



Differences in 24-h average PM_{2.5} concentrations between the beta attenuation monitor (BAM) and the dichotomous sampler (Dichot)



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HIGHLIGHTS

- The PM_{2.5} beta attenuation monitors (BAMs) without FEM designation was studied.
- PM_{2.5} concentrations were overestimated by the BAMs compared to a manual sampler.
- Acid gas absorption by glass fiber filters is the major cause of the overestimation by the BAMs.
- Aerosol water content also affects the overestimation.

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ABSTRACT

In this study, PM_{2.5} concentrations were measured simultaneously by a Dichotomous sampler (Dichot, Model SA241, Andersen Inc., Georgia, USA) (PM_{2.5,D}) and a beta attenuation monitor (BAM) (PM_{2.5,B}) at each of three air monitoring stations in Taiwan. Results show that PM_{2.5,B} concentrations measured by the VEREWA-F701 BAM (without federal equivalent method (FEM) designation) are consistently higher than PM_{2.5,D} concentrations by 58.4 ± 37.4% at Jhongshan station, while less overestimation exists at Sinhuang and Judong stations, which is 29.8 ± 20.2 and 28.4 ± 19.0%, respectively, where the earlier version of the Met-One BAM-1020s (without FEM designation) are used. Different factors influencing the overestimation, which include aerosol water content, volatilization of inorganic species and positive artifacts due to acid gas adsorption by the glass fiber filter tapes were studied for the BAM-1020. Results show that the overestimation is mainly caused by the positive artifacts due to acid gas adsorption by the glass fiber filter tapes used in the BAM-1020. Aerosol water content and volatilization loss of inorganic semi-volatile species are found to be less important to the overestimation.

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1. Introduction

The dichotomous sampler (Dichot) and Beta attenuation mass monitor (BAM) are commonly used instruments for measuring ambient fine particle (PM_{2.5}) concentrations in Taiwan. The Dichot is a manual PM₁₀ FRM (federal reference method) sampler that collects aerosols for 24-h for determining the daily average PM_{2.5} concentration by the gravimetric measurement method. The collected samples can also be analyzed for chemical compositions for identifying possible PM_{2.5} sources. In addition, the Dichot simultaneously collects both PM_{2.5} and coarse particle (PM_{10-2.5}) samples and has often been used for particulate matter (PM)

studies in Taiwan (Tsai and Perng, 1998; Chen et al., 2010; Zhu et al., 2010; Liu et al., 2011; Gugamsetty et al., 2012). The BAM is a continuous monitor that provides hourly PM_{2.5} data and is used in Taiwan air quality monitoring network for determining the compliance with the ambient air quality standards. Its measurement principle is based on the relationship between the attenuation of beta ray and the particle deposit on the filter tape, which can be described as (Jaklevic et al., 1981):

$$I = I_0 e^{-\mu x} \quad (1)$$

where I and I_0 are the attenuated and un-attenuated beta ray intensities (counts s⁻¹), respectively, μ is the mass absorption coefficient (m² kg⁻¹), and x is the mass areal density of particle deposit (kg m⁻²).

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Differences in measured PM concentrations between manual samplers and the BAM often exist as documented in many open literature. This problem is more severe under high humidity conditions. At ambient relative humidity (RH) higher than 85%, water absorbed on aerosols was found to result in higher PM₁₀ concentrations in the Wedding beta gauge monitor (USEPA FEM, EQPM-0391-081) as compared to the Sierra-Andersen SA1200 hi-vol sampler (Chang et al., 2001; Tsai et al., 2006). Chang and Tsai (2003) developed a model to calculate the effect of RH on the reading of the PM₁₀ beta gauge monitor. Results showed that absorbed water did not evaporate completely at RH higher than 85% and remaining water in particles accounted for higher beta gauge readings than hi-vol PM₁₀ concentrations. Many other researchers also found differences existed between the PM₁₀ or PM_{2.5} concentrations of the BAM and manual samplers (Arends et al., 2000; Hauck et al., 2004; Huang and Tai, 2008; Salminen and Karlsson, 2003; Shin et al., 2011; Takahashi et al., 2008; Watanabe et al., 2000). To resolve this problem, the BAM of Met One, Inc. (Model 1020, Met One Instruments Inc., Washington, USA, hereafter referred as BAM-1020) uses a “smart heater” to control the RH of incoming aerosol stream to 35% or below for minimizing the positive artifact due to aerosol water content.

Gobeli et al. (2008) pointed out that earlier version of the BAM-1020 still showed a moderate positive multiplicative bias (10–15%) as compared to the results of the collocated manual samplers even after when a smart heater was used. This is possibly due to positive sampling artifacts formed on the glass fiber filter tapes used in the BAM-1020 in which adsorbed gaseous HNO₃ and SO₂ were measured as particulate NO₃⁻ and SO₄²⁻, respectively (Coutant, 1977; Liberti et al., 1978; Appel et al., 1984; Lipfert, 1994; Hsu et al., 2007), while Teflon filters used in manual samplers are inert to the adsorption of these gaseous species. The bias was eliminated in the new version of the BAM-1020 after physical and operational modifications (Gobeli et al., 2008) by probably adjusting μ for PM_{2.5} data conversion, which later became the Federal Equivalent Method (FEM) in 2008 with the designation number EQPM-0308-170. Successful field comparison tests with BGI PQ-200 PM_{2.5} FRM samplers equipped with very sharp cut cyclone (VSCC) PM_{2.5} inlets showed that the new BAM-1020 met the US-EPA comparability criteria with the slopes of linear regression ranging from 0.94 to 1.02 and the intercepts ranging from -0.96 to 0.56 (Gobeli et al., 2008).

However, some measurement differences between the new BAM-1020 and the FRM manual sampler still exist in addition to the differences in the slopes of linear regression which range from 0.94 to 1.02 at four different sites, as can be observed in Fig. (1)–(4) of Gobeli et al. (2008). This is because the concentration of acid gases might differ from one site to the other resulting in different extent of positive artifacts.

There are 74 non-FEM-designated BAMs used in the existing Taiwan air monitoring stations (TAMS), in which half are earlier version of the BAM-1020 and the other half are the BAMs from VEREWA company (Model F701, VEREWA, Germany, hereafter referred as VEREWA-F701). The existing BAM-1020s used in the TAMS were acquired in 2005 when the BAM-1020 had not been designated as the FEM. The data obtained from these non-designated BAMs and those from manual samplers are therefore expected to be different.

Beside the influencing factors mentioned above, the volatilization of collected particles during sampling process also contributes to the measurement difference between the BAM and Dichot. The evaporation of semi-volatile species, such as NH₄Cl and NH₄NO₃, may occur when ambient temperature changes or pressure drop increases across the filter during sampling (Wang

and John, 1988; Zhang and McMurry, 1987, 1992; Cheng and Tsai, 1997). Since the filter material and face velocity across the filter are different between the BAM and the manual sampler, pressure drop may also differ resulting in different extent of volatilization.

In this study, field comparison tests between the BAM and Dichot were conducted at three TAMS for quantifying the differences between these two instruments. Factors influencing the measurement differences were studied, including aerosol water content, volatilization of inorganic species, and positive artifacts due to acid gas adsorption by the glass fiber filter tapes of the BAM.

2. Experimental methods

The sampling was conducted from May 2011 to December 2012 at three air monitoring stations, namely Sinjhuang (25°02'N, 121°25'E), Jhongshan (25°03'N, 121°31'E), and Judong, (24°44'N, 121°05'E) stations located in northern Taiwan as shown in Fig. 1. Totally, 108 24-h samples (34 for Sinjhuang, 38 for Jhongshan, and 36 for Judong) were collected by the Dichot while hourly PM_{2.5} concentrations were continuously monitored by a collocated BAM at each of these stations. The BAM-1020 was used in Sinjhuang and Judong stations while the VEREWA-F701 was used in Jhongshan station. The BAMs installed permanently at the monitoring stations were operated by the Taiwan EPA while the same Dichot was moved to different stations at different days for the comparison study. A smart heater (Model BX-827, Met One Instruments Inc., Washington, USA) is installed in the BAM-1020 to control the RH of the incoming aerosol stream to 35% or below for minimizing the positive artifacts due to aerosol water content. Whenever the humidity of the aerosol stream exceeded the RH set-point of 35%, the heater will warm the sampled air until the RH reduced to 35% or below. Similarly, a heater coil with the controller is also installed in the VEREWA-F701 for the dehumidification of the incoming aerosol stream. All of the instruments were operated at the flow rate of 16.7 L min⁻¹ which was calibrated by using a bubble flow meter (Gilibrator-2 system, Sensidyne, USA). Glass fiber filter tapes (BAM-1020: Code 400-80021, Hario sci.; VEREWA-F701: BF703GF45, VEREWA) were used in the BAMs while Teflon filters (Teflo R2PL037, Pall Corp., New York, USA) were used in the Dichot. Hourly continuous data of the BAMs were obtained from the Taiwan EPA and converted into 24-h average data in accordance to the sampling schedule of the Dichot which normally started from 3 to 4 PM on a sampling day.

To quantify the positive artifacts in the BAMs due to gas absorption by the glass fiber filter tapes, comparison tests by using two collocated Dichots for 24 h were conducted at the NCTU campus from Jan. to Mar. 2013, in which one of the Dichot was equipped with the Teflon filter while the other was equipped with the glass fiber filter cut from the glass fiber filter tape of the BAM-1020. Totally seventeen 24-h sampling data were collected.

All sampling filters were weighed by a microbalance (Model CP2P-F, Sartorius, Germany) before and after 24-h sampling after they were conditioned for 24-h in an environment conditioning room where the RH and temperature were kept at 40 ± 2% and 21 ± 1 °C, respectively. The electrostatic charge of the Teflon filters was eliminated by an ionizing air blower (Model CSD-0911, MELSEI, Japan) before weighing. The precision of weighing was determined to be 2 µg by repeated weighing for at least five times. After gravimetric analysis, the filters were analyzed by an ion chromatograph (IC, Model DX-120, Dionex Corp, Sunnyvale, CA) for ionic species of F⁻, Cl⁻, NO₃⁻, SO₄²⁻, NH₄⁺, Na⁺, K⁺, Mg²⁺, and Ca²⁺.

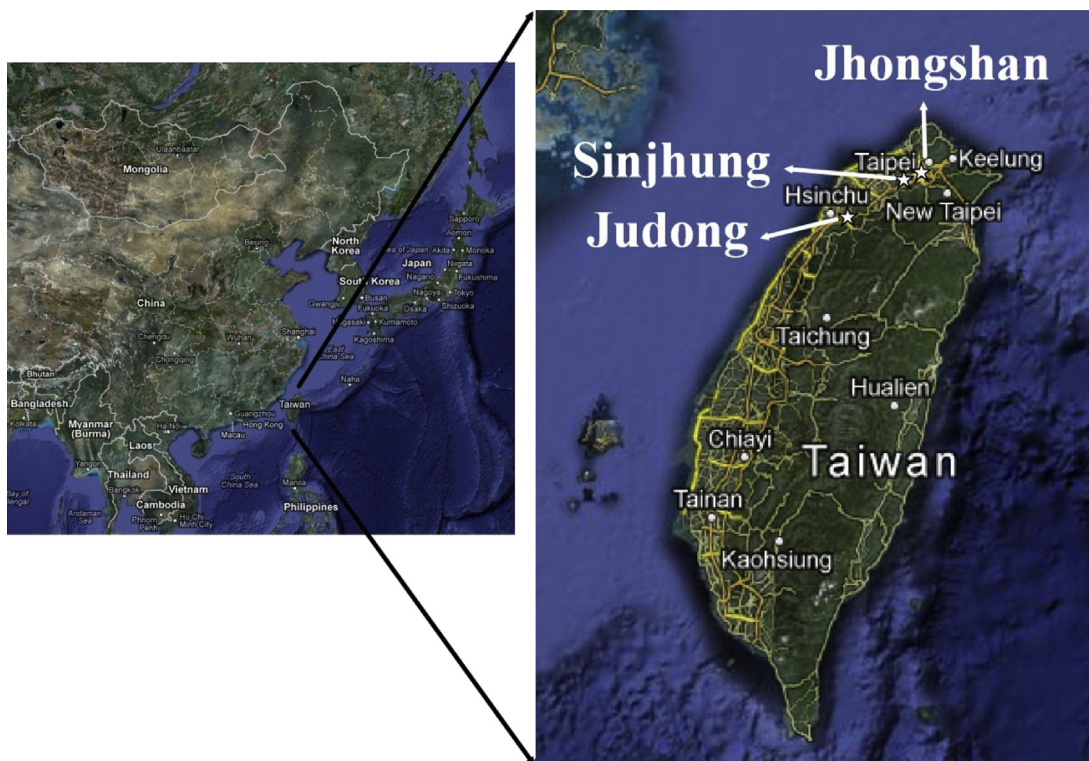


Fig. 1. Location of sampling sites.

3. Results and discussions

Fig. 2 (a)–(c) show the $PM_{2.5}$ concentrations measured by the BAM ($PM_{2.5,B}$) and those by the Dichot ($PM_{2.5,D}$) at Sinjhuang, Jhongsan, and Judong stations, respectively. It can be seen that $PM_{2.5,B}$ concentrations correlate linearly with the $PM_{2.5,D}$ concentrations very well with the slope of 1.31 and 1.25 (intercept at $0.0 \mu\text{g m}^{-3}$), and R^2 of 0.86 and 0.93, respectively, at Sinjhuang and Judong stations. $PM_{2.5,B}$ concentrations were higher than $PM_{2.5,D}$ concentrations by 29.8 ± 20.2 and $28.4 \pm 19.0\%$, respectively, at these two stations. However, poorer correlation ($R^2 = 0.50$) and larger difference ($58.4 \pm 37.4\%$) between $PM_{2.5,B}$ and $PM_{2.5,D}$ concentrations was observed at Jhongsan station. This is possibly due to the difference in the instrument type, in which the BAM-1020 was used in Sinjhuang and Judong stations while VEREWA-F701 was used in Jhongsan station.

The possible influencing factors to the measurement differences between the BAM-1020 and Dichot, including aerosol water content, volatilization of inorganic species and positive artifacts due to acid gas adsorption by the glass fiber filter tapes, will be discussed further below. Since the VEREWA-F701 used in Jhongsan station has never received the FEM designation and its measurement data are quite different from those of the BAM-1020, there is no further discussion on its data in the following sections.

3.1. The effect of aerosol water content

The reading of the BAM may be influenced by the ambient RH because of water adsorption by inorganic aerosols when the deliquescence point is exceeded (Pilinis et al., 1989; Lee et al., 2001; Chang et al., 2001; Khlystov et al., 2005). To examine this effect, the theoretical water content of ambient aerosols (W , $\mu\text{g m}^{-3}$) in

$PM_{2.5,D}$ was calculated by the ISORROPIA II (Fountoukis and Nenes, 2007) (W_{ISO} , $\mu\text{g m}^{-3}$) and E-AIM (Wexler and Clegg, 2002) (W_{AIM} , $\mu\text{g m}^{-3}$) models. W is mainly governed by the relative abundance of inorganic salts in aerosols with a possible influence by water-soluble organic matter at low RH of 50% (Aggarwal et al., 2007). As most of the RH is greater than 60% in Taiwan (data are shown in Fig. 3), only the influence of inorganic ions on W is considered in this study.

The relationship between the ratio of calculated W to $PM_{2.5,D}$ and RH is shown in Fig. 3, in which the RH is shown to be mostly greater than 60% and high $W/PM_{2.5,D}$ ratios are seen as the air environment in Taiwan is humid. The ratios increase exponentially with increasing RH and can become greater than 0.5 as the RH is higher than 80–85%. Since the controlled humidity after the smart heater was not monitored during sampling days, it is hard to determine how much aerosol water content was removed. Therefore, the estimated W was added to the $PM_{2.5,D}$ directly for comparison with $PM_{2.5,B}$. The comparison between $PM_{2.5,B}$ and $PM_{2.5,D} + W_{ISO}$ or $PM_{2.5,D} + W_{AIM}$ at both Sinjhuang and Judong stations is shown in Fig. 4 (a) or (b), respectively. The relationship between $PM_{2.5,B}$ and $PM_{2.5,D}$ is also shown in the figures for comparison. Results show that $PM_{2.5,B}$ concentrations at both stations are consistently higher than $PM_{2.5,D}$ concentrations by $28.96 \pm 19.46\%$, and both are also highly correlated with the R^2 of 0.90. After adding W_{ISO} or W_{AIM} to $PM_{2.5,D}$, the measurement difference between the BAM-1020 and Dichot is found to decrease to $7.0 \pm 22.6\%$ or $8.3 \pm 26.5\%$, respectively, but the original good correlation between $PM_{2.5,B}$ and $PM_{2.5,D}$ is lost with the decrease of R^2 from 0.90 to 0.62 or 0.56, respectively. This indicates that aerosol water content is not the major influencing factor on the difference between $PM_{2.5,B}$ and $PM_{2.5,D}$ and other possible factors need to be examined further.

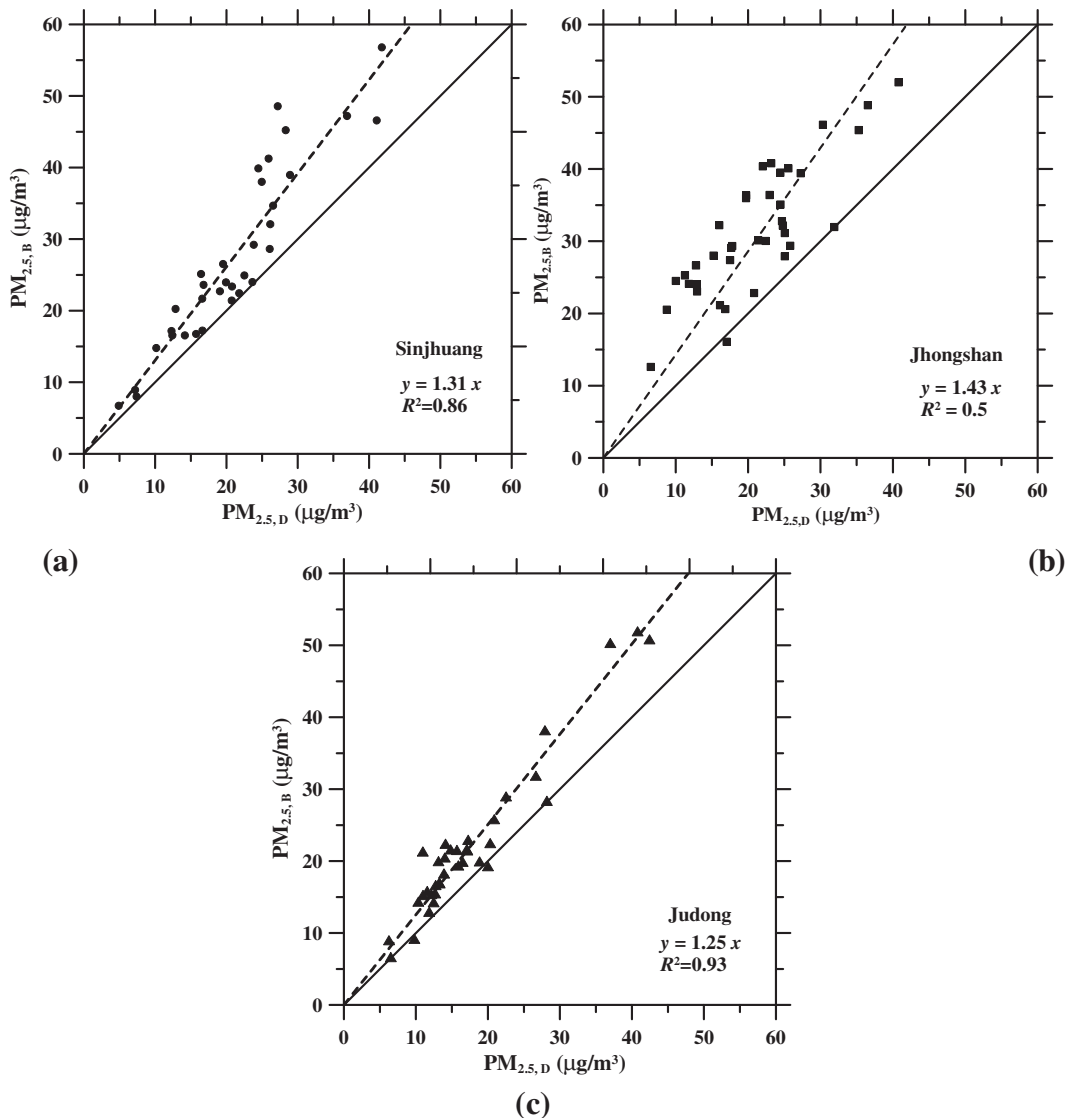


Fig. 2. Comparison of $PM_{2.5,D}$ with $PM_{2.5,B}$ concentrations at (a) Sinjhuang (number of sample = 34), (b) Jhongshan (number of sample = 38) and (c) Judong stations (number of sample = 36).

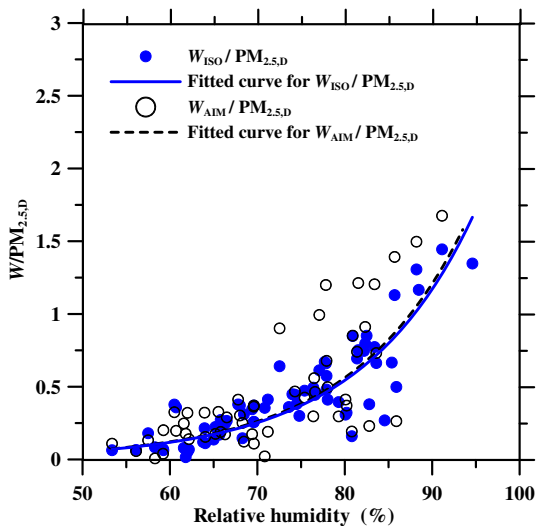


Fig. 3. Calculated aerosol water content versus relative humidity, at Sinjhuang and Judong stations.

3.2. The effect of semi-volatile inorganic aerosols

Semi-volatile species such as ammonium nitrate and ammonium chloride evaporate from filters during sampling. To examine this effect on the difference between $PM_{2.5,B}$ and $PM_{2.5,D}$, the volatilization loss of inorganic species in both BAM-1020 and Dichot during sampling is estimated using the model of Zhang and McMurry (1991). The sampling efficiency for a semi-volatile aerosol species, η_e , is defined as:

$$\eta_e = \frac{1}{1 + \xi \left[\frac{\rho_0}{\rho_e} + \left(\eta_e - \frac{\rho_0}{\rho_e} \right) / \delta \right] \rho_e / C_m} \quad (2)$$

where ρ_0 is the gas-phase concentration of the species at the sampler inlet; ρ_e is the equilibrium gas-phase concentration in the atmosphere; ξ and δ are the dimensionless pressure ratios which are defined as $\Delta P / (P_0 - \Delta P)$ and $\Delta P / P_0$, respectively; P_0 represents the inlet pressure while ΔP denotes the pressure drop

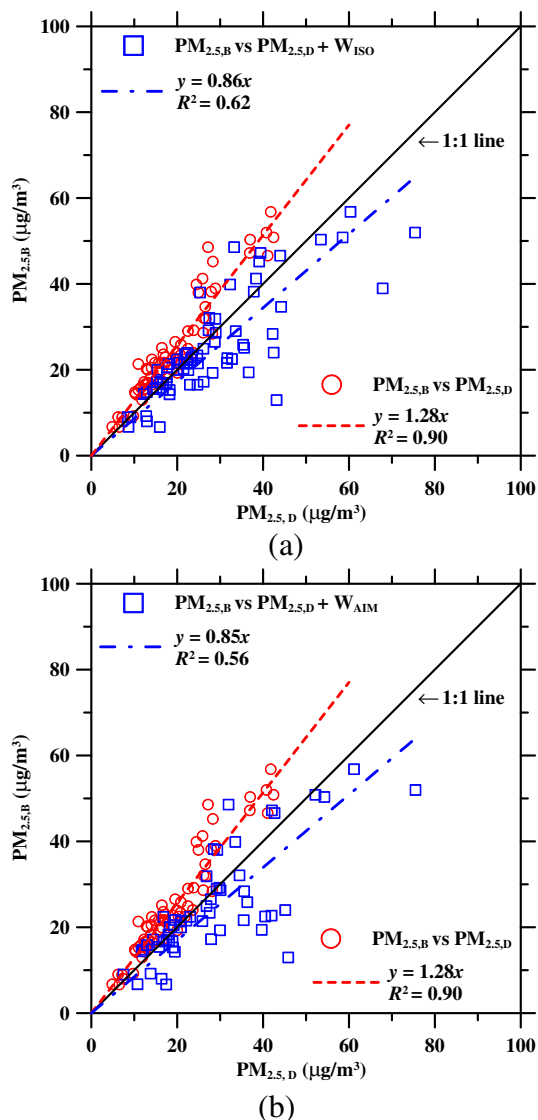


Fig. 4. Relationship of $PM_{2.5,B}$ between (a) $PM_{2.5,D} + W_{ISO}$ and (b) $PM_{2.5,D} + W_{AIM}$, at Sinjhuang and Judong stations.

across the filter; C_m is the species concentration in the particle collected on the filter. More detail calculation procedure is given in the Supporting information. Table 1 summarizes the mean concentrations of inorganic ions during the sampling days at Sinjhuang and Judong stations. It can be seen that NH_4^+ and NO_3^- are the major components of the semi-volatile species. Therefore, only the volatilization of ammonium nitrate is estimated in this study.

The percentage of the evaporated ammonium nitrate concentration (EM_B) in $PM_{2.5,B}$, versus the percentage of the evaporated ammonium nitrate concentration (EM_D) in $PM_{2.5,D}$ is shown in Fig. 5 for comparison. Most of the data show the volatilization loss in the BAM-1020 is much higher than that in the Dichot mainly due to the higher pressure drop in the former. However, both EM_B and EM_D concentrations are very low which range from 0.06 to 1.04 and 0.001–1.06 $\mu g\ m^{-3}$, respectively, accounting averagely for only 1.16% in $PM_{2.5,B}$ and 0.34% in $PM_{2.5,D}$, respectively. That is, the effect of volatilization loss on the difference between $PM_{2.5,B}$ and $PM_{2.5,D}$ is not a dominant factor.

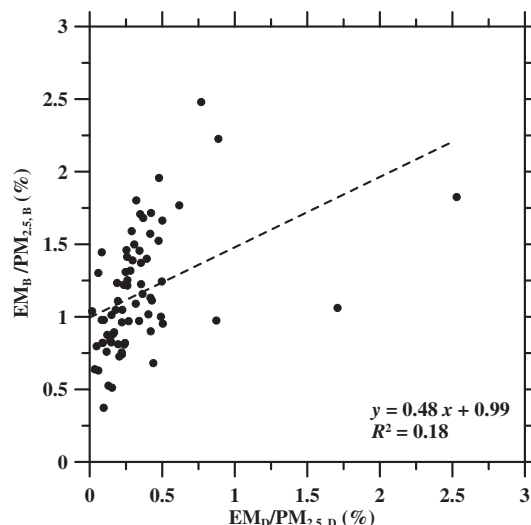


Fig. 5. Percentage of EM_D in $PM_{2.5,D}$ versus percentage of EM_B in $PM_{2.5,B}$ at Sinjhuang and Judong stations. (EM_B and EM_D are evaporated ammonium nitrate concentrations in $PM_{2.5,B}$ and $PM_{2.5,D}$, respectively).

3.3. The effect of acid gas adsorption by glass fiber filter

Fig. 6 shows the comparison of $PM_{2.5}$ concentrations measured by the Dichot equipped with Teflon filters ($PM_{2.5,DT}$, range: 5.2–68.0 $\mu g\ m^{-3}$) with those determined by glass fiber filters ($PM_{2.5,DG}$, range: 6.7–83.3 $\mu g\ m^{-3}$) at the NCTU campus. Since more inorganic species were collected by glass fiber filters than Teflon filters as can be seen in Table 2, the total oversampled inorganic ion concentrations in glass fiber filters (ion_{G-T}) are subtracted from the $PM_{2.5,DG}$ concentrations and the data are also plotted in Fig. 6 for comparison. Results show that the correlation between $PM_{2.5,DT}$ and $PM_{2.5,DG}$ is quite linear with the slope of 1.17 (intercept at 0.0 $\mu g\ m^{-3}$) and R^2 of 0.99. The $PM_{2.5,DG}$ concentrations are higher than $PM_{2.5,DT}$ concentrations by $21.2 \pm 9.8\%$ which is comparable to but slightly less than the difference between $PM_{2.5,B}$ and $PM_{2.5,D}$ at Sinjhuang and Judong stations. The latter is 29.8 ± 20.2 and $28.4 \pm 19.0\%$, respectively. After subtracting the

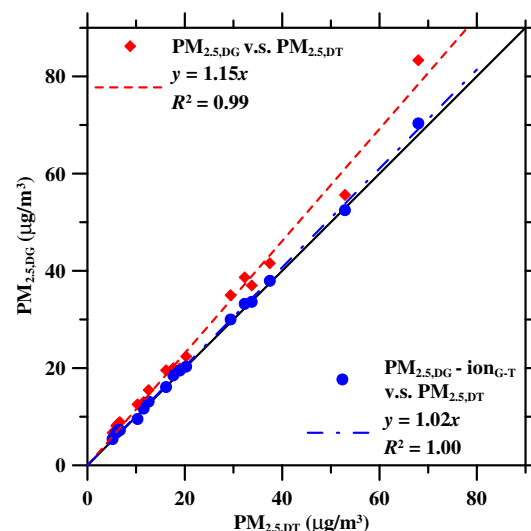


Fig. 6. Comparison of $PM_{2.5,DT}$ with $PM_{2.5,DG}$ concentrations at the NCTU campus (number of sample = 17).

Table 1Mean concentrations of inorganic ions at Sinjhuang (number of sample = 34) and Judong (number of sample = 36) (Unit: $\mu\text{g m}^{-3}$).

	F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺	NH ₄ ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Total ions
Sinjhuang	0.13 ± 0.14	0.15 ± 0.17	0.50 ± 0.81	5.56 ± 2.65	0.21 ± 0.10	1.67 ± 0.87	0.20 ± 0.13	0.03 ± 0.03	0.09 ± 0.06	8.54 ± 3.63
Per. ^a	1.52%	1.76%	5.85%	65.11%	2.46%	19.56%	2.34%	0.35%	1.05%	100.0%
Judong	0.05 ± 0.06	0.09 ± 0.12	0.24 ± 0.41	5.61 ± 3.45	0.26 ± 0.2	1.51 ± 1.13	0.20 ± 0.14	0.05 ± 0.04	0.14 ± 0.11	8.14 ± 4.54
Per.	0.61%	1.11%	2.95%	68.92%	3.19%	18.55%	2.46%	0.61%	1.72%	100.0%

^a Percentages of each ion concentration in total ion concentration.**Table 2**Mean concentrations of inorganic ions in the PM_{2.5} samples collected by Teflon and glass fiber filters (number of samples = 17) (Unit: $\mu\text{g m}^{-3}$).

	F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Na ⁺	NH ₄ ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Total ions
Teflon	FB ^a	ND ^c	0.01 ± 0.01	ND	0.02 ± 0.01	0.03 ± 0.03	ND	0.01 ± 0.02	0.01 ± 0.01	0.09 ± 0.06
	S ^b	0.05 ± 0.05	0.12 ± 0.24	2.23 ± 3.09	8.57 ± 4.59	0.46 ± 0.42	3.39 ± 2.82	0.45 ± 0.45	0.22 ± 0.19	0.10 ± 0.06
	S – FB	0.04 ± 0.05	0.11 ± 0.23	2.23 ± 3.09	8.56 ± 4.60	0.42 ± 0.41	3.39 ± 2.82	0.44 ± 0.46	0.22 ± 0.19	0.09 ± 0.07
Glass fiber	FB ^a	0.03 ± 0.03	0.17 ± 0.08	0.11 ± 0.05	3.81 ± 2.71	3.98 ± 1.52	ND	0.46 ± 0.17	0.11 ± 0.07	0.18 ± 0.12
	S ^b	0.08 ± 0.07	0.81 ± 0.49	3.16 ± 3.58	13.21 ± 5.17	4.69 ± 2.01	3.66 ± 3.54	1.22 ± 0.51	0.32 ± 0.27	0.35 ± 0.14
	S – FB	0.05 ± 0.06	0.64 ± 0.46	3.05 ± 3.58	9.41 ± 5.36	0.71 ± 0.73	3.66 ± 3.54	0.76 ± 0.57	0.21 ± 0.23	0.17 ± 0.15
	ion _{G-T} ^d	0.00 ± 0.04	0.53 ± 0.34	0.83 ± 0.76	0.85 ± 1.25	0.29 ± 0.70	0.27 ± 0.99	0.32 ± 0.25	-0.01 ± 0.08	0.07 ± 0.14
	% ^e	0.00%	16.83%	26.35%	26.98%	9.21%	8.57%	10.16%	-0.32%	2.22%

^a Mean concentrations in field blank samples.^b Mean concentrations in 24-h samples, 16.7 L min⁻¹.^c Below detection limit.^d Differences between the “S–FB” in glass fiber and Teflon filter samples.^e Percentage of each ion concentration in total ion concentration in the “ion_{G-T}” row.

total oversampled ion concentrations in glass fiber filters from PM_{2.5,DG} concentrations, PM_{2.5,DG-ion_{G-T}} concentrations are found in good agreement with PM_{2.5,DT} concentrations with an average difference of less than 3.8%. From Table 2, it is also seen that the blank levels of many ions in glass fiber filters are higher than those in Teflon filters, in which the total ion concentrations are 7.16 ± 0.96 and $0.07 \pm 0.05 \mu\text{g m}^{-3}$, respectively. Similarly, high blank levels for many elements in the glass fiber filters of the BAM were also observed by *Waston et al. (2012)*. Major components of the oversampled ion in glass fiber filter are Cl⁻, NO₃⁻, and SO₄²⁻, the total concentration of which account for 70.16% of the total oversampled ion concentration.

From the above results, it can be concluded that the higher concentrations measured by the non-designated BAM-1020 at Sinjhuang (overestimated by $29.8 \pm 20.2\%$) and Judong (overestimated by $28.4 \pm 19.0\%$) stations is dominated by the positive artifacts due to acid gas adsorption by the glass fiber filter tapes used in the BAM-1020.

4. Conclusion

This study shows that PM_{2.5,B} concentrations are consistently higher than the PM_{2.5,D} concentrations at three investigated air monitoring stations where non-FEM-designated BAMs are used. PM_{2.5} concentrations at Jhongshan station, where the VEREWA-F701 is used, is overestimated by $58.4 \pm 37.4\%$ as compared to PM_{2.5,D} concentrations. Less overestimation at Sinjhuang and Judong station exists, which is 29.8 ± 20.2 and $28.4 \pm 19.0\%$, respectively, where the BAM-1020s are used. Different factors influencing the measurement differences between the Dichot and BAM-1020, including aerosol water content, volatilization of inorganic species and positive artifacts due to acid gas adsorption by the glass fiber filter tapes, were investigated in this paper.

Results show that the difference between PM_{2.5,B} and PM_{2.5,D} concentrations is mainly caused by the positive artifacts due to acid gas adsorption by the glass fiber filter tapes used in the BAM-1020, which could account for as much as $21.2 \pm 9.8\%$ overestimation. After considering aerosol water content in PM_{2.5}, difference between PM_{2.5,B} and PM_{2.5,D} was decreased from 28.96 to 7.0–8.3%,

but R^2 between them was also decreased from 0.90 to 0.62–0.56. This indicates that aerosol water content cannot be used to explain the measurement difference between the BAM-1020 and Dichot. Estimated volatilization loss of ammonium nitrate in the BAM-1020 was found to be higher than that in the Dichot, but it accounted for only 1.16% in PM_{2.5,B} concentrations in average. Since high temperature will result in more volatilization of semi-volatile species, for the future studies, there is a need to monitor the temperature controlled by the smart heater and to evaluate the effect of such increased temperature on the evaporation loss of sampled particles.

In the future, the PM_{2.5} monitors used in the TAMS will be replaced by the FEM-designated instruments, such as the new BAM-1020, the TEOM with filter dynamic measurement system (TEOM-FDMS) (Model 1405-DF, Thermo, designation number: EQPM-0609-182), the continuous ambient particle monitor (Model 5040i, Thermo, designation number: EQPM-0609-183), and the Beta^{PLUS} particle measurement system (Model 602, Teledyne, designation number: EQPM-0912-204) etc. It is expected the measurement difference between these FEM-designated instruments and the manual FRM samplers will be reduced. However, since most of the FEM-designated BAMs use the glass fiber filter tapes, their measurement data may still have some differences from those of FRM samplers as the concentrations of acid gases are different in Taiwan. It is recommended that the positive artifacts be resolved completely by replacing the glass fiber filters with Teflon-coated glass fiber filters or any other materials inert to acid gases adsorption.

Acknowledgments

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Appendix ASupplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.atmosenv.2013.04.062>.

References

- Aggarwal, S.G., Mochida, M., Kitamori, Y., Kawamura, K., 2007. Chemical closure study on hygroscopic properties of urban aerosol particle in Sapporo, Japan. *Environmental Science and Technology* 41, 6920–6925.
- Appel, B.R., Tokiwa, Y., Haik, M., Koehn, E.L., 1984. Artifact particulate sulfate and nitrate formation on filter media. *Atmospheric Environment* 18, 409–416.
- Arends, B.G., Nell, J., Rutten, S.M., 2000. Field comparison of four PM₁₀ samplers in a polluted area in the Netherlands. *Journal of Aerosol Science* 31, 512–513.
- Chang, C.T., Tsai, C.J., Lee, C.T., Chang, S.Y., Cheng, M.T., Chein, H.M., 2001. Differences in PM₁₀ concentrations measured by β -gauge monitor and Hi-vol Sampler. *Atmospheric Environment* 35, 5741–5748.
- Chang, C.T., Tsai, C.J., 2003. A model for the relative humidity effect on the readings of the PM₁₀ beta-gauge monitor. *Journal of Aerosol Science* 34, 1685–1697.
- Cheng, Y.H., Tsai, C.J., 1997. Evaporation loss of ammonium nitrate during filter sampling. *Journal of Aerosol Science* 28, 1553–1567.
- Chen, S.C., Tsai, C.J., Huang, C.Y., Chen, H.D., Chen, S.J., Lin, C.C., Tsai, J.H., Chou, C.C.K., Lung, C., Huang, W.R., Roam, G.D., Wu, W.Y., Smolik, J., Dzumbova, L., 2010. Chemical mass closure and chemical characteristic of ambient ultrafine particles and other PM fractions. *Aerosol Science and Technology* 44, 713–723.
- Coutant, R.W., 1977. Effect of environmental variables on collection of atmospheric sulfate. *Environmental Science and Technology* 11, 873–878.
- Fountoukis, C., Nenes, A., 2007. ISORROPIA II: a computationally efficient thermodynamic equilibrium model for $K^+ - Ca^{2+} - Mg^{2+} - NH_4^+ - Na^+ - SO_4^{2-} - NO_3^- - Cl^- - H_2O$ aerosols. *Atmospheric Chemistry and Physics* 7, 4539–4659.
- Gobeli, D., Schloesser, H., PottbergMet, T., 2008. Met One Instruments BAM-1020 Beta Attenuation Mass Monitor US-EPA PM_{2.5} Federal Equivalent Method Field Test Results. Paper # 2008-A-485-AWMA.
- Gugamsetty, B., Wei, H., Liu, C.N., Awasthi, A., Chen, S.C., Tsai, C.J., Roam, G.D., Wu, Y.C., Chen, C.F., 2012. Source characterization and apportionment of PM₁₀, PM_{2.5}, PM_{0.1} using positive matrix factorization in Shinjung Station, Taiwan. *Aerosol and Air Quality Research* 12, 472–491.
- Hauck, H., Berner, A., Gomiscek, B., Stopper, S., Puxbaum, H., Preining, O., Kundi, M., 2004. On the equivalence of gravimetric PM data with TEOM and beta-attenuation measurements. *Journal of Aerosol Science* 35, 1135–1149.
- Hsu, Y.M., Kollett, J., Wysocki, K., Wu, C.Y., Lundgren, D.A., Birky, B.K., 2007. Positive artifact sulfate formation from SO₂ adsorption in the silica gel sampler used in NIOSH method 7903. *Environmental Science and Technology* 41, 6205–6209.
- Huang, C.H., Tai, C.Y., 2008. Relative humidity effect on PM_{2.5} reading recorded by collocated beta attenuation monitors. *Environmental Engineering Science* 25, 1079–1089.
- Jaklevic, J.M., Gatti, R.C., Goulding, F.S., Loo, B.W., 1981. A β -gauge method applied to aerosol samples. *Environmental Science and Technology* 15, 680–686.
- Khlystov, A., Stanier, C.O., Takahama, S., Pandis, S., 2005. Water content of ambient aerosol sampling during the Pittsburgh air quality study. *Journal of Geophysical Research* 110. D07S10.1–D07S10.10.
- Lee, W.M.G., Huang, W.M., Chen, Y.Y., 2001. Effect of relative humidity on mixed aerosols in atmosphere. *Journal of Environmental Science Health Part A* 36, 533–544.
- Liberti, A., Brocco, D., Possanzini, M., 1978. Adsorption and oxidation of sulfur dioxide on particles. *Atmosphere Environment* 12, 255–261.
- Lipfert, F.W., 1994. Filter artifacts associated with particulate measurements: recent evidence and effects on statistical relationships. *Atmospheric Environment* 28, 3233–3249.
- Liu, C.N., Chen, S.C., Tsai, C.J., 2011. A novel multi-filter PM₁₀–PM_{2.5} sampler (MFPPS). *Aerosol Science and Technology* 45, 1480–1487.
- Pilinis, C., Seinfeld, J.H., Grosjean, D., 1989. Water content of atmospheric aerosols. *Atmospheric Environment* 23, 1601–1606.
- Salminen, K., Karlsson, V., 2003. Comparability of low-volume PM₁₀ sampler with β -attenuation monitor in background air. *Atmospheric Environment* 37, 3707–3712.
- Shin, S.E., Jung, C.H., Kim, Y.P., 2011. Analysis of the measurement difference for the PM₁₀ concentrations between beta-ray absorption and gravimetric methods at Gosan. *Aerosol and Air Quality Research* 11, 846–853.
- Tsai, C.J., Perng, S.N., 1998. Artifacts of ionic species for Hi-vol PM₁₀ dichot samplers. *Atmospheric Environment* 32, 1605–1613.
- Tsai, C.J., Chang, C.T., Huang, C.H., 2006. Direct field observation of the relative humidity effect on the β -gauge readings. *Journal of the Air and Waste Management Association* 56, 834–840.
- Takahashi, K., Minoura, H., Sakamoto, K., 2008. Examination of discrepancies between beta-attenuation and gravimetric methods for the monitoring of particulate matter. *Atmospheric Environment* 42, 5232–5240.
- Wang, H.C., John, W., 1988. Characteristics of the Berner impactor for sampling inorganic ions. *Aerosol Science and Technology* 8, 157–172.
- Waston, J.G., Chow, J.C., Chen, L.W.A., Kohl, S.D., Casuccio, G.S., Lersch, T.L., Langston, R., 2012. Elemental and morphological analyses of filter tape deposits from a beta attenuation monitor. *Atmospheric Environment* 106, 181–189.
- Watanabe, I., Endo, O., Goto, S., Tanabe, K., Mizoguchi, T., Matsushita, H., 2000. A comparison study of measured values for ambient suspended particulate matter using β attenuation method and gravimetric high-volume method. From intermittent monitoring data at two sites in Tokyo for a decade. *Journal of Environmental Chemistry* 10, 557–572.
- Wexler, A.S., Clegg, S.L., 2002. Atmospheric aerosol models for systems including the ions H^+ , NH_4^+ , Na^+ , SO_4^{2-} , NO_3^- , Cl^- , Br^- and H_2O . *Journal of Geophysical Research* 107 (D14). art. no. 4207.
- Zhang, X.Q., McMurry, P.H., 1987. Theoretical analysis of evaporative losses from impactor and filter deposits. *Atmospheric Environment* 21, 1779–1789.
- Zhang, X.Q., McMurry, P.H., 1991. Theoretical analysis of evaporative losses of adsorbed or absorbed species during atmospheric aerosol sampling. *Environmental Science and Technology* 25, 456–459.
- Zhang, X.Q., McMurry, P.H., 1992. Evaporative losses of fine particulate nitrates during sampling. *Atmospheric Environment* 26, 3305–3312.
- Zhu, C.S., Chen, C.C., Cao, J.J., Tsai, C.J., Chou, C.C.K., Liu, S.C., Roam, G.D., 2010. Characterization of carbon fractions for atmospheric fine particles and nanoparticles in a highway tunnel. *Atmospheric Environment* 44, 2668–2673.