Commercialization of Diesel Particulate Filter (DPF)

Toshihiko Nishiyama
Nobuhiko Emori

Diesel engines are expected to be main power sources for industrial machines in the future as well as the present day because of their superior economical efficiency, reliability and durability. At the same time, they are regarded to be one of the serious contributors of air pollution. For that reason, the regulations are rapidly becoming more and more stringent. So far, a lot of research has mainly been made on combustion. However, it is close to the limit and an after-treatment system seems essential to clear Tier 4 regulations, which is expected to go into effect around 2010. Komatsu has developed a new compact DPF ahead of the competitors to meet future regulations, utilizing the past experiences with a black smoke removing device prescribed in the tunnel specifications.

Key Words: *Diesel Particulate Filter (DPF), Diesel Engine, Emission Regulations*

1. Background

Exhaust gas from diesel engines includes black smoke, SOF (soluble organic fraction), unburned fuel, lubrication oil, etc. in the form of PM (particulate matter), as shown in **Fig. 1**. Airborne fine particles contained in the PM are feared to cause bronchitic asthma and lung cancer.

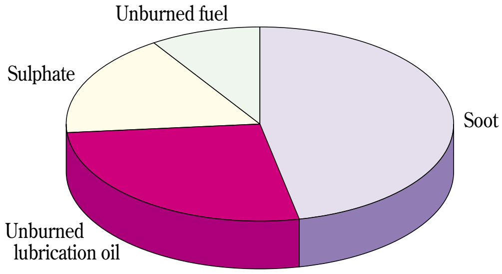

Fig. 1 Content of diesel exhaust gas

Fig. 2 shows the trend for PM regulations in the field of industrial machinery. At present, the use of a diesel particulate filter (DPF) is required only in highway tunnels controlled by Ministry of Land, Infrastructure and Transport. But around 2010 when Tier 4 regulations will be put in force, DPF will presumably be used in all sorts of work in the regulated areas. Even before 2010, i.e. around 2006, the State of California is expected to further its PM regulation, keeping DPF in mind. On the domestic scene, the truck manufacturers are believed to install DPF in their trucks to conform to the new long-term regulations of trucks whose enforcement is scheduled for 2005. Likewise similar regulations are likely to be imposed on industrial diesel engines in general within a timeframe of several years from now.

Year	'00	'01	'02	'03	'04	'05	'06	'07	'08	'20XX
Emission regulations in tunnel by Ministry of Construction	Target model: Construction equipment used in tunnel Content of regulation: Soot to be reduced by 80%									
Emission regulations by Ministry of Land, Infrastructure and Transport	Target model: Construction equipment in general 1st regulation: Black smoke: To be reduced to 50%				2nd regulation: PM: 0.2 – 0.3 g/kWh (75 – 560 kW) Black smoke: To be reduced to 40% 50 ppm light oil					
Emission regulations by Ministry of the Environment	Target model: Diesel-powered special vehicle				PM: 0.2 – 0.3 g/kWh (75 – 560 kW) Black emission gas: To be reduced to 40% (checked at mandatory inspection)					
EPA	Tier 1 225 – 450kW	Tier 2 PM: 0.2g/kW	75 – 130kW	Tier 2 PM: 0.3g/kW			Tier 3 PM: 0.13g/kW?			Tier 4 PM: 0.01g/kW?
EU	Euro 1 130 – 560kW	75 – 130kW	Euro 2 PM: 0.2g/kW	Euro 2 PM: 0.3g/kW					Euro 3 PM: 0.15g/kW?	Euro 4 PM: 0.02g/kW?
Our response with DPF		Checking required quality in most stringent cases	Translation of required quality into various applications Preparations for order receipt, sales of DPF as single commodity (tunnel & urban specs)		Retrofitting DPF to special vehicle			Starting DPF sales to regulation-intensified areas		Starting DPF sales to all construction equipment in all regulated areas

Fig. 2 Trend for PM regulation

2. PM reducing mechanism

It is a generally practiced method for reducing soot, one of the PM constituents, that soot is arrested by filter walls that have alternately clogged pores on either side, and burnt under certain conditions. However, the temperature at which soot spontaneously ignites is 550 to 600˚C, namely pretty high temperature that is not available under the normal conditions of engine running. For this reason, a heater or a burner is used for burning soot. Another method employed is lowering the ignition temperature aided by the work of catalyst. Rather, this is the mainstream method currently, in part because heaters have not solved the reliability problem yet, and in part because handling a heater is rather complex. Catalyst coating has an effect of removing other hazardous substances such as HC and CO in addition to PM. In the case of buses and trucks in urban use, however, burning temperature cannot be reached even with catalyst, requiring a means to raise the exhaust gas temperature like a post-injection. Fortunately, burning at normal temperature is possible with the construction equipment excluding exceptional applications, since they are used under relatively heavy load.

There are two ways of installing catalyst. A method that calls wide attention recently is what is termed "indirect oxidation type" developed by Johnson-Matthew. In this method, oxidation catalyst is provided at the front portion of a filter, which converts NO into NO_2. The created NO_2 burns the soot stuck to the filter through oxidation process. Merits of this method are:

① Reaction from NO to NO_2 occurs at a comparatively low temperature of 250˚C, so that the reaction at a low temperature is easy.
② The catalyst and the filter are separated from each other, so that no ashes pile up on the catalyst.
③ The catalyst is immune to the temperature of burning soot, so that its quality hardly deteriorates.

On the other hand, the following demerits are enumerated.

① The required parts double in number, occupying larger space.
② Reaction from NO to NO_2 hardly occurs when fuel of high sulfur content is used, or when the exhaust gas temperature is high.

These demerits have made it difficult to apply this method to construction equipment whose engine room is usually narrow and the exhaust gas of which shows high temperature. In this project, we opted for a method of coating catalyst direct on the filter surface, as has been the case with a ceramic exhaust muffler. **Fig. 3** and **Fig. 4** show the structures of both DPF systems, and **Table 1** compares their performance.

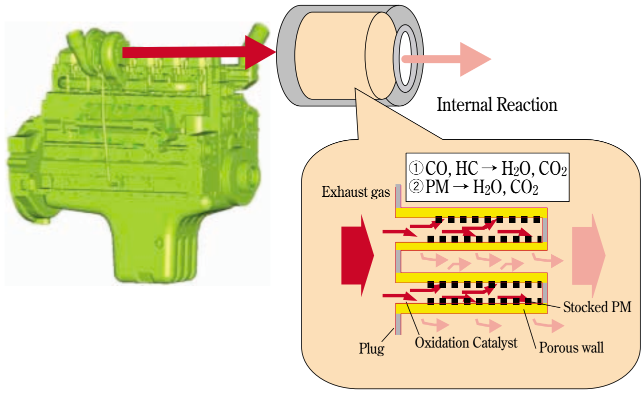

Fig. 3 Direct oxidation type DPF

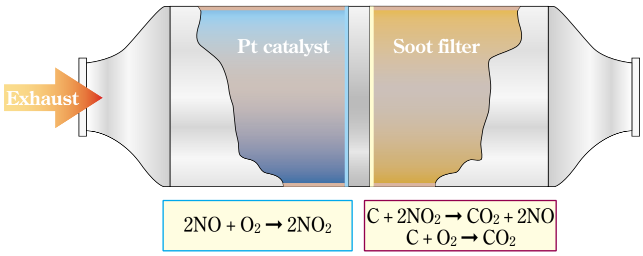

Fig. 4 Indirect oxidation type DPF

Table 1 Comparison of DPF systems

Regenerative Method	Regeneration by Catalyst		Regeneration by Heater (switching type)
	Direct oxidation type	Indirect oxidation type	
PM arresting efficiency	○	○	× (When fiber is in use)
Burning condition Low temperature	○	○	◎
High temperature	◎	×	◎
Impact by NOx	△	×	◎
Durability Broken honeycomb	○	○	×
Deteriorated catalyst	○	◎	—
Impact by sulphur content	△ (PM increases)	×	◎
Complexity in control	◎	◎	×
Occupied space	◎	○	×
Cost Initial cost	◎	○	×
Maintenance cost	○	◎	×
System evolution (Bonding with DeNOx catalyst)	◎ (Possible)	△ (Possible but location restricted)	○
Overall judgement	◎	○	×

3. Komatsu's DPF development concept

Komatsu started with the manufacture of DPF (ceramic exhaust muffler) for application to tunnels managed by the then Ministry of Transport (currently Ministry of Land, Infrastructure and Transport) in 1989, and has maintained the manufacture up to the present. Now our DPF has to overcome the following problems to clear future regulations.

(1) PM arresting rate is rather low.
The Ministry's rule stipulates that the soot arresting rate be more than 80%, which our DPF certainly satisfies. But when PM is taken up as a whole, the arresting rate is lower than 80%, not sufficient to undisputedly conform to Tier 4.
(2) Life and cleaning interval is short.
So long as the application is limited to tunnel specifications, no complaint has been filed against the current life of the initial 1000 hours plus another 500 hours after reversal, 1500 hours in total. But when it is installed in construction equipment in general, the maintenance interval must be drastically prolonged.
(3) DPF occupies large space and is not easy to install.
When the current ceramic exhaust muffler was developed for the first time, people showed little interest in the product inside the company. Moreover, there was not a sufficient variety of filter size available in those days. As a result, several pieces of DPF of the same size had to be put together and used in a set, which led to larger weight and installing space. In some instance, they were mounted on top of the engine hood.

Taking those drawbacks into consideration, the following targets are set in the development of a new DPF.
(1) High PM arresting rate
(2) Longer cleaning interval and longer life
(3) Compact and interchangeable with the current exhaust muffler

4. Avenue and features

If the DPF performance was limited only to the PM arresting rate, there was already a DPF developed that had attained approx. 90%. But this is a world of ambivalence. A higher arresting rate is liable to easier clogging, which in turn means a shorter life. To achieve a longer life, all that should be done is to simply increase the filter capacity, but at the expense of compactness. An assignment the design engineers were faced with then was how to compromise the contradicting factors, optimizing each component. What made a great contribution to the solution of this problem was a high- density cell. **Fig. 5** shows a 300 cpsi cell which we adopted this time and a 100 cpsi cell, as contrasted with each other. The former has an area 1.7 times as large as the latter in the same volume. That is translated into a catalyst surface area enlarged that much and lower pressure loss.

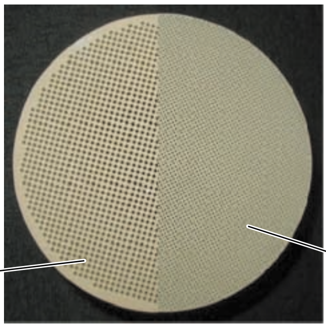

Fig. 5 Comparison of new and old filters

The second improvement was about catalyst. A coating method different from the preceding one was applied to DPF for the first time. The new method contributed to improving the reaction and enhancing durability of DPF. While considering a unique characteristic in the application of construction equipment that they are commonly used under the heavy load condition, we succeeded in drastically reducing the consumption of precious metal used for catalyst. Precious metal accounts for the most part of the catalyst production cost, therefore, its reduced consumption largely contributed to the overall cost reduction efforts.

The third improvement was to assure even gas flow at the inlet. Unlike buses and trucks, an exhaust muffler is housed in the engine room in the case of construction equipment. In this regard, gas flow-in and flow-out in the axial direction is desirable from the standpoint of even gas flow. Construction equipment cannot adopt this gas flow pattern due to the above reason. Instead, a pattern of gas flow-in and flow-out in the radial direction is adopted in most cases of models. It is understood from **Fig. 6** showing a rough sketch of an exhaust muffler that gas at the inlet is deflected in the opposite direction to flow-in and naturally causes soot to pile up. In that case, a large heat distribution occurs at the time of burning and the muffler is highly likely to fail.

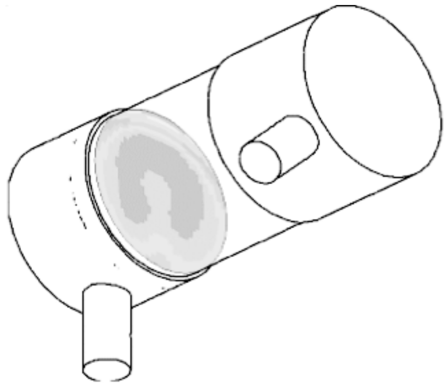

Fig. 6 Distribution of gas flow at inlet (conventional type)

We carried out a CFD analysis to correct the drawback as discussed above, and **Fig. 7** shows an improved exhaust muffler that is resulted from the analysis. It is provided with a perforated cylindrical metal sheet and a resistance plate at the inlet, which are supposed to optimize magnitude and location of resistance in the gas flow to assure even gas flow.

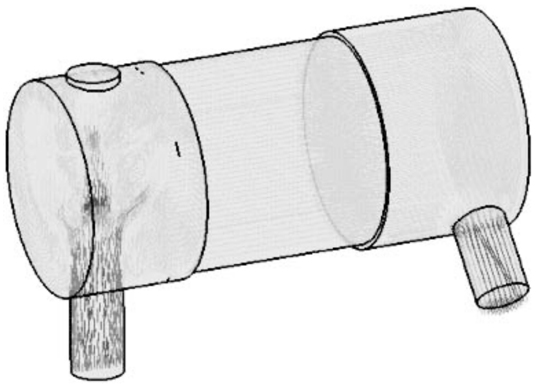

Fig. 7 Distribution of gas flow at inlet (improved type)

5. Determining filter size

A factor determining the filter size is its cleaning interval and the life up until the next replacement. In addition, it is necessary to pay attention to noise abatement, as the filter often doubles as an exhaust muffler.

The filter life is commonly determined as a period until the specified exhaust gas pressure is reached. This exhaust gas pressure is defined as a limit up to which no negative impact is imposed on the engine performance and durability, or as a limit up to which DPF does not fail at the time of soot burning. The biggest factor of pushing up the exhaust gas pressure is a balance between the amount of generated soot and the amount of combustible soot. Even so, it is also necessary to make allowances for the accumulated ash, catalyst deterioration with age, the increase of soot and exhaust gas temperature due to the rising exhaust gas pressure, etc.

5.1 Forecast of generated soot amount

Working modes of construction equipment may be more or less safely sorted out into some patterns. Hence the first assignment is to strike a balance between the generated amount of soot and the regenerated amount after combustion in each pattern. Let's take V shape work by a front-end loader for example. The operation pattern is shown in **Fig. 8**.

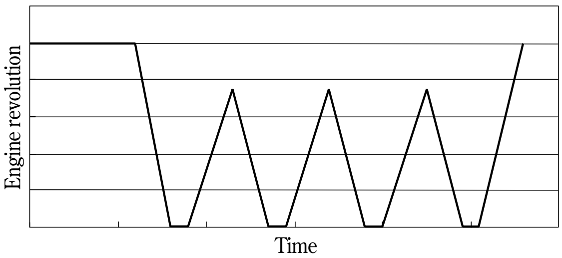

Fig. 8 Front-end loader work cycle time pattern

For the purpose of checking the generated amount of soot, it suffices to bench-test an engine, simulating this pattern and take measurement by means of a full dilution tunnel. But there is a possibility that DPF is retrofitted to various kinds of construction equipment, therefore, we worked out a simpler calculation formula.

For calculating a soot amount generated under the normal and constant operation of an engine, there is a MIRA formula that makes a calculation based on Bosch smoke number.

$$S = 0.982 \times BSU \times 10\wedge (0.1276 \times BSU - 1.66)$$

A point at issue here is an estimate at a transitional period. An acceleration time has been classified into the initial acceleration time when an engine generates a large amount of soot, and the subsequent acceleration time when the soot amount is limited. For the initial acceleration time, a measured Bosch smoke number value was converted using the above formula. For the subsequent acceleration time, a Bosch smoke number value at the peak under the normal, constant operation of the engine was converted again using the above formula. The initial acceleration time was worked out by an opacity measurement. When the calculated value was compared with the value obtained from an experiment by means of a full dilution tunnel, there was comparatively high compatibility with each other. Hence we trust that there is no problem with the use of this simple calculation method. Now Bosch smoke number of the exhaust gas is a function of the exhaust gas pressure. An experiment discloses that it changes linearly. In other words, there is a tendency that the soot concentration rises and the amount of soot piled on the DPF increases, as DPF clogging continues.

5.2 Estimate of burned soot amount

The soot burning amount can be obtained using the Arrhenius equation with a soot combustible amount per unit area of the DPF surface as a function of temperature.

Fig. 9 shows the results of this calculation. Since an operation cycle time of construction equipment is usually comparatively short, the above calculation is made based on a premise that the catalyst temperature remains constant during one operation cycle time. Meanwhile, the exhaust gas temperature is a function of the exhaust gas pressure, and rises as DPF clogging goes on. That phenomenon works to increase the amount of burned soot.

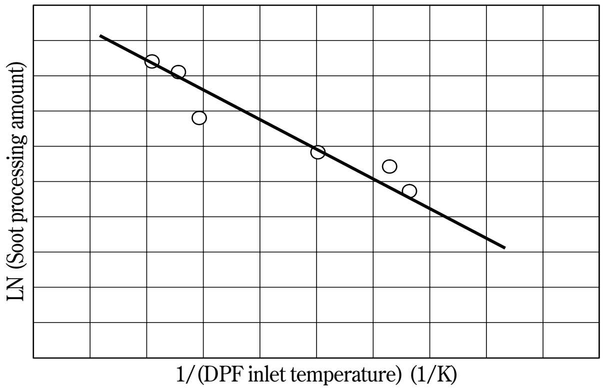

Fig. 9 Catalyst processing capability

5.3 Estimate of pressure loss

The following are included in the category of DPF pressure loss.

(1) Loss due to abrupt expansion or bending of piping at the DPF inlet and outlet
(2) Airflow resistance in a new filter
(3) Airflow resistance due to accumulated soot and ashes

(1) and (2) factors remain invariable in value, while factor (3) changes with age. We first obtained a pressure loss coefficient of the soot unit amount per unit area from increments of the piled-up soot and pressure loss. Then we assumed that the pressure loss coefficient was in proportion to the soot amount and pressure loss was in proportion to the velocity head.

5.4 Deterioration of catalyst

Causes for the catalyst activation to deteriorate are:

(1) Deterioration in activation of the catalyst itself
(2) Reduction of reaction surface due to ashes piled up on the catalyst surface

The type of catalyst that is coated on a filter as in the new DPF is termed "direct soot oxidizing catalyst", and was feared to dissipate through evaporation. But the fact was that a reaction from NO to NO_2 was going on at the same time, and no marked deterioration was noticed. On the other hand, phenomenon (2) above was believed to be steadily taking place, considering the fact that the balance temperature was rising. Hence metallic contents in the lubrication oil as well as sulphuric content in the fuel should be deemed an important factor. We implemented the calculation on the assumption that the extent of deterioration was in proportion to the accumulated ash amount per surface unit area, and the accumulated ash amount was in proportion to the sulphur content in the fuel and fuel consumption amount.

5.5 Results of calculation for simulation

Shown in **Fig. 10** are a comparison between the calculation value and the experimental value regarding the conventional DPF of 2 − ϕ7.5 × 7" with 100 cpsi and the calculation value of the newly developed DPF of ϕ12" × 9" with 300 cpsi.

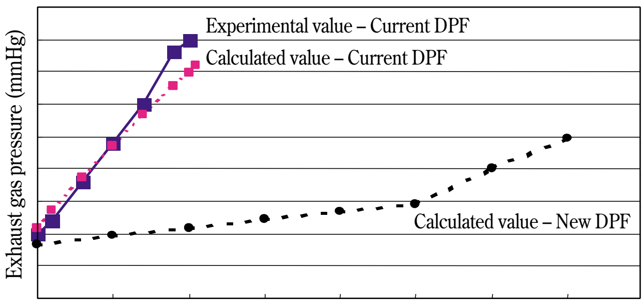

Fig. 10 Result of life estimate

Both the calculated and experimental values of the current DPF show high concurrence except for the last portion. The current 100 cpsi DPF shows gradual accumulation of soot from the initial stage and eventually reaches the pressure limit. With the newly developed DPF, its soot disposal capability exceeds the soot pileup amount for a considerable long time and thereafter the curve rises rather sharply.

We carried out this calculation for each major application of the engines and determined the optimum DPF size. The calculation results are shown in **Table 2**.

Table 2 DPF lineup

Notation	Engine	Volume (ℓ)	Muffler Size (mm)	New DPF (300cpsi)	
				Filter Size	Body Size
KCM-1	3D84	1.5	ϕ150 × 380	ϕ5.66" × 5"	ϕ156 × 375
KCM-1	4D84	2.0	ϕ170 × 465	ϕ5.66" × 5"	ϕ156 × 450
KCM-3	4D95	3.3	ϕ220 × 450	ϕ7.5" × 7"	ϕ203 × 450
KCM-4	4D102	3.9	ϕ220 × 600	ϕ9" × 7"	ϕ241 × 450
KCM-5	6D102	5.9	ϕ280 × 525	ϕ12" × 7"	ϕ318 × 525
KCM-6	6D114	7.2	ϕ280 × 675	ϕ12" × 9"	ϕ318 × 700
KCM-7	6D125	11.0	ϕ280 × 800	ϕ12" × 12"	ϕ318 × 700
KCM-8	6D140	15.2	ϕ340 × 800	ϕ12" × 14"	ϕ318 × 775
KCM-10	6D170	23.2	ϕ460 × 700	2 − ϕ12" × 12"	318 × 697 × 800

A single filter is enough for the Komatsu's line of engines up to 6D140, and a lineup of the filters with almost complete interchangeability with the current exhaust mufflers has been prepared. **Fig. 12** shows the structure and **Fig. 13** shows how the new filter is installed on an actual engine.


Fig. 12 Cross-sectional view of DPF for PC200 excavator engine

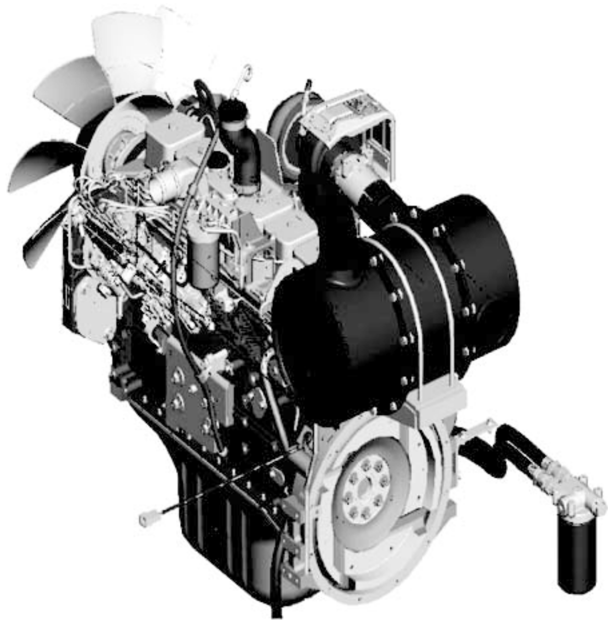
Fig. 13 DPF mounted on PC200 excavator engine

6. Test results

Fig. 14 shows the effect of emission reduction. The newly developed DPF demonstrates excellence over the conventional DPF across all the items of comparison.

Fig. 15 deals with noise characteristics. A damping characteristic nearly equal to that of the conventional exhaust muffler can be obtained from the new DPF. Hence it can well substitute the conventional exhaust muffler.

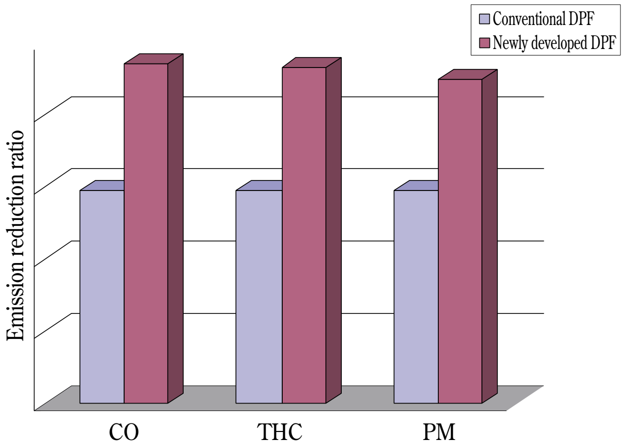

Fig. 14 Emission reduction characteristic

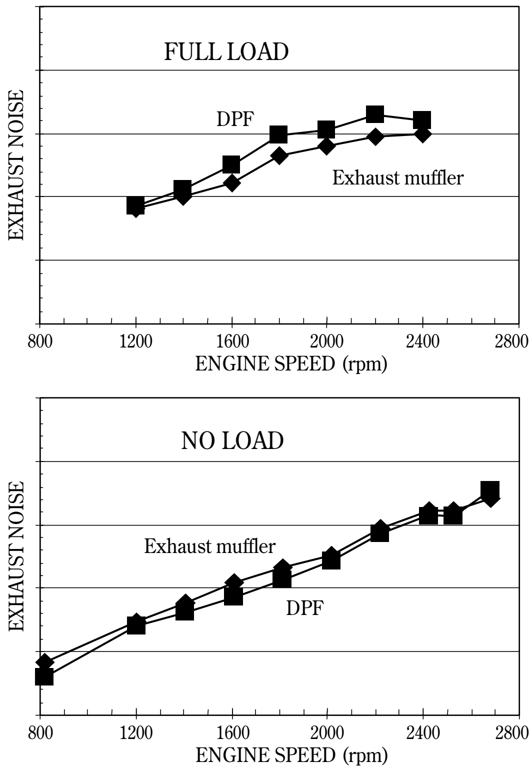

Fig. 15 Noise characteristic

7. Conclusion

We are now confident that utilizing the past experiences with tunnel specifications, we could successfully develop a compact DPF with higher efficiency and longer life plus nearly full interchangeability with the current exhaust mufflers. The new DPF will be able to conform to emission regulations in the near future. As the next step, we will press ahead with further cost reduction so that the cost will not be a stumbling block for the sales promotion efforts. It is our hope to see it will be widely accepted in the world markets now that it has been proven very effective to protecting the environment.

Introduction of the writers

Toshihiko Nishiyama
Entered Komatsu in 1969.
Currently working in Component Research & Development Group, IPA, Ltd.

Nobuhiko Emori
Entered Komatsu in 1983.
Currently working in Component Research & Development Group, IPA, Ltd.

[A few words from the writers]

Our DPF is a product closely connected with the protection of the global environment. Keeping the fact in mind, we have strived to always go even a step ahead of the competitors. Hopefully the product will also boost a good image of our company in the society. The vital parts of DPF, i.e. filters and catalyst, are manufactured based on our suppliers' technology. For this reason, it was rather difficult to characterize the new DPF. It happened, however, that the two suppliers started with the development of new products around the same time and Komatsu was the first to utilize them. We could fully enjoy the good luck.