MEASUREMENTS OF THE DRY DEPOSITION VELOCITY FOR SUSPENDED PARTICLES OVER THE SUBURBS OF BEIJING

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ABSTRACT

On the basis of the data of concentrations as well as wind and temperature, simultaneously observed in the north suburb of Beijing, measurements have been made of the dry deposition velocities of suspended particles. Results show that, over such an environment, the dry deposition velocities for suspended particles vary from 0.15 to 10.62 cm s^{-1}, which are comparable with those over forests, that the average surface resistance in the transfer process of particles is about four times as large as the aerodynamic resistance, and that the dry deposition velocity is well related to the frictional velocity in terms of positive correlation function.

I. INTRODUCTION

Dry depositon is one of the removal processes, as well as an important subject in the studies of air pollution. From the view point of probability, people are more concerned with the dry deposition than with the wet deposition. In recent years, with increasing interest in mesoscale or long-range air pollution, more and more measurements of dry deposition velocity have been performed. However, most of them have been conducted under the conditions that the surface feature is either water and snow, or a grassland, where the roughness length is small and the material to be measured is only in gas phase (Owers et al., 1974; Shepherd, 1974; Garland, 1973).

On the other hand, suspended particles are one of the main pollutants released from all over the world. So far little work has been done in this field, and measurements of their deposition velocities, especially under the conditions of rough terrain (such as urban or metropolitan) are even more lacking due to the limitations of observational sites and technology (Sehmel, 1980, McMahon, 1979).

In this paper, the deposition velocities for suspended particles in the north suburb of Beijing are measured by the method of concentration profile, which was obtained from a meteorological tower in association with the data of wind and temperature.

II. THEORY OF DRY DEPOSITION

The phenomenon of dry deposition is a result of transfer of pollutants. Normally deposition velocity V_d is used as a measure of the deposition effect of a material transported from the atmosphere to the ground surface. It is equal to the ratio of material flux to concentration and can be written as

$$V_d(z) = F/C(z). \quad (1)$$

Generally speaking, the material carried out from the atmosphere to the ground is mainly dominated by the transport and diffusion of the atmosphere and the sorption of the ground surface (Wesely, 1977) if gravitational force is ignored. In the constant flux layer, advection and turbulence are the fundamental transport forces. If air flow is horizontally homogeneous, the flux of material transported downward is then related to diffusivity $K_M(z)$ and can be given by

$$F=K_M(z)\frac{dC}{dz}, \tag{2}$$

where z is the height above the ground. Integrating Eq. (2) with respect to height from z_1 to z, we have

$$F=\frac{C(z)-C(z_1)}{\int_{z_1}^{z}dz/K(z)}=\frac{C(z)-C(z_1)}{r_a(z)}, \tag{3}$$

where $r_a(z)$ is the aerodynamic resistance of a material suffered from.

The sorption of ground surface is determined by the feature of the ground. The rate of absorption at the surface is expected to be proportional to the concentration C_s, immediately adjacent to the surface. The flux of material can then be written as

$$F=C_s/r_s, \tag{4}$$

where r_s is the surface resistance.

Let $C(z_1)=C_s$ as z_1 approximates zero, and substitute Eq. (4) into (3), then

$$F=C(z)/(r_a(z)+r_s) \tag{5}$$

can be obtained. From Eqs. (1) and (5) it can be seen that the relationship between dry deposition velocity and transfer resistance is held, i.e.

$$V_d(z)=\frac{1}{r_a(z)+r_s}=\frac{1}{R_t}, \tag{6}$$

where R_t is the total resistance in the process of downward transport.

Up to now, the above equations mathematically represent the fundamental physical processes and effective factors that material suffered in the process of transport from the atmosphere down to the ground. It can be easily seen that V_d may be calculated from Eqs. (1) and (3) or from Eqs. (1) and (4). Unfortunately r_s in Eq. (4) is affected by many factors and is difficult to be measured, so that V_d has to be calculated from Eqs. (1) and (3). With assumption of $K_M(z)=K_m(z)$, where $K_m(z)$ is the diffusivity of momentum, and utilizing the method of micrometeorology, V_d can be obtained from the wind, temperature and concentration profiles measured simultaneously.

According to similary theory, the diffusivity of momentum can be written as

$$K_m=ku_*z/\phi_m, \tag{7}$$

where k is the von Karman's constant, approx. 0.4; u_* is the frictional velocity; ϕ_m is the dimensionless wind shear function and is related to atmospheric stability. In this paper, Businger's (1973) formulae are selected, i.e.

$$\phi_m=(1+4.7z/L)=(1-4.7Ri)^{-1}, \quad Ri\geqslant 0. \tag{8}$$

$$\phi_m=(1-15z/L)^{-1/4}=(1-15Ri)^{-1/4}, \quad Ri\leqslant 0. \tag{9}$$

Thus V_d can be obtained.

It should be noted that in the calculation of V_d, errors may be brought due to the assumption of $K_M(z)=K_m(z)$. As a matter of fact, the aerodynamic resistance of a material in the transportation from the atmosphere down to the ground is greater than that of momentum. Therefore a corrective factor r_b, according to Owen and Thompson (1963) is introduced. r_b is given by

$$r_b=(Bu_*)^{-1}, \tag{10}$$

where B is the dimensionless Stanton number. Thus Eq. (6) can be rewritten as

$$V_d=1/[(r_a'-r_b)+r_s]=1/R_t, \tag{11}$$

where r_a' is the resistance of momentum in the transportation from the atmosphere down to the ground.

III. EXPERIMENTAL METHOD

1. *General Picture of the Field*

The field is situated at the north suburb of Beijing. A 325 m meteorological tower stands there and there are some houses, farmlands and trees around. The ground surface is either covered with withered grass or bared. To the north and south of the tower, there are Madian village and Xiaoguan town and there is no huge pollutant source near by.

2. *Observation*

Wind, temperature and concentration profiles are simultaneously observed by the 325m meteorological tower. Data for wind direction and speed are taken from the heights of 9, 15, 32, and 47 m on the tower. But for temperature, one more level i.e. 1 m above the ground is required. All above data are observed every 20 minutes and processed by a minicomputer, and the averages in 10 min. period before observation are provided.

Observations for particles are set at heights of 2, 10, 16, 33 and 48 m on the tower. Sampling period is 120—180 min. Samples are analysed by weight.

In addition, relative humidity and sky condition are also observed.

3. *Instruments*

A special potentiometer is used as a sensor of wind direction. The flexible arm of the potentiometer and wind vane are coaxial. Three-cup anemometers are used and their threshold wind speeds are 0.4 m s^{-1}. Wind measurement range is 0.4—50 m s^{-1}.

Dew-1 type thermometer is used as a sensor. The measuring accuracy is smaller than

Table 1. Technical Indices for Samplers

Type	Range for Collecting Particles		Rate of Flow (m³/min)
	Class	Aerodynamic Diameter (μm)	
CQ-DLL3	0	—0.38	0.92
	1	0.38—1.50	
	2	1.50—3.29	
	3	3.29—5.78	
	4	5.78—7.92	
	5	7.92—10.00	
Laoshan		TSP	0.11

0.1°C and the temperature to be measured is in the range of −59.9—59.9 °C. The detail can be seen from Ref. Li Xingsheng et al. (1979).

Huge volume cascade air sampler Model CQ-DLL3 and Laoshan sampler are selected for collecting particles. The former is used for particles whose diameter is smaller than 10 μm and the latter, for total suspended particles. Functions of the instruments are listed in Table 1.

IV. DATA ANALYSES AND RESULTS

Wind, temperature and concentration were simultaneously observed on November 1—15, 1985 and data of their profiles, under stable, neutral and unstable conditions were obtained. The meteorological conditions during the experiments are listed in Table 2.

Table 2. General Situation for Meteorology

No.	Date	Time	Sky condition	Relative Humidity	Surface
1	1 November 1984	14.00—17.00	Clear	24—30	Dry
2	1 November 1984	18.00—21.00	Clear	33—40	Dry
3	2 November 1984	08.00—11.00	Clear	42—72	Dry
4	2 November 1984	18.00—21.00	Clear	59—83	Dry
5	2 November 1984	21.30—00.30	Clear	77—87	Dry
6	3 November 1984	01.00—04.00	Clear	81—97	Dry
7	3 November 1984	08.00—11.00	Clear	37—90	Dry
8	3 November 1984	13.00—16.00	Clear	30—35	Dry
9	3 November 1984	18.00—21.00	Clear	57—85	Dry
10	5 November 1984	19.00—22.00	9/Ac.	61—74	Dry
11	6 November 1984	08.00—11.00	10/Ac.	24—31	Dry
12	12 November 1984	08.00—11.00	Cloudy	64—92	Damp
13	12 November 1984	13.20—16.20	Cloudy	88—94	Damp
14	14 Novemer 1984	09.13—12.13	Cloudy	84—100	Damp
15	14 November 1984	14.15—16.15	Cloudy	83—86	Damp
16	14 November 1984	18.25—21.25	Cloudy	91—94	Damp
17	15 November 1984	10.12—13.12	Cloudy	88—95	Damp

In order to calculate dry deposition velocity as being described in Section II, and insure available results, the observational data must be pretreated. Sampling of concentration has to be done in a time period of 2—3 h due to the limitation of accuracy of the instrument. In this period, atmospheric stability may change a great deal that would have effects on the calculations of aerodynamic resistance and deposition velocity. Therefore, data for those extremely changed meteorological conditions are omitted. In order to obtain the averages of atmospheric stability and frictional velocity and to calculate deposition velocity, data for wind and temperature are firstly regressed and then those read out from the regression line are used to calculate the Richardson number Ri and frictional velocity u_*. The method for calculating Ri and u_* can be found from Chen Panqin (1983), Panofsky (1963).

Similarly, regression analysis is also used for the results of every experiment in order

Table 3. Deposition Velocities for Different Classes

No.	Class 0	Class 1	Class 2	V_d(cm s^{-1}) Class 3	Class 4	Class 5
1	5.77		4	4.99	2.93	4.44
2	0.28	1.77	1.77	0.81	0.15	0.89
3	3.15		2.13			3.69
4	4.10	3.65	2.01		2.57	2.19
5	1.00	3.59	2.89		5.37	2.65
6	2.02	4.73	4.14	2.47	2.83	2.65
7	1.02	1.75				
8	2.69	9.33	2.98			
9	3.04	4.58	3.55	3.22		6.34
10	3.13	5.99	3.73	5.37	7.70	1.89
11	5.07	2.66		1.33	1.83	
12	2.49	4.74	5.94	2.63		1.64
13	10.62	1.47	7 60	1.95	3.10	1.88
14		1.30	3.90	5.20		
15	1.00	3.85	1.88	0.98		
16		1.09				1.37
17	0.78	1.08	1.99	0.86	2.58	0.88

Table 4. Deposition Velocities for SP and TSP in cm/s

	SP				TSP			
No.	$V_d(10)$	$V_d(16)$	$V_d(33)$	$V_d(48)$	$V_d(10)$	$V_d(16)$	$V_d(33)$	$V_d(48)$
1	6.74	10.93	24.20	41.11	7.69	12.93	32.47	56.51
2	0.37	0.51	0.75	0.89	1.38	2.23	4.81	7.93
3	2.14	2.90	4.24	5.03	4.19	5.99	9.65	12.16
4	1.98	2.74	4.15	5.02	4.36	6.59	12.06	16.79
5	2.44	3.39	5.20	6.34	4.93	7.47	13.67	19.02
6	2.90	4.18	6.87	8.77	2.71	3.88	6.27	7.92
7	0.35	0.45	0.59	0.66	0.85	1.15	1.67	1.97
8	2.65	3.60	5.26	6.25	5.56	8.00	13.09	16.69
9	2.83	4.01	6.37	7.96	3.63	5.29	8.92	11.61
10	1.25	1.70	2.51	2.98	2.12	3.00	4.75	5.92
11								
12					3.50	5.10	8.56	11.10
13	2.27	3.17	4.90	6.01	3.22	4.67	7.74	9.97
14	1.58	2.09	2.93	3.39	6.09	8.67	13.90	17.47
15	1.38	1.90	2.85	3.43	2.52	3.67	6.16	8.00
16	0.53	0.68	0.85	0.94	1.01	1.38	2.06	2.47
17	3.56	5.48	10.46	15.11	2.10	2.99	4.80	6.03
Mean	2.20	3.18	5.48	7.59	3.49	5.19	9.41	13.84

to eliminate man-made random errors. Of course, those with poor coefficients are omitted, only the data on the regression line are put in use in practice.

Shown in Table 3 and 4 are the dry deposition velocities calculated from Eqs. (1) and (3) according to the method described in Section II with assumption of $K_M(z)=K_m(z)$ and introducing correction factor r_b. Table 3 gives the dry deposition velocities obtained from the huge volume cascade samplers under various meteorological conditions. It can be seen that for suspended particles whose diameters are smaller than 10 μm, the dry deposition velocities are in the range of 0.15—10.62 cm s^{-1}, and that there is no obvious function relationship between deposition velocity and diameter of the particle, which indicates that there are many factors influencing particles in the process of deposition.

Table 4 shows the dry deposition velocities both for suspended and total suspended particles at the heights of 10, 15, 33, and 48 m respectively. It indicates that the deposition velocities increase with height, and that for the same height the deposition velocities of total suspended particles are larger than that of suspended particles. This may be caused by the different diameters of particles and the differences of concentration profiles.

The surface has important effects on deposition velocity. It has a roughness length of 0.69 m and 0.88 m when the wind blows from South and North respectively. Table 5 gives calculated aerodynamic and surface resistances with the assumption of B=5. It can be seen that in north suburb of Beijing, the surface resistance plays an important role in the process of deposition than aerodynamic resistance.

Table 5. Aerodynamic and Surface Resistances

No.	Ri	u_* (m s^{-1})	$r_a'+r_b$ (s cm^{-1})	r_s (s cm^{-1})	$r_s/(r_a'+r_b)$
1	0.0750	0.44	0.13	0.02	0.15
2	0.1756	0.17	0.49	2.21	4.51
3	−0.9149	0.28	0.08	0.38	4.75
4	1.8917	0.26	0.13	0.38	2.92
5	0.5557	0.25	0.11	0.30	2.73
6	0.8089	0.23	0.13	0.21	1.62
7	−0.3606	0.15	0.19	2.67	14.05
8	−0.4128	0.43	0.08	0.29	3.63
9	0.9570	0.26	0.12	0.23	1.92
10	0.7867	0.20	0.15	0.65	4.33
11	0.0582	0.53			
12	−0.0412	0.34			
13	−0.0929	0.31	0.13	0.31	2.38
14	−3.5394	0.27	0.07	0.57	8.14
15	−0.7595	0.15	0.16	0.56	3.50
16	−0.6018	0.13	0.20	1.69	8.45
17	−0.0916	0.23	0.17	0.11	0.64

Given in Table 6 are the results obtained from the experiments both at home and abroad. It shows that the deposition velocities are as large as that over forests but greater than that over grassland which has a small roughness length. The reason for this is that in the environment of urban suburbs, the acting surface between the particles and the surface is larger and the probability of particles being captured increases due to the change of the ground surface and the increase of building and roughness length, so that the deposition becomes obvious. It can be drawn from this that the effect of roughness length on deposition velocity is very important.

Table 6. Some Results for V_d

Depositing material	Diameter D (μm)	Deposition Surface	V_d(cm/s.)	Ref.
Particles	—0.38	Urban suburbs	0.28—10.62	This paper
	0.38—1.50		1.08—5.99	
	1.50—3.29		1.77—5.94	
	3.29—5.78		0.81—5.37	
	5.78—7.92	with Z_0=0.79m	0.15—5.37	
	7.92—10.0		0.88—6.34	
	—100		0.85—7.69	
Particles	0.05—1	Z_0=0.03m	0.12—1.18	Wesely(1977)
Natural aerosol	1.00—10	Grass sward	0.80	Clough(1973)
ZnS	5	Sagebrush	1.5—3.40	Nickola(1976)
Uranin	2	*Pine and oak* Shoots	0.003—10	Sehmel(1980)
	5		0.02—30	
	10		0.10—60	
Pollen	20	Forest	1.50	Raynor(1976)
	32—35		3.30	
	90—100		20	

The relationships between dry deposition velocity and frictional velocity are shown in Figs. 1 and 2. It can be seen that positive correlations between them are held. The correlation coefficients and regression equations are

$$R=0.77,\ V_d=13.236u_*-1.1199 \text{ for SP},$$

$$R=0.83,\ V_d=17.396u_*-0.9665 \text{ for TSP}.$$

Because of the very good relationship between V_d and u_*, the author should suggest that, as long as the number of times for observation is enough, a regression equation between V_d and u_* may be very well established, from which V_d can be calculated. The above results have provided a base for calculating dry deposition velocity in such an environment of Beijing suburbs.

V. SUMMARY

The above analyses show that:

1. For particles whose diameters are smaller than 10 μm, the deposition velocities exist about two orders of magnitude in difference. On the average, the deposition velocities of total suspended particles are larger than that of suspended particles.

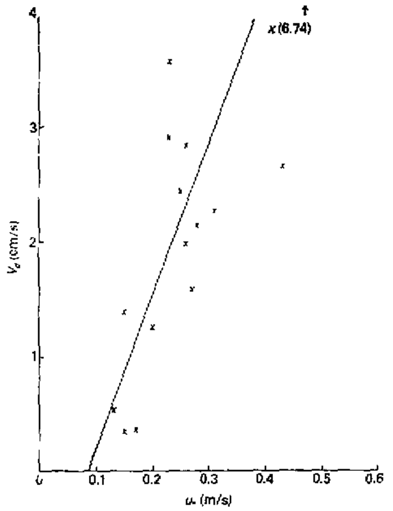

Fig. 1. The deposition velocity V_d for SP plotted against the frictional velocity u_*.

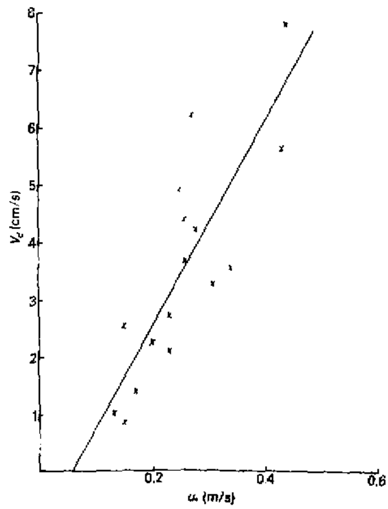

Fig. 2. The aeposition velocity V_d for TSP plotted against the frictional velocity u_*.

2. In such an environment of Beijing suburbs, suspended particles have deposition velocities which are comparable with those over forests, and the average surface resistance is about four times as large as the aerodynamic resistance.

3. For either suspended particles or total suspended particles, there obviously exist the relationships of positive correlative function. From the view point of application, for any specific area, if there are enough data of observation, the dry deposition velocity may be calculated from a regression equation obtained.

4. The method of concentration profile used in this paper does not take gravitational force into account. It may cause error in the calculation of V_d for TSP, and in this regard much research work needs to be done.

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