

Penetration Calibration and Verification for the Solid Particle Counting System with Polydisperse and Monodisperse Particles

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ABSTRACT

Monodisperse and polydisperse Sodium Chloride (NaCl) particles were used to calibrate the solid particle penetration for the Volatile Particle Remover (VPR) in a Horiba prototype Solid Particle Counting System (SPCS). Prior to the calibration, dilution ratios on the SPCS are verified carefully with a flame ionization analyzer (FIA). Size distributions for polydisperse aerosols upstream and downstream of the Volatile Particle Remover (VPR) were measured with a Scanning Mobility Particle Sizer (SMPS). It is found that overall penetrations for polydisperse aerosols are larger than 95%. Geometric standard deviations from the raw and the diluted by the VPR are within $\pm 1.5\%$ difference. Thus, shapes of size distributions aren't changed after dilution. Geometric mean diameters shift a little, on average $\pm 5\%$ after dilution. Therefore, the VPR doesn't change the aerosol characteristics after the aerosol is diluted and heated up to 320 °C.

Penetrations with monodisperse solid particles meet current PMP recommendation. Minimum solid particle penetrations for 30 nm, 50 nm, and 100 nm particles are found at 78.2%, 90.6%, and 81.4% respectively. At 30 nm, penetrations show a big variation with dilution ratios. One of reasons may be due to higher sample flow to reduce the diffusion losses in the system; and the other reason may be due to uncertainties induced by the low detection efficiency at 30 nm for the condensation particle counter (CPC) and low upstream aerosol concentration.

It may be a good practice to evaluate the penetration of the VPR by measuring upstream and downstream

polydisperse aerosol size distributions although it isn't recommended by PMP at this moment. It gives more information about the VPR performance than the monodisperse particle described by the PMP. In the meantime, the polydisperse aerosol is easier to be generated and handled.

INTRODUCTION

European Particle Measurement Program (PMP) proposed a draft regulation for measuring solid particle number emission in exhaust from Light-duty diesel vehicles. The measurement system consists of a pre-classifier, a hot particle diluter (PND1), an evaporation unit (EU), a cold particle diluter (PND2), and a condensation particle counter (CPC). The PND1, EU, and PND2 are referred to as the Volatile Particle Remover (VPR). Figure 1 illustrates a block diagram for the system.

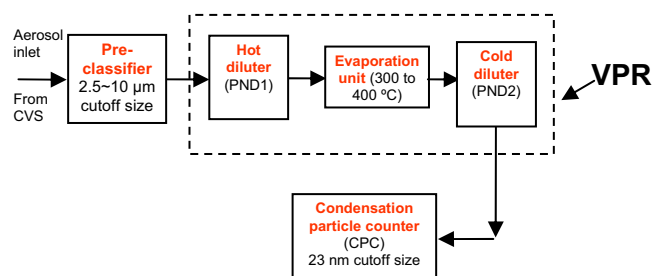


Figure 1. Schematic for solid particle counting system

The VPR receives an aerosol flow from the pre-classifier. The aerosol is diluted in the PND1 with hot dilution air flow. The EU in the VPR is operated at a high

temperature (300 to 400 °C) to evaporate volatile particles into gas phase. By following dilution from the PND2 with room temperature dilution air, the aerosol is cooled down, and the concentration of the volatile material in gas phase is reduced to a much lower level to avoid new formation of the volatile particles by nucleation. Thus, volatile particles are removed, and solid particles only move into the CPC. The concentration of the solid particles is measured in the CPC.

A solid particle counting system (SPCS) has been developed to meet PMP recommendations for solid particle measurements from light-duty diesel vehicles [5, 6, 7]. Two wide range continuous diluters (WRCD) were used as PND1 and PND2 respectively in the instrument. Figure 2 [5] illustrates the schematic of the WRCD. By adjusting the make-up air flow with the mass flow controller II, the sample flow rate is changed. As a result, the dilution ratio can be adjusted over a wide range. As shown in figure 2, there are no moving parts and dead volume in the WRCD. Since the sample flow is measured accurately with an orifice flow meter in real-time in the WRCD, accurate real-time dilution ratios are obtained over a wide dilution ratio range. More details about the WRCD can be found in reference [5].

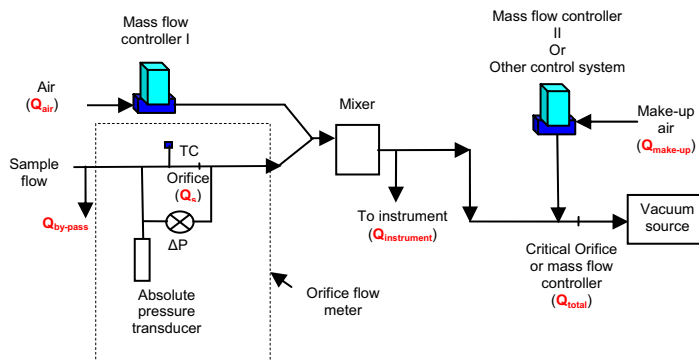


Figure 2. Schematic of the wide range continuous diluter (WRCD) [5]

The prototype SPCS has been tested at many laboratories. It is very sensitive, has a wide dynamic range, and is able to be used with vehicles having different technologies and aftertreatment devices. The instrument is sensitive to measure solid particle number emissions for post-DPFs [2, 7].

To ensure that the instrument works properly, the PMP recommends that the solid particle penetration on the volatile particle remover (VPR) should be calibrated or verified. Monodisperse solid particles with 30, 50, and 100 nm diameters are recommended for the penetration test. Minimum penetrations for 30, 50, and 100 nm solid particles are 50%, 55%, and 60%, respectively [1, 4].

Although new calibration procedures, which may be different to that published in the current draft proposal [1, 4], have been proposed and discussed by the PMP, we

calibrated the VPR of the SPCS following recommendations published in the draft regulation [4] in this study. The solid particle penetration of the VPR in the SPCS is calibrated by monodisperse and polydisperse particles. Findings from this study are discussed in the paper.

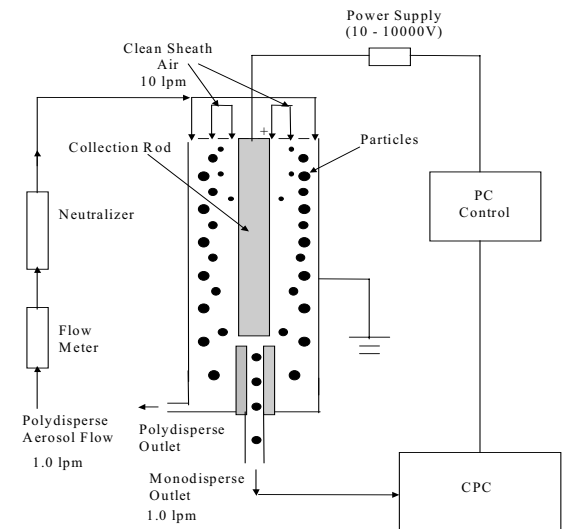


Figure 3. Schematic of the Scanning mobility particle sizer (SMPS)

SCANNING MOBILITY PARTICLE SIZER [3, 10, 12]

Figure 3 shows the schematic for the scanning mobility particle sizer (SMPS). The SMPS consists of a neutralizer, a mobility analyzer, a power supply, a condensation particle counter (CPC), and a data acquisition system, etc. The aerosol is charged to Boltzmann equilibrium when it moves through the neutralizer. Particle free sheath air enters the mobility analyzer from the top of the analyzer. The flow moves downward through a mesh screen which makes the flow uniform before it enters the annular space between the cylinder and the collection rod. The aerosol flow enters the mobility analyzer, and moves downward with the sheath air flow smoothly without mixing. The housing of the cylinder is grounded, and a positive potential is applied to the collection rod. An electrical field is generated between the cylinder and the collection rod. As a result, particles with negative charges move to the collection rod, and particles with positive charges move away from the collection rod. Particles with the right electrical mobility exit the mobility analyzer from the outlet port of the instrument. Finally, the number concentration of the monodisperse particles is counted in the CPC. The electrical mobility of the selected particle is defined in equation 1 [3]:

$$Z_P^* = (q_c + q_m) \frac{\ln(\frac{r_2}{r_1})}{4\pi V L} \quad (1)$$

Where, Z_p^* is the electrical mobility; q_c is the total sheath air flow; q_m is the excess air flow; r_1 and r_2 are the outer and inner radii of the annular gap; V is the voltage applied to the collection rod; and, L is the length of the collection rod.

In equation 2, it presents the electrical mobility as a function of particle size. i is the number of negative or positive charge (depending on the sign of the potential applied on the collection rod.). e is the elementary charge. C is the slip correction coefficient. D_p is particle diameter. μ is the gas viscosity. For particles smaller than $1.0 \mu\text{m}$, it is assumed that one charge is carried. Thus, i equals to 1.

$$Z_p^* = \frac{ieC}{3\pi\mu D_p} \quad (2)$$

For the monodisperse aerosol exiting from the mobility analyzer, the transfer function Ω has a trapezoidal shape centered at Z_p^* . The half-width of the trapezoid is expressed in equation 3. The maximum and minimum electrical mobility for the monodisperse aerosol are presented in equations 4 and 5.

$$\Delta Z_p = (q_s + q_a) \frac{\ln(\frac{r_2}{r_1})}{4\pi VL} \quad (3)$$

$$Z_{p \max}^* = Z_p^* + \Delta Z_p \quad (4)$$

$$Z_{p \min}^* = Z_p^* - \Delta Z_p \quad (5)$$

Where, q_s is the monodisperse flow; and q_a is the polydisperse aerosol flow; $Z_{p \max}^*$ is the maximum electrical mobility; and $Z_{p \min}^*$ is the minimum electrical mobility in the monodisperse aerosol.

At an ideal condition, the transfer function at Z_p^* equals to 1.0. The shape of the transfer function is a triangle centered at Z_p^* . The average transfer function Ω_{AV} for the monodisperse is 0.5.

The CPC counts particles by the pulse which is generated while the particle moves through the laser detection region. At a low concentration, one particle generates one pulse. By summing those pulses, the concentration of the aerosol can be calculated. To obtain a good statistic for particle number measurement, one particle at least needs to be detected during SMPS scanning at a single size channel. Thus, the limit of detection (LOD) for the number concentration at size D_p can be obtained from equations 6 and 7. The effect of multiple charges is ignored at here.

$$N = \frac{1}{Q_{CPC} * t} \quad (6)$$

$$N_{LOD} = N * Dr * \left(\frac{1}{E}\right) * \left(\frac{1}{1-L}\right) * \left(\frac{1}{\Omega_{AV}}\right) * \left(\frac{1}{\eta}\right) \quad (7)$$

Where, N is the number concentration for the monodisperse aerosol while one particle only is detected in a single size channel; N_{LOD} is the limit of detection for number concentration with a good statistic in the polydisperse aerosol; Q_{CPC} is the aerosol flow moving through the CPC laser detection region; t is the scanning time for a single size; Dr is the dilution ratio in the CPC; E is the detection efficiency of the CPC at size D_p ; L is the diffusion losses for size D_p in the SMPS; Ω_{AV} is the average transfer function for the monodisperse; η is the fraction of particles carrying one negative or positive charge.

In term of $DN/D\log D_p$, equations 6 and 7 can be expressed:

$$\begin{aligned} & (DN/D\log D_p)_{LOD} \\ &= Dr * \frac{1}{Q_{CPC} * t} * \left(\frac{1}{E}\right) * \left(\frac{1}{1-L}\right) \\ & * \left(\frac{1}{\Omega_{AV}}\right) * \left(\frac{1}{\eta}\right) * \left(\frac{1}{\Delta\log D_p}\right) \end{aligned} \quad (8)$$

EXPERIMENTAL SETUP

In the draft regulation, it is recommended that monodisperse aerosols are applied to calibrate the solid particle penetration for the VPR. Except calibrating the VPR with the monodisperse aerosol following the PMP recommendation, we calibrated the VPR with polydisperse aerosols in this study since the polydisperse aerosol is much easier to be generated and handled, and is similar to real size distributions found in diesel aerosols.

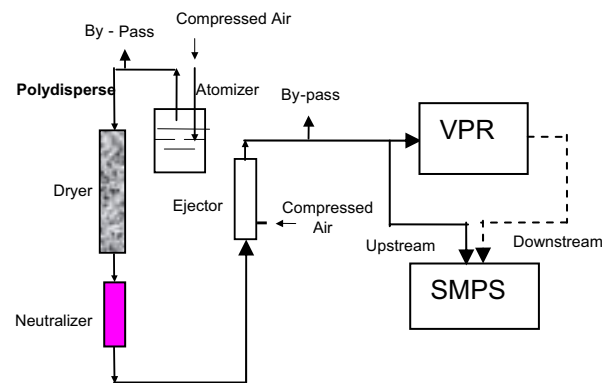


Figure 4. Solid particle calibration for the VPR with polydisperse aerosol

Figure 4 shows the flow schematic for the VPR calibration with the polydisperse aerosol. Sodium Chloride (NaCl) aerosol is generated with the atomizer. The moisture in the aerosol is removed with the diffusion dryer. The desiccant in the dryer is fresh and in a good condition to ensure that the aerosol is dry. A by-pass is