Laboratory study of the performances of two individual Condensation Particle Counters

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Abstract. In the general framework of investigating the performances of instruments that can be deployed in occupational hygiene to assess exposure to airborne nanoparticles, this study aims at providing new data relative to two new specimens of individual Condensation Particle Counters (CPC). Though a variety of instruments are available on the market, CPC constitute the devices that are used the most. Designed by the American company Enmont LLC, the first individual CPC allow personal measurements to be carried out. Here, the reliability of the PUFP C110 and C200 has been characterized in the laboratory. Our experimental results highlight that both individual CPC under study are impacted by both particle size (underestimation of the number concentration of ~20% when the modal diameter is lower than 40 nm, \( n = 21 \)) and hydrophobicity (~60% to ~90% compared to the reference concentration when aerosols are hydrophobic, \( n = 15 \)). Except from these specific cases \( (n = 44) \), both individual CPC have a comparable and satisfying response (+30% with regards to the reference concentration).

1. Motivation and objectives

As a complement to conventional sampling approaches, which provide information on the average exposure of workers, strategies for assessing occupational exposure to airborne nanoparticles advise the use of time-resolved techniques [1-3]. In most cases, few is known about the performances of direct-reading instruments when challenged by aerosols representative of those encountered in workplaces.

This study fits into the general framework of investigating the performances of instruments that can be deployed in occupational hygiene to assess exposure to airborne nanoparticles. To this end, Condensation Particle Counters (CPC) constitute the devices that are used the most [4], thanks to their field portability, and in spite of a large variety of instruments are available on the market.

First developed over a century ago [5, 6], CPC are based on the optical detection of particles artificially grown through the condensation of an adsorbed vapor on their surface. The devices record the number concentration of airborne particles per unit of air volume. In particular, number concentration stemming from CPC measurements can be used for airborne nanoparticle monitoring, task emission classification, and for evaluating the performance of protective equipment against nanoparticles, as well as for indoor air quality monitoring [7]. CPC have been associated with European standards recently published, one of them being devoted to their design and use [8], a second one dealing with their implementation as part of a strategy to assess exposure to airborne nanomaterials [9]; their use is also mentioned in OECD guidelines [10].

Ideally, such measurements are to be performed directly on the worker, in order to best describe its own occupational exposure. Recently, individual CPC have been designed and patented by Enmont LLC
[11], thus allowing personal measurements to be carried out. The first model, the PUFP C100, has been investigated in the laboratory [12] and implemented in measurement campaigns [13, 14]. The data published indicate a good correlation with reference instruments, provided that particles are not hydrophobic, which is typical of water-based CPC and has been shown previously [15, 16].

In this work, the reliability of two new specimens, the PUFP C110 and C200, have been characterized in the laboratory.

2. Materials and methods

Experiments were conducted in the laboratory on test aerosol produced in the CAIMAN facility [17]. The setup consisted of the simultaneous measurement of the number concentration of airborne particles by a reference CPC (TSI model 3752) and the two individual CPC (PUFP) under study. Table 1 summarizes the technical specifications of the three CPC involved in this study.

|                         | TSI 3752 | PUFP C110 | PUFP C200 |
|-------------------------|----------|-----------|-----------|
| flow rate (L/min)       | 1.5 ± 0.05 | 0.3 ± 0.03 | 0.25 ± 0.025 |
| d50 (nm)                | 4        | 5         | 6         |
| max. conc. in single count mode* (#/cm³) | 10⁴ | 2.10⁴ | 2.10⁴ |
| working fluid           | Butanol  | Water     | Water     |
| dimensions (H x W x L, cm) | 30 x 28.6 x 34.3 | 7 x 11 x 19 | 7 x 10 x 13 |
| weight (kg)             | 9        | 1         | 0.75      |
| battery lifetime (h)    | NA       | 6         | 3         |

* with coincidence correction

Along with the number concentration, the number size distribution of the test aerosols was determined by means of a SMPS, composed of a Differential Mobility Analyzer (DMA TSI model 3081) and a CPC (TSI model 3787).

2.1. Test aerosols

The test aerosols (Table 2) consisted of metal-based (C, Al, Ti, Cu) airborne particles produced by electro-erosion (PALAS, GFG-1000), salts (NaCl, KCl, CsCl) produced from nebulized aqueous solutions (PALAS, AGK2000) and liquid particles (n-C₁₃ to n-C₁₆, DEHS) produced by nebulization as well thanks to a home-made Laskin-type generator [18] and introduced within the CAIMAN test bench.

| Substance | Range of number concentration (10³ #/cm³) | Range of modal diameter (nm) |
|-----------|------------------------------------------|-----------------------------|
| Electro-erosion |                                         |                             |
| Al        | 19.0 – 251.6                             | 14 – 121                    |
| Ti        | 23.5 – 138.7                             | 40 – 197                    |
| Cu        | 34.4 – 163.5                             | 16 – 33                     |
| C         | 2.3 – 150.0                              | 44 – 148                    |
| Nebulization |                                         |                             |
| NaCl      | 30.1 – 79.9                              | 36 – 84                     |
| KCl       | 58.2 – 101.0                             | 35 – 75                     |
| CsCl      | 22.5 – 117.9                             | 81 – 105                    |
| n-C₁₃    | 67.3 – 321.7                             | 42 – 43                     |
| n-C₁₄    | 19.7 – 80.8                              | 48 – 49                     |
| n-C₁₅    | 8.1 – 35.2                               | 36 – 38                     |
| n-C₁₆    | 37.1 – 160.0                             | 31 – 32                     |
| DEHS      | 7.7 – 94.1                               | 159 – 172                   |
Overall, 80 different conditions were investigated, covering a range of number concentrations from 2,000 to 300,000 #/cm³, as stated in Table 2. To investigate the effect of particle hydrophobicity, ~20% (n = 15) of the test aerosols consisted of hydrophobic airborne particles.

Examples of test aerosols are given in Figure 1. For each condition, a log-normal fit was performed, leading to the determination of the modal diameter, as indicated in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Test aerosols produced in the laboratory for the study of CPC performance

### 2.2. Data processing

A typical time profile of the number concentrations recorded simultaneously by the three CPC is depicted in Figure 2, highlighting the presence of multiple concentration steps during a run. The grey areas represent the periods where aerosol stability was considered to be reached (data points presenting a coefficient of variation of more than 5% were disregarded), thus allowing the number concentrations to be averaged and compared with the reference ones.

![Figure 2](image2.png)

**Figure 2.** Example of a time profile of the number concentration

From such time series, pair-plots between each CPC under study and the reference CPC can be obtained. Further, the ratios R between the concentration measured by one of CPCs under study (\(\bar{X}\)) and
the corresponding reference concentration \( \bar{X}_{\text{ref}} \) were calculated for each experimental condition according to:

\[
R = \frac{\bar{X}}{\bar{X}_{\text{ref}}}
\]

leading to a set of data for each CPC under study.

3. Results and discussion

3.1. Comparison of the number concentrations with regards to the reference measurement

The average number concentrations reported by the two individual CPC are represented against the average concentrations given by the reference CPC in Figure 3. In this Figure, the grey areas correspond to the first bisector ± 30%, the shape of the points is material-dependent, while the colors are related to either the modal diameter of the test aerosol (green/orange) or the hydrophobic nature of the particles (blue). In the absence of technical specifications on the diameter for which a counting efficiency greater than 90% is ensured, the threshold of 40 nm was chosen to distinguish between the “smaller” and the “larger” test aerosols. This value is supported by our experimental data aiming at determining the \( d_{50} \) of the two PUFP (Figure 5).

![Pair-plots of the average number concentrations reported by the two CPC under study and the reference CPC](image)

Figure 3. Pair-plots of the average number concentrations reported by the two CPC under study and the reference CPC

Figure 3 highlights that both the PUFP C110 and C200 have a similar behaviour. Except for hydrophobic particles, there is a good agreement between both PUFP and the reference CPC, within ± 30%, for concentrations up to \( 2.10^5 \) #/cm\(^3\), whatever the substance. For hydrophobic aerosols (blue points), it is clear from Figure 3 that water-based PUFP underestimate the reference concentrations, by -60% to -90%. In addition, for aerosols presenting the smaller modal diameter (orange points), both PUFP tend to slightly underestimate the reference concentration. These observations are gathered in Figure 4 as boxplots.
Figure 4. Summary of the experimental results as boxplots

Figure 4 supports the previous remarks, highlighting a systematic slight overestimation (by ~20%) of the concentration by both PUFP for non-hydrophobic aerosols with modal diameters larger than 40 nm (green boxes). As soon as the aerosols are composed of a majority of particles smaller than 40 nm (orange boxes), the two CPC under study tend to underestimate the number concentration. Finally, it is worth noting that the two individual CPC are not suited for measuring hydrophobic aerosols (blue boxes), which is due to the use of water as working fluid.

3.2. Counting efficiency

To better understand the effect of modal diameter on the response of the two personal CPC, complementary experiments were carried out to determine their counting efficiency curves. Such experiments involved DMA-selected monodisperse aerosols of Cu and C in a range from 10 to 100 nm, as shown in Figure 5.
Figure 5 evidences that the smallest particles are not correctly counted by the two CPC under study, with counting efficiencies decreasing when decreasing the size of the particles below ~ 50 nm. Contrary to the manufacturer’s specifications (Table 1), our results yield 50% counting efficiency diameters between 20 and 25 nm, which is far from the specified 5-6 nm. To date, it remains difficult to formulate hypothesis to explain the differences observed.

Nonetheless, the data presented in Figure 5 provide elements supporting the underestimation of the number concentration observed for the aerosols mainly composed of particles with diameters lower than 40 nm, as stated in the comments from Figures 3 and 4.

3.3. Response time

Finally, the response time of the two PUFP has been investigated by means of a specific setup involving a three-way valve, thus allowing quick concentration steps to be generated.

Indeed, in this setup, one of the two inlets of the valve is connected to a constant aerosol source, the second one being in line with a HEPA filter, while the outlet is connected to the PUFP. Therefore, generating a concentration step (positive or negative) consists of changing the position of the valve.

Typical response profiles for both an increase and a decrease of the number concentration are displayed in Figure 6 for the two CPC under study.

![Figure 6. Time response of the two personal CPC](image)

The experimental results show a similar response of the two PUFP, with 95% response times of 3-4 seconds in the case of an increase in concentration, and 2-3 seconds in the case of a decrease of concentration.
3.4. Example of field-application
A preliminary use of the two CPCs in an occupational setting has also been carried out. This measurement was performed during the visit of a production unit of titanium dioxide. The PUFP C110 was worn by a person, side by side with a DiSCmini [19], as shown in Figure 7. It is important to note that the DiSCmini is not rigorously a particle counter, since it is based on electrical measurements; therefore, the data provided here shall be considered as illustrative and interpreted in terms of relative variations. A thorough study of the performances of multiple specimens of DiSCmini, including their capability of accurately measuring the number concentration with regards to the same reference CPC (TSI model 3752), was recently published [20].

Between these two signals, Spearman correlation coefficient was found to be 0.88, which attests of a similar behaviour between the two instruments, and demonstrates the field-applicability of the personal CPC.

![Figure 7. Time profile of the number concentration during the visit of a TiO2 production unit](image)

4. Conclusions
This experimental laboratory work aimed at characterizing the performances of two personal, water-based, battery-operated CPC that were recently developed: the PUFP C110 and the PUFP C200, designed by the American company Enmont LLC.

Our results, based on 80 test aerosols produced in the laboratory, highlight that both CPC have a similar performance. In the absence of hydrophobic particles, the concentration returned by the two CPC under study are within ± 30% of the reference concentration. The response of the CPC was found to be slightly sensitive to the mode of the aerosols measured, depending on the counting efficiency curve of the CPC investigated. In addition, a significant effect of particle hydrophobicity on the response of the two individual CPC was demonstrated.

This work highlights the need for conducting such intercomparisons prior to field campaigns, especially when strategies involving parallel measurements are carried out. Indeed, such studies help better define the scope of use of each instrument, and provide elements that enable explain the possible discrepancies between them when used in parallel.

A first use of these instruments was carried out in a production plant. If other exposure measurements still need to be performed, this first set of data confirmed their suitability for personal field measurements.

Finally, it is worth mentioning that the development of new devices including particle sampling is on-going, therefore allowing both direct-reading measurement and simultaneous sampling for further off-line analysis. This is for instance the case of the model CT100 designed for “Viral Pathogen
Sampling” according to the manufacturer. We believe that such devices could be useful in the assessment of occupational exposure, since they offer the advantages of the two complementary approaches, i.e. exposure monitoring and characterization.

References
[1] WITSCHGER O., LE BIHAN O., REYNIER M., DURAND C., MARCHETTO A., ZIMMERMANN E., & CHARPENTIER D. - Préconisations en matière de caractérisation des potentiels d'émission et d'exposition professionnelle aux aérosols lors d'opérations mettant en œuvre des nanomatériaux. *Hygiène et Sécurité du Travail*, 2012, **226**, 41-55.

[2] OSTRAA T. M. L., THORNBURG J. W., & MALLOY Q. G. J. - Measurement strategies of airborne nanomaterials. *Environ. Eng. Sci.*, 2013, **30**, 126-132.

[3] EASTLAKE A. C., BEAUCHAM C., MARTINEZ K. F., DAHM M. M., SPARKS C., HODSON L. L., & GERACI C. L. - Refinement of the Nanoparticle Emission Assessment Technique into the Nanomaterial Exposure Assessment Technique (NEAT 2.0). *Journal of Occupational and Environmental Hygiene*, 2016, **13**, 708-717.

[4] VIITANEN A.-K., UUKSULAINEN S., KOIVISTO A. J., HÄMERI K., & KAUPPINEN T. - Workplace Measurements of Ultrafine Particles—A Literature Review. *Annals of Work Exposures and Health*, 2017, **61**, 749-758.

[5] AITKEN J. - On the Number of Dust Particles in the Atmosphere. *Nature*, 1888, **37**, 428-430.

[6] MAYNARD A. D. - Learning from the past. *Nature Nanotechnology*, 2015, **10**, 482-483.

[7] ISO - ISO 16000-34:2018-08. *Indoor air - Part 34: Strategies for the measurement of airborne particles*. 2018.

[8] CEN - EN 16897. *Workplace exposure - Characterization of ultrafine aerosols/nanoaerosols - Determination of number concentration using condensation particle counters*. 2017.

[9] CEN - EN 17058. *Workplace exposure — Assessment of inhalation exposure to nano-objects and their agglomerates and aggregates*. 2018.

[10] OECD - Harmonized tiered approach to measure and assess the potential exposure to airborne emissions of engineered nano-objects and their agglomerates and aggregates at workplaces. *ENV/JM/MONO(2015)19*, 2015, **55**, 51.

[11] HE X., SON S.-Y., JAMES K., YERMAKOV M., REPONEN T., MCKAY R. T., & GRINSHPUN S. A. - Analytical performance issues: exploring a novel ultrafine particle counter for utilization in respiratory protection studies. *Journal of occupational and environmental hygiene*, 2013, **10**, D52-D54.

[12] ASBACH C., SCHMITZ A., SCHMIDT F., MONZ C., & TODEA A. M. - Intercomparison of a personal CPC and different conventional CPCs. *Aerosol and Air Quality Research*, 2017, **17**, 1132-1141.

[13] RYAN P. H., SON S. Y., WOLFE C., LOCKEY J., BROKAMP C., & LEMASTERS G. - A field application of a personal sensor for ultrafine particle exposure in children. *Science of the Total Environment*, 2015, **508**, 366-373.

[14] GRABINSKI C. M., METHNER M. M., JACKSON J. M., MOORE A. L., FLORY L. E., TILLY T., HUSSAIN S. M., & OTT D. K. - Characterization of exposure to byproducts from firing lead-free frangible ammunition in an enclosed, ventilated firing range. *Journal of Occupational and Environmental Hygiene*, 2017, **14**, 461-472.

[15] BAU S., PAYET R., TRITSCHER T., & WITSCHGER O. - Intercomparison in the laboratory of various Condensation Particle Counters challenged by nanoaerosols in the range 6 – 460 nm. *Journal of Physics: Conference Series*, 2019, **1323**, 012004.

[16] BAU S., TOUSSAINT A., PAYET R., & WITSCHGER O. - Performance study of various Condensation Particle Counters (CPCs): development of a methodology based on steady-state airborne DEHS particles and application to a series of handheld and stationary CPCs. *Journal of Physics: Conference Series*, 2017, **838**, 012002.
[17] JACOBY J., BAU S., & WITSCHGER O. - CAIMAN: a versatile facility to produce aerosols of nanoparticles. *Journal of Physics: Conference Series*, 2011, 304, 012014.

[18] SABROSKE K. R., HOYING D. A., & RABE D. C. - *Laskin nozzle particle generator*, 1996, US patent number 5 498 374.

[19] BAU S., ZIMMERMANN B., PAYET R., & WITSCHGER O. - Laboratory study of the performance of the miniature Diffusion Size Classifier (DiSCmini) for various aerosols in the 15-400 nm range. *Environmental Science: Processes and Impacts*, 2015, 17, 261-269.

[20] BAU S., PAYET R., WITSCHGER O., AUDIGNON DURAND S., & GALEY L. - Mesure en temps réel de l'exposition individuelle aux nanoparticules sous forme d'aérosols : performances et exemple d'application du DiSCmini. *Hygiène et Sécurité du Travail*, 2021, 262, 56-62.