduced at almost same timing in Europe, U.S.A and Japan for next regulations. Figure 1 shows NRTC mode specification.

As Figure1 shows that off-road application test procedure has a lot of higher loads and engine speeds compared to diesel passenger car/truck. Therefore, aftertreatment system has to consider design and specification with high SV(Space Velocity) and gas temperature.

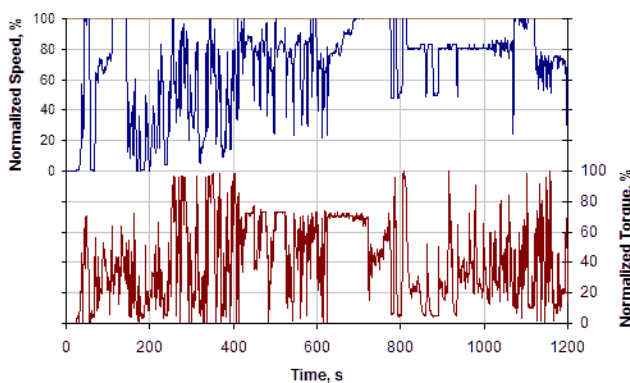


Fig.1 NRTC mode specification

2.3. Exhaust gas emission legislations

Off-road engine emission legislations in Europe and U.S. are applied to engine unit, and Japan is applied to machinery unit. But from engine power range viewpoint, these are almost same emission regulation level. Therefore, it is able to apply by same specification engine worldwide compared to diesel passenger car/truck.

Table 1 shows PM, NMHC (Non-Methane HydroCarbons) and NOx off-road engine emission legislations in Europe and U.S. Especially, PM level will be required to reduce until 1/10~1/20

Table 1 US and EU off-road legislations

		2009	2010	2011	2012	2013	2014	2015	2016
>19kW	US	NOx+NMHC 7.5 PM 0.4							
	EU	No limit							
19kW-437	US	NOx+NMHC 7.5 PM 0.3				NOx+NMHC 4.7 PM 0.3			
	EU	NOx+HC 7.5 PM 0.6							
37kW-456	US	NOx+NMHC 4.7 PM 0.3				NOx+NMHC 4.7 PM 0.03			
	EU	NOx+NMHC 4.7 PM 0.4							
56kW-475	US	NOx+NMHC 4.7 PM 0.4		NOx 3.4 NMHC 0.19 PM 0.02		NOx 0.4 NMHC 0.19 PM 0.02			
	EU	NOx+HC 4.7 PM 0.4		NOx 3.3 NMHC 0.19 PM 0.025		NOx 0.4 NMHC 0.19 PM 0.025			
75kW-130	US	NOx+NMHC 4.0 PM 0.3		NOx 3.4 NMHC 0.19 PM 0.02		NOx 0.4 NMHC 0.19 PM 0.02			
	EU	NOx+HC 4.0 PM 0.3		NOx 3.4 NMHC 0.19 PM 0.025		NOx 0.4 NMHC 0.19 PM 0.025			
130kW-560	US	NOx+NMHC 4.0 PM 0.2		NOx 2.0 NMHC 0.19 PM 0.02		NOx 0.4 NMHC 0.19 PM 0.02			
	EU	NOx+HC 4.0 PM 0.2		NOx 2.0 NMHC 0.19 PM 0.025		NOx 0.4 NMHC 0.19 PM 0.025			

compared to current level from 2011~2012. For instance, Figure 2 shows history of PM and NOx+NMHC in U.S (37~56kW). In addition, over 56 kW engines are distinguish NMHC from NOx. Consequently, DOC performance would be required to reduce hydrocarbonous emissions (SOF in PM and NMHC) before long.

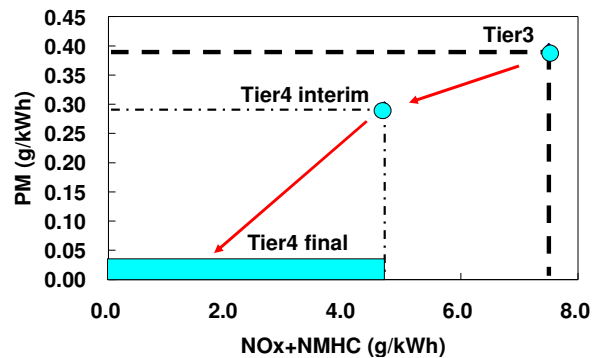


Fig.2 History of NOx+NMHC and PM emission level (37~56kW)

3. LS substrates as DOC-solutions for off road engines

As mentioned, reduction of hydrocarbonous emissions (SOF in PM and NMHC) are critical issues for consolidation of worldwide off-road engine emission control. But it is difficult to adopt cutting edge engine technology such as diesel passenger car / truck, due to limitation cost and different usage conditions. For that reason, DOC is one of most effective device for the emission reduction method. However, optimized catalytic converter development for off-road engine would be indispensable due to totally different requirement compared to diesel passenger car/truck. For that purpose, we assumed that metal LS substrate was applied for several off-road applications. From hydrodynamic and heat transfer viewpoint, optimized metal LS substrate was calculated for off-road application. And it was validated about possibility of theoretical DOC performance gain by metal LS substrate.

3.1 Possibility of theoretical DOC performance gain by metal LS substrate

Normally, SOF and NMHC reduction rates are improved by DOC that is thought of as follows:

- Larger catalyst volume (→smaller SV).
- Larger amount of PGM (Precious Metal)
- Larger cell density and GSA (Geometric Surface Area)
- Installation to uniformity and slow gas flow place.

However, off-road engine has several problems, which are limitation of cost, pressure loss at rated power, limitation space, each different engine/machine application maker. Therefore, it has to be considered another solution for DOC performance gain due to difficult to achievement as mentioned above. For this solution, metal LS substrate that improvement of inside substrate was investigated. It

was confirmed possibility of theoretical DOC performance gain. Mainly, two crucial issues were validated for effective utilization of catalyst that are as follows:

- Efficiently contact with exhaust gas to catalyst on substrate.
- Improvement of uneven gas flow.

3.2. LS-Design® substrate configuration and aim

Ceramic and metal standard substrates are widely applied to DOC. Especially, metal LS substrate has special shovel on corrugated foil which punched out on the foil regularly. Figure 3 shows metal LS substrate and foils specification. This structure would have being advantages that are as follows:

- The shovel contact with exhaust gas directly.
- Generation of gas turbulence at each substrate channel
- Dispersion of exhaust gas to left/right cells.

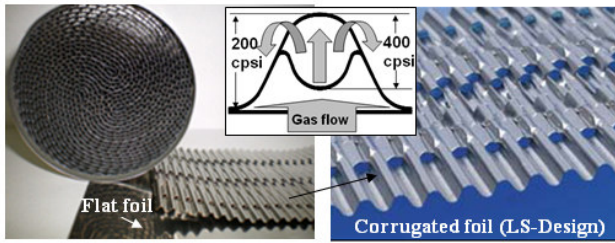


Fig.3 Metal LS-design® substrate (Flat & corrugated foils)

3.3. Comparison of mass transfer coefficient by calculation

Once light-off-temperature is achieved improvement of mass transfer coefficient is most effective method due to efficiently contact with exhaust gas to catalyst on substrate. This chapter carried out theoretical mass transfer comparison by standard substrate and metal LS substrate.

Mass transfer with fluid in pipe has a lot of reports since early times. General mass transfer coefficient β_0 (m/s) is defined by equation below.

$$\beta_0 = \frac{D \cdot Sh}{L} \quad (1)$$

D is diffusion coefficient (m^2/s), L is length scale (m), Sh is Sherwood number, which the mass transfer appears to operate a dimensionless number. It represents the ratio of convective to diffusive mass transport. Sh is designated by function below.

$$Sh = f(Re; Sc) \quad (2)$$

It is expressed by function of Re (Reynolds number) and Sc (Schmidt number). Where, $Re_{channel}$ and $Sc_{channels}$ are possible to handle about substrate channel at exhaust pipe by writing it in the form below.

$$Sc_{channel} = \frac{\nu}{D_{1,2}} \quad (3)$$

$$Re_{channel} = \frac{\omega_{channel} \cdot dh_{channel}}{\nu} \quad (4)$$

ν is dynamic viscosity of exhaust gas (m^2/s), $D_{1,2}$ is diffusion coefficient of binary components in exhaust gas (m^2/s), $\omega_{channel}$ is exhaust gas velocity in substrate channel (m/s), $dh_{channel}$ is hydraulic diameter in substrate channel (m). Where, equation (1) is also optimized to give the following.

$$\beta_{channel} = \frac{D_{1,2} \cdot Sh_{channel}}{dh_{channel}} \quad (5)$$

As the most common way to optimize mass transfer cell density can be increased. Because of this the hydraulic diameter decreases on the other side the Sh -number decreases and the mass transfer coefficient increases only slightly. But the other value which is important for mass transfer increases by increasing the cell density: the geometric surface of the catalytic converter. In total is possible to achieve at constant dimensions better performance of the catalytic converter. But you have to pay for this achievement by higher backpressure. Another possibility of increasing substrate performance should be possible by increasing the mass transfer at constant cell density. This is the way the LS structure tries to solve the challenge.

Figure 4 is illustrated pattern diagrams in substrate channel by metal standard and LS substrates. And Figure 5 shows the calculated mass transfer coefficients comparison by specific condition of off-road engine (=High load and temperature).

Generally speaking, momentary gas flow into cross section of substrate inlet is estimated almost turbulent flow ($Re_{substrate} > 10000$)⁽³⁾

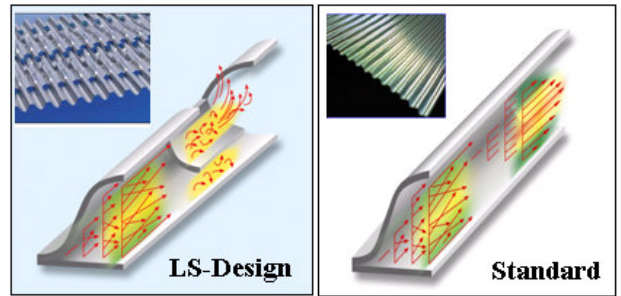


Fig.4 LS-design / Standard substrates channel and gas flow

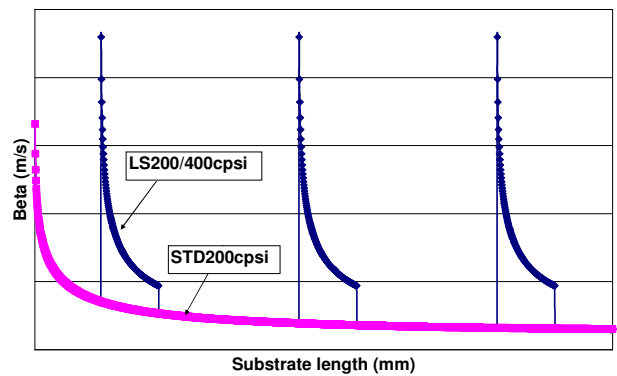


Fig.5 Theoretical mass transfer coefficient comparison (Sh base)

As shown in Figure 4 catalyst activation is increased by gas turbulence at substrate inlet. However, exhaust gas has to be handled by forced laminar flow ($Re_{channel} < 2100$)⁽³⁾ when it flows into each substrate channel. For that reason, it is conjectured that standard substrate has decreased mass transfer coefficient towards the outlet substrate as shown in Figure 5. In contrast, metal LS substrate is able to generate gas turbulent at shovel forcedly as shown in Figure 4. Therefore, it is able to increase momentary mass transfer coefficient at equal interval shovels as shown in Figure 5 due to momentary increasing $Re_{channel}$ and $Sh_{channel}$. This result indicates metal LS substrate can improve theoretical mass transfer coefficient by specific condition of off-road engine.

4. Actual HC emission reduction test by gas rig test

By previous chapter, theoretical performance gain of catalyst activity was confirmed by LS substrate. This chapter described that actual HC emission reduction confirmed with different parameter conditions (=variety of $Re_{channel}$) by gas rig tests. Also it was validated by a detailed comparison with theoretical calculations and actual results. As the result, LS substrate was investigated for feasibility of catalytic converter improvement by specific condition (=high SV and temperature) of off-road engine.

4.1. Test setup and procedure

Figure 6 shows gas rig test setup diagram. The test conditions were assumed typical usage of off-road engine (e.g. High temperature with large SV, low temperature with large SV). And the test procedure is the following:

- Controlled and measured air (5~50kg/h) was heated up to 200~500°C.
- HC (C_3H_6 ; Propene) gas was mixed in heated air, which was made HC gas concentration at 250ppm by volume.
- The HC gas was flown into catalytic converters, which consisted of catalyst (both Pt=1.77g/L) on metal standard 200cpsi and LS200/400cpsi substrates ($\varnothing 40.0\text{mm} \times L 50.8\text{mm}$).
- Inlet/outlet the catalytic converter gases in HC concentration were measured by FID (Flame Ionization Detector). HC reduction rate of each catalytic converter were calculated by FID measurements results.

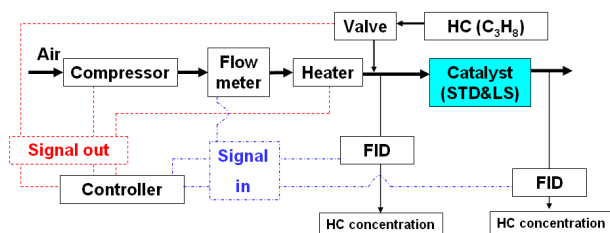


Fig.6 Gas rig test setup

4.2 Test results and discussion

To begin with, HC conversion efficiency comparison by 400°C is shown in Figure 7. LS 200/400 cpsi substrate exceeded standard 200cpsi substrate HC reduction rate by all gas flow conditions. Additionally, the larger gas flow rates are on standard 200cpsi substrate, the lower HC conversion rates are confirmed (max. approx. 30% down). But, LS 200/400 cpsi substrate is fairly maintained the HC conversion rate compared to Standard 200cpsi substrate. Even though the larger gas flow rates, metal LS200/400 cpsi substrate are seen to keep the high HC conversion rate (max. approx. 9% down). Also, other temperature ranges test results have been confirmed same as the 400°C test result. Secondly, Figure 8 shows the all temperature ranges test results by advantage of LS 200/400 cpsi substrate compared to Standard 200cpsi substrate based on SV. It is notable that advantage of HC reduction is not only high temperature but also 200C, in case of large $Re_{channel}$. In addition, it was confirmed that the advantage of LS 200/400 cpsi substrate was increased with increasing SV. And it was clearly shown that reduction possibility of hydrocarbons emissions (such as SOF and NMHC) due to catalyst activation improvement by LS substrate.

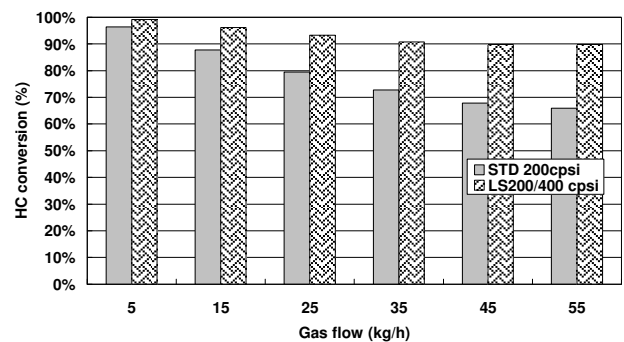


Fig.7 HC conversion efficiency comparison at 400°C

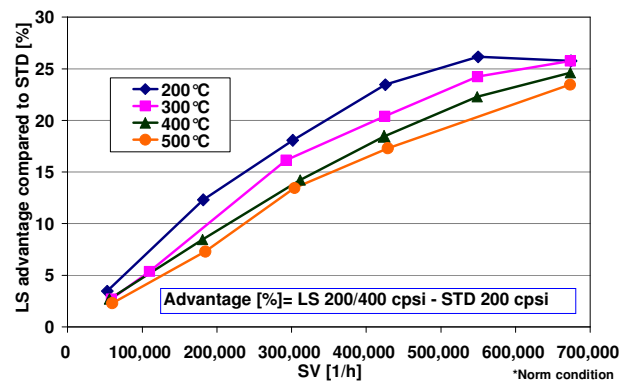


Fig.8 LS Advantage compared to Standard (based on SV)

4.3 Fitting of Sh-Correlations

A typical light off curve for an oxidation catalyst is shown in fig. 9. It displays this conversion efficiency as a function of the catalyst temperature. Regarding a light-off-diagram you can split this graph into several phases in Fig 9.

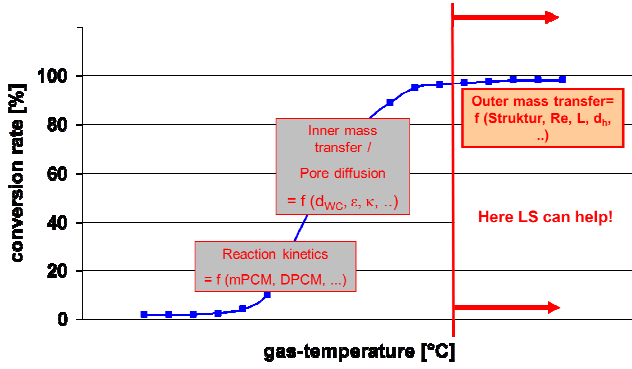


Fig 9: The phases of Light-Off

At low temperatures only the reaction kinetics is relevant for the total reaction velocity. When the temperature increases the reaction kinetics increases and the concentration of the educts in the depth of the washcoat becomes lower. Now the inner mass transfer (pore diffusion) becomes important which is here the time limiting step to bring the reactands from outer catalyst surface (channel wall) into the washcoat pores. At even higher temperature the pollutions within the pore system of the washcoat decrease further, until the reaction takes only place on the top of the washcoat which is in direct contact to the channel gas flow, because the reaction is so fast. At this high temperature level the outer mass transfer is the limiting step and is also relevant for the entire conversion efficiency.

In typical DOC, in dependence of the catalyst used (Pt-loading etc.), this the case from 200°C onwards.

With LS or other structured substrates only the outer mass transfer can be influenced. Because of this in the following only results of conversion tests at high temperatures are examined.

The equation ⁴⁾:

$$\ln \frac{c_{out}}{c_{in}} = - \frac{p_{gas}}{N_{gas} RT_{gas}} A \frac{k}{1 + \frac{k}{\beta}} \quad (6)$$

can be transformed, assuming that the chemical reaction (described by k) is much quicker than the diffusion (described by β), to

$$\beta = - \frac{V \cdot \varepsilon \cdot \omega_{channel}}{L} \frac{1}{A} \ln \frac{c_{out}}{c_{in}} \quad (7)$$

By variation of mass flow, temperature and length of substrates it was possible to estimate Sh numbers as a function of Re as plotted in fig. 10. It becomes clear, that by using LS Sh number and therefore the mass transfer coefficient can dramatically be increased by factors up to 2 in comparison to standard channels, depended on flow conditions. There is an analogy between the Sh number and the Nu number which describes the heat transfer of structures. Because of this the LS structure has big advantages during cold start - it heats up much quicker.

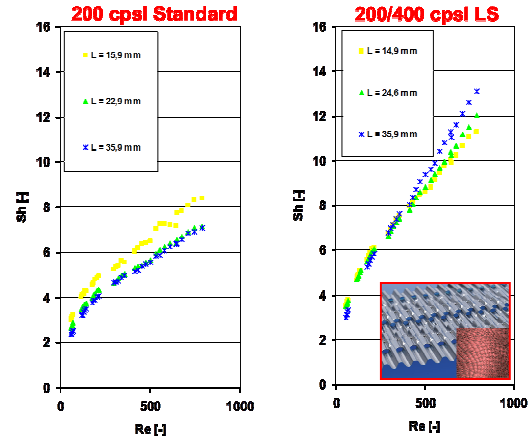


Fig 10: Sh over Re for Standard- and LS-structure

5. Improvement of radial flow dispersion by using LS structure

Off-road engine is very difficult to set up by large catalytic converter and homogeneous gas flow objections due to severe limitation space. For that reason, it has prospects of installation at uneven gas flow phase, such as below exhaust manifold. In this case, exhaust gas is flown into catalytic converter by uneven gas distribution that leads to catalyst deactivation. Therefore, it is conjectured that improvement of gas distribution leads to catalyst improved efficiency.

Dispersion of exhaust gas to left/right cell after direct contact at shovel is one of metal LS substrate's advantages. But it is very difficult to calculate the precise dispersion ratio because of a lot of exhaust gas parameters (Mass flow, temperature, pressure, velocity and inlet distribution). For that solution, Uniformity Index (UI) was measured that were based on each channel gas velocity at uneven gas flow place. Thereby, it was confirmed how much improvement of gas distribution.

5.1 Gas flow distribution experimental set up, procedure and results

Figure 11 shows picture of gas flow distribution experimental apparatus. In order to assess the gas flow distributions, gas flow velocity of outlet substrates were measured. The condition for gas flow velocity experimental was as follows:

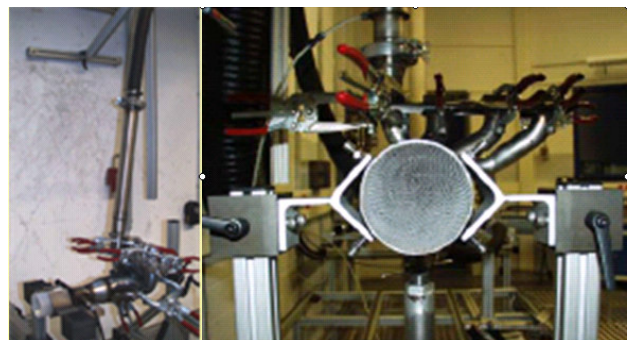


Fig.11 Picture of gas flow distribution experimental apparatus

- Metal standard and LS substrates ($\varnothing 98.4\text{mm} \times L113\text{mm}$) were setup to outlet of 4 cylinder manifold.
- Gas flow was assumed high load of off-road engine, it was used air of 50°C and 350kg/h into each manifold cylinder.
- The gas flow velocity was measured with 5mm grid size and 293 effective measurement points behind catalyst.

To begin with, Figure 12 summarizes the results of the gas flow velocity measurements by standard and LS substrates. Standard 400cps substrate is seen uneven flow velocity condition, which same as inlet substrate condition. In contrast, LS 200/400 cps substrate is obviously seen homogenization of gas flow velocity distribution compared to standard 400cps substrate. Furthermore, larger cell density of LS 300/600 cps substrate is seen to increase to almost all of outlet substrate.

Secondly, UI results calculated from measurements are shown in Figure 13. Standard 400cps substrate is seen considerable variation among each cylinder. But, LS 200/400 cps and 300cps are seen tiny variation among each cylinder. Also, LS 200/400 cps substrate which is half cell of standard 400cps improves 0.4~9.0% of UI (Average: approx. 5%) against standard substrate, moreover, LS 300/600 cps substrate improves 7.5~18.1% of UI (Average: approx. 13%). A higher UI has mainly three advantages:

- The available volume of a catalytic converter is better utilized.
- The backpressure of the catalyst decreases.
- The aging of the catalyst is reduced.

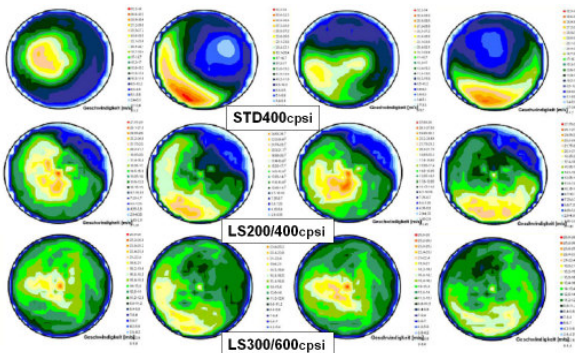


Fig.12 Gas flow velocity distribution test results (STD and LS) ($\varnothing 98.4\text{mm} \times L113\text{mm}$, flow rate and temp.: 350kg/h , 50°C)

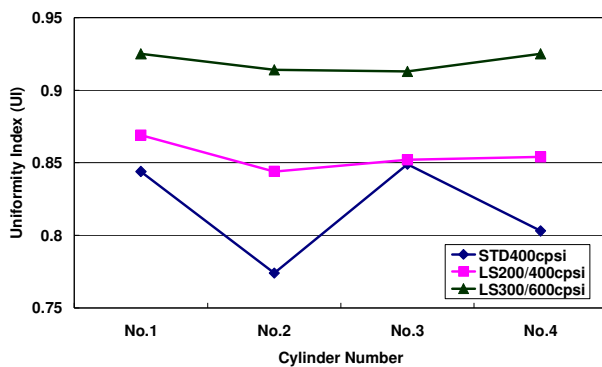


Fig.13 UI comparison results by STD and LS

6. Emission tests by actual off road engines

Finally, possibility of catalytic converter minimization was discussed due to specific small space of off-road engine. This chapter shows reduction possibility of LS substrate from standard size. By advantage of LS substrate were validated at actual off-road engines for feasibility of keeping equal or superior emission reduction performance with reduction volume.

6.1 Off-road small CNG engine application

HC emission test of small off-road engine was carried out with CNG (Compressed Natural Gas) fuel. The CNG is contained over 90% of Methane (CH_4), which most stable molecular structure in hydrocarbons, and it is very difficult to reduce in exhaust emission.

6.1.1 Test set up and test procedure

Diagram of small off-road engine test setup is shown in Figure 14.

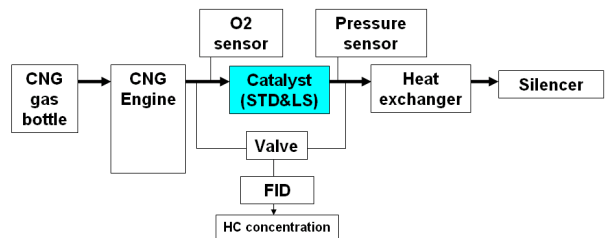


Fig.14 Small off-road CNG engine test setup

And details of each catalysts and substrates in catalytic converter are as follows:

-Metal standard substrate: Dia $50.8\text{mm} \times L 80\text{mm}$ (0.162Liter), 600cps,

PGM loading: $\text{Pt}2.0\text{g/L}$ (Total amount 0.324g)

-Metal LS substrate: Dia $50 \text{ mm} \times L 63\text{mm}$ (0.124Liter), 400/800cps LS,

PGM loading: $\text{Pt}2.0\text{g/L}$ (Total amount 0.248g)

Metal LS substrate specifications were reduced 23.5% of volume (=PGM) and 37.1% of GSA compared to metal standard substrate.

And the test procedure is the following:

- CNG engine (displacement: 0.2Liter) was run with CNG fuel ($90\% > \text{CH}_4$) by rated power condition (Air mass flow: $0.2\text{m}^3/\text{min}$)
- After the combustion, engine out gas (approx. 330°C) was introduced into each catalytic converter.
- Inlet/outlet the catalytic converter gases in HC concentration were measured by FID. HC reduction rate of each catalytic converter were calculated by FID measurements results.
- Also, the Inlet/outlet catalytic converter gas temperatures were measured for heat exchanger system.

This off-road engine has to collect the exhaust gas energy for other application via heat exchanger. Therefore, it is not only HC reduction performance, but also increasing of exhaust gas temperature is requested after catalytic converter.

6.1.2 Test results and discussion

Figure 15 shows comparison results of relative HC emission reduction and temperatures up. It was confirmed that LS 400/800 cpsi substrate of approx. 24% reduction volume / PGM was keeping equal or superior emission reduction performance compared to Standard 600cps substrate. Additionally, it is shown that LS 400cps substrate (Delta temp. 27°C) has increased 22°C temperature up against standard 600cps substrate (Delta temp. 5°C). For that reasons, the reduction volume and PGM feasibilities were demonstrated for actual off-road engine by each parameter optimization of mass transfer coefficient with LS substrate. Also, if one assumes that the catalytic converter was objected to an exhaust gas mass flow, which heats up the substrate, both convective heat transfer rate and substrate heat capacity (J/K) would be important factors for the heating up behavior of the substrate. In this evaluation engine test, the heat capacity of LS 400/800cps substrate was approx. -20% smaller than standard 600cps substrate. Normally, reduction of standard substrate volume, PGM and GSA would lead to catalyst deactivation. However, in case of LS substrate, it is conjectured that catalytic converter is improved by consideration of mass transfer coefficients and heat capacity optimization.

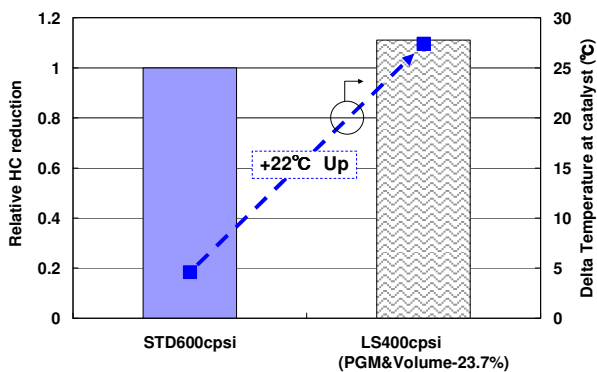


Fig.15 Comparison of relative HC reduction and ΔT at Catalyst

6.2 Off-road diesel engine application

On the basis of previous results, this final section was focused on SOF reduction possibility by LS substrate due to off-road diesel engine application. Generally speaking, it is difficult to reduce SOF in solid PM by catalytic converter. But, by using the LS structure for off-road diesel engine application, it was not only HC emission reduction, but also SOF reduction would be possible.

Figure 16 shows statistics results of relative PM reduction comparison by various off-road diesel engines (Rated power:

37~130kW) with NRTC and C1 mode. Even though 25~35% reduction volume against ceramic substrate, metal LS substrates have kept 1.28~1.35 times higher relative PM reductions. Hereby, Optimized metal LS substrate was confirmed about contribution of SOF reduction on catalytic converter.

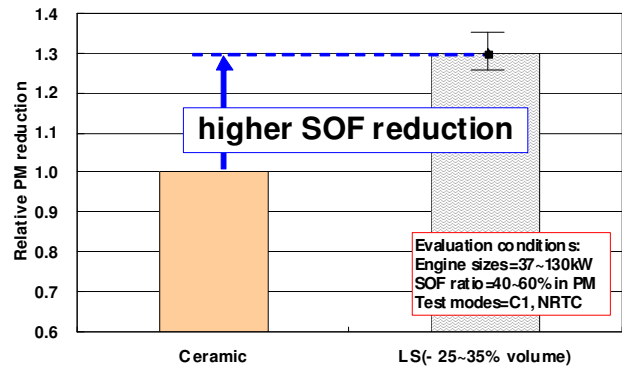


Fig.16 Statistics results of relative PM emission tests comparison

7. Summary/Conclusion

This paper proposed optimized solution of metal LS substrate in catalytic converter for specific problems of the off-road engine application. This was demonstrated by calculation, gas rig testings, flow bench testing and engine bench testing. In this study the findings for the metal LS substrate are as follows:

- (1) Theoretical optimization of catalytic converter upgrade was established by definition of each parameter in metal LS substrate.
- (2) High reduction rates of hydrocarbons emissions such as HC and SOF were demonstrated by gas rig and off-road engine tests.
- (3) Volume optimization possibility of catalytic converter was confirmed by various rated power off-road diesel engines due to consideration of limitation space in off-road engine.

Reference

- (1) T.Nohara, K.Komatsu, K.Maeno: Reduction technique of diesel and gasoline exhaust emission by metallic structures substrates, JSAE Kanto branch annual congress 2007, D2-4, p.131-134 (2007)
- (2) Central Environment Council / Air and Environment Research Group: Future Policy for Motor Vehicle Emission Reduction (Ninth report), Ministry of the Environment Government of Japan, 2008, 16p.
- (3) Donald Q. KERN, Allan D.Kraus: Extended surface heat transfer, McGraw-Hill, Inc., New York, 1972, 805p.
- (4) Hans D. Baehr, Karl Stephan: Wärme- und Stoffübertragung; 2nd edition, Springer Lehrbuch, 1996, p. 242-246