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1 **PM_{0.1} non-bouncing impactor (NBI) for ultrafine particle mass and number**
2 **measurements**

3
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16
17 **Abstract**

18 This study designed and tested a 30 L/min PM_{0.1} non-bouncing impactor (PM_{0.1} NBI) for
19 ultrafine particle (UFP) mass concentration measurement. The PM_{0.1} NBI uses a wetted glass
20 fiber filter with continuous water injection to maintain a clean surface, preventing particle
21 loading and bounce effects. Lab tests showed the 30 L/min PM_{0.1} NBI outperformed the
22 PM_{0.1} stage of NCTU micro-orifice cascade impactor (NMCI, non-rotating) with a silicon
23 oil-coated aluminum foil substrate in collecting solid particles, as the particle collection
24 efficiency of the latter decreased obviously with increasing particle aerodynamic diameter for
25 particles larger than ca. 300 nm, an apparent particle bounce phenomenon. The ambient field
26 tests showed very close UFP mass concentrations between the PM_{0.1} NBI sampler (the PM_{0.1}

27 NBI preceded by 3 stages with 18, 10, and 2.5 micrometer cutoff sizes) and the reference
28 rotating 10-stages NMCI with the difference of $\pm 0.5 \mu\text{g}/\text{m}^3$ only. In addition, the 3 L/min
29 $\text{PM}_{0.1}$ NBI was combined with a condensation particle counter to measure the UFP number
30 concentrations which were shown to be very close to those of the reference with the
31 difference of $\pm 5\%$ only in the laboratory tests for loaded particle mass up to 300 μg . Good
32 agreement was also found in the field tests. Therefore, the current 3 L/min $\text{PM}_{0.1}$ NBI and the
33 future PM NBI with smaller flow rates (0.2-2.1 L/min) and larger cut-sizes (such as 0.4-0.9
34 μm) can be used as viable UFP classifiers for improving UFP measurement accuracy both in
35 mass concentrations and number concentrations and reducing the maintenance needs for the
36 UFP classifiers which are important to long-term sampling and monitoring.

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41 Keywords: ultrafine particle, $\text{PM}_{0.1}$, cascade impactor, particle loading, particle bounce

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43

44 1. Introduction

45 Exposure to air pollution is estimated to cause about seven million premature deaths
46 every year and new air quality guidelines were updated in 2021 in which PM_{2.5} daily and
47 hourly AQG levels (air quality goal) were further lowered to 15 and 5 µg/m³ from 25 and 10
48 µg/m³, respectively, to help reduce PM_{2.5} levels and decrease its health burden (WHO, 2021).
49 Due to health concerns of UFPs (ultrafine particles or PM_{0.1}, particles with aerodynamic
50 diameters, D_{pa} , smaller than 0.1 µm) (HEI, 2013; Ohlwein et al., 2019), BC/EC (black
51 carbon or elemental carbon) (US EPA, 2019) and SDS (particles originating from sand and
52 dust storms) (Querol et al., 2019), actions to enhance research on the UFP risks and develop
53 the corresponding mitigation methods were summarized in qualitative good practice
54 statements, despite insufficient data to provide recommendations for AQG levels and interim
55 targets for these specific types of PM (WHO, 2021). Practices to integrate UFP monitoring
56 into the existing air quality monitoring, prioritize UFP source emission control, and advance
57 approaches to the assessment of exposure to UFP for epidemiological studies and UFP
58 management are recommended (WHO, 2021).

59 Exposure assessment for UFPs is typically based on particle number concentrations (NCs)
60 (Ohlwein et al., 2019), particle mass concentrations (MCs) (Kumar et al., 2021), or
61 lung-deposited surface area (Geiss et al., 2016). Among them, NC is the most common choice
62 because the related measurement technologies are well-established (WHO, 2021), and UFPs
63 are the main contributors to the total number of particles in the atmosphere (Morawska et al.,
64 2008; Chen et al., 2010a). For the size distribution measurement of submicron particles
65 including UFPs, a scanning mobility particle sizer (SMPS) incorporating a single-stage inlet
66 impactor, an electrostatic classifier and a condensation particle counter (CPC), is the most
67 commonly used instrument. The impactor removes particles larger than a known D_{pa} which
68 sets the upper limit of the SMPS, thereby easing the multiple charge correction in the data
69 inversion program (He and Dhaniyala, 2013). However, the high cost and complexity of the

70 SMPS limit its widespread use in large-scale UFP monitoring networks (Abdillah and Wang,
71 2023). In addition, the inlet impactor without a coated impaction substrate or with a silicone
72 oil-coated substrate is known to be affected by particle bounce and loading effects (Le and
73 Tsai, 2017; 2021). Therefore, regular maintenance is needed to keep its size-classifying
74 performance accuracy during long-term monitoring and when particle concentration is high,
75 such as in a highway tunnel (Chen et al., 2010a and 2010b) or welding booth (Chang et al.,
76 2013), where $PM_{2.5}$ and UFP MCs can be as high as 78 and $33.2 \mu\text{g}/\text{m}^3$, or 1,500 and 430
77 $\mu\text{g}/\text{m}^3$, respectively.

78 For physicochemical and toxicity assessment of UFPs (Chen et al., 2010b; Tsai et al.,
79 2011; Kumar et al., 2021), mass-based measurement is required with a minimum sample
80 mass of 100 μg and 1000 μg for the former and latter, respectively (Kumar et al., 2021). This
81 amount of UFP sampling can be achieved in the high-concentration tunnels and workplace
82 environments mentioned above, but it is a challenge in ambient settings where UFP
83 concentrations are typically low, e.g. $2.2 \mu\text{g}/\text{m}^3$ in roadside (Chen et al., 2010b), $0.7 \mu\text{g}/\text{m}^3$ in
84 forest (Chen et al., 2010b), and $<0.5 \mu\text{g}/\text{m}^3$ in California city (Xue and Kleeman, 2022),
85 unless extended periods up to a few days or at high flow rates are used (Kumar et al., 2021;
86 Xue et al., 2020). Most UFP samplers with high flow rates are cascade impactors that operate
87 at flow rates ranging from several hundreds to 1100 liters per minute, and the $PM_{0.1}$ stage in
88 these samplers is usually preceded by two to three stages, such as the high-volume ultrafine
89 particle sampler (550 L/min, 2 stages: 2.5 and 0.15 μm) (Misra et al., 2002), the harvard
90 high-volume cascade impactor (850 L/min, 3 stages: 2.4, 0.9 and 0.2 μm) (Sillanpaa et al.,
91 2003), and the high-volume impactor Sampler (400 L/min, 2 stages: 2.5 and 0.18 μm) (Saleh
92 et al., 2019). However, the D_{pa50} of the $PM_{0.1}$ stage in these samplers is 0.15, 0.2, and 0.18
93 μm only, respectively, which are considered quasi-UFPs but not true UFPs (Xue and Kleeman,
94 2022; Kumar et al., 2021; Sotty et al., 2019). Quartz fiber substrate used in the $PM_{0.1}$ stage of
95 high-volume ultrafine particle sampler eliminates initial particle bounce, but the maximum

96 loaded particle mass (M_L) is limited to 60 mg, while the polyurethane foam substrate in
97 harvard high-volume cascade impactor can increase the M_L but the particle collection
98 efficiency curve is less steep than that of the flat substrate, as the air can penetrate into the
99 porous substrate leading to increased collection of large particles due to inertia impaction and
100 UFPs due to diffusion. (Huang et al., 2001; Sillanpaa et al., 2003; Huang and Tsai, 2005).
101 Therefore, a silicon oil-coated smooth impaction surface is a better choice to achieve a more
102 accurate measurement, especially for the classification of nanoparticles (Chen et al., 2018),
103 but particle bounce and loading effects still need to be overcome (Le and Tsai, 2017; Le et al.,
104 2022).

105 The UFPs measurement can be achieved using samplers that operate at a medium flow
106 rate of 9 to 40 L/min (Chen et al., 2010a and 2010b; Kumar et al., 2021), such as the
107 micro-orifice uniform deposit impactor (MOUDI, 30 L/min, Marple et al., 1991), the NCTU
108 micro-orifice cascade impactor (NMCI, 30 L/min, Liu et al., 2013; Chien et al., 2015), and
109 the nanosampler (40L/min, Furuuchi et al., 2010;). The $PM_{0.1}$ stage in the former two
110 devices is preceded by a 0.18 μm -stage while nanosampler is preceded by a 0.5 μm -stage.
111 MOUDI and NMCI employ rotating stages and silicon oil-coated substrates to increase the
112 M_L , but the rotating feature does not exist in both high-volume UFP samplers and
113 nanosampler. The mass collected on each stage of the MOUDI is limited to 3 mg (Marple et
114 al., 1991) because the coating layer becomes ineffective with particle accumulation and
115 particle bounce may occur from particle mounds (Tsai and Cheng, 1995; Misra et al., 2002).

116 For personal sampling of UFPs in workplaces, our group has developed a personal
117 nanoparticle sampler (PENS, Tsai et al., 2012) which consists of a $PM_{4.0}$ cyclone-inlet and a
118 micro-orifice impactor with D_{pa50} of 100 nm. Nevertheless, there is a M_L limit of 1.78 mg. To
119 eliminate the particle loading effect, a 3.0 L/min NIC (Nanoparticle Inertial Classifier, Le et
120 al., 2022) which is based on the non-bouncing feature of 16.7 L/min $PM_{2.5}$ M-WINS
121 (modified well impactor ninety-six, Le and Tsai, 2017; Le et al., 2020), was developed in

122 which clean water is injected continuously at 0.3 mL/min flow rate (or vacuum oil is applied
123 once per day for one minute at 3 mL/min each time) upward through a small drilled hole (1
124 mm diameter) located at the center of the glass fiber filter (GFF) impaction surface to wash
125 off the deposited particles. The spent water/oil is then drained off from the hole at the edge of
126 the impaction surface. The impaction substrate is thus free from loaded particle accumulation.

127 In this study, the non-bouncing impactor technique of our group was employed to modify
128 the 9th stage of the NMCI (Liu et al., 2013) as the 30 L/min PM_{0.1} Non-Bouncing Impactor
129 (30 L/min PM_{0.1} NBI) for UFP MC measurement, in particular for long-term sampling if
130 enough UFP mass is desired. The NIC developed previously (hereafter called as 3 L/min
131 PM_{0.1} NBI) was used to replace the traditional impactor at the inlet of CPC or SMPS for
132 long-term UFP NC measurement. The performance of these PM_{0.1} NBIs was tested for the
133 particle loading effect both in the laboratory and in an ambient environment using the
134 10-stage NMCI and SMPS as the references for MC and NC measurements, respectively.

135

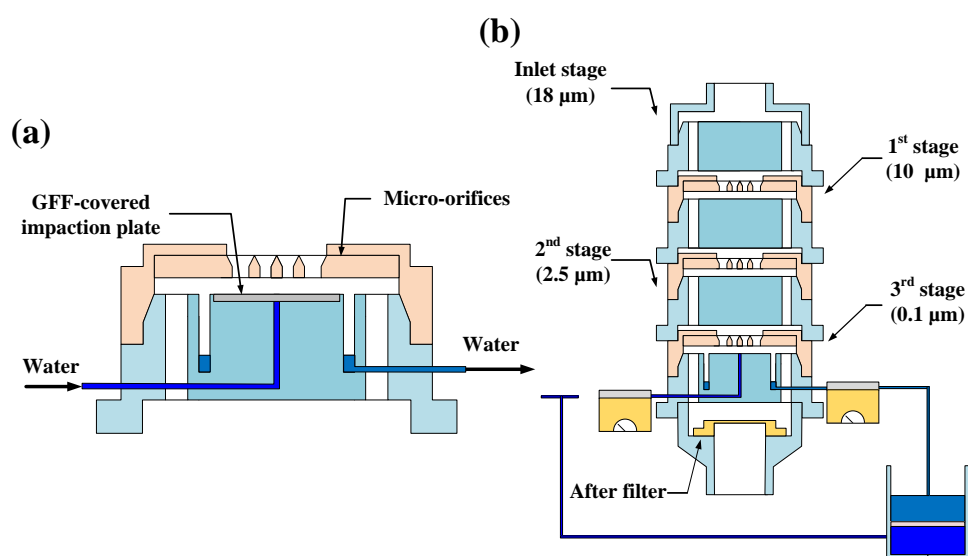
136 **2 Experimental methods**

137 **2.1 UFP MC measurement**

138 *Design of 30 L/min PM_{0.1} NBI and sampling system*

139 The 30 L/min PM_{0.1} NBI is designed by modifying the 9th stage (PM_{0.1} stage) of the
140 NMCI, which consists of a nozzle plate having 2000 nozzles with a nozzle diameter of 55 µm
141 and an impaction plate covered by a 37-mm GFF (Model TE-G653-37, TISCH) as shown in
142 Fig. 1a. De-ionized water is injected by a peristaltic pump continuously upward via a 1-mm
143 hole (internal diameter) drilled through the impactor plate and GFF with a flow rate of 0.5
144 mL/min to wet the GFF and remove deposited particles. Spent water then flows into the
145 annular cavity around the impaction plate and is drained by another peristaltic pump. The 30
146 L/min PM_{0.1} NBI was used for the particle collection efficiency test in the laboratory test
147 while a complete 30 L/min PM_{0.1} NBI sampler (NBIS) shown in Fig. 1b was used for the

148 particle loading and field tests. The 30 L/min PM_{0.1} NBIS consists of the 30 L/min PM_{0.1} NBI,
 149 preceded by 3 non-rotating impaction stages: the inlet stage (D_{pa50} of 18 μm), the first stage
 150 (D_{pa50} of 10 μm), and the second stage (D_{pa50} of 2.5 μm) followed by an after filter (47-mm
 151 Teflon filter, Model R2PL047, Pall) to collect UFP. The three preceding stages are used to
 152 remove coarse particles to avoid nozzle clogging in the PM_{0.1} stage. The first two stages are
 153 the same as those of the NMCI while the diameter of 10 nozzles of the 2nd stage was reduced
 154 to 2.1 mm and re-calibrated to be 2.5 μm as will be shown in a later publication.



155
 156 Fig. 1. Schematic diagram of the (a) 30 L/min PM_{0.1} NBI (b) 30 L/min PM_{0.1} NBI sampler
 157 (NBIS), non-rotating

158

159 *Particle collection efficiency test*

160 The experimental setup used for testing the particle collection efficiency of the 30 L/min
 161 PM_{0.1} NBI is depicted in Fig. S1 (Section B) of the supplementary information (SI) and is
 162 similar to the one described in Le et al. (2022). Liquid dioctyl sebacate (DOS) and solid NaCl
 163 particles were generated by the evaporation-condensation method and by an atomizer
 164 followed by a diffusion dryer, respectively. The generated particles were charge neutralized
 165 and classified into monodisperse particles by a differential mobility analyzer (Model 3081,
 166 TSI). The particle concentrations were measured upstream and downstream of the NBI by

167 using a home-made faraday-cup with an electrometer (Model 6514, Keithley) to determine
 168 the particle collection efficiency (η , %) calculated by (Le et al., 2022):

169

$$170 \quad \eta = \left(1 - \frac{I_{down}}{I_{up}}\right) \times 100 \quad (1)$$

171

172 where I_{up} and I_{down} is the upstream and downstream particle currents (μA), respectively. Then,
 173 the particle collection efficiency curve and D_{pa50} were determined by fitting the measured
 174 data using the following equation (Le et al., 2022; Le and Tsai, 2017):

175

$$176 \quad \eta(D_{pa}) = 100\% - a - b \left[1 - \left[1 + \exp\left(\frac{D_{pa} + d \ln\left(\frac{1}{2^e - 1}\right) - c}{d}\right) \right]^{-e} \right] \quad (2)$$

177

178 where a, b, c, d, and e are the fitting parameters. The classification curve sharpness (κ) was
 179 also calculated as the square root of the ratio of D_{pa84} and D_{pa16} which correspond to the
 180 particle collection efficiency of 84% and 16%, respectively. In addition, a single 9th stage of
 181 the NMCI was also tested for comparison, where the impaction substrate is the silicone oil
 182 (Model KF96SP, Shin-Etsu Chem. Co., Ltd., Japan)-coated aluminum foil substrate (47mm,
 183 Allfield Ltd., Taiwan).

184

185 *Particle loading test in the laboratory*

186 The experimental setup of the particle loading test of the 30 L/min $\text{PM}_{0.1}$ NBIS is
 187 depicted in Fig. S2 (Section B) of the SI. For comparison, a 30 L/min traditional cascade
 188 impactor-R (TCI-R) consisting of rotating stages 0, 1, 2 and 9 (the cut-sizes of 18, 10, 2.5
 189 and 0.1 μm , respectively) of the NMCI and an after filter (47-mm Teflon filter, Model
 190 R2PL047, Pall) was also tested. All 4 stages of the TCI-R use rotating and silicon oil-coated

191 aluminum foil substrates. Similar to the 30 L/min PM_{0.1} NBIS, the PM_{0.1} stage of the TCI-R
192 was preceded by the PM_{2.5} stage to examine the possible particle loading effect which may
193 also occur in High-Volume UFP samplers described earlier. The quasi-UFP stages of these
194 samplers are all preceded by an upper stage with 0.9 to 2.5 µm as the cutoff size.

195 The particle loading tests were conducted using nano-TiO₂ particles (AERODISP P25,
196 Degussa, Germany) which were dried in an oven at 105°C for 2 hours before use. Particles
197 were dispersed using a small-scale powder disperser (SSPD, Model 3433, TSI) and then
198 introduced to the NBIS and TCI-R for PM_{0.1} MC measurement by weighing the particle
199 masses on the after filters before and after each test. Based on experimental data of the
200 SSPD-dispersed nano-TiO₂ particles, which showed UFP and TSP mass concentrations to be
201 92 and 3,427 µg/cm³, respectively (Le et al., 2022), the UFP/TSP fraction is calculated to be
202 2.68%. As these particles were reported to have stable mass and number size distributions
203 (Tsai et al., 2012; Le et al., 2022), the UFP/TSP fraction of 2.68% is assumed to remain
204 constant in this study and is used for comparison with measurements from the NBIS and
205 TCI-R in this loading test.

206 The M_L of the PM_{0.1} stage of the TCI-R was obtained by weighing the silicone
207 oil-coated aluminum foil substrates before and after the tests. The M_L of the NBIS-PM_{0.1}
208 stage was calculated using the formula ((TSP × PM_{2.5}/TSP ratio) - PM_{0.1}) (unit: mg). Note
209 that the TSP value was obtained from a 5 L/min filter cassette containing a 47-mm Teflon
210 filter, which was collocated with the NBIS and TCI-R. The particle loading effect of the
211 NBIS and TCI-R was checked by the relationship of the measured UFP MCs with different
212 M_L and compared with the reference UFP values.

213

214 *Field test in ambient conditions*

215 The field comparison tests were performed on the roof of the Institute of Environmental
216 Engineering at National Yang Ming Chiao Tung University. The roof is situated 20 meters

217 above the ground and is close to the Hsinchu Science Industrial Park and the main roads of
218 Hsinchu City, where there is heavy traffic flow during the morning and evening rush hours.
219 The 30 L/min PM_{0.1} NBIS, 10-stage rotating NMCI, and TCI-R were used in the test as
220 shown in Fig. S3 (Section B) of the SI. In addition, the TCI-NR (i.e., the TCI with
221 non-rotating silicon oil-coated aluminum foil substrate) instead of TCI-R was also tested for
222 comparison purposes. Two comparison tests were conducted, test-1 was to compare the NBIS,
223 NMCI, and TCI-R, while test-2 was to compare the NBIS, NMCI, and TCI-NR. Four and
224 five 24-hr average UFP samples were collected for test-1 and test-2, respectively from
225 December 2021 to March 2022, when daily average PM_{2.5} concentration varied from 10 to 40
226 $\mu\text{g}/\text{m}^3$, temperature varied from 14 to 24 °C, and relative humidity varied from 62 to 75%.

227 The M_L on the PM_{0.1} stage of the TCI-R or -NR was obtained by weight gain on the
228 stage, while the M_L on the PM_{0.1} stage of the NBIS was calculated using the formula (PM_{2.5}
229 mass in the NMCI - PM_{0.1} mass in NBIS). It is worth noting that the relative percent
230 differences (RPD) of the PM_{2.5} MCs measured by the NMCI, TCI-R, and -NR average 6.2%
231 as shown in Table S1 (Section A), implying the accuracy of the comparison tests. The
232 accuracy of the PM_{0.1} measurement was evaluated based on comparing the PM_{0.1} MCs
233 measured by the tested devices with those of the NMCI as the reference.

234

235 **2.2 UFP NC measurement**

236 The UFP NC or size distribution monitoring system, shown in Fig. S4 (Section B) of the
237 SI, uses the 3 L/min PM_{0.1} NBI as the inlet of a commercial CPC (Model 3788, TSI) or a
238 SMPS (Model 3936, TSI), respectively. The systems for UFP NCs or size distribution
239 measurement are named NBI-CPC or NBI-SMPS. Because the flow rate of the PM_{0.1} NBI is
240 3 L/min, 2.4/2.7 L/min has to be bypassed when the inlet flow rate of CPC/SMPS is 0.6/0.3
241 L/min.

242

243 *Particle loading test in the laboratory*

244 The effect of loaded particle mass (M_L) of the 3 L/min NBI is examined by the
245 relationship of the ratio of the UFP NCs of the NBI-CPC to those of the reference SMPS with
246 various M_L . Here the SMPS is used as the reference instrument where a TSI inlet impactor
247 (nozzle diameter: 0.0457 cm) was first tested for the particle loading effect to determine the
248 acceptable M_L of 150 μg before use. The inlet impactor was cleaned before the M_L exceeded
249 the acceptable value to maintain good classification performance.

250 The experimental setup of the particle loading test for the SMPS's TSI inlet impactor is
251 shown in Fig S5 (Section B) of the SI. The SMPS equipped with a 0.0457 cm-nozzle inlet
252 impactor (D_{pa50} : 410 nm) was operated at an aerosol flow of 0.6 L/min and a sheath flow of 3
253 L/min. The polydisperse NaCl particles were introduced into the SMPS to measure the
254 particle number distribution, which was recorded over time. The particle loading effect of the
255 SMPS inlet impactor was evaluated based on the variation of the particle number distribution
256 with loaded particle mass (M_L) which was obtained by determining the mass difference of the
257 impaction substrate by weighing before and after each loading test.

258 The experimental setup of the particle loading test of the NBI coupled with the CPC is
259 shown in Fig. S6 (Section B) of the SI. Similar to the particle loading test of the SMPS inlet
260 impactor, the generated NaCl particles were introduced simultaneously into the collocated
261 NBI-CPC and SMPS to measure the UFP NC and number size distribution, respectively. The
262 SMPS used in this test applies a 0.3 L/min CPC (Model 3776, TSI), in which the SMPS inlet
263 impactor (nozzle size of 0.0457 cm) has a D_{pa50} of 615 nm. As the D_{pa50} is much larger than
264 100 nm, the UFP measurement in SMPS is not affected (He and Dhaniyala, 2013). The
265 effective density used for the conversion of the electrical mobility diameter (D_{pe})-based
266 SMPS data to the D_{pa} -based values using the conversion equation Eq. S1 in Section C of the
267 SI, is 1.7 g/cm^3 for NaCl particles. The M_L was determined by integrating the mass
268 distribution converted from the number distribution with the details provided in Section D of

269 the SI. A traditional impactor (TI, i.e., the 3 L/min PM_{0.1} NBI used a silicone oil-coated
270 aluminum substrate instead of the water-wetted GFF) used as the inlet of the CPC was also
271 tested for comparison.

272

273 *Field comparison test*

274 The field comparison test of the 3.0 L/min NBI-CPC versus the SMPS as the reference
275 was carried out at the same location as that of 30 L/min PM_{0.1} NBIS test, and lasted for five
276 days (08-13 Jan 2023). Fig. S7 (Section B) of the SI shows the test setup which consists of a
277 PM₁₀ inlet and a Very Sharp Cut Cyclone PM_{2.5} inlet (Le et al., 2020) followed by NBI-CPC
278 and SMPS. After PM_{2.5} inlet, the 16.7 L/min air flow was split into three streams: 3 L/min for
279 the NBI-CPC, 0.3 L/min for the SMPS, and 13.4 L/min for the bypass flow. The UFP NCs
280 were measured by the NBI-CPC and compared with the reference values (i.e. NCs of D_{pa}
281 smaller than 100 nm) determined from the particle number distribution (D_{pe} of 14-700 nm)
282 monitored by the SMPS. The effective density used for the size conversion is chosen to be
283 1.2 g/cm³, which is typical in an urban environment (Liao et al., 2019).

284

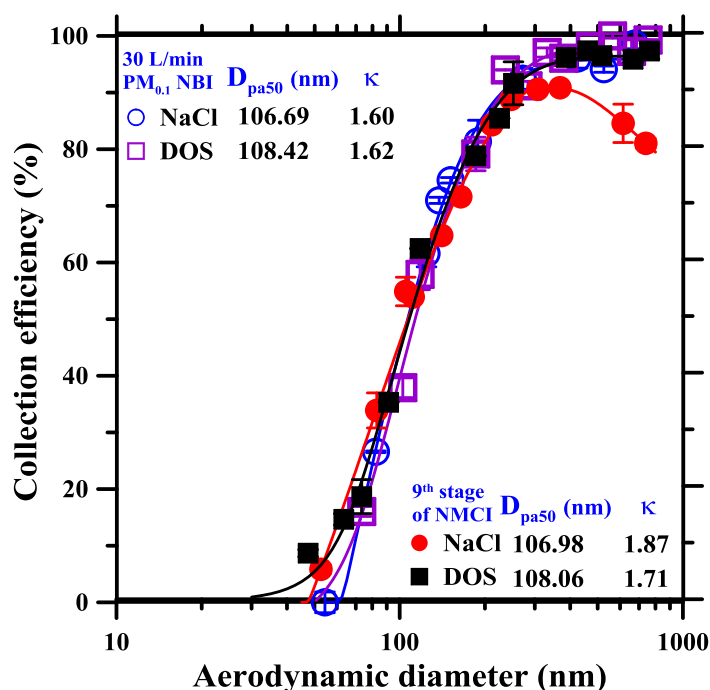
285 **3. Results and Discussion**

286 **3.1 UFP MC measurement**

287 **Particle collection efficiency test in the laboratory**

288 Fig. 2 shows the particle collection efficiency curves of the 30 L/min PM_{0.1} NBI and 9th
289 stage of the NMCI for different particle types. The PM_{0.1} NBI has D_{pa50} of 107 nm and κ of
290 1.60 for solid NaCl particles, and D_{pa50} of 108 nm and κ of 1.62 for liquid DOS particles,
291 demonstrating good cut-off performance with the cut-size close to the expected 100 nm (Le et
292 al., 2022). In comparison, the NMCI-PM_{0.1} stage (9th stage) also shows good classification
293 performance for liquid DOS particles with a cut-size of 108 nm and κ of 1.71, which agrees
294 well with the test results for liquid particles in the previous studies (Liu et al., 2013; Chien et

295 al., 2015). For solid NaCl particles, D_{pa50} and κ of the NMCI-PM_{0.1} stage are also 107 nm and
 296 1.87, respectively, similar to those of the 30 L/min PM_{0.1} NBI sampler, but the particle
 297 collection efficiencies become lower than those of liquid particles when particles are larger
 298 than the cut-size. The decrease in the collection efficiency becomes much more obvious as
 299 D_{pa} is larger than 300 nm due to solid particle bounce in the NMCI-PM_{0.1} stage with the
 300 rotating, silicone oil-coated aluminum foil substrate. In the NMCI-PM_{0.1} stage with
 301 silicone-oil coated
 302



303
 304 Fig. 2. Particle collection efficiency of the PM_{0.1} stage of the NBIS and 9th stage of the NMCI
 305
 306 aluminum substrate, an oil-free spot is formed under each nozzle since the air jet velocity is
 307 as high as 144 m/s resulting in particle bounce similar to that observed in the previous study
 308 of our group (Tsai et al., 2012) in which a silicone-oil coated Teflon filter (10 μ m pore size)
 309 had to be used to resolve this issue and prevent particle bounce. The Teflon filter has a
 310 uniform micro-pore structure, which facilitates capturing and retaining liquid within its pores
 311 throughout surface (Turner and Hering, 1987). Similar phenomena have been observed in

312 other substrate materials having micro-porous structure, such as oil-soaked sintered metal
313 disks (Reischl and John, 1978). Besides, continuous water injection at the center of the
314 substrate helps maintain a steady supply of water to keep the GFF surface wet (Le et al.,
315 2022). Therefore, the air jet won't push water aside and leave a dry spot beneath each of the
316 nozzles.

317 However, solid particle bounce does not occur easily in the 10-stage NMCI, in which the
318 $PM_{0.1}$ stage is preceded by the 0.18- μm stage (8th stage). Only particles smaller than 180 nm
319 are collected on the $PM_{0.1}$ stage thereby eliminating possible particle bounce effect. But if a
320 traditional $PM_{0.1}$ impactor is preceded by a upstream stage with a cut-size larger than about
321 0.2~0.3 μm , such as 0.5 μm in nanosampler (KANOMAX, Japan) (Furuuchi et al., 2010) or
322 0.9-2.5 μm in the high-volume UFP impactors, it is very likely that particle bounce could
323 occur on the $PM_{0.1}$ stage leading to overestimation of UFP MCs. This will be demonstrated in
324 the following section where the test results of 4-stage TCIs, whose $PM_{0.1}$ stage is preceded by
325 the $PM_{2.5}$ stage, are shown.

326

327 *Particle loading test in the laboratory*

328 Fig. 3 shows the $PM_{0.1}$ MCs measured by the NBIS and TCI-R at various nano- TiO_2 M_L .
329 Since the source generating particles was stable during the test, the inlet $PM_{0.1}$ concentration
330 can be assumed to be constant and is calculated to be 105.46 $\mu g/m^3$ (based on the measured
331 TSP concentration of 3.93 $mg/m^3 \times PM_{0.1}/TSP$ ratio of 2.68%). This inlet concentration
332 value is used as the reference, represented as the solid line in Fig. 3, to evaluate the
333 performance of the NBIS and TCI-R.

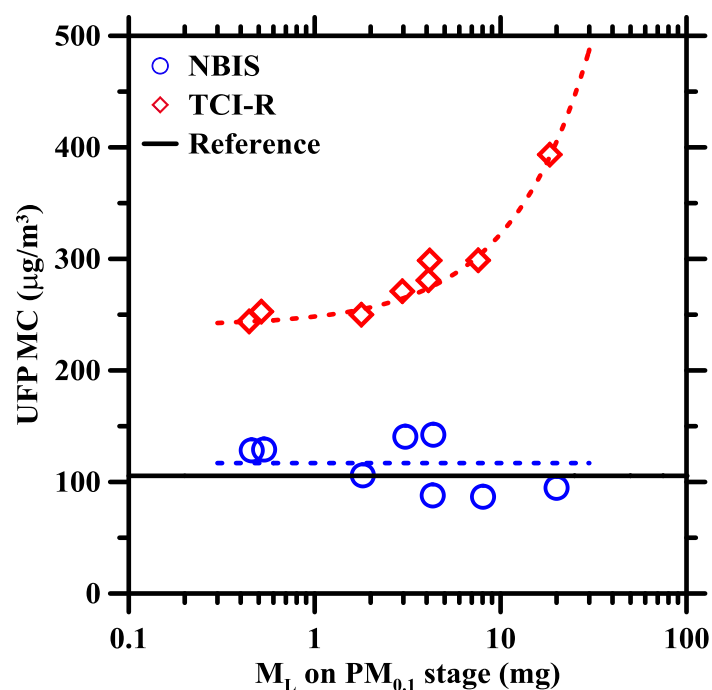


Fig. 3. UFP MC by the NBIS and TCI-R versus M_L .

334

335

336

337 Initially, the TCI-R measures $PM_{0.1}$ MC of $244 \mu\text{g}/\text{m}^3$ at an M_L as low as 0.44 mg,
 338 which is much higher than the reference value of $105.46 \mu\text{g}/\text{m}^3$. It indicates an
 339 over-measurement problem of the TCI-R with the rotating, silicon oil-coated impaction
 340 substrate. The initial over-measurement occurs due to the "initial bounce" for particles larger
 341 than 300 nm from the $PM_{0.1}$ stage, which is explained earlier in the previous section.
 342 Subsequently, the measured $PM_{0.1}$ MC of the TCI-R increases slightly to $268 \mu\text{g}/\text{m}^3$ from 244
 343 $\mu\text{g}/\text{m}^3$ when the particle mass load is increased to 2.96 mg from 0.44 mg.

344 The acceptable M_L limit of 3.0 mg was suggested by Marple et al. (1991). When the M_L
 345 is increased from 3.0 to 18.38 mg, the measured $PM_{0.1}$ MC is increased to $394 \mu\text{g}/\text{m}^3$, or 1.6
 346 times the initial value. This indicates particle overloading effect induces more particle bounce
 347 in the TCI-R when the M_L exceeds 3 mg. Therefore, the use of a preceding stage with $D_{pa} <$
 348 300 nm is needed for the $PM_{0.1}$ TCI-R to prevent initial solid particle bounce and its
 349 impaction substrate needs to be cleaned and re-oiled regularly to prevent the
 350 over-measurement.

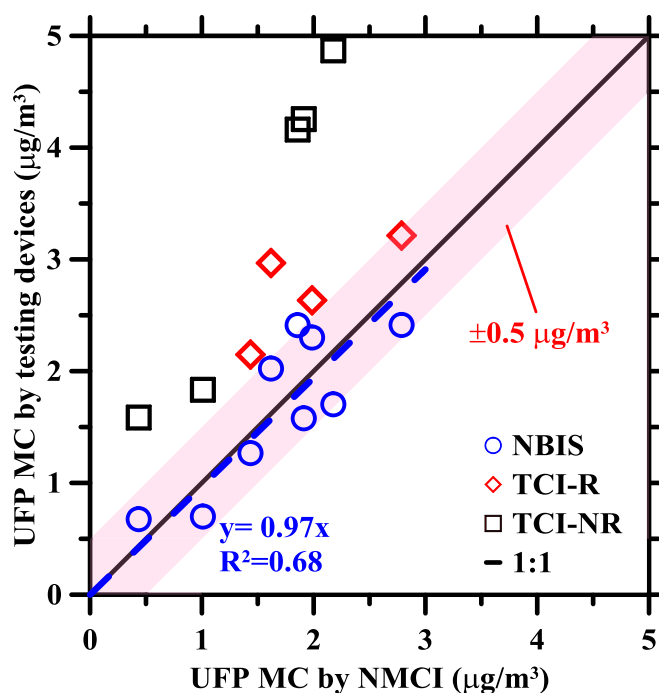
351 In comparison, NBIS measures the $PM_{0.1}$ concentration of $128 \mu\text{g}/\text{m}^3$ at an M_L of 0.46
352 mg, which is close to the reference value of $105.46 \mu\text{g}/\text{m}^3$. The small difference in MCs is
353 attributed to the experimental uncertainty of the low collected mass ($<20 \mu\text{g}$). It indicates that
354 the NBIS has no initial particle bounce since the water-wetted GFF impaction substrate
355 retains water effectively in the pores to prevent solid particle bounce. When the M_L is
356 increased to 20.01 mg, the NBIS $PM_{0.1}$ MC still keeps at $94.74 \mu\text{g}/\text{m}^3$. The average MC is
357 $117 \pm 22 \mu\text{g}/\text{m}^3$ for M_L ranging from 0.46 to 20.01 mg, which is within 10% bias compared to
358 reference value. Therefore, the 30 L/min $PM_{0.1}$ NBIS has no particle bounce and loading
359 effects, and is capable of sampling $PM_{0.1}$ MC at high concentration environments with good
360 accuracy.

361

362 *Field comparison test*

363 The performance of the NBIS and TCIs (rotating or non-rotating stages) in the ambient
364 air with low particle MCs is also tested. Fig. 4 displays the ambient $PM_{0.1}$ MCs measured by
365 three devices, NBIS, TCI-R, and TCI-NR, versus reference $PM_{0.1}$ MCs measured by the
366 rotating 10-stage NMCI. The results show that the NBIS $PM_{0.1}$ MCs vary from 0.68 to 2.41
367 $\mu\text{g}/\text{m}^3$, which are close to the NMCI $PM_{0.1}$ MCs ranging from 0.44 to $2.79 \mu\text{g}/\text{m}^3$ with the
368 concentration difference of less than $\pm 0.5 \mu\text{g}/\text{m}^3$ (difference averages only $-0.02 \pm 0.36 \mu\text{g}/\text{m}^3$).
369 The linear regression analysis shows a high accuracy (slope=0.97) and a medium correlation
370 ($R^2=0.68$) of the NBIS with the NMCI. This means that the NBIS can measure $PM_{0.1}$ MC
371 accurately even in low UFP concentration environments.

372



373

374

Fig. 4. Comparison of the UFP MC by the TCI and NBIS to the NMCI

375

376 In comparison, the TCI-R measures the $\text{PM}_{0.1}$ MCs of 2.15 to 3.21 $\mu\text{g/m}^3$ when the
 377 corresponding NMCI $\text{PM}_{0.1}$ MCs range from 1.44 to 2.79 $\mu\text{g/m}^3$. It is seen that the
 378 concentration difference between the TCI-R and NMCI exceeds $\pm 0.5 \mu\text{g/m}^3$ and the TCI-R
 379 $\text{PM}_{0.1}$ MCs are persistently higher than the NMCI $\text{PM}_{0.1}$ levels. It indicates the
 380 over-measurement of the TCI-R occurs due to the bounce for particles larger than 300 nm
 381 since its $\text{PM}_{0.1}$ stage is preceded by the stage with 2.5 μm cut-size, which is much larger than
 382 300 nm. The average concentration difference is slightly higher at $0.78 \pm 0.34 \mu\text{g/m}^3$ for all
 383 sampling days since no severe particle bounce caused by particle overloading effect as the M_L
 384 on $\text{PM}_{0.1}$ stage, $< 1.2 \text{ mg}$, is low.

385 In contrast, the TCI-NR measures the $\text{PM}_{0.1}$ MCs of 1.59 to 4.87 $\mu\text{g/m}^3$ when the NMCI
 386 $\text{PM}_{0.1}$ MCs values vary from 0.44 to 2.18 $\mu\text{g/m}^3$. As shown clearly in Fig. 4, the
 387 over-measurement of the TCI-NR is serious with the concentration difference of 0.82 to 2.69
 388 $\mu\text{g/m}^3$ when the M_L on the $\text{PM}_{0.1}$ stage is less than 1.2 mg. This is because the particle bounce
 389 in the traditional $\text{PM}_{0.1}$ impactor with the non-rotating substrate is more severe than that with

390 the rotating substrate, which was found in our previous study (Tsai et al., 2012). In addition,
391 over-measurement becomes more serious with the increase in ambient $PM_{0.1}$ concentration
392 due to particle mounds formed underneath the nozzles resulting in a serious particle
393 overloading effect.

394 The difference in the UFP MC measurement performance between TCI-R and TCI-NR
395 can be explained by the difference in the particle deposited areas on the substrates, which can
396 be calculated as the sum of projection areas of all nozzles (diameter of nozzle=55 μm ,
397 number of the nozzle=2000) in the TCI-NR and the nozzle distribution area of 25 mm in the
398 TCI-R (Feng et al., 2016). Without rotating the substrate, the TCI-NR has a particle deposited
399 area of $4.60 \times 10^{-6} \text{ m}^2$ while the TCI-R with the rotating substrate has an area of $4.91 \times 10^{-4} \text{ m}^2$,
400 which is approximately 100 times that of the former. Therefore, M_L per unit deposition area
401 on the $PM_{0.1}$ stage of TCI-R is much smaller than the one of TCI-NR. However, this rotating
402 feature does not exist in all high-volume UFP samplers and Kanomax nanosampler, in
403 addition to the afore-mentioned problems associated with the cut-size much larger than 300
404 nm for the $PM_{0.1}$ preceding stage.

405

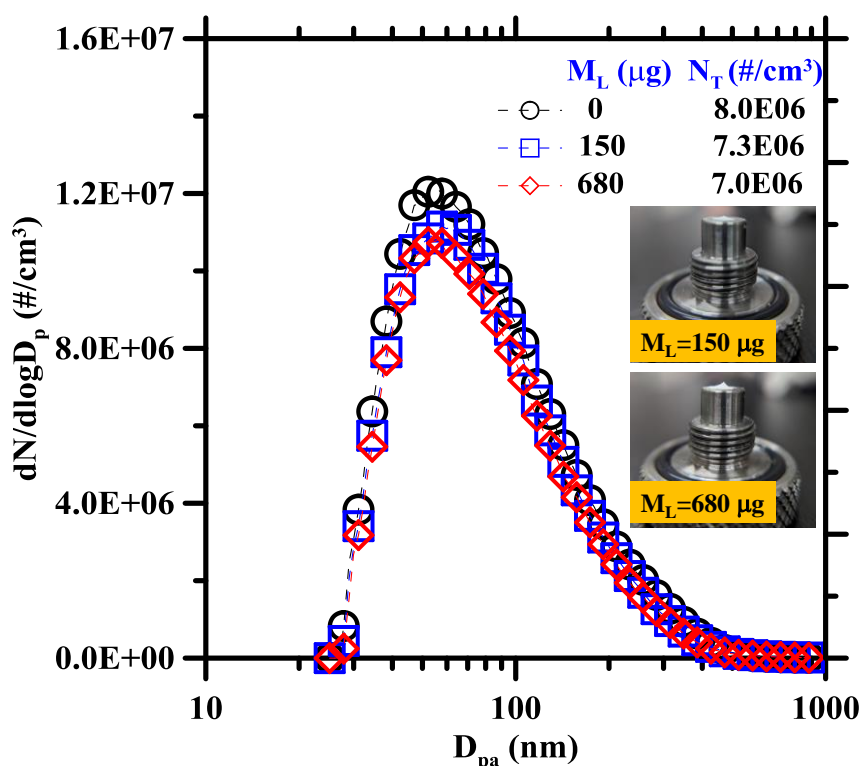
406 3.2 UFP NC measurement

407 *Particle loading test in the laboratory*

408 Fig. 5 shows the particle number distribution measured by the SMPS with a 0.0457
409 cm-nozzle inlet impactor at various M_L . Initially, the particle number distribution has the
410 CMAD, GSD, and total NCs of 56 nm, 1.8, and $8.0E06 \text{ \#/cm}^3$, respectively. However, with
411 the increase in M_L to 150 and 680 μg , the total NCs are decreased to 7.3×10^6 and 7.0×10^6
412 \#/cm^3 , respectively, which is 9 and 14% lower than the initial value. The decrease in particle
413 NC is due to the particle loading effect owing to the particle mound formed on the impaction
414 substrate (Le and Tsai, 2017; 2021). Particles smaller than the cut-size are collected as the
415 jet-to-plate distance was shortened. As shown in Fig. 5, the particle mound at the M_L of 680

416 μg is larger and higher than the one at the M_L of $150 \mu\text{g}$, indicating particle loading effect
 417 becomes worse leading to lower NCs. The present test results for the TSI inlet impactor (data
 418 not shown) also confirm that the D_{pa50} is decreased from the initial value of 410 nm (flow
 419 rate: 0.6 L/min) to 360 and 348 nm as the M_L is increased from 0 to 150 and $480 \mu\text{g}$,
 420 respectively, leading to the NC under-measurement by the SMPS. Therefore, the SMPS inlet
 421 impactor with a nozzle size of 0.0457 cm needs to be cleaned regularly when the M_L exceeds
 422 $150 \mu\text{g}$ to maintain a good performance with an acceptable bias of 10% .

423



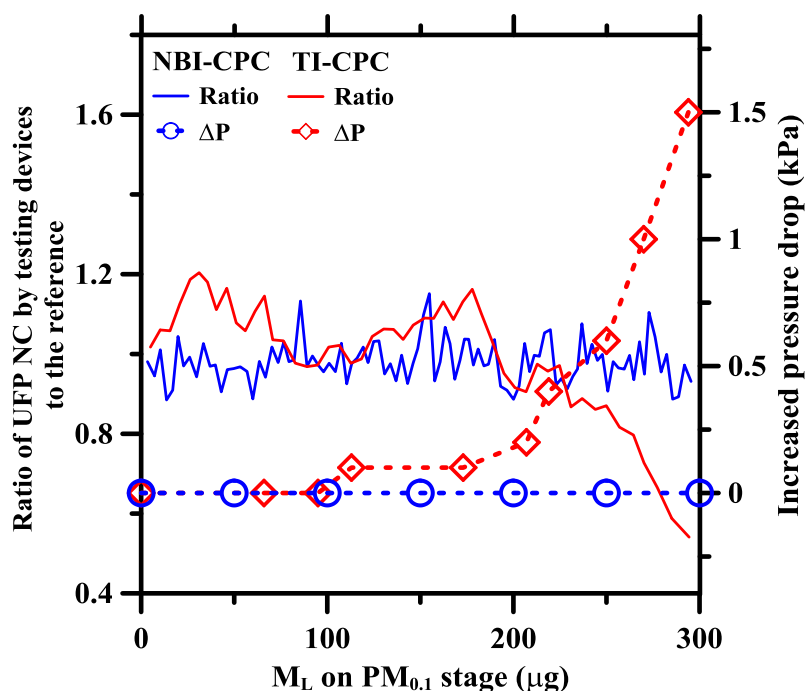
424

425 Fig. 5 The particle distribution by the SMPS with the TSI inlet impactor (nozzle: 0.0457 cm)
 426 at various loaded masses.

427

428 After determining the acceptable M_L of $150 \mu\text{g}$ of the SMPS impactor, the comparison
 429 tests of the NBI-CPC, TI-CPC and SMPS were conducted, during which the SMPS impactor
 430 was cleaned every 5 min to eliminate the particle loading effect. Fig. 6 presents the ratios of
 431 the $\text{PM}_{0.1}$ NCs measured by the NBI-CPC and TI-CPC to those of the SMPS at different M_L

432 of NaCl particles. The ratio of the $PM_{0.1}$ NCs measured by the TI-CPC to the SMPS is found
 433 to



434

435 Fig. 6. The ratio of UFP NC by the NBI-CPC to that by the SMPS at various M_L

436

437 be 1.08 ± 0.07 and 1.05 ± 0.06 when the M_L is less than $100 \mu\text{g}$ and in the range of $100\text{-}200 \mu\text{g}$,
 438 respectively. This indicates that the performance of the TI-CPC with a loaded mass of less
 439 than $200 \mu\text{g}$ is comparable to the SMPS. However, the ratio is decreased to 0.92 and 0.52
 440 when the M_L is increased to 200 and $300 \mu\text{g}$. The reduction in the ratio indicates the decrease
 441 in the $PM_{0.1}$ NC measured by the TI-CPC when the M_L increases. With the silicon oil-coated
 442 substrate, the particle mound is formed as evident by the increase in the pressure drop from
 443 8.1 kPa to 8.3 and 15 kPa , respectively, at the M_L of 200 and $350 \mu\text{g}$. As a result, more
 444 incoming particles are collected by the deposited particle mound, fewer particles enter the
 445 CPC and are measured.

446 In comparison, the $PM_{0.1}$ NBI-CPC with the water-wetted GFF substrate shows good
 447 performance for $PM_{0.1}$ NC measurement as the ratios of $PM_{0.1}$ NC to the SMPS are 0.97 ± 0.05 ,
 448 0.99 ± 0.05 , and 0.97 ± 0.06 with the M_L in the range of $0\text{-}100$, $100\text{-}200$, and $200\text{-}300 \mu\text{g}$,

449 respectively. The initial ratio is close to 1 and remains constant despite the increase in the M_L ,
450 which implies that the NBI-CPC can measure $PM_{0.1}$ NC accurately without a particle loading
451 effect. This is due to the effective removal of particle deposits by water washing the
452 GFF-covered substrate. In addition, the constant pressure drop during the particle loading
453 process also supports the finding that there is no particle mound formed on the impaction
454 substrate.

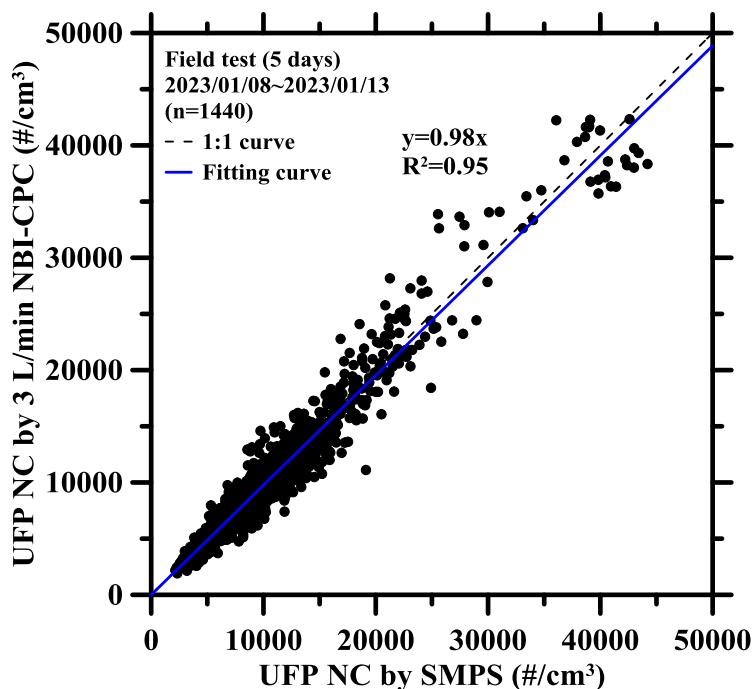
455 In this study, the 3 L/min $PM_{0.1}$ NBI is also used to replace the TSI inlet impactor of the
456 SMPS as the $PM_{0.1}$ NBI-SMPS for the UFP size distribution measurement without particle
457 loading effect. The results show that the UFP size distribution measured by the $PM_{0.1}$
458 NBI-SMPS remains stable with the increase in the M_L up to 1.1 mg (see in the Fig. S8
459 (Section B) of the SI). The good cut-off characteristics of the NBI results in a size distribution
460 with a nearly ideal cut-off for particles smaller than 100 nm and the effective removal of
461 particle larger than 100 nm. These results demonstrate that 3.0 L/min $PM_{0.1}$ NBI can be a
462 viable classifying device for long-term monitoring for the SMPS with a minimum
463 maintenance need. In the future, the NBI with larger cut-sizes (such as $PM_{0.4}$ – $PM_{0.9}$ NBI
464 with 0.4-0.9 μm cut-sizes similar to those of the SMPS inlet impactors) can be designed to
465 replace the original SMPS inlet impactor to obtain unbiased aerosol size distributions, which
466 otherwise could be affected by particle bounce and loading effects.

467

468 *Field comparison test in the ambient condition*

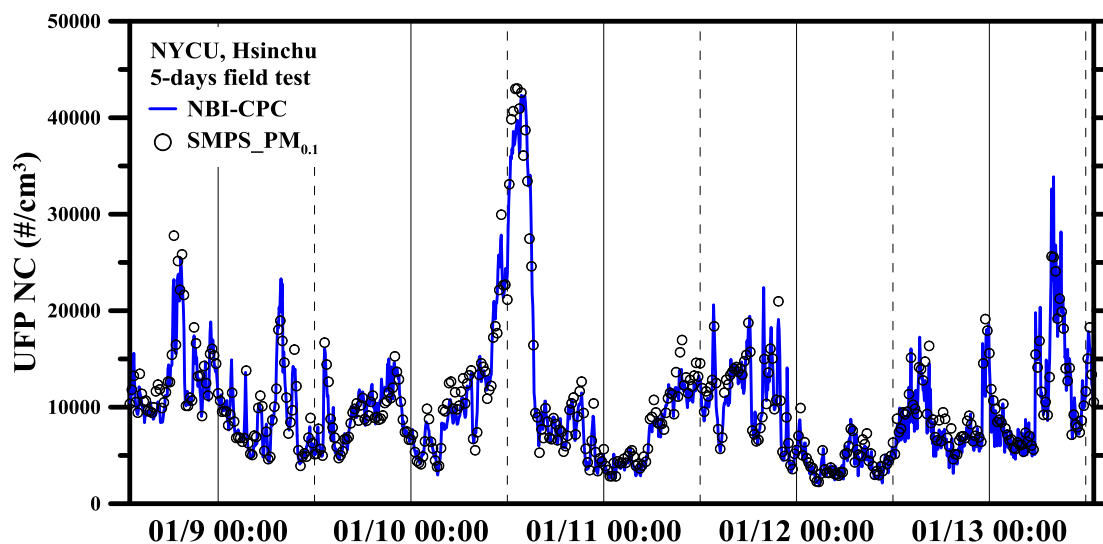
469 Fig. 7 displays the correlation plot for $PM_{0.1}$ NCs measured by the 3 L/min $PM_{0.1}$
470 NBI-CPC and SMPS in the field test. To maintain the good performance of the SMPS which
471 was used as the reference, the SMPS impactor was cleaned daily. The results show that the
472 slope and R^2 of the linear regression lines of pairwise comparisons are 0.98 and 0.95,
473 respectively (No. of 5-min average data: 1440). The $PM_{0.1}$ NCs of the NBI-CPC ranges from
474 1,907 to 42,326 $\#/cm^3$ during the 5-day monitoring period, which are close to those of the

475 SMPS (i.e. particles smaller than 100 nm) varying from 2,146 to 44,196 #/cm³. This indicates
476 a good agreement between the UFP NC measurement of the NBI-CPC and SMPS.



477
478 Fig. 7. Correlation plot for UFP NC by the NBI-CPC and SMPS with an inlet impactor
479 cleaned daily in the field test

480
481 As shown in Fig. 8, both devices correlate very well at low concentrations and high
482 peaks. The peak NC bias is less than 5% while the lowest NC bias is 11%. The measurement
483 bias in low concentration ranges is attributed to the uncertainty of the CPC measurement limit
484 and the SMPS scanning range limit. The uncertainty is 10% for particle concentrations of
485 1000 #/cm³



486

487

Fig. 8. Field comparison of the UFP NCs by NBI-CPC and SMPS

488

489 in the CPC according to the TSI manual, and 10% for particles with a D_{pe} ranging from 20 to
 490 200 nm in the SMPS (Wiedensohler et al., 2012).

491 Note that even higher correlation of the two devices (slope = 0.99) can be achieved by
 492 changing the effective density from 1.2 to 1.3 g/cm^3 in the period of mid-noon (11:00 to
 493 14:00) for converting SMPS D_{pe} -data to D_{pa} -data (Lin et al., 2018). It is reported that a
 494 higher effective density was found for particles with a high proportion of ammonium sulfate
 495 and ammonium nitrate salts formed during mid-noon owing to photochemical reactions (Yin
 496 et al., 2015). That is, the SMPS data can't be used to obtain the actual UFP NC directly due to
 497 some uncertainties in effective particle density. In contrast, the $\text{PM}_{0.1}$ NBI-CPC is a relatively
 498 convenient choice for obtaining UFP NC since the measurement is based on D_{pa} .

499

500 4. Conclusion

501 This study designed and tested a 30 L/min $\text{PM}_{0.1}$ non-bouncing impactor (30 L/min $\text{PM}_{0.1}$
 502 NBI) and a NBIS ($\text{PM}_{0.1}$ non-bouncing impactor sampler, the $\text{PM}_{0.1}$ stage with 3 preceding
 503 stages) for accurate UFP MC measurement without the issues of particle loading and bounce.
 504 The NBI uses clean water to wet the GFF continuously, which prevents particle bounce and

505 helps remove deposited particles and provides a clean impaction surface without particle
506 loading effect since particle loaded mass M_L on the substrate is essentially zero. In
507 comparison, the impactor with a silicon oil-coated aluminum foil substrate has an obvious
508 decreasing efficiency for particles larger than 300 nm due to particle bounce. The laboratory
509 particle loading tests further show that the NBIS samples accurate UFP MCs with M_L on the
510 $PM_{0.1}$ stage up to 21 mg with the difference of ca. 10%, while the traditional cascade
511 impactor TCI-R over-measures MC initially due to initial particle bounce for particles larger
512 than 300 nm and the over-estimation increases very much when the M_L exceeded 3 mg due to
513 over-loading effect. In the ambient field tests, the UFP MCs of the NBIS differ by only ± 0.5
514 $\mu\text{g}/\text{m}^3$ as compared to those of the rotating 10-stages NMCI (reference) while TCI-R also
515 shows over-measurement by $0.8 \mu\text{g}/\text{m}^3$ in average due to the bounce for particles larger than
516 300 nm. Furthermore, the TCI-NR shows higher over-measurement which increases further
517 with increasing ambient concentration.

518 For the UFP NC measurement, the previously developed 3 L/min NIC (or called as 3
519 L/min $PM_{0.1}$ NBI in this study) is combined with a CPC as NBI-CPC, and it shows stable and
520 accurate performance with M_L up to 300 μg , while the impactor with the non-rotating,
521 silicone oil-coated substrate under-measures owing to over-collection for particles smaller
522 than the cut-size when M_L exceeds 200 μg . In ambient field tests, the 3 L/min $PM_{0.1}$
523 NBI-CPC measures NCs in good agreement with the SMPS reference values, with a linear
524 regression slope of 0.98 and an R^2 of 0.95, respectively. This study concludes that traditional
525 impactors with silicon oil-coated substrate can over-measure and under-measure the UFP
526 MCs and NCs, respectively, due to particle bounce and loading effects, and the use of the
527 NBI devices developed in this study can eliminate these effects to provide accurate UFP
528 measurements.

529 In the future, the 30 L/min $PM_{0.1}$ NBI can be used to obtain enough UFP mass of over
530 1000 μg for toxicity study in one day for high UFP MC environments of several tens or

531 thousands of $\mu\text{g}/\text{m}^3$, or several 30 L/min $\text{PM}_{0.1}$ NBIs can be arranged in parallel to provide a
 532 higher flow rate and longer sampling days when UFP MC is low at several $\mu\text{g}/\text{m}^3$ only. For
 533 long-term UFP NC measurement, the 3.0 L/min $\text{PM}_{0.1}$ NBI-CPC is a viable instrument with a
 534 minimum maintenance need. In the future, the NBI with smaller flow rate and larger cut-sizes
 535 (such as $\text{PM}_{0.4} - \text{PM}_{0.9}$ NBI with 0.4-0.9 μm cut-sizes similar to those of the SMPS inlet
 536 impactors) can be designed to replace the original SMPS inlet impactor to obtain the unbiased
 537 aerosol size distributions without particle bounce and loading effects for long-term
 538 monitoring applications.

539

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545

546 **List of abbreviations**

D_{pa}	Aerodynamic diameter	NC	Number concentration
$D_{\text{pa}50}$	Cutoff aerodynamic diameter	NIC	Nanoparticle inertial classifier
GFF	Glass fiber filter	NMCI	NCTU micro-orifice cascade impactor
MC	Mass concentration	PENS	Personal nanoparticle sampler
M_L	loaded particle mass	TCI	Traditional cascade impactor
MOUDI	Micro-orifice uniform deposit impactor	TCI-R	Traditional cascade impactor with rotating stages
NBI	Non-bouncing impactor	TCI-NR	Traditional cascade impactor

with non-rotating stages

NBIS Non-bouncing impactor sampler UFP Ultrafine particle

547

548 **CRedit author statement**

549 **Wen-Cheng Gong:** Data curation, Carrying out the experiment, Figure preparation, Writing,
550 Reviewing, Editing and Finalizing the manuscript.

551 **Nicolas Jidenko:** Rewiewing and Conceptualization

552 **Yang-Rei Li:** Data curation, Carrying out the experiments, Figure preparation

553 **Thi-Cuc Le:** Data curation, Writing, Reviewing, Editing the manuscript

554 **Jean-Pascal Borra:** Conceptualization, Methodology and Rewiewing

555 **Chuen-Jinn Tsai:** Conceptualization, Reviewing and Editing the final manuscript

556

557 **Reference**

558 Abdillah, S. F., & Wang, Y. F. (2022). Ambient ultrafine particle (PM_{0.1}): sources,
559 characteristics, measurements and exposure implications on human health. *Environ.*
560 *Res.*, 115061.

561 Bateman, A.P., Belassein, H. & Martin, S.T. (2014). Impactor apparatus for the study of
562 particle rebound: relative humidity and capillary forces. *Aerosol Sci. Technol.*, 48(1),
563 42-52.

564 Chang, C., Demokritou, P., Shafer, M., & Christiani, D. (2013). Physicochemical and
565 toxicological characteristics of welding fume derived particles generated from real
566 time welding processes. *Environ. Sci.: Process. Impacts*, 15(1), 214-224.

- 567 Chen, S. C., Tsai, C. J., Chou, C. C. K., Roam, G. D., Cheng, S. S., & Wang, Y. N. (2010a).
568 Ultrafine particles at three different sampling locations in Taiwan. *Atmos. Environ.*,
569 44(4), 533-540.
- 570 Chen, S. C., Tsai, C. J., Huang, C. Y., Chen, H. D., Chen, S. J., Lin, C. C., ... & Dzumbova, L.
571 (2010b). Chemical mass closure and chemical characteristics of ambient ultrafine
572 particles and other PM fractions. *Aerosol Sci. Technol.*, 44(9), 713-723.
- 573 Chen, M., Romay, F. J., & Marple, V. A. (2018). Design and evaluation of a low flow
574 personal cascade impactor. *Aerosol Sci. Technol.*, 52(2), 192-197.
- 575 Chien, C. L., Tien, C. Y., Liu, C. N., Ye, H., Huang, W. & Tsai, C. J. (2015). Design and
576 testing of the NCTU micro-orifice cascade impactor (the NMCI) for the measurement
577 of nanoparticle size distributions. *Aerosol Sci. Technol.*, 49(10), 1009-1018.
- 578 Feng, J. Q. (2016). A computational study of particle deposition patterns from a circular
579 laminar jet. arXiv preprint arXiv:1608.04605.
- 580 Furuuchi, M., Eryu, K., Nagura, M., Hata, M., Kato, T., Tajima, N., ... & Otani, Y. (2010).
581 Development and performance evaluation of air sampler with inertial filter for
582 nanoparticle sampling. *Aerosol Air Qual. Res.*, 10(2), 185-192.
- 583 Geiss, O., Bianchi, I., & Barrero-Moreno, J. (2016). Lung-deposited surface area
584 concentration measurements in selected occupational and non-occupational
585 environments. *J. Aerosol Sci.*, 96: 24-37.

- 586 He, M., & Dhaniyala, S. (2013). A multiple charging correction algorithm for scanning
587 electrical mobility spectrometer data. *J. Aerosol Sci.*, 61: 13-26.
- 588 HEI Review Panel on Ultrafine Particles. (2013). Understanding the health effects of ambient
589 ultrafine particles. HEI Perspectives 3. Boston, MA, HEI.
- 590 Huang, C. H., Tsai, C. J., & Shih, T. S. (2001). Particle collection efficiency of an inertial
591 impactor with porous metal substrates. *J. Aerosol Sci.*, 32(9), 1035-1044.
- 592 Huang, C. H., Chang, C. S., Chang, S. H., Tsai, C. J., Shih, T. S., & Tang, D. T. (2005). Use
593 of porous foam as the substrate of an impactor for respirable aerosol sampling. *J.*
594 *Aerosol Sci.*, 36(11), 1373-1386.
- 595 Kumar, P., Kalaiarasan, G., Porter, A. E., Pinna, A., Kłosowski, M. M., Demokritou, P., ... &
596 Dilliway, C. (2021). An overview of methods of fine and ultrafine particle collection
597 for physicochemical characterisation and toxicity assessments. *Sci. Total Environ.*,
598 756, 143553.
- 599 Le, T. C. & Tsai, C. J. (2017). Novel non-bouncing PM_{2.5} impactor modified from well
600 impactor ninety-six. *Aerosol Sci. Technol.*, 51(11), 1287-1295.
- 601 Le, T. C., Fu, C. X., Sung, J. C., Li, Z. Y., Pui, D. Y., & Tsai, C. J. (2020). The performance of
602 the PM_{2.5} VSCC and oil-wetted M-WINS in long-term field sampling studies. *Atmos.*
603 *Environ.*, 239, 117804.
- 604 Le, T. C. & Tsai, C. J. (2021). Inertial Impaction Technique for the Classification of

- 605 Particulate Matters and Nanoparticles: A Review. *KONA Powder Part. J.*, 38, 42-63.
- 606 Le, T. C., Lin, C. H., Gong, W.C., Ždimal, V., Pui, D.Y. & Tsai, C.J. (2022). Novel inertial
607 impactor for nanoparticle classification without particle loading effect. *J. Aerosol Sci.*,
608 159, 105879.
- 609 Liao, B. X., Gong, W. C., Li, Z., & Tsai, C. J. (2019). A mass correction method for the
610 aerosol particle mass analyzer to measure the particle mass of sub-50 nm
611 nanoparticles. *Aerosol Sci. Technol.*, 53(9), 1056-1066.
- 612 Liu, C. N., Awasthi, A., Hung, Y. H., & Tsai, C. J. (2013). Collection efficiency and interstage
613 loss of nanoparticles in micro-orifice-based cascade impactors. *Atmos. Environ.*, 69,
614 325-333.
- 615 Marple, V. A., Rubow, K. L. & Behm, S. M. (1991). A microorifice uniform deposit impactor
616 (MOUDI): description, calibration, and use. *Aerosol Sci. Technol.*, 14, 434-446.
- 617 Misra, C., Kim, S., Shen, S., & Sioutas, C. (2002). A high flow rate, very low pressure drop
618 impactor for inertial separation of ultrafine from accumulation mode particles. *J.*
619 *Aerosol Sci.*, 33(5), 735-752.
- 620 Morawska, L., Ristovski, Z., Jayaratne, E. R., Keogh, D. U., & Ling, X. (2008). Ambient
621 nano and ultrafine particles from motor vehicle emissions: Characteristics, ambient
622 processing and implications on human exposure. *Atmos. Environ.*, 42(35), 8113-8138.
- 623 Ohlwein, S., Kappeler, R., Kutlar Joss, M., Künzli, N., & Hoffmann, B. (2019). Health

- 624 effects of ultrafine particles: a systematic literature review update of epidemiological
625 evidence. *Int. J. Public Health*, 64, 547-559.
- 626 Querol, X., Tobías, A., Pérez, N., Karanasiou, A., Amato, F., Stafoggia, M., ... & Alastuey, A.
627 (2019). Monitoring the impact of desert dust outbreaks for air quality for health
628 studies. *Environ. Int.*, 130, 104867.
- 629 Reischl, G. P., & John, W. (1978). The collection efficiency of impaction surfaces: a new
630 impaction surface. *Staub - Reinhalt. Luft* 1978, 38, 55.
- 631 Saleh, Y., Antherieu, S., Dusautoir, R., Y. Alleman, L., Sotty, J., De Sousa, C., ... &
632 Lo-Guidice, J. M. (2019). Exposure to atmospheric ultrafine particles induces severe
633 lung inflammatory response and tissue remodeling in mice. *Int. J. Environ. Res.*
634 *Public Health*, 16(7), 1210.
- 635 Sillanpää, M., Hillamo, R., Mäkelä, T., Pennanen, A. S., & Salonen, R. O. (2003). Field and
636 laboratory tests of a high volume cascade impactor. *J. Aerosol Sci.*, 34(4), 485-500.
- 637 Sotty, J., Garçon, G., Denayer, F. O., Alleman, L. Y., Saleh, Y., Perdrix, E., ... & Canivet, L.
638 (2019). Toxicological effects of ambient fine (PM_{2.5-0.18}) and ultrafine (PM_{0.18})
639 particles in healthy and diseased 3D organo-typic mucociliary-phenotype models.
640 *Environ. Res.*, 176, 108538.
- 641 Tsai, C. J., & Cheng, Y. H. (1995). Solid particle collection characteristics on impaction
642 surfaces of different designs. *Aerosol Sci. Technol.*, 23(1), 96-106.

- 643 Tsai, C. J., Huang, C. Y., Chen, S. C., Ho, C. E., Huang, C. H., Chen, C. W., ... & Ellenbecker,
644 M. J. (2011). Exposure assessment of nano-sized and respirable particles at different
645 workplaces. *J Nanopart Res.*, 13, 4161-4172.
- 646 Tsai, C. J., Liu, C. N., Hung, S. M., Chen, S. C., Uang, S. N., Cheng, Y. S., & Zhou, Y. (2012).
647 Novel active personal nanoparticle sampler for the exposure assessment of
648 nanoparticles in workplaces. *Environ. Sci. Technol.*, 46(8), 4546-4552.
- 649 Tsai, C. J., Lin, G. Y., Liu, C. N., He, C. E., & Chen, C. W. (2012). Characteristic of
650 nanoparticles generated from different nano-powders by using different dispersion
651 methods. *J Nanopart. Res.*, 14, 1-12.
- 652 Turner, J. R., & Hering, S. V. (1987). Greased and oiled substrates as bounce-free impaction
653 surfaces. *J. Aerosol Sci.*, 18(2), 215-224.
- 654 USEPA (2019) Integrated science assessment (ISA) for particulate matter (final report,
655 December 2019). Washington (DC): Environmental Protection Agency
- 656 Wiedensohler, A., Birmili, W., Nowak, A., Sonntag, A., Weinhold, K., Merkel, M., ... &
657 Bastian, S. (2012). Mobility particle size spectrometers: harmonization of technical
658 standards and data structure to facilitate high quality long-term observations of
659 atmospheric particle number size distributions. *Atmos. Meas. Tech.*, 5(3), 657-685.
- 660 WHO (2021). Who global air quality guidelines: particulate matter (PM_{2.5} and PM₁₀), ozone,
661 nitrogen dioxide, sulfur dioxide and carbon monoxide: executive summary, World

662 Health Organization.

663 Xue, W., Xue, J., Mousavi, A., Sioutas, C., & Kleeman, M. J. (2020). Positive matrix
664 factorization of ultrafine particle mass (PM_{0.1}) at three sites in California. *Sci. Total*
665 *Environ.*, 715: 136902.

666 Xue, W., & Kleeman, M. J. (2022). Comparison of size-resolved PM elements measured
667 using aluminum foil and Teflon impaction substrates: Implications for ultrafine
668 particle source apportionment and future sampling networks in California. *Sci. Total*
669 *Environ.*, 156523.

670 Yin, Z., Ye, X., Jiang, S., Tao, Y., Shi, Y., Yang, X., & Chen, J. (2015). Size-resolved effective
671 density of urban aerosols in Shanghai. *Atmos. Environ.*, 100, 133-140.

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