Uncertainties in the determination of the penetration efficiency of the volatile particle remover used in number emission measurement of non-volatile nanoparticles from aircraft turbine engines

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Introduction

- A new standard is going to be set by the International Civil Aviation Organization (ICAO) on emission of non-volatile particulate matter (nvPM) mass and number from aircraft turbine engines. The SAE Aerospace Information Report (AIR) 6241 describes the instrumentation and measurement protocol for the new standard.
- The method for particle number measurement in AIR6241 is similar to that for automotive emission standards in Europe (the PMP method). The instrument system consists of a condensation particle counter (CPC) and a volatile particle remover (VPR). A difference is that the lower limit of the particle size range in AIR6241 is 10 nm, while that of PMP is 23 nm.
- The difference in the lower size limit resulted in changes in requirements in the specifications of both CPC and VPR. For the CPC, the detection efficiency must be equal to or greater than 0.5 and 0.9 at 10 nm and 15 nm, respectively. For the VPR, the penetration efficiency for non-volatile particles at particle size d_i, Pen(d_i), which is defined by Eq. (1), must be equal to or greater than 0.30, 0.55, 0.65 and 0.70 at 15 nm, 30 nm, 50 nm and 100 nm, respectively:

$$\mathrm{Pen}(d_i) = \frac{\mathrm{DF} \times N_{\mathrm{out}}(d_i)}{N_{\mathrm{in}}(d_i)} \qquad (1)$$

  where $N_{\mathrm{in}}(d_i)$ and $N_{\mathrm{out}}(d_i)$ are the upstream and downstream concentrations, respectively, and DF is the dilution factor of the VPR.
- Since the evaluation of Pen at 15 nm is relatively new, we investigated potential sources of error in the determination of Pen(15nm) and attempted to evaluate its uncertainty quantitatively.
- We tested a unit of the AVL Particle Counter Aviation (APC Aviation). The dilution factor settings were either 68, 340, or 1349, all of which were tested in this study.

Experimental method

The method for the determination of Pen was based on AIR6241. Size-classified, non-volatile test particles were introduced into the VPR of the APC Aviation while the particle number concentrations upstream and downstream of the VPR were measured simultaneously with two CPCs (**Figure 1**).

- The test particles were soot generated by a propane diffusion flame with a Combustion Aerosol Standard (CAST) generator (Matter Engineering) after thermal pre-treatment at about 350 °C in a tube furnace, bipolar charge conditioning with 3 MBq of Am-241, and electrical mobility classification by a differential mobility analyzer (DMA) at 15 nm, 30 nm, 50 nm, or 100 nm.
- Two DMA systems were used to cover the wide particle size range; at 15 nm and 30 nm, a TSI model 3085 nano DMA was used at the sheath air flow rate of 30 L/min and the aerosol flow rate of 3 L/min. At 50 nm and 100 nm, a long-column DMA by Sibata Scientific Technology Ltd. (Soka, Japan) was used at the sheath air flow rate of 50 L/min and the aerosol flow rate of 5 L/min.
- The two CPCs were both TSI model 3775 of d_{50}=4 nm, operated in high flow mode.
- Two SMPS systems were used to measure particle size distributions.
- All tubing connections for aerosols were made of conductive silicone tubes.

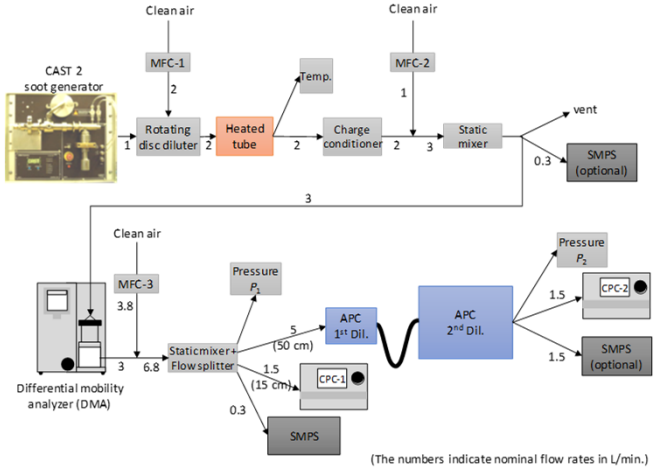


Figure 1 – Schematic of the test setup

- The Pen value was calculated with the following equation:

$$\mathrm{Pen} = \frac{\mathrm{DF}_2 \cdot N_{\mathrm{out}}}{N_{\mathrm{in}}} = \frac{\mathrm{DF}_2 \cdot \frac{N_{\mathrm{CPC-2}}}{\eta_{\mathrm{CPC-2}}} \cdot \frac{P_0 T_2}{P_2 T_0}}{\frac{N_{\mathrm{CPC-1}}}{\eta_{\mathrm{CPC-1}}} \cdot \frac{P_0 T_1}{P_1 T_0}} = \mathrm{DF}_2 \cdot \frac{N_{\mathrm{CPC-2}}}{N_{\mathrm{CPC-1}}} \cdot \frac{\eta_{\mathrm{CPC-1}}}{\eta_{\mathrm{CPC-2}}} \cdot \frac{P_1 T_2}{P_2 T_1} \qquad (2)$$

  where $N_{\mathrm{CPC-1}}$, $N_{\mathrm{CPC-2}}$, $\eta_{\mathrm{CPC-1}}$, $\eta_{\mathrm{CPC-2}}$ are the reported concentrations and the detection efficiencies of CPC-1 and CPC-2, respectively, and, P_1, T_1, P_2, T_2 are the pressure and temperature at CPC-1 and CPC-2, respectively.
- For each test condition, CPC readings were recorded for 5 minutes at 1-s interval. From the 5 minutes of data, five 1-min averages were calculated. The first 1-min data was discarded, and the remaining four 1-min data were used to calculate four Pen values and their average and standard deviation.

Results of the Pen evaluation

Figure 2 shows the results of our Pen evaluation at the four sizes and at the three dilution levels. The error bars indicate expanded uncertainties for repeatability with the coverage factor of 2. The horizontal line in light blue indicates the pass/fail line; if a point is above the line, it is a pass. Out of the 12 points, 11 points were above the line. On the other hand, there was one point, i.e., at 15 nm at DF = 1349, that was below the line. The results at 15 nm indicated a large variation of Pen against DF. The results at 30 nm also showed a weak DF dependence.

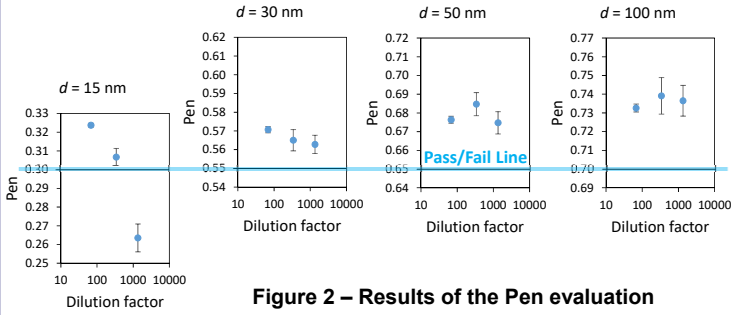


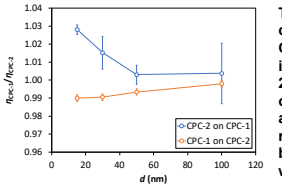
Figure 2 – Results of the Pen evaluation

We sought for reasons for the variability of the Pen value against DF in our system and method, but were not able to find any significant problems. We were not able to rule out the possibility that the variability was due to the performance of the VPR.

Uncertainties in the Pen evaluation

During this study, we identified several potential sources of error in the Pen evaluation. The following lists major ones and their magnitudes in our study at 15 nm.

- **Size of the test particles** Pen would have an error if the size of the test particles has an error. The sensitivity coefficient of Pen with respect to particle size d (d(Pen)/d(d)) for the tested VPR was experimentally evaluated to be 0.030 nm^{-1} at 15 nm. In this study, the DMA was calibrated with a size standard polystyrene latex particles of 29 nm and the standard uncertainty of the size of our 15-nm test particles classified by the DMA was evaluated to be 0.4 nm. The standard uncertainty of Pen due to particle size was therefore evaluated to be 0.012.
- **Low particle counts for N_{out}** When DF was highest (i.e., 1349) and d was smallest (i.e., 15 nm), N_{out} was about 1 cm^{-3} when the upstream concentration was 5000 cm^{-3}. The concentration of 1 cm^{-3} gave 300 particle counts in 1-min average for the CPC used in this study which had the detector flow rate of 0.3 L/min. Such low counts would give large random effects in the calculated number concentration. Assuming that the particle counts followed the Poisson probability distribution, the relative standard deviation was 6 %. Since we repeated 1-min measurements for four times, the average from the four repeated measurements would have a relative standard uncertainty of 6 %/√4 = 3 %, or 0.009 in the standard uncertainty for Pen = 0.3.
- **Charge state of the test particles** Pen were compared between two charge states; one was all +1 charged, and the other was neutralized, with an additional Am-241 charge conditioner after the DMA. Pen with neutralized test particles was slightly larger. and the difference was as large as 0.007 at 15 nm.
- **Detection efficiency of the CPCs** If the detection efficiencies of the two CPCs have large uncertainties, Pen would have large uncertainties. In our study, the ratio of the detection efficiencies in Eq. (2) $\eta_{\mathrm{CPC-1}}/\eta_{\mathrm{CPC-2}}$ was 0.995 and its standard uncertainty of $\eta_{\mathrm{CPC-1}}/\eta_{\mathrm{CPC-2}}$ was 0.016, which corresponded to 0.005 in the standard uncertainty for Pen = 0.3.
- **Mixing of multiply-charged particles in the test particles** In DMA-classified test particles, multiply charged particles are bigger than singly charged ones. Since larger particles have higher Pen, the mixing of larger multiply-charged particles would give positive biases to Pen. In our study, this bias was estimated to be 0.003 at 15 nm.
- **Biases caused by unpredictable losses in tubing** Losses in the tubing may be significantly affected by bends for particles as small as 15 nm. A simple experiment in our lab revealed substantial biases in comparison of the detection efficiencies of the two CPCs used in this study. As stated earlier, the detection efficiency ratio was 0.995, which was determined by our primary concentration standard. The ratio differed significantly in the experiment shown in **Figure 3.** We interpreted that the reason for the deviation was due to the bends of the tubes after the flow splitter. We have not been able to quantify this effect well.



The detection efficiency was compared between CPC-1 and CPC-2 in an experiment shown in the picture. In one case, CPC-2 was on top of CPC-1. In the other case, vice versa. The apparent detection efficiency ratios were significantly different between the two configurations, which was certainly an artefact.

Figure 3 – Direct comparison of the detection efficiency of the two CPCs and observed ratios

These uncertainties added up to approximately 0.03 (10 %) in the expanded uncertainty (k=2) for Pen = 0.3 with our test system even after careful characterization.

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