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Technical Note

Estimates of Atmospheric Aerosols Adhered to the High Voltage Electric Wire in the Yangtze River Delta Region of China

Jingliang Hao[1], Leiming Zhang[2], Tianliang Zhao[1*], Song Gao[3], Jie Li[3], Yongwei Wang[1]

[1] *Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, School of Atmospheric Physics, Nanjing University of Information, Science and Technology, Nanjing, Jiangsu 210044, China*
[2] *Air Quality Research Division, Environment and Climate Change Canada, Toronto, Ontario M3H5T4, Canada*
[3] *Jiangsu Electric Power Company Electric Power Research Institute, Nanjing, Jiangsu 211103, China*

ABSTRACT

Atmospheric aerosol particles can collect on and adhere to high voltage electrical wires, causing power loss as well as other detrimental effects on electrical insulation. The mass of fine particles ($PM_{2.5}$) adhering to wires has been estimated using a modified size-resolved particle dry deposition model and a range of annual average $PM_{2.5}$ concentrations found in literature for the Yangtze River Delta region of China. Annual mass collected by the surface of a unit length (1 m) of wire with a radius of 0.5 cm is estimated to be in the range 1.56×10^4–1.46×10^5 µg. The actual mass adhering to the wire may be reduced by 85% of these estimated values considering the washing-off effects of rain. For a wire of 1.0 cm in radius, the annual mass on the wire is estimated to be in the range of 4.68×10^3–4.35×10^4 µg after considering the effects of rain. This study provides a first estimation of particle mass collected by electrical wires, although with large uncertainties, which can be used for subsequent impact studies of aerosol pollution on electricity transfer.

Keywords: Dry deposition model; Electric wire; Mass of $PM_{2.5}$.

INTRODUCTION

Mass concentrations in air of atmospheric aerosol particles have been at high levels across China (Tao *et al.*, 2017) in the most recent decades due to increasing energy consumption (Wang *et al.*, 2016; Ma *et al.*, 2017) and rapid economic growth (Liu *et al.*, 2016; He *et al.*, 2017; Sun *et al.*, 2017). Increased aerosol air concentrations can enhanced particle deposition amounts to any surfaces including high voltage electric wires with the power loss. In particular, particle deposition on insulator can decrease flashover voltage and increase leakage current, posing a threat to electric power supply safety (Wu *et al.*, 2004; Zhao *et al.*, 2007; Li *et al.*, 2014; Hu *et al.*, 2015). Particle deposition (marine salt, industrial and agricultural pollutants), in the presence of elevated humidity levels, greatly increase the surface conductivity of lines and substations insulators and can lead to surface discharges and electrical short-circuits. The persistence of these conditions poses a threat to the continuity of service of the electrical grid and may produce extended blackouts in large areas of the network such as the blackout phenomena due to pollution on the whole island of Sardinia, Italy (Troccoli *et al.*, 2014).

Some efforts have been made to simulate the impact of particle pollution on flashover incidents (Gençoğlu *et al.*, 2008; Jiang *et al.*, 2010), but little has been done to estimate the amount of particle mass deposition on electric wires. The purpose of the present study aims to provide a rough estimation of particle mass adhered to high-voltage electric wires in the Yangtze River Delta region of China. To do this, the size-resolved particle dry deposition model of Zhang *et al.* (2001) is first modified to include the effect of electric charge since this mechanism might be important in the collection of fine particles by electric wires. Modeled dry deposition velocities under typical turbulent conditions are then combined with a range of annual average $PM_{2.5}$ concentrations found in this region, as documented in Tao *et al.* (2017). Coarse particles are not considered here since they may not be adhered to the wire permanently due to blowing off effects by strong winds and washing off effects by rain. Uncertainty analyses have also been conducted to provide a range of possible values for the estimated annual particle mass adhered to different sizes of wires.

[*]Corresponding author.
Tel.: 86+152 51709481; Fax: 86-25 58699771
E-mail address: tlzhao@nuist.edu.cn

METHODOLOGY

Dry deposition flux to various land surfaces is commonly based on unit land surface area. Electric wire is in cylinder shape so the particle mass adhered to electric wire is calculated based on a unit length in this study with surface area as a function of wire diameter. The size-resolved particle dry deposition model of Zhang *et al.* (2001) is modified to estimate the rate of particles adhered to surface of electric wire. The collection efficiencies of particles by electric wire surface are certainly different from those by land surfaces so modifications are made as detailed below.

According to Zhang *et al.* (2001), particle dry deposition velocity (V_d) is calculated as:

$$V_d = \frac{1}{\left(R_a + R_s\right)} \quad (1)$$

where R_a and R_s are aerodynamic and surface resistance, respectively. Because wire is installed at high levels in the sky where winds are generally strong, R_a should be negligible in most cases. A value of 10 s^{-1} m is used throughout the study. Note that the gravitational setting velocity in the original formula was excluded here considering the cylinder shaper of the wire surface may not collect all the particles through this mechanism. Besides, gravitational setting is a minor contributor to the deposition of fine particles (Zhang and He, 2014), which is the focus of the present study as further explained below.

The surface resistance is parameterized as a function of various collection mechanisms:

$$R_s = \frac{1}{\varepsilon_0 u_* \left(E_B + E_{IM} + E_{IN} + E_E\right) R_1}, \quad (2)$$

where ε_0 is an empirical constant (0.3), u_* is friction velocity, E_B, E_{IM}, E_{IN} and E_E are collection efficiencies by Brownian diffusion, impaction, interception, and electric charge, respectively. R_1 is the factor considering particle rebound (the fraction of particles collide with the surface and not bounced back). E_B and E_{IM} by electric wire surface are considered to be smaller than any land surface described in Zhang *et al.* (2001) so the minimum values (such as over bares soil) are used here for these two terms. E_{IN} is calculated as a function of particle diameter and wire radius. A value of 0.5 cm is used for wire radius as the base case in the present study based on a survey in the studied region.

E_E is a new term added in this study, representing the collection efficiency by electric force generated by wire on particles. According to Wang *et al.* (2010), E_E is parameterized as:

$$E_E = \frac{16KC_cQq}{3\pi\mu_a VD^2 d_p} \quad (3)$$

where $K = 9 \times 10^9$ (N m^2 C^{-2}), C_C is Cunningham correction factor as a function of particle diameter and the mean free path of air molecules, Q and q are the surface charge of high voltage wire and particle, respectively, μ_a is air viscosity, V is gravitational setting velocity of particles, and D and d_p are the diameters of wire and particle, respectively. Q was expressed as:

$$Q = \sigma S \quad (4)$$

where σ is surface charge density of high voltage wire and the value was taken from Jiang *et al.* (2015) as 12×10^{-6} (C m^{-2}). S can be calculated as a product of section girth and length of wire. Here, the length of wire was chosen as 100 times of particle size in order to generate effective electric force between wire and any size particles. q can be calculated according to Wang *et al.* (2010):

$$q = a\,\partial d_p^2, \quad (5)$$

where $a = 0.83 \times 10^{-6}$ and ∂ (C m^{-2}) is an empirical parameter that can vary between 0 and 7. Here ∂ is taken as 7 because the electric field around high voltage wire is very strong.

Particle mass deposit and adhere to a wire (M) can then be estimated as:

$$M = C \times V_d \times (2\pi rL) \times t \quad (6)$$

where C is the mass concentration of particles in air, r is the wire radius, L is wire length, t is the time period. Considering that large particles collide with wire may not easily adhere to the wire since they can easily be blown away by strong winds or washed off by rain, only fine particles ($PM_{2.5}$) are considered in Eq. (6). Since particle size distribution is needed for calculating size-resolved V_d, a log-normal size distribution is assumed following Zhang and He (2014) with geometric mass median diameter and geometric standard deviation chosen as 0.4 µm and 2.2, respectively.

RESULTS

Dry Deposition Velocity

Fig. 1 shows a comparison of size-resolved V_d calculated using the modified and the original models with a u_* value of 0.5 m s^{-1}. It is seen that adding electric charge only affect V_d of particles in the size range of 0.2–6 µm, for which V_d can be increased by up to two times. However, V_d for this size range of particles are at the minimum values so the overall effect on the bulk V_d of all particles should be very small. To verify this, bulk V_d of $PM_{2.5}$ is obtained by integrating the size-resolved V_d using the size-distribution assumed above. The differences in the bulk V_d between the modified (0.062 cm s^{-1}) and original model (0.06 cm s^{-1}) was only 3.3%.

The size-resolved V_d from the modified model under different u_* conditions are shown in Fig. 2. V_d increases with increasing u_* for all particle sizes. When u_* increased from 0.2 to 1.0 m s^{-1} (or five times), V_d also increased by up to five times for most particle sizes. The bulk V_d for $PM_{2.5}$ shows an almost perfect linear relationship between

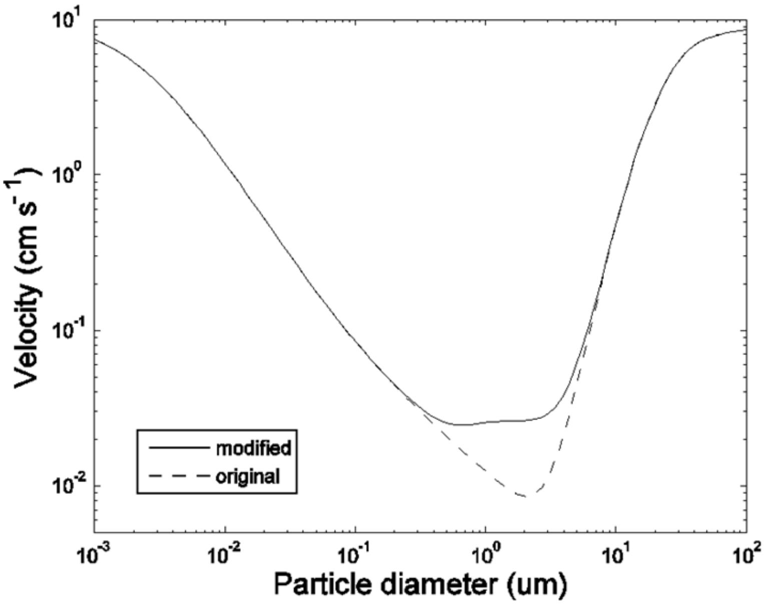

Fig. 1. Size-resolved V_d from the modified and the original models.

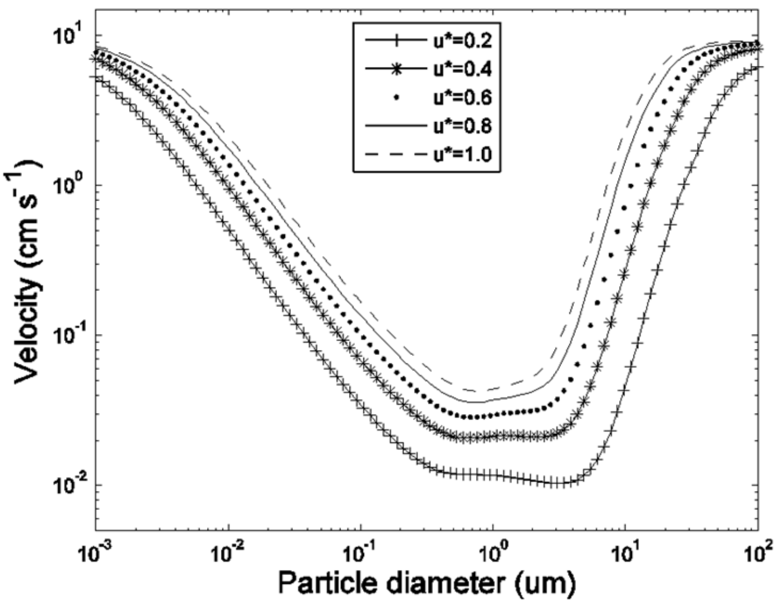

Fig. 2. Modeled size-resolved V_d under different u_* conditions.

V_d and u_* (Table 1), e.g., V_d (cm s^{-1}) = 0.1226 u_*, similar to what was found in an earlier study (Zhang and He, 2014).

Aerosol Mass Adhered to Electric Wire

Eq. (6) is used to estimate particle mass adhered to a wire accumulated during one year period (t = 1 year). A unit length of wire (L = 1 m) with a radius of 0.5 cm is chosen as the base case. A range of V_d values (0.025–0.122 cm s^{-1}) is applied to two different $PM_{2.5}$ concentration scenarios (63–121 µg m^{-3}), which represent lower- and upper-end annual average concentrations found in the Yangtze River Delta region of China (Tao *et al.*, 2017). Annual mass of $PM_{2.5}$ collected by the unit-length wire is estimated to be in the range of 1.56 × 10^4–1.46 × 10^5 µg. This large range is due the large range of the estimated V_d as well as the variations in $PM_{2.5}$ mass concentration.

Uncertainty Analysis

There are many uncertainties in the above estimated aerosol mass adhered to the wire. To explore how sensitive the estimated mass to various assumed variables, sensitivity tests are conducted below on model parameters as well as environmental factors, such as considering washing off effects by rain, using higher collection efficiencies (E_B and E_{IM}), and estimating for a different size of wire.

Potter *et al.* (1991) estimated that 85% particle mass deposited to forest leaves can be washed off by rain. The percentage can be even higher for the case of wire-adsorbed

Table 1. The modeled bulk V_d of $PM_{2.5}$ under five different u_* conditions and estimated $PM_{2.5}$ mass adhered to unit-length wire (1 m) during one year period under five different u_* and two different $PM_{2.5}$ concentration scenarios.

u_* (m s^{-1})	0.2	0.4	0.6	0.8	1.0
V_d (cm s^{-1})	0.025	0.05	0.074	0.098	0.122
Particle mas - Base case					
$PM_{2.5}$ (63 µg m^{-3})	1.56×10^4	3.12×10^4	4.62×10^4	6.11×10^4	7.61×10^4
$PM_{2.5}$ (121 µg m^{-3})	3.00×10^4	5.99×10^4	8.87×10^4	1.17×10^5	1.46×10^5
Particle mass - Case 1 (Base case plus washed off effect by rain)					
$PM_{2.5}$ (63 µg m^{-3})	2.34×10^3	4.68×10^3	6.92×10^3	9.17×10^3	1.14×10^4
$PM_{2.5}$ (121 µg m^{-3})	4.49×10^3	8.99×10^3	1.33×10^4	1.76×10^4	2.19×10^4
Particle mass - Case 2 (Case 1 plus adjusted E_B and E_{IM})					
$PM_{2.5}$ (63 µg m^{-3})	9.30×10^3	1.85×10^4	2.78×10^4	3.69×10^4	4.64×10^4
$PM_{2.5}$ (121 µg m^{-3})	1.79×10^4	3.56×10^4	5.33×10^4	7.10×10^4	8.89×10^4
Particle mass - Case 3 (Case 1 plus wire radius of 1.0 cm)					
$PM_{2.5}$ (63 µg m^{-3})	4.68×10^3	9.17×10^3	1.37×10^4	1.82×10^4	2.26×10^4
$PM_{2.5}$ (121 µg m^{-3})	8.99×10^3	1.76×10^4	2.62×10^4	3.49×10^4	4.35×10^4

particles. Using the same percentage number, the mass of $PM_{2.5}$ adhered to an unit-length wire with a radius of 0.5 cm should then be revised to 2.34×10^3–2.19×10^4 µg (Case 1 in Table 1).

In Eq. (2), the lowest E_B and E_{IM} values over land surface (except water) were chosen for the case of wire surface assuming wire collects particles slower than any land surface by these two mechanisms. If these two values were adjusted to medium values shown in Zhang *et al.* (2001), the revised estimation would be in the range of 9.30×10^3–8.89×10^4 µg, (Case 2 in Table 1), which are about three times higher of the original estimation (Case 1 in Table 1).

If considering a thicker wire such as using a wire radius of 1 cm, the annual mass adhered to the wire is estimated to be in the range of 4.68×10^3–4.35×10^4 µg (Case 3 in Table 1), basically double of those from Case 1, as is supported by from Eq. (6).

CONCLUSIONS

Under typical aerosol pollution conditions in the Yangtze River Delta region of China, particle mass collecting on and adhering to high-voltage electrical wires is estimated to be on the order 10^3–10^4 µg per unit length (1 m) wire during a one year period. These numbers can be used as a first estimation for studying the impact of aerosol deposition on issues related to electrical wiring, keeping in mind that such an estimation does not include contributions from fog, humidity, or icy conditions when aerosol deposition might be substantially enhanced. Future studies may focus on chemically resolved particle mass deposited on wires, as charged ions potentially have the strongest negative impact on insulators, as well as introduce the deposition scheme into a 3-D air quality model.

This study provides a first estimation of particle mass collected on electrical wires, although with large uncertainties in the physical and chemical physical interaction between the aerosols and the wire surface, which can be used for subsequent impact studies of aerosol pollution on electricity transfer. Flashovers caused by long-term dust contamination mainly take place on dirty insulators rather than on power lines, which have a simpler shape than those of insulators.

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