A Field Study of Three Collocated Ambient PM_{10} Samplers

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Abstract

The performances of three ambient PM_{10} samplers were studied at three monitoring stations in Taiwan. It was found that differences in the daily measured PM_{10} concentrations of the SA 1200 and Wedding high-volume samplers are now within ±10% since the former now has a closer cut-point to the latter than in the earlier SA 321 A model. The Wedding beta gauge automatic sampler was found to be applicable in rainy and humid weather conditions in Taiwan. Its daily PM_{10} concentrations are typically within ±10% of those of the Wedding high-volume sampler. The particle loading effect of Wedding high-volume and beta gauge samplers was found to be important. To avoid sampling errors due to the loading effect with ambient PM_{10} samplers, they must be cleaned regularly at an interval depending on the ambient particulate level.

1 Introduction

Because of their ability to penetrate and deposit in the tracheobronchial and alveolar regions of the respiratory tract, particulate matter smaller than 10 µm in aerodynamic diameter (so-called PM_{10}) poses a significant health risk to humans. The US Environmental Protection Agency (US EPA) has promulgated new size-specific national ambient air quality standards for particulate matter, or PM_{10} standards, to replace the previous standards for total suspended particulate (TSP) [1]. The Taiwan Environmental Protection Agency (Taiwan EPA) has also adopted similar PM_{10} standards but kept the TSP standards. According to the Taiwan national ambient air quality standards, the current 24-h and annual average PM_{10} standards are 125 and 65 $\mu g/m^3$, respectively. For comparison purposes, the corresponding TSP standards are 250 and 130 $\mu g/m^3$, respectively.

The US EPA has set performance specifications and test procedures for PM_{10} sampling methods in Title 40 of the Code of Federal Regulations (40 CFR Part 53, US EPA [2]). A candidate PM_{10} sampler must be tested according to the test procedures and meet the performance specifications (US EPA [2]) in order to be approved as an EPA-designated reference or equivalent method. Table 1 shows the performance specifications regarding the sampling effectiveness and cut-point of PM_{10} samplers. The cut-point is defined as the aerodynamic diameter at which the sampling effectiveness is 50%. An EPA-designated PM_{10} sampler must have a 10 ± 0.5 µm cut-point in for each wind speed of 2, 8 and 24 km/h. The PM_{10} sampler is also tested by comparing it with the sampling effectiveness of an ideal sampler based on a specified mass concentration distribution. The ideal sampler has a sampling effectiveness curve based on measurements of particle deposition as a function of aerodynamic diameter in the respiratory tract below the larynx during oral breathing through a mouthpiece [3].

Table 1: Performance specifications of sampling effectiveness and cut-point for PM_{10} samplers (US EPA [2]).

Parameter	Specification
Sampling effectiveness	
Liquid particles	Expected mass concentrations calculated from the sampling effective curves for all three windspeeds (2, 8 and 24 km/h) must be within ±10% of that calculated for the specified ideal sampler
Solid particles	Sampling effectiveness for 25-µm particles must be no more than 5% above that obtained for liquid particles of same size
Cut-point	10 ± 0.5 µm aerodynamic diameter

The Taiwan EPA has recently installed many automatic Wedding beta gauge PM_{10} samplers to monitor hourly PM_{10} concentrations island-wise in Taiwan. The Taiwan EPA is concerned whether these samplers will measure daily PM_{10} concentrations accurately under highly humid and often rainy conditions in Taiwan. In particular, the Wedding beta gauge PM_{10} samplers will be run unattended except during periodic flowrate calibration and inlet cleaning.

There are also many Sierra-Andersen Model 1200 (SA 1200) and Wedding high-volume PM_{10} samplers currently being used in Taiwan. SA 1200 sampler, which was described in *McFarland* and *Ortiz* [4], is a modified version of the Sierra-Andersen Model 321 A sampler (SA 321 A) [5]. The inlet of the SA 1200 is a single-stage multi-jet impactor whereas that of the SA 321 A is a double-stage impactor. Both samplers have a flow rate of 1.13 m^3/min. The Wedding high-volume sampler, which has a cyclonic inlet size fractionation, also has a flow rate of 1.13 m^3/min and is identical with the GMW 9000 sampler originally developed by *Wedding* and *Weigand* [6]. Slight modifications were the replacement of the oiled plastic surface with an oiled sintered metal surface, and the redesign of the inlet to provide convenient access for periodic cleaning.

Both SA 321 A samplers and Wedding samplers were fully tested in many different wind tunnel facilities as shown in *Ranade* et al. [1] and in the field under different conditions by *Rodes*

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et al. [7] and *Purdue* et al. [8]. The SA 1200 sampler was tested by *McFarland* and *Ortiz* [4] in the laboratory but has never been tested in the field.

The automatic Wedding beta gauge sampler is a sampler capable of measuring hourly PM_{10} concentrations continuously. It consists of a 10-μm cut-point inlet, a 100-μCi ^{14}C source, a solid-state semiconductor detector and a critical flow device to control the sampling flow rate at 18.9 l/min. A detailed description of and field tests with this sampler were presented by *Wedding* and *Weigand* [9].

2 Previous Work

Substantial disagreement between SA 321 A and Wedding samplers were found in field tests especially when the impaction surface of the SA 321 A sampler was not oiled, as pointed out by *Rodes* et al. [7] and *Purdue* et al. [8]. For example, according to the so-called Phoenix III study at Phoenix by *Purdue* et al. [8], unoiled SA 321 A samplers produced PM_{10} concentrations that were 58% higher than those with uncleaned Wedding samplers.

John et al. [10] investigated three different possible mechanisms in order to explain the oversampling of unoiled SA 321 A samplers in the Phoenix III study. These included re-entrainment by air flow, re-entrainment by particle collision and deagglomeration of particles on the impaction plate. They found that re-entrainment of 10-μm deposited ammonium fluorescein particles due to air flow alone was negligibly small. Re-entrainment of 10-μm deposited fluorescein particles was observed when clay particles (mode aerodynamic diameter, 13 μm; geometric standard deviation, 2.0) were sampled through an SA 321 A sampler. Such re-entrainment was induced by collisions between impacting clay particles and deposited fluorescein particles on the impaction surface.

Deagglomeration of large particles, which occurs when large particles impact on the unoiled surface or when large deposited particles are bombarded with other incoming particles, was found to be the principal mechanism of oversampling by an SA 321 A sampler.

Cleaning and reoiling the impaction surface of a sampler can reduce re-entrainment and deagglomeration effects, which lower the measurement PM_{10} concentrations. Oiling the impaction surface can also lead to a loading or soiling effect [7-8, 10]. The particle deposit on a soiled surface can project upwards into an air stream and capture particles that are smaller than the cut-point. As a result, a soiled sampler measured lower PM_{10} concentrations than its cleaned counterpart. For example, in the field study by *Purdue* et al. [8], it was found that an oiled SA 321 A sampler collected 16% less mass than an unoiled SA 321 A sampler. This indicates a reduction in re-entrainment and deagglomeration.

The Wedding high-volume sampler also has a soiling effect. In the same study by *Purdue* et al. [8], an uncleaned Wedding sampler was found to collect 16% less mass than a cleaned Wedding sampler. *John* and *Wang* [11] demonstrated the soiling effect in their laboratory and showed that the cut-point of a heavily loaded Wedding sampler in the Phoenix III test decreased from the original 9.0 to 7.8 μm. The cut-point of a less heavily loaded SA 321 A sampler decreased from the original 9.8 to 9.1 μm.

In addition, using the Phoenix III data, *John* and *Wang* [11] quantified the loading effect by calculating the fractional difference between the concentrations from an oiled SA 321 A or a Wedding high-volume sampler and a dichotomous sampler versus the cumulative mass in the sampler. The cumulative mass was calculated from the difference between the mass sampled with a collocated TSP sampler and the mass obtained by the PM_{10} sampler. The slope of the regression line was −0.0221/g for the oiled SA 321 A and −0.0223/g for the Wedding sampler. As shown in Table 2, at a wind speed of 8 km/h, in the wind-tunnel test by *Ranade* et al. [1], the cut-point of the SA 321 A inlet, 10-10.5 μm (*Wedding* and *Weigand's* 9.1 μm is disregarded), is shown to be about 1 μm greater than the Wedding inlet, 9.5-9.9 μm (Texas A & M's 8.8 μm is disregarded). At other wind speeds, similar differences also exist. These differences in inlet cut-points can explain the observed 15% difference between the oiled SA 321 A and the cleaned Wedding samplers in the Phoenix III test by *Purdue* et al. [8]. Also shown in Table 2, the cutpoint of the SA 1200 sampler, 9.5-9.7 μm, is smaller than that of the SA 321 A sampler, 10-10.5 μm. It is expected that when compared with the SA 321 A sampler, the SA 1200 sampler will yield measured PM_{10} concentrations closer to those of the Wedding high-volume sampler.

Table 2: Cut-points (μm) for the SA 321 A, SA 1200 and Wedding samplers (*Ranade* et al. [1]; *McFarland* and *Ortiz* [4]).

Sampler	Test facility	Wind speed (km/h)		
		2	8	24
SA 321 A	EPA	10.7	10.5	–
	Texas A & M	9.7	10.0	9.6
	Warren Spring Lab.	10	10	9.7
	Wedding and Weigand	6.5	9.1	10.1
SA 1200	Texas A & M	9.5	9.7	9.5
Wedding high-volume	EPA	9.6	9.5	–
	Texas A & M	9.0	8.8	8.8
	Wedding and Weigand	9.6	9.9	9.9

Wedding and *Weigand* [9] provided the only test results with the Wedding beta gauge sampler found in the literature. They showed that the daily PM_{10} means of the Wedding beta gauge sampler agree perfectly well with the Wedding high-volume sampler. However, the soiling effect of the inlet was not quantified.

Since the SA 1200 and Wedding beta gauge samplers have not been widely tested under ambient conditions similar to those prevailing in Taiwan, this study was carried out to conduct field comparison tests in order to understand performance differences between an SA 1200 high-volume, a Wedding high-volume and a Wedding beta gauge sampler.

3 Experimental Procedure

The field tests were conducted at three monitoring stations from March to June 1993. The first station is located in a polluted city where the daily average PM_{10} concentration is very high, typically about 150 μg/m^3. The second station is located in a cleaner region where daily average PM_{10} concentration is about 80 μg/m^3. The third station is in a very clean region where daily average PM_{10} concentration is only about 30 μg/m^3. At the first two stations, all three PM_{10} samplers were tested. At the third station, only the two high-volume samplers were tested.

Depending on the station, the height of the sampling inlets was typically 10-16 m above the ground. Each different sampler had a slightly different height. For example, at the first station, the heights were 16, 14.2 and 14 m above the ground for the Wedding beta gauge, Wedding high-volume and SA 1200 sampler, respectively. The horizontal distance between samplers was 2-4 m to avoid flow interference. It is believed that such an arrangement would not introduce spatial differences between samplers.

The impaction surface of the SA 1200 sampler was cleaned and sprayed with silicone grease before each sampling day. It was intended that the measured PM_{10} concentrations of the SA 1200 sampler would be used as a standard in this comparison study. Typical particle mass loadings were 0.24, 0.13 and 0.05 g/day for the high-volume samplers and 0.004, 0.002 and 0.0008 g/day for the beta gauge sampler at the first, second and third stations, respectively. The mass loading was computed based on the measured PM_{10} concentrations of the SA 1200 sampler. Such an estimation is reasonably correct knowing that the daily average total particulate concentration in Taiwan is typically twice the PM_{10} values.

The particle collection surfaces of the Wedding high-volume and beta gauge samplers were cleaned once every 2 weeks at the first station and once every 4 weeks at the second station. The collection surface of the Wedding high-volume sampler at the third station was also cleaned once every 2 weeks.

During the field study at the first and third stations, the weather was mostly sunny, the daily average temperature typically being 20-28 °C, and the daily average relative humidity was typically 70% to less than 80%. However, during the first half of the study at the third station, there were scattered showers or drizzle every day. The daily average relative humidity was typically higher than 80% with hourly relative humidity values as high as 90-100% immediately before or after the rain. During the rainy days at the second station, the daily average concentrations dropped from 80 to 57 $\mu g/m^3$ because of aerosol scavenging by rain.

The filter-papers for high-volume samplers, which were glass-fibre filters, were conditioned for 24-48 h in a humidity-controlled chamber (relative humidity 40 ± 5%, temperature 20 ± 3 °C) before and after sampling. During the days with scattered showers or drizzle, the filter-papers were conditioned long enough until the filter weights no longer changed. However, in the case of heavy and continuous rainy days, the filter samples were too wet and the experiment had to be discontinued.

Each sampling period commenced from 10 a.m. to the same time the next day. The daily average concentrations for the Wedding beta gauge sampler were computed based on 24 hourly readings for each sampling period. These concentrations were compared with those for the high-volume samplers, which were obtained by dividing the sample weights by the total sampled air volume at 25 °C and 1 atm. The experiment also recorded the hourly weather data, including rain intensity, wind speed, wind direction, relative humidity and temperature.

4 Experimental Results

4.1 Wedding High-Volume Sampler

Both the Wedding and SA 1200 high-volume samplers are reference samplers designated by the US EPA. Anderson samplers have a long history of sampling higher PM_{10} concentrations than Wedding samplers. Each modified version of Anderson sampler results in a smaller cut-point and closer measured PM_{10} concentrations when compared with a Wedding sampler.

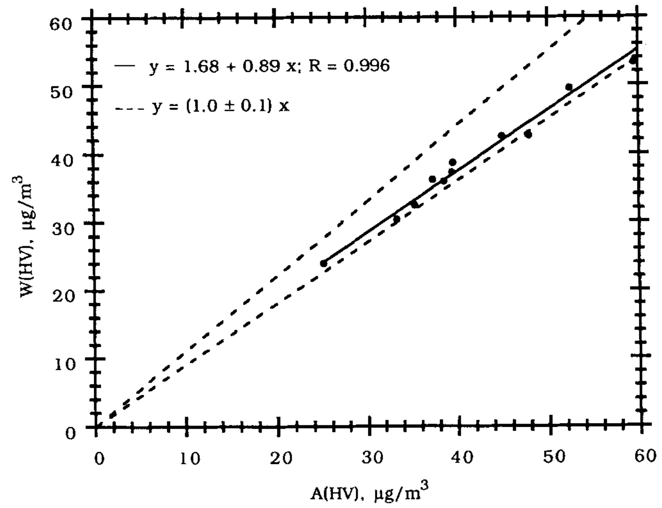

Fig. 1: Comparison of daily average PM_{10} concentrations between Wedding and SA 1200 high-volume samplers at the third station. W(HV), Wedding high-volume sampler; A(HV), SA 1200 high-volume sampler.

The SA 1200 sampler is the latest Anderson sampler with the lowest cut-point, hence its measured PM_{10} concentration will be closest to that for the Wedding high-volume sampler. Figure 1 shows a comparison of PM_{10} concentrations between two high-volume samplers at the third station. It shows that the measured PM_{10} concentrations of the Wedding high-volume sampler are still lower than those of the SA 1200 sampler, the difference being 5-11%. Such a difference is the smallest found so far in the literature.

A loading effect occurs with the Wedding high-volume sampler which is cleaned periodically. The test results for the loading effect will be explained later. Immediately after cleaning the Wedding high-volume sampler, the difference between the measured PM_{10} concentrations is only 5% at the third station. Similar experimental results are found at the first and second stations, where the difference between the two newly cleaned high-volume samplers is 7 and 11%, respectively. It can be concluded that both the Wedding and SA 1200 samplers now produce PM_{10} concentrations that are fairly close to each other.

4.2 Wedding Beta Gauge Sampler

The hourly PM_{10} concentrations recorded by the Wedding beta gauge sampler were found to be stable and reasonable, especially in good weather conditions. Typical daily experimental data acquired at the second station at a rainy day are shown in Figure 2. It shows that even on rainy days, the Wedding beta gauge is capable of capturing detailed hourly variation of PM_{10} concentrations. The aerosol increased from less than 60 $\mu g/m^3$ in the morning to nearly 160 $\mu g/m^3$ at night, and was then scavenged by the showers between 22:00 and 1:00. After the rain, hourly PM_{10} concentration dropped from the maximum value of 160 $\mu g/m^3$ to 80 $\mu g/m^3$ and the relative humidity increased from 80% to nearly 100% in the same period. The daily average PM_{10} concentration was calculated to be 90 $\mu g/m^3$. On the same day, the PM_{10} concentrations measured by the SA 1200 and Wedding high-volume samplers were slightly different, 99.7 and 89.6 $\mu g/m^3$, respectively. The differences in the measured concentrations depend on inlet cleaning, weather conditions and the differences in inlet designs. It is therefore concluded that the Wedding beta gauge

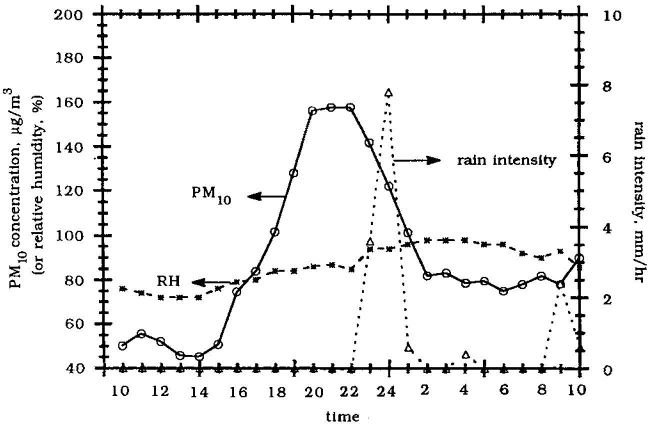

Fig. 2: Typical hourly PM_{10} concentration variation as recorded by the Wedding beta gauge sampler on a rainy day at the third station.

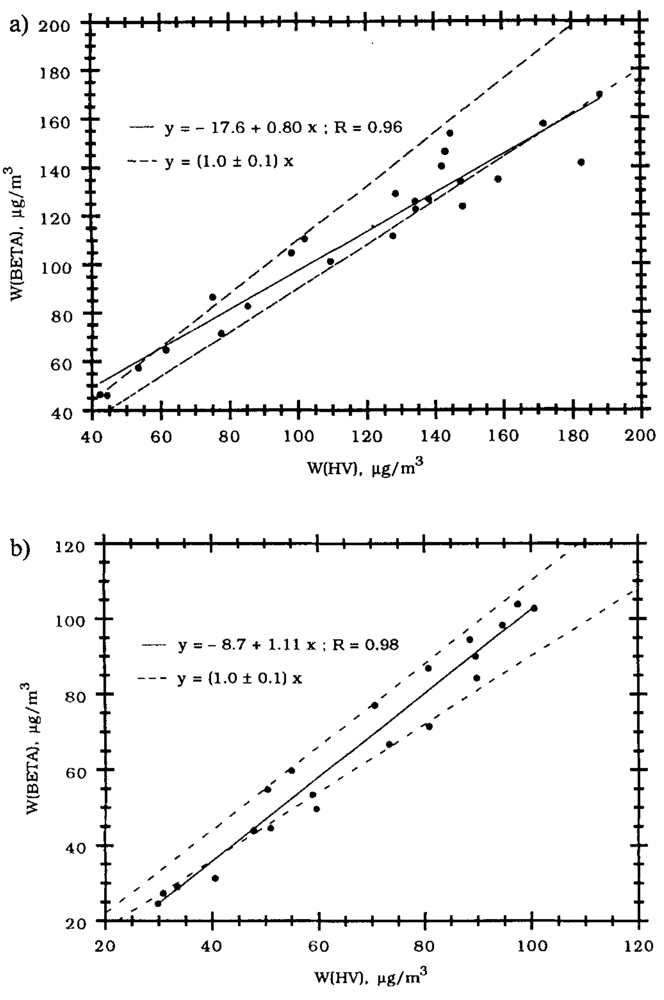

Fig. 3: Comparison of daily average PM_{10} concentrations between Wedding high-volume and Wedding beta gauge samplers at (a) first station and (b) second station. W(BETA), Wedding beta gauge sampler.

can be used not only in good weather conditions but also rainy conditions in Taiwan.

A comparison of daily PM_{10} concentrations with the Wedding high-volume and beta gauge samplers at the first and second stations is shown in Figure 3(a) and (b). Except on highly polluted days when the daily PM_{10} concentrations with the Wedding beta gauge are more than 10% lower than those with the Wedding high-volume sampler, Figure 3(a) shows that Wedding beta gauge sampler is capable of measuring daily PM_{10} concentrations within ±10% of those of the Wedding high-volume sampler of the time. The larger than 10% difference at high PM_{10} concentrations may be caused by the greater loading effect of the Wedding beta gauge, which has a much smaller flow rate and hence smaller inlet cross-section than the Wedding high-volume sampler. At the second station where daily

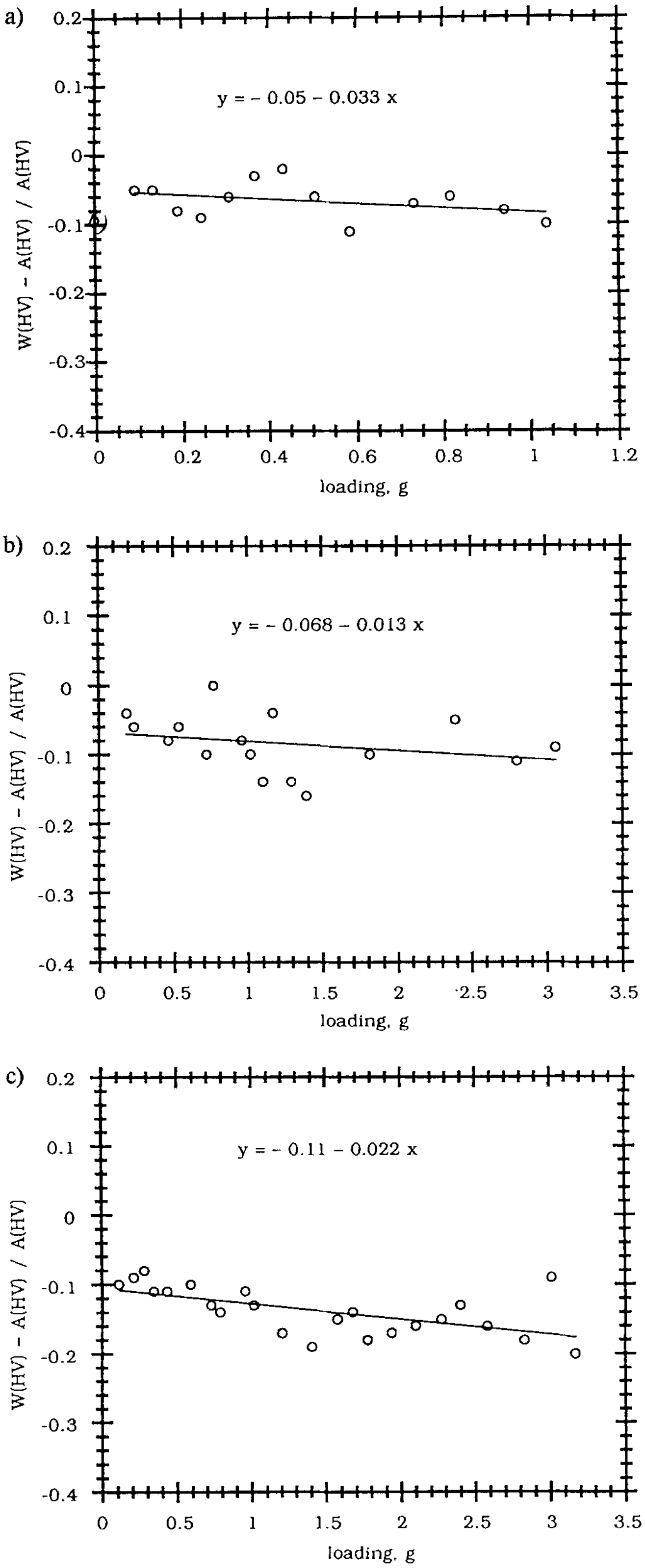

Fig. 4: Loading effect expressed as fractional difference between Wedding and SA 1200 high-volume samplers versus cumulated mass. (a) Third station; (b) first station; (c) second station.

PM_{10} concentrations are usually lower than those at the first station, Figure 3(b) also shows that the PM_{10} concentration difference between the two samplers is typically within ±10%. The above comparison test proves that daily PM_{10} concentrations calculated from hourly measured concentrations with the Wedding beta gauge deviate within an acceptable range from those measured by the Wedding high-volume sampler.

4.3 Loading Effect of Wedding Samplers

The loading effect of Wedding beta gauge and high-volume samplers was investigated using a daily cleaned and reoiled SA 1200 sampler as a reference. The test results for the Wedding high-volume and beta gauge samplers are plotted in Figures 4 and 5, respectively. Loading on the particle collection surface is calculated from the product of the measured PM_{10} concentration, sampling volumetric flow rate and total sampling time since the cleaning of the Wedding samplers. At the third station, Figure 4(a) shows the fractional difference between the Wedding high-volume and SA 1200 samplers versus particle loading. The intercept is −0.05 and the slope is 0.033/g. The intercept represents the difference between sampled values for the two newly cleaned samplers, as explained before. The slope means that as particles accumulate on the collection surface in the Wedding high-volume sampler, the cut-point becomes smaller and the sampler collects less particle mass.

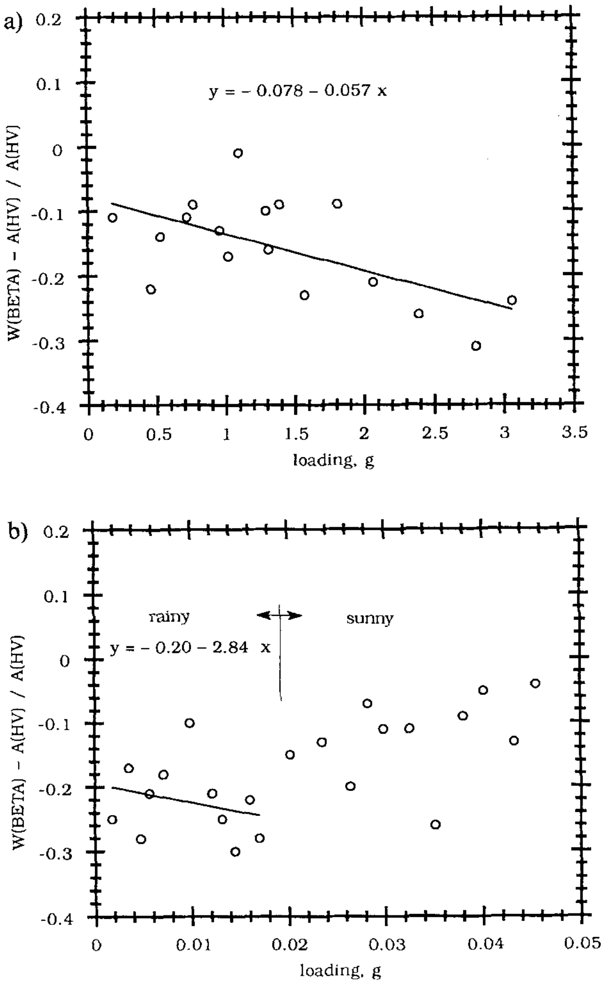

Fig. 5: Loading effect expressed as fractional difference between Wedding beta gauge and SA 1200 high-volume samplers versus cumulated mass. (a) First station; (b) second station.

At the first and second stations the intercepts are −0.068 and −0.11 and the slopes are −0.013/g and −0.022/g, respectively, as shown in Figures 4(b) and (c). The loading effect is also apparent. In this study, the slopes of the curves at all three stations are close to that found for the Wedding high-volume sampler by *John* and *Wang* [11], i.e. −0.0223/g.

The daily measured PM_{10} concentrations with the Wedding beta gauge sampler are lower than those with the SA 1200 sampler. It also has a loading effect that reduces its measured PM_{10} concentrations, as is evident in Figures 5(a) and (b) at the first and second stations, respectively. At the first station, the intercept is −0.089 and the slope is −2.70/g. Hence the difference between daily PM_{10} concentrations increases from the original 9% when the Wedding beta gauge is newly cleaned to 23% at the end of 12 days of sampling.

During rainy days at the second station, the intercept is −0.20 and the slope is −2.84/g. The large intercept during rainy days indicates that there could be more artifacts formed due to aqueous chemical reactions on the filter of the high-volume sampler, which increase its measured PM_{10} concentrations. However, the amount artifacts was not quantified in this study. When it turned sunny at a loading of 0.02 g, the difference between the measured concentrations of the two samplers immediately became smaller. However, the reason why the intercept becomes positive could not be explained.

5 Conclusions

A comparison test of three collocated samplers was conducted at three monitoring stations in Taiwan. The test results indicate that compared with the earlier SA 321A model, the Andersen SA 1200 high-volume sampler now has measured PM_{10} concentrations much closer to those of the Wedding high-volume sampler because the two samplers now have closer cut-points. The difference is now less than 10% when the particle collection surfaces of the two samplers remain clean.

The measured daily PM_{10} concentrations with the Wedding beta gauge sampler are typically within ±10% of those of the Wedding high-volume sampler. The Wedding beta gauge is able to capture detailed hourly PM_{10} concentrations even during rainy and humid conditions with reasonable accuracy.

Loading effects of both Wedding high-volume and beta gauge samplers were determined. The intercept of the Wedding high-volume sampler is from −0.013 to −0.033/g, which is comparable to the previously determined value of −0.0223/g. The intercept of the Wedding beta gauge sampler is from −2.7/g to −2.84/g. It is suggested that the inlet of a Wedding beta gauge sampler be cleaned once every week at a polluted area in order to limit its measured error to within 10% due to loading effect.

6 Acknowledgements

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7 References

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