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Differences in PM_{10} concentrations measured by β-gauge monitor and hi-vol sampler

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Abstract

In this paper, differences between the 24-h average PM_{10} concentrations of Wedding β-gauge monitor and Andersen or Wedding hi-vol sampler were studied. When the deliquescent point is not exceeded, PM_{10} concentrations of the β-gauge are close to those of the manual samplers. The ratio of β-gauge PM_{10} to Andersen PM_{10} and Wedding PM_{10} is 1.08 ± 0.06 and 1.09 ± 0.12, respectively. However, when the deliquescent point is exceeded, water absorption by the inorganics of aerosols leads to higher PM_{10} concentrations of the β-gauge compared to those of the manual sampler. The ratio of β-gauge PM_{10} to Andersen PM_{10} and Wedding PM_{10} is 1.21 ± 0.22 and 1.27 ± 0.15, respectively. However, due to evaporation of water from the aerosols collected on the filter tape of the β-gauge, differences in PM_{10} concentrations are much less than theoretically calculated.

Keywords: β-gauge; Water content; PM_{10}; Relative humidity

1. Introduction

The manual hi-vol Andersen SA1200 PM_{10} sampler, described in McFarland and Ortiz (1987), is a modified version of the Sierra–Andersen Model 321 A sampler (SA321) which is one of the US EPA-designated reference PM_{10} samplers (US EPA, 1987). The sampler is operated at $1.13\,m^3$/min and the PM_{10} inlet of the sampler is a single-stage multi-jet impactor. PM_{10} particles are collected by a filter paper and weighed to determine the daily PM_{10} concentration. In order to remove the influence of water on filter weighing, the standard operation procedure specifies that PM_{10} filters should be equilibrated at a constant temperature, within ± 3°C between 15°C and 30°C, and at constant relative humidity (RH), within $\pm 5\%$ between 20% and 45%. (US EPA, 1987).

The Wedding β-gauge PM_{10} monitor is one of the US EPA-designated equivalent methods (No. EQPM-0391-081). The PM_{10} inlet is a cyclone operated at 18.9 l/min. PM_{10} particles are continuously collected on the filter tape and detected once every hour. Unlike manual sampler, the filters are not conditioned before detection and aerosol particles may absorb water when the deliquescence point is exceeded (Pilinis and Seinfeld, 1989; Seinfeld and Pandis, 1998), which may lead to overestimation of PM_{10} concentrations. At the present time, the hourly PM_{10} concentrations are routinely measured by the automatic Wedding β-gauge PM_{10} monitors in Taiwan's air quality monitoring network. Due to the frequent occurrence of high humidity in the ambient air in Taiwan, Taiwan EPA is very interested to know if the readings of the monitors are influenced by ambient humidity.

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The major factors that may lead to differences in PM_{10} concentrations between two samplers include (1) the cutoff aerodynamic diameter and the penetration curve of the inlet (McFarland and Ortiz, 1987; Ranade et al., 1990; Tsai, 1995; Tsai and Cheng, 1996) (2) deposited particles on the impaction surface or inner surface which may reduce particle penetration (John et al., 1991; John and Wang, 1991) (3) the deliquescence of aerosols (Meng et al., 1995; Pilinis and Seinfeld, 1989) (4) the evaporation loss of volatile species of aerosols (Zhang and McMurry, 1987, 1992; Cheng and Tsai, 1997).

Wedding and Weigand (1993) showed that the cut-points of the inlet of the Wedding β-gauge monitor are 9.94, 9.96 and 9.51 μm at the wind speed of 2, 8 and 24 km/h, respectively. At the same wind speeds, these diameters are very close to 9.5, 9.7 and 9.5 μm of the Andersen SA1200 sampler (McFarland and Ortiz, 1987), and 9.6, 9.9 and 9.9 μm of the Wedding hi-vol sampler (Ranade et al., 1990). Measured PM_{10} concentrations of these three samplers were expected to be very close to each other. According to Tsai (1995), if the impaction/inner surface of the inlet is cleaned regularly, the PM_{10} concentrations measured by the Wedding PM_{10} hi-vol are 5–11% lower than those of Andersen SA1200 hi-vol samplers. Besides, Tsai and Cheng (1996) also indicated that the daily average PM_{10} concentration readings of the SA1200 sampler were about 7.2–9.3% greater than those of the Wedding PM_{10} hi-vol sampler. However, this study did not have a firm conclusion on the effect of RH on the differences in concentrations measured between the manual hi-vol samplers and automatic monitors.

In contrast to the previous research findings, Ono et al. (2000) indicated that the average PM_{10} concentrations measured by Andersen sampler and Wedding samplers were about 25% and 35% lower than that measured by TEOM, respectively, while that the TEOM, the Dichot and the Partisol, which all use the same PM_{10} inlet design, agreed within 10% and within 1% in the case of the TEOM and Partisol. They argued that the Wedding and Andersen hi-vol monitors have lower cut-points than the TEOM, Dichot and Partisol monitors which were claimed to have cut-points around 10 μm.

Meng et al. (1995) used SCAPE (Kim et al., 1993a, b) to estimate the water content associated with the inorganic fraction of $PM_{2.5}$ and PM_{10} mass in the ambient air of the South Coast Air Basin of California. Their theoretical calculation showed that when the ambient RHs were low, overmeasurement of the total aerosol mass occurred due to the addition of water onto particles during the gravimetric measurements, which were typically conducted at RH of 45%. However, when the ambient RHs were high, their calculation showed a loss of water during the gravimetric measurement of $PM_{2.5}$ and PM_{10}.

In this study, two PM_{10} hi-vol samplers (Andersen SA1200 or Wedding sampler) were collocated with the Wedding β-gauge monitor and the daily averaged PM_{10} concentrations were compared. Glass fiber filters were used in the samplers and monitor. For manual samplers, the filters were conditioned at temperature and RH of $20 \pm 3^{\circ}C$ and $45 \pm 5\%$, respectively, which are within the EPA specification.

The study was conducted at four different locations, namely, Chung-Shan, Ta-Yuan, Chu-Shan and Ta-Liao air monitors in Taiwan as shown in Fig. 1. These air-monitoring stations are all located in a primary school or kindergarten. The heights of the sampling inlets are 12, 5, 8.5 and 8.5 m above the ground for these four stations, respectively. Chung-Shan station is in Taipei city where traffic is heavy. Ta-Yuan station is a rural site in northern Taiwan. Chu-Shan station is located in central Taiwan and is also a rural site. Ta-Liao station is located in southern Taiwan and is influenced by the heavy industry in the nearby Kaoshiung city.

The sampling period and number of samplers taken are listed in Table 1. Totally there were 60 samples in which six were taken in November 1999 at Ta-Liao station and the other 54 in September–November 2000 at four stations. Also, listed in Table 1 are the daily average PM_{10} concentrations, chemical compositions, temperature and humidity. In northern Taiwan (Chung-Shan and Ta-Yuan station), both daily PM_{10} concentrations and RH were lower than those in the rest of Taiwan. In southern Taiwan (Ta-Liao station), where both PM_{10} concentrations and RH values were the

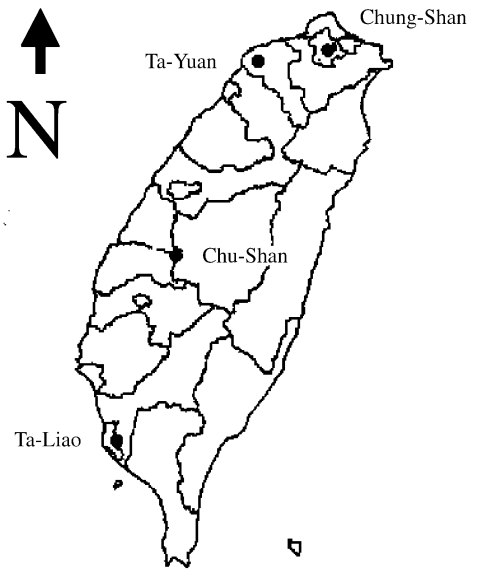

Fig. 1. The location of four sampling stations.

Table 1
Sampling information: location, date, PM_{10} concentration, aerosol species concentration and environmental conditions

Location	Sampling date	Sampler (no. of samples)	PM_{10}	Cl^-	SO_4^{2-}	NO_3^-	Na^+	NH_4^+	EC	OC	Other	RH(%)	T(°C)
Ta-Liao	23–28 November 1999	W(6)[a]	118.25±28.8[c] (69.5–159.0)[d]	4.51±2.70 (2.03–10.2)	27.81±9.42 (15.6–43.7)	18.97±8.21 (5.1–30.4)	1.07±0.43 (0.33–1.79)	9.82±3.75 (4.0–16.3)	13.14±4.21 (6.96–18.6)	8.59±2.16 (4.69–11.4)	34.33±14.3 (3.1–49.16)	83.20±2.93 (77.7–85.7)	24.14±1.63 (20.9–25.1)
Chung-Shan	29 September–13 October 2000	W(14)	51.27±7.39 (42.9–56.99)	2.78±0.67 (2.01–3.24)	7.93±0.91 (7.26–8.96)	2.57±0.85 (1.70–3.40)	2.06±0.54 (1.54–2.63)	2.63±0.15 (2.47–2.78)	12.51±3.04 (10.0–15.9)	8.65±2.02 (7.26–11.0)	12.15±3.85 (9.26–16.5)	63.22±1.87 (59.7–66.2)	28.10±0.89 (26.4–29.4)
Ta-Yuan	30 September–7 October 2000	A(12)[b]	47.35±13.17 (35.63–63.9)	5.72±1.59 (3.70–7.54)	7.79±4.92 (2.17–13.4)	4.09±2.59 (2.17–7.92)	2.08±0.65 (1.91–2.81)	2.84±1.27 (1.92–4.73)	3.33±2.45 (0.10–5.62)	2.12±1.68 (0.10–4.09)	19.41±14.1 (10.1–40.1)	73.86±1.76 (72.0–76.0)	27.23±0.51 (26.6–27.8)
Chu-Shan	20–30 October 2000	A(14)	88.74±28.95 (55.5–108.5)	2.81±2.67 (0.48–5.73)	12.40±4.66 (7.16–14.0)	10.34±6.62 (3.02–15.9)	2.92±2.85 (0.48–6.04)	4.56±1.76 (2.70–6.20)	12.14±4.40 (7.47–16.2)	10.87±3.34 (9.70–14.6)	32.71±5.98 (25.9–37.2)	69.36±2.37 (64.7–72.6)	25.76±1.43 (23.3–27.1)
Ta-Liao	11–28 November 2000	W(5)A(9)	144.69±46.0 (84.7–196.0)	4.99±1.26 (3.62–6.49)	21.49±12.4 (7.99–36.2)	29.54±14.7 (8.86–40.2)	2.21±0.36 (1.75–2.50)	12.57±5.74 (5.37–19.3)	14.91±3.39 (10.7–18.7)	17.69±4.29 (12.2–22.7)	41.27±14.1 (27.8–59.6)	83.57±4.26 (76.4–90.0)	24.33±0.57 (23.2–24.8)

[a] W: Wedding hi-vol PM_{10} manual sampler.
[b] A: Andersen hi-vol PM_{10} manual sampler.
[c] Ave.±std. dev.
[d] Range, unit: μg/m^3.

highest and RH was usually higher than the deliquescent point at night. Major components of hi-vol PM_{10} samples were sulfate, nitrate, EC and OC.

2. Estimation of water content in PM_{10} of β-gauge sampler

For the manual samplers, the filters must be placed in a conditioning chamber for at least 24 h before and after sampling. Over the sampling period, the measured PM_{10} concentrations, which are called "dry" PM_{10} concentrations in this paper, represent particle concentrations containing only a small amount of water in equilibrium with the temperature and RH of the chamber. There is no information of "hourly" PM_{10} concentrations. On the other hand, the hourly readings of the automatic β-gauge monitor may be influenced by RH because of water absorption by the inorganic mass of aerosols when the deliquescent point is exceeded. It is expected that the daily PM_{10} concentrations calculated from the hourly readings of the β-gauge monitors must be higher than those of the manual PM_{10} samplers when the ambient RH is high. However, because water and evaporative species may evaporate from the wet aerosols due to the pressure drop across the filter paper and the change of saturated conditions, it is difficult to predict the differences of daily average PM_{10} concentrations of the automatic β-gauge monitor and manual sampler.

The purpose of this study is to develop a practical method to estimate the water content in the PM_{10} measured by the β-gauge monitor. In this method, the purely theoretical water content of ambient aerosols was calculated by the ISORROPIA model (Nenes et al., 1998) based on the thermodynamic equilibrium of inorganic aerosols. The evaporation loss on the filter paper of the automatic β-gauge monitor was also considered by introducing a correction factor α. The theoretical water content of "wet" aerosols was adjusted by the factor α, so that 24-h time-averaged "dry" PM_{10} concentrations is the same for both hi-vol sampler and automatic β-gauge PM_{10} monitor.

At the ith sampling hour, suppose that hourly β-gauge reading, $PM'_{10,\beta,i}$, can be calculated from the 24-h time-averaged PM_{10} concentrations by the hi-vol sampler, $PM_{10,m,i}$, and the water content, Wat_i is corrected by the factor α in that hour:

$$PM'_{10,\beta,i} = PM_{10,m,i} + \alpha\, Wat_i, \tag{1}$$

where Wat_i is calculated by ISORROPIA model based on the inorganic ion concentrations of $PM_{10,m,i}$ as shown in Table 1. The ratio of the actual hourly reading of the β-gauge monitor, $PM_{10,\beta,i}$ to $PM'_{10,\beta,i}$ equals R_i,

$$R_i = \frac{PM_{10,\beta,i}}{PM'_{10,\beta,i}}. \tag{2}$$

Combing Eqs. (1) and (2)

$$R_i = \frac{\mathrm{PM}_{10,\beta,i}}{\mathrm{PM}_{10,\mathrm{m},i} + \alpha\,\mathrm{Wat}_i}. \quad (3)$$

Supposed that $\mathrm{PM}'_{10,\mathrm{m},i}$ is the "dry" aerosol concentrations at the ith hour, then

$$\mathrm{PM}'_{10,\mathrm{m},i} = \mathrm{PM}_{10,\mathrm{m},i} R_i. \quad (4)$$

The 24-h time-averaged "dry" PM_{10} concentrations calculated from hourly values should be equal to $\mathrm{PM}_{10,\mathrm{m},i}$, or

$$\frac{1}{n}\sum_{i=1}^{n} \mathrm{PM}'_{10,\mathrm{m},i} = \mathrm{PM}_{10,\mathrm{m},i}, \quad (5)$$

where $n = 24$ h in the study. Combing Eqs. (4) and (5), one obtains

$$\frac{1}{n}\sum_{i=1}^{n} \mathrm{PM}_{10,\mathrm{m},i} R_i = \mathrm{PM}_{10,\mathrm{m},i}. \quad (6)$$

After substituting R_i into Eq. (6), one gets

$$\frac{1}{n}\sum_{i=1}^{n} \frac{\mathrm{PM}_{10,\mathrm{m},i}\mathrm{PM}_{10,\beta}}{\mathrm{PM}_{10,\mathrm{m},i} + \alpha\mathrm{Wat}_i} = \mathrm{PM}_{10,\mathrm{m},i}. \quad (7)$$

Eliminating $\mathrm{PM}_{10,\mathrm{m},i}$ on both the sides, one obtains

$$\frac{1}{n}\sum_{i=1}^{n} \frac{\mathrm{PM}_{10,\beta}}{\mathrm{PM}_{10,\mathrm{m},i} + \alpha\,\mathrm{Wat}_i} = 1. \quad (8)$$

The factor α can be found by the trial and error method, so that Eq. (8) is satisfied. Eq. (4) can further be used to find the theoretical hourly "dry" aerosol concentrations, $\mathrm{PM}'_{10,\mathrm{m},i}$. The difference between the theoretical hourly "dry" aerosol concentrations and the hourly "wet" aerosol concentration of the β-gauge monitor, represents the apparent hourly water content measured by the β-gauge monitor.

3. Results and discussion

3.1. Hourly PM_{10} and water content

Typical simulated results of hourly "dry" PM_{10} concentrations and aerosol water content at Ta-Liao (23 November 1999) and Chung-Shan (30 September 2000) are shown in Figs. 2 and 3, respectively. Also, shown in the figures are the hourly RH and temperature. At Ta-Liao station (Fig 2(b)), where both RH (especially at night) and PM_{10} were typically very high, water constituted a significant fraction of PM_{10} mass. The PM_{10} concentration measured by the β-gauge was 125.7 μg/m^3 at 08:00, it started to increase from 106.9 μg/m^3 at 11:00 and peaked at 15:00 with PM_{10} of 339.3 μg/m^3, then fluctuated between 210 and 348 μg/m^3 from 15:00 to 07:00 the next day. The corresponding RH decreased from 83.2% at 08:00 to 62.2% at 11:00, and started to increase to 95.3% and was nearly constant

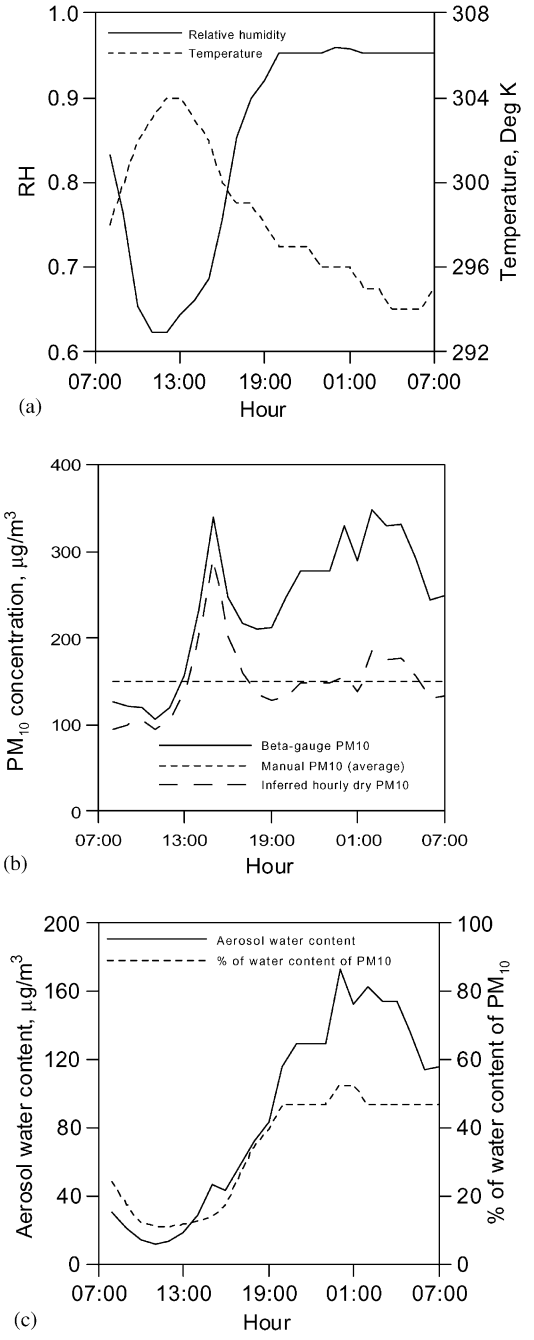

Fig. 2. (a) Temperature and RH; (b) PM_{10} concentration; (c) Aerosol water content and % of water content versus time at Ta-Liao, 23 November 1999.

from 20:00 until 07:00 the next day. The simulated "dry" concentrations were found to be close to the values measured by the β-gauge before 16:00 and water content was below 47 μg/m^3 (Fig. 2(c)). During the night from 19:00 to 07:00 the next day when RH was high, the

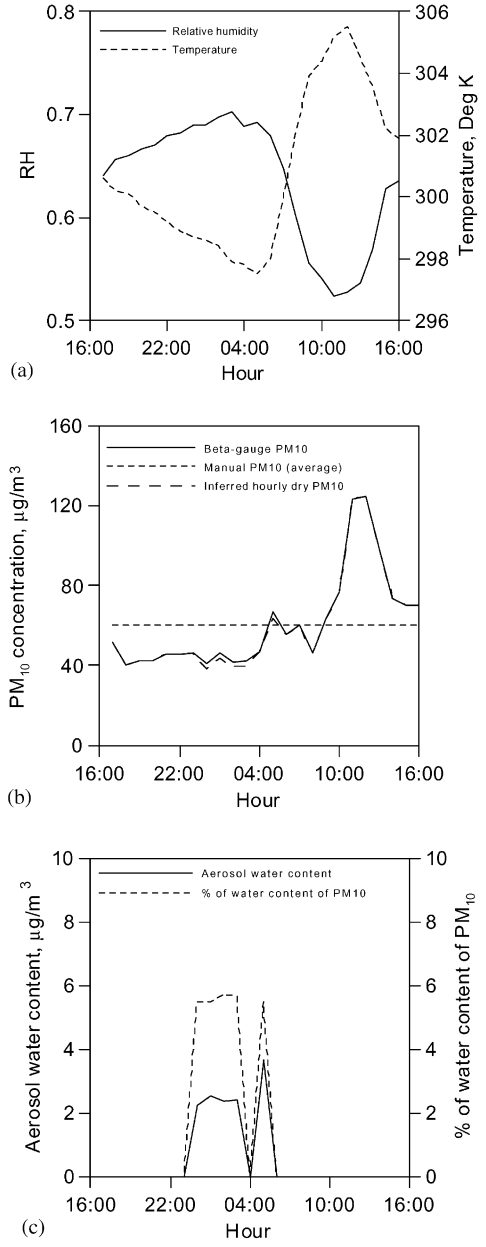

Fig. 3. (a) Temperature and RH; (b) PM_{10} concentration; (c) Aerosol water content and % of water content versus time at Chung-Shan, 30 September 2000.

aerosol water content and percent of water content of PM_{10} were also high, which were between 84 and 172 μg/m^3 accounting for about 47–53% of PM_{10} mass. On the daily average, the percent of water content of PM_{10} was $33.56 \pm 16.02\%$.

In comparison, the water content in aerosols was low at Chung-Shan station where the RH and PM_{10} were not as high as those of Ta-Liao station, as shown in Fig. 3. From 17:00 to 05:00 the next day, the hourly PM_{10} concentrations were lower than 60 μg/m^3 and RH varied between 65% and 70%. The PM_{10} concentrations varied from 42 to 124 μg/m^3 when RH was typically less than 60% from 08:00 to 11:00. The simulated "dry" PM_{10} concentrations were almost equal to the values measured by the β-gauge except from 23:00 to 06:00 the next day when RH was slightly over the deliquescence point, RH ≈ 68%. During the period, both the aerosol water content and the percent of water content of PM_{10} were very low with the range from 2.2 to 3.7 μg/m^3 and from 5.5% to 5.7%, respectively. On the daily average, the percent of water content of PM_{10}, $1.16 \pm 2.31\%$, was very low.

3.2. Correction factor α

The correction factor α was used to account for the evaporation of unbound water from the aerosols collected on the filter tape of the β-gauge monitor. Theoretically, α should range from 0 to 1. In this study, the correction factor α was found to decrease with the increasing ambient RH as shown in Fig. 4. The best fit of the calculated correction factor versus RH can be written as

$$\alpha = -3.49 \frac{\mathrm{RH}(\%)}{100} + 3.47. \quad (12)$$

That is, α is close to 1 as RH is near to the deliquescent point (RH ≈ 65–70%). It decreases with the increasing RH and becomes 0.15 when RH is 95%. At high humidity, a very small value of α indicates that the theoretical β-gauge readings (dry PM_{10} plus water content calculated from ISORROPIA) at high RH will be overestimated substantially.

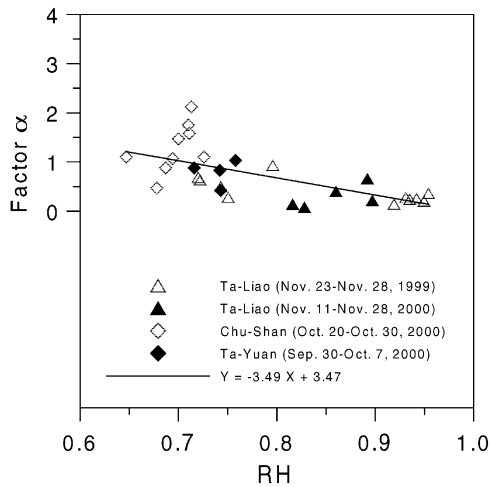

Fig. 4. Relationship of correction factor α and RH.

There are several calculated α values greater than 1 when RH is around 70% for the non-urban Chu-Shan station. This is probably due to the enhancement of water absorption by inorganics at the presence of organics (Saxena et al., 1995).

3.3. Comparison of the PM_{10} concentrations

Comparison of daily average PM_{10} concentrations between the β-gauge PM_{10} monitor and the manual sampler is shown in Fig. 5. The best-fit equation for the $PM_{10,\beta}$ (β-gauge) versus $PM_{10,A}$(Andersen) and $PM_{10,\beta}$ versus $PM_{10,W}$ (Wedding) is the following:

$$PM_{10,A} = 0.90PM_{10,\beta} - 3.74 \quad (\mu g/m^3), \tag{13}$$

$$PM_{10,W} = 0.74PM_{10,\beta} + 7.88 \quad (\mu g/m^3), \tag{14}$$

That is, the PM_{10} concentrations of the β-gauge are, in general, higher than those of the manual Andersen or Wedding sampler. Compared to the Wedding sampler, PM_{10} concentrations of the Andersen sampler are closer to the Wedding β-gauge. This is because the measured PM_{10} concentrations of the Wedding sampler are lower than those of the Andersen sampler (Tsai, 1995; Tsai and Cheng, 1996). Despite water absorption by aerosols at high humidity, the comparison shows that the PM_{10} concentrations of manual sampler are not very different from those of the β-gauge due to water evaporation during the sampling process. The ratio of β-gauge PM_{10} to Andersen PM_{10} and Wedding PM_{10} is 1.08 ± 0.06 and 1.09 ± 0.12, respectively.

The ratio of PM_{10} concentration of the β-gauge to the manual sampler is shown in Fig. 6. When the RH is below 70%, the deliquescence point is usually not exceeded, the ratio is close to 1 indicating that the inlet penetration efficiency of the Wedding β-gauge and

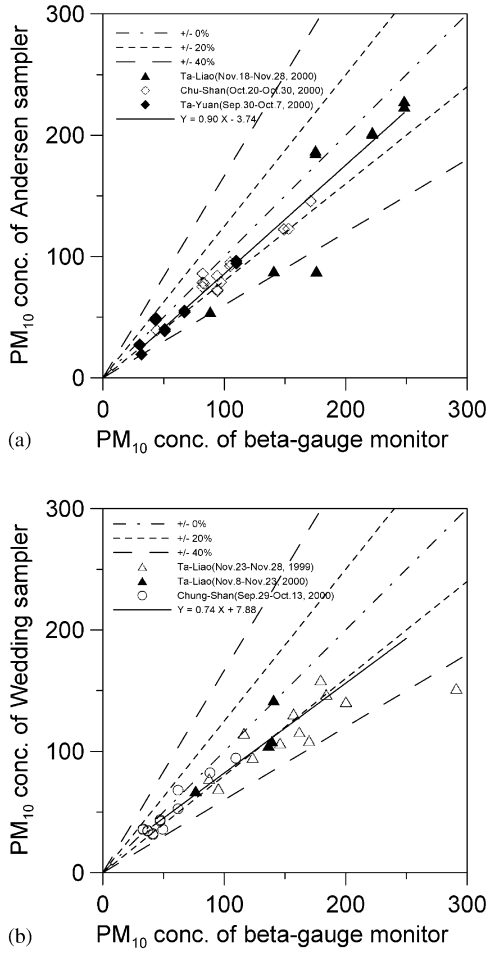

Fig. 5. Relationship between PM_{10} concentrations of Wedding β-gauge and (a) Andersen; and (b) Wedding hi-vol sampler.

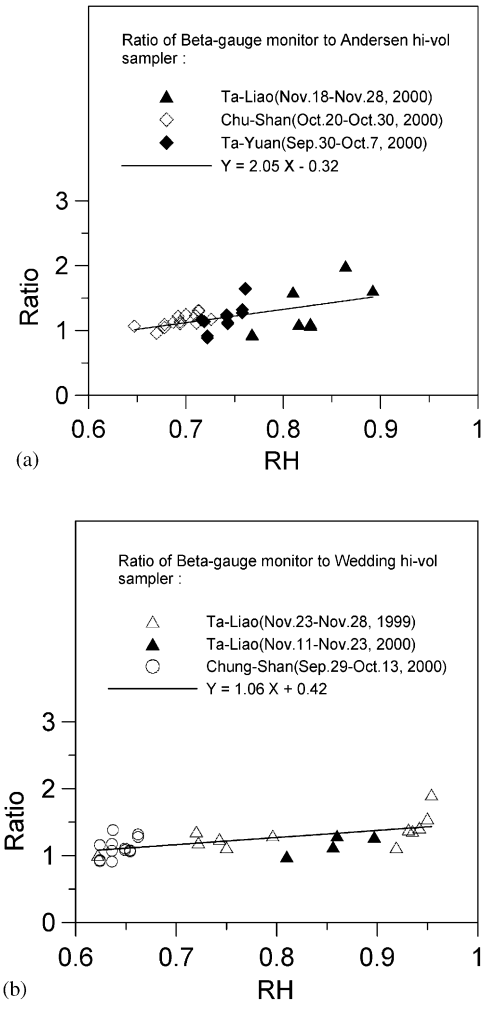

Fig. 6. The ratio of PM_{10} concentrations of Wedding β-gauge to (a) Andersen; and (b) Wedding hi-vol sampler versus RH.

manual sampler is not very different. When the deliquescent point is exceeded, the ratio is found to increase slowly with the increasing RH due to water absorption. Evaporation of water from the aerosols collected on the filter tape of the β-gauge also occurs during sampling, such that the ratio is not very much different from 1 at very high RH.

Expressions of the best-fit lines in Fig. 6 in the range of $100\% \geqslant RH \geqslant 60\%$ are

$$\frac{PM_{10,\beta}}{PM_{10,A}} = 2.05\frac{RH(\%)}{100} - 0.32, \quad (15)$$

$$\frac{PM_{10,\beta}}{PM_{10,W}} = 1.06\frac{RH(\%)}{100} + 0.42. \quad (16)$$

The ratio of β-gauge PM_{10} to Andersen PM_{10} and Wedding PM_{10} is 1.21 ± 0.22 and 1.27 ± 0.15, respectively.

4. Conclusions

The experiment conducted in Taiwan, in this study, indicated that the daily PM_{10} concentrations calculated from the hourly readings of the Wedding β-gauge PM_{10} monitor and those measured by the manual hi-vol PM_{10} sampler were quite close when the deliquescence point of aerosols was not exceeded. However, when the deliquescence point was exceeded, the PM_{10} concentrations of the Wedding β-gauge were higher than those of the manual hi-vol PM_{10} sampler and the differences were found to increase with the increasing ambient RH. Assuming that the theoretical "wet" PM_{10} of the β-gauge monitor contains of two parts: (1) "dry" PM_{10}, determined by the hi-vol sampler, and (2) aerosol water mass, theoretically calculated by the ISORROPIA model (Nenes et al., 1998), the theoretical PM_{10} concentrations are found to be much higher than the actual readings of the β-gauge monitor especially when the ambient RHs are high. The deviation is due to the evaporation of unbound water from the aerosols collected on the filter tape of the β-gauge monitor. In this paper, a correction factor α is used to account for the evaporation loss such that the theoretical hourly "wet" PM_{10} concentrations agree with the actual readings of the β-gauge monitor. It is found that the correction factor α decreases with the increasing RH indicating that more water evaporation occurs when more water is absorbed by the aerosols.

To calculate the amount of water evaporation during the sampling process such that the differences between the PM_{10} concentrations of the β-gauge and manual sampler can be quantified better, many parameters such as pressure drop across the filter and particle size distribution, and the dynamic change of pollutant concentrations and environmental conditions must be known. It is worthwhile to continue the study in this aspect.

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