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Please find as attached files a manuscript untitled:

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Best regards.

Pierre Roupsard

1 **HIGHLIGHTS:**

- 2 Submicron aerosol deposition on urban surfaces is studied in a wind tunnel.
- 3 Associated turbulent parameters are measured or estimated with a hot wire anemometry.
- 4 Settling has an influence on deposition on smooth surface and at low wind speed.
- 5 Submicron aerosol deposition is dependent on turbulent deposition processes.

1 **MEASUREMENT IN A WIND TUNNEL OF DRY DEPOSITION VELOCITIES OF SUBMICRON**
2 **AEROSOL WITH ASSOCIATED TURBULENCE ONTO ROUGH AND SMOOTH URBAN SURFACES**

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24 **ABSTRACT:**

25 In the event of accidental discharges of radionuclides in particulate form by a nuclear plant, dry deposition
26 is the only transfer pathway under dry atmospheric conditions. In this case, for the urban environment,
27 these deposits must be assessed precisely in the urban canopy to estimate the doses potentially received
28 by the population. The objectives of this wind tunnel study are to measure dry deposition velocities of a
29 submicron fluorescein aerosol onto horizontal and vertical urban surfaces of glass, cement facing and
30 grass for several wind speeds and to measure the turbulence parameters associated with these
31 deposition velocities. These deposition velocities are then compared to data of the literature and to the

32 results of two models for dry deposition. The dry deposition velocity of the fluorescein aerosol increases
33 with the intensity of the turbulence. This highlights the importance of the turbulent processes of impaction
34 and interception in deposition. However, the ratio of dry deposition velocity to friction velocity depends on
35 the surface type. It depends on the turbulence conditions in the boundary layer. These turbulent dry
36 deposition processes thus vary in importance depending on the studied surface. Finally, settling
37 represents a significant part of the deposition for low wind speeds and for smooth surfaces. This wind
38 tunnel study permits the study of the deposition as a function of turbulent processes. It should be
39 supplemented by *in situ* experiments to take into account all the physical processes involved under real
40 conditions.

41

42 **KEYWORDS:** Dry Deposition, Deposition Velocity, Submicron Aerosol, Urban Surfaces, Wind Tunnel.

43

44 I. Introduction

45 In a polluted atmosphere or during transit of a plume containing stable or radioactive pollutants, and in the
46 absence of rainfall events, dry deposition is the only transfer pathway from the air to the surface for
47 particles and pollutants. At present, this dry deposition has been studied especially on natural surfaces
48 representing the first link in the human food chain, but very little in the urban environment (Kelly, 1987;
49 Fowler *et al.*, 2009). However, a significant portion of the human population is concentrated in the urban
50 environment, and in the case of passage of a radioactive plume, the quantity of radionuclides deposited
51 by aerosols must be taken into account in estimating the dose rates received by the population (Kelly,
52 1987). Precise assessment of the transfer of pollutants by dry deposition of aerosols can thus be very
53 important, and the lack of significant data for the urban environment is now acknowledged. Dry deposition
54 of aerosols depends on the aerosol diameter, the deposition surface (the roughness and temperature, for
55 example) and the turbulence conditions (Sehmel, 1980). Therefore aerosols do not deposit
56 homogeneously in the urban environment. In the case of radioactive pollutants, this deposition must be
57 studied for various surfaces, on a wall or street level, and not for an urban canopy, on a neighbourhood or
58 city level, because the distribution of the deposits must be known precisely to assess the doses received
59 by the residents. The dry deposition velocity is the coefficient used to quantify the transfer of aerosol
60 particles by dry deposition in the environment. Most of the measurements of dry deposition velocities on
61 urban surfaces in urban environments were conducted by Roed (1983, 1985, 1987) as a result of the
62 fallout from nuclear tests and the Chernobyl accident, and by Pesava *et al.* (1999) and Maro *et al.* (2010)
63 with a tracer aerosol generated *in situ*. However, these deposition velocities are not associated with
64 precise measurements of turbulence or local meteorology. Presently, there are very few experimental
65 data related to turbulent parameters for urban environments and surfaces. As a result there are significant
66 uncertainties in the use of predictive models of deposition for this environment (Fowler *et al.*, 2009).
67 Urban environments are complex and heterogeneous from the point of view of the turbulence and
68 measurements under simple conditions should aid in understanding the deposition processes and
69 quantifying deposition velocities on urban surfaces. The wind tunnel is an advantageous tool. It can be
70 used as an initial approach to quantifying dry deposition velocities as a function of a restricted number of
71 controlled parameters and reproducible experiments can be conducted. Dry deposition has already been
72 the subject of wind tunnel studies, on natural surfaces (Chamberlain, 1967) or on smooth and rough
73 substrates (Liu and Agarwal, 1974; Horvath *et al.*, 1996; Toprak *et al.*, 1997; Dai *et al.*, 2001), but rather
74 for micron particles. However, the accumulation mode of the atmospheric aerosol ($0.1 \mu\text{m} \leq d_p \leq 1 \mu\text{m}$) is

75 the mode that is the primary vector for chemical pollutants and radionuclides. It is the mode on which the
76 surface distribution of the atmospheric aerosol is centred (Gründel and Porstendörfer, 2004; Van
77 Dingenen *et al.*, 2004; Papastefanou, 2008). Moreover, it transports these pollutants over large distances
78 from a source to the urban environments, due to a relatively long residence time in the atmosphere
79 (Jaenicke, 1988; Papastefanou, 2006). While the deposition of particles greater than a micrometre most
80 often studied is strongly affected by sedimentation, deposition of submicron aerosols, which are less
81 studied, results from the contribution of several physical processes (Brownian diffusion, impaction,
82 interception). The main objective of this study is to quantify dry deposition velocities of a submicron
83 aerosol on horizontal and vertical urban surfaces, for several wind speeds and under isothermal
84 conditions in the wind tunnel. Various turbulent boundary layer conditions are thus encountered. These
85 turbulence conditions associated with the dry deposition velocities are quantified by hot wire anemometer
86 measurements and focus especially on determination of the friction velocities. Finally, the data from this
87 study are compared to data in the literature and to operational models, solved analytically, developed for
88 smooth surfaces (Lai and Nazaroff, 2000) and natural canopies (Zhang *et al.*, 2001).

89 II. Experimental setup

90 *II.1 The wind tunnel and the studied surfaces*

91 The experiments were conducted in a recirculating wind tunnel of the IRPHE (University of Aix-Marseille,
92 campus of Luminy, Marseille, France). The experimental test section is a glass channel with a stainless
93 steel base 8650 mm long and a cross-section 280 mm high and 640 mm width. Airflow speeds between
94 0.5 and 19 m s⁻¹ can be generated. Deposition was studied on horizontal conventional glass surfaces,
95 cement facing and synthetic grass in a first experimental campaign (Fig. 1.a), then on vertical
96 conventional glass and cement facing surfaces in a second campaign (Fig. 1.b). The commercial names
97 of the materials and the roughness parameters of the cement facing (Flori *et al.*, 2007) and synthetic
98 grass are listed in Table 1. The roughness parameters of the cement facing measured by laser roughness
99 measurements are the arithmetic mean deviation of the profile R_a , the standard deviation of the profile R_q ,
100 the valley depth of the profile R_v and the peak height of the profile R_p . The synthetic grass is composed of
101 primary straight blades grouped into tufts, and thinner and shorter curly blades included in the canopy to
102 make it denser. The parameters characterising the synthetic grass were determined by the authors for the
103 primary straight blades and are the average canopy height h_c , the length of the straight blades l_b , the
104 width of these blades w_b , the number of tufts per square metre n_t and the number of straight blades per

105 square metre n_b . During the experiments on horizontal surfaces, the bottom of the test section was
 106 successively completely covered by each type of surface to develop the boundary layers and turbulence
 107 conditions characteristic of each surface.

108 Table 1: characteristics of the studied surfaces.

	Conventional glass	Cement facing	Synthetic grass
Commercial name	Planilux®, Saint-Gobain	Fema®-Therm-Mineralputz 5 mm	"Romana"
Roughness parameters	Glass thickness = 4 mm	$R_a = 0.57$ mm $R_q = 0.74$ mm $R_v = 2.36$ mm $R_p = 1.86$ mm	$h_c = 34 \pm 2$ mm $l_b = 38.4 \pm 1.9$ mm $w_b = 1.2 \pm 0.1$ mm $n_t = 10364$ m ⁻² $n_b = 164675$ m ⁻²

109
 110 In the same way, a vertical wall of the test section was successively covered with conventional glass and
 111 cement facing, to measure deposition on a vertical wall. It should be noted that glass cover the walls in
 112 the form of a pavement of square plates 200 mm on a side, while the cement facing and synthetic grass
 113 covered the wind tunnel homogeneously and continuously. To study deposition over a broad range of
 114 wind speeds that can be encountered in the urban environments, airflows of speeds u_{ref} of 1.3, 5.0 and
 115 9.9 m s⁻¹ were generated in the test section. The turbulence was quantified above all the horizontal
 116 surfaces.

117 **II.2 Quantification of the dry deposition velocity V_d**

118 The dry deposition velocity V_d (m s⁻¹) of an aerosol is defined by Chamberlain and Chadwick (1953, in
 119 Sehmel, 1980) as the ratio of the surface flux of dry deposition F (kg m⁻² s⁻¹; by convention a deposition
 120 flux is negative) by the average concentration of the aerosol in the air C (kg m⁻³) at a given height (1).

$$V_d = \frac{-F}{C} \quad (1)$$

121 A common approach to measure dry deposition velocities is to use a stable or radioactive chemical tracer
 122 for the studied aerosol. This method has the advantage of directly measuring a quantity of tracer, and
 123 thus of particles, in number or in mass. The deposition flux F is calculated according to (2), $M_{substrate}$ (kg) is
 124 the mass of tracer, $A_{substrate}$ (m²) is the total surface of the substrate sample, and t (s) is the duration of the
 125 experiment.

$$-F = \frac{M_{\text{substrate}}}{A_{\text{substrate}} t} \quad (2)$$

126 The average concentration C is calculated according to (3), with M_{filter} (kg) the mass of tracer collected on
 127 the filter with an airflow rate Q_{filter} ($\text{m}^3 \text{s}^{-1}$) over the same duration t .

$$C = \frac{M_{\text{filter}}}{Q_{\text{filter}} t} \quad (3)$$

128 A slightly polydispersed monomodal submicron dry fluorescein aerosol (uranine, $\rho = 1500 \text{ kg m}^{-3}$)
 129 generated with a pneumatic generator is used as a tracer. The operating principle of this generator is
 130 described in French standard NF X 44-011. A fluorescein solution is nebulised, the produced droplets are
 131 sorted by centripetal filters, then entrained and dried by a dry air flow to obtain a dry solid fluorescein
 132 aerosol. The granulometric mass distribution of this aerosol was measured by three samplings with a
 133 Dekati (LPI) low pressure cascade impactor (separation of the particles over 12 stages of cutoff diameters
 134 between 24 nm and 9.55 μm) and gave on average an aerodynamic mass median diameter d_{amm} of
 135 $0.27 \pm 0.07 \mu\text{m}$ with a geometric standard deviation of 2.06 ± 0.23 (Fig. 2). The air recirculation in the
 136 wind tunnel allows to generate particles only for the first two minutes of the experiment and to let the
 137 concentration to decrease with time until the end of the experiment. Substrate samples are removed at
 138 the end of the fifteen minutes of the experiment. The generated aerosol is introduced at the outlet of the
 139 test section to be mixed with air in the recirculation section of the wind tunnel so that its concentration will
 140 be homogeneous over the test section inlet. It is injected at the centre of the cross-section with a
 141 horizontal copper injection nozzle regularly pierced along a line oriented toward the outlet duct with an
 142 airflow rate of $10.8 \text{ m}^3 \text{ h}^{-1}$. Finally, the air in the test section is renewed between experiments by
 143 extracting air towards the exterior. The dry deposition fluxes are measured by exposure of samples
 144 (square plates 200 mm on a side composed of the studied substrates) to the fluorescein aerosols for a
 145 the experiment time. Samples are used for several experiments. After they are rinsed with distilled water
 146 and dried at room temperature, the substrates are placed in the test section with great care so as not to
 147 pollute them with fluorescein deposited on the walls of the test section. The static electrical charge is
 148 consistently removed from the synthetic grass samples by spraying the blades with denatured ethanol.
 149 The charge state of these specimens is then checked with a fieldmeter (Eltex EMF 58). During the
 150 experiments on horizontal substrates, three rows of three samples placed across the width of the test
 151 section are incorporated into the substrate studied at various distances from the test section inlet. These
 152 distances from the inlet are also called "fetch" (m). The edges of these specimens adjoin the substrate
 153 surfaces covering the base of the test section. The leading edges of each row of samples are located at

154 1.0, 5.0 and 6.8 m from the inlet. Each type of substrate is studied separately, as the base of the section
155 is completely covered by a single type of substrate. To measure dry deposition velocities on vertical
156 surfaces, the vertical wall used is covered in the same way with the studied substrate, from the test
157 section inlet to 6 m inside the test section. Three samples are intercalated lengthwise into this vertical
158 wall, with leading edges at 4.8, 5.0 and 5.2 m, to measure the dry deposition fluxes. These specimens are
159 centred in height, 40 mm from the base of the test section. In parallel, samples are taken on cellulose
160 filters (Whatman 1440-047) throughout the exposure time of the specimens to the aerosol in order to
161 quantify its concentration in the air of the test section. Bent copper sampling tubes with a 10 mm inside
162 diameter are introduced from the top of the section so as not to perturb the flow above the studied
163 surfaces and connected to filter holders with 500 mm long fluoroelastomer tubing. During the experiments
164 on horizontal substrates, three samples are taken on filters 10 mm above the surface halfway across the
165 test section, downstream of the specimens, with the inlet of the tube just behind each row of samples
166 (fetch = 1.2, 5.2 and 7.0 m) so as not to perturb the flow over the specimens and thus not to perturb
167 deposition. Likewise, for the experiments on vertical substrates, a sample is taken on a filter just behind
168 the third specimen, 10 mm from the wall, halfway up the test section. In each experiment, a sample is
169 taken on a filter at the centre of the test section, 5.2 m from its entrance, to control *a posteriori* the
170 homogeneity of the particle concentration in the air in the section during the experiment. Collection flow
171 rates are between 7.6 and 8.6 L min⁻¹ and are checked with a TSI 4000 Series mass flowmeter. The
172 samples and filters are carefully removed, wrapped in aluminium foil to avoid any pollution, and then
173 treated for measurement. Fluorescein is hydrophilic, thus the deposited particles are dissolved simply by
174 rinsing the surface with a pH 9 solution of ammonia water using a syringe (with successive rinsings with
175 the same solution for the glass and cement facing) or directly by soaking (synthetic grass). The filters are
176 immersed directly in the ammonia water to dissolve the filtered fluorescein particles. These solutions are
177 measured with a fluorescence spectrometer (Jobin Yvon Horiba FluoroMax-3) to determine $M_{\text{substrate}}$ and
178 M_{filter} . The background fluorescence of each type of surface is subtracted from the measurement result.
179 Experiments are conducted at least twice to ensure their repeatability.

180 ***II.3 Estimation of the turbulent parameters***

181 In the wind tunnel, in the absence of heat exchange on the studied surface, the turbulent parameter
182 mainly associated with V_d is the friction velocity u_* (m s⁻¹) because it quantifies mechanical turbulence that
183 enhances the aerosol deposition. Also, it is one of the parameters necessary in modelling V_d in confined
184 environments (Lai and Nazaroff, 2000) or *in situ* (Zhang *et al.*, 2001). It quantifies the turbulence

185 generated by shear of a flow over a surface and is used as a reference velocity near the wall. The friction
 186 velocity is estimated with (4) by measuring τ_p ($\text{kg m}^{-1} \text{s}^{-2}$), the frictional or shear stress at the wall, with ρ
 187 (kg m^{-3}) the fluid density.

$$u_* = \sqrt{\frac{\tau_p}{\rho}} \quad (4)$$

188 It can also be estimated with (5) using velocity profile measurements above the surface.

$$\frac{u(z)}{u_*} = \frac{1}{\kappa} \ln \frac{z-d}{z_0} \quad (5)$$

$$\frac{u(z)}{u_*} = \frac{1}{\kappa} \ln \frac{z-d}{k_s} + B \quad (6)$$

189 In (5), $u(z)$ (m s^{-1}) is the mean velocity in the flow direction measured at the vertical position z (m), and
 190 κ (0.4), d (m) and z_0 (m) are respectively the Von Karman constant, the displacement height and the
 191 aerodynamic roughness height. The friction velocity can be estimated by fitting this relation in the
 192 logarithmic overlap area of the velocity profile of a developed turbulent boundary layer; u_* , d and z_0 are
 193 then the parameters to be fitted. The aerodynamic roughness height is flow-dependent for dynamically
 194 smooth flows and depends on roughness geometry for fully rough flows (Raupach *et al.*, 1991). For
 195 synthetic grass, z_0 is equal to $0.13h_c$ (Tanner and Pelton, 1960, Stanhill, 1969 in Raupach *et al.*, 1991).
 196 For cement facing, z_0 , is determined from (5) and (6), and equal to $k_s \exp(-B\kappa)$ ($B = 8.5$; Schlichting, 1968),
 197 with $k_s = R_v + R_p$. For glass, d is equal to zero and z_0 can vary. The relative turbulence intensity I (%) is
 198 another dimensionless magnitude that quantifies the turbulent agitation (u' , w') of a flow by comparison to
 199 the average motion (\bar{u}) at a distance z from the wall. The relative turbulence intensities for the
 200 components u and w (I_u and I_w) can be calculated according to (7.a) and (7.b).

$$I_u = \frac{\sqrt{\overline{u'^2}}}{\bar{u}} ; I_w = \frac{\sqrt{\overline{w'^2}}}{\bar{u}} \quad (7.a); (7.b)$$

201 With this magnitude, turbulence can be classified into three categories: low (1%), medium (10%) and high
 202 (20% and more). The turbulent parameters were estimated in absence of aerosol injection for horizontal
 203 surfaces using hot-wire anemometry operating at high frequency. The system used is a probe with two
 204 crossed hot wires (type 55P61) combined with a *Streamline* anemometry system (Dantec Dynamics). It
 205 measures u , the horizontal component of velocity in the flow direction, and w , the vertical component, at
 206 high frequencies (2.5 kHz for $u_{\text{ref}} = 1.3 \text{ m s}^{-1}$ and 10 kHz for $u_{\text{ref}} = 5.0$ and 9.9 m s^{-1} , u_{ref} measured at the
 207 center of the test section of the wind tunnel) with a 50 seconds acquisition duration in each position.

208 These turbulence measurements were conducted above each surface type for each u_{ref} and for each
 209 fetch above the centre of the central substrate sample, by vertical profiles of 40 points between
 210 $z = 2.5$ mm and $z = 200$ mm above the roughnesses of the surfaces.

211 III. Results and discussions

212 III.1 Dry deposition velocities V_d

213 The measured concentrations of aerosols in the air show no significant difference between the sample in
 214 the centre of the test section and samples 10 mm from the walls during the experiments (median
 215 deviation of 6.6%) and show homogenisation of the aerosol concentration in the air recirculation circuit of
 216 the wind tunnel. The average dry deposition velocities on each type of horizontal surface are calculated
 217 from the deposition fluxes at 1.0, 5.0 and 6.8 m from the test section inlet and the associated
 218 concentrations for each flow speed. They show neither variation with the fetch, nor a notable difference
 219 between the specimens at the centre of the row and those on the sides. The average dry deposition
 220 velocities calculated for each type of surface, horizontal and vertical, and for each airflow speed u_{ref} are
 221 shown in Table 2 and Fig. 3. The dry deposition velocities measured on horizontal surfaces vary from
 222 $1.2 \cdot 10^{-5} \text{ m s}^{-1}$ on conventional glass for $u_{ref} = 1.3 \text{ m s}^{-1}$, to $1.4 \cdot 10^{-3} \text{ m s}^{-1}$ on synthetic grass for
 223 $u_{ref} = 9.9 \text{ m s}^{-1}$. Thus there is a factor of over two orders of magnitude between the lowest and highest
 224 values measured on these urban surfaces.

225 Table 2: average V_d as a function of u_{ref} .

$u_{ref} \text{ (m s}^{-1}\text{)}$	$V_d \text{ (x } 10^{-5} \text{ m s}^{-1}\text{)}$				
	Glass		Cement facing		Synthetic grass
	Horizontal	Vertical	Horizontal	Vertical	
1.3	1.4 ± 0.4		2.2 ± 0.9	1.4 ± 0.3	28.1 ± 8.4
5.0	2.3 ± 1.3	1.1 ± 0.4	4.8 ± 1.8	3.6 ± 0.7	54.6 ± 19.3
9.9	4.5 ± 2.0	2.4 ± 0.3	7.2 ± 1.6	8.0 ± 2.0	124.7 ± 29.6

226
 227 Those measured on vertical surfaces vary from $1.1 \cdot 10^{-5} \text{ m s}^{-1}$ on conventional glass for $u_{ref} = 5.0 \text{ m s}^{-1}$ to
 228 $8.0 \cdot 10^{-5} \text{ m s}^{-1}$ on cement facing for $u_{ref} = 9.9 \text{ m s}^{-1}$. The dry deposition velocity V_d could not be measured
 229 on vertical conventional glass for $u_{ref} = 1.3 \text{ m s}^{-1}$ during the experimental campaign.

230 **III.2 Turbulent parameters**

231 Aerodynamic parameters determined by hot wire measurements are listed in Table 3. All the developed
232 boundary layers are turbulent at fetches of 1.1, 5.1 and 6.9 m, with a transition zone to the logarithmic
233 profile (Fig. 4). The friction velocities are determined by fitting the logarithmic relation (5) to the mean
234 velocity profiles. The estimated friction velocities decrease for an increasing fetch. This variation is
235 consistent with the reduction in the stress at the wall τ_p upon development of a completely turbulent
236 boundary layer (Antonia and Luxton, 1971). The representation of the profiles in terms of dimensionless
237 velocity $(u + \Delta u)^+$ and dimensionless vertical position $(z + d)^+$ ($u^+ = u / u_*$; $z^+ = z u_* / \nu$, with ν the kinematic
238 viscosity of air) and the mean velocity shifts values Δu , with $\Delta u = \ln z_0^+ + C$ ($C = 5$), show the different
239 rough regimes of the flows generated by each surface type at each u_{ref} (Krogstad and Antonia, 1999).
240 The profiles of I_u and I_w were calculated using (7.a) and (7.b), and profiles of I_w are shown in Fig. 5. All the
241 profiles over u and w have the same shape, with a maximum I_{wmax} in the immediate vicinity of the surface.
242 The calculated values are shown in Table 3. For equal u_{ref} , the values of I_{umax} and I_{wmax} are higher for
243 synthetic grass than for cement facing, and higher for cement facing than for glass, with I_{umax} greater than
244 I_{wmax} . These observations are consistent with the observations of Antonia and Luxton (1971) for a
245 boundary layer on a rough surface. Unlike the friction velocities, these relative turbulence intensities show
246 no notable decrease as a function of the fetch but are essentially constant at each fetch for the same
247 surface at the same flow speed.

248 **III.3 Discussions**

249 The average deposition velocities for each type of surface and each u_{ref} (Table 2) have been compared to
250 the data of the literature (Fig. 6). The deposition velocities measured in this study are of the same order of
251 magnitude as those in the literature for smooth surfaces and grass. The absence of data on the geometry
252 of the surface roughnesses studied by Toprak et al. (1997) makes it impossible to understand the
253 differences in the measured V_d . The dry deposition velocities vary with the mean air flow speed, the
254 surface type and the orientation of the surface. On horizontal surfaces, V_d varies on average by a factor of
255 1.7 and 23.7 respectively between conventional glass and cement facing and between conventional glass
256 and synthetic grass, and by a factor of 1.9 and 3.6 between $u_{ref} = 1.3 \text{ m s}^{-1}$ and $u_{ref} = 5.0 \text{ m s}^{-1}$ and
257 between $u_{ref} = 1.3 \text{ m s}^{-1}$ and $u_{ref} = 9.9 \text{ m s}^{-1}$ respectively.

258

Table 3: aerodynamic parameters for each surface as a function of u_{ref} and the fetch.

Fetch (m)	u_{ref} ($m s^{-1}$)	Conventional glass					Cement facing						Synthetic grass					
		V_d (10^{-4} $m s^{-1}$)	u^* ($m s^{-1}$)	z_0 (10^{-2} mm)	I_{umax} (%)	I_{wmax} (%)	V_d (10^{-4} $m s^{-1}$)	u^* ($m s^{-1}$)	z_0 (10^{-2} mm)	d (mm)	I_{umax} (%)	I_{wmax} (%)	V_d (10^{-4} $m s^{-1}$)	u^* ($m s^{-1}$)	z_0 (mm)	d (mm)	I_{umax} (%)	I_{wmax} (%)
1.1		1.7					3.1						3.3	0.17	4.4	23.9	38.3	18.7
5.1	1.3	1.2	0.06	8.5	25.4	7.2	1.9	0.07	0.1	5.6	25.8	7.4	2.6	0.13	4.4	20.9	33.5	14.9
6.9		1.1	0.06	8.7	24.7	7.5	1.8	0.07	0.1	4.5	26.8	7.0	2.6	0.13	4.4	16.1	35.3	16.6
1.1		2.8	0.26	9.9	23.6	10.1	4.9	0.33	0.1	6.4	21.2	11.0	7.0	0.67	4.4	24.0	44.7	23.7
5.1	5.0	1.4	0.23	4.2	21.2	8.7	4.3	0.29	0.1	4.0	24.3	10.1	5.8	0.52	4.4	17.6	47.6	24.9
6.9		2.2	0.20	1.9	21.2	8.1	5.2	0.27	0.1	2.5	24.0	10.2	3.9	0.56	4.4	13.1	42.5	23.4
1.1		5.6	0.50	5.9	19.1	9.3	7.6	0.66	0.1	5.1	22.8	11.7	13.1	1.37	4.4	24.0	46.6	26.0
5.1	9.9	2.9	0.46	3.1	18.7	8.6	6.5	0.54	0.1	4.0	23.5	10.5	12.1	1.06	4.4	15.6	44.7	25.6
6.9		6.3	0.38	1.5	16.9	8.9	7.4	0.54	0.1	2.8	25.4	11.2	12.1	1.05	4.4	9.0	44.6	24.8

262

263 These results show the importance of turbulent processes of interception and impaction for this size
264 range of particles, dependent respectively on the sizes of the aerosol and the obstacle, and on the Stokes
265 number (itself dependent on the relaxation time of the aerosol, the flow speed and the size of the
266 obstacle). Moreover, the measured differences in deposition velocities between horizontal and vertical
267 walls, conventional glass and cement facing are on the order of the sedimentation velocity for the
268 fluorescein aerosol calculated with (7) from the distribution of Fig 2.

$$V_s = \sum_{i=1}^{12} \frac{d_{pi}^2 g C_{ui} \rho}{18\nu} m_{ni} = 1.10 \pm 0.37 \cdot 10^{-5} \text{ m s}^{-1} \quad (7)$$

269 Here, g is the gravitational acceleration (9.81 m s^{-2}), ρ is the density of the particles (1000 kg m^{-3} for
270 aerodynamic diameters determined with a cascade impactor,) C_{ui} is the Cunningham correctional factor
271 for the aerosol of diameter d_{pi} (geometric diameter of stage i of the cascade impactor), ν is the kinematic
272 viscosity of air ($1.5 \cdot 10^{-5} \text{ m}^2 \text{ s}^{-1}$) and m_{ni} is the fluorescein mass on stage i normalised to the total mass of
273 fluorescein collected on the 12 stages. For low wind speeds, the contribution of sedimentation to
274 deposition of this fluorescein aerosol is therefore non-negligible, contrary to what is usually believed for
275 submicron aerosols. It can double the deposition velocity between a vertical wall and a horizontal wall, or
276 even represent the entire deposit on a smooth horizontal wall for a low wind speed, as for glass with
277 $u_{ref} = 1.3 \text{ m s}^{-1}$. It should also be noted that deposition velocities on horizontal and vertical cement facing
278 are approximately equal at $u_{ref} = 9.9 \text{ m s}^{-1}$. As the deposition flux depends on the vertical wind speed and
279 its fluctuations, the deposition velocity V_d is shown in Fig. 7 as a function of the maximum relative
280 turbulence intensity over w , I_{wmax} . An increase in deposition flux with turbulence intensity was already
281 observed by Dai *et al.* (2001) for a smooth surface. Our graph shows a variation in V_d as a function of I_{wmax}
282 independent of a particular type of surface. This observation is of interest as it represents V_d as a function
283 of a single turbulent parameter for several surface types.

284 The parameter usually related to V_d is the friction velocity u_* , as it quantifies the turbulence in a boundary
285 layer. It is one of the main parameters used in the deposition models developed for inside and outside
286 environments. The calculated deposition velocities for the polydispersed fluorescein aerosol with the
287 models of Lai and Nazaroff (2000) and of Zhang *et al.* (2001) (with zero aerodynamic resistance, because
288 the concentration above the surface is consistent with that measured in the centre of the test section),
289 and the data of this study are shown as a function of u_* in Fig. 8. The friction velocities of the vertical
290 surfaces associated with the V_d are those estimated for the same horizontal surfaces and same u_{ref} at the

291 fetch 5.0 m. The model of Lai and Nazaroff (2000) correctly estimates the deposition velocities on glass
292 for u_* greater than 0.2 m s^{-1} , but seems to overestimate them below this for horizontal glass.

293 On the other hand, Zhang *et al.* (2001) systematically overestimate V_d on grass by more than a factor of
294 5. This resistive model uses Brownian diffusion as the principal deposition process for a submicron
295 aerosol deposition on grass and underestimates interception and impaction processes. By comparison,
296 the recent mechanistic model of Petroff *et al.* (2008) accords more importance to interception for this
297 aerosol size range. It is in a better agreement with Chamberlain (1967) data on grass in a wind tunnel for
298 micron and submicron aerosols than Zhang *et al.* (2001). This shows the limits of the operational model of
299 Zhang *et al.* (2001) in assessing V_d on grass precisely, and the need to either improve consideration of
300 turbulent processes in deposition on grass, or to estimate V_d from mechanistic models like that of Petroff
301 *et al.* (2008) that better account for these turbulent processes.

302 In the literature, dry deposition velocities measured *in situ* are generally normalised to u_* . In this case, the
303 sedimentation velocity V_s (7), a non-turbulent deposition process, must be subtracted from V_d . In recent
304 studies of transfers in natural environments, the ratio of V_d and u_* was found to be independent of the
305 various surfaces studied under neutral and stable conditions and approximately equal to $2 \cdot 10^{-3}$ (Damay,
306 2010; Donateo *et al.*, 2010). On the contrary, in this study, this ratio depends on the type of surface
307 (Fig. 9) and thus on the flow conditions and the structure of the boundary layer. It is therefore determined
308 by the importance of interception and impaction in the deposition process. The ratio is $5.3 \pm 4.1 \cdot 10^{-5}$ for
309 conventional glass, $1.5 \pm 0.6 \cdot 10^{-4}$ for cement facing, and $1.3 \pm 0.3 \cdot 10^{-3}$ for synthetic grass. The
310 experimental results are close to the estimate of the model of Lai and Nazaroff (2000) for glass
311 ($5.0 \pm 0.1 \cdot 10^{-5}$) and the *in situ* values of Damay (2010) on a grassland, $0.8 \cdot 10^{-3}$ and $1.6 \cdot 10^{-3}$ respectively
312 for $d_p = 0.20$ and $0.32 \mu\text{m}$, for synthetic grass.

313 In the urban canopy, in the urban sub-layer of the atmospheric boundary layer, measurable friction
314 velocity u_* in the boundary layers of the surfaces is not obvious. Use of u_* alone as a turbulent parameter
315 seems thus to be limited in modelling deposition on heterogeneous urban surfaces. As an initial
316 approach, in the context of operational models to give quick estimates of deposition velocities, wind
317 speed in the streets could turn out to be a good parameter, as it is easily measurable or modelled.

318 Empirical parameterisation of V_d as a linear function of u_{ref} for each type of surface according to the data
319 of Table 2 could be a good first approximation.

320 IV. Conclusions

321 Presently, there is little experimental data on dry deposition velocities for the urban environment. This
322 wind tunnel study was conducted to measure V_d and the associated turbulent parameters for a
323 polydispersed submicron aerosol on urban surfaces. The deposition velocity V_d was measured on three
324 urban surfaces types, horizontal and vertical, and for three flow speeds u_{ref} , and these data were
325 compared to the data of other authors. These deposition velocities show dependence on both u_{ref} and the
326 type of deposition surface, confirming the importance of the turbulent processes of interception and
327 impaction in deposition for an aerosol of this size. However, sedimentation is responsible for a large part
328 of the deposition for smooth horizontal surfaces and for low u_{ref} . The model of Lai and Nazaroff (2000)
329 correctly estimates V_d on glass, while Zhang *et al.* (2001) substantially overestimate it on grass. Finally,
330 this work reveals that parameterisation of V_d as a function of u_{ref} may be relevant for the urban
331 environment in an operational context.

332 This wind tunnel study treats only a limited number of parameters and types of surfaces. However, it
333 highlights the absence of a single parameterisation for the deposition velocity as a function of
334 aerodynamic parameters for smooth or rough surfaces. This absence is certainly due to the lack of
335 reported data with turbulent parameters and the lack of deposition experiments on rough walls, even for
336 simple roughness geometries. In the case of pollution by radionuclides, the disparity in the deposition
337 velocities about two orders of magnitude measured in this study shows the importance of a local estimate
338 of depositions in the urban canopy for each surface, rather than an estimate on the scale of entire
339 neighbourhoods. Finally, a wind tunnel study can only constitute a first step in studying dry deposition in
340 the urban environment and should be supplemented by *in situ* measurements.

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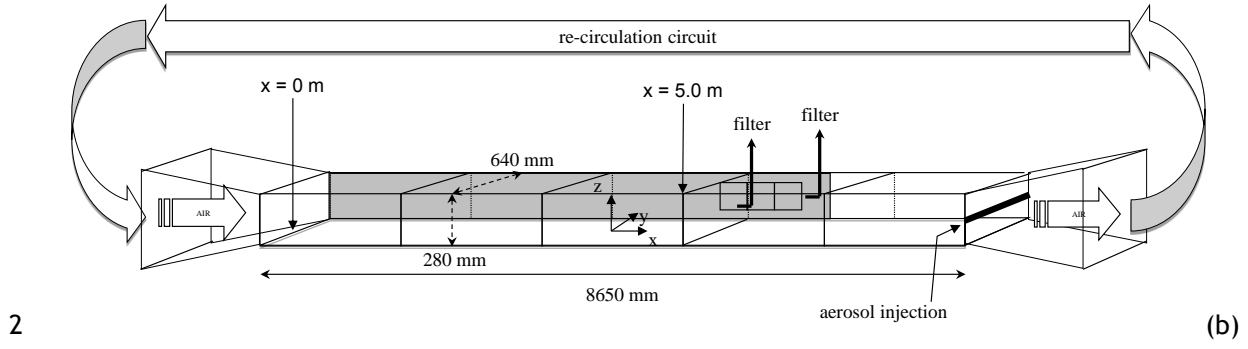
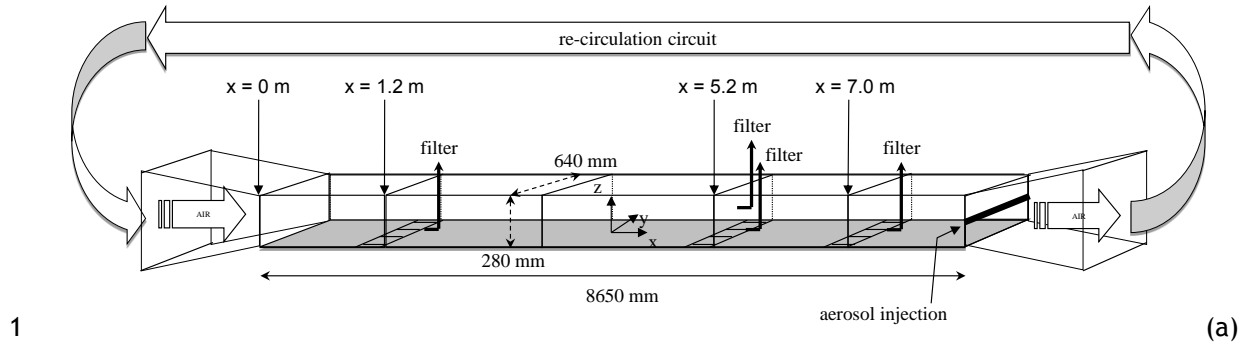
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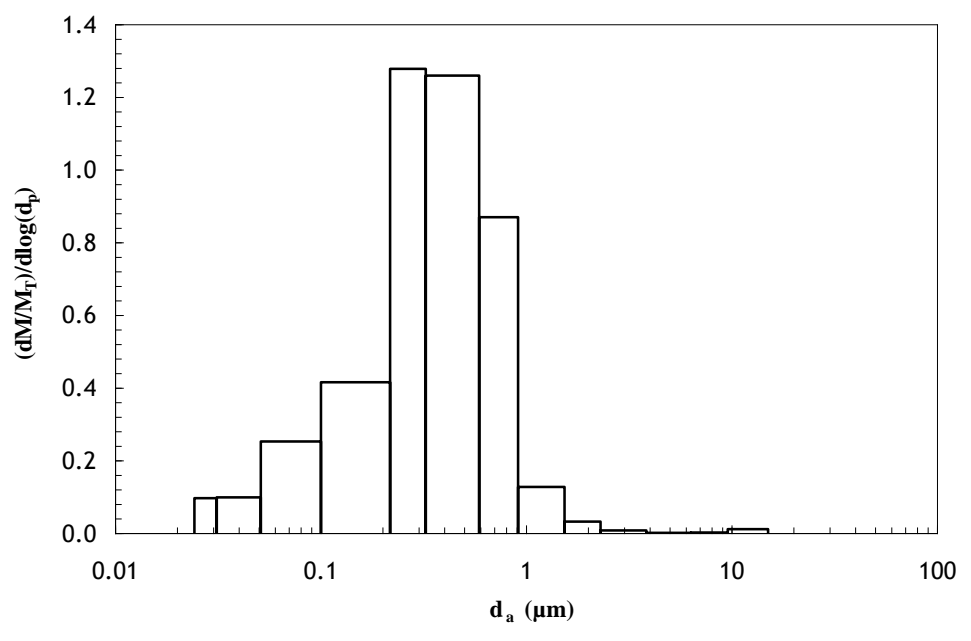
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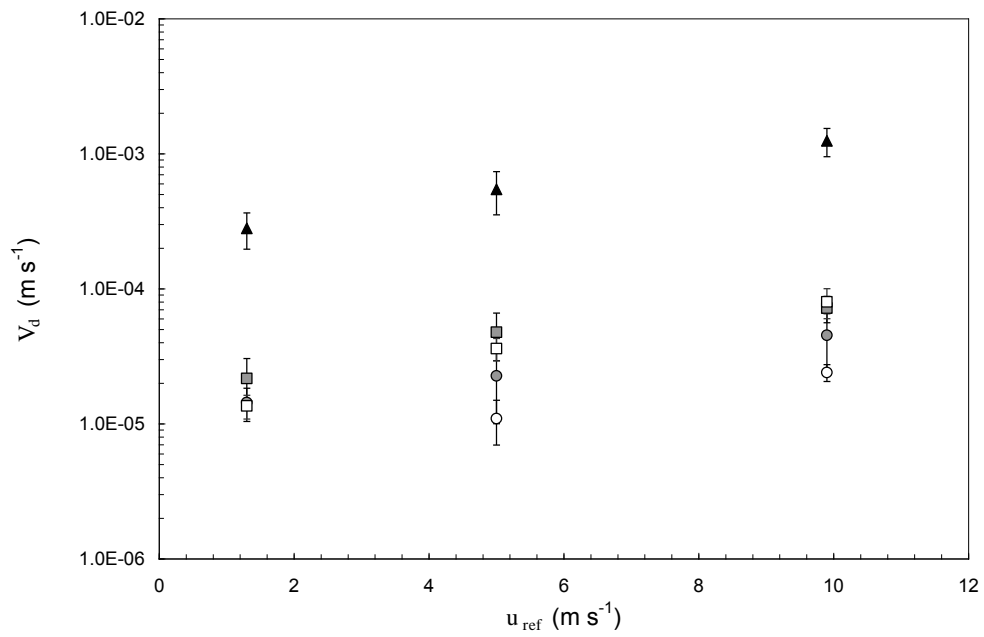
3 Fig. 1: illustrations of the wind tunnel configurations to study deposition on horizontal (a) and vertical (b)
4 walls; the studied surface is grey; the substrates samples are the grey squares.

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8 Fig. 2: normalised granulometric mass distribution of the fluorescein aerosol.

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12 Fig. 3: average V_d as a function of u_{ref} .

13 ● Horizontal conventional glass; ○ Vertical conventional glass;

14 ■ Horizontal cement facing; □ Vertical cement facing;

15 ▲ Synthetic grass.

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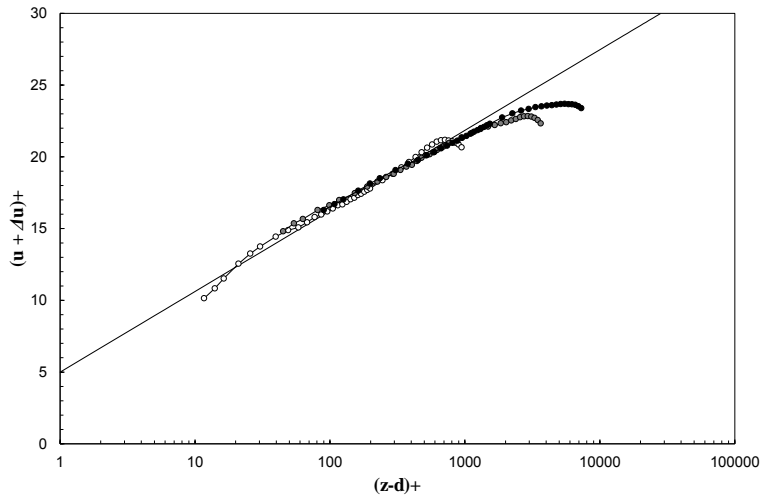
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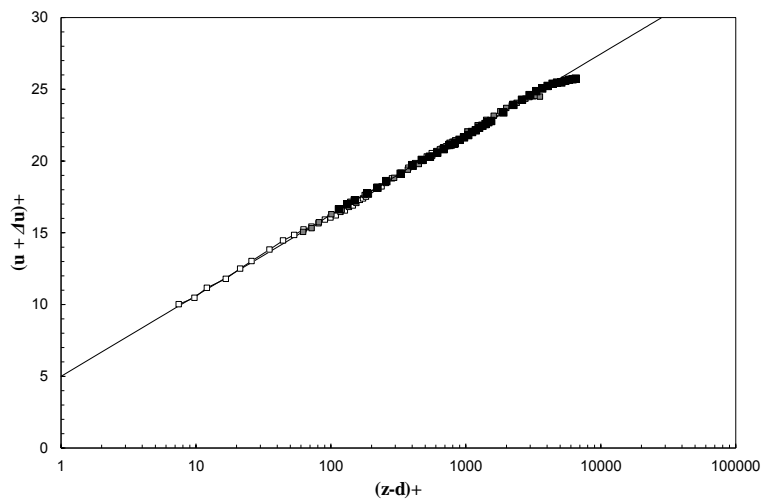
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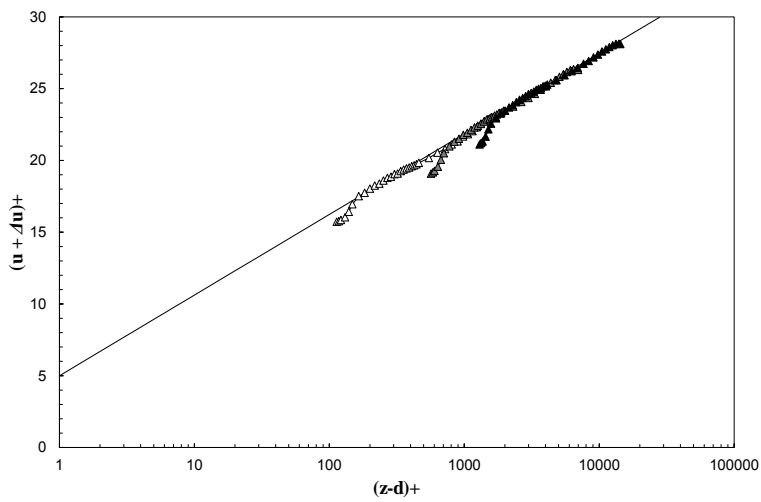
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26 a)



27 b)



28 c)

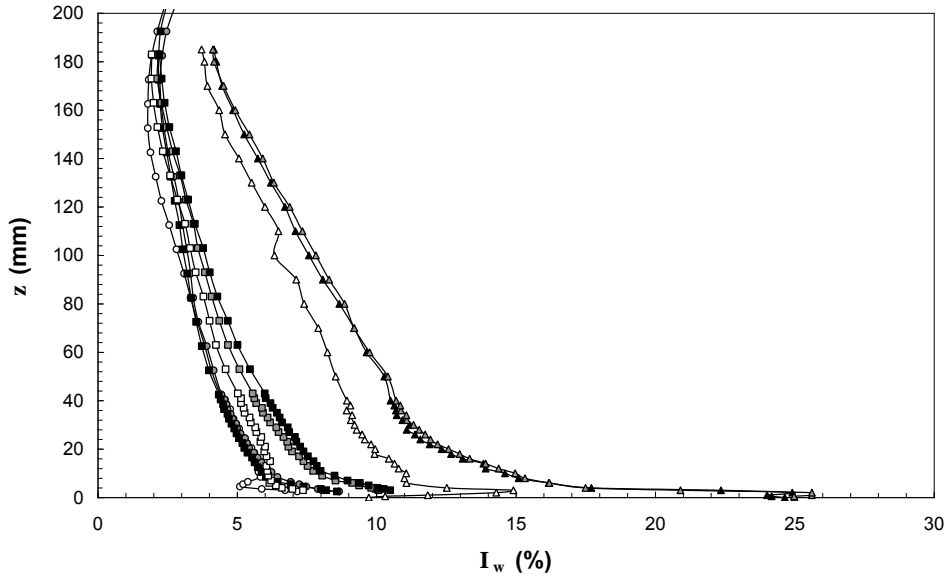
29 Fig. 4: u_+ as a function of z_+ for a fetch of 5.10 m for each type of surface and each u_{ref} .

30 a) Conventional glass: \circ $u_{ref} = 1.3 \text{ m s}^{-1}$; \odot $u_{ref} = 5.0 \text{ m s}^{-1}$; \bullet $u_{ref} = 9.9 \text{ m s}^{-1}$;

31 b) Cement facing: \square $u_{ref} = 1.3 \text{ m s}^{-1}$; \blacksquare $u_{ref} = 5.0 \text{ m s}^{-1}$; \blacksquare $u_{ref} = 9.9 \text{ m s}^{-1}$;

32 c) Synthetic grass: \triangle $u_{ref} = 1.3 \text{ m s}^{-1}$; \triangle $u_{ref} = 5.0 \text{ m s}^{-1}$; \blacktriangle $u_{ref} = 9.9 \text{ m s}^{-1}$.

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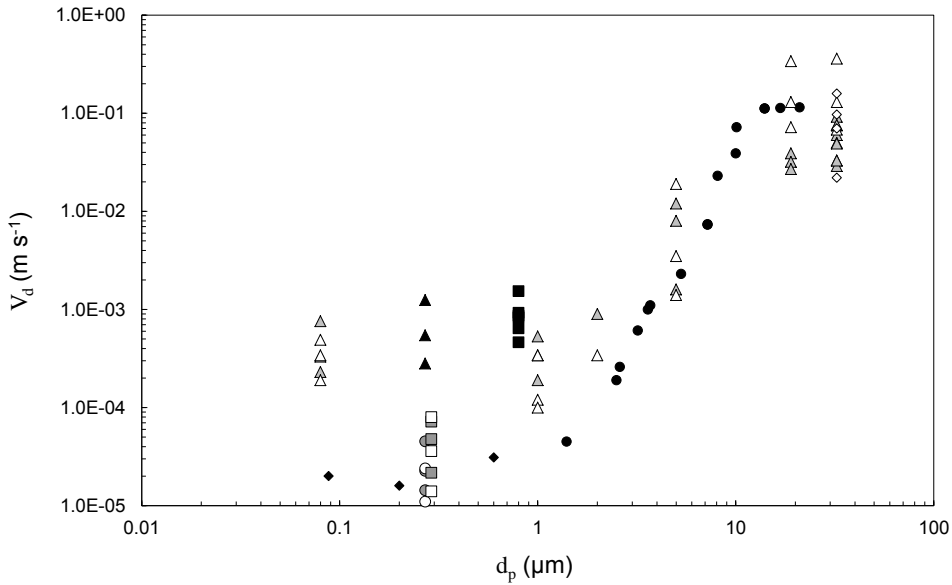
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35 Fig. 5: I_w as a function of z for a fetch of 5.10 m, for each surface type and each u_{ref} .

36 Conventional glass: \circ $u_{ref} = 1.3 \text{ m s}^{-1}$; \odot $u_{ref} = 5.0 \text{ m s}^{-1}$; \bullet $u_{ref} = 9.9 \text{ m s}^{-1}$;

37 Cement facing: \square $u_{ref} = 1.3 \text{ m s}^{-1}$; \blacksquare $u_{ref} = 5.0 \text{ m s}^{-1}$; \blacksquare $u_{ref} = 9.9 \text{ m s}^{-1}$;

38 Synthetic grass: \triangle $u_{ref} = 1.3 \text{ m s}^{-1}$; \blacktriangle $u_{ref} = 5.0 \text{ m s}^{-1}$; \blacktriangle $u_{ref} = 9.9 \text{ m s}^{-1}$.



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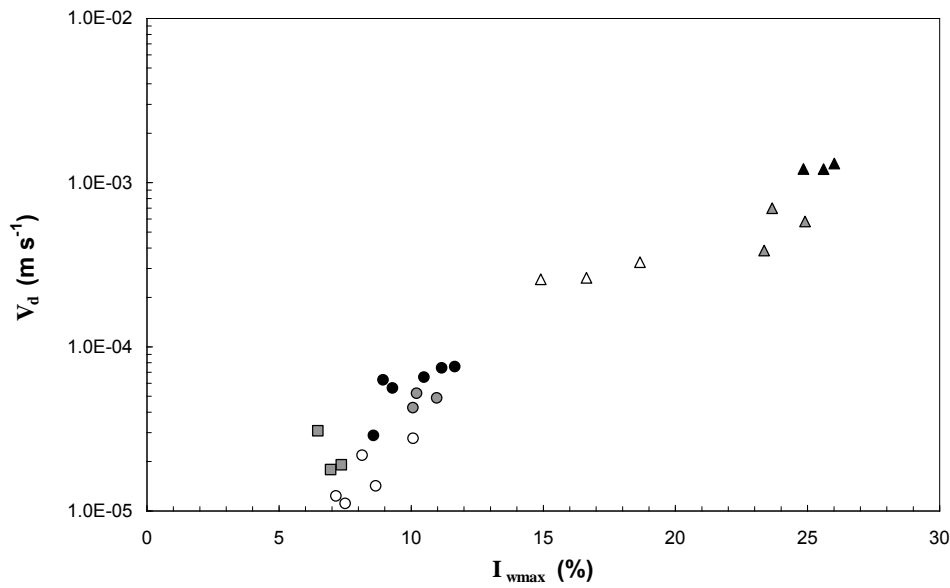
40 Fig. 6: mean V_d of this study and V_d from the literature as a function of d_p .

41 \bullet Vertical glass (Liu and Agarwal, 1974); \blacklozenge Glass (Horvath *et al.*, 1996); \diamond horizontal sticky rough glass
 42 (Chamberlain, 1967); \blacksquare Cement (Toprak *et al.*, 1997); \triangle Sticky artificial grass, \blacktriangle Real grass
 43 (Chamberlain, 1967);

44 This study: \odot Horizontal conventional glass; \circ Vertical conventional glass;

45 \blacksquare Horizontal cement facing; \square Vertical cement facing;

46 \blacktriangle Synthetic grass.



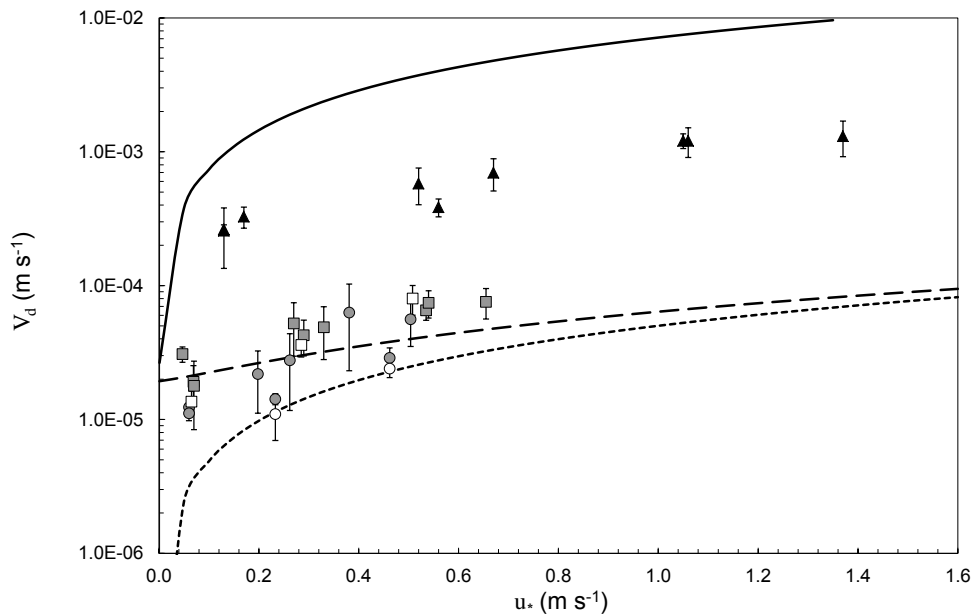
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48 Fig. 7: average V_d as a function of I_{wmax} for each type of surface.

49 Conventional glass: \circ $u_{ref} = 1.3 \text{ m s}^{-1}$; \bullet $u_{ref} = 5.0 \text{ m s}^{-1}$; \bullet $u_{ref} = 9.9 \text{ m s}^{-1}$;

50 Cement facing: \square $u_{ref} = 1.3 \text{ m s}^{-1}$; \blacksquare $u_{ref} = 5.0 \text{ m s}^{-1}$; \blacksquare $u_{ref} = 9.9 \text{ m s}^{-1}$;

51 Synthetic grass: \triangle $u_{ref} = 1.3 \text{ m s}^{-1}$; \triangle $u_{ref} = 5.0 \text{ m s}^{-1}$; \blacktriangle $u_{ref} = 9.9 \text{ m s}^{-1}$.



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53 Fig. 8: V_d as a function of u_* , comparison of model to measurements.

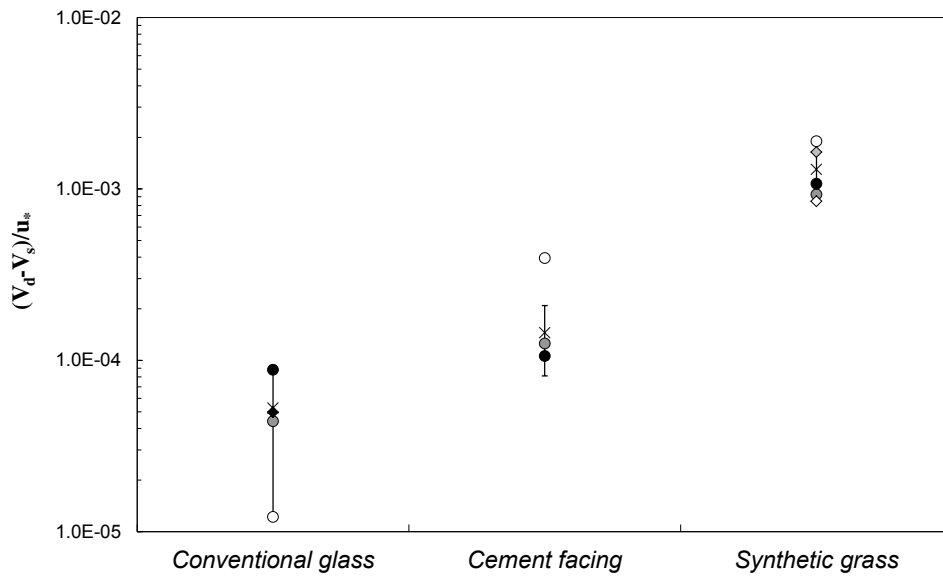
54 --- Horizontal smooth wall, - - - Vertical smooth wall (Lai and Nazaroff, 2000);

55 — Grass (Zhang *et al.*, 2001);

56 This study: \bullet Horizontal conventional glass; \circ Vertical conventional glass;

57 \blacksquare Horizontal cement facing; \square Vertical cement facing;

58 \blacktriangle Synthetic grass.



59

60 Fig. 9: $\frac{V_d - V_s}{u_*}$ ratios for each type of horizontal surface.

61 ◆ Smooth wall (Lai and Nazaroff, 2000);

62 ◇ Grass ($d_p = 0.202 \mu\text{m}$), ◇ Grass ($d_p = 0.316 \mu\text{m}$) (Damay, 2010);

63 This study: ○ $u_{ref} = 1.3 \text{ m s}^{-1}$; ● $u_{ref} = 5.0 \text{ m s}^{-1}$; ● $u_{ref} = 9.9 \text{ m s}^{-1}$; x mean on all u_{ref} for each surface.