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Determining $PM_{2.5}$ dry deposition velocity on plant leaves: An indirect experimental method

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ABSTRACT

Trees and green spaces have been proved to play an important role in purifying urban atmospheric particulate matter and result to the overall improvement of air quality. However, a primary setback was the need for an accurate and easier method to measure the deposition velocity (V_d) of $PM_{2.5}$ retained on plant leaves. This paper established an indirect method of measurement for determining V_d: the indirect method was derived from a closed system (smog chamber), and an exponential attenuation model was used to measure the decline in $PM_{2.5}$ concentration under conditions caused by hanging leaves in the chamber, and an empty chamber without leaves, respectively. The value of V_d was thus calculated by fitting data to prevent inaccurate results caused by a single measurement error. The experimental conditions such as initial concentration, test duration, and time interval (Δt) were then determined from empirical observations. The equation showed that V_d could be determined only by measuring the attenuation rate constant, k, and the leaf area, LA. Although the particle size, tested tree species and some other experimental conditions may affect the determination results of V_d, the values of V_d tested by indirect method were still within scientifically acceptable range. Overall, along with the traditional wind tunnel method, the indirect measurement is considered as the complement for a less expensive and easier way to determine V_d, and offers a novel idea that V_d might be gained by attenuation equation, and can augment the choices for researchers to quantify the ability of retaining particles.

1. Introduction

Atmospheric particulate matter, or atmospheric aerosols, is a primary airborne pollutant (Wang et al., 2015). Fine particulate matter ($PM_{2.5}$) is limited to a diametre less than or equal to 2.5 microns and lingers in the atmosphere due to its slow sedimentation rate. This, coupled with the ability for $PM_{2.5}$ to be transmitted over a long range, creates a serious threat to human health (Calderón-Garcidueñas et al., 2015).

Green spaces and urban forestry, as the primary biotic components of urban infrastructures, assist in the mitigation and deposition of exogenous atmospheric particulate matter and have critical roles in the overall influence of air quality (Willis and Petrokofsky, 2017; Escobedo et al., 2015), even though it also has been pointed out that vegetation can emit substances and degrade air quality under some circumstance (Eisenman et al., 2019). Plant leaves and branches, due to their microstructure on the surface, can directly intercept and retain large dust particles from the atmosphere, and areas rich in vegetation (tree belt, parks, etc.) reduce wind speeds, influence wind direction, and cause zones of recirculation, affecting both the settlement of air pollutants and the formation of secondary organic aerosol (SOA) (Liu and Zhang, 2015; Shi et al., 2018; Viippola et al., 2018). Numerous studies have already demonstrated the importance of dry deposition in the removal of airborne pollutant particles (Janhall, 2015; Fowler, 2002; Tong et al., 2015; Yang et al., 2015; Brantley et al., 2014; Sæbø et al., 2012; Mohan, 2016; Sun et al., 2014), and deposition flux (*F*) is described as Eq. (1):

$$F\ (\mu g\ /m^2/hr) = V_d \times C \tag{1}$$

where V_d is the deposition velocity (m/hr or cm/s) of particulate matter to a certain surface, which varies depending on surface roughness and surrounding environmental conditions, and C is the concentration of

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atmospheric particulate matter in a local environment (μg/m^3). Therefore, V_d could be used as a direct determinant of the ability for plants to remove atmospheric particulate matter (Freer-Smith et al., 2004).

A primary issue in this investigation was the need for a method to directly measure concentrations of $PM_{2.5}$ retained on plant leaves under realistic environmental conditions. As the dust found on leaf surfaces is often a mixture of miscellaneous coarse and fine particles, accurate measurements of $PM_{2.5}$ concentration were difficult to distinguish. Thus, the V_d of particulate matter pollutants maintained on the surfaces of plant leaves were measured using the Empirical Formula and Wind Tunnel Test (Huang et al., 2013). The Empirical Formula method utilized a simplified one-dimensional depositional model to calculate the V_d of atmospheric pollutants (Eq. (2)).

$$V_d = \frac{1}{R_{tot}} = \frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c} \tag{2}$$

where V_d is the reciprocal of resistance to deposition, R_{tot}, which equals the sum of the reciprocal aerodynamic resistance (R_a), boundary resistance (R_b), and surface resistance (R_c) of each transport process (Davidson and Wu, 1990). According to the UFORE model developed by Nowak (Nowak, 1994), the resistance parametres of PM_{10}, SO_2, NO_2 and CO were found in existing literature or measured using the empirical formula (Nowak and Crane, 2000; Nowak et al., 2008); the resuspension rate was set to 50% (Nowak and Crane, 2008).

However, in this study, the empirical formula was not applicable to the measurement of $PM_{2.5}$, and no significant parametre values were reported. Beckett and Freer-Smith utilized the Wind Tunnel Test to simulate $PM_{2.5}$ using NaCl as a tracer (Freer-Smith et al., 2004; Beckett et al., 2000). The V_d of eleven species of broadleaf trees and two species of coniferous trees were measured. Pullman measured the V_d of $PM_{2.5}$ and determined the resuspension rates for three coniferous species (*Pinus strobus*, *Taxus cuspidata*, and *Tsuga canadensis*) using KNO_3 as a tracer (Pullman, 2009). Nowak estimated the different levels of $PM_{2.5}$ deposited onto vegetation found in ten U.S. cities and assessed the implications of $PM_{2.5}$ pollution on human health.

A wind tunnel, as a kind of semi-enclosed or closed pipeline, is affected little by the surrounding conditions, thus is often applied to simulate the air flow that can be controlled on purpose. With regular maintenance, the quality of the air flow produced by wind tunnel is relatively stable, such as the uniformity of the velocity distribution, and the deviation of the mean direction of the flow along the axis of the wind tunnel. Despite its potential to be effective, the measurement of V_d for $PM_{2.5}$ found on plant leaves using the wind tunnel method still has some shortcomings, such as higher cost and the need for a larger place. Therefore, the smog chamber method is widely used in many fields and was effectively applied in many studies on air pollutant including plant-atmosphere boundary studies (Hwang et al., 2011), semiviolate organic compounds (Chandramouli et al., 2003), and aromatic hydrocarbons (Li et al., 2018). As smog chamber could simulate the omni-directional flow condition surrounding the tree leaves, which is more similar to the actual environmental circumstance. It is considered as an important complementary method of the wind tunnel.

Many studies introduced NaCl or KNO_3 as a tracer (particle diametre range from 0.8 to 1.2 μm), which was more focused the smaller sized part of $PM_{2.5}$. Because the concentration and mass of particles deposited on the leaves varied due to the differences in particle size, smaller particles were less frequently fixed on leaves, and the measured V_d were typically less than larger particles. As a result, fine salt particles could function more effectively as tracers for $PM_{1.0}$ than for $PM_{2.5}$, and larger sized part of $PM_{2.5}$ was also need to be considered.

In summary, V_d was used to directly measure the ability for vegetation to purify atmospheric $PM_{2.5}$ pollution, despite several shortcomings present in the current methodologies. Although wind tunnel simulation is currently recognized as the most accurate and up-to-date method for measuring V_d, the wind tunnel equipment was pricey, the procedure was demanding, and the fine salt particles as tracers significantly differed in size in comparison to the $PM_{2.5}$ particles. For these reasons, the original goal of this study was using smog chamber simulation and larger sized particles of $PM_{2.5}$, to develop an indirect method as a complement to accurately measure V_d, yield more reliable results, and be easily applicable during experimentation.

2. Materials and methods

2.1. Theoretical derivation of vd calculation

The wind tunnel provided an open system that could simulate both natural airflow and environmental conditions. Unlike this, the indirect method was derived from a closed system for experimentation. The indirect method of determining V_d was applied as follows: first $PM_{2.5}$ powder was deposited into a closed container (dubbed, the smog chamber), while it has been found that more pathlines were found to form in the smog chamber, which may help the particles to disperse more evenly (Hwang et al., 2011). Within the metal chamber, the concentration of $PM_{2.5}$ gradually declined, caused by the deposition and collision of the particles against the inner walls. This process can be described using the exponential attenuation model (Eq. (3))

$$y(t) = C_0 \bullet e^{-jt} \tag{3}$$

where *y(t)* is the concentration of $PM_{2.5}$ in the chamber at a given moment *t*, C_0 is the initial concentration of $PM_{2.5}$ (μg/m^3) in the smog chamber, and *j* is the attenuation rate constant (s^{-1}), only in relation to surrounding environmental conditions.

The leaf samples were washed until sufficiently clean and suspended in the chamber to dry, and the entire process was repeated. In the second trial, the concentration of $PM_{2.5}$ declined faster than observed in the first trial because the leaves increased the contact area of the particles in the chamber, resulting in faster deposition. This process can also be depicted by the exponential attenuation model (Eq. (4)):

$$z(t) = C_0 \bullet e^{-kt} \tag{4}$$

where *z(t)* is the concentration of $PM_{2.5}$ found in the chamber containing the suspended leaves at a given moment *t*, C_0 is the initial concentration of $PM_{2.5}$ in the chamber, and *k* is another attenuation rate constant under the given conditions.

These equations can be summarized graphically, as displayed in Fig. 1. The upper curve showed the concentration of $PM_{2.5}$ in the empty chamber (the control group), while the lower curve showed the concentration in the chamber containing the leaves (the experimental group). After a short period of time (Δt), $PM_{2.5}$ concentration in the chamber decreased to:

$$z(t + \Delta t) = C_0 \bullet e^{k(t+\Delta t)} \tag{5}$$

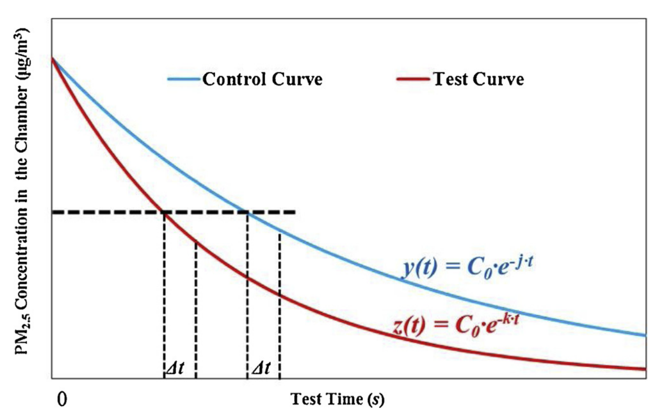

Fig. 1. Exponential decay curve of $PM_{2.5}$ concentration in the chamber with and without leaves.

For the control curve, the initial concentration of $PM_{2.5}$ was the same as that of the experimental curve, so $y(t')$ is set equal to $z(t)$.

$$y(t') = z(t)$$
$$C_0 \cdot e^{-j\cdot t'} = C_0 \cdot e^{-k\cdot t}$$
$$\text{Then } t' = kt/j \tag{6}$$

After a short period of time (Δt), the control curve was reduced to:

$$y(t' + \Delta t) = C_0 \cdot e^{-j(t'+\Delta t)} = C_0 \cdot e^{-k\cdot t - j\cdot \Delta t} \tag{7}$$

Based on the formula used to calculate V_d, the following equation can be derived:

$$V_d(t) = \frac{y(t'+\Delta t) - z(t+\Delta t)}{z(t)\cdot \Delta t}\cdot \frac{V}{LA} = \frac{C_0 \times e^{-kt-j\cdot\Delta t} - C_0 \times e^{-k(t+\Delta t)}}{C_0 \times e^{-kt}\cdot \Delta t}\cdot \frac{V}{LA} = (e^{-j\cdot\Delta t} - e^{-k\cdot\Delta t})\cdot \frac{V}{LA\cdot \Delta t} \tag{8}$$

where LA is the leaf area of the sample plants species, and V is the volume of the chamber.

The leaf area (LA) and the volume of the chamber (V) could easily be measured using the given Eq. (8). The remaining tasks were to determine the quantitative values for j, k, and Δt.

2.2. $PM_{2.5}$ powders as tracer

Diamond powder (diametre $\varphi \le 2.5\,\mu m$) was used as a tracer for $PM_{2.5}$ in this particular study. Diamond is characterized as a very chemically stable compound, and would theoretically be a good option as tracer. The distribution of the circumferences of fine diamond particles was tested using aerosol spectrometre (Grimm11-R, Grimm Aerosol Technik, Germany), which contained 31 different sized channels and a measurement range of 0.25–32 µm. Fig. 2 shows that fewer 2.5 µm particles accounted for 98% of the total mass concentration, and that the diamond powder was mainly composed of particles with diametres of 1.8–2.5 µm particles, which was the larger sized part of $PM_{2.5}$.

2.3. Smog chamber

The smog chamber (shown as Fig. 3) used in this study is a closed cylindrical stainless steel container. Both the lid and bottom surface of the chamber are circular, with the diametre and height of 800 mm. Small holes are present on the roof of the chamber, so the tracer particles could travel across the metal barrier and access the aerosol spectrometre. A small fan, installed at the center of the bottom surface of the chamber, is used to adjust wind speed inside the chamber within a range (0–7 m/s). A purification device is connected to the system to artificially produce an atmosphere with a very low particle concentration. Pure nitrogen gas filters into the chamber and flushes the inner wall, using a 20 air inlet connected from the roof to an outer pump through an open outlet on the bottom of the chamber. After repeating the nitrogen rinse procedure, the $PM_{2.5}$ concentration in the chamber can fall to less than $2\,\mu g/m^3$, guaranteeing that the rest of the experiment would be conducted under controlled environmental conditions.

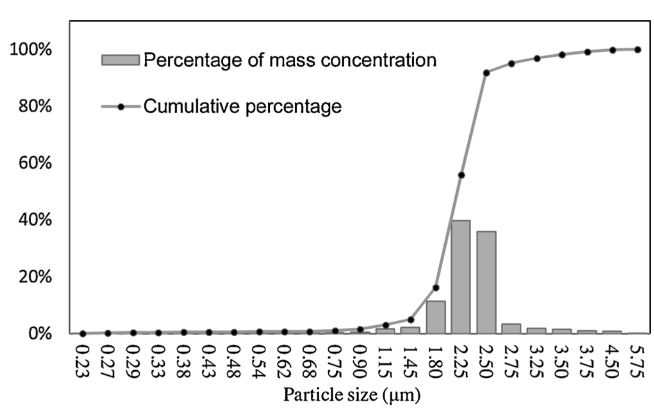

Fig. 2. Size distribution of the fine diamond particles.

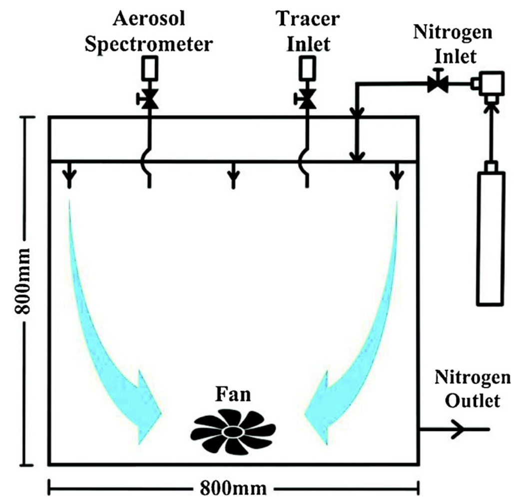

Fig. 3. Schematic of the smog chamber.

2.4. Experiment

An aerosol spectrometre was connected to the smog chamber through the roof with the sensor fixed to the center of the chamber. Pure nitrogen gas was diffused throughout the chamber until the $PM_{2.5}$ concentration dropped to below $2\,\mu g/m^3$. The wind speed in the chamber was consequently adjusted to 1 m/s to ensure that $PM_{2.5}$ would be well dispersed throughout the chamber. Furthermore, a controlled amount of diamond powder was added and circulated throughout the chamber. When a spike in the concentration of $PM_{2.5}$ inside the chamber occurred, and then a gradual decline, the aerosol spectrometre began recording the concentrations in 6 s intervals. The initial concentrations of $PM_{2.5}$ were measured at 36–1210 $\mu g/m^3$, and the experiment was concluded once the concentration reached a point below 20 $\mu g/m^3$.

All the recorded data were fit into an exponential attenuation model, and attenuation rate constant j and k were calculated using the MATLAB Version 2016a (The MathWorks, Inc. USA).

3. Results and discussion

3.1. $PM_{2.5}$ deposition under different initial concentration

The $PM_{2.5}$ deposition data could be described by the exponential attenuation model under variable initial concentrations, so we took the logarithm of both sides of the original formula to arrive at the following Eq. (10):

$$\ln y(t) = \ln(C_0 \cdot e^{-j\cdot t}) \tag{9}$$

$$\ln y(t) = -j\cdot t + \ln C_0 \tag{10}$$

Therefore, these fitted exponential attenuation curves became straight lines in the logarithmic coordinate axis. Experiments under different initial $PM_{2.5}$ concentrations were conducted, and the resulting fitted curves were shown in Fig. 4:

The concentrations of $PM_{2.5}$ in the chamber did not decline to zero, as the deposition and desorption of particulate matter stayed the same under a low-concentration-environment at the end of the experiment.

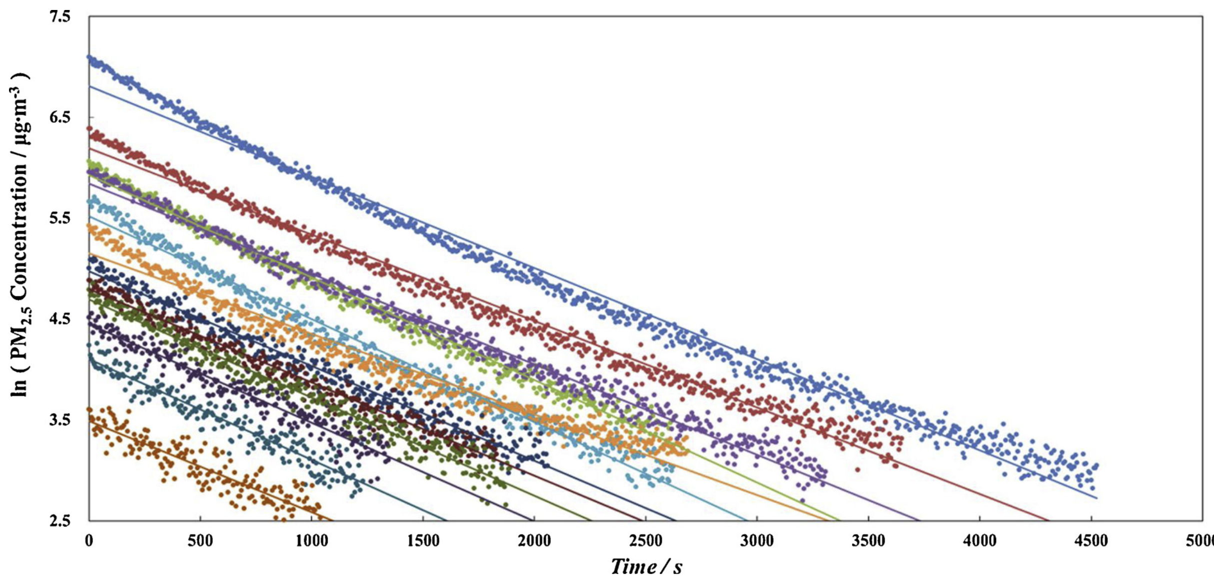

Fig. 4. $PM_{2.5}$ attenuation and fitted lines under different initial concentrations.

Table 1
Fitted equations under different initial $PM_{2.5}$ concentrations.

C_o(μg/m^3)	lnC_o	fitted equation	R^2	Number recorded (n)
1212	7.10	$y = -0.0009224\,x + 6.8089585$	0.9888	750
596	6.39	$y = -0.0008963\,x + 6.1898527$	0.9882	610
436	6.08	$y = -0.0010153\,x + 5.9246726$	0.9894	550
387	5.96	$y = -0.0009256\,x + 5.8417752$	0.9884	451
288	5.67	$y = -0.0010401\,x + 5.5165984$	0.9817	450
227	5.42	$y = -0.0008872\,x + 5.1487266$	0.9636	445
148	5.00	$y = -0.0009483\,x + 4.9720274$	0.9754	345
132	4.88	$y = -0.0009428\,x + 4.7925230$	0.9679	300
120	4.79	$y = -0.0009717\,x + 4.6925081$	0.9686	310
91	4.51	$y = -0.0009667\,x + 4.4488296$	0.9315	225
69	4.23	$y = -0.0009864\,x + 4.0996349$	0.9170	210
36	3.58	$y = -0.0009022\,x + 3.4893314$	0.8216	175

The final concentrations of $PM_{2.5}$ remained 12–20 μg/m^3 in the chamber with a corresponding logarithm range of 2.5–3.0. The initial concentration, fitted equation, and determination coefficient (R^2) were shown in Table 1, respectively.

All fitted equations had acceptable R-squared values (greater than 0.82), which showed that the exponential attenuation model could accurately measure the decay of $PM_{2.5}$ concentration in the chamber. The fitted values of j were close under different initial concentrations (between 0.0008872 and 0.0010401), and the mean and variability coefficients were 0.009504 and 5.01%, respectively. The information given in Fig. 4 also provided evidence that both a higher initial concentration and longer testing duration affected the exponential attenuation fitting results. Thus, it was absolutely necessary to determine the initial concentration of $PM_{2.5}$ and the duration of the test for this method.

3.2. Determine of initial concentration of $PM_{2.5}$ and test time duration

All of the curves displayed in Fig. 4 were fitted again under varying initial concentrations (e^4-e^7μg/m^3) and test durations (1000–3000 s). We calculated the j value of each curve, and the average j value, standard error, and coefficient of variation (CV) under each separate condition as displayed in Table 2:

Table 2 showed that when the initial concentration was around 400 μg/m^3 (ln$C$ = 6), and the test duration was 3000 s, both the standard error of the fitted j value (0.0000691) and discrete coefficient (0.071) achieved a minimum. Therefore, for the indirect method, the initial $PM_{2.5}$ concentration was identified as 400 μg/m^3 with a j value of 0.0009612. The test duration for the fitted control curve was 3000 s. For the fitted test curve, the test duration reached 3000 s, or the experiment was concluded when the concentration reached less than 20 μg/m^3 in the chamber.

3.3. Determine of Δt

According to the above Eq. (8):

$$V_d(t) = (e^{-j\bullet\Delta t} - e^{-k\bullet\Delta t})\bullet\frac{V}{LA\bullet\Delta t} \quad (8)$$

The volume of the smog chamber, V, and constant j values of the attenuation rate were already identified. The k values could be obtained by experimentation, and the LA could be obtained through scanning (WinFolia Pro 2016, WinFolia, Canada). Hence, the duration of the short time interval (Δt) also needed to be determined.

We utilized *Cinnamomum camphora*, a common evergreen broad-leaved tree species in subtropical area of East Asia, as an example. In the trial, we used 30 leaves for each replication. The measured $PM_{2.5}$ concentration in the chamber and the fitted curve were shown in Fig. 5.

Thus, the fitted k was 0.002046s^{-1}, the total leaf area of *Cinnamomum camphora* was 0.09947 m^2, and the volume of smog chamber was 0.402 m^3. Time intervals (Δt) were set to 1000s, 100 s, 10 s, 1 s, 0.1 s, 0.01 s, 0.001 s, and 0.0001 s, and the deposition velocity (V_d) was calculated according to Eq. (8). The results were shown in Fig. 6.

Table 2
j value and coefficient of variations (CV) under all different conditions.

ln(*C*)	1000s		2000s		3000s		4000s	
	j (10^{-4})	CV	j (10^{-4})	CV	j (10^{-4})	CV	j (10^{-4})	CV
7	10.985 ± 1.273	0.116	10.130 ± 0.736	0.073	8.978 ± 2.734	0.305	8.904 ± 2.732	0.307
6	10.791 ± 1.278	0.118	9.926 ± 0.752	0.076	9.612 ± 0.691	0.071	9.576 ± 0.747	0.078
5	9.9307 ± 0.982	0.099	9.259 ± 0.757	0.082	—	—	—	—
4	8.4306 ± 0.803	0.095	—	—	—	—	—	—

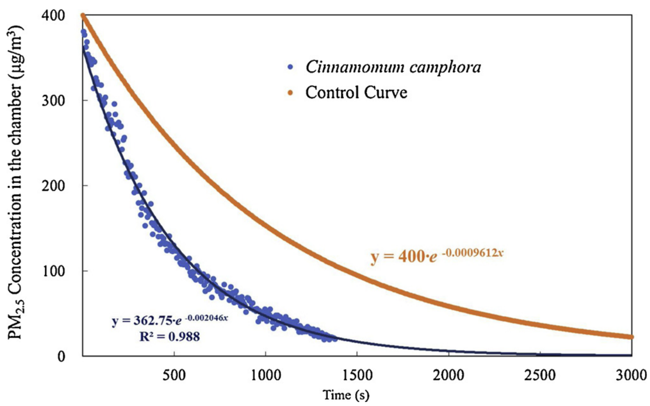

Fig. 5. Decay and fitted curve of $PM_{2.5}$ concentration in the chamber.

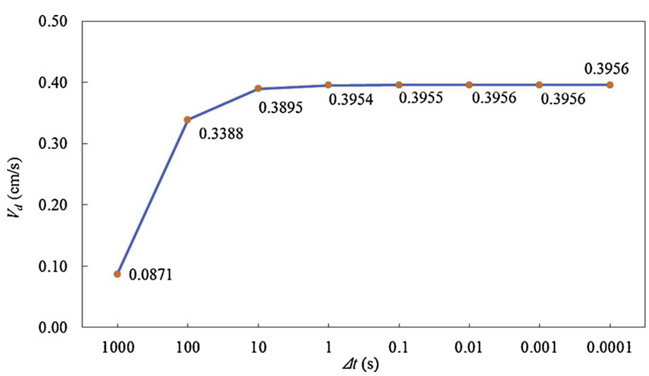

Fig. 6. $PM_{2.5}$ deposition velocity (V_d) calculated at different time interval (Δt).

The data compiled into Fig. 5 implies that a greater time interval lead to smaller V_d values, but when the time interval was less than 10 s, the V_d calculated was stable. Thus, we set the time interval to 1 s, so that V_d could be further simplified into:

$$V_d(t) = (e^{-j} - e^{-k})\bullet\frac{V}{LA} \quad (11)$$

Eq. (11) was the final formula incorporated into the V_d test, and indicated that V_d could only be determined by measuring the attenuation rate constant *k*, and the leaf area *LA*.

3.4. Comparison with the wind tunnel method

Fifteen different species of common greening trees in the subtropical area of East Asia were selected for analysis: *Sabina chinensis*, *Podocarpus macrophyllus*, *Cedrus deodara*, *Pinus parviflora*, *Metasequoia glyptostroboides*, *Cinnamomum camphora*, *Ligustrum lucidum*, *Magnolia grandiflora*, *Elaeocarpus decipiens*, *Sapindus saponaria*, *Sophora japonica*, *Firmiana simplex*, *Salix babylonica*, *Prunus cerasifera* f. *Atropurpurea*, and *Ginkgo biloba*. There were 11 broadleaved and 4 coniferous species. All leaf samples were taken from the Shanghai Jiao Tong University Botanical Garden, on the same day in July 2017. Leaf samples were collected from approximately 150–300 healthy leaves found on the southern section of each plant, and were at approximately 2/3 the height of the plant. The leaves were measured immediately after they were brought back to the laboratory. The indirect method was used to determine the V_d of each tree species, and leaf area was scanned, and then measured using the WinFolia-2016 image analysis (Regent Instruments Inc., Canada). Experiments were repeated three times, and the mean was calculated as the test value. For each test, the total leaf area was approximately 300 cm^2, which meant 30 leaves for middle-sized broad-leaved species or 100–120 leaves for conifers such as *Picea* and *Pinaceae*.

The deposition velocities of $PM_{2.5}$ to trees from literature were also collected. These papers measured V_d for 16 tree species under wind speeds of 3.0–6.5 m/s (Freer-Smith et al., 2004; Beckett et al., 2000; Pullman, 2009; Nowak et al., 2013). Table 3 has listed the methods and results of published studies with wind tunnels and our indirect way. Generally, the results obtained by indirect method were slightly higher than the ones with wind tunnel. However, aside from the fundamental ideological differences between the direct and indirect method, there were also many discrepancies in particle sizes, tree selection, tracer selection, detection methods, exposure duration and so on. Therefore, all these factors may affect the results of V_d determination.

Firstly, the particle size was considered as the main factor that affect the results of V_d determination in different methods. Slinn (Slinn, 1982) established a model to describe the V_d associated with particle size, and found that V_d increased with the growth of particle size ($d_p > 0.3$ μm). Litschke and Kuttler (Litschke and Kuttler, 2008) have collected several V_d values determined by field measurements in different methods, Despite the fact that Slinn's model of particle size and V_d may have neglected some details, such as magnitude by phoretic processes along an electric potential gradient or a thermal gradient, overall V_d and particle are still positively correlated. The findings in some published papers can also support this theory (Contini et al., 2010; Matsuda et al., 2010; Langner et al., 2011).

For fine particles ($d_p \leq 2.5$ μm), when the particle diametre falls between 1 μm and 2.5 μm, the dry deposition process is mainly affected by gravitational sedimentation, and the larger the particle is, more rapid it falls (Mohan, 2016). When the particle diametre is with the range from 0.1 μm to 1 μm, impaction and interception become the main factors. Particulates with a diametre less than 0.1 μm are mainly affected by diffusion (Litschke and Kuttler, 2008). The diamond powder used in this study had a diametre of 1.8–2.5 μm. The particle size was much larger than the NaCl tracer that Beckett and Freer-Smith used (0.80–1.28 μm). For this reason, the value of V_d (0.064–2.853 cm/s) determined by indirect method was slightly larger than the wind tunnel by Beckett (0.08-0.15 cm/s) and Freer-Smith (0.004–1.167 cm/s). However, after comparing with the modelled and measured values of V_d summarized by Litschke and Kuttler (Litschke and Kuttler, 2008), we found that the V_d determined by indirect method were still in a reasonable range.

Secondly, the different tree species selected may also result in the value discrepancy between each method. For example, Beckett (Beckett et al., 2000) found that the V_d of coniferous trees (0.76–1.15 cm/s) was significantly higher than those of broadleaved ones (0.08-0.39 cm/s), which was attributed to the more complex spatial distribution of

Table 3
Comparison of wind tunnel and indirect method.

Literature	Method	Particle size (μm)	Tracer	Detection method	Wind speed ($m{\cdot}s^{-1}$)	Exposure duration (min)	Tree species	V_d ($cm{\cdot}s^{-1}$)
Freer-Smith et al. (2004)	wind tunnel	0.8 (observed by scanning electron microscope)	NaCl	total mass of Na^+	3.0	10	*Acer pseudo-platanus*#	0.042
							Alnus glutinosa#	0.125
							Eucalyptus globulus#	0.018
							Ficus nitida#	0.004
							Fraxinus excelsior#	0.178
							*Pseudotsuga menziesii**	1.167
							Quercus petraea#	0.956
Beckett et al. (2000)	wind tunnel	1.28 (observed by scanning electron microscope)	NaCl	total mass of Na^+	3.0	10	*Acer campestre*#	0.08
							*Cupressocyparis leylandii**	0.76
							Pinus nigra var. *maritima**	1.15
							Populus deltoides x trichocarpa 'Beaupré'#	0.12
							Sorbus intermedia#	0.39
Pullman (2009)	wind tunnel	2.5	KNO_3	electrical conductivity	6.5	30	*Picea abies**	0.0189
		(milled but the size is not observed or verified)					*Pinus strobus**	0.0108
							*Tsuga canadensis**	0.0193
							*Tsuga japonica**	0.0058
This study	smog chamber	1.8–2.5	diamond powder	indirect	2	50	*Cedrus deodara**	0.319
		(verified by spectrometre)					*Cinnamomum camphora*#	0.239
							Elaeocarpus decipiens#	0.334
							Firmiana simplex#	0.064
							Ginkgo biloba#	0.263
							Ligustrum lucidum#	0.317
							Magnolia grandiflora#	0.305
							*Metasequoia glyptostroboides**	0.380
							*Pinus parviflora**	2.853
							Podocarpus macrophyllus#	0.237
							Prunus cerasifera f. *Atropurpurea*#	0.374
							Salix babylonica#	0.277
							*Sabina chinensis**	0.216
							Sapindus saponaria#	0.291
							Sophora japonica#	0.435

Notes: * stands for coniferous trees; # stands for broadleaved trees.

branches and leaves of coniferous trees. In this study, the mean V_d of coniferous trees (0.216–2.853 cm/s) measured by indirect method was also significantly higher than those of broadleaved trees (0.064–0.435 cm/s). Even for the same type of trees, due to the differences of leaf functional traits, such as surface roughness and width-length ratio, they can also cause the difference of results by direct and indirect method (Weerakkody et al., 2018; Vogel, 1989).

In addition, tracer selection, detection methods, exposure duration and some other experimental conditions were also the influential factors affecting the results of V_d determination. As shown in Table 3, although Beckett, Freer-Smith and Pullman all used wind tunnel equipment, the experimental conditions were not the same. Beckett and Freer-Smith invented NaCl as tracer, exposed the tested trees for 10 min, and determined the V_d value according to the total mass of Na^+ by spectrophotometre. Pullman used milled KNO_3 as the tracer, exposed the tested trees for 30 min, and determined the V_d through measuring the electrical conductivity in the solution. The results showed that the V_d by Pullman were obviously smaller than those by Beckett and Freer-Smith, which proved that different experimental conditions can also affect the results of V_d determination. In this indirect method, the dynamic changes of particle concentration in the smog chamber were continuously detected by multi-channel spectrometre within 50 min. Compared with the direct method, which the determinations of Na^+ and the electrical conductivity both required to wash off the tracers and dissolve them in deionized water, the indirect method could obtain the data without extra treatments, and this can reduce the experimental errors to a certain extent.

Given that there were many factors that could affect the determined results in different methods, it's highly required to use the same tracer and the same tree species to conduct experiments in order to compare the differences between wind tunnel and indirect methods.

4. Conclusions

This paper established an indirect method as a complement to measure $PM_{2.5}$ dry deposition velocity on plant leaves. Based on the theoretical derivation of the testing method for V_d, a smog chamber facility was developed, and diamond powder with a larger size range between 1.5–2.5 μm was selected as the test material. The experimental conditions such as the initial concentration, test duration, and time interval (Δt) were determined. Subsequently, the theoretical calculation of the V_d equation was simplified, which showed that V_d could be determined only by measuring the attenuation rate constant k, and leaf area (LA).

Although the indirect method had a completely different measurement process from the direct method, particularly the wind tunnel, the main idea of the indirect method was still to create a space where environmental conditions could be controlled, and changes could be accurately measured before and after the procedure. In this method, smog chamber could simulate the omni-directional flow condition surrounding the tree leaves, and the most important factor in the equation to calculate V_d, the attenuation rate constant k, was generated by fitting data to prevent inaccurate results caused by a single measurement error.

Since the particle sizes, tested species and other experimental conditions used in different methods varied from one to another, the results of V_d determination by indirect method differed from the direct (wind tunnel) ones, but the values of V_d were still within acceptable range. Therefore, more experiments should be conducted to verify this outcome.

Besides, there are still limitations in determining V_d under controlled conditions, whether the wind tunnel or the indirect method, and the assessment of V_d is mostly conducted at the scales of several leaves or branchlets. However, the process of aero particulates retention by vegetation under actual conditions is much more complex, which could be affected by landscape geometry, turbulence, particulates component, etc. Therefore, both the wind tunnel and the indirect method are basically aiming at the influence by one single factor (tree species, wind speed, etc.). As to evaluate the potential of dust retention by plants on a larger scale, real-time field observations are the better way to improved design or adaptive management.

CRediT authorship contribution statement

Shan Yin: Conceptualization. **Xuyi Zhang:** Methodology, Investigation, Formal analysis. **Annie Yu:** Investigation, Writing - review & editing. **Ningxiao Sun:** Investigation, Resources. **Junyao Lyu:** Data curation. **Penghua Zhu:** Resources. **Chunjiang Liu:** Writing - review & editing, Project administration.

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