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Comparison of Two Ambient Beta Gauge PM_{10} Samplers

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ABSTRACT

This paper reports on the performance of the Kimoto 180 sampler and the Wedding ambient PM_{10} beta gauge sampler. Monodisperse ammonium fluorescein test particles were generated in the laboratory and used to determine the penetration curve of the Kimoto 180 cyclonic inlet. It was found that the actual D_{pa50} of the Kimoto 180 inlet, 3.5 μm, is much lower than the designated standard value, 10 μm. In the field test, the two beta gauge samplers were collocated with an Andersen SA 1200 high-volume sampler to compare their measured daily average PM_{10} concentrations.

The low D_{pa50} of the Kimoto 180 inlet serves to explain why its daily average PM_{10} concentrations were much lower than the actual PM_{10} concentrations found in the field study. In addition, the PM_{10} concentrations of the Kimoto 180 beta gauge sampler were found to be seriously affected by the water vapor content of the ambient air. In contrast, the daily average PM_{10} concentrations of the Wedding beta gauge sampler were found to be more accurate, and influences by ambient conditions were insignificant.

INTRODUCTION

Normally, daily average ambient PM_{10} concentrations are measured by a reference PM_{10} sampler that is tested according to the test procedures and performance specifications for PM_{10} sampling methods, such as those set by the U.S. Environmental Protection Agency (U.S. EPA). A PM_{10} sampler must be tested in a wind tunnel to show a 10 ± 0.5 μm cutpoint in aerodynamic diameter (D_{pa50}) for each wind speed of 2, 8, and 24 km/hr.[1] The U.S. EPA also certifies beta attenuation as an equivalent method, capable of hourly sampling with near real-time analysis. For example, the automatic Wedding beta gauge PM_{10} sampler described in Wedding and Weigand[2] represents such an equivalent method.

> **IMPLICATIONS**
>
> This study demonstrates that performance specifications and test procedures for the PM_{10} sampling methods set by the U.S. EPA are important and must be followed in the development, selection, and use of ambient PM_{10} samplers. The experimental data obtained for the Kimoto 180 and Wedding PM_{10} beta gauge samplers help air quality monitoring personnel better understand the performance of beta gauge samplers. Possible influences on beta gauge readings by ambient air conditions are also reported.

Both the Wedding and the Kimoto 180 (Model 180, Kimoto Electric Co. LTD., Japan) automatic beta gauge PM_{10} samplers are currently used in Taiwan. It is important to know whether these two different samplers produce accurate data, compared with high-volume samplers certified by the U.S. EPA. In particular, the Kimoto 180 beta gauge PM_{10} sampler deserves more attention, as its performance has rarely been discussed in the open literature.

The Wedding beta gauge sampler[2] (henceforth the "Wedding beta gauge") consists of a cyclonic inlet of 10 μm in D_{pa50}, a 100 μCi ^{14}C source, a solid-state semiconductor detector with a count rate capable of greater than 10^5 counts/sec, and a critical flow device to control the volumetric flow rate of 18.9 liters/min at ambient conditions. The manufacturer claims that the resolution of the sampler is less than 3.0 μg/m³. The inlet was tested in a wind tunnel and D_{pa50} was shown to be 9.94, 9.96, and 9.51 μm for wind speeds of 2, 8, and 24 km/hr, respectively.[2] In the field test,[2] the Wedding beta gauge sampler was shown to provide daily average PM_{10} concentrations almost identical to the Wedding high-volume samplers. The readings of the Wedding beta gauge sampler were also shown to have little bearing on the variations of temperature and relative humidity in a laboratory comparison test of five different beta gauge samplers.[3]

Very little discussion about the Kimoto 180 can be found in the open literature. According to the manufacturer's operating manual, the Kimoto 180 has a cyclonic inlet of 6.5 μm in D_{pa50}, a less than 100 μCi ^{147}PM source, a scintillation detector with a count rate of 13,000 to 16,000 counts/sec, and a rotameter-type automatic flow controller that regulates the flow at 18 liters/min at ambient conditions. The sensitivity of the sampler is ± 10 μg/m³. The Kimoto 180 has a D_{pa50} much lower than 10 μm, and obviously this will result in a substantial underestimation of actual PM_{10} concentrations.

The operation principle and design considerations of a beta gauge sampler can be seen in Jaklevic et al.[4] and Lilienfeld.[5] Taking into consideration the influence of air in the source-detector gap and filter medium, the attenuation of beta particles through a filter medium with a particle deposit can be described by the following equation:

$$I = I_1 e^{-(\mu \delta + \mu_f \delta_f + \mu_{air} \delta_{air})} \quad (1)$$

or

$$= I_o e^{-(\mu \delta)} \quad (2)$$

In Equation (1), I_1 and I are the unattenuated and attenuated count rates respectively; δ, δ_f and δ_{air} are the mass per unit area (g/cm^2) and μ, μ_f, and μ_a are the mass absorption coefficient (cm^2/g) of the particle deposit, filter medium, and air in the source-detector gap, respectively. The value of δ_{air} can be calculated from the air density ρ_{air} and source-detector gap x as $\delta_{air} = \rho_{air}\, x_{air}$. Equation (2) is more often cited than Equation (1). I_0 in Equation (2) is equal to $I_1 e^{-(\mu_f \delta_f + \mu_{air} \delta_{air})}$. The mass absorption coefficient μ depends on Z/A (where Z = atomic number; A = atomic mass) of a material. It was shown experimentally[4] that μ is nearly a constant, ranging from 0.152-0.172 for compounds which have Z/A greater than 0.456. Since most aerosol compounds except lead have Z/A greater than 0.456, μ is normally considered a constant in a beta gauge sampler. The beta gauge sampler is usually calibrated in a laboratory wind tunnel, using a test aerosol, although it can also be calibrated for the type of aerosol to be sampled.

Sources of measurement error of a PM_{10} beta gauge sampler are: variations in air density due to ambient pressure and temperature fluctuations;[4,5] statistical counting errors;[4,5] different orientations of the filter paper at initial and final measurements of beta count through a sample;[6] filter inhomogeneity;[4] relative humidity;[3,5] and the soiling effect of the cyclonic inlet[7,8] etc. Most of these errors can be minimized by performing an initial beta count measurement before sampling. The soiling effect of cyclonic inlets can be minimized by cleaning the inlets regularly.

Water vapor content in the atmosphere may be an important factor affecting the readings of a beta gauge sampler. In particular, the relative humidity (RH) in Taiwan is often greater than 75% throughout the year. In summer, ambient air temperatures as high as 30 °C to 40 °C and RH as high as 90% to 100% are not uncommon. At high RH conditions, glass fiber filters may absorb water[9] and gain weight. But since an unattenuated beta count of the filter media is taken for each sample, if the atmospheric conditions do not change significantly during one hour of sampling, the water vapor absorption by the filter media is expected to be insignificant.

However, it is hard to eliminate the effect of water vapor absorption by the particle deposit. Collected inorganic salts on the filter medium are mostly hygroscopic.[10,11] At high RH, they absorb water vapor readily, turn into liquid phase, and grow in size. This may also increase the indicated particle concentration readings of a beta gauge sampler. Whether a sampler should include the water vapor content in the determination of mass concentration has rarely been discussed in the open literature.

This paper first describes the laboratory test method and results of the collection efficiency of the cyclonic inlet of the Kimoto 180. A Sierra-Andersen Model 1200 high-volume PM_{10} sampler (SA 1200) was used as a standard to compare the computed 24-hour daily average PM_{10} concentration readings of both beta gauge samplers at three air monitoring stations (Yun-Ho, Chung-Li, and Chia-Yi) in an effort to determine the accuracy of the readings and the possible influences of ambient air conditions. It should be noted that the filters of the SA 1200 were conditioned in a chamber maintained at RH = 40 ± 5%, T = 20 ± 3 °C before and after sampling and weighing. The effect of water vapor absorption by the filter media on the PM_{10} concentration measurement was minimized. Therefore, it was expected that calculated daily average PM_{10} concentration readings of the beta gauge samplers would be greater than those of the SA 1200 sampler, given that other conditions were fixed.

The SA 1200, which was described in McFarland and Ortiz,[12] is the latest Sierra-Andersen model with the smallest cutpoint of all models. The cutpoints are 9.5, 9.7, and 9.5 μm at wind speeds of 2, 8, and 24 km/h respectively, for the SA 1200 high-volume sampler;[12] or 9.6 and 9.5 at wind speeds of 2 and 8 km/h, respectively, for the Wedding high-volume sampler.[1] Measured PM_{10} concentrations for these two samplers were expected to be very close to each other. Results of an independent field study conducted from July to December 1993 at three other stations (Kuang-Inn, Hsin-Chu, and Hsiao-Kang) indicate that the daily average PM_{10} concentration readings of the SA 1200 sampler are about 7.2% to 9.3% greater than those of the Wedding high-volume sampler, as shown in Figure 1. The Hsiao-Kang station is close to a southern industrial zone, where PM_{10} concentrations are high, ranging from 40 μg/m^3 to 200 μg/m^3. The other two stations are in a rural area, where PM_{10} concentrations are usually below 80 μg/m^3.

Laboratory and Field Evaluations of Kimoto 180

Since the cutpoint of the cyclonic inlet of the Kimoto 180 was suspected to be much lower than 10 μm, its penetration curve was first evaluated experimentally in the laboratory. The experimental setup is shown in Figure 2. Solid

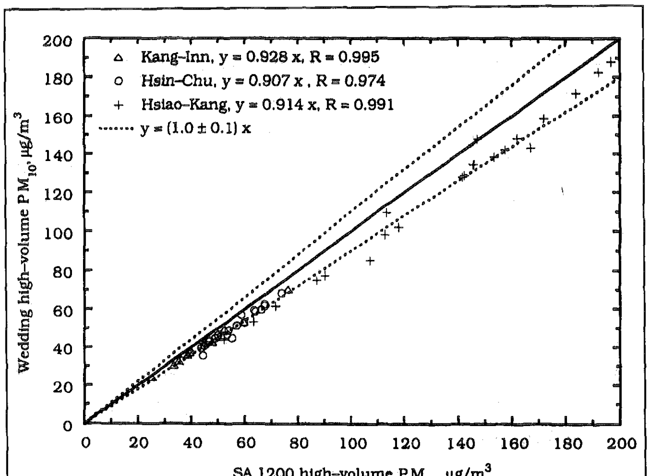

Figure 1. Comparison of daily average PM_{10} concentrations of SA 1200 and Wedding PM_{10} high-volume samplers at three monitoring stations. Linear regression of data points is forced to pass through the origin.

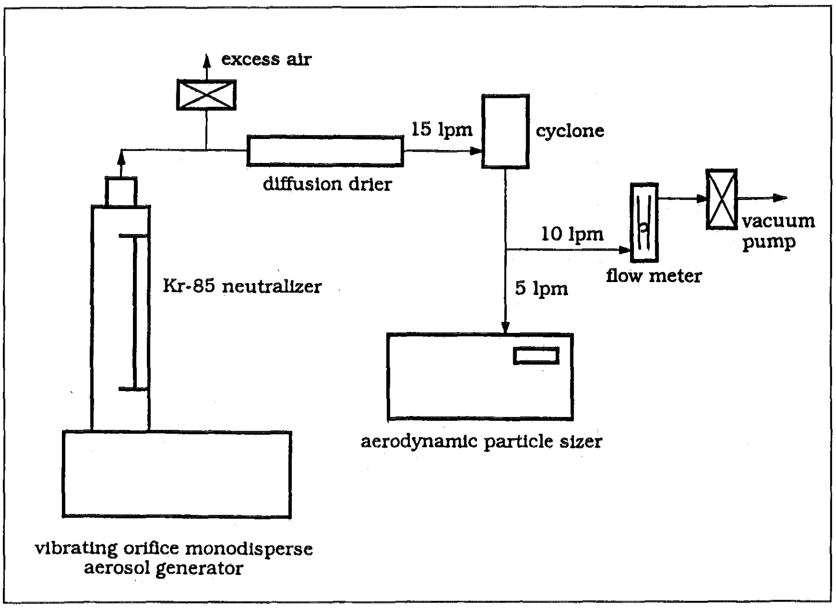

Figure 2. Schematic diagram of the experimental setup used to determine the penetration curve of the cyclonic inlet of the Kimoto beta gauge sampler.

monodisperse ammonium fluorescein particles (density = 1.35 g/cm³) were generated by a vibrating orifice monodisperse aerosol generator (Model 3450, TSI Inc., St. Paul), using the technique of Vanderpool and Rubow.[13] The sizing accuracy of test particles was determined independently by an aerodynamic particle sizer (Model APS 3310A, TSI Inc.) and a scanning electron microscope and was found to be within ± 5% of the stated value. The aerosol was neutralized using a Kr-85 charge neutralizer (Model 3077, TSI Inc.), dried in a silica gel diffusion drier, and then introduced into the cyclone.

The penetration of the cyclone, P, was determined from the inlet concentration C_{in} and outlet concentration C_{out} measured by the aerodynamic particle sizer as follows :

$$P = 1 - C_{out} / C_{in} \quad (3)$$

During the test, C_{in} of the test aerosol was found to be steady within ± 4%. C_{in} was nearly equal to C_{out} in the absence of the cyclone, indicating that particle transport loss was negligible.

The penetration curves for the experimental data and manufacturer's data for the Kimoto 180 beta gauge inlet, as well as for the Wedding beta gauge,[2] is shown in Figure 3. The experimental data indicate that the D_{pa50} of the Kimoto beta gauge inlet is only 3.5 µm, which is too small for the sampler to be called a PM_{10} sampler. The sampler was expected to produce PM_{10} readings lower than actual values, and deviations in particle size were expected to increase.

To validate that the Kimoto 180 would indeed indicate PM_{10} concentrations lower than actual values, the sampler was further tested at the Yun-Ho station. Detailed experimental procedures are discussed in the next section. A MOUDI cascade impactor (Model 100 MSP Corp., Minneapolis, Minn.) was collocated at the station to measure atmospheric particle size distribution. The cutpoints of the MOUDI from stages 1 to 9 are 18, 10, 5.6, 3.2, 1.8, 1.0, 0.56, 0.32 and 0.18 µm, respectively. An after filter collects particles with D_{pa} less than 0.18 µm.

Since the inlet penetration efficiencies for both the Kimoto 180 and the SA 1200 samplers are nearly 100% when D_{pa} is less than 1.8 µm, only particle mass distribution data for particles greater than 1.8 µm and less than 18 µm in D_{pa} are used to examine the differences between the PM_{10} concentration measurements of the Kimoto and SA 1200 samplers. The 18 µm and 1.8 µm correspond to the cutpoints of the first and fifth stage of the MOUDI. The theoretical particle concentrations of the Kimoto 180, M_k, and SA 1200 high-volume sampler, M_A, for D_{pa} from 1.8 to 18 µm can be calculated from particle mass distribution and penetration functions as follows:

$$M_K = \int_{1.8}^{18} \eta_K(D_{pa})\, f_M(D_{pa})\, dD_{pa} \quad (4)$$

$$M_A = \int_{1.8}^{18} \eta_A(D_{pa})\, f_M(D_{pa})\, dD_{pa} \quad (5)$$

where $f_M(D_{pa})$ is the particle mass distribution determined by MOUDI; $\eta_k(D_{pa})$ is the penetration function of the Kimoto 180 determined in the laboratory, and $\eta_A(D_{pa})$ is that of the SA 1200 sampler[12], respectively.

The results at the Yun-Ho station are shown in Figure 4. It is apparent that the Kimoto 180 daily average PM_{10} concentration readings (expressed as open circles in the figure), which were calculated from the hourly readings, are far too low compared to those from the SA 1200 sampler. At high PM_{10} concentrations, the deviation is as high as 50%. The deviation is less severe when PM_{10} concentrations are smaller

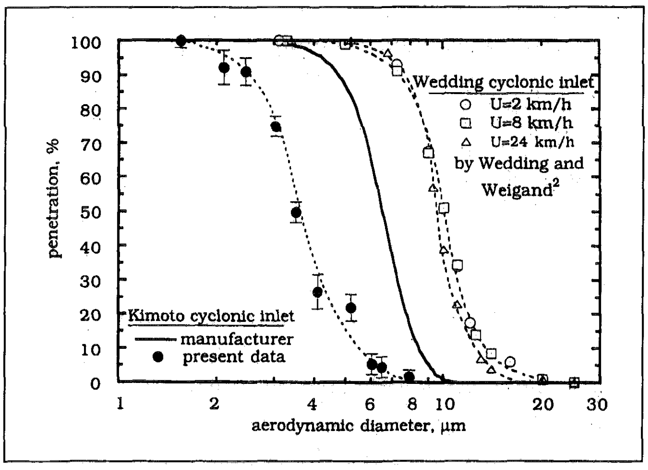

Figure 3. Comparison of penetration curves of the cyclonic inlets of Wedding and Kimoto beta gauge samplers. Dashed lines represent cubic splines through data points.

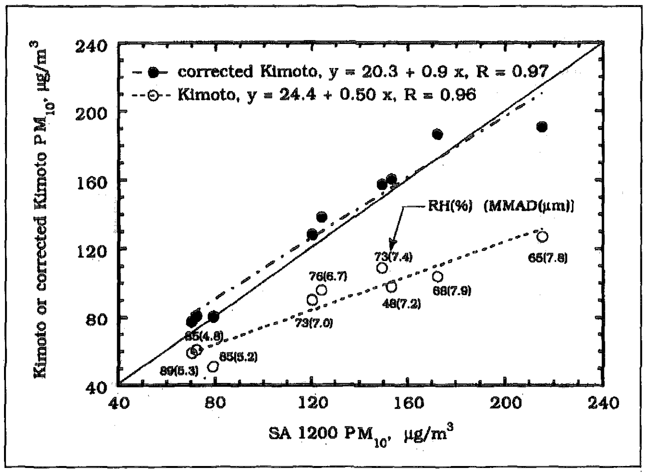

Figure 4. Comparison of daily average PM_{10} concentrations of the Kimoto 180 beta gauge sampler with those of the SA 1200 sampler at Yun-Ho monitoring station. Corrected Kimoto PM_{10} concentration is the original PM_{10} concentration plus M_A-M_k. Relative humidity and MMAD are also indicated.

than 100 μg/m³. This is because the coarse particle fraction is smaller when the PM_{10} concentration is lower.

Theoretical coarse particle concentrations of the Kimoto 180, M_k, were found to be smaller than those of the SA 1200 sampler, M_A. The differences are M_A-M_K. The corrected Kimoto PM_{10} concentrations, expressed as closed circles in Figure 4, are the summation of Kimoto PM_{10} concentration readings and M_A-M_K. It is seen that corrected Kimoto PM_{10} concentration readings are now very close to, but still about 10% greater than those of the SA 1200 sampler. The reason the corrected PM_{10} concentrations are greater than those of the SA 1200 is because of the water vapor effect on beta gauge samplers, as discussed in the previous section.

Comparison of Wedding and Kimoto Beta Gauges

The Wedding beta gauge, Kimoto 180 beta gauge, and SA 1200 sampler were collocated at Yun-Ho, Chung-Li, and Chia-Yi stations from January to June 1994. While the heights of the sampling inlets ranged from 10 to 16 meters above the ground, the inlets were at the same height at a given location. The horizontal distance between samplers was 2 to 4 meters to avoid flow interference. The impaction surface of the SA 1200 sampler was cleaned and sprayed with silicone grease before each sampling day, which commenced at 10 a.m. and ended at 10 a.m. the next day. The inlets of both beta gauges were cleaned every two days.

The glass fiber filters for the SA 1200 sample were conditioned for 48 hours in a humidity-controlled chamber (RH = 40 ± 5%, T = 20 ± 3 °C) before and after sampling and weighing.

During this study, the daily average temperature was typically 10 °C to 30 °C and daily average RH was typically 60% to 100%. In addition to hourly PM_{10} concentration readings of the beta gauges, hourly ambient conditions (such as RH and temperature), and weather conditions (such as rain intensity, wind speed, and wind direction) were also recorded and stored in the data processing unit of the monitoring station.

Daily average PM_{10} concentrations of both beta gauge samplers were computed from hourly readings during the same period as the SA 1200 sampler. The results are shown in Figure 5(a) for RH ≥ 80% and 5(b) for RH < 80% for all three monitoring stations. It is apparent that PM_{10} concentrations of the Wedding beta gauge are much closer to those of the SA 1200 sampler than the Kimoto 180 concentrations are. The slopes of linear regression are 1.13 (RH ≥ 80%) and 1.15 (RH < 80%) for the Wedding beta gauge and 0.76 (RH ≥ 80%) and 0.40 (RH < 80%) for the Kimoto 180 beta gauge, respectively. It is seen that the effect of RH is insignificant in the Wedding beta gauge readings. However, serious underestimation of PM_{10} concentrations by the Kimoto 180 is again apparent, due to the fact that its penetration

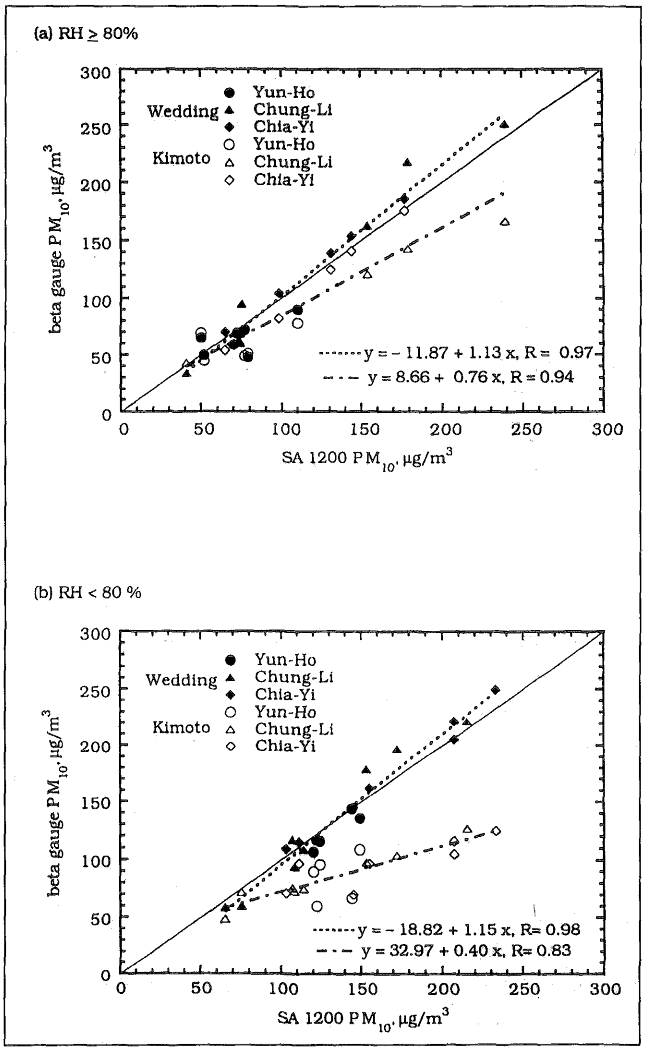

Figure 5. Comparison of daily average PM_{10} concentrations from the SA 1200 sampler with those from the Wedding and Kimoto beta gauge samplers at three monitoring stations: (a) RH ≥ 80%; (b) RH < 80%.

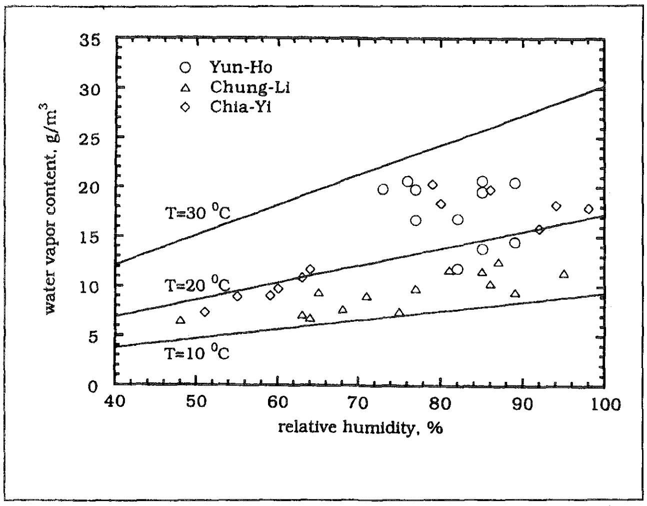

Figure 6. Water vapor content expressed as a function of temperature and relative humidity during the experimental period. Solid lines are theoretical curves.

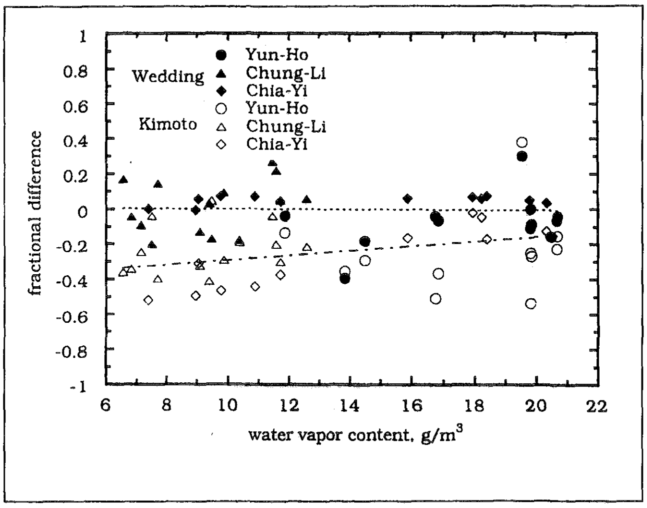

Figure 7. Fractional difference between the Kimoto beta gauge sampler and the SA 1200 sampler versus water vapor content.

curve is lower than the designated 10 µm, as discussed previously. The amount of underestimation increases with increasing PM_{10} concentrations, since high PM_{10} concentrations are usually associated with coarser particles. For example, the mass median aerodynamic diameter (MMAD) is about 5.0, 7.0, and 8.0 µm when the SA 1200 PM_{10} readings are about 70, 120, and >180 µg/m^3, respectively, as shown in Figure 4. The geometric diameter for coarse particles ranges from 1.94 to 2.4. High humidity implies that more water vapor may be absorbed by the increased amount of particles present at high PM_{10} concentrations. The effect on the Kimoto 180 is to increase the PM_{10} readings and to reduce the degree of underestimation, as shown in Figure 4.

Daily average water vapor content, expressed as g/m^3 (actual) during the experimental period, is shown in Figure 6. The solid line is calculated theoretically, based on the method described in Leung and Li.[14] It is clear that water vapor content increases with increasing temperatures and RH. It typically ranges from 5 g/m^3 to 20 g/m^3, and is greater than 20 g/m^3 in some cases in Taiwan. The performance of a beta gauge sampler can be examined further using a plot of fractional difference, which is defined as the difference between daily average PM_{10} concentrations from the beta gauge and from the SA 1200 sampler, divided by the daily average PM_{10} concentrations from the SA 1200 sampler, versus water vapor content, as shown in Figure 7. The Wedding beta gauge readings do not appear to be influenced by water vapor content within experimental errors. On the other hand, the effect of water vapor content on the Kimoto 180 readings is dramatic. The fractional difference of the Kimoto 180 tends to increase from -0.33 to -0.17 when water vapor content increases from 6 g/m^3 to 21 g/m^3. Analysis of the data shows that the fractional difference is influenced more by RH than temperature. Using RH as a reference, the fractional difference of the Kimoto 180 increases from -0.5 to 0.0 for RH increases from 50% to 100%.

CONCLUSIONS AND DISCUSSIONS

Our research found that the Kimoto 180 beta gauge sampler underestimates PM_{10} readings seriously because the cutpoint of its inlet, 3.5 µm, is much smaller than 10 µm. Deviations ranging from 0% to 50% were observed; these increased when PM_{10} concentrations increased or when water vapor content decreased. Although high water vapor content clearly increased the Kimoto 180 readings, the reasons for this remain to be investigated. It is suspected that water vapor absorption by the particle deposit may cause such an increase. On the other hand, the Wedding beta gauge was observed to be more accurate, and its readings were influenced insignificantly (within experimental errors) by the water vapor content.

In the other independent study, the daily average PM_{10} concentrations of the Wedding high-volume PM_{10} sampler were found to be 7.2% to 9.3% lower than those of the SA 1200 sampler. If the inlet penetration curve of the Wedding beta gauge was similar to that of the Wedding high-volume PM_{10} sampler, one would expect to see similar differences in the daily average PM_{10} concentrations, when the Wedding beta gauge was compared with the SA 1200 sampler. However, current experimental results do not reveal such differences. Further investigations in this regard are necessary.

Fundamental differences exist in the working principle, sampling, and analysis procedure of the high-volume and beta gauge samplers. It is anticipated that the two samplers will have differences in daily average PM_{10} concentrations since the former measures standard PM_{10} concentrations, while the latter measures actual PM_{10} concentrations. In addition, the water vapor effect on the measured concentrations is minimized, due to its absorption by the filter media, in the case of a high-volume sampler. In comparison to this, in the case of a beta gauge sampler, the unattenuated beta count is taken from the filter media without sampling any of the air flowing through it, so the conditions can be quite different from the high-volume sampling conditions. As a result, water vapor content may possibly result in higher PM_{10} concentrations, due to high water vapor content in the air gap and water absorption by the filter media or deposited particles. Elimination of the effect of water vapor content on the performance of a beta gauge sampler is critical, and specification of water vapor content in the test procedure of a beta gauge sampler seems warranted.

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