

Optimization of PM Measurements with a Number Counting Method

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ABSTRACT

Repeatabilities of PM measurements on a heavy-duty diesel engine equipped with a diesel particulate filter (DPF) using a filter weighing method and a number counting method with a full flow dilution system and a partial flow system were evaluated. The filter method with partial flow exhibited the best repeatability. However, a good correlation between the full flow and the partial flow number counting results suggests that the fluctuations observed using the number counting method were caused by changes in the engine exhaust. Applying a strict preconditioning procedure should improve the repeatability of the number counting method because this method is more sensitive than the filter weighing method. In addition, the effects of the specifications for the number counting method were evaluated. The results indicate that the hose length from the tip of the sampling probe to the inlet of the number counting system had a negligible effect. In the cold mode, particle adsorption in the full flow dilution system was observed, and it was remarkable when the induction hose temperature was below 30 °C.

INTRODUCTION

Particle emission from vehicles is regulated by weighing a filter which traps particles from the exhaust. However, there is concern that the health effects from PM are not a function of the weight, but of the surface area or the number density of the particles [1-3]. In addition, the amount of PM emission from a diesel engine with a diesel particulate filter (DPF) is difficult to detect consistently using the traditional filter weighing method [4]. As a result of these arguments, the European Commission has decided to introduce a new particle emission measurement method for a type approval test of light duty vehicles [5] based on discussions of the Particle Measurement Programme (PMP) of GRPE under UNECE [6]. It is a number counting method which uses a two-stage dilution system with hot and cold air to remove volatile particles [7], and several commercial devices to measure the particle number by using the PMP method have been developed [8-10].

Recently, application of the number counting method to heavy-duty diesel engines has become the focus of interest. The number counting method is evaluated in relation to the repeatability and reproducibility in comparison to the traditional filter weighing method using the exhaust from a DPF-equipped diesel engine. In addition, researchers are concerned with its compatibility with a partial flow dilution system. It has been suggested that the number counting method has a higher sensitivity than that of the filter weighing method. However, there is a concern that this higher sensitivity will cause more fluctuations in the results. A round robin test and a validation exercise for evaluating the repeatability and reproducibility have been planned under the PMP framework.

In advance of the PMP activity, this paper reports the repeatability of the number counting method, its compatibility with a partial flow system, and the effects of the system specifications on the results. The repeatability tests and the compatibility tests were performed by comparing the results of the number counting and filter weighing methods in WHTC cold, WHTC hot, ETC, WHSC, ESC, and JE05 modes. Effects estimations were carried out using continuous WHTC cold and WHTC hot modes. Effects of DPF soot loading, probe location in the number counting system, and the length of induction hose of the probe were examined.

EXPERIMENTAL SETUP

Specifications of the test engine are listed in Table 1. A Hino 7.684 L 6-cylinder engine, which was equipped with an intercooler, a turbocharger, a common rail injection system, and a DPF, was used. Its emissions met Japan's 2005 regulations, which are almost the same as the EURO IV regulations.

Figure 1 shows the experimental setup. Exhaust gas from the engine through the DPF was introduced into the full flow dilution system and the partial flow dilution system. In the full flow dilution system, a two-stage dilution system was used. The flow rate of the primary dilutor in the full flow system was set to 50 m³/min. The split ratio of the partial flow was set to 350, which corresponds to a dilution factor of almost 23. The

parameters were set to keep the temperatures of the filter holders, which were located downstream of the dilution systems, below 52 °C. Both diluted gases from the full and partial flow systems were introduced into the filter holders and the number counting system. There were cyclones, of which the 50% cut off point was 2.5 µm, upstream of the filter holder, and they were kept at 47 ± 5 °C.

Table 1 Specifications of the test engine.

Engine Model	J08E-TP
Constructor	Hino
Configuration	Inline 6 cyl. w/ I.C, T. C
Bore x Stroke	112 x 130
Inj. System	Common Rail (Max 1600 bar)
Emission Reduction Devices	DPF w/ CAT, Cooled EGR
Displacement	7.684 L
Compression Ratio	18
Max Power	117 kW / 2700 rpm
Max Torque	716 N-m / 1600 rpm
Emission level	2005 Japan NOx and PM 10 % reduction

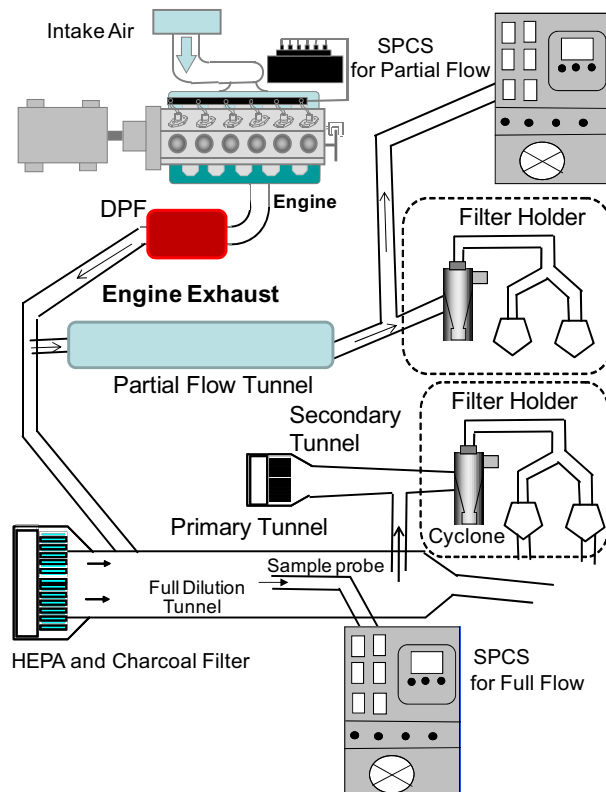


Fig. 1 Experimental apparatus.

TX 40 filters with a diameter of 47 mm were employed for this study. The sample PM was weighed 24 h after the test using a microbalance with a minimum graduation of 0.1 µg. During the soaking time, the trap

filters were kept in an air-conditioned chamber at a temperature of 22 ± 5 °C and a relative humidity of 45 ± 8%. These settings for the filter weighing method meet with US 2007 regulations [11].

In the number counting system, two MEXA1000-SPCS (Horiba) were used for both the full and partial flow systems. Settings and conditioning procedures were the same for each flow system. This system meets with the PMP methodology shown in Fig. 2. Gas was sampled from the primary dilution tunnel and introduced into PND 1 via a cyclone pre-classifier. A 2 m hose heated to 191 °C was used as the induction hose into the cyclone from the dilution tunnel. At PND 1, the gas was heated to 150 °C and diluted with hot air at the same temperature. After that, the gas was introduced into PND 2 through the evaporation tube, which was kept at 300 °C. At PND 2, the gas was diluted with air at ambient temperature, and the mixture was introduced into the particle counter. These procedures remove volatile particles, which cause fluctuations in the measurements. In this study, dilution factors for PND 1 and PND 2 were set to 15 and 20, respectively. The recent PMP methodology requires that the results be adjusted using fr , which is the mean penetration efficiency of 30, 50, and 100 nm diameter particles through the volatile particle remover (VPR). However, in this study, this adjustment was not performed.

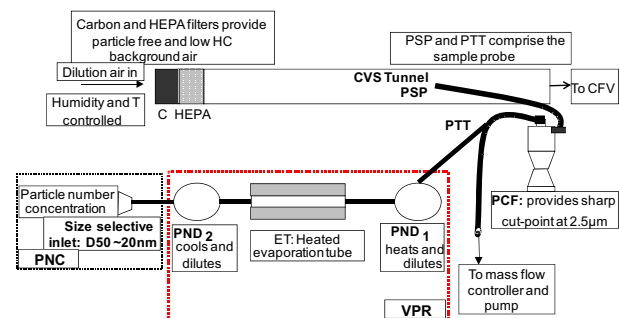


Fig. 2 Schematic of the PMP number counting system.

Both particle number counters (PNCs) used in this study were calibrated by using the AIST PNC calibration service [12]. The PNC detection limits are shown in Fig. 3. A recent requirement for the PMP methodology is that the counting efficiencies for particles with electrical mobility diameters of 23 ± 1 nm and 41 ± 1 nm must be 50 ± 12% and >90%, respectively [13]. This requirement is shown as black rectangles in Fig. 3. The fall off curve of the partial flow PNC lies slightly on the smaller side of that of full flow PNC, and the 50% cut off point was near the border of the area of the PMP requirement. Calibrations using the AIST standard number counter were performed at 5 points in the concentration range from 2 × 10³ to 1 × 10⁴ #/cm³. Both PNCs showed good linearity, and deviations from the standard number counter were less than 5%.

RF06-03 fuel was used as a test fuel, since it will also be used in the PMP validation exercise. For the

repeatability estimation, WHTC cold, WHTC hot, ETC, WHSC, ESC, and JE05 modes were tested 8 times each.

The apparatus allowed us to observe 4 different PM measurements (filter weight with full flow, filter weight with partial flow, number counting with full flow, and number counting with partial flow) simultaneously.

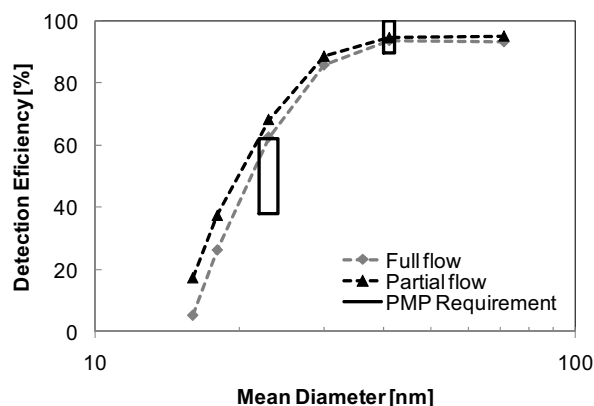


Fig. 3 Detection efficiency of the PNCs for full flow and partial flow systems as a function of the mean particle diameter.

RESULTS

COMPARISON OF THE REPEATABILITY BETWEEN THE FILTER WEIGHING AND NUMBER COUNTING METHODS – Figure 4 shows the mean PM emissions and COV values obtained from the filter weighing method with full flow and partial flow. The results using the full flow system were slightly higher than those using the partial flow system. It is suggested that the longer travel distance of the PM sample in the full flow system results in higher adsorption into the walls or other places. The results of all modes except JE05 were almost the same: 1 mg/kWh for full flow and 2 mg/kWh for partial flow. The PM values in the JE05 mode were two times higher than those in the other modes. The absolute COV values with full flow and partial flow were almost 0.5 and 0.15, respectively. In other words, the values differ from each other by nearly a factor of 3. The net weights of the trapped PM with full flow were on the order of 1 μg , and those with partial flow were on the order of 10 μg . Therefore, the small amount of trapped PM results in higher fluctuations in the full flow results.

Figure 5 shows the mean PM emissions and COV values using the number counting method. There were no remarkable differences in both the mean PM emission and COV values between full flow and partial flow systems. In the case of the filter weighing method, the highest emission was observed in the JE05 mode. However, in the case of the number counting method, the highest emission was observed in the WHTC cold mode, which is the only cold start mode in this study, suggesting that the low exhaust gas temperature at the beginning of the cold start mode prevents the VPR in the

number counting system from effectively removing the volatile particles. COV values (~ 0.5) with full flow and partial flow, shown in Fig. 5, were similar to each other, and they were almost the same as those from the full flow filter weighing method. The results in the ETC and ESC modes had standard deviations that were larger than the mean values.

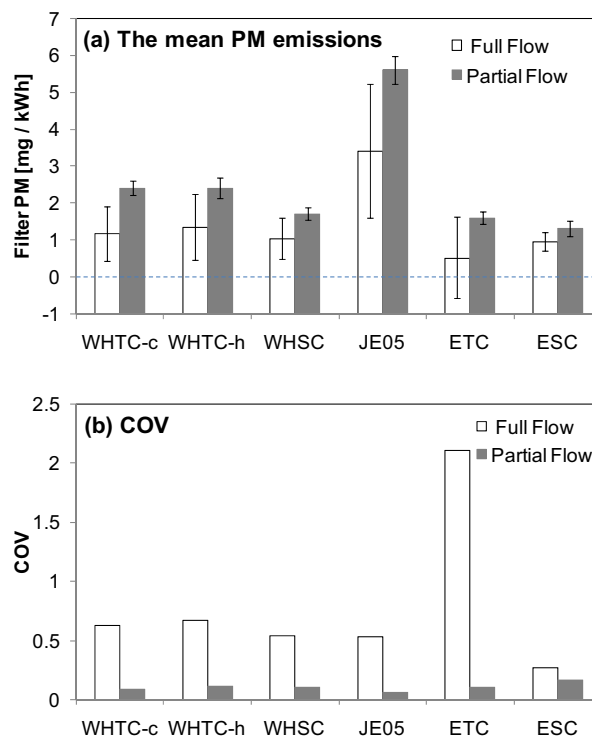


Fig. 4 Mean values of PM emission using the filter weighing method (a) and COV (b) in various test modes.

Figs. 4 and 5 indicate that the repeatabilities of the number counting method with full flow, the filter weighing method with full flow, and the filter weighing method with partial flow were almost the same. The filter weighing method with partial flow had the best repeatability because the amount of PM trapped by the filter was larger. Figure 6 shows the mean values of the ratio of the full flow and partial flow results (F/P) from 8 runs of simultaneous tests in each mode and COVs of F/P acquired from the filter weighing method. F/P values in Fig. 6 were almost 0.6 for each mode. As with the results shown in Fig. 4 (a), some values of F/P were smaller, which may be due to adsorption of particles onto the system walls of the full flow system. COV values were almost the same as those from the full flow weighing method, shown in Fig. 4 (b). This is because, although COV values from the partial flow weighing method were low, the high fluctuation in the values from the full flow filter weighing method results in high COVs of the filter weighing F/P.