Study on Hysteresis Phenomena of Diesel Particulate Trap

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ABSTRACT

The reduction characteristics of a particulate trap was studied with various engine operating modes. Hysteresis of total particulate concentration by operating history was observed in constant engine speed test. The concentration of Soluble Organic Fraction (SOF) is effected by the operating history and particulate filter temperature.

The 13 mode steady state tests with additional three modified patterns were conducted to clarify the effect of operating history on trap efficiency evaluation. Particulate concentration is decreased by trap installation. But reduction ratio varied as the test pattern altered. Operating pattern should be determined carefully to evaluate the particulate reduction efficiency.

INTRODUCTION

The particulate trap has potentiality to be an effective after-treatment device for the future emission control. Many kinds of trap system have been developed and tested. Yet, there is few report which researched or referred effect of test mode on particulate trap's evaluation results. There is a few report on absorption / discharge of SOF in catalytic converter as well.[1] In this paper, authors conducted a trap evaluation test with various operating modes[2,3]. The trap system with reverse jet cleaning regeneration is tested to evaluate particulate reduction performance. Characteristics of reduction ratio is studied on not only total particulate but also dry soot and SOF. As SOF in the engine exhaust change its phase as its temperature alters, trapping efficiency tends to vary at the same time. It is important to find the effect of operating pattern on trap evaluation.
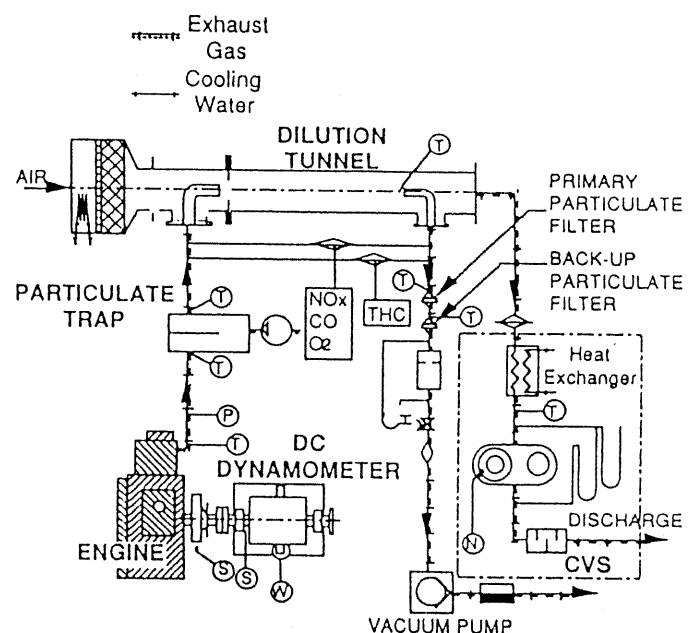
TEST EQUIPMENT AND METHOD

Fig.1 Schematic diagram of evaluation test apparatus

Table 1 Specification of test engine

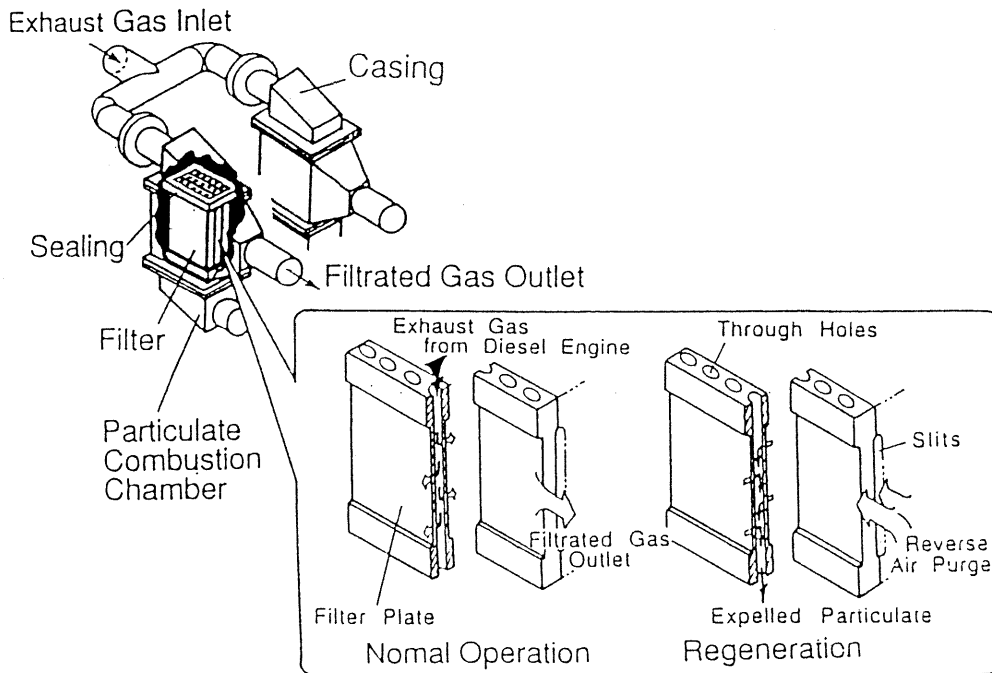| Engine	Water - Cooled Horizontal 4 Stroke Direct Injection Compression Ignition
Cylinder	1
Bore x Stroke	113 x 115 mm
Displacement Volume	1132 ml
Compression Ratio	16.3
Continuous Output	14.2 kW / 2200 rpm
Injection Timing Static Dynamic	17 °BTDC 13 °BTDC
Injection Pump Plunger	Bosch type ø8 mm
Injector Openning Pressure	Hole type 4-0.33 mm 21.1 MPa
Swirl Ratio	2.3 ± 0.1

Fig.2 Schematic of particulate trap and its gas flow

Table 2 Specification of particulate filter

Bulk Density	1.58
Porosity	35-41%
Average Pore Diameter	15 μ m
Bending Strength at 25deg C	28MPa
Thermal Expansion	0.08%

A schematic diagram of the experimental apparatus is shown in Fig. 1. A small size single-cylinder high speed direct injection engine with a combustion chamber of a troidal type has been used as a test engine.

Its specifications are shown in Table 1. Its bore and stroke are 113mm and 115mm, respectively. JIS #2 grade diesel fuel has been used.

The particulate trap consists of a ceramic filter and a reverse flow cleaning regeneration unit. The schematic of the trap and gas flow of the filter is shown in Fig.2. Unlike other conventional particulate traps, collected particulate is not oxidized on the filter wall. Instead, particulate is removed from the filter wall by pulse jet reverse air flow. The particulate is collected in the combustion chamber which is located at the vessel bottom. Particulate is burnt by electric heater. Common failures of filter wall melt-down and crack during oxidizing particulate on the filter wall are eliminated by using this method.[4] Specifications of ceramic filter are

shown in Table 2.

Particulate reduction efficiency is evaluated with the full-flow dilution tunnel. The inner diameter of the tunnel is 208mm.

The trap has been installed 1.5m downstream from the engine's exhaust port. When the trap was not installed, a straight pipe of SUS304 was attached..

A PTFE coated filter (Pallflex TX40 HI-20-WW) with a filtration accuracy of 0.3 μ m has been used as a particulate collecting filter. SOF in particulate has been separated by Soxhlet extracting method using dichloromethane as a solvent. In this case, solvent temperature has been 60 deg C and extracting time was six hours. THC in the exhaust gas was measured by HFID method.Temperature of the sampling line was heated to 191 deg C. Exhaust gas temperature is measured at 50mm downstream of exhaust port. Temperatures at inlet and outlet of the trap were also measured. The temperatures were measured by type-K thermo-couples

TEST RESULTS

Constant Engine Speed Test

The relation between total particulate concentration (dry soot and SOF) and engine load at engine speed of 1500rpm is shown in Fig.3. In the case where trap is installed, mark ▲ is for the case where engine load was increased in steps from 0%. Mark ■ is for the case where the load was decreased from 110%. In both cases, total particulate concentration was reduced by trap installation In case where the trap is installed, total particulate concentration when engine load increased differs from that of decreased. That is, total particulate concentration has hysteresis against engine load when the trap is installed.

The relations of dry soot concentration and SOF concentration against engine load under the conditions are shown in Fig. 4 and Fig.5. In this case where the trap is installed, mark △ is for the case where engine load was increased in steps from 0% and mark ☐ is for case where the load was decreased from 110%. The test engine has general characteristics of particulate emission of direct injection diesel engines. The concentration of dry soot is low and the concentration of SOF is high in the low engine load. The concentration of dry soot is high and the concentration of SOF is low in the high engine load.

Dry soot concentration shown in Fig. 4 can be remarkably decreased with the trap in the high load range where its concentration is high. In the low load range, the concentration of emitted dry soot is low and within the limit of measurement precision regardless of the trap installation. In both high and low ranges, dry soot concentration is kept sufficiently low by the trap installation. The difference in dry soot concentration is little in comparison with total particulate and SOF at the same load between two cases when the engine load increased and decreased, and it is in the limit of measurement precision.

SOF concentration in Fig. 5 shows different result from dry soot concentration in Fig.4. The emission of SOF was observed in high engine load when the load is gradually increased. At 100% engine load, the concentration with trap is greater than the value of without-trap. When the trap was installed, the hysteresis of SOF and the total particulate concentration becomes identical. The hysteresis of total particulate concentration seemed to be caused by SOF concentration hysteresis.
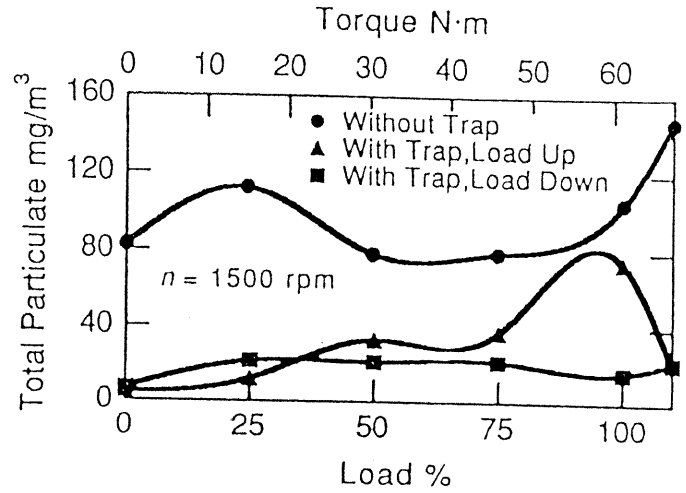

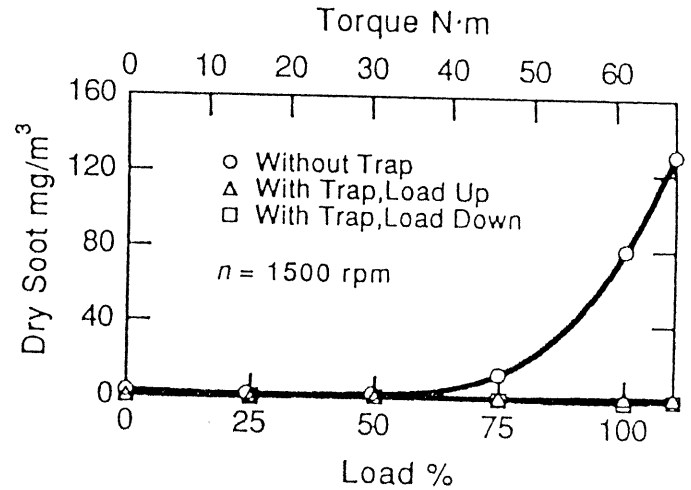Fig.3 Effect of load variation on total particulate

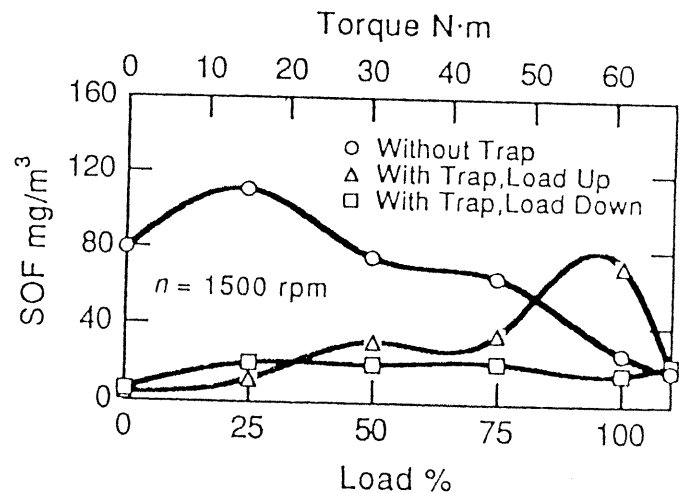Fig.4 Effect of load variation on dry soot

Fig.5 Effect of load variation on SOF

Phenomena observed in the tests is explained as follows.

1,SOF exists in different forms, such as gaseous or liquid state depending on its temperature.

2.Boiling point of SOF content distributes in gas temperature of the evaluating tests.

3.Regeneration by reverse jet cleaning can remove dry soot trapped on the filter wall, while SOF remains on the filter wall.

4.When both engine load and filter temperature are low, SOF is accumulated on filter.

5,Once the SOF is accumulated on the filter and its temperature rises by high load engine exhaust, discharge of SOF takes place. the discharge ends when SOF vaporization is over.
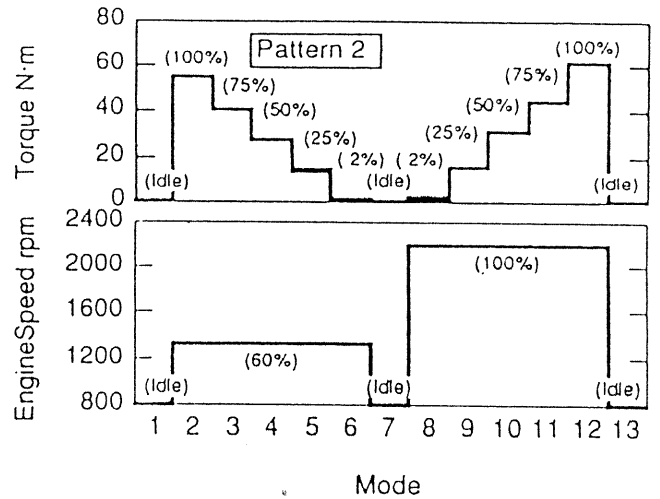
13 Mode Test

In order to evaluate the effect of engine load history on trap reduction evaluation, the mode tests were conducted. The 13 mode test which is practically used to evaluate the heavy-duty engine is modified to four patterns including its original form as shown in Fig.6. Pattern 1 is the regular combination of engine speed and engine load, equivalent to SAE J1003. Other three have combination of different sequence of the speed and the load. Pattern 2 has the same sequence of the engine load and reverse speed sequence. Pattern 3 has the same sequence of engine speed, but reverse sequence of engine load. Pattern 4 has reverse sequence of both speed and load.

Each mode has run time of 600 second at the evaluation test. Length of sampling of total particulate at the downstream of the trap was 300 seconds. SAE J1003 weighing factor was used for the mode average calculation of mode average particulate concentration. 30 minutes of engine rating run was conducted prior to each pattern test. The aim of the run is to equalize the amount of residue SOF in the filter.
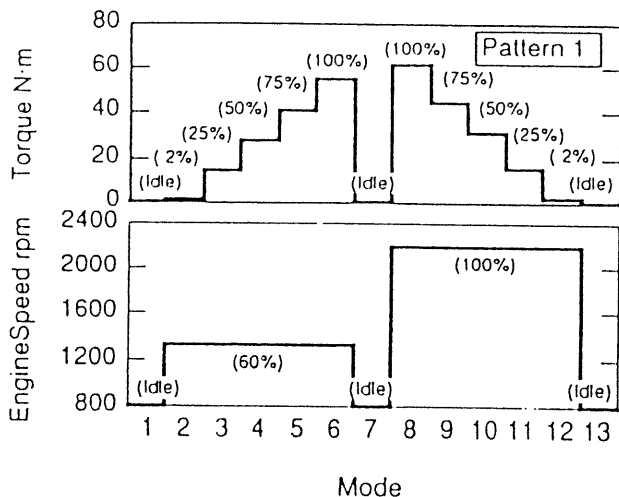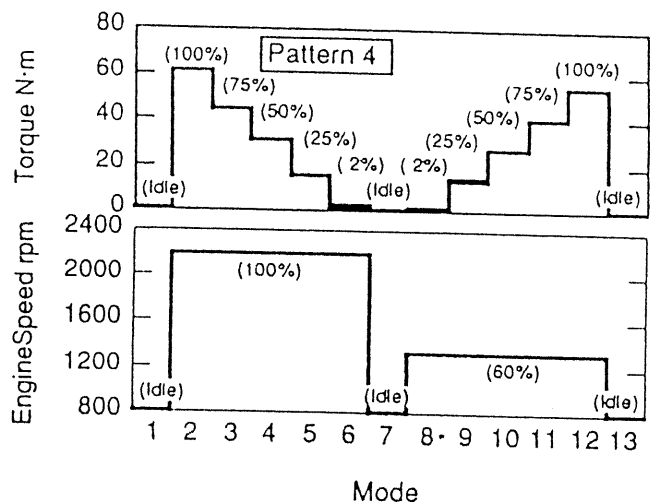

(a) Pattern 1

(b) Pattern 2
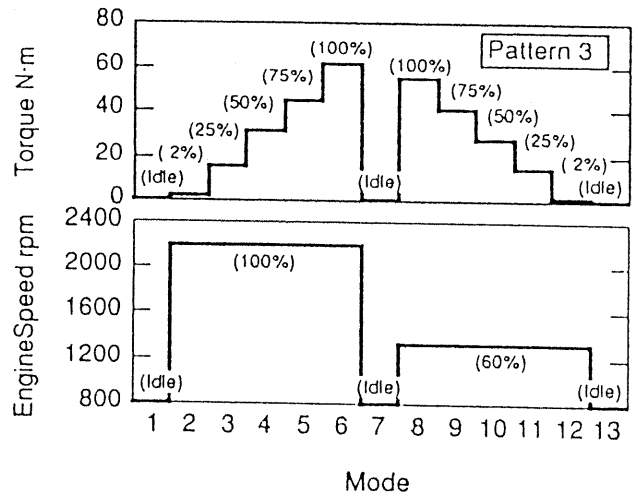
(c) Pattern 3

(d) Pattern 4

Fig.6 13 mode tested pattern

13 Mode Test Results

Test results of 13 mode pattern 1 to 4 are shown in Fig.7. Left column of each mode shows value without trap and right, value with trap. Concentration of dry soot (Insoluble Fraction) is reduced in all patterns. The trap is effective to reduce dry soot in the diesel exhaust. Total particulate concentration differs in each pattern and each mode. SOF concentration is notably different in each test with trap installation.

In pattern 1, which is equivalent to the original, SOF concentration increases in modes 6, 8 and 9. SOF concentration with the trap exceeds the value without one. This is discharge of SOF, accumulated in the filter while exhaust gas temperature is low in modes 1 through 5. Amount of discharged SOF decreases as the exhaust temperature declined with lesser engine load.

In pattern 2, with reverse speed sequence, SOF concentration remains low in mode 1 to 8. Then, discharge of SOF was observed in modes 10 to 12. SOF is accumulated to the filter when filter temperature is low in modes 1 and 3 to 8. As mode 2 with 100% load with 60% speed emerged in early part of the test, SOF discharge is not obvious in this mode. Increase of discharged SOF in modes 10 to 12 of pattern 2 is greater than that in modes 6 to 8 of pattern 1

In pattern 3, total particulate concentration decreased in all modes by the trap installation. Less SOF accumulation to the filter in modes 2 to 6 is considered to be the reason. Rating engine speed in those modes tends to keep the filter temperature high. (Patterns 1 and 2 have 60%of rating speed in the same modes.) Amount of SOF accumulation to the filter is little when engine load is high in modes 8 and 9. Because small amount of SOF is contained in the exhaust gas. These are considered to be the reasons for the less concentration in pattern 3.
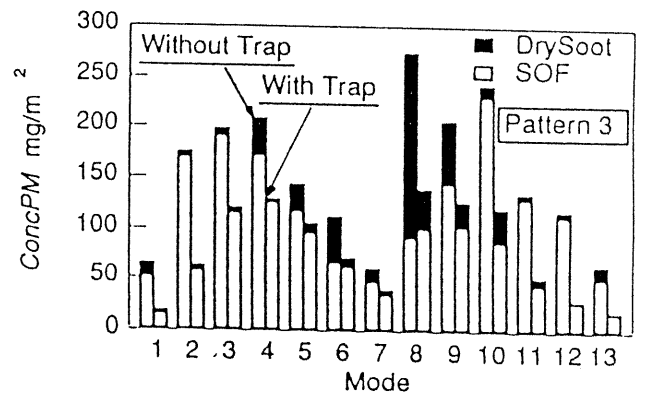
In pattern 4 with reverse sequence of engine load and engine speed, total particulate concentration decreases in all modes with trap installation.
The reason for the result is relatively low temperature in modes 10 to 12 with 60% engine speed.
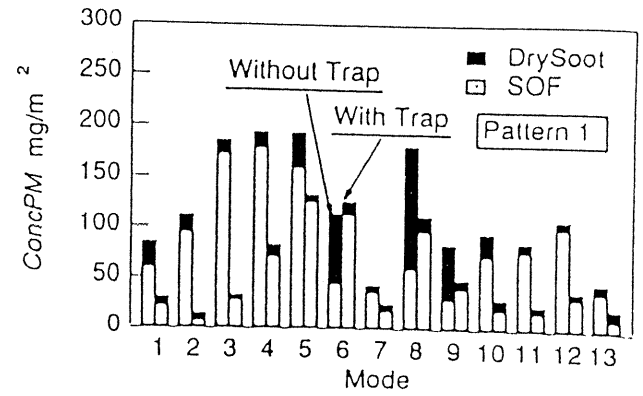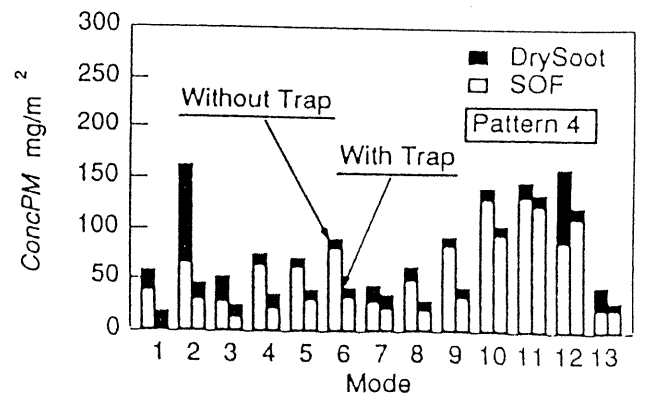

(a) Mode Pattern 1
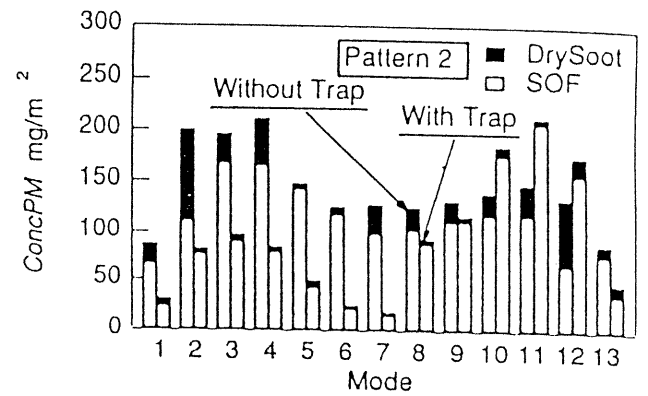
(b) Mode Pattern 2

(c) Mode Pattern 3

(d) Mode Pattern 4

Fig.7 Particulate concentration

Effect of Inlet Gas Temperature

The relation between SOF concentration ratio (with trap/without trap) and trap inlet gas temperature is shown in Fig.8. It is the case of 1320 rpm,60% engine speed. When the SOF concentration exceeds 1, it means that the SOF concentration was increased by the particulate trap installation.The concentration ratio increases as the Inlet temperature rises. It is observed that the SOF discharge and inlet gas temperature have close relation. It is also seen that mode pattern or mode history influences concentration ratio. That is, when load is in increasing state, SOF discharge phenomena becomes more obvious than that of decreasing state.

As filter temperature decides state of SOF and is a dominant factor of the discharge phenomena, heat capacity of the filter influences the test result, too.
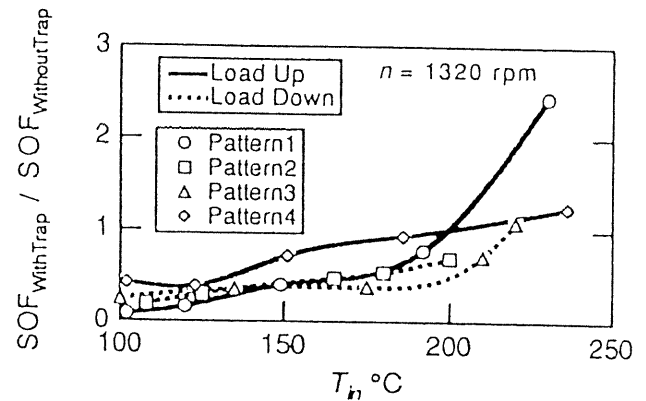
13 Mode Average Reduction Ratio

Specific Emission of Particulate Matter and reduction ratio of each mode pattern average are shown in Fig.9. Both SEPM and reduction ratio of dry soot (ISF) do not show any connection to the test pattern.

Dry soot concentration was constantly reduced by the trap installation. SEPM and reduction ratio of SOF widely varied from pattern number. It is also inconsistent when trap is not installed. SOF reduction ratio in pattern 2 is 7%, while in other three patterns, the ratio is between upper 30% and 50%. Total particulate reduction ratio in pattern 2 was 22% which was also the lowest among the four patterns. Total particulate concentration, specially SOF reduction rate was strongly effected by evaluating pattern with trap installation. For instance, pattern 1, equivalent to formal SAE evaluation pattern, gave the best result of trap efficiency (or reduction rate) while pattern 2 resulted in the poorest performance. In order to evaluate the performance of the particulate trap, it is very important to select adequate evaluation mode.

CONCLUSIONS

1.Particulate reduction ratio is influenced by testing mode pattern. Evaluation test mode for the particulate traps should be determined reasonably.

2.SOF reduction ratio varies as operating pattern and operating history changes while dry soot reduction ratio is constantly high.

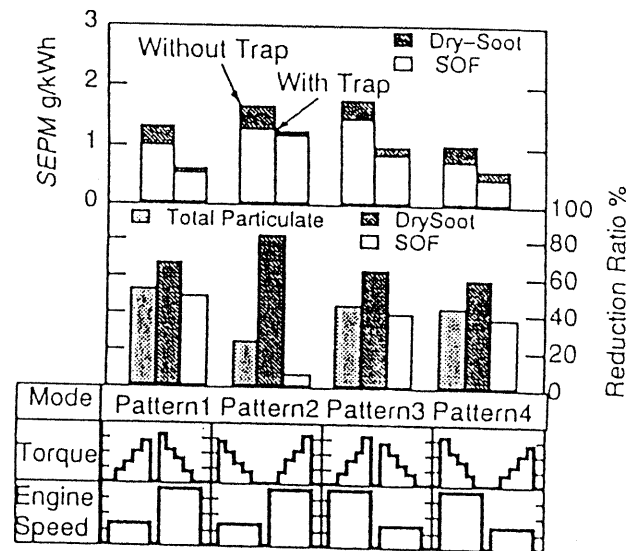3.SOF accumulation/discharge behavior is firmly linked to filter temperature.

Fig.8 Effect of trap inlet temperature on SOF concentration ratio

Fig.9 Effect of mode pattern on particulate emission

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3)Funayama,Tanabe,Sato Study on Diesel Particulate Trap, Society of Internal Combustion 10th Annual Symposium 1992

4)Takesa,Uchiyama,Enamito,   Development of Particulate Trap System with Cross Flow Ceramic Filter and Reverse Cleaning Regeneration, SAE Paper 910326 (1991)