


# The resuspension chamber as a tool for complex characterization of the quartz test aerosol

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## Resuspenzní komora jako nástroj ke komplexní charakterizaci křemenného aerosolového prachu

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křemenný prach

aerosoly

resuspenzní komora

### Abstract

A quartz test powder aerosol was dispersed in a cylindrical resuspension chamber ( $V=0.437 \text{ m}^3$ ,  $S=0.35 \text{ m}^2$ ,  $S/V=8.38$ ) and the temporal variation of size distribution was viewed on-line by an APS (Aerodynamic Particle Sizer) analyzer under the conditions of a controlled temperature of  $20^\circ\text{C}$  and a relative humidity (RH) of 50 %. The optimal mass load of the powder (with the highest mass concentrations after suspension) was 10 mg. The total number of 300 size distributions was used to calculate the average number and mass size distribution. The number or mass median particle diameter was  $1.07 \mu\text{m}$  or  $2.42 \mu\text{m}$  respectively. The median particle diameters were later used as input parameters into the mathematical models of project SPREAD. Deposition velocities of the particles suspended in the chamber were studied under the conditions of ventilators on and ventilators off. The calculated deposition velocity obtained with switched off ventilators was compared to the model of terminal settling velocity. The results were within 10 % agreement. The particle median diameters were inputted together with the surface parameters used in project SPREAD in the Raupach model and the change of deposition velocity with increasing wind speed was evaluated. It was found that increasing wind velocity and obstacles have the highest influence on the deposition velocity of particles of this size.

**Keywords:** resuspension chamber, APS, settling velocity, Stokes number

### Abstrakt

Částice křemenného aerosolového prachu byly dispergovány a on-line sledovány pomocí APS (Aerodynamic Particle

Sizer) v cylindrické resuspenzní komoře ( $V=0.437 \text{ m}^3$ ,  $S=0.35 \text{ m}^2$ ,  $S/V=8.38$ ) za kontrolovaných podmínek teploty ( $20 \text{ }^\circ\text{C}$ ) a relativní vlhkosti (50 %). Byla stanovena optimální navážka vzorku (umožňující maximální hmotnostní koncentraci aerosolu po suspenzi)- 10 mg. Z 300 velikostních distribucí byla spočítány průměrné velikostní distribuce počtu a hmoty křemenných částic. Průměrná velikost částice ve velikostní distribuci počtu byla  $1.07 \text{ }\mu\text{m}$  a  $2.42 \text{ }\mu\text{m}$  u velikostní distribuce hmoty. Statistické hodnoty velikostních průměrné velikostní distribuce počtu a hmoty částic byly použity jako vstupní parametry do matematických modelů projektu SPREAD. U částic jednotlivých velikostí byly studovány depoziční rychlosti za podmínek vypnutých a zapnutých ventilátorů. Depoziční rychlosti vypočítané za podmínek vypnutých ventilátorů byly porovnány s modelem konečné usazovací rychlosti. Obě rychlosti se od sebe nelišily víc jak o 10 %. Průměrná velikost částic z velikostní distribuce počtu částic a parametry povrchu při disperzi částic řízenou explozí během projektu SPREAD byly vloženy do Raupachova modelu k vypočítání depoziční rychlosti částic se zvyšující se rychlostí větru. Bylo zjištěno, že při zvyšující se rychlosti větru dochází u částic této velikosti ke snižování depoziční rychlosti.

**Klíčová slova:** resuspenzní komora, APS, depoziční rychlost, Stokesovo číslo

## 1. Introduction

The resuspension chamber is a very useful tool for the suspension and collection of aerosol particulates in a controlled laboratory environment. The obtained data are used for the determination of the particulate suspendability, physical characteristics and chemical composition. All this information is needed in order to estimate the toxicological risks connected to the emission of such particulates into the atmosphere from different source materials, natural and industrial accidents and terrorist attacks. The physical and chemical parameters from such studies are being used in models which evaluate the toxicological risks of emission and dispersion of such particulates under various different circumstances.

During the twentieth century, many works described devices for the production or resuspension of dust. These devices were designed for various purposes, for example: for the simulation of the contaminated air inside a dusty factory hall (Dahman *et al.*, 1997); the control of industrial processes (ASTM, 1984); in the pharmaceutical industry for the development of dry inhalers which maximize the concentration of fine aerosol in order to achieve the longest possible path for the particles inside the respiratory tract after their inhalation (Hindle *et al.*, 1996; Concessio *et al.*, 1997; Newman and Buse, 2002; Newman, 2004); for the exposure of laboratory animals to high concentrations of mineral aerosols in studies of respiratory diseases (Muhle *et al.*, 1990); for the preparation of samples for chemical analyses (Morales *et al.*, 1994); for the measurement of the ecophysiological effect of dust on leaves (Hirano *et al.*, 1995); and for the simulation of the penetration of solid particles into buildings (Chen *et al.*, 1999; Lewis, 1995). For many years, standard dusts have been prepared, with different sizes of particles and different indices of light refraction. These standards have been used for capture effectiveness tests of filtration devices and for tests of optical devices measuring light dispersion on the aerosol particles such as the Arizona Dust, which has been used since the 1940s (SAE, 1943).

One of the first laboratory devices for the testing of dust production from different materials was designed by Andreassen, Hofman-Bang and Rasmusen (Andreassen *et al.*, 1939). Their experiment used a long, thin-walled tube in which they measured the settling time of particles of various materials and deduced their size from Stokes Law. This study also included the first measurements of the fractionation of particles under different conditions, in their case the relative humidity and moisture of the parent material. Their device is considered the precursor of series of modern devices for the production of dust and observation of the free fall of particles of various sizes (Heitbrink *et al.*, 1992; Cheng and Yeh, 1979; Lanning *et al.*, 1995; Sutter *et al.*, 1982). The more recent dust formation devices use the principle of vibration screening (Deichman and Dustshaker, 1944; Sonkin *et al.*, 1946), or produce the dust by means of a scraper breaking the material mounted on a rotating cylinder (Graham *et al.*, 1985; Wright, 1950).

The majority of laboratory methods which deal with the production of dust from a parent material or with resuspension in relation to the atmospheric aerosol (both in the interior and the exterior environment) have one common feature: the physical sampling on the filtration media with a subsequent gravimetric analysis. The references very rarely mention the use of other techniques based on optical sensors (Chen *et al.*, 1999) or TEOM (Tapered-Element Oscillation Microbalance) (Breum *et al.*, 1999; Bussaca *et al.*, 1997). Various technologies used for the suspension of aerosol under laboratory conditions have been summarized in the work of Gill, Zobeck and Stout (Gill *et al.*, 2006).

In this paper I would like to present the results of a complex physical characterization of quartz test aerosol, which was used in the Czech research project SPREAD. The main aim of project SPREAD was to create a useful mathematical model which would simulate the process of the dispersion of aerosol particles after the explosion of a “dirty bomb” in different environments. For these purposes several controlled outdoor explosions of quartz test powder were performed. The incurred dust cloud mass concentration was monitored by six laser nephelometers (DustTracks – 8520, TSI) and a series of passive dosimeters placed downwind on the path of the dust cloud. The obtained concentrations were compared with the dispersion model. The results of the project are presented in the work of Skřehot (Skřehot *et al.*, 2008). To obtain a rough idea about the quartz test powder size distribution and dominant particle diameter I performed several pneumatic suspensions of the powder in the chamber and in-situ monitored the suspended particles with an APS (Aerodynamic Particulate Sizer) analyzer. The aerosol number and mass size distribution statistic are presented in this paper. The median particle diameters were used later in the dispersion model of project SPREAD.

## 2. Experiment

A resuspension chamber linked to an APS of the Institute for Environmental Studies, Charles University was used for the complex characterization of the physical properties of quartz test particles (mass density  $2.4 \text{ g}\cdot\text{cm}^3$ ) (see figure 1). The total volume ( $V$ ) of the chamber was  $0.437 \text{ m}^3$ , the inner surface ( $S$ ) was  $0.35 \text{ m}^2$  and the ratio  $S/V$  was 8.375. The working section of the chamber was 1.205 m long with a cross section of  $0.33 \text{ m}^2$ . Two asynchronous ventilators were positioned in the center of the chamber walls, opposite each other. Their maximum regulated power was 15 W and they were mounted onto rotating heads, allowing the air flow to be directed (up to  $5 \text{ m}\cdot\text{s}^{-1}$ ). The ventilator setting in our study generated a spiral air flow at the sides of the wall from the middle part of the chamber to the top. Individual samples of quartz powder were weighed and placed into a glass tube with four jet openings at the bottom (see figure 2). The tube was inserted into a bushing in the center of the upper base of the chamber. The quartz sample was then pneumatically dispersed without pre-sieving by 0.8 L of dried and clean compressed air from a steel bottle of compressed air (pressure after the first stage 9-10 atm). The velocity of the flow through the jets reached  $6 \text{ m}\cdot\text{s}^{-1}$ . The process of suspension was monitored by a small camera focused on the jets of the suspension tube. Dispersions of the quartz dust were performed at a temperature of  $20 \text{ }^\circ\text{C}$  and RH (relative humidity) 50 %. Figure 2. shows the resuspension of the quartz test powder in the chamber.



**Figure 1: Resuspension chamber**

The dispersed aerosol was then evaluated by an APS, which was connected to the bottom of the chamber. The aerosol was diluted by clean air, and properties such as number, mass and surface distributions were viewed on-line and recorded during the suspension of the quartz aerosol.



a

b



**Figure 2: Suspension of experimental quartz powder: a) before suspension, b) dust plume during suspension**

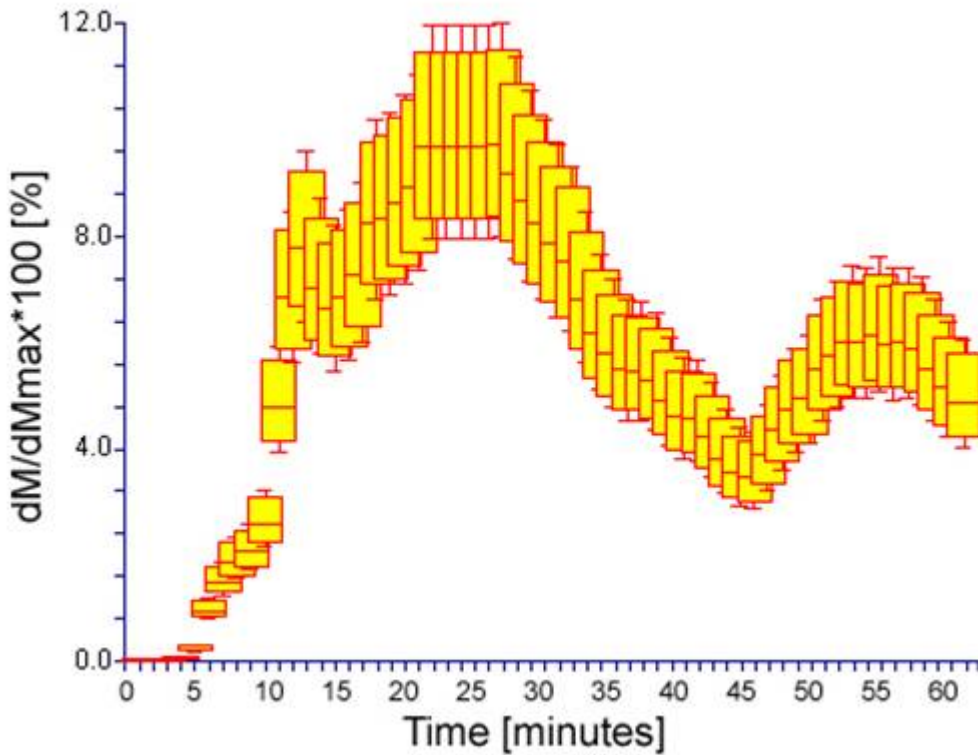
### 3. Results and discussion

A total number of 25 dispersions were performed to investigate the proper mass load for dispersion in order to obtain maximum aerosol mass concentration - 5 dispersions for each mass load (10, 25, 50, 75 and 100 mg) under the conditions of 20 °C and RH (Relative Humidity) 50 %. The density of the quartz test powder was  $2.4 \text{ g}\cdot\text{cm}^{-3}$ . The number concentration of dispersed particulates was high - up to  $10^7 \text{ (\#}\cdot\text{cm}^{-3})$  - therefore the analyzed air was diluted with clean dry air (coefficient of dilution 6.7). The level of resuspension of individual samples of different masses is expressed as a percentage of the measured mass concentration in relation to the maximum possible mass concentration calculated for the individual loads. Table 1 shows the maximum mass concentrations ( $\text{mg}\cdot\text{m}^{-3}$ ) for the suspension of different mass samples within the volume of the resuspension chamber.

Suspended sample mass [mg]	Mass concentration at 100 % suspension [ $\text{mg}\cdot\text{m}^{-3}$ ]
10	22.88
25	57.25
50	114.41
75	171.62
100	228.83

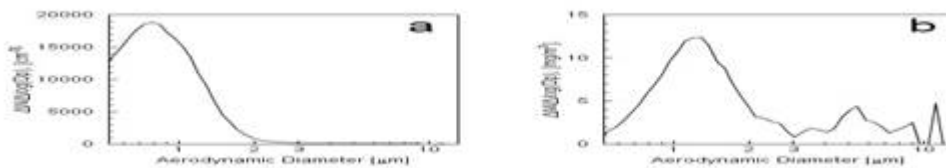
**Table 1: Maximum mass concentration of the suspension of 10, 25, 50, 75 and 100 mg symplex; Suspended sample mass [mg]Mass concentration at 100 % suspension [ $\text{mg}\cdot\text{m}^{-3}$ ]**  
**1022.882557.2550114.4175171.62100228.83**

The optimum mass load to obtain maximum mass concentration was 10 mg. On average, maximum mass concentration reached 10 % of its maximum possible load (see figure 3). Figure 3 shows the scatter plot of time-resolved mass concentrations after dispersing 10 mg of quartz powder.



**Figure 3: Scatter plot of time-resolved mass concentration after dispersing 10 mg of quartz powder showing maximum, 75<sup>th</sup> percentile, median, 25<sup>th</sup> percentile and minimum value for each time period**

After the optimal mass load determination, 5 dispersions were performed and recorded in 5 s intervals. About 720 size distributions were gathered, 300 with the highest mass concentration were selected for determination of average number and mass size distribution, which characterizes the state when the maximum number of particulates is dispersed in the chamber (See figure 4).



**Figure 4: a) Average number size distribution of aerosol particles, b) Average mass size distribution of aerosol particles**

In figure 4a it is seen that the peak with the maximum number of particulates reaches almost  $2 \cdot 10^4$  particulates per  $\text{cm}^3$  with the diameter  $0.7 \mu\text{m}$ . The average particulate size in the number-size spectrum is  $1.07 \mu\text{m}$ . Figure 4b shows the mass size distribution and is characterized by several peaks:  $1.29 \mu\text{m}$  ( $12.3 \text{ mg} \cdot \text{m}^{-3}$ ),  $4.7 \mu\text{m}$  ( $3.16 \text{ mg} \cdot \text{m}^{-3}$ ),  $6.7 \mu\text{m}$  ( $2.5 \text{ mg} \cdot \text{m}^{-3}$ ) and  $11 \mu\text{m}$  ( $4.7 \text{ mg} \cdot \text{m}^{-3}$ ). The average particle size in the mass concentration-size spectrum is  $2.42 \mu\text{m}$ . Additional statistical data is listed in table 2.

	Number concentration	Surface area concentration	Mass concentration

<b>Median (µm)</b>	0.976	1.34	1.65
<b>Average (µm)</b>	1.07	1.60	2.42
<b>Geometric average (µm)</b>	0.994	1.39	1.90
<b>Modus (µm)</b>	1.04	1.38	1.49
<b>Geometric standard deviation</b>	1.44	1.62	1.90
<b>Total concentration</b>	10 <sup>5</sup> (#·cm <sup>-3</sup> )	15·10 <sup>3</sup> (µm <sup>2</sup> ·cm <sup>-3</sup> )	6.00 (mg·m <sup>-3</sup> )

**Table 2: Statistical data for the dispersed quartz powder measured by APS**

One of the important characteristics of dispersed quartz powder is the deposition velocity in the volume of the chamber, which is essential for the determination of the minimum time used for suspension evaluation. The deposition velocities of different sized particles can be calculated with the basic formula:

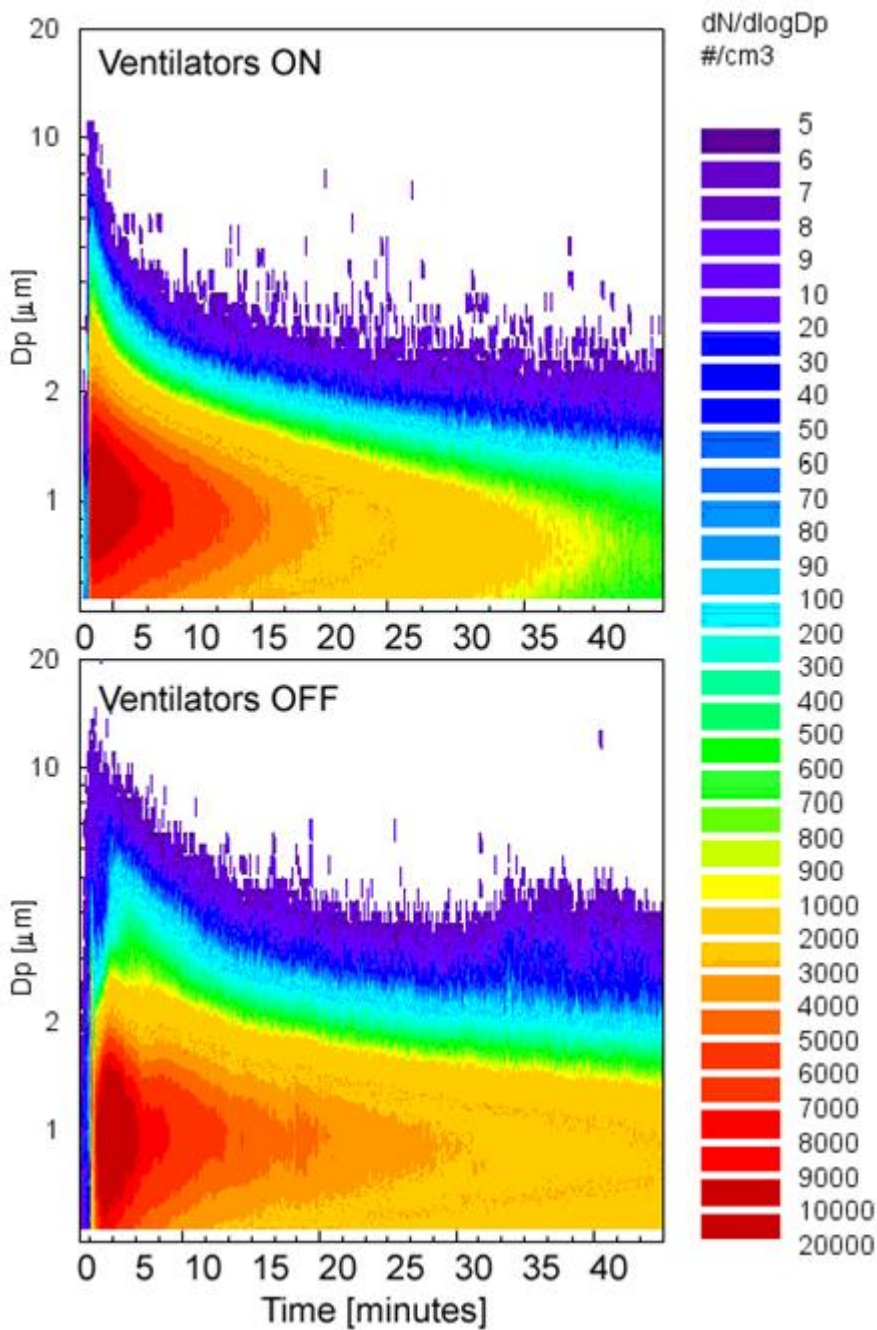
$$N = N_0 \cdot \exp(-\beta t),$$

where  $N$  is the current number of particles,  $N_0$  is the initial number of particles,  $\beta$  is the deposition velocity constant and  $t$  is the time. This model can be applied to the data obtained from the APS, while the deposition velocity can be calculated in the following way:

$$V_d = \frac{V \cdot \beta}{S},$$

where  $S$  and  $V$  are geometrical surface and volume of the chamber respectively. Three suspensions of each sample were carried out with the ventilators switched off and on under the conditions of 20 °C and RH of 50 %. The load of the quartz powder mass was 10 mg. Figure 5 shows selected suspensions of the quartz powder with the ventilators switched on and off. During the selected resuspension of the quartz powder with the ventilators switched on, the maximum number concentration was 10<sup>4</sup> particles per cm<sup>3</sup>, the aerodynamic particle diameter of dominating particulates was 1.04 µm. The whole measurement took 85 minutes (the first 45 minutes are shown), at the end of which the aerodynamic particle diameter of most dominant particle was only 0.8 µm. During the resuspension of the quartz powder with the ventilators switched off, the maximum number concentration was 10<sup>4</sup> particles per cm<sup>3</sup>, and the aerodynamic particle diameter was again dominated by the particle with a diameter of 1.04 µm. This whole measurement took 223 minutes (only the first 45 minutes are shown), at the end of which the aerodynamic particle diameter of the most dominating particle was 0.8 µm, the same as in the previous case.

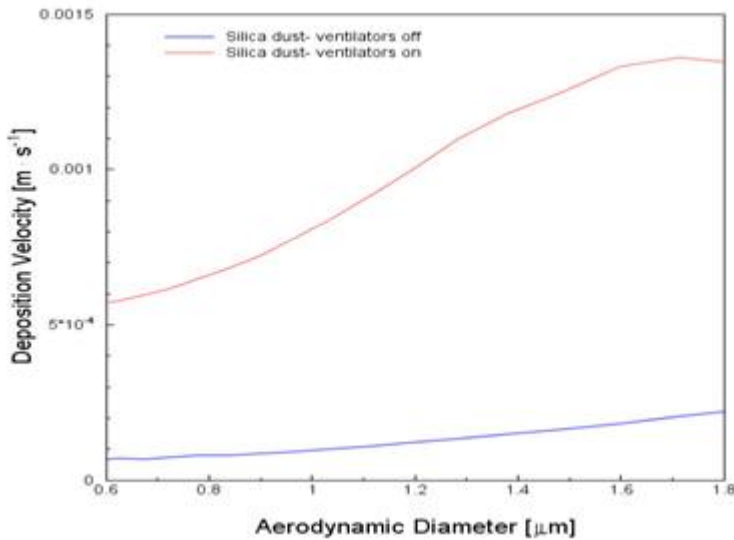




**Figure 5: Temporal variation of number size distributions of dispersed quartz powder measured by APS with ventilators switched on and off**

After performing all dispersions under defined ventilator conditions, the average deposition velocity was estimated for the particulates which dominate the quartz powder (0.6 - 1.8  $\mu\text{m}$ ). Figure 6 shows the calculated deposition velocity for both ventilator conditions.





**Figure 6: Average deposition velocity of quartz powder measured under conditions of ventilators on and off**

It can be seen that air flow ( $5 \text{ m}\cdot\text{s}^{-1}$ ) increases the deposition of the particles by about 14 times for the particles of size  $1.7 \text{ }\mu\text{m}$ , while for the particles around size  $0.6 \text{ }\mu\text{m}$  it is only 6 times. Particles are deposited to the inner surface of the chamber.

The obtained values of the deposition velocity of the quartz powder were compared with the model of sedimentation. The results were computed for mass median particle diameters of the powder sample -  $1.07 \text{ }\mu\text{m}$  under the conditions of switched off ventilators. With the previous mathematical assumption, the deposition velocity in still air (ventilators off) for  $1.07 \text{ }\mu\text{m}$  particle was calculated and resulted in  $7.69 \cdot 10^{-4} \text{ m}\cdot\text{s}^{-1}$ . From the model of Terminal settling velocity (Hinds, 1999), where:

$$V_{TS} = \frac{V - \beta}{S}$$

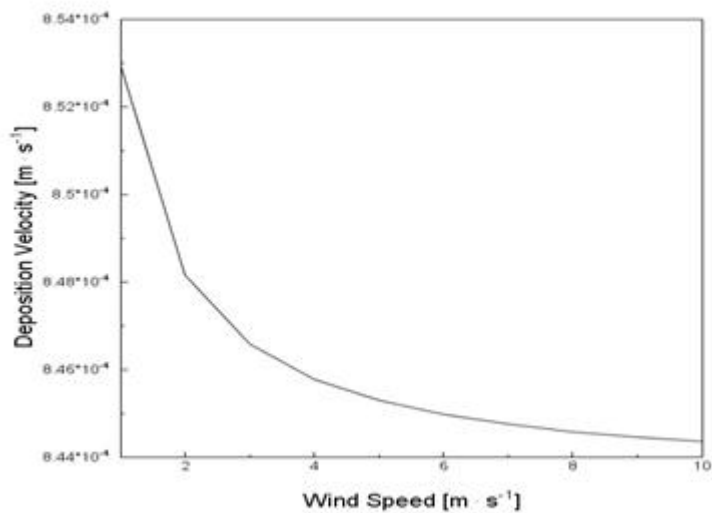
for particles of aerodynamic diameter  $D_p > 1 \text{ }\mu\text{m}$  and  $Re$  (Reynolds number)  $< 1.0$ , where  $\rho_p$  is the particle density,  $d$ -particle diameter,  $g$ - gravity acceleration and  $\eta$  viscosity, the sedimentation velocity was determined to be  $8.3 \cdot 10^{-4} \text{ m}\cdot\text{s}^{-1}$ . Experimentally obtained deposition velocity differs from the terminal settling velocity model by only  $0.61 \cdot 10^{-4} \text{ m}\cdot\text{s}^{-1}$  and therefore dispersion results correspond very well with the model of sedimentation.

In real atmosphere the deposition of particles is rather more complicated, due to the large number of factors which are not all present in the laboratory environment. Using the Raupach model (Raupach *et al.*, 2001), where:

$$V_d = \frac{V_{TS} \cdot \left( \frac{1 + \frac{u_*^2}{u_r^2}}{1 + \frac{u_*^2}{u_r^2} + \frac{a_f}{St}} \right)}{1 + \frac{a_f}{St}}$$

$V_d$  is the dry deposition velocity,  $V_{TS}$  is the terminal settling velocity (the particle has a larger diameter than  $1 \text{ }\mu\text{m}$  so the Cunningham slip correction factor can be neglected),  $u_*$  is the friction velocity derived for a surface with grass up to  $10 \text{ cm}$  in height ( $0.36 \text{ m}\cdot\text{s}^{-1}$ ) (Lees *et al.*, 1996),  $u_r$  is the wind speed,  $a_f$  is the empirical parameter (2),  $St$  is the Stokes number,  $\beta$  is the coefficient of the surface type derived for grasslands (1.2) (Zhang *et al.*, 2001),  $a_v$  is the empirical parameter (8) and  $Sc$  is the Schmidt number. The dry deposition velocity of particles with diameter  $1.07 \text{ }\mu\text{m}$

was calculated for velocities of wind from 1-10  $\text{m}\cdot\text{s}^{-1}$  (See figure 7). The parameters that were chosen in the model represent the surface field characteristics of the grass field tests performed during project SPREAD.



**Figure 6: Modeled dry deposition velocity of quartz powder measured in the air above a grass surface calculated for wind speed from 1-10  $\text{m}\cdot\text{s}^{-1}$**

From figure 6 it is apparent that the deposition velocity decreases with increasing wind speed above the grass surface, therefore in the real atmosphere the deposition velocity is decreased by increasing wind velocity and for a particle with size around  $1\ \mu\text{m}$  the deposition velocity is low, so the wind flow and obstacles play the major role in deposition.

#### 4. Conclusion

A resuspension chamber was used to disperse and characterize the quartz powder using the APS in terms of optimal load for dispersion, average size and mass size distribution. Firstly, the optimal sample mass was investigated to obtain the maximum mass concentration after dispersion. With the determined optimal mass sample, the average number size and mass size distributions were obtained together with basic aerosol statistics.

In further dispersion the quartz powder was investigated for the plate-out rate under different conditions - with ventilators switched on and off. The plate-out rate was calculated from the particle decay in time. The plate-out rate of the most common particle, obtained under the condition of switched off ventilators, was compared with the model of terminal settling velocity. The results of the model and measurement correspond with each other.

The Raupach model was used to investigate the deposition velocity under outdoor atmospheric conditions. It was found that for the most common quartz test powder particle size, the deposition velocity decreases with the increasing wind. Particles around this size are easily carried by the wind, and therefore a major role for the deposition of these particles is played by wind flow, turbulence and obstacles.

When performing the dispersions of quartz test powder or any other aerosol in the real atmosphere or working environment using a controlled explosion or during an accident, the deposition velocities of particles around  $1\ \mu\text{m}$  are so slow that sedimentation of these particles during short time intervals (a few minutes) can be neglected and only the parameters of the air flow and turbulence need be taken into consideration, because these have the highest influence on the particle transportation and occasional deposition.

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