Selected Article

Continuous Solid Particle Counting System, MEXA-2000SPCS series

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MEXA-2000SPCS and MEXA-2100SPCS continuously measure the number of solid particle in specified range of size, which is emitted from engines. MEXA-2000SPCS is designed to mainly measures particles emissions by being connected to a full-flow dilution tunnel. It covers requirements described in UN/ECE Regulation No.83, Rev.3, Amend.2, which has been adopted as a test procedure for Euro 5/6, latest regulations in Europe. MEXA-2000SPCS has been downsized to 1/3 of the conventional mode, MEXA-1000SPCS, by optimizing configuration to regulation requirements. The small dimensions make easier to install and transport system in or between laboratories. On the other hand, MEXA-2100SPCS is designed for direct sampling measurements without tunnel dilution. MEXA-2000SPCS series can be used for various test applications by such sampling variation and also prepared options.

Introduction

The European Union (EU) has decided to add particle number (PN) limits to LDV emission regulations as Euro 5/6, in addition to the conventional PM mass emission limits. Measurement technology to be applied for particle number counting has been considered since 2001, by a working party under the United Nations Economic Commission for Europe (UN/ECE). On April 2009, it was published as the UN/ECE Regulation No.83, Revision3, Amendment2[1]. In advance of that, the EU has announced PN limits for LDV as Commission Regulation (EC) No.692/2008[2] on July 2008, on the assumption that a new measurement method is published as amended Regulation No.83. The EC regulation says PN limit of 6.0×10^{11} particles/km will be introduced for diesel vehicles in 2011 as Euro 5, and PN limit for gasoline vehicles will be also decided for Euro 6 which becomes effective in 2014.

Based on this regulation trend in Europe, HORIBA has released a solid particle counting system, MEXA-1000SPCS. Then, we have developed additional models

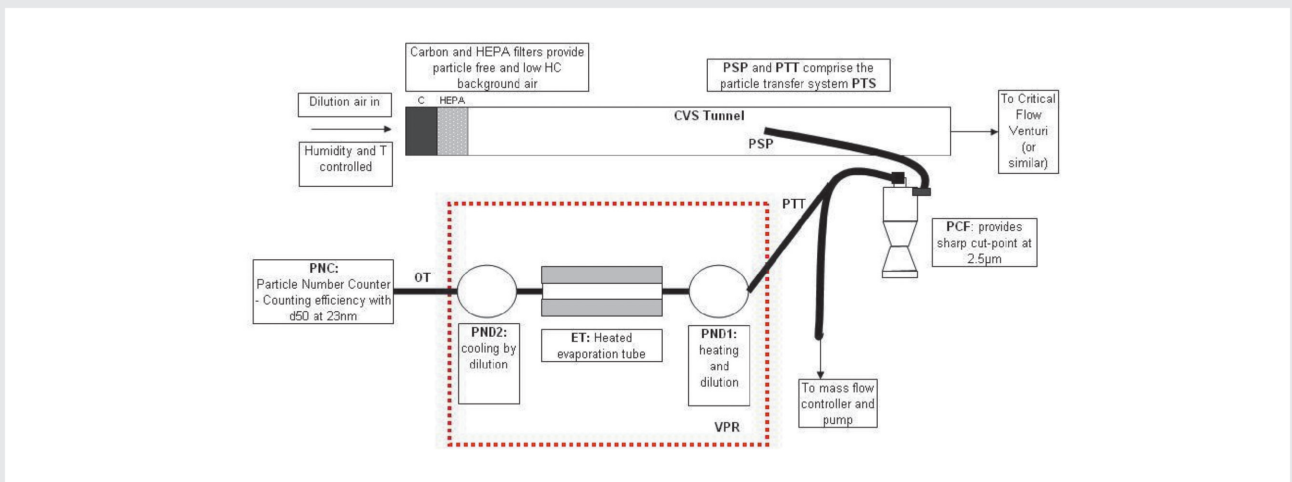

Figure 1 Solid particle counting system recommended in Euro5/6[1]

of solid particle counting system, MEXA-2000SPCS and MEXA-2100SPCS, specialized on compliance with latest regulation in which more concrete requirements are described. This article contains overview and performance evaluation of MEXA-2000SPCS series.

Requirements for PN Counting System in Euro 5/6

Required System Configuration

Figure 1 shows a schematic of the particle counting system required in Euro 5 and Euro 6[1]. A probe collects diluted exhaust gas from a full-flow dilution tunnel, via a pre-classifier which provides 50% particle cutoff between 2.5 and 10µm size range. Hot diluter (PND1) dilutes exhaust gas with high temperature, 150 ºC to 400 ºC, to prevent volatile particles consist of SOF and sulfur compounds from generating. Volatile particles that have been generated in the tunnel are vaporized in evaporation tube (ET, 300 ºC to 400 ºC). Then, sample gas is cooled down to 35 ºC in cold diluter (PND2), to prevent particle generation by re-condensation and also particle loss by thermophoresis. The regulation recommends that dilution ratio of PND1 can be changed in a range from 10 to 200, and that of PND2 can be fixed at a proper ratio from 10 to 15. By this configuration from PND1 to PND2, which is called volatile particle remover (VPR), only solid particles are introduced into a particle number counter (PNC). As the PNC, a condensation particle counter (CPC) should be applied. The cutoff size of the CPC is defined as 23 nm in order to secure the correlation among several counting systems.

Pre-classifier shown in the above configuration is not necessary if the sample probe to be inserted into the tunnel has the same function. Figure 2 shows an example of so-called "hatted probe" shown in the regulation, which can be used as an alternative to pre-classifiers.

System Performance and Calibration / Verification

Euro 5/6 requires calibration of CPC in the counting system at least once a year. However, it is very difficult to prepare standard substances for solid particles with known concentration. Therefore, at the calibration, CPC counts for sample particles are verified by comparing with outputs of an aerosol electrometer. Here, as sample particles, mono-dispersed particles extracted from multi-dispersed particles generated by some methods are used. CPC can be also calibrated by comparing with a "reference CPC", which has been calibrated in the above matter. For both cases, required calibration accuracy is more than 0.97 as the coefficient of determination (R^2) of regression equation between reference concentrations and CPC outputs.

Euro 5/6 also requires quality control checks of particle counting system, such as particle concentration reduction factor (PCRF) check, volatile particle removal efficiency check, and CPC status check, as summarized below. Descriptions in [ ] represent frequencies for each checks.

- PCRF shall meet the criteria below:
  $0.95 < fr\ (30\ \text{nm}) / fr\ (100\ \text{nm}) < 1.3$, and
  $0.95 < fr\ (50\ \text{nm}) / fr\ (100\ \text{nm}) < 1.2$;
  where, $fr\ (d)$ = reduction factor of solid particle diameter, *d*.
  [once a year]
- Volatile particle removal efficiency of tetracontane ($CH_3(CH_2)_{38}CH_3$) particles shall be more than 99.0%. [once a year]
- Zero level, which means concentration level when HEPA-filtered ambient air is introduced, shall be less than 0.5 particles/cm^3 for the overall system. [per test]
- Flow rate of CPC sample shall be within +/-5% of

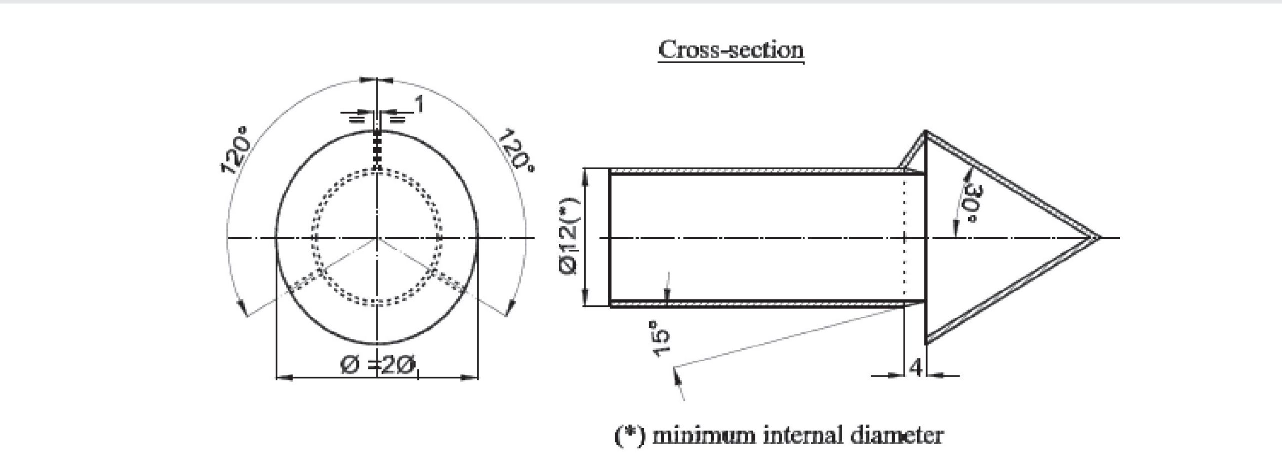

Figure 2 Example of hatted probe[1]

standard value. [once a month]

- For CPC only, zero level shall be 0.2 particles/cm^3 or more, and ambient air level shall be at least 100 particles/cm^3. [once a day]

Here, PCRF is obtained by dividing particle concentration at VPR inlet, $N_{in}(d)$, by particle concentration at VPR outlet, $N_{out}(d)$.

$$fr\ (d)=\frac{N_{in}\ (d)}{N_{out}\ (d)}$$

PCRF includes dilution factor (DF) as well as solid particle penetration factor at VPR, because VPR is equipped with two diluters (PND1, PND2). Mean PCRF ($\overline{fr}$) is an averaged PCRF of particle diameter 30 nm, 50 nm and 100 nm when fixing the DF in VPR at a constant value.

$$\overline{fr}=\frac{fr\ (30\ nm)+fr\ (50\ nm)+fr\ (100\ nm)}{3}$$

Mean PCRF is used for calculating particle number emission per mileage, in particles/km. It converts particle concentration output from CPC into original particle concentration at VPR inlet before dilution.

Overview of MEXA-2000SPCS series

Development Concept

When the committee under the UN began to consider particle counting techniques as preamble for coming Euro 5/6, HORIBA also started the R&D of a solid particle counting system. MEXA-1000SPCS was promptly released through such a development activity[3-5]. However, it covers higher specifications than Euro 5/6 requirements, because it had been developed according to draft regulation before final requirements were officially published. Since a lot of functions make the MEXA-1000SPCS's dimension big, it is not always easy to install or transfer the system. Therefore, we have newly developed MEXA-2000SPCS series which has limited configuration to target latest requirements of Euro 5/6.

Characteristics of MEXA-2000SPCS series

Figure 3 shows an appearance of MEXA-2000SPCS, and Table 1 shows brief specifications. MEXA-2000SPCS is designed to be connected with a full flow dilution tunnel as required in the regulation for LDV. Basic functions are almost the same with MEXA-1000SPCS. Compared to MEXA-1000SPCS, MEXA-2000SPCS is downsized to 1/3 in height, as the most distinctive characteristic. On the other hand, MEXA-2100SPCS is mainly for direct sampling measurement from a tailpipe that can be exposed to high temperature and high pressure. For other functions and configurations than that related to sampling method, specifications of MEXA-2100SPCS are almost the same as MEXA-2000SPCS. Main characteristics of the series are described below based on MEXA-2000SPCS.

Figure 3 MEXA-2000SPCS (main cabinet)

Table 1 Outline of MEXA-2000SPCS

Model	MEXA-2000SPCS
Measureing item and range	Number concentration of solid particles; 0-10000 up to 50000 particles/cm^3 (after dulution)
Configuration (Standard)	- Main cabinet, including volatile particle remover (VPR) and particle number counter (PNC) - Control PC (laptop type)
VPR	- Diluter and DF: Primary diluter: DF 10 to 200 Secondary diluter: DF 15 - Sample flow: 10 L/min
PNC	Detector: Condensation particle counting (CPC)
Dimensions	434 (w) x 731 (D) x 600 (H) mm (Excluding control PC, options, and any projection)

(1) System Configuration

For MEXA-2000SPCS, essential components to measure particle number in compliance with Euro 5/6, such as VPR (PND1, ET, PND2) and CPC, are all installed in a cabinet. Contrarily, cyclone as pre-classifier, for which a special-shaped probe called "hatted probe" can substitute, is prepared as an option to be installed externally. In addition, parts for unusual checks, e.g. DF check, is also separated from the MEXA-2000SPCS main cabinet, though MEXA-1000SPCS includes such functions as

standard configuration. As a result, main cabinet can be drastically downsized and it makes easier to transfer and install the system in engine test cells.

(2) Optimization of DF Range

Available range of DF in MEXA-1000SPCS is 10 to 700 for PND1 and 10 to 50 for PND2, which is fairly wider than that required in the regulation. On the other hand, DF in MEXA-2000SPCS is changeable from 10 to 200 for PND1 and is fixed at 15 for PND2, as just required. This modification made it possible to apply continuous dilutor[3-5] only for PND1, while MEXA-1000SPCS uses two continuous dilutors for both PND1 and PND2. This simplified configuration of diluters contributes to downsize the system with high dilution accuracy maintained.

(3) Software

Euro 5/6 requires calibration and checks of particle counting system to keep reliability of measurements. MEXA-2000SPCS can control various check sequences with software as well as MEXA-1000SPCS. Representative sequences are listed below.

- PCRF check for VPR
- Check of volatile particle removal efficiency in VPR
- Zero level and ambient air level check for overall system
- Sample flow rate check for CPC
- Zero level check for CPC
- Linearity check for system and CPC
- DF check

Euro 5/6 requires a special reference (material and instrument) for CPC sensitivity calibration, so that it is not easy to calibrate systems on sites. The linearity check is performed as a substitution for the calibration, in which required accuracy (coefficient of determination) at calibration is applied as criterion. DF check is not required in Euro 5/6, however it's also an important check for keeping accuracy.

MEXA-2000SPCS has some additional functions applied to the latest regulation, such as conversion of diluted particle number concentration into raw concentration with Mean PCRF.

(4) Option Line up

MEXA-2000SPCS series have variety of option units, taking possible applications and performance checks into consideration.

- Cyclone unit (CYU): external cyclone unit
- Sample return unit (SRU): for sending back bypassed sample into the tunnel
- DF checker (DFC): for checking dilution factor
- Linearity check unit (LCU): solid particle generator for linearity check and PCRF check
- Volatile-particle generation unit (VGU): for checking volatile particle removal efficiency

Figure 4 shows system layouts including optional units. The combination of MEXA-2000SPCS series and optional units allows sampling particles from a wide variety of sources, i.e. not only from a dilution tunnel but also from an engine exhaust pipe without dilution.

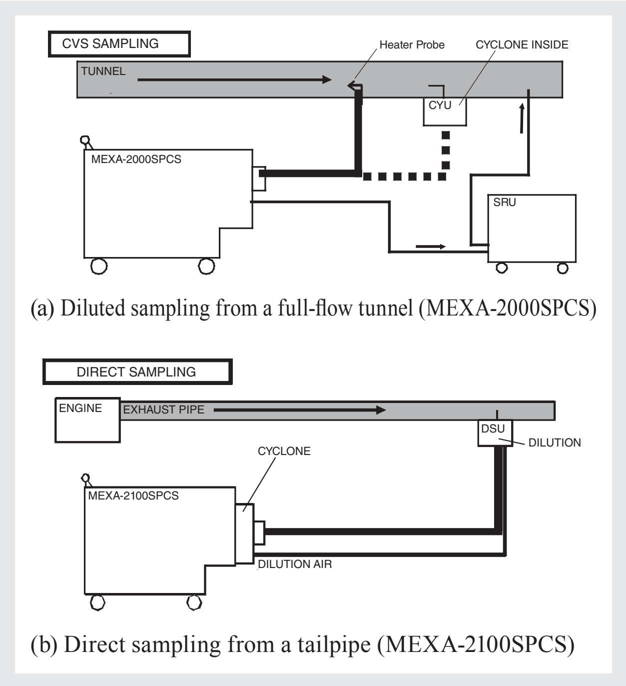

Figure 4 Applications of MEXA-2000SPCS series

Basic Performance of MEXA-2000SPCS series

Particle Concentration Reduction Factor (PCRF)

Figure 5 shows experimental setup for PCRF evaluation. Sample solid particles are supplied from LCU that generates sodium chloride (NaCl) particles by atomizing NaCl solution and evaporating water fraction. A differential mobility analyzer (DMA) classifies generated particles to extract particles in target size, i.e. 30, 50 or

10 nm. PCRF is obtained by comparing particle number concentration monitored by CPC at VPR upstream with

that at VPR downstream.

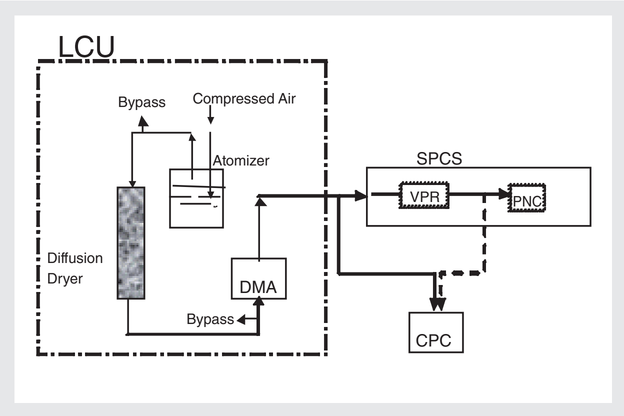

Figure 5 Setup for PCRF evaluation

Figure 6 shows a result of PCRF evaluation when changing DF setting in the range of 150 to 3000. Horizontal axis is particle diameter (*Dp*) and vertical axis is PCRF which is normalized by that of 100 nm PCRF, *fr* (100 nm). Criteria required in the regulation are 95% to 130% for diameter of 30 nm as *fr* (30 nm)/*fr* (100 nm), and 95% to 120% for 50 nm as *fr* (50 nm) / *fr* (100 nm). As shown in the figure, PCRF values of all DF settings meet this requirement.

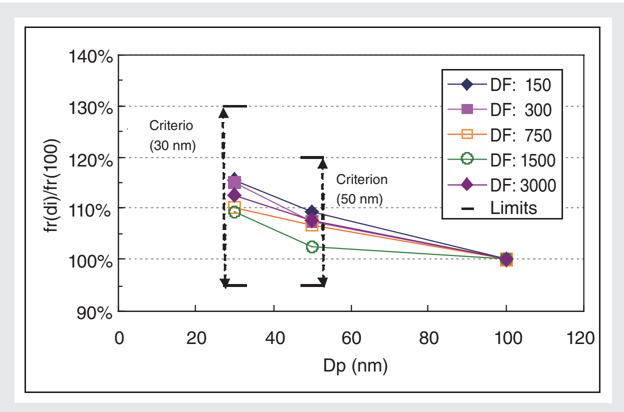

Figure 6 Evaluation result of PCRF

Volatile Particle Removal Efficiency

Figure 7 shows experimental setup for evaluating volatile particle removal efficiency. Tetracontane particles specified as reference particle are generated from VGU and then classified by DMA. Volatile particle removal efficiency is calculated from particle number concentration at VPR upstream and that at VPR downstream, in the same manner with PCRF evaluation.

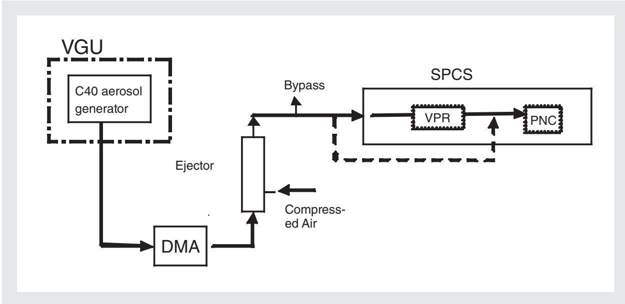

Figure 7 Setup for evaluating volatile particle removal efficiency

Figure 8 shows removal efficiency results of volatile particles of diameter 30 nm, 50 nm and 100 nm, with changing temperature in evaporation tube from 320 ºC to 380 ºC. Although lower temperature gives lower efficiency especially at particle size of 100 nm, the efficiency is more than 99.5% for all evaluated conditions. This satisfies regulation requirement, i.e. greater than 99%.

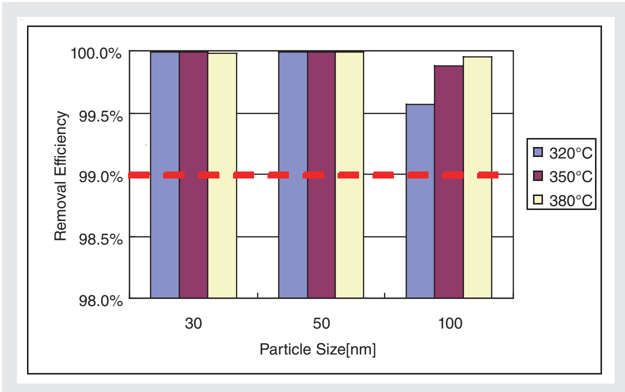

Figure 8 Evaluation result of volatile particle removal efficiency

Accuracy of Dilution Factor

MEXA-2000SPCS has a function to check actual DF using span gas by connecting to DFC and an external gas analyzer. Figure 9 shows a test result of error (%) of actual DF against set value, which was obtained using 2 sets of MEXA-2000SPCS, SPCS1 and SPCS2. A nitric oxide (NO) analyzer utilizing chemiluminescent detection (CLD) is used to check NO concentration before and after dilution. It is shown that error of actual DF is within ±5% for wide range of 150 to 3000. No criterion for DF accuracy is described in the latest Euro 5/6 regulation, however "within ±10%" was suggested at drafting stage.

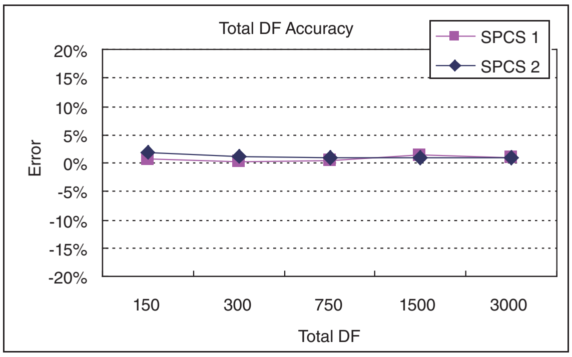

Figure 9 Evaluation result of dilution factor

Figure 10 shows correlation between DF and PCRF of diameter 100 nm, *fr* (100 nm). The slope of regression equation is 1.0323, slightly larger than 1. This result is adequate enough, because PCRF includes particle penetration coefficient of VPR. Good correlation of 0.9996 as coefficient of determination supports that DF accuracy provides PCRF stability, too.

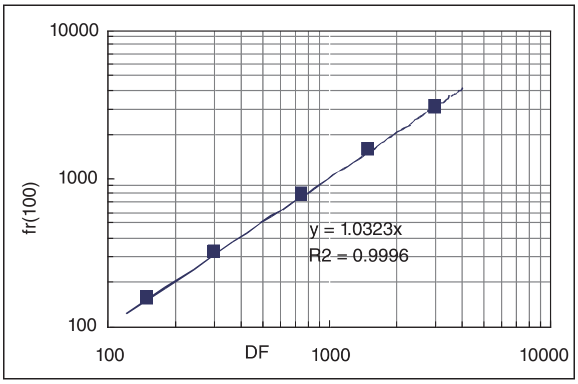

Figure 10 Correlation of DF and PCRF (at particle size of 100 nm)

Vehicle/Engine Tests Using MEXA-2000SPCS

This section describes correlation test between MEXA-2000SPCS and MEXA-1000SPCS with a diesel engine and a gasoline vehicle.

Experimental Set-up

Figure 11 shows the set-up for vehicle test using a full-flow tunnel as an example. A hatted probe is used to sample particles from the tunnel. The sample line after the probe is branched into two, and each line is connected to MEXA-100SPCS or MEXA-2000SPCS respectively with a heated tube of 47 ºC. Because MEXA-2000SPCS has no internal cyclone, built-in cyclone of MEXA-1000SPCS is also skipped to make measurement condition similar. Both systems have the same DF setting of VPR.
Set-up for engine test is almost the same with that for vehicle, other than using a partial-flow tunnel.

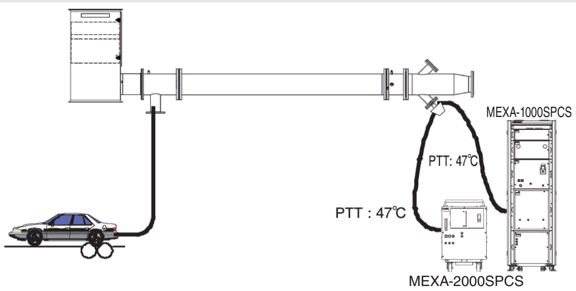

Figure 11 Set-up for vehicle test

Continuous Measurement of Particle Number Concentration

Figure 12 shows a measurement result of particle number concentration from a vehicle with a 2.0-liter diesel engine and a DPF. Japanese JC08 driving cycle was used.

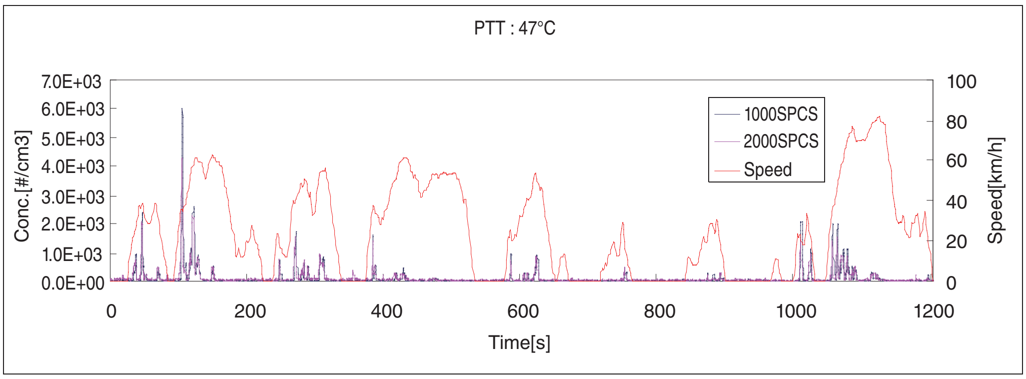

Figure 12 Particle number concentration in real-time (diesel vehicle, JC08 driving cycle)

Behavior of particle number concentration, such as peak positions and intensities, is similar between MEXA-1000SPCS and MEXA-2000SPCS. Total particle number emissions measured by the systems are also almost equivalent, i.e. 2.29×10^{10} particles/test in MEXA-1000SPCS and 2.36×10^{10} particles/test in MEXA-2000SPCS.

Correlation with MEXA-1000SPCS

Figure 13 shows correlation of total particle number emission by MEXA-1000SPCS and MEXA-2000SPCS confirmed with a diesel engine with 2.0 L of displacement. Tests were conducted under various conditions, e.g. transient/steady-state condition and with/without DPF. There is a great difference in emitted particle number, 10^4 to 10^5 times, depending on with/without DPF. However, MEXA-1000SPCS and MEXA-2000SPCS show good correlation each other in such a wide range.

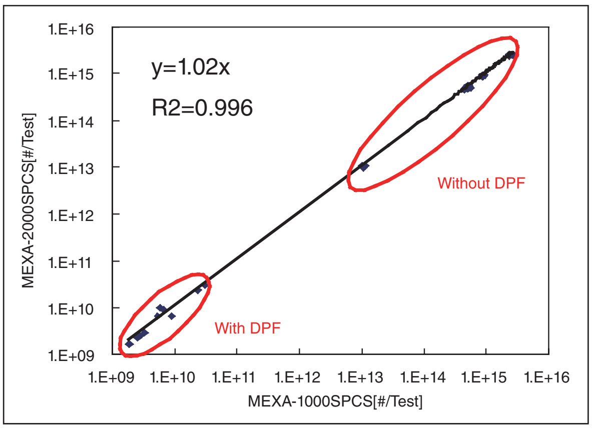

Figure 13 Correlation of total particle number emission (diesel engine)

Dependency on Driving Cycles

Figure 14 shows a comparison of particle number emissions measured by MEXA-1000SPCS and MEXA-2000SPCS during FTR75, NEDC, and steady state driving cycle. A direct-injection gasoline vehicle was used in this test. Correlation between the systems is kept even though there are differences in engine state at starting, exhaust flow rate, and exhaust temperature.

Conclusion

This article describes new solid particle counting system, MEXA-2000SPCS series, targeting at Euro 5/6 which is a latest regulation in Europe. MEXA-2000SPCS are drastically downsized with the superior performance of conventional MEXA-1000SPCS maintained, by optimizing specification and configuration to specialize in regulation requirements. Series line-up, such as MEXA-2000SPCS for diluting measurements by a full-flow tunnel and MEXA-2100SPCS for direct measurements, and various options cover a wide range of applications from certification testing to engine R&D.

In the future, particle counting may be introduced into the regulations for other vehicle categories and countries/areas, and will come to be paid more attention. We expect that MEXA-2000SPCS series take an important role for low concentration particle measurement in R&D field of engines and after treatment systems, as well as MEXA-1000SPCS.

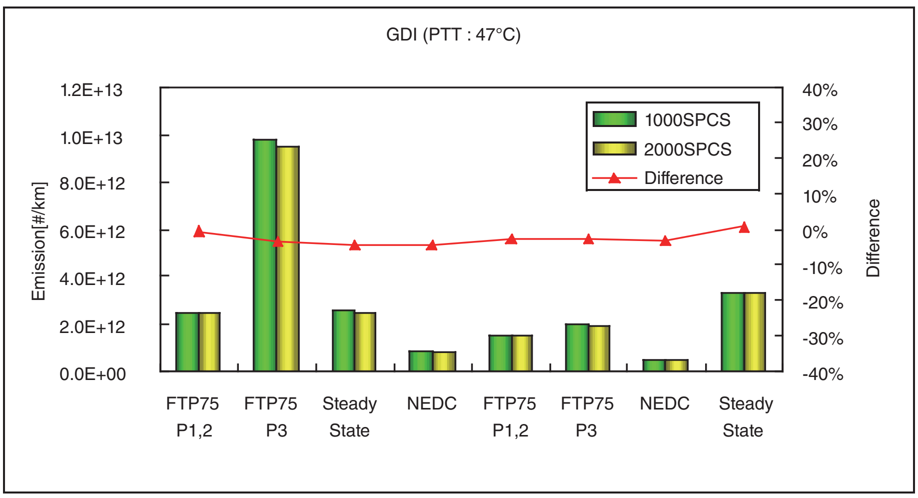

Figure 14 Particle number emission under various driving cycle (direct-injection gasoline vehicle)

Abbreviation
CPC: Condensation Particle Counter
DF: Dilution Factor
DMA: Differential Mobility Analyzer
DPF: Diesel Particulate Filter
ET: Evaporation Tube
PCRF: Particle Concentration Reduction Factor
PMP: Particle Measurement Program
PNC: Particle Number Counter
PND: Particle Number Diluter
SOF: Soluble Organic Fraction
SMPS: Scanning Mobility Particle Sizer
VPR: Volatile Particle Remover

References

[1] UN/ECE Regulation No.83, Revision 3, Amendment 2; http://www.unece.org/trans/main/wp29/wp29regs/r083r3a2e.pdf
[2] COMMISSION REGULATION (EC) No 692/2008; http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:199:0001:0001:EN:PDF
[3] Asano, I; et. al.. Development of Solid Particle Measurement System for engine exhaust emission. Transaction of Society of Automotive Engineers of Japan. Vol.30, No.3, p. 43-48. 2007.
[4] Asano, I; et. al.. Investigation of Soot Emission Behavior using a Solid Particle Counting System. 2007 JSAE Annual Congress (Fall) Proceedings. No.115-07, p. 13-16. 2007.
[5] Kusaka, T; et. al.. Real Time Solid Particle Counting System MEXA-1000SPCS, HORIBA Readout English Edition No.13, p. 50-59. 2010.

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