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1 In situ NO abatement by photocatalysis – study under 2 continuous NO injection in a 10-m³ experimental 3 chamber

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9 **Abstract**

10 Air pollution is a serious public health concern in France and many other countries. Nitrogen oxides (NO_x)
11 include nitrogen monoxide (NO) and nitrogen dioxide (NO₂). They are mainly outdoor pollutants
12 produced during combustion of fossil fuel. These gases can easily infiltrate buildings and thus increase
13 indoor pollution. The recommended guideline values for NO₂ are 200 µg/m³ (short-term exposure) and
14 40 µg/m³ (long-term exposure). Although no guideline values exist for NO, this gas can be oxidized by
15 atmospheric ozone and thus produce NO₂. This paper studies the depollution efficiency of photocatalysis
16 towards indoor NO. Experiments were conducted at real scale, in a 10-m³ experimental chamber
17 developed at the LMDC and used as a reactor. The interior walls of the chamber were equipped with
18 painted plasterboards treated with photocatalytic coating (3 g/m² of TiO₂). Gas was continuously
19 injected into the chamber according to a specific procedure: (1) pollutant injection at high flow rate to
20 reach 200 ppb of NO, (2) pollutant injection at low flow rate in order to keep the NO concentration
21 constant at 200±10 ppb, and (3) photocatalysis activation by switching on the light. Typical indoor
22 lighting systems (fluorescent tubes, LED and halogen bulbs) were tested and UV fluorescent tubes were
23 also used to optimise the photocatalytic efficiency. Results showed that NO indoor concentration was
24 reduced by photocatalysis in real-world conditions. Significant NO degradation was obtained under
25 visible light. In addition, using the experimental procedure presented in this paper, a new method for
26 evaluating air depollution efficiency by photocatalysis at real scale is proposed.

27 *Keywords:* Photocatalysis, NO_x, in situ, experimental chamber, TiO₂, visible light, indoor air quality

28 **Acknowledgments**

29 The authors are grateful to CRISTAL for providing the photocatalytic products, to the Laplace laboratory
30 for its expertise in spectroscopy, and to Bronkhorst for financing the equipment used for flow
31 measurement and control.

32 **1 Introduction**

33 Improving air quality has been a major concern in industrial countries for some years (Solomon 2012; Li
34 et al. 2016; World Health Organization 2016). A considerable number of studies have dealt with the
35 subject from various points of view: socio-economic impacts (General & Kopp 2014), substances
36 qualified as pollutants (Colls 2002), political decisions concerning air pollution reduction (Fenger 2009)
37 and so on. Improvement of air quality has relied on two types of action: (1) limiting pollution production
38 as much as possible by effective production control (EU 2008), and (2) using techniques to treat already
39 existing air pollutants.

40 This paper focuses on nitrogen oxides (NO_x). This group of gaseous pollutants includes nitric oxide (NO)
41 and nitrogen dioxide (NO₂). In urban areas, combustion processes release large amounts of NO_x, the
42 main sources being traffic and industries. Indoors, NO_x are produced by chimneys, gas burners, cooking
43 devices and tobacco smoke. Furthermore NO_x can infiltrate from outdoors (Blondeau et al. 2005). Since
44 over 80% of our time is spent in an indoor environment (Klepeis et al. 2001), it is primordial to increase
45 the understanding of indoor pollution, identify the types of pollutants, and evaluate, control and reduce
46 their concentrations. Nowadays, guideline values exist to help public authorities to combat air pollution.
47 They were established by organisations such as the World Health Organization (WHO) and the French
48 Indoor Air Quality Observatory (OQAI) (Mosqueron & Nedellec 2005; World Health Organization 2006;
49 Krzyzanowski & Cohen 2008; General & Kopp 2014). For example, NO₂ guideline values are: 200 µg/m³
50 for short-term exposure and 40 µg/m³ for long-term exposure. Limit values for NO have not been
51 defined yet (Mosqueron & Nedellec 2004; Mosqueron & Nedellec 2005) even though NO and NO₂
52 concentrations are directly related. In fact, while most car exhaust systems produce mainly NO, part of it
53 can react with the atmospheric ozone and form NO₂ (Mills & Elouali 2015).

54 For a few decades, photocatalysis has been put forward as a means to fight air pollution (Fujishima et al.
55 2000). Studies on the use of semi-conductors such as TiO₂ or ZnO are abundant in the literature
56 (Fujishima et al. 2008; Yu & Brouwers 2009; Lin et al. 2013; Zhong & Haghghat 2015; Ren et al. 2017).
57 Most experimental studies have been performed under laboratory conditions at different reactor scales
58 (Horgnies et al. 2015; Toro et al. 2016a; Ifang et al. 2014; Horgnies et al. 2012; Ren et al. 2017; Martinez
59 et al. 2011; Hot, Topalov et al. 2017; Hernández Rodríguez et al. 2016; Hüsken et al. 2009; Aïssa et al.
60 2011). Often, photocatalytic oxidation (PCO) efficiency is estimated using international standards and
61 recommendations (ISO 22197-1 2016; CEN/TS 16980-1 2016). However, experiments carried out under
62 such conditions are not very realistic representations of actual applications, where photocatalytic
63 coatings are applied on large existing surfaces, and some authors have worked on this problem.
64 Assessing PCO efficiency towards air pollution under real-world conditions is a tricky task and only a few
65 studies on this subject have been published so far (Maggos et al. 2007; Maggos et al. 2008; Gallus et al.
66 2015; Hot, Martinez, et al. 2017; Chen & Chu 2011; Crain et al. 2016; Horgnies et al. 2015; Guerrini
67 2012). Moreover, only a handful of them are related to indoor air. In this paper, PCO of NO under real-
68 world conditions is described, where “real-world conditions” should be understood as those existing in
69 an actual house, built from common materials and enabling natural exchanges with the ambient
70 environment. In the work reported here, a specific experimental procedure was used to evaluate the
71 reduction of NO indoor concentration under different lighting systems over a few hours. Two different

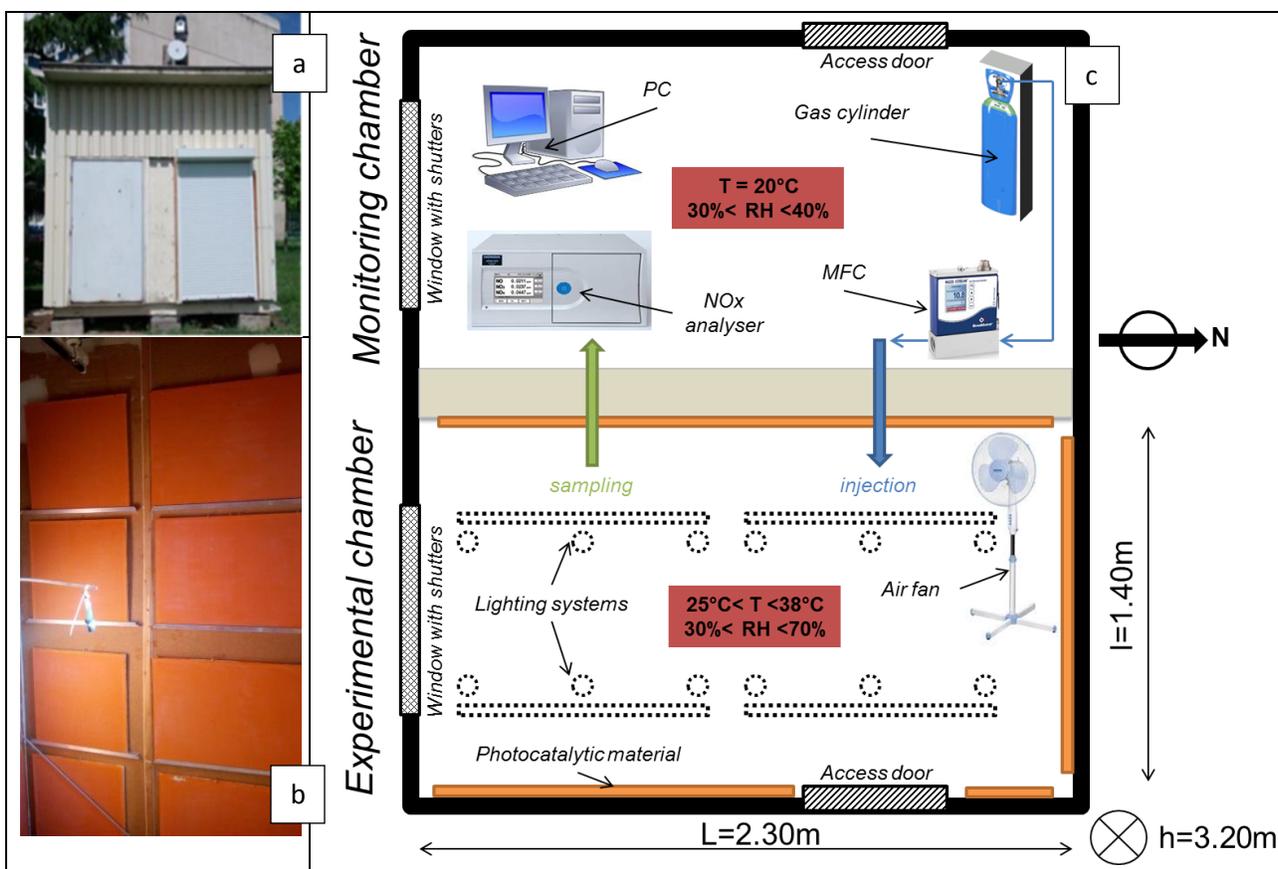
72 methods are also proposed for evaluating photocatalytic depollution efficiency from available
73 experimental data.

74 2 Materials and methods

75 2.1 Materials

76 2.1.1 Experimental house

77 The air depollution efficiency of photocatalytic materials towards NO was evaluated under real-world
78 conditions by using a small experimental house designed by the LMDC (Laboratory of Materials and
79 Durability of Constructions, UPS/INSA, Toulouse, France). A schematic representation and some
80 photographs of this experimental house are shown in Figure 1.



81
82 **Figure 1 – Experimental house developed at the LMDC for photocatalytic assessment - (a) Outside view (South wall), (b)**
83 **Photograph of the photocatalytic material (North wall), (c) Schematic representation of inside (viewed from above)**

84 The isolated house was a simple metal framework structure composed of four walls, a rectangular floor
85 and a flat roof. Inside, a wall divided the house into two chambers: (1) the experimental chamber (used
86 as a photocatalytic reactor), and (2) the control chamber (used for equipment storage and experiment
87 devices). The interior walls were covered by chipboard and each room had an external door and a

88 window. Two stainless tubes (6 mm in diameter) connected the chambers through the internal wall: one
89 was used for gaseous pollutant injection, the other for air sampling.

90 The experimental chamber (roughly 10 m³) was used as a vast photocatalytic reactor. Gaseous pollution
91 was injected into it from the control chamber and was then diluted with indoor air. Some of this air was
92 sampled. The experimental chamber was equipped with an air fan to improve pollution homogenisation
93 and repeatability. No other mechanical ventilation was installed and the door and window were kept
94 closed. However, indoor/outdoor exchanges occurred due to natural leakage. Thus, a standardised air
95 tightness test was conducted (NF EN ISO 9972 2016). For an overpressure and underpressure of 4 Pa,
96 total air leakage was 33-37 m³.h⁻¹ and, for 50 Pa, leakage was 160-180 m³.h⁻¹. The $Q_{4Pa-surf}$, which is the
97 main indicator of air-tightness, was 1.32-1.44 m³.h⁻¹.m⁻². The experimental chamber was therefore
98 qualified as class D (A being the best and E the worst). This chamber was designed to assess
99 photocatalytic activity occurring on the walls. Rather than treating existing interior wall surfaces directly,
100 we applied the photocatalyst to removable plasterboards covering the walls, which enabled various
101 photocatalytic materials to be tested. Aluminium U profiles were fixed on the internal walls to allow
102 plasterboard plates be mounted and removed easily. On the ceiling, artificial lighting systems were
103 installed to test various illumination conditions. Window shutters were kept closed to ensure that there
104 was no interference with natural light and to allow tests to be carried out in the dark without activating
105 the photocatalytic material. Temperature, relative humidity and indoor/outdoor pressure variations
106 were not controlled (see Figure 1c); these parameters were influenced by the weather conditions and
107 were constantly measured by probes (KIMO). During tests, the interior of the experimental chamber
108 could be observed from the monitoring chamber via a camera.

109 The monitoring chamber was used to supervise experiments. As can be seen in Figure 1c, a gas cylinder
110 (Air Liquide – 45 ppm of NO stabilised in N₂) was connected to a mass flow controller (MFC from M+W
111 Instrumentation). The flow rate of pollution was thus controlled before its injection into the
112 experimental chamber through the first stainless tube. Using the second stainless tube, polluted air was
113 sampled at 1 l/min without affecting the pollution level inside the experimental chamber. A NO_x
114 analyser (HORIBA APNA-370) in the monitoring chamber measured NO_x (NO and NO₂) concentrations in
115 the sampled air. This apparatus gave instantaneous results and enabled continuous monitoring and
116 recording (one mean value every 5 min). The analyser was connected to a PC to store data and the
117 evolution of pollution was observed graphically in real time. A camera was also connected to the PC. To
118 preserve equipment service life, temperature and relative humidity (RH) were controlled by air
119 conditioning (20°C and 30-40% RH). Finally, artificial lighting was also switched on/off from the
120 monitoring room.

121 **2.1.2 Photocatalytic material**

122 The photocatalytic material consisted of painted plasterboards (used as the substrate) coated with a TiO₂
123 aqueous solution (used as the photocatalyst). Standard plasterboards (Placoplatre® BA 13) were
124 purchased and cut into pieces with specific dimensions to fit the indoor walls of the experimental
125 chamber (100x50 cm², 75x50 cm², 50x50 cm² and 50x25 cm²). The edges of each piece were covered
126 with an adhesive tape. Then, each plasterboard plate was painted with orange water-based acrylic paint
127 containing natural pigment (provided by LRVision Company). Two layers were applied to plasterboard

128 surfaces using a paint roller. The photocatalytic dispersion was prepared by diluting a water-based
129 commercial product (CristalACTiV™ S5-300B, TiO₂ content: 18 wt%) to obtain an aqueous solution
130 containing 6 wt% of dry TiO₂. Three layers of this dispersion were applied to the plasterboard surfaces
131 with the help of a brush. The total quantity of TiO₂ (dry matter) on substrate surfaces was 2.9±0.1 g/m².
132 This quantity was controlled and determined by weighing the recipient containing the TiO₂ dispersion
133 and the brush before and after coating each plasterboard sample. The targeted value of 3 g/m² of
134 photocatalytic product on the surface was chosen according to previous research work carried out by the
135 same authors (Hot, Topalov et al. 2017). Finally, each photocatalytic plasterboard sample was mounted
136 on the walls inside the experimental chamber. An area of 9.3 m² of plasterboards was used to cover
137 about half of the total indoor surface (ceiling, floor, door and window excluded).

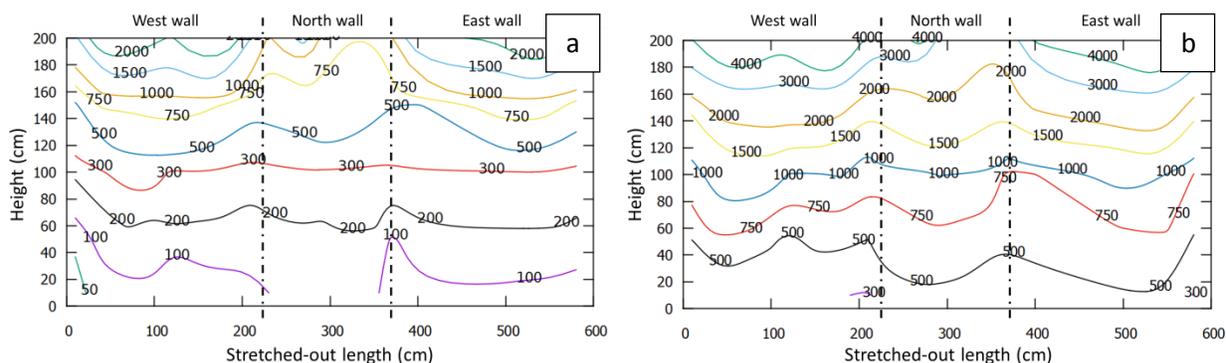
138 **2.1.3 Lighting conditions**

139 Photocatalysis requires light and its activity is strongly dependent on light wavelengths and intensities.
140 As the literature shows, UV-A lighting systems with wavelengths between 370 and 380 nm are very
141 suitable for TiO₂ activation (Rajeshwar 2007; Ohama & Van Gemert 2011; Gaya & Abdullah 2008;
142 Mamaghani et al. 2017). However, these illumination conditions are very limited in indoor environments.
143 The objective of this paper was to study PCO under real-world conditions, so experiments were carried
144 out under typical indoor lighting conditions. Three different types of visible light lamps were used: (1)
145 four fluorescent tubes (Sylvania Luxline T8, 30 W, 2400 lm), (2) twelve LED bulbs (GE Energy Smart, 40 W,
146 470 lm), and (3) twelve halogen bulbs (Lumipro Eco, 55 W, 630 lm). Experiments were also conducted
147 under UV light provided by four fluorescent tubes (Narva Blacklight blue LT-T8, 30 W) to observe the
148 results under optimal conditions. During an experiment, the light was controlled from the monitoring
149 chamber. The lamps were turned on or off by switches and light amplitude (brightness) could be
150 adjusted by a dimmer. Here, the dimmer was always set to its brightest position in order to obtain
151 optimal illumination. Thus, in this study, lighting conditions were characterised by the type of lamp, its
152 wavelength and the irradiation intensity on the plasterboard surfaces.

153 Light intensity was measured with a radiometer (Gigahertz-Optik X1.1 Optometer) equipped with two
154 detectors: a UV-A detector for wavelengths between 315 and 400 nm (model UV-3717) and a visible
155 detector for wavelengths between 400 and 800 nm (model RW-3703). Firstly, the light intensity received
156 by the surface of the photocatalytic material was investigated. Measurements were made at around 100
157 selected points to map the light intensity distribution on the walls. The map obtained under UV,
158 illustrated in Figure 2, shows that light was able to reach every corner of the photocatalytic material.
159 However, its intensity was dependent on the distance from the light source and ranged from 50 mW/m²
160 (at floor level, 3 m from source) to 2,000 mW/m² (at approximately 2 m height, 1 m from source).
161 Furthermore, at the same heights, the light appeared to be quite evenly distributed over the three walls
162 (slightly lower on the North wall), and it was thus possible to quantify the received irradiation using a
163 single mean value. Therefore, each lighting condition was expressed by the mean intensity value
164 obtained at three different heights. The results are summarised in Table 1. The intensities of visible
165 wavelengths under UV light or UV wavelengths under visible light were negligible.

166 To get an idea of a typical indoor light magnitude, a prior measurement campaign was carried out at the
167 LMDC. Three rooms were targeted (office, lab room and classroom). Inside each room, light intensity was

168 recorded at different times of day over several days. Detectors were placed at 100 cm from the floor and
 169 were not exposed to direct sunlight. Visible and UV light intensity were measured under a combination
 170 of natural and artificial lighting. More details can be found in Hot, Topalov et al. (2017). The lowest mean
 171 UV intensity was 50 mW/m² and the highest was 260 mW/m², depending on the room location and
 172 aspect. These values were slightly lower than the ones obtained in the experimental chamber.
 173 Concerning visible light intensity, the lowest and highest mean values were respectively 2,200 mW/m²
 174 and 7,680 mW/m²: much higher than the values in the experimental chamber (from 300 to 6,100
 175 mW/m² depending on the kind of lamps used). This was mostly due to the absence of natural light in the
 176 experimental chamber. In all cases, the experimental lighting conditions tested were considered to be
 177 representative of indoor environments.



178
 179 **Figure 2 – Light mapping: irradiation received on photocatalytic material surfaces in the experimental chamber: (a) UV**
 180 **lighting system (in mW/m²), (b) Fluorescent lighting system (in mW/m²)**

181 **Table 1 – Mean light irradiation values received by photocatalytic material at different heights in the experimental chamber**
 182 **(in mW/m²)**

Height (cm)	UV lighting 315< λ <400 nm		Visible lighting 400< λ <800 nm	
	Fluorescent	Fluorescent	LED	Halogen
20	40±20	400±100	300±100	900±100
100	300±50	1,000±200	800±200	1,700±300
180	1,200±300	2,500±500	2,300±300	6,100±500

183
 184 According to the UV lamp data sheet, its distribution spectrum varies between 350 and 400 nm with a
 185 peak around 365 nm. In the case of visible lighting, the emission wavelengths of each system were
 186 investigated using a spectro-radiometer (Jeti specbos 1201) and the distribution spectrum of each lamp
 187 was obtained between 380 and 780 nm. The results are given in Figure 3. The fluorescent lamp showed a
 188 discontinuous spectrum with the luminous intensity focused on three major peaks: 436 nm, 544 nm and
 189 612 nm. The halogen lamp had a rising, continuous spectrum with no dominant wavelengths. The LED
 190 lamp had a first peak around 450 nm and a second one around 605 nm, which were wider than the peaks
 191 of fluorescent light.

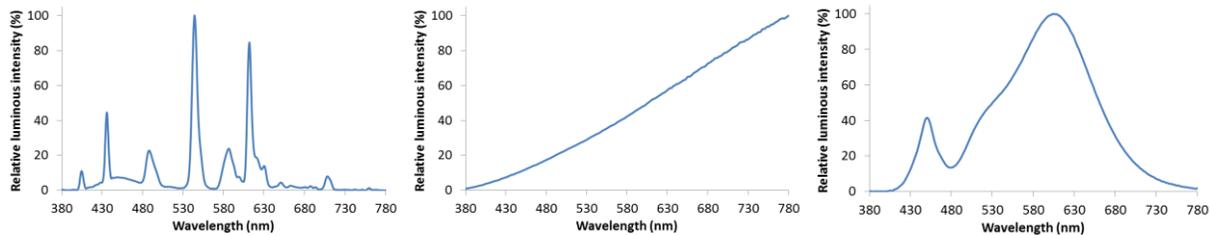


Figure 3 – Spectrum distribution between 380 and 780 nm: (a) Fluorescent, (b) Halogen, (c) LED

2.2 Experimental procedure

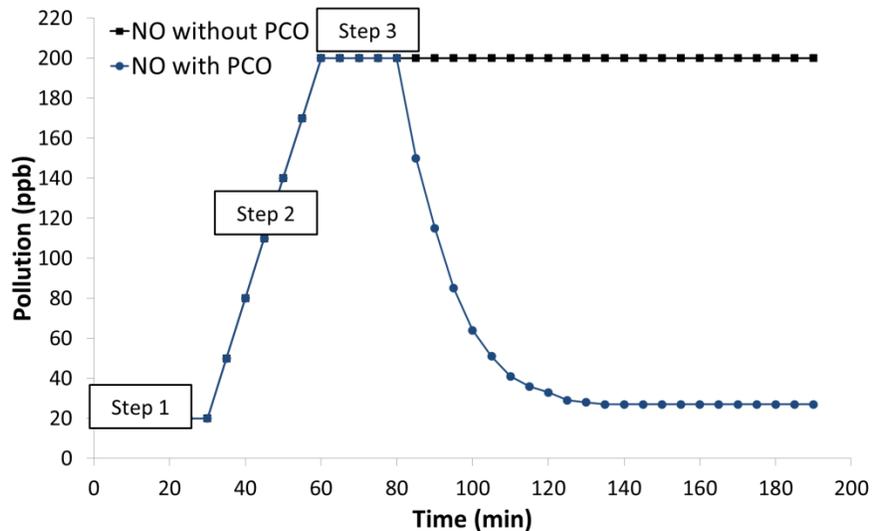
The experimental procedure consisted of injecting NO at a high flow rate until its concentration inside the experimental chamber reached 200 ppb. NO flow rate was then lowered to keep a constant level of pollution in the chamber (sufficient continuous NO injection to compensate for air leakage). PCO was then activated by switching on the light. The four steps listed below, illustrated in Figure 4, summarize this procedure:

Step 1: Background NO_x level assessment (30 min). Before NO pollutant injection, NO_x levels existing in the experimental chamber due to infiltration (outdoor pollution) were evaluated.

Step 2: NO injection until 200 ppb was reached (30 min). During this step, NO was injected at a high flow rate (1.5 l/min for approximately 30 min) in order to reach 200 ppb of pollution inside the experimental chamber.

Step 3: NO concentration kept constant at 200 ppb (180 min). Once the concentration of 200 ppb was reached in the experimental chamber, the flow rate was lowered (0.3±0.02 l/min) in order to maintain a constant NO pollution level over 180 min (± 2 ppb after 20 min and ± 10 ppb after 180 min).

Step 4: Photocatalysis activation (160 min). After observing pollution stability for 20 min, the light was switched on to activate photocatalysis. Depollution efficiency was evaluated with different lighting systems by following the NO concentration for up to 160 min.



211

212

Figure 4 – A theoretical step by step diagram of the experimental procedure followed

213

In order to validate this experimental procedure, especially steps 2 and 3, a series of blank tests were first conducted in the dark (light OFF). For these tests, a constant pollution level was kept for more than 3h with a tolerance of ± 2 ppb after 20 min and ± 10 ppb after 180 min. In some cases, during the first few minutes of the pollution stabilisation step, it was necessary to adjust the flow rate (0.3 ± 0.02 l/min). Moreover, it was observed that maintaining a constant pollution level was harder on windy days. Photocatalytic tests were carried out three times to ensure a good repeatability.

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219 3 Results and discussion

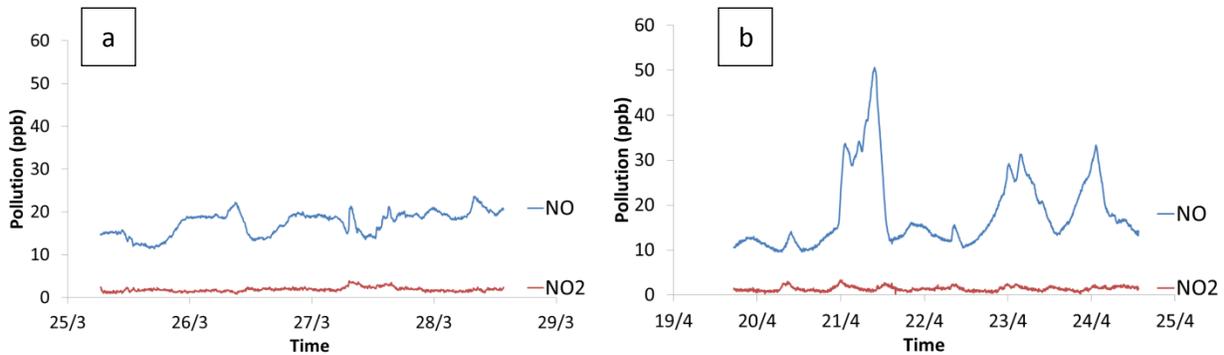
220 3.1 Background NO_x levels

221 The first step of the study was to collect data on NO_x background levels in the experimental chamber. As reported in the literature (Laurence 2015; Baukal 2005; Ao et al. 2003), NO_x are atmospheric gaseous pollutants that can easily infiltrate indoor air, so their levels and evolutions are strongly dependent on the surrounding environment. However, pollution levels also depend on the air exchange rate, which varies according to the building materials, insulation and ventilation (Blondeau et al. 2005). In this study, the NO_x analyser was used to monitor NO and NO₂ concentrations in outdoor air before the tests were carried out in the experimental chamber. The results revealed that outdoor air pollution was relatively low, probably because the experimental house was located on Toulouse university campus, surrounded by green spaces, far from boulevards and roadways.

230 Background pollution levels measured in the experimental chamber for a few days in March and April 2017 are illustrated in Figure 5. During March, pollution was relatively low and no peaks were observed for the 4-day period investigated. The background pollution level of NO_x was thus estimated from this measurement campaign: NO was between 10 and 20 ppb and NO₂ was below the analyser detection value of 3 ppb. During April, three NO peaks were observed in the 5 day investigation period: NO rose from a background level of 10-12 ppb to 50 ppb for the first peak and to 30 ppb for the other two. Each

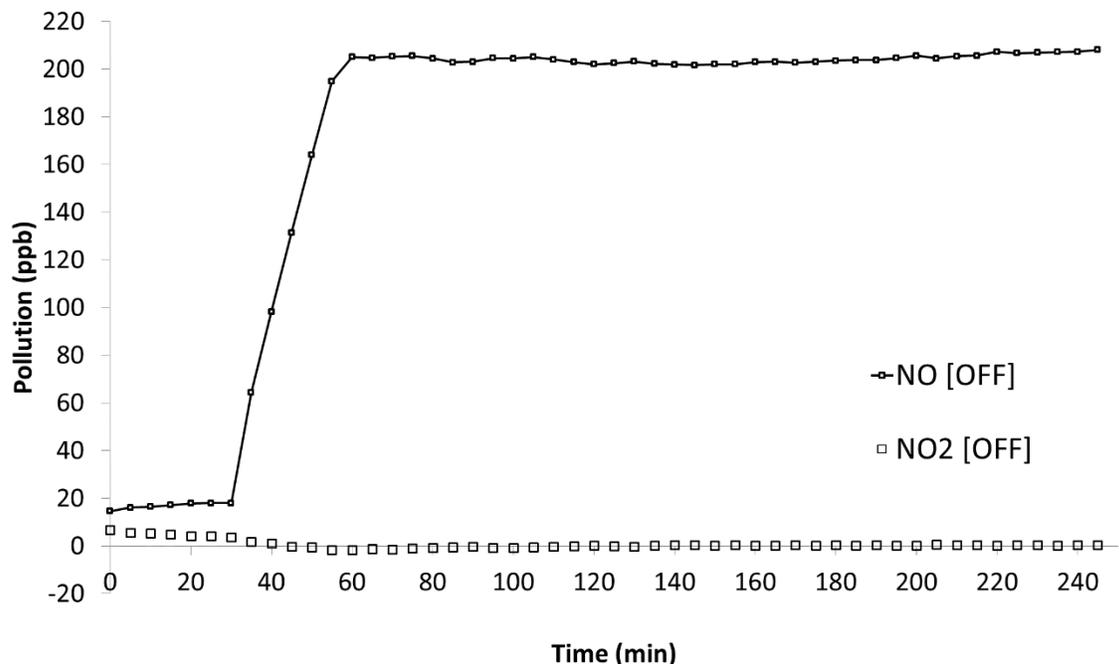
235

236 peak lasted for a few hours. In contrast, NO₂ level remained under 3 ppb even when NO peaks appeared.
237 Tests in the experimental chamber were thus carried out only if the NO initial background concentration
238 (step 1) before injection was less than 30 ppb. Otherwise, tests were held over to a later date to ensure
239 no initial pollution.



240
241 **Figure 5 – NO_x concentrations in the experimental chamber coming from outdoor pollution - (a) 25-28 March 2017, (b) 20-24**
242 **April 2017**

243
244 **3.2 NO_x concentrations without photocatalysis**
245 The second step was to continuously inject NO into the experimental chamber without light (light OFF)
246 to ensure that a constant pollution level could be reached and maintained for at least 180 min. This
247 blank test in the dark was conducted in the presence of photocatalytic plasterboards on the walls. In
248 fact, no significant difference was noticed between tests carried out with and without photocatalytic
249 material on the walls. This observation is in accordance with research work reported in the literature
250 showing that NO has no adsorption properties (Maggos et al. 2007; Maggos et al. 2008; Hot, Martinez et
251 al. 2017). The NO and NO₂ concentrations obtained over 240 min in the dark are given in Figure 6.



252

253 **Figure 6 – Blank test: NO and NO₂ concentrations in the chamber in the dark before and during continuous NO injection**

254 From t=0 min to t=30 min (step 1), NO_x concentration monitoring showed the expected NO and NO₂
 255 background levels: around 15-20 ppb of NO and 0-5 ppb of NO₂. Starting at t=30 min, NO was
 256 continuously injected at 1.5 l/min for about 28-30 min to reach 200 ppb (step 2). The pollution
 257 increased linearly, at a rate of 6.3±0.2 ppb/min. During this step, NO₂ concentration remained between 0
 258 and 3 ppb. Just before 200 ppb was reached, the flow rate was lowered to 0.3 l/min in order to
 259 maintain pollution at a constant level (step 3). NO pollution stabilized after only 5 min and lasted for 3
 260 hours. Here again, NO₂ concentration remained low, (close to 0 ppb), which highlighted the absence of
 261 reaction between NO and NO₂ under these experimental conditions, especially in the dark. Therefore,
 262 steps 1 and 2 above allowed an NO concentration of 200 ppb to be reached rapidly in the experimental
 263 chamber and maintained it constant over 3 hours.

264 3.3 NO_x concentrations with photocatalysis

265 3.3.1 Under UV light

266 Figure 7 shows the variation of NO concentration in the experimental chamber when the UV light was
 267 switched on after step 2 (i.e. when NO pollution level had become constant).

268

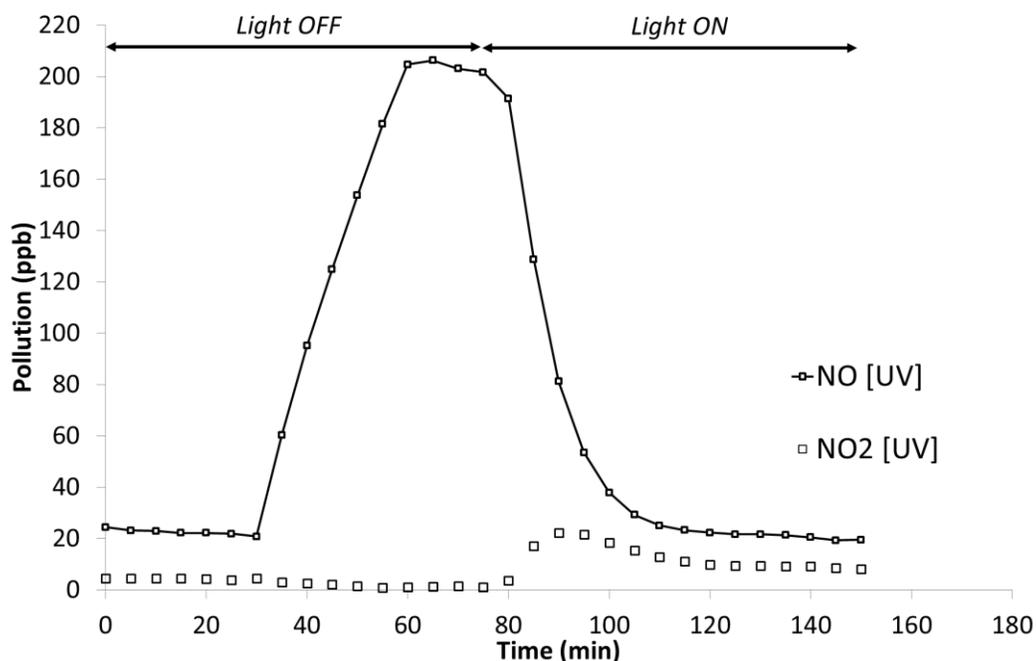


Figure 7 – NO photocatalytic degradation in the experimental chamber under UV light

269
 270
 271 Steps 1 and 2 were identical to the blank test conducted without light. After the pollution injection flow
 272 rate was lowered (at t=60 min), NO concentration was monitored in the dark for an extra 20 min to
 273 ensure it remained constant. At t=80 min, UV light was switched on to initiate photocatalytic oxidation. It
 274 can be seen in Figure 7 that, under UV light, photocatalysis had a significant depolluting effect with
 275 respect to NO. After only 20 min of photocatalytic activity (at t=100 min), NO concentration had fallen to
 276 39.7 ppb. After 40 min (at t=120 min), the NO rate had returned to its minimum value, i.e. the
 277 background value (cf. part 3.1). The test was finally stopped after 70 min of UV illumination (at t=150
 278 min) because NO and NO₂ concentrations remained constant.

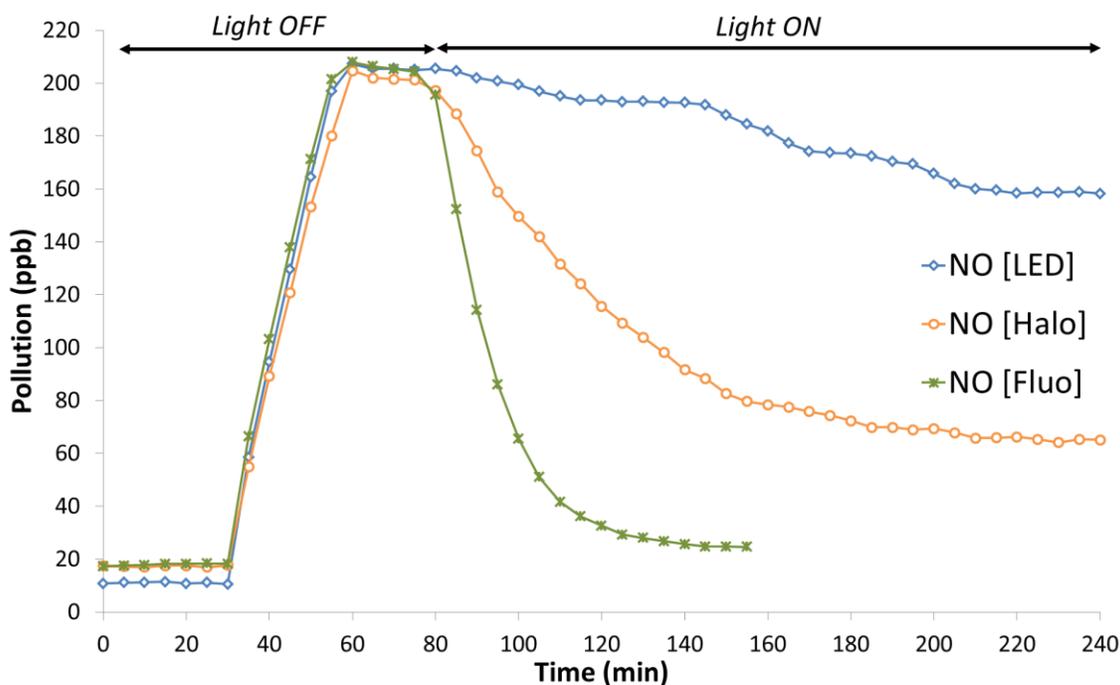
279 Regarding NO₂, generation of this gas was observed during the first 10 min of photocatalytic activity
 280 (from t=80 min to t=90 min). While NO decreased from 200 to 80 ppb, NO₂ increased from 0 to about 20
 281 ppb. Then, when the NO concentration stabilised at 20 ppb, NO₂ also decreased but remained at 8 ppb,
 282 which was higher than the background level (cf. part 3.1). Here, a mechanism of NO photocatalysis over
 283 TiO₂ is highlighted; NO₂ formed as a by-product at first but then some of it was destroyed. This
 284 observation is consistent with results reported by Hot, Martinez et al. (2017) in the case of NO static
 285 injection. More generally, NO₂ generation has always been observed in tests carried out at laboratory
 286 scale using photocatalytic reactor (Martinez et al. 2011; Martinez et al. 2013; Hot, Topalov et al. 2017;
 287 Karapati et al. 2014; Hernández Rodríguez et al. 2016; Crain et al. 2016; Ifang et al. 2014).

288 Results obtained in this study proved that our experimental chamber constituted a pertinent tool for
 289 assessing PCO at real scale and in real time. It was very remarkable that the entire injected NO was
 290 destroyed, showing that the depollution efficiency was almost 100% for the experimental conditions
 291 used here.

292 **3.3.2 Under visible light**

293 The photocatalytic degradation of NO under three visible lighting systems was assessed. The results are
294 shown in Figure 8.

295

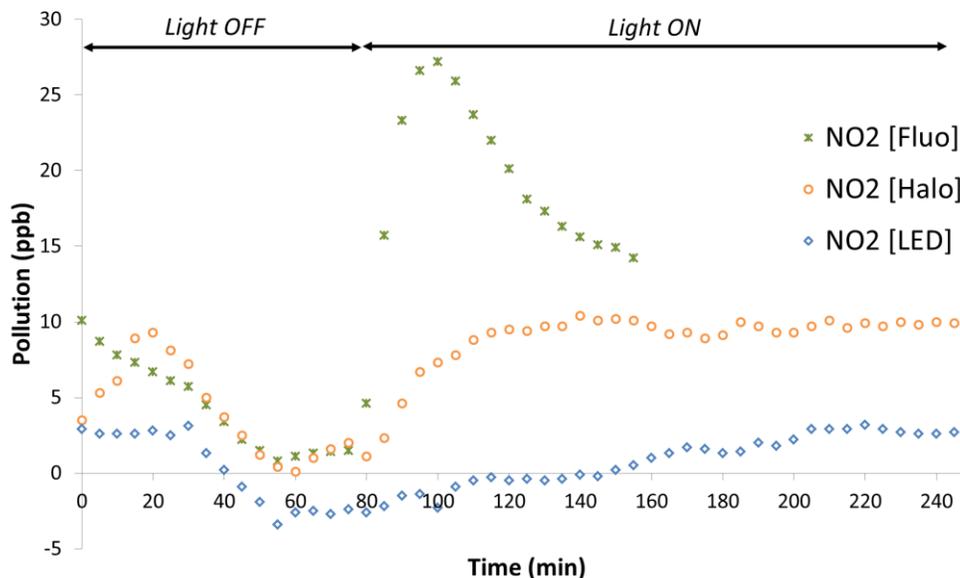


296

297 **Figure 8 – Typical NO photocatalytic degradation in the experimental chamber under various visible lighting systems:**
298 **Fluorescent, Halogen and LED**

299 As expected, photocatalysis efficiency was dependent on the lighting systems used. The best
300 photocatalytic degradation was obtained with fluorescent tubes. With this system, the NO concentration
301 had fallen to 65.4 ppb after 20 min (at t=100 min) and the minimal value was reached after a further 50
302 min (at t=150 min). NO concentration remained constant and low, at a value around 25 ppb, which was
303 slightly higher than the background pollution level. In this case, efficiency was nearly 98%. Halogen lamps
304 led to lower degradation kinetics as the steady state was reached after 140 min of irradiation, with a
305 final NO concentration of 64 ppb. Efficiency was thus around 78%. With LED used as lighting system, the
306 photocatalytic activity was clearly less effective. In fact, NO concentration was around 159 ppb after 140
307 min of irradiation. The efficiency was only 22%. These results show that photocatalysis could be highly
308 effective under visible light if a suitable lighting system was used. According to Table 1, halogen bulbs
309 produced the highest light irradiation but the photocatalytic oxidation was not as effective as that
310 observed with fluorescent tubes. In the case of LED, NO degradation was minimal although the light
311 irradiation (intensity) was almost identical to that of fluorescent tubes. These results stress the influence
312 of the light spectrum.

313



314

315 **Figure 9 – NO₂ concentrations during NO oxidation by photocatalysis under different visible lighting systems: Fluorescent,**
 316 **Halogen and LED**

317 Figure 9 shows NO₂ concentration variations obtained during tests carried out under visible light. NO₂
 318 production was observed with fluorescent light. Because of the uncertainty on the NO₂ measurement (±5
 319 ppb), the production of NO₂ under halogen and LED lamps was not clearly quantified. With visible
 320 fluorescent tubes, NO₂ production was maximal during the first 20 min of the photocatalytic reaction and
 321 then fell as has previously been observed with UV fluorescent tubes. With halogen and LED bulbs, NO₂
 322 production lasted longer at a lower level.

323 **3.4 Photocatalysis efficiency with respect to NO**

324 NO photocatalytic depollution was assessed by two different methods. Firstly, the PCO slope and the
 325 lowest NO concentration values were determined as shown in Figure 9. The intersection of these two
 326 lines gave the time needed by the PCO to reach more than 85% of its maximum reaction efficiency.
 327 Secondly, the depollution rate was evaluated by comparing the quantity of NO obtained after PCO to the
 328 quantity without PCO (blank test).

329 **3.4.1 PCO potential: slope & lowest NO level**

330 The PCO potential was a method suggested by the authors to estimate the photocatalysis efficiency. This
 331 also allowed the efficiency of different lighting systems to be classified according to photoactivity. Two
 332 values were assessed: (1) the slope of NO decrease under PCO, and (2) the lowest NO concentration
 333 recorded after a maximum of 3 hours' illumination. The uncertainty on the slope was also estimated
 334 from the different measurements. Experiments were stopped earlier if a steady state was reached. The
 335 results are summarised in Table 2 and a graphical illustration of this method is given in Figure 10.

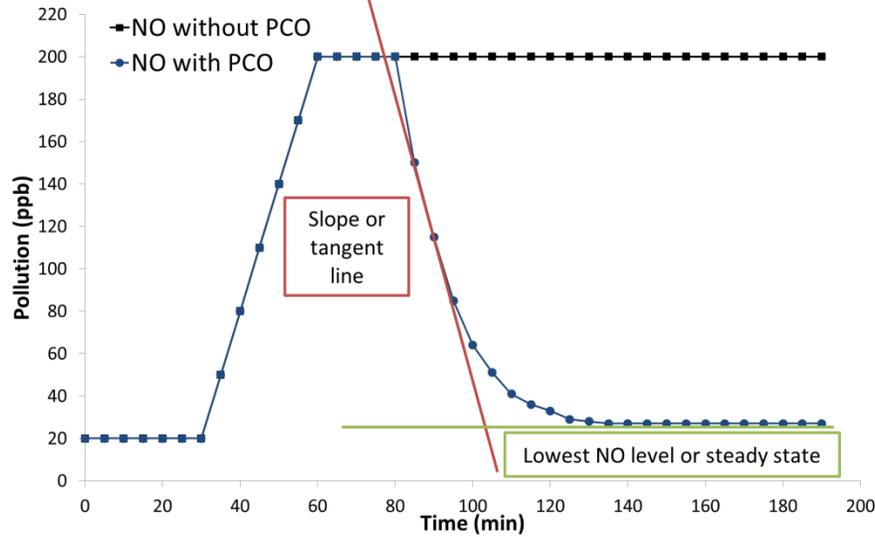


Figure 10 – Graphical illustration of PCO potential method

Table 2 – Values and uncertainties obtained to assess PCO potential under UV and visible light.

Lighting system	UV	Fluo	Halo	LED
Slope (ppb/min)	7.7±1.2	5.9±0.8	1.9±0.4	0.3±0.1
Lowest NO level (ppb)	20±5	25±5	64±5	160±5

3.4.2 PCO depollution rate

The PCO depollution rate was a second method suggested by the authors to evaluate photocatalysis efficiency. It consisted of assessing the mass of NO degraded by a square metre of photocatalytic material over a period of one minute. The mass of NO injected after t=80 min (light OFF) was first calculated for each test using equation (1):

$$M_{NO\ Blank} = M_{NO\ gc} * \frac{1}{V} * \phi * t \quad (1)$$

where $M_{NO\ Blank}$ is the mass of NO injected (in μg) during the blank test, $M_{NO\ gc}$ is the mass of NO in the gas cylinder (45 ppm or 55 215 $\mu\text{g}/\text{m}^3$), V is the chamber volume ($10\ \text{m}^3$), ϕ is the injection flow rate (0.3 l/min) and t is the injection time (min).

Then, the area under the blank test curve was calculated from t=80 min to the end of the test (A_{Blank}). In the same way, the area under each curve obtained with PCO was calculated (A_{PCO}). This allowed the area of NO removed ($A_{NO\ rem}$) - given in equation (2) and illustrated in Figure 11 - to be assessed.

$$A_{Blank} - A_{PCO} = A_{NO\ rem} \quad (2)$$

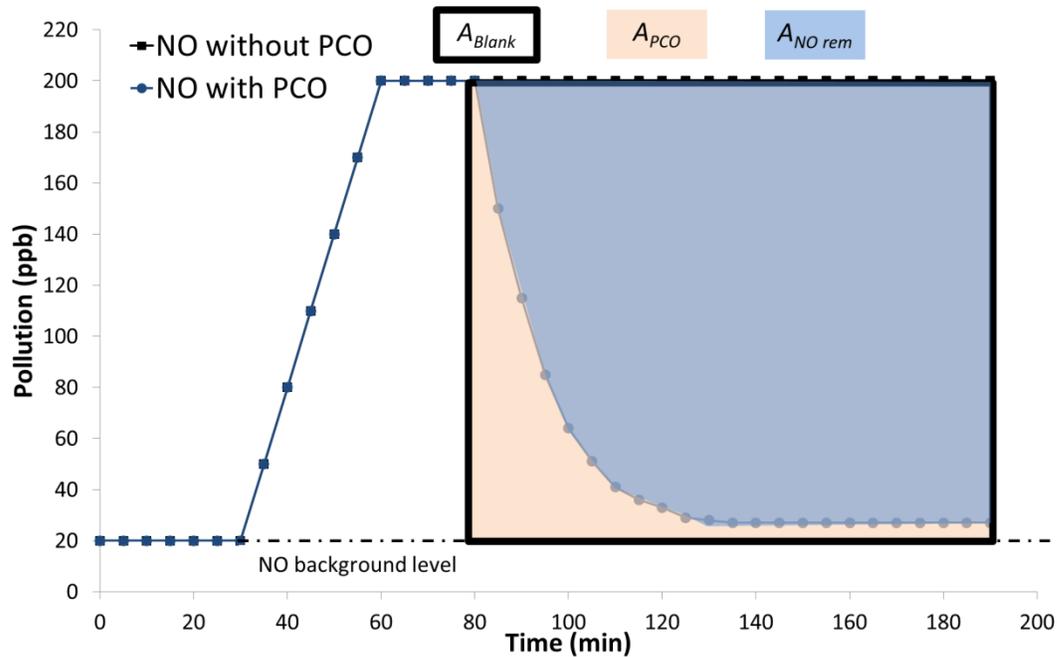
This area was used to determine the mass of NO removed ($M_{NO\ rem}$) according to equation (3).

$$M_{NO\ rem} = \frac{A_{NO\ rem}}{A_{Blank}} * M_{NO\ Blank} \quad (3)$$

355 Finally, equation (4) was used to obtain the depollution rate, DR ($\mu\text{g}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$). S_{PC} was the total area
 356 covered by the photocatalytic material (m^2) and t_{PC} was the total time of light irradiation (min). Results
 357 are presented in Table 3.

358
$$DR = \frac{M_{NO\ removed}}{S_{PC} \cdot t_{PC}} \quad (4)$$

359



360

361

Figure 11 – Graphical illustration of PCO depollution rate method

362

Table 3 – Results obtained for PCO depollution rate calculation

Lighting system	mass of NO injected (after t=80min)	NO injection time (after t=80min)	NO mass removed	Depollution rate
UV	1 160 μg	70 min	1 100 μg	1.60 $\mu\text{g}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$
Fluorescent	1 325 μg	80 min	1 230 μg	1.55 $\mu\text{g}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$
Halogen	2 650 μg	160 min	1 700 μg	1.08 $\mu\text{g}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$
LED	2 650 μg	160 min	400 μg	0.26 $\mu\text{g}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$

363

364 A similar method was used by Maggos et al. to evaluate the depollution rate of a TiO_2 photocatalytic
 365 paint in a 917 m^3 , artificially closed car park (Maggos et al. 2007). The paint contained 10% TiO_2 and was
 366 applied over the total surface area of the ceiling (322 m^2). These authors reported a DR between 3 and
 367 $7.8 \mu\text{g}\cdot\text{min}^{-1}\cdot\text{m}^{-2}$ under UV light. A total of 20 UV lamps were used to provide $1 \text{ W}/\text{cm}^2$ on the surface of
 368 the photocatalytic material. However, the pollution was generated from the exhaust gases of a running
 369 vehicle and different pollutants were thus present simultaneously (NO_x , VOCs, CO, CO_2). Also, the NO
 370 concentrations tested were much higher (between 650 ppb and 1 300 ppb). Under these experimental

371 conditions, Maggos et al. estimated the global photocatalytic removal of NO at around 20%. This value is
372 lower than the ones obtained in this study: almost 100% and more than 95% were respectively reached
373 under UV and visible light provided by fluorescent tubes. Therefore, care is needed when dealing with
374 DR as its value could be over- or under-estimated if other information, such as initial or final pollutant
375 concentration (the lowest value reached), is not specified.

376 **4 Conclusions**

377 Studies aimed at assessing PCO efficiency are mainly conducted at laboratory scale using a reactor and
378 most of them are inspired by ISO 22197. However, this standard is not suitable for real-world
379 applications. For example, the controlled experimental conditions, such as the small reactor volume, the
380 residence and contact time of the pollutant, or the lighting system (UV and high intensity), are not
381 representative of tests in situ and cannot be simply extrapolated to a larger scale. In this paper, a new,
382 simple method for assessing PCO of gaseous air pollutants under real-world conditions has been
383 presented. The targeted pollutant was NO. Its degradation by photocatalysis was studied using a specific
384 procedure in an experimental chamber developed at the LMDC. Various lighting systems were tested to
385 compare PCO efficiency under UV and visible light. The results clearly showed that the lighting systems
386 played an important role in the photocatalytic efficiency. Under UV, nearly 100 % of NO was removed by
387 PCO. Moreover, this study highlighted the reduction of NO concentration under visible light, especially
388 from fluorescent tubes. Results showed 97 % degradation under visible light from fluorescent tubes, 78
389 % under visible light from halogen bulbs and 30 % under visible light from LED bulbs. LED lighting is
390 gaining in popularity because of its light output coupled with its low energy consumption. The
391 abatement reaction rate with this lighting is lower than those obtained with other systems.
392 Nevertheless, the abatement remains significant and could even be improved by doping the
393 photocatalyst as shown by several authors (Zhou et al. 2007; Todorova et al. 2013; Hu et al. 2015).

394 The experimental procedure proposed here allowed PCO to be tested at larger scale, under realistic
395 conditions, such as chamber volume, pollutant injection flow rate and lighting condition. In a future
396 publication, the authors will propose a simple numerical model that describes the pollutant evolution
397 observed during the different stages of the experiment. Then, an attempt will be made to link results
398 obtained in this experimental chamber and in a reactor at a lab scale in order to suggest a numerical
399 model able to predict real scale results from those found using a reactor.

400

401 **5 References**

402 Aïssa AH, Puzenat E, Plassais A, Herrmann JM, Haehnel C, Guillard C (2011) Characterization and
403 photocatalytic performance in air of cementitious materials containing TiO₂. Case study of
404 formaldehyde removal. *Applied Catalysis B: Environmental*, 107(1–2), pp.1–8.

405 Ao CH, Lee SC, Mak CL, Chan LY (2003) Photodegradation of volatile organic compounds (VOCs) and NO
406 for indoor air purification using TiO₂: Promotion versus inhibition effect of NO. *Applied Catalysis B:
407 Environmental*, 42(2), pp.119–129.

- 408 Baukal C (2005) Everything you need to know about NO_x. *Metal Finishing*, 103(11), pp.18–24.
- 409 Blondeau P, Iordache V, Poupard O, Genin D, Allard F (2005) Relationship between outdoor and indoor
410 air quality in eight French schools. *Indoor Air*, 15(1), pp.2–12.
- 411 CEN/TS 16980-1 (2016) Photocatalysis - Continuous Flow Test Methods - Part 1: Determination Of The
412 Degradation Of Nitric Oxide (NO) In The Air By Photocatalytic Materials. *EUROPEAN COMMITTEE*
413 *FOR STANDARDIZATION*.
- 414 Chen M, Chu JW (2011) NO_x photocatalytic degradation on active concrete road surface - From
415 experiment to real-scale application. *Journal of Cleaner Production*, 19(11), pp.1266–1272.
416 Available at: <http://dx.doi.org/10.1016/j.jclepro.2011.03.001>.
- 417 Colls J (2002) *Air Pollution @ 2002* 2nd Edition., London: Spoon Press.
- 418 Crain N, Juenger M, Cros C, Terpeluk A, Burriss L, McDonald-Buller E, Sullivan D, Kimura Y, Spinhirne J,
419 Rung M (2016) Laboratory and Field Studies of Photocatalytic NO_x and O₃ Removal by Coatings on
420 Concrete - TECHNICAL REPORT 0-6636-1, Available at: [http://library.ctr.utexas.edu/ctr-](http://library.ctr.utexas.edu/ctr-publications/0-6636-1.pdf)
421 [publications/0-6636-1.pdf](http://library.ctr.utexas.edu/ctr-publications/0-6636-1.pdf).
- 422 EU (2008) Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on
423 ambient air quality and cleaner air for Europe. *Official Journal of the European Communities*, 152,
424 pp.1–43.
- 425 Fenger J (2009) Air pollution in the last 50 years - From local to global. *Atmospheric Environment*, 43(1),
426 pp.13–22. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2008.09.061>.
- 427 Fujishima A, Rao TN, Tryk DA, (2000) Titanium dioxide photocatalysis. *Journal of Photochemistry and*
428 *Photobiology C: Photochemistry Reviews*, 1(1), pp.1–21. Available at:
429 <http://www.sciencedirect.com/science/article/pii/S1389556700000022>.
- 430 Fujishima A, Zhang X, Tryk DA, (2008) TiO₂ photocatalysis and related surface phenomena. *Surface*
431 *Science Reports*, 63(12), pp.515–582.
- 432 Gallus M, Akylas V, Barmpas F, Beeldens A, Boonen E, Boréave A, Cazaunau M, Chen H, Daële V, Doussin
433 JF, Dupart Y, Gaimoz C, George C, Grosselin B, Herrmann H, Ifang S, Kurtenbach R, Maille M,
434 Mellouki A, Miet K, Mothes F, Moussiopoulos N, Poulain L, Rabe R, Zapf P, Kleffmann J (2015)
435 Photocatalytic de-pollution in the Leopold II tunnel in Brussels: NO_x abatement results. *Building*
436 *and Environment*, 84(2), pp.125–133.
- 437 Gaya UI, Abdullah AH (2008) Heterogeneous photocatalytic degradation of organic contaminants over
438 titanium dioxide: A review of fundamentals, progress and problems. *Journal of Photochemistry and*
439 *Photobiology C: Photochemistry Reviews*, 9(1), pp.1–12. Available at:
440 <http://linkinghub.elsevier.com/retrieve/pii/S1389556708000300>.
- 441 General T, Kopp P (2014) ANSES Note and recommendations 2011-CRD-11 / Study of the socio-economic
442 cost of indoor air pollutants, Available at: [https://www.anses.fr/en/documents/AUT-Ra-](https://www.anses.fr/en/documents/AUT-Ra-CoutAirInterieurSHS2014-02EN.pdf)
443 [CoutAirInterieurSHS2014-02EN.pdf](https://www.anses.fr/en/documents/AUT-Ra-CoutAirInterieurSHS2014-02EN.pdf).
- 444 Guerrini GL (2012) Photocatalytic performances in a city tunnel in Rome: NO_x monitoring results.
445 *Construction and Building Materials*, 27(1), pp.165–175. Available at:

- 446 <http://dx.doi.org/10.1016/j.conbuildmat.2011.07.065>.
- 447 Hernández Rodríguez MJ, Pulido Melián E, González Díaz O, Araña J, Macías M, González Orive A, Doña
448 Rodríguez JM (2016) Comparison of supported TiO₂ catalysts in the photocatalytic degradation of
449 NOx. *Journal of Molecular Catalysis A: Chemical*, 413, pp.56–66.
- 450 Horgnies M, Dubois-Brugger I, Gartner EM (2012) NOx de-pollution by hardened concrete and the
451 influence of activated charcoal additions. *Cement and Concrete Research*, 42(10), pp.1348–1355.
452 Available at: <http://dx.doi.org/10.1016/j.cemconres.2012.06.007>.
- 453 Horgnies M, Dubois-Brugger I, Stora E (2015) An innovative de-polluting concrete doped with activated
454 carbon to enhance air quality. In *10th International Concrete Sustainability Conference (NRMCA), At*
455 *Miami (USA)*. pp. 0–13.
- 456 Hot J, Topalov J, Ringot E, Bertron A (2017) Investigation on parameters affecting the effectiveness of
457 photocatalytic functional coatings to degrade NO : TiO₂ amount on surface, illumination and
458 substrate roughness. *International Journal of Photoenergy*, pp.1–35.
- 459 Hot J, Martinez T, Wayser B, Ringot E, Bertron A (2017) Photocatalytic degradation of NO/NO₂ gas
460 injected into a 10-m³ experimental chamber. *Environmental Science and Pollution Research*, 24(14),
461 pp.12562–12570. Available at: <http://dx.doi.org/10.1007/s11356-016-7701-2>.
- 462 Hu Y, Song X, Jiang S, Wei C (2015) Enhanced photocatalytic activity of Pt-doped TiO₂ for NOx oxidation
463 both under UV and visible light irradiation: A synergistic effect of lattice Pt⁴⁺ and surface PtO.
464 *Chemical Engineering Journal*, 274(x), pp.102–112. Available at:
465 <http://dx.doi.org/10.1016/j.cej.2015.03.135>.
- 466 Hüsken G, Hunger M, Brouwers HJH (2009) Experimental study of photocatalytic concrete products for
467 air purification. *Building and Environment*, 44(12), pp.2463–2474. Available at:
468 <http://dx.doi.org/10.1016/j.buildenv.2009.04.010>.
- 469 Ifang S, Gallus M, Liedtke S, Kurtenbach R, Wiesen P, Kleffmann J (2014) Standardization methods for
470 testing photo-catalytic air remediation materials: Problems and solution. *Atmospheric Environment*,
471 91, pp.154–161. Available at: <http://dx.doi.org/10.1016/j.atmosenv.2014.04.001>.
- 472 ISO 22197-1 (2016) Fine ceramics (advanced ceramics, advanced technical ceramics) - Test method for
473 air-purification performance of semiconducting photocatalytic materials - Part 1: Removal of nitric
474 oxide. *AFNOR*. Available at: www.afnor.org.
- 475 Karapati S, Giannakopoulou T, Todorova N, Boukos N, Antiohos S, Papageorgiou D, Chaniotakis E,
476 Dimotikali D, Trapalis C (2014) TiO₂ functionalization for efficient NOx removal in photoactive
477 cement. *Applied Surface Science*, 319(1), pp.29–36. Available at:
478 <http://dx.doi.org/10.1016/j.apsusc.2014.07.162>.
- 479 Klepeis NE, Nelson WC, Ott WR, Robinson JP, Tsang AM, Switzer P, Behar JV, Hern SC, Engelmann WH
480 (2001) The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to
481 environmental pollutants. *Journal of Exposure Analysis and Environmental Epidemiology*, 11(3),
482 pp.231–252. Available at: <http://www.nature.com/doi/10.1038/sj.jea.7500165>.
- 483 Krzyzanowski M, Cohen A (2008) Update of WHO air quality guidelines. *Air Quality, Atmosphere and*
484 *Health*, pp.7–13.

- 485 Laurence G (2015) *Traitement de l'air intérieur par photocatalyse. Performance et innocuité de systèmes*
486 *et matériaux - Rapport de recherche ADEME,*
- 487 Li Y, Henze DK, Jack D, Kinney PL (2016) The influence of air quality model resolution on health impact
488 assessment for fine particulate matter and its components. *Air Quality, Atmosphere and Health,*
489 pp.51–68.
- 490 Lin L, Chai Y, Zhao B, Wei W, He D, He B, Tang Q (2013) Photocatalytic oxidation for degradation of VOCs.
491 *Open Journal of Inorganic Chemistry,* 3(January), pp.14–25.
- 492 Maggos T, Bartzis JG, Liakou M, Gobin C (2007) Photocatalytic degradation of NO_x gases using TiO₂-
493 containing paint: A real scale study. *Journal of Hazardous Materials,* 146(3), pp.668–673.
- 494 Maggos T, Plassais A, Bartzis JG, Vasilakos C, Moussiopoulos N, Bonafous L (2008) Photocatalytic
495 degradation of NO_x in a pilot street canyon configuration using TiO₂-mortar panels. *Environmental*
496 *Monitoring and Assessment,* 136(1–3), pp.35–44.
- 497 Mamaghani AH, Haghghat F, Lee CS (2017) Photocatalytic oxidation technology for indoor environment
498 air purification: The state-of-the-art. *Applied Catalysis B: Environmental,* 203, pp.247–269. Available
499 at: <http://dx.doi.org/10.1016/j.apcatb.2016.10.037>.
- 500 Martinez T, Bertron A, Ringot E, Escadeillas G (2011) Degradation of NO using photocatalytic coatings
501 applied to different substrates. *Building and Environment,* 46(9), pp.1808–1816.
- 502 Martinez, T, Dompont D, Bertron A, Escadeillas G (2013) Photocatalytic coatings for building materials:
503 degradation of NO_x and inhibition of algal growth. *International Journal of Restoration, Repair and*
504 *Renewal of Built Environment,* 4(1), pp.520–533.
- 505 Mills A, Elouali S (2015) The nitric oxide ISO photocatalytic reactor system: Measurement of NO_x removal
506 activity and capacity. *Journal of Photochemistry and Photobiology A: Chemistry,* 305(x), pp.29–36.
- 507 Mosqueron L, Nedellec V (2004) Inventaire des données françaises sur la qualité de l'air à l'intérieur des
508 bâtiments : Actualisation des données sur la période 2001-2004. *Observatoire de la qualité de l'air*
509 *intérieur (OQAI),* pp.1–61
- 510 Mosqueron L, Nedellec V (2005) Hiérarchisation sanitaire des paramètres d'intérêt pour l'observatoire
511 de la qualité de l'air intérieur : application aux phtalates, parafines chlorées à chaîne courte,
512 organo-étains, alkyl phénols et retardateurs de flamme bromés. *CSTB,* pp.1–98.
- 513 NF EN ISO 9972 (2016) Thermal performance of buildings - Determination of air permeability of buildings
514 - Fan pressurization method. *AFNOR.* Available at: www.afnor.org.
- 515 Ohama Y, Van Gemert D (2011) *Applications of Titanium Dioxide Photocatalysis to Construction*
516 *Materials : State-of-the-Art Report of the RILEM Technical Committee 194-TDP* Y. Ohama & D. Van
517 Gemert, eds., Dordrecht: Springer Netherlands. Available at: [http://link.springer.com/10.1007/978-](http://link.springer.com/10.1007/978-94-007-1297-3)
518 [94-007-1297-3](http://link.springer.com/10.1007/978-94-007-1297-3).
- 519 Rajeshwar K (2007) Fundamentals of Semiconductors Electrochemistry and Photoelectrochemistry.
520 *Encyclopedia of Electrochemistry,* pp.1–51.
- 521 Ren H, Koshy P, Chen WF, Qi S, Sorrell CC (2017) Photocatalytic materials and technologies for air
522 purification. *Journal of Hazardous Materials,* 325, pp.340–366. Available at:

523 <http://dx.doi.org/10.1016/j.jhazmat.2016.08.072>.

524 Solomon PA (2012) Introduction : special issue of air quality , atmosphere and health for air pollution and
525 health : bridging the gap from sources-to-health outcomes. *Air Quality, Atmosphere and Health*,
526 pp.3–8.

527 Todorova N, Vaimakis T, Petrakis D, Hishita S, Boukos N, Giannakopoulou T, Giannouri M, Antiohos S,
528 Papageorgiou D, Chaniotakis E, Trapalis C (2013) N and N,S-doped TiO₂ photocatalysts and their
529 activity in NO_x oxidation. *Catalysis Today*, 209(2), pp.41–46. Available at:
530 <http://dx.doi.org/10.1016/j.cattod.2012.11.019>.

531 Toro C, Jobson BT, Haselbach L, Shen S, Chung SH (2016) Photoactive roadways: Determination of CO,
532 NO and VOC uptake coefficients and photolabile side product yields on TiO₂ treated asphalt and
533 concrete. *Atmospheric Environment*, 139, pp.37–45.

534 World Health Organization (2006) WHO Air quality guidelines for particulate matter, ozone, nitrogen
535 dioxide and sulfur dioxide: global update 2005: summary of risk assessment. *Geneva: World Health
536 Organization*, pp.1–22. Available at:
537 http://whqlibdoc.who.int/hq/2006/WHO_SDE_PHE_OEH_06.02_eng.pdf?ua=1.

538 World Health Organization (2016) Ambient Air Pollution: A global assessment of exposure and burden of
539 disease. *World Health Organization*, pp.1–131. Available at: www.who.int.org.

540 Yu QL, Brouwers HJH (2009) Indoor air purification using heterogeneous photocatalytic oxidation. Part I:
541 Experimental study. *Applied Catalysis B: Environmental*, 92(3–4), pp.454–461.

542 Zhong L, Haghghat F (2015) Photocatalytic air cleaners and materials technologies - Abilities and
543 limitations. *Building and Environment*, 91, pp.191–203. Available at:
544 <http://dx.doi.org/10.1016/j.buildenv.2015.01.033>.

545 Zhou L, Tan X, Zhao L, Sun M (2007) Photocatalytic oxidation of NO_x over visible-light-responsive
546 nitrogen-doped TiO₂. *Korean Journal of Chemical Engineering*, 24(6), pp.1017–1021.

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548