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Efficiency of Big Spring Number Eight (BSNE) and Modified Wilson and Cook (MWAC) samplers to collect PM10, PM2.5 and PM1

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ABSTRACT

The internal efficiency of Big Spring Number Eight (BSNE) and Modified Wilson and Cook (MWAC) samplers for trapping PM10, PM2.5 and PM1 were tested in a wind tunnel, at two wind speeds (3.0 and 6.8 m s^{-1}) in the saltation zone (SAZ) and the suspension zone (SAZ). PM concentrations measured in the inlet and the outlet of both samplers were correlated and the slopes of fitting equations were used for calculating sampling efficiencies. Results showed that BSNE efficiencies ranged from 12% to 32% for PM10, from 0% to 19% for PM2.5 and from 0% to 12% for PM1. The BSNE's efficiency decreased with decreasing particle sizes in SAZ and SUZ at both wind speeds as a consequence of the very low deposition velocity of the finest size particles. The BSNE's efficiency increased with increasing wind speed in SAZ for PM10 and PM2.5 and in SUZ for PM2.5. The MWAC's efficiency ranged from 1% to 20% for PM10, from 0% to 15% for PM2.5 and from 0% to 16% for PM1. The MWAC efficiency was 0% for PM10, PM2.5 and PM1 in the SUZ at 3 m s^{-1} and for PM2.5 and PM1 in the SUZ at 6.8 m s^{-1}. These results provide evidence that the efficiency of BSNE and MWAC for trapping PM10 change with wind speed and position of the sampler. Results also show that BSNEs and MWACs can potentially be used for PM10 emission studies but more research is needed in order to understand and improve their efficiency.

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1. Introduction

Respirable dust with diameters smaller than 10, 2.5 and 1 μm (PM10, PM2.5 and PM1) has taken relevance in the last decades as consequence of their effects on human health and the environment (Kohfeld and Tegen, 2007; Olson and Boison, 2005). PM10 are responsible for negative effects on health like respiratory diseases, allergies, heart diseases and increased infant mortality (Morman and Plumlee, 2013). PM10 also affects the environment modifying, for example, the radiation balance and the nutrient cycle (Jickells et al., 2005; Redmond et al., 2010; Kumar et al., 2015). Because of that many countries and regions established standards for air quality in relation to PM10 concentrations (EU, 2008; Sharratt and Auvermann, 2014).

Globally, 20% of PM10 emissions are produced in vegetated surfaces, deserts and agricultural lands (Ginoux and Prospero, 2012). Our understanding of the global dust cycle is limited by a dearth of information about dust sources, especially small-scale features which could account for a large fraction of global emissions (Ginoux and Prospero, 2012). Wind erosion studies can be an important source of information on emission sources of respirable mineral dust, as long as the collection efficiency of PM10 collectors used is known.

Many samplers have been developed for measuring the material transported by wind (Goossens et al., 2000), though the Big Spring Number Eight (BSNE, Fryrear, 1986) and the Modified Wilson and Cook (MWAC, Wilson and Cook, 1980; Kuntze et al., 1990) samplers are the most commonly used (Zobeck et al., 2003). These samplers are widely used in wind erosion studies where the amount and the quality of the material transported by the wind are studied. Previous studies showed that BSNE's and MWAC's efficiencies change with particle size and wind speed (Mendez et al., 2011; Shao et al., 1993; Bakkum, 1994; Pollet, 1995; Goossens et al., 2000). Goossens and Buck (2012) found that the BSNE's efficiency decreases from 70% for particles of 70 μm in size to 18% for particles of 10 μm in diameter. MWAC's efficiency was 0% for particles smaller than 50 μm and increased with increasing particle size up to 69.5% (Feras et al., 2008). The relative efficiency of MWCAs in relation to BSNEs was measured in the field by Mendez et al. (2011) who found that MWACs efficiency increased

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with decreasing particle sizes and increasing wind speeds. However, those studies had been developed for particles coarser than 10 μm where the dry sedimentation is the main deposition mechanisms. A lack of information exists in relation to BSNE's efficiency for collecting PM10. Sharratt et al. (2007) used a mass balance in a wind tunnel by adding a known mass of PM10 at the inlet of a BSNE. They determined that BSNE's efficiency for trapping PM10 was 10% at 18 m s^{-1} wind speed and 25% at 5 m s^{-1}. Shao et al. (1993), analyzing the particle size distribution of the material trapped by the sampler and the particle size distribution of the material used in the experiment concluding that the entrapment efficiency of BSNEs was 40% for particles smaller than 10 μm. Goossens and Buck (2012) estimated that BSNE's efficiency was 6.74% for PM1.0; 7.64% for PM2.5 and 8.54% for PM4. However, direct measurements of BSNE's efficiency for catching PM2.5 and PM1 are lacking. Also, no mention in the literature has been found about MWAC's efficiencies for trapping PM10, PM2.5 and PM1.

Aim of this study was to measure the internal efficiency of BSNE and MWAC samplers for trapping PM10, PM2.5 and PM1 by means of direct and simultaneous measurements of the inflowing and outflowing particles.

2. Materials and methods

PM emissions were simulated in a wind tunnel at the Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany. The wind tunnel is 7 m long, 0.7 m wide and 0.7 m high

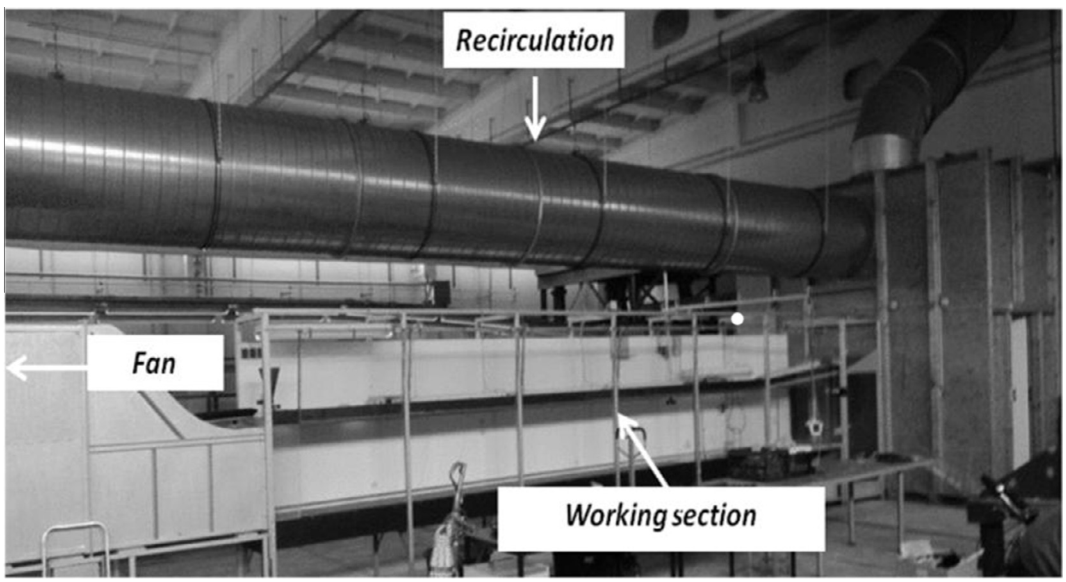

Fig. 1. Wind tunnel details.

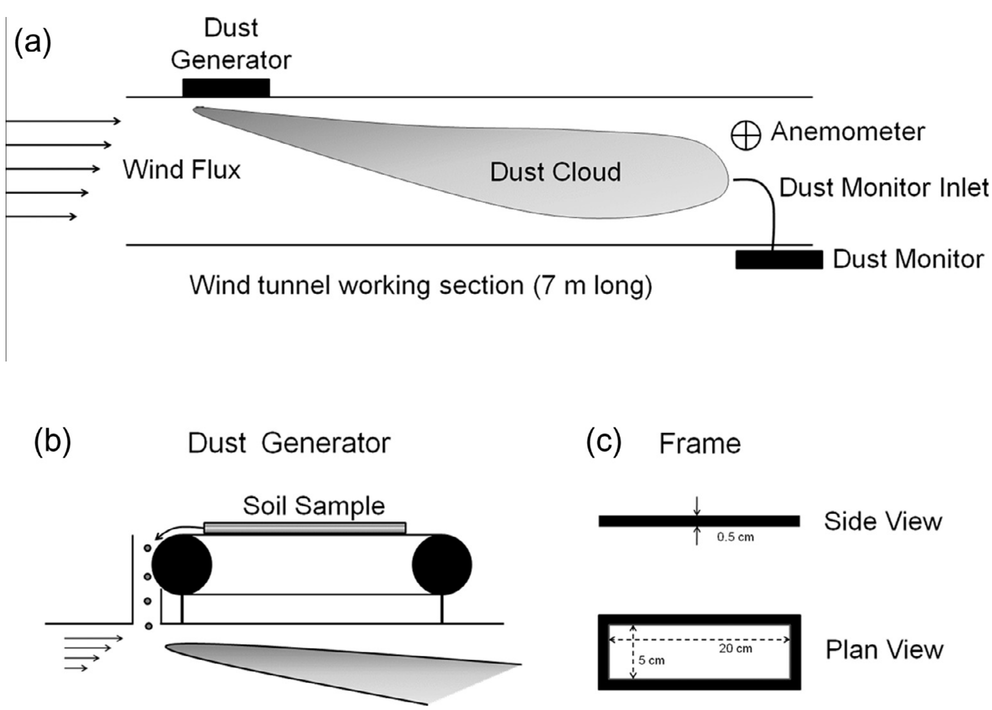

Fig. 2. Wind tunnel working section (a) dust generator (b) and frame (c).

(Fig. 1). The dust was generated by the sorting effects of soil material falling into a horizontal stream (principle of cross-flow gravitational separation). A conveyor belt was placed at the top of the beginning of the working section of the wind tunnel transporting the soil material inside the wind tunnel with a constant supplying rate (Fig. 2a and b). The soil was placed on the conveyor belt in a frame of 20 cm in length and 10 cm in width in a 0.5 cm thick layer (100 cm^3) which is covered by a plastic plate to minimize moisture changes during the runs (Fig. 2c). More constructive details of the wind tunnel and the dust generation can be found in Funk et al. (2008), Aimar et al. (2012).

The BSNE and MWAC were placed at the end of the working section of the wind tunnel (Fig. 2). The MWAC used had a plastic pipe instead of a glass pipe. In a previous wind tunnel experiment MWAC of both types were tested together at different heights (0.01, 0.09, 0.17, 0.21 and 0.4 m height) (Fig. 3). It was confirmed that the collector performance was identical. The plastic pipe-MWAC gave identical results as the original MWAC (glass pipe). The plastic pipe device has the advantage of having a larger inlet and outlet diameter and it can be drill easily. Two Grimm Environmental Dust Monitors (EDM#107) were used for PM measurements. One of the Grimms measured PM at the inlet and the other one at the outlet of the sampler (Fig. 4). Both Grimms were installed, as shown in Fig. 5, in order to avoid disturbing the air flux inside of the BSNE and MWAC while taking a part of the passing air. In the MWAC, both Grimms were installed in the walls of the inlet and outlet plastic pipes.

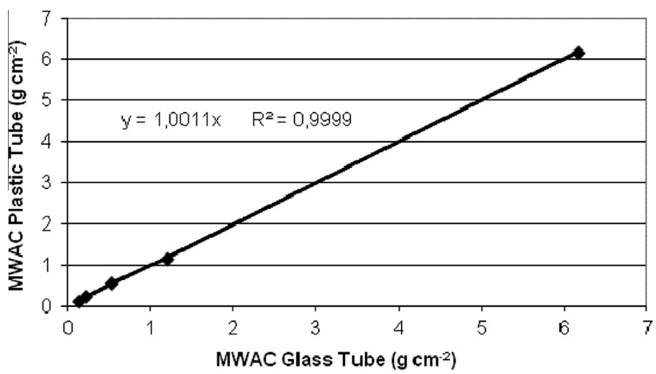

Fig. 3. Horizontal mass flux (g cm^{-2}) of MWAC with glass tube against MWAC with plastic at different height (0.01, 0.09, 0.17, 0.21 and 0.4 m).

A BSNE consist of an upper sampling unit and one storage pan assembled below it (Fryrear, 1986). A second sampling unit with a closed inlet was put on the BSNE to measure the PM concentrations of the outgoing air (Figs. 4 and 5). The PM concentration in the storage pan was measured through a hole to detect particles reaching this part of the BSNE. A third EDM#107 was installed next to the sampler inlet in order to measure the PM concentration of the arriving air. Each Grimm EDM#107 recorded the PM10, PM2.5 and PM1 air concentrations with a frequency of six seconds. The concentration of particles smaller than 10, 2.5 and 1 μm was automatically given in the output spreadsheet of the spectrometer. The data of the Grimm EDM#107 installed in the wind tunnel close to the sampler inlet were missed and because of that the entering efficiency of the sampler was not measured. However the concentration of PM10 was automatically given in the output screen spreadsheet of the Grimm. The PM concentrations were controlled to be similar during each experiment.

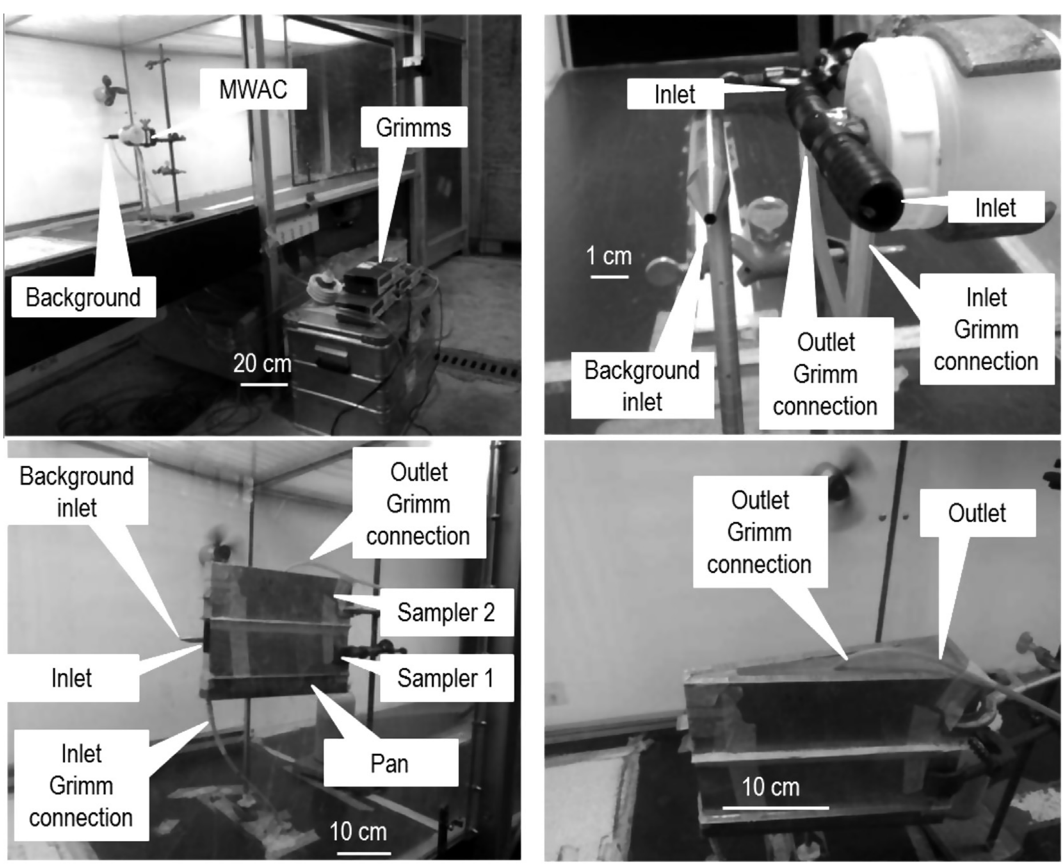

Fig. 4. Grimm Environmental Dust Monitors (EDM#107) installed in the MWAC (upper pictures) and BSNE (bottom pictures).

The soil used for this study was sandy with 2.9% coarse sand, 25.9% medium sand, 58.1% fine sand, 3.1% coarse silt, 3.0% medium silt, 1.0% fine silt, 6.0% clay and a total carbon content of 970 mg/100 g. The soil was dried at 21 °C and sieved through 2 mm. The wind tunnel was run in the recirculation mode, recirculating the enclosed air mass of 128 m^3, without incorporation of air from outside the tunnel. Simulations were split in two parts (Fig. 2): in the first part, PM emissions were measured during the continuous fall of the soil sample into the wind tunnel. Under these conditions PM emissions increased with time. The second part of the simulation was performed without adding further soil material in the wind tunnel, conditions under which PM concentrations slowly decreased with time. In the first step of the experiment the samplers were installed in a condition similar to the saltation zone (SAZ). In the second part of the experiment the samplers were installed in a condition similar to the suspension zone (SUZ) of the wind erosion event.

All wind simulations were performed by duplicate, at two different wind speeds 3 and 6.8 m s^{-1}, and each experiment lasted 10 min. Wind velocities were controlled with a high precision hot wire anemometer (Fa. Lambrecht). The positions of Grimm EDM#107 in the inlet and outlet of each sampler were changed between the first and the second measurement to prevent systematic errors by possible differences in the collection efficiency of the samplers.

PM concentrations measured in the inlet and the outlet of both samplers were correlated by means of simple linear regression test analysis using the calculation tool system of Microsoft Excel (Eq. (1)).

$$OC = a\ IC \tag{1}$$

where OC is the outlet PM concentration, a is the slope of the regression line and IC the inlet PM concentration.

The slopes of fitting equations of the regression analysis were used for calculating sampling efficiencies of BSNE and MWAC samplers with the following equation:

$$SE = (1 - a) \times 100 \tag{2}$$

where SE is the sampler's efficiency and a is the slope of the regression line of Eq. (1).

3. Results and discussion

Results show that PM10, PM2.5 and PM1 concentrations measured in the inlet and the outlet of the BSNE correlated linearly in the saltation zone (SAZ) and the suspension zone (SUZ) at both wind velocities ($P < 0.01$) (Fig. 6). The slope of the regression curve was used to calculate the efficiency of the traps by means of Eq. (2).

BSNE's efficiencies ranged from 12% to 32% for PM10, from 0% to 19% for PM2.5 and from 0% to 12% for PM1 (Table 1). Sharratt et al. (2007) determined, using the mass balance method in a wind tunnel, that BSNE efficiency for collecting PM10 in a silty – loam soil was 10% at a wind velocity of 18 m s^{-1} and 25% at a wind velocity of 5 m s^{-1}. The last value is similar to BSNE's efficiency for collecting PM10 in the SUZ at 6.8 m s^{-1} wind speed found in our study. Goossens and Buck (2012) correlated the BSNE's efficiencies and the particle size for particles between 10 and 100 μm in diameter, and extrapolating they estimated that the efficiencies of BSNE to catch PM2.5 and PM1 were 9.13% and 7.3% respectively. These efficiencies are similar to those found in the present study for BSNE in the SUZ. Shao et al. (1993), analyzing the particle-size distribution, estimated a BSNE's efficiency of 40% relative to an isokinetic trap for particles smaller than 10 μm. This efficiency is mainly caused by the transport of the clay particles as aggregates or skins upon sand grains.

BSNE's efficiency decreased with decreasing particle sizes (PM10 < PM2.5 < PM1) in SAZ and SUZ at both wind speeds (Table 1). For a wind speed of 3 m s^{-1} BSNE efficiencies were close to 0% for PM2.5 and PM1 in the SAZ but the efficiencies were 11% in the SUZ (Table 1). When wind speed was 6.8 m s^{-1} BSNE's efficiency was higher for PM2.5 than for PM1 in the SAZ and SUZ. The BSNE's efficiency for catching PM1 was close to 0% in the SAZ at 6.8 m s^{-1}. Our results show that BSNE's efficiency decreased when particle size decreased. This result is in agreement with those of previous studies for particles transported by suspension but for sizes coarser than 10 μm (Goossens and Buck, 2012; Feras et al., 2008). Our results and those of previous studies can be explained by the very low deposition velocity of the finest size particles, as most of them follow the air stream throughout the BSNE. In this regard, Sippola and Nazaroff (2004) found in experiments with particle sizes of 1, 3, 5, 9, and 16 μm in diameter and different air speeds in a S-shaped steel duct system, that the deposition velocities (it means adhesion) increase with increasing in particle size. The main mechanism of deposition of smaller particles is impaction at the edges.

When the same particle size and the same wind speed were analyzed, the BSNE's efficiency was in SUZ higher than in SAZ (Table 1). This can be explained by the bigger particles sizes transported in the air flux in SAZ. Those particles enter the BSNEs with

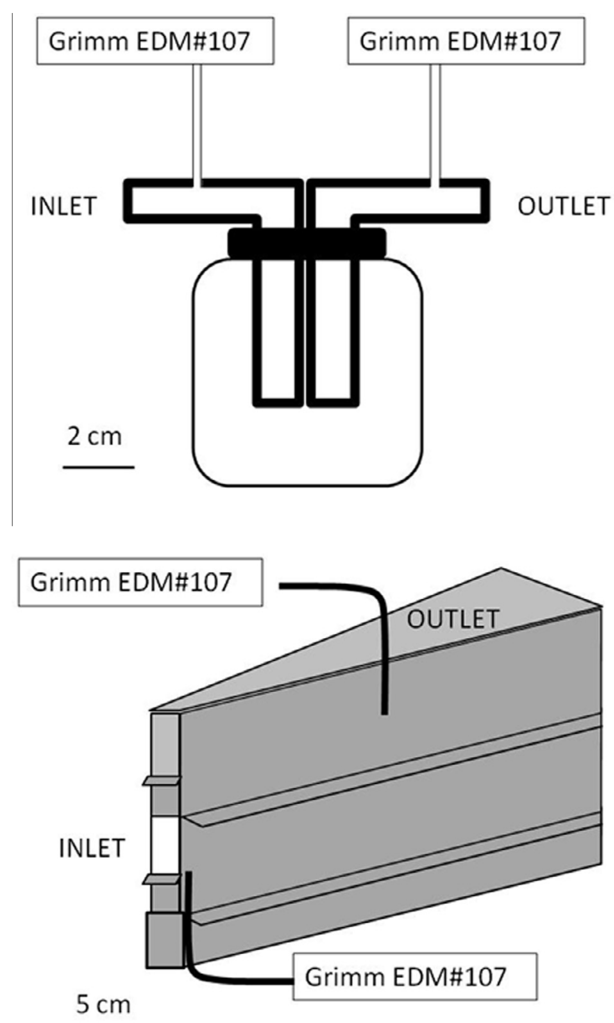

Fig. 5. Details of Grimm Environmental Dust Monitors (EDM#107) installation in BSNE and MWAC samplers.

higher inertia and hit the walls and the mesh, releasing the already deposited particles of PM10, PM2.5 and PM1. This mechanism also explains the lower correlation coefficients between the inlet and outlet PM concentrations in SAZ compared to the correlation coefficients obtained in SUZ (Fig. 6). In SUZ the particles are not big enough to hit the walls and release the particles trapped by adhesion to the sampler walls.

The BSNE's efficiency increased with increasing wind speed in SAZ for PM10 and PM2.5 and in SUZ for PM2.5 (Table 1). In relation to that, Goossens and Offer (2000) found that BSNE's efficiency for catching material transported by suspension increased lightly when the wind speed was increased from 1 to 5 m s^{-1}. Sippola and Nazaroff (2004) found that the deposition increase with increasing air velocity through a S-shaped duct for all particles sizes between 1 and 16 μm. Thatcher et al. (2002) studying the effects of air speed on particle deposition rate found that increasing the mean airspeed from 5 to 19 cm s^{-1}, by means of increasing fan speed, increased the deposition rate for all particle sizes studied by factors from 1.3 to 2.4, affecting larger particles more than smaller ones. Results found here can be explained by the dry deposition curve of PM as function of time for a closed room with stagnant air and turbulent air. In a closed room with stagnating air, PM of the same size will settle at the same speed, so that sedimentation will take several minutes to several hours. In a closed room with turbulent air, some PM will settle immediately and another will continue to be stirred beyond the settle time in a stagnant air. In moving air, particles more frequently contact the walls or the surfaces, over which they are retained by electrostatics or van-der-Waals forces. Therefore, once in contact with a surface, particles adhere very strong. PM1 particles are attached on surfaces by forces which are 10^6-times greater than the gravitational force (Bowling, 1988). Probably, the turbulent air flux inside the trap was higher at the highest wind speed, which favored the PM sedimentation and BSNE's efficiency. However the higher turbulent air flux inside the trap at higher wind speeds was not enough to improve PM1 sedimentation. Nomura et al. (1997) found that particles deposition in indoor air is due primarily to turbulent diffusion to the boundary layer at macroscopic surfaces within the room.

The results for MWAC show a lineal relationship between inlet and outlet PM10, PM2.5 y PM1 concentrations in all treatments ($P < 0.01$), excepting for SAZ at 6.8 m s^{-1} (Fig. 7). This experiment was repeated four times and no relations between inlet and outlet PM concentration were found in any case (Fig. 8). The results of this experiment can only be explained by the existence of alternating PM accumulation and re-suspension processes within the trap. Probably, PM was accumulated at the bottom of the trap (Fig. 9 left) and after that it was re-suspended by larger particles which enter the trap sporadically (Fig. 9 right). This can explain the strong variability between inlet and outlet PM concentrations.

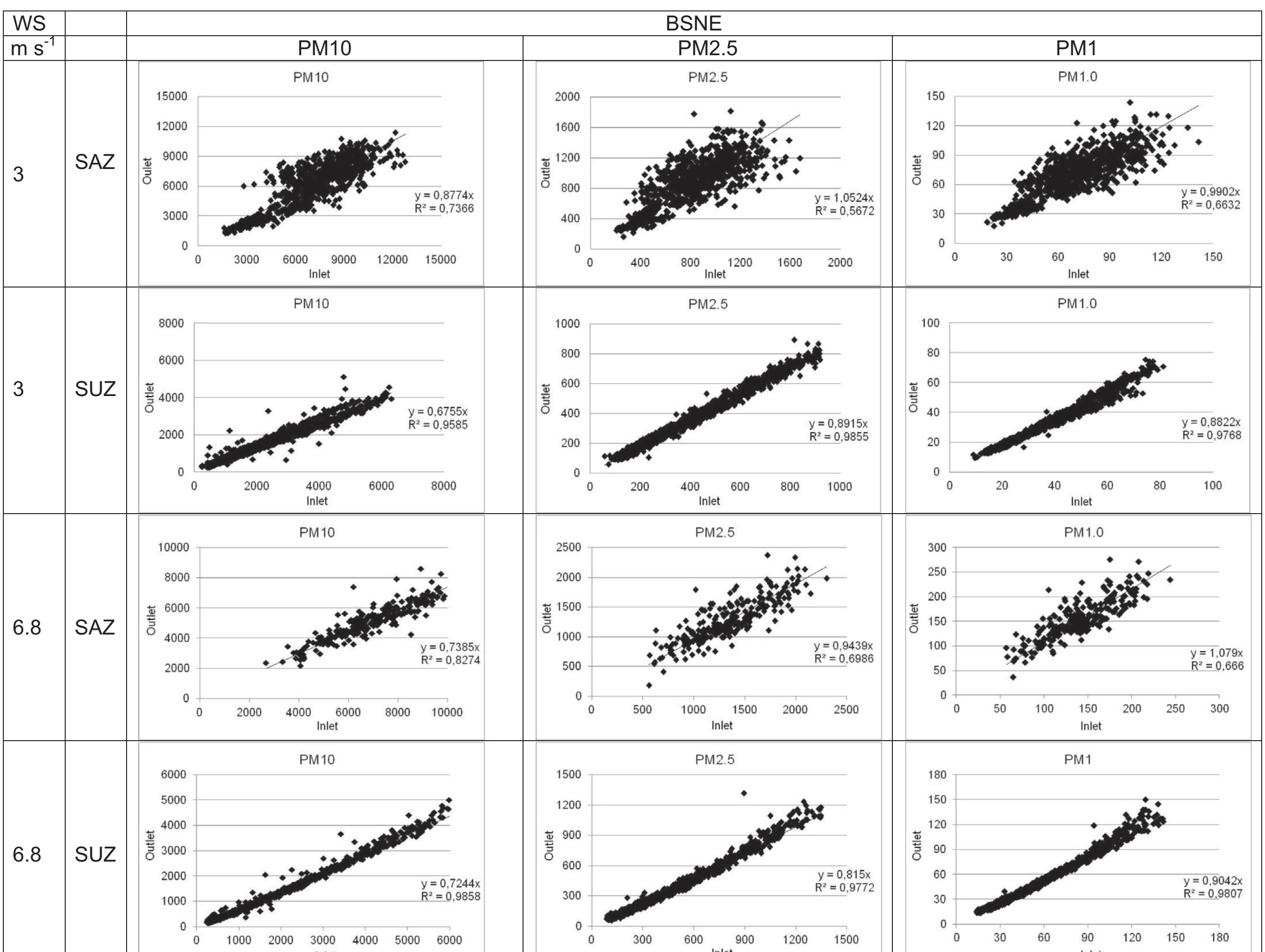

Fig. 6. PM concentration (μg m^{-3}) at the outlet as a function of the PM concentration at inlet of BSNE for three particle sizes and two wind speeds. Where WS is wind speed, SAZ saltation zone and SUZ suspension zone.

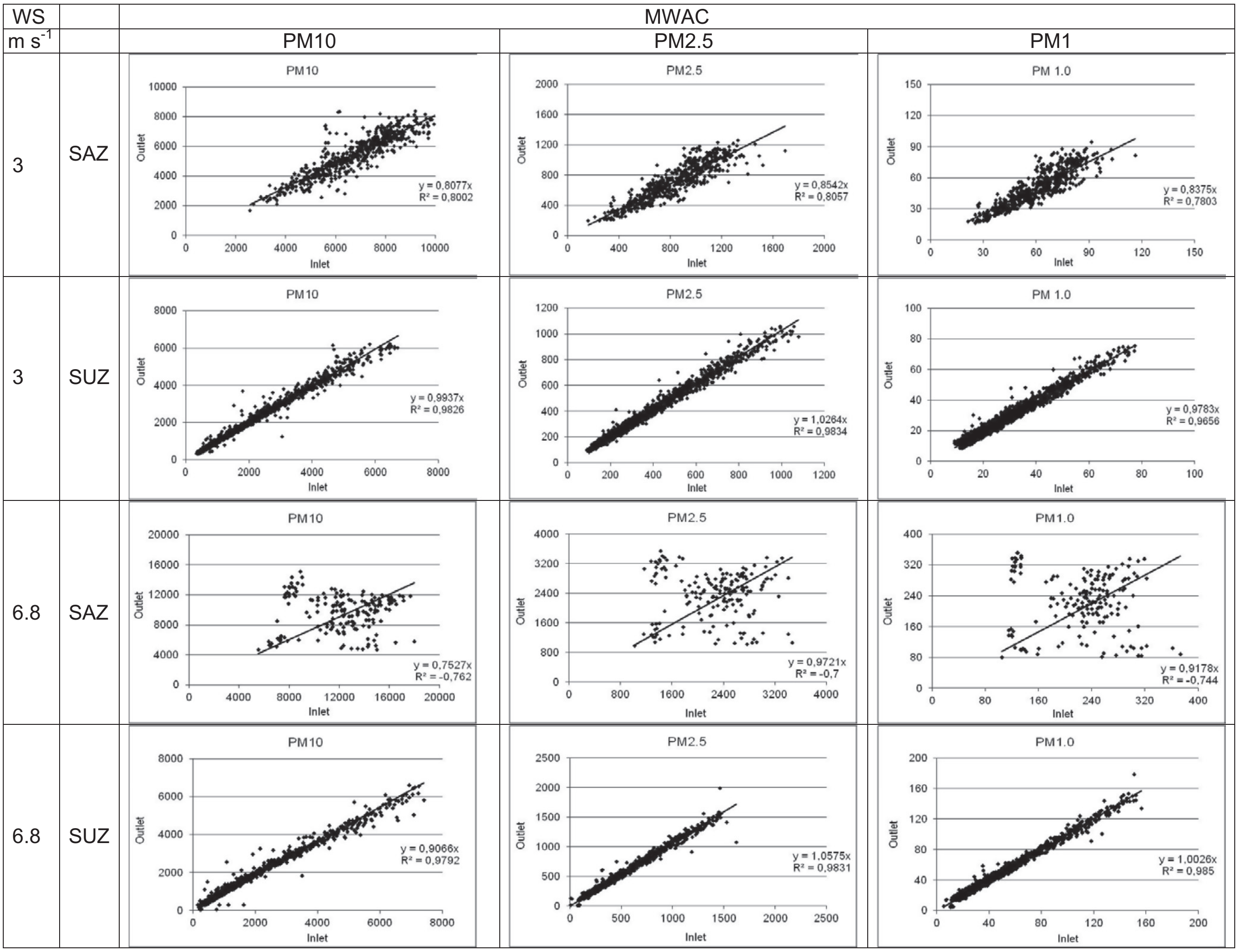

Fig. 7. PM concentration (μg m^{-3}) at the outlet as a function of the PM concentration at inlet of MWAC for three particle sizes and two wind speeds. Where WS is wind speed, SAZ saltation zone and SUZ suspension zone.

Table 1
Efficiencies of BSNE and MWAC for catching PM in the saltation zone (SAZ) and suspension zone (SUZ) at two wind speeds.

Particle size (μm)	SAZ				SUZ			
	3 m s^{-1}		6.8 m s^{-1}		3 m s^{-1}		6.8 m s^{-1}	
	BSNE	MWAC	BSNE	MWAC (%)	BSNE	MWAC	BSNE	MWAC
PM10	12.3	19.2	26.1	nd	32.4	0.6	27.6	9.3
PM2.5	0	14.6	5.6	nd	10.8	0	18.5	0
PM1	1.0	16.2	0	nd	11.8	2.1	9.6	0

nd = not determined.

The MWAC's efficiency ranged from 0.6% to 19.2% for PM10, from 0% to 14.6% for PM2.5 and from 0% to 16.2% for PM1 (Fig. 7). No results on direct measurements of MWAC's efficiencies for trapping PM10, PM2.5 and PM1 were found in the literature. MWAC's efficiency was higher than 14% in the SAZ at 3 m s^{-1} for the three particle sizes analyzed and for PM10 in SUZ at 6.8 m s^{-1}. However, MWAC efficiency was close to 0% for PM10, PM2.5 and PM1 in the SUZ at 3 m s^{-1} and for PM2.5 and PM1 in SUZ at 6.8 m s^{-1}. These results can be explained considering that in SUZ the air flux is less turbulent being not strong enough to produce the particle deposition. Nomura et al. (1997), in a laboratory experiment using an aerosol chamber, showed that particle deposition in indoor air is due primarily to turbulent diffusion to the boundary layer at macroscopic surfaces within the room. Our results are in agreement with those of Feras et al. (2008) who found that MWAC's efficiency was 0% for particles smaller than 50 μm transported by suspension at a wind speed of 13.4 m s^{-1}.

The highest efficiencies of MWAC existed in SAZ at 3 m s^{-1} for all analyzed particles sizes (Fig. 7). This can be explained considering that coarser particles are transported in SAZ, which is closer to the equilibrium of transport capacity than in SUZ. If these coarser particles enter the trap they favor the turbulent air flux inside it and the deposition of PM. However, these coarse particles are also responsible of the re-suspension at a wind speed of 6.8 m s^{-1}.

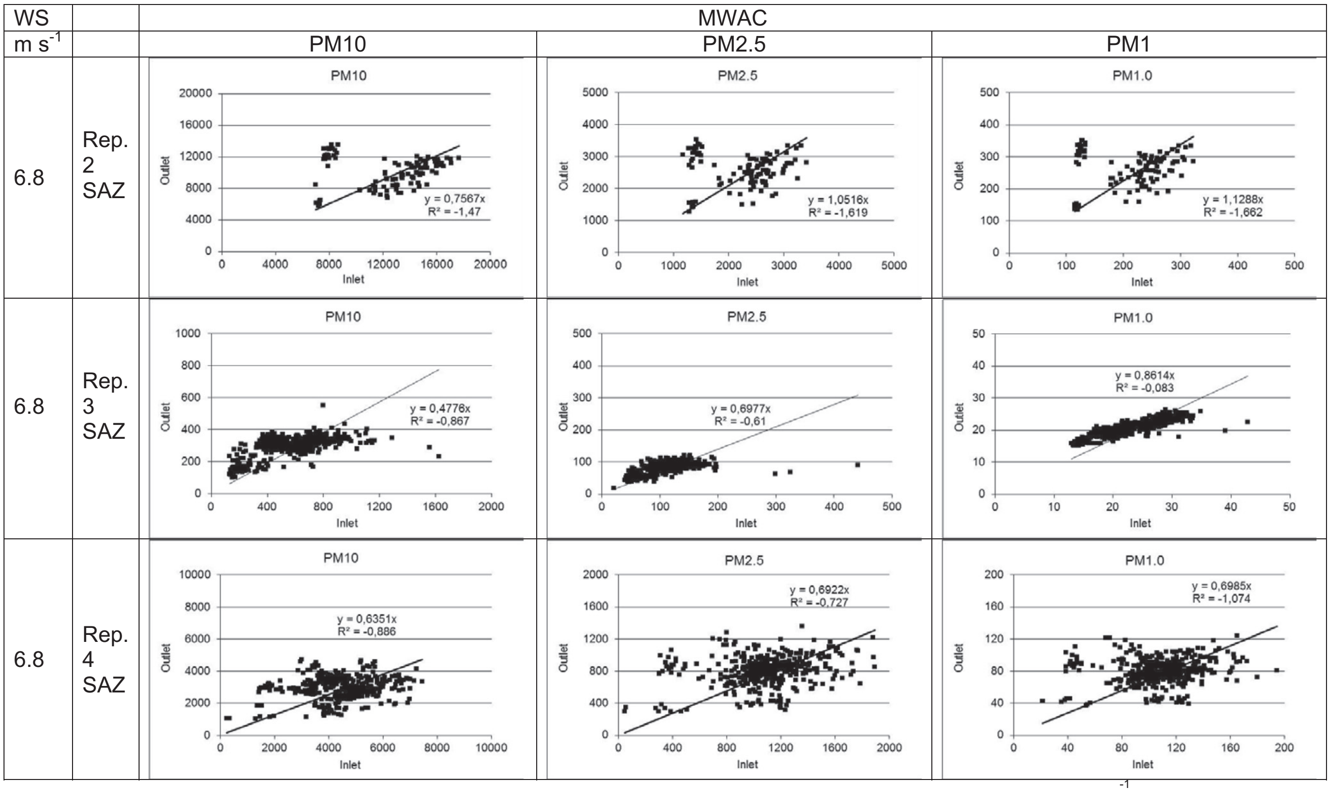

Fig. 8. PM concentration (μg m^{-3}) at the outlet as a function of the PM concentration at inlet of MWAC in the saltation zone (SAZ) at 6.8 m s^{-1} wind speed. Where WS is wind speed and Rep. repetition.

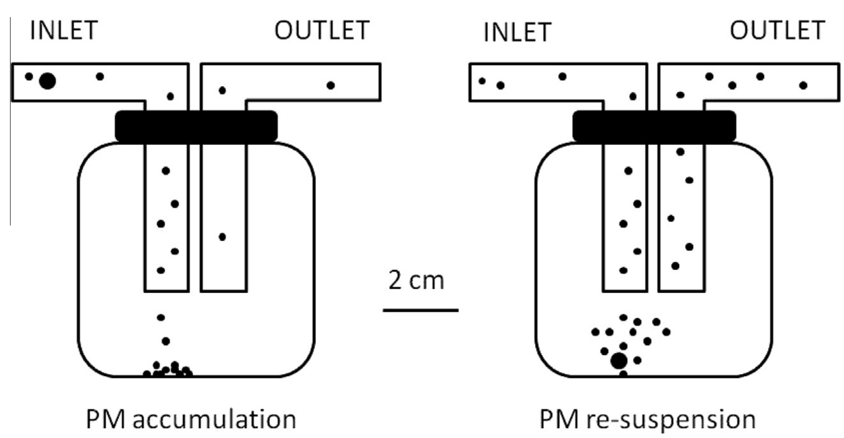

Fig. 9. Schematic representation of the probable processes of PM accumulation (Left) and re-suspension (Right) within MWAC samplers. Particles are not drawn in scale.

The comparison between traps showed that MWAC's efficiencies for trapping PM10, PM2.5 and PM1 were higher than those of BSNE's in SAZ at 3 m s^{-1} (Figs. 6 and 7). This can be explained on the basis of the different constructive details of the traps. BSNE's efficiencies were lower in SAZ, probably as a consequence of the larger inlet surface and the larger inner surface of the mesh between both parts, so that coarse particles transported in the air flux entering to the trap, hit and abrade the surfaces where the PM were already deposited. This mechanism released PM and reduced BSNE efficiency in SAZ. However, as concluded before, coarse particles transported in SAZ can promote the turbulent flux in the MWAC, improving its efficiency. On the other hand, BSNE's efficiencies to trap PM10, PM2.5 and PM1 were higher than MWAC's efficiencies in SUZ at wind speeds of 3 and 6.8 m s^{-1} (Figs. 6 and 7). In SUZ smaller particles have not enough inertia to release the particles already deposited at the surfaces of the BSNE. However, the lower inertia of the particles transported in SUZ is not enough to produce turbulent air flux inside the MWAC and allow the deposition of PM.

The different behavior of the BSNE and the MWAC to trap PM in SAZ and SUZ at different wind speeds probably also depends on the shape, dimensions and materials of the traps. Van de Vate (1972), using monodisperse polystyrene latex particles with diameters ranging from 0.09 to 1.3 μm, found that the deposition rate depends on the particle's terminal settling velocity, vessel height, vessel surface area, the particle diffusion coefficient, vessel volume and diffusion boundary layer thickness. Harrison (1979), using polystyrene latex, showed that the gravitational settling and convective diffusion losses of spherical latex aerosol particles to the inside walls of the aerosol container are dependent on the nature of the surface. Previous studies showed that the microscale roughness of the deposition surface may influence particle deposition rates. In relation to that, theoretical analyses and experimental results suggest that roughness elements of even a few microns in size could increase deposition (Browne, 1974; Fan and Ahmadi, 1993; Sehmel, 1973). Sippola and Nazaroff (2004) find that particle deposition rate in an insulated duct of acoustic fiberglass increased from 0.8 to 800 times compare to steel ducts. The magnitude of the increase in the deposition rate depended of the position of the deposition, the particle size and wind speed. All those studies showed that the material used to construct the sampler is also important for particle deposition rate and sampler efficiency. This knowledge can be potentially used for introducing modifications in the traps in order to improve their efficiency to catch PM.

4. Conclusions

The efficiencies of BSNE and MWAC for catching PM10, PM2.5 and PM1 changed with traps positions (saltation zone or suspension zone) and wind speed. In general terms, the efficiencies of BSNE and MWAC increased with increasing wind speeds: higher wind speeds seem to favor the air flux turbulence inside the trap, improving the turbulent deposition of PM. The BSNE's efficiency was higher than MWAC's efficiency in the suspension zone at wind speeds of 3 and 6.8 m s^{-1}, while MWAC's efficiency was higher that BSNE's efficiency in the saltation zone at a wind speed of 3 m s^{-1}. These results are still insufficient to fully describe the wind velocity and collector position effect on collector's efficiency, but provide evidences that collector's efficiency change as a function of these variables. Results also showed that BSNEs and MWACs can be potentially used for PM10, PM2.5 and PM1 emission studies but more research is needed in order to understand and improve their efficiency.

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