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NANO-PARTICLE EMISSION CHARACTERISTICS OF EUROPEAN AND WORLDWIDE HARMONIZED TEST CYCLES FOR HEAVY-DUTY DIESEL ENGINES

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ABSTRACT−This study was conducted for the experimental comparison of particulate emission characteristics between the European and World-Harmonized test cycles for a heavy-duty diesel engine as part of the UN/ECE PMP ILCE of the Korea Particulate Measurement Program. To verify the particulate mass and particle number concentrations from various operating modes, ETC/ESC and WHTC/WHSC, were evaluated. Both will be enacted in Euro VI emission legislation. The real-time particle emissions from a Mercedes OM501 heavy-duty golden engine with a catalyst based uncoated golden DPF were measured with CPC and DMS during daily test protocol. Real-time particle formation of the transient cycles ETC and WHTC were strongly correlated with engine operating conditions and after-treatment device temperature. The higher particle number concentration during the ESC #7 to #10 mode was ascribed to passive DPF regeneration and the thermal release of low volatile particles at high exhaust temperature conditions. The detailed average particle number concentration equipped for golden DPF reached approximately 4.783E+11 #/kWh (weighted WHTC), 6.087E+10 #/kWh (WHSC), 4.596E+10 #/kWh (ETC), and 3.389E+12 #/kWh (ESC). Particle masses ranged from 0.0011 g/kWh (WHSC) to 0.0031 g/kWh (ESC). The particle number concentration and mass reduction of DPF reached about 99%, except for an ESC with a reduction of 95%.

KEY WORDS : European cycles, Worldwide harmonized test cycles, Nano-particles, Condensation particle counter, Differential mobility spectrometer, Diesel particulate filter

1. INTRODUCTION

To address the worldwide climate change problem, the EU (European Union), Japan, California, and Korea have been establishing or tightening CO_2 and fuel economy standards for automobiles. Increasingly stringent exhaust emission regulations have resulted in the development of more energy efficient and environmentally friendly internal combustion engine technologies (Kim and Lee, 2007; Zhao, 2010).

Diesel is the most efficient internal combustion engine fuel providing more power and fuel efficiency than gasoline, CNG (compressed natural gas), and LPG (liquefied petroleum gas) (Arcoumanis *et al*., 2008; Ristovski *et al*., 2000, 2005). Although diesel engines perform well with respect to low CO, HCs, and CO_2 emissions, diesel combustion inherently tends to produce significant amounts of PM (particulate matter) caused by incomplete combustion around individual fuel droplets in the combustion zone (Eastwood, 2008; Rakopolous and Giakoumis, 2009). PM has been suspected of causing acute and chronic damage to the human pulmonary and cardiovascular systems by the CARB (California Air Resources Board) (Anderson *et al*., 2001, 2004; Kittelson, 1998; Kittelson and Simone, 1999). Currently, the diesel PM standard is not based on the particle number (#/km), but rather on the particle mass (g/km) which can not sufficiently represent the toxicity of diesel-oriented nano-particles (Myung *et al*., 2009a; Sturgess *et al*., 2008; Vouitsis *et al*., 2003).

Thus, the international PMP (Particle Measurement Programme) has been developing a new particle number measurement technique through the ILCE (Inter-Laboratory Correlation Exercise) on LDVs (light-duty vehicles) for Euro V standards and on heavy-duty engines for Euro VI standards, to complement or replace mass-based PM measurement procedures (Anderson *et al*., 2007, 2010; Lee *et al*., 2008, 2009; Roberto *et al*., 2007). Number-based PM measurement procedure prevents the possibility that the Euro VI PM mass limit is met using open filters that would enable a high number of ultra fine particles to pass (Giechaskiel *et al*., 2008b; May *et al*., 2007, 2008). In particular, two golden engines meeting the Euro III emission regulation were employed in the PMP to develop and finalize a robust inter-laboratory guide for heavy-duty engines testing under UN-GRPE phase 3 ILCE for the VE (validation exercise) with the IVECO Cursor 8 engine and

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round-robin with Daimler engine, respectively (Anderson and Clarke, 2008). For the round-robin tests, laboratories from the EU, Japan, Korea, and Canada are participating. In test procedures for heavy-duty diesel engine, the WHTC (worldwide heavy-duty transient cycle) and WHSC (worldwide heavy-duty steady-state cycle) are scheduled to replace the conventional ESC (european stationary cycle) and ETC (european transient cycle) in the emission legislation for Euro IV (Giechaskiel *et al*., 2008a; May *et al*., 2007; TRANS-WP29-GRPE-41, 2001).

The purpose of this study is to report the experimental evaluation results on the particle numbers and mass concentrations, particle size distribution, filtration efficiency of DPF (diesel particulate filter), and repeatability of the European and WHTC (world-harmonized test cycle) for a heavy-duty diesel engine as part of the UN/ECE PMP ILCE in the Korea PMP. These results will be used to establish a nano-particle numeric standard for heavy-duty diesel engines, and provide repeatability and reproducibility criteria for domestic round-robin testing.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1. Specifications of Test engine and Procedure

Heavy-duty diesel engine and exhaust systems, including exhaust pipes with DPF and EMS (engine management systems), were provided by the PMP for the international ILCE. The engine is a turbocharged Euro III-compliant Daimler OM501 equipped with catalyst-based uncoated DPF. Detailed engine specifications are summarized in Table 1.

Engine setting and speeds conditions for various test modes were followed based on PMP procedures (Stein, 2008). Domestic RF-06 grade diesel fuel with sulfur content below 10 ppm was employed. A single batch of fuel was supplied by SK Energy, and its specifications are given in Table 2. Before testing the engine, 10W-40 grade engine oil was flushed and filled to eliminate lubricant effects on nano-particle emissions.

The testing procedure for the heavy-duty engine was strictly followed to provide the variability of repetitions in particle measurements. The test protocol for the ILCE consisted of at least eight repetitions of cold WHTC, hot WHTC preceded by a 10 min soak, ETC, and ESC cycles, as shown in Table 3. The continuity protocol between each transient cycle (defined as 5 min at idle and 5 min of operation at the ESC mode 7, plus 3 min at idle) was applied to ensure identical temperature profiles of the engine and exhaust after-treatment devices (Anderson *et al*., 2010). When the daily protocol was finished, engine-out emissions were measured to quantify the filtration efficiency of the DPF.

Table 1. Golden engine specifications

Manufacturer	Daimler AG
Type	OM501 LA
Rated power	290 kW @ 1,800 rpm
Max. net torque	1,850 Nm @ 1,080 rpm
Max. permitted speed	2,300 rpm
Idle speed	560±50 rpm
Bore × Stroke (mm)	130×150
Capacity	11, 946 cm^3
Firing order	1-4-2-5-3-6

Table 2. Specifications of reference fuel (RF-06 grade)

Test items and units	Korea	PMP
Density 15°C kg/m^3	827.2893	834.9
Sulfur mg/kg	5.3968	7.0
Cetane index	56.8393	53.1
Polycyclic aromatics wt%	1.6205	5.1

Table 3. Daily protocol of heavy-duty diesel engine

Previous lab	Day 0	Day 1-8
	Oil change	IFV
	2h ESC Mode 10	Cold WHTC
	3 x ETC	10 minute soak
		Hot WHTC
		10 minute at WHSC mode 9
		WHSC
		CP
		ETC
		CP
		ESC
2h ESC Mode 10	Precon.	Precon.

IFV : instrument Functional verification

CP : continuity protocol

Precon. : 15min ESC mode 10, 30min ESC mode 7

2.2. Primary Dilution and Particulate Analysis System

A full-flow constant volume sampler (CVS) exhaust dilution tunnel system (AVL CVS i60) meeting the requirements of Regulation 49 was used. The flow rate of dilute exhaust gas through the tunnel was 80 m^3/min at standard reference conditions. (i.e. 20°C and 1 bar). The air used for the primary dilution of exhaust in the CVS tunnel was first passed through a first HEPA (high efficiency particulate air) type charcoal-scrubbed filter, and then passed through a secondary HEPA filter.

The mass of particulate material was measured using a system composed of a particulate mass sampler, a sample pre-classifier, and a filter holder assembly. A sample probe (sharp-edged and open ended) was fitted near the center line in the dilution tunnel, 10 tunnel diameters downstream of the gas inlet. The dilution tunnel had an internal diameter of 23 mm. A cyclone pre-classifier (2.5 μm cut point) was used. The particulate mass system was heated externally to 47±5°C using a heating controller. The heated elements included the filter holder and transfer tubing and had a residence time greater than 0.2 s when calculated at the required flow rate of 45 L/min. Pallflex TX40 fluorocarbon coated glass filters were used to collect particulates. The mass collected was measured using as analytical balance (Sintronix, model SE 2-F) with a resolution of 0.1 in accordance with the test procedure.

The number of particles emitted by the golden engine was determined using a GPMS (golden particle measurement system). The GPMS system has two main parts: 1) a particle sampling system consisting of a sampling and particle pre-classifier (cyclone with d50% = 2.5 μm), and 2) particle conditioning and measurement system consisting of a VPR (volatile particle remover) and a PNC (particle number counter) unit. The VPR provides heated dilution, thermal conditioning of the sample aerosol, and secondary dilution for cooling and freezing of the sample evolution prior to entry into the PNC. The PNC unit is a particle counter (TSI 3010D) with the lower cut-off modified to 23 nm by the manufacturer (Giechaskiel *et al*., 2008a; Lee *et al*., 2008; Myung *et al*., 2009b; Anderson *et al*., 2010).

In addition to particle number concentration, the DMS500 (Cambustion Co.) positioned at engine-out and afterward DPF was used to analyze the particle size distribution emitted from the heavy duty engine. The DMS500, which is based on the same operating principle as the DMA (differential mobility analyzer) of the SMPS (scanning mobility particle sizer) measures the number of particles and their spectral weighting in the 5 nm to 2.5 μm size range with a scan time of 200 ms (Cambustion, 2008). Details of the experimental system for heavy-duty round-robin testing at NIER (National Institute of Environmental Research) in Korea are shown in Figure 1.

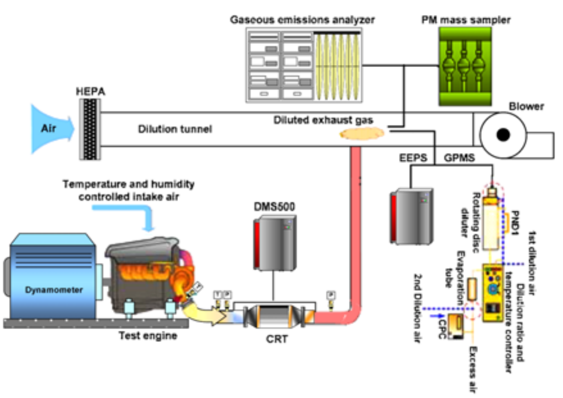

Figure 1. Experimental setup for heavy-duty round-robin testing at the NIER.

2.3. Calculation Procedure of Total Particle Number

Total particle number (PN) emissions for each mode were calculated by means of the following equation by particle number measurement procedure Regulation 49 (Giechaskiel *et al*, 2008b).

$$PN = N\frac{G_{EDFW}}{W_{act}}t \quad (1)$$

$$N = PRF\frac{PNC}{\rho}10^6 \quad (2)$$

In Equations, PNC (#/cm^3) is the average concentration over the cycle given by the CPC, PRF is particle concentration reduction factor or DF (dilution factor), ρ (kg/m^3) represents the density of the gas at the nozzle pressure and at the temperature of the PNC (=1.2), G_{EDFW} (kg/h) is flow rate of diluted exhaust gas, t (h) is the duration of the cycle, and W_{act} (kWh) is the actual cycle work.

For the ESC case, G_{EDFW} and W_{act} are calculated by following equations. P_i (W) is the power at mode i and WF_i is the weighting factor of mode i.

$$G_{EDFW} = \sum_{i=1}^{n} G_{EDFW,i} WF_i \quad (3)$$

$$W_{act} = \frac{\sum_{i=1}^{n} P_i WF_i}{t} \quad (4)$$

For the WHTC, the weighted results should be calculated using the adjustment factors of 14% cold WHTC plus 86% hot WHTC as shown in Equation (5).

$$e = k_r\left(\frac{(0.14 \times N_{cold})}{(0.14 \times W_{act,cold})} + \frac{(0.86 \times N_{hot})}{(0.86 \times W_{act,hot})}\right) \quad (5)$$

Where:

N_{cold} : total number of particles emitted over the WHTC cold test cycles

N_{hot} : total number of particles emitted over the WHTC hot test cycles

$W_{act,\ cold}$: cold actual cycle work in kWh

$W_{act,\ hot}$: hot actual cycle work in kWh

k_r : regenerative adjustment (in the case of engines without periodically regenerating after-treatment k_r=1)

3. RESULTS AND DISCUSSION

3.1. Real-time Particle Emission Characteristics with Various Engine Operating Cycles

Figure 2 shows real-time particle emissions of various engine operating cycles with an after-treatment device. In the case of the cold WHTC mode, 10^4 #/cm^3 order of particles were emitted during the 450 s from cold start, and after 750 s, the number of particles decreased by approximately 2 orders of magnitude due to the high filtration efficiency of the DPF. We note that the accumulated particles in the previous preconditioning operation were released from the DPF during the cold transient starting phase in which temperature maintains still low condition. Thus, nano-particles were not deposited on the surface of the filter or emitted through porosity inside the filter because the diffusion velocity decreased during the low DPF temperature condition zone (Eastwood, 2008; Rakopolous and Giakoumis, 2009).

Compared with the cold WHTC mode, the particle

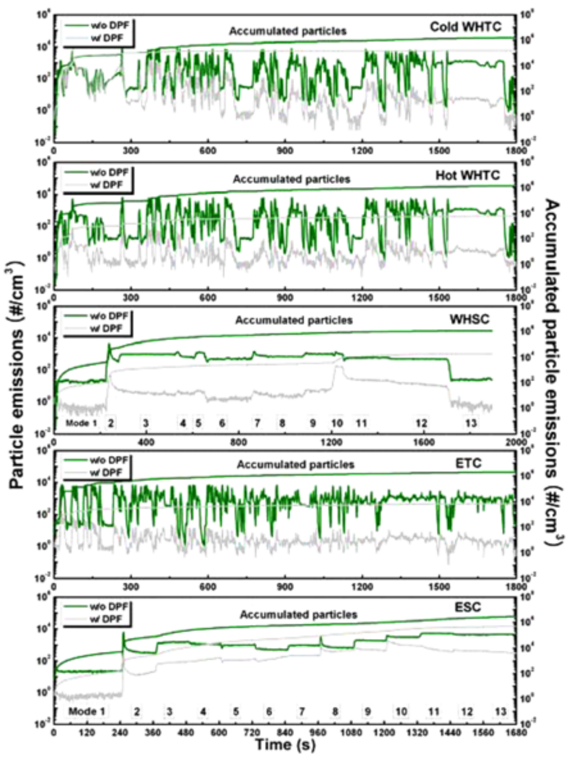

Figure 2. Real-time particle concentration and accumulated particle number with European/WHTC modes.

concentration was reduced by two order of magnitude and was maintained below 10^1 #/cm^3, for the hot WHTC and ETC modes due to the high DPF temperature. The cumulative particle number emissions over 10^6 #/cm^3 of the engine-out condition were reduced to 10^5 #/cm^3 cold WHTC and 10^4 #/cm^3, respectively.

Within the 13 measured points of the WHSC mode with DPF, the particle emission at the WHSC #10, for which the operating conditions were 100% engine power and 87% rated engine speed, showed a clear trend of insufficient filtration efficiency. The particle spike can be seen in the WHSC #10 mode for both the real-time particle emission and the cumulative particle concentration profile. The accumulated particles showed a reduction of 2 orders of magnitude from 10^6 #/cm^3 to 10^4 #/cm^3 in the WHSC mode. From the ESC mode #3 with 50% engine load and 85% speed to mode #10 with 100% engine load and 85% speed, the particle concentration steadily increased even though the DPF was installed. The real-time particle concentration reached approximately 10^3 #/cm^3 despite the after-treatment device during the ESC #8~#10 modes because of passive regeneration in the filter. The total accumulated level of the ESC mode with DPF measured below 10^6 #/cm^3, which was much higher than other test modes.

Figure 3 shows the effects of the after-treatment device on particle size distribution and number concentration for the WHTC, WHSC, and ETC modes using the DMS500. Particle sizes from an internal combustion engine are generally classified into the nucleation and accumulation modes as distinguished by particle diameter (Kittelson, 1998). In this study, the nucleation and accumulation mode have particle diameters of less than approximately 50 nm, and from 50 nm to 1,000 nm, respectively. In the case of hot WHTC, WHSC, and ETC, a nuclei mode below Dp < 30 nm was observed after DPF, and the particle number concentration ranged from 10^2 #/cm^3 to 10^4 #/cm^3 consecutively. The particle size range of 30 nm < Dp < 400 nm was evenly distributed and its order ranged between 10^3 #/cm^3 to 10^4 #/cm^3 after DPF. Most particles with a DPF decreased by two to three orders of magnitude except the cold WHTC mode that involved cold start operation.

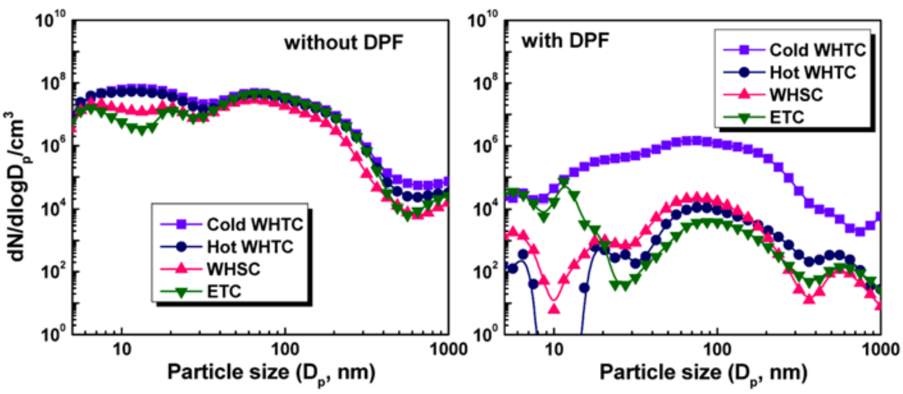

Figure 3. Particle size distribution and number concentration of WHTC, WHSC, and ETC modes.

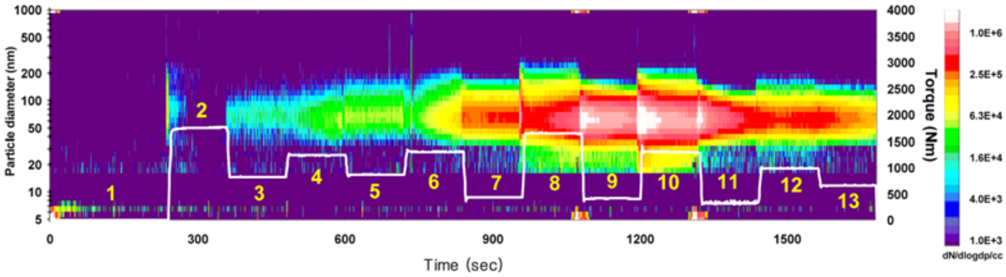

Figure 4. Time-resolved particle size distribution spectra of ESC mode after DPF.

Figure 4 shows the time-resolved particle size distribution spectra of the DPF-equipped ESC mode using the DMS500. Based on the particle spectra of the ESC mode, the accumulation mode of 50 to 200 nm wasdistinctly emitted during the #6 to #13 modes whose order of magnitude reached over 10^5 #/cm^3. The formation of the nuclei mode, Dp < 50 nm in ESC # 8 to #10 modes occurred because the higher exhaust temperature led to passive DPF regeneration and thermal release of low volatility particles.

3.2. Comparison of Particle Numbers and Mass Emissions for Each Mode

Figure 5 shows the averaged particle number and mass of various engine operating cycles with an after-treatment device. Particle number (particle mass) results over various engine operation cycles showed that weighted WHTC was 4.783E+11 #/kWh (2.0 mg/kWh), WHSC 6.087E+10 #/kWh (1.1 mg/kWh), ETC 4.596E+10 #/kWh (1.5 mg/kWh), and ESC 3.389E+12 #/kWh (3.1 mg/kWh). The filtration efficiency of the particle number concentration and mass reached approximately 99%, except for an ESC mass efficiency of 95% due to the passive regeneration during the # 8 to #10 modes.

The ratio of the standard deviation over the average value of particle emissions (tested eight times), COV (coefficient of variance), is summarized in Table 4.

When repeated emission tests are performed in the same laboratory within a short period of time, the results should be reasonably consistent. The COV of the cold WHTC mode showed good repeatability at 26% for the particle mass and 28% for the particle number because of the soot loading procedure on the DPF through preconditioning. The COV of particle number and mass ranged from 49% (hot WHTC) to 73% (ETC), and 22% (ESC) to 107% (ETC).

A COV of 22% of the particle mass in the ETC mode means that its variation with DPF regeneration was negligible.

Figure 6 shows an image of soot deposition and morphology on fiber filters using an FESEM (field emission scanning electron microscope, Hitachi S-4300) over various test modes. The typical particle size distribution of the diesel engine exhibited a log-normal size around 100 nm, as shown in Figures 3 and 4, similar-sized particles that appeared to be agglomerated chains or clusters (Eastwood, 2008) were deposited on the fiber filter for various operating cycles without DPF. In addition, smaller and fewer particles were observed with filtration, except in the cold WHTC mode, including the cold start phase with DPF-equipped cases.

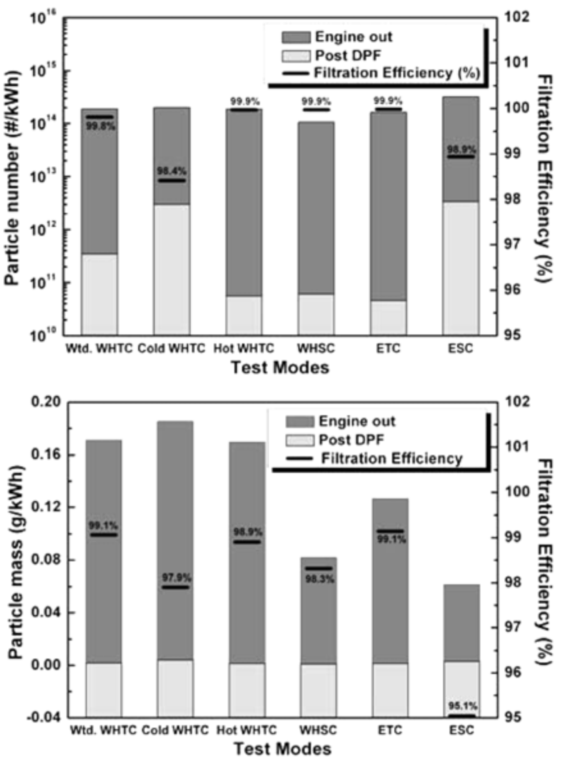

Figure 5. Average particle number and mass emissions for various test modes.

4. CONCLUSION

In this study, a comparison of nano-particle concentrations and particle mass emissions between the European and WHTC for a golden heavy-duty diesel engine, as part of the UN/ECE PMP ILCE, was performed. Based on the daily protocol suggested by the PMP, the filtration efficiency and repeatability of golden DPF with particle size distributions for various test cycles were also investigated. The major findings are summarized as follows.

Table 4. Detailed particle emissions and COV for various modes.

Engine-out/after DPF						
Cycle	Weighted WHTC	Cold WHTC	Hot WHTC	WHSC	ETC	ESC
PM (g/kWh)	0.1717/0.0020	0.1855/0.0042	0.1695/0.0016	0.0818/0.0011	0.1266/0.0015	0.0615/0.0031
PN (#/kWh)	1.901E+14/ 4.783E+11	2.012E+14/ 3.004E+12	1.882E+14/ 5.604E+10	1.060E+14/ 6.087E+10	1.625E+14/ 4.596E+10	3.206E+14/ 3.389E+12
Conversion Efficiencies						
PM	98.9%	97.9%	98.9%	98.3%	99.1%	95.1%
PN	99.7%	98.4%	99.9%	99.9%	99.9%	98.9%
COV						
PM	30%	26%	38%	41%	107%	22%
PN	25%	28%	49%	46%	73%	51%

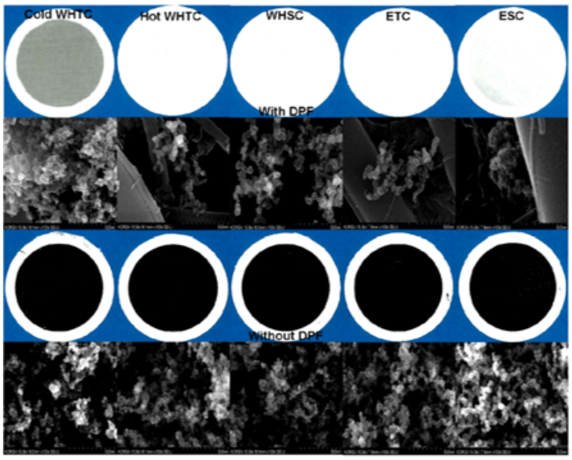

Figure 6. Comparison of particle filters morphology by FESEM on various test modes.

(1) In the cold WHTC mode, particles on the order of 10^4 #/cm^3 were emitted during 450 s from cold start, and the level steadily decreased to 10^1 #/cm^3. The real-time particle concentration in the ESC mode reached approximately 10^3 #/cm^3 desipite the aftertreatment device during the ESC #8 to #10 modes because of passive regeneration in the filter.

(2) Particle emissions over various engine certification cycles showed that the particle number concentrations (#/kWh) with DPF were 4.783E+11 (weighted WHTC), 6.087E+10 (WHSC), 4.596E+10 (ETC), and 3.389E+12 (ESC). Particle mass (g/kWh) ranged from 0.0011 (WHSC) to 0.0031 (ESC). The repeatability of particle number and mass values reached approximately 22~107% and 25~73%, respectively. The large COV of the particle emissions was ascribed to the ETC mode, which produces values of 107% and 73%. The DPF efficiency of particle number concentration and mass reached around 99%, except for an ESC mass efficiency of 95%.

(3) The particle size distribution of WHTC, WHSC, ETC, and ESC with a DPF-equipped diesel engine was bi-modal, consisting of nucleation and accumulation modes. From the FESEM image, the agglomerated chain or cluster particles around 100 nm were captured despite DPF, but smaller particles were observed, except for in the cold WHTC mode.

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