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Direct Field Observation of the Relative Humidity Effect on the β -Gauge Readings

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ABSTRACT

The effect of ambient relative humidity (RH) on hourly particulate matter (PM₁₀) readings of β -gauge monitors has been studied using two collocated monitors in the field. The inlet air of monitor 1 was conditioned with water vapor to increase its RH, whereas monitor 2 operated normally in ambient conditions. Experimental data showed that PM₁₀ readings of monitor 1 were nearly the same as monitor 2, as long as the RH of its conditioned incoming air did not exceed ~80–85%. However, when the RH exceeded ~80–85%, PM₁₀ readings of monitor 1 became higher than monitor 2, and the difference increased with increasing RH. The measurement of pressure drop across the filter was also conducted, and the data revealed that the increase of pressure drop per unit of PM₁₀ concentration decreased when RH was higher than ~80–85%, as compared with the case when RH was lower than 80–85%. This is perhaps because of more porous structure of deposited particles in the β -gauge monitor when RH is greater than ~80–85%. The theoretical calculation using an evaporation model and a thermodynamic model has been conducted to simulate the β -gauge readings. The results show that the theoretical PM₁₀ concentrations using the evaporation model are in better agreement with the actual β -gauge readings than those using the thermodynamic equilibrium model.

INTRODUCTION

The automatic Wedding β -gauge particulate matter (PM₁₀) monitor is one of the most popular semi-real-time aerosol monitors to measure hourly PM₁₀ concentrations

IMPLICATIONS

β -Gauge monitors are widely used in ambient particle measurement. The effect of the ambient RH on the β -gauge reading has to be investigated more carefully, especially in monitoring locations where the RH is high. This study provides direct evidence of the influence of the RH on the readings and shows that the influence is small when the RH is less than ~80–85%. However, when the RH is greater than ~80–85%, then the β -gauge monitor will overpredict the PM₁₀ concentrations.

in the ambient air. The Wedding β -gauge PM₁₀ system has a cyclone as the PM₁₀ inlet, and the flow rate is 18.9 L/min. It is an equivalent method for PM₁₀ monitoring as designated by the U.S. Environmental Protection Agency.¹ The β -gauge method is based on the attenuation of β particles as they pass through the filter tape and its collected particles. Before a sampling cycle begins, the carbon-14 source of the monitor emits β particles through a reference position of the blank filter tape. After detecting the initial or background count rate through the blank tape, the tape is moved to the sampling position under the inlet exhaust tube, and a sampling cycle begins.² After 54 min of the sampling cycle, the sampling manifold opens, and the filter tape with collected particles is returned under the carbon-14 source. When the sampling manifold closes, the source emits β particles again to measure the attenuation count rate because of the presence of collected particles. By calculating the difference of the attenuation count rates before and after sampling, the PM₁₀ concentration in that hour can be obtained.

Because of the frequent occurrence of high relative humidity (RH) in the ambient air of Taiwan, Taiwan Environmental Protection Agency is concerned about the influence of RH on the PM₁₀ readings of the automatic Wedding β -gauge PM₁₀ monitors. Chang et al.³ conducted a field study at four monitoring stations in Taiwan and found that the PM₁₀ concentrations of the Wedding β gauge were quite close to the measured values of the manual high-volume samplers when the ambient RH was lower than the deliquescence RH (DRH) of aerosols. However, when the DRH was exceeded, the PM₁₀ concentrations of the β gauge were found to be higher than those of the manual high-volume sampler, and the differences increased with increasing ambient RH. The experimental PM₁₀ concentration ratio of the β gauge to the high-volume sampler was further compared with the theoretical ratio assuming that the water content calculated by the ISORROPIA thermodynamic model⁴ was entirely associated with the collected particles of the β -gauge monitor, and there was no water evaporation loss during sampling. The results show that the thermodynamic model overpredicts water content in particles of the β -gauge monitor. Chang and Tsai⁵ further developed an evaporation model to determine water evaporation loss from

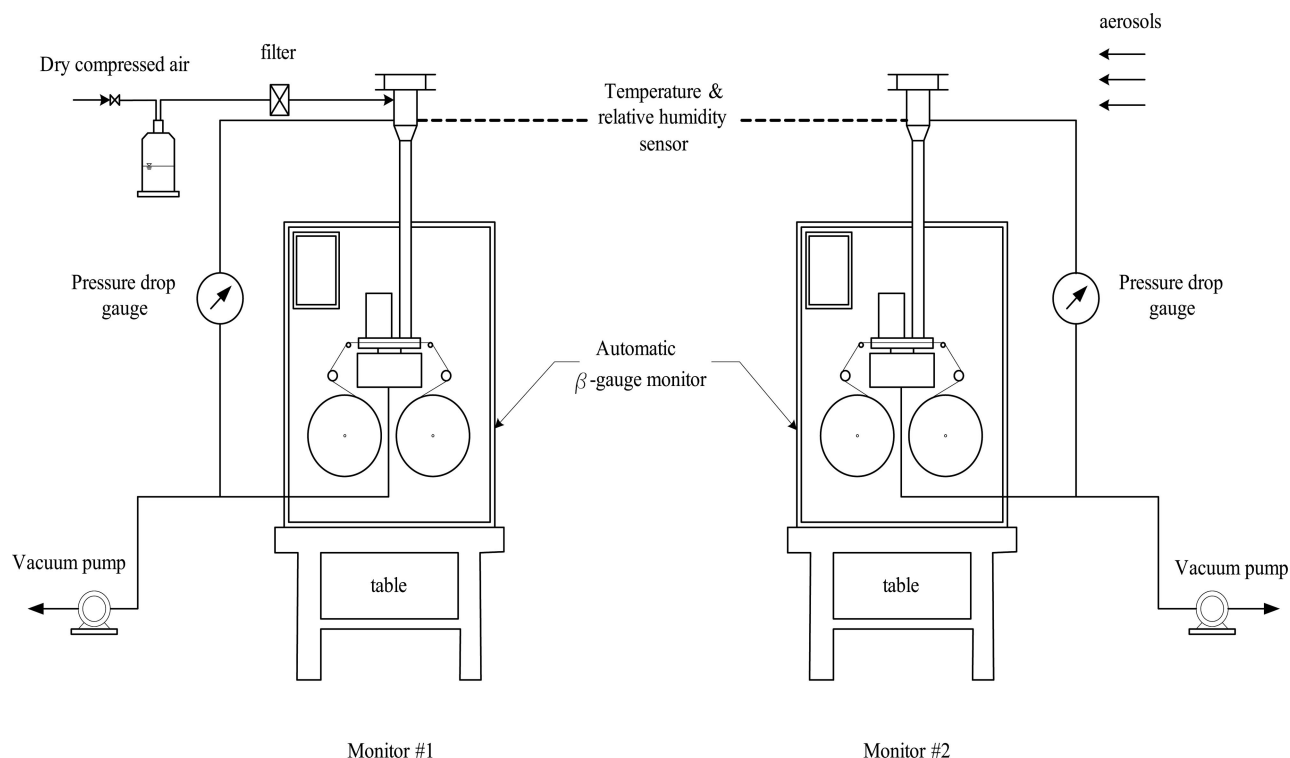


Figure 1. Setup of the field experiment for the influence of RH on hourly PM_{10} readings between two Wedding β -gauge monitors.

collected particles on the filter tape of the β gauge during the sampling process and in the monitoring room for monitors that are operated in an air-conditioned room. The results show that the evaporation model is more accurate than thermodynamic model, and the simulated β -gauge PM_{10} concentrations are close to the actual readings. Remaining water in particles explains the reason why the β -gauge readings are higher than the concentrations of the high-volume sampler when the RH is higher than $\sim 85\%$, and the differences increase with increasing ambient RH.

In some cases, β -gauge monitors are located in the field instead of inside fixed monitoring stations. Under ambient conditions, it is worthwhile to know whether RH still has an effect on the readings. In this study, we aim at providing direct evidence of the humidity effect on the hourly β -gauge PM_{10} readings for the monitors exposed to the field conditions. We compared the hourly readings of two collocated Wedding β -gauge monitors: the incoming air of monitor 1 was conditioned with water vapor so that its RH was higher than that of monitor 2. The PM_{10} readings and the pressure drop across the filter of both β -gauge monitors were measured at different ambient RHs. The theoretical PM_{10} readings using an evaporation model and a thermodynamic model were also calculated to compare with the PM_{10} β -gauge readings obtained in the present study.

In the filter sampling process, interparticle and gas-particle interactions and the dissociation of semivolatile species occur, which create sampling artifacts.⁶⁻⁹ These sampling artifacts are assumed to cancel out between two identical β -gauge monitors in this study. Therefore, any difference found in the study will result from different

amount of water absorption and evaporation between two β -gauge monitors operating at different RHs.

EXPERIMENTAL WORK

Two Wedding β -gauge monitors, monitor 1 and 2, were collocated on the fourth floor of the Institute of Environmental Engineering, National Chiao Tung University (NCTU), which is 8.5 m above the ground. The campus of NCTU is close to Hsinchu city, which is 104 km² in area with a population of $\sim 350,000$. This typical urban city in Taiwan is loaded with cars on the streets and is renowned for its high-tech semiconductor and optoelectronic industries. The city is located in the northern part of Taiwan and close to the western coast of the island.

Figure 1 shows the experimental setup. The incoming air of monitor 1 was conditioned with water vapor at the inlet by fine deionized water mist generated by an impinger or an ultrasonic atomizing generator (Ultrasonic nozzle, Model 8700, Sono-Tek Inc.) to increase its RH while monitor 2 was operated as usual. The flow rate of fine water mist was adjusted to be 0.5 L/min, which was much smaller than the β -gauge flow rate. The generated water vapor was filtered before introducing it into the inlet to remove residual particles that might influence the readings of monitor 1. The hourly PM_{10} concentration and the pressure drop of the two monitors were recorded and compared. There are total of four test periods generating 36 hourly PM_{10} datasets. The first two test periods were run from 3:00 p.m. on May 24 to 7:00 a.m. on May 25 and from 4:00 p.m. on May 26 to 8:00 p.m. on May 27, 2002. During these two periods, the ambient RH (or the RH of monitor 2) ranged from 62.5% to 82.8%, and the

Table 1. Size distribution parameters and ion concentrations.

| Concentration ($\mu\text{g}/\text{m}^3$) | Sodium | Chloride | Nitrate | Sulfate | Ammonium | MMAD (μm) | σ_g |
|-----------------------------------------------|--------|----------|---------|---------|----------|---------------------------|--------------|
| May 24–25 | 0.93 | 1.64 | 4.10 | 7.91 | 2.87 | Fine-0.47 Coarse-3.1 | 1.19 1.54 |
| May 26–27 | 1.37 | 2.30 | 3.91 | 9.24 | 4.14 | Fine-0.41 Coarse-3.6 | 1.31 1.64 |
| June 23 | 0.36 | 0.83 | 2.73 | 3.85 | 1.34 | Fine-0.25 Coarse-3.2 | 1.45 1.51 |
| June 24 | 0.47 | 1.23 | 3.18 | 4.26 | 2.29 | Fine-0.21 Coarse-2.9 | 1.39 1.47 |

MMAD = mass median aerodynamic diameter; σ_g = geometric standard deviation.

RH of monitor 1 was raised 5.3–8% higher than the ambient RH. Most of the time the RH of monitor 1 was <85%, and only occasionally it exceeded 85%. In the last two test periods, the RH of monitor 2 was intentionally increased to a value >90% by generating more water vapor using the ultrasonic atomizing generator. The tests were run from 4:00 to 12:00 p.m., June 23, and from 4:00 to 12:00 p.m., June 24, 2002, at which time the ambient RH (or the RH of monitor 2) ranged from 71% to 79.2%, and the RH of monitor 1 was 16.1–22.9% higher than the ambient RH.

During the studies, the aerosol size distributions were measured by a Micro-Orifice Uniform Deposit Impactor (Model 100, MSP Corp.) using Teflon filters as substrates, and the distributions were found to be bimodal. The ion concentrations were determined by ion chromatography (Model 4500i, Dionex Corp.). For example, in the test period of May 24–25, the mass median aerodynamic diameter and geometric standard deviation of fine and coarse particles were measured to be 0.47 and 3.10 μm and 1.19 and 1.54 μm , respectively. The ion concentrations of sodium, chloride, nitrate, sulfate, and ammonium were found to be 0.93, 1.64, 4.1, 7.91, and 2.87 $\mu\text{g}/\text{m}^3$, respectively. Results of the size distribution parameters and ion concentrations of all sampling periods are shown in Table 1. The size distribution and ion concentration data were used in the theoretical modeling of the hourly β -gauge readings.

On June 26, 2002, a test was further conducted to see whether the differences in PM_{10} readings of the two monitors were caused by different amounts of water vapor absorbed in the glass fiber filter tapes when the RHs of the two monitors were different. Ambient aerosol particles were removed entirely by replacing the PM_{10} inlets of both monitors with 47-mm filter holders while keeping the RHs of two monitors different. The ambient RH ranged from 73.7 to 96.5%, and the RH of monitor 1 ranged from 78.2 to 100%. As will be shown later, test results show that both monitors indicated zero PM_{10} concentrations, which pointed out that water absorption on the glass filter tapes did not affect β -gauge readings in this study. All of the differences in the PM_{10} readings of the two monitors resulted from different amounts of water vapor absorbed on the collected particles.

Theoretical Methods

Two methods were used in this study to predict the β -gauge readings: ISORROPIA thermodynamic model⁴ and evaporation model. ISORROPIA is a model that calculates the composition and phase state of an ammonia-sulfate-nitrate-chloride-sodium-water inorganic aerosol in thermodynamic equilibrium with gas-phase precursors. The ion concentrations determined in this study and shown in Table 1 were used to calculate the water content, which is assumed to be associated with the collected particles of the β -gauge monitor, and there is no water evaporation loss during sampling. The theoretical β -gauge PM_{10} reading is the sum of the water content and the “dry” PM_{10} concentration, determined by the β -gauge when the RH is low, typically <80%. In the evaporation model, the evaporated water mass during sampling was calculated based on the work of Cheng and Tsai⁸ and Chang and Tsai.⁵ The evaporated water mass was deducted from the PM_{10} concentration determined by the thermodynamic model. According to the model,⁸ the saturation ratio of water vapor concentration at the downstream of the filter, S_{out} , can be calculated as:

$$S_{\text{out}} = \chi + \frac{4\alpha \cdot \exp(\beta) - (S_{\text{in}} - \chi)}{[(1 + \alpha)^2 \exp(\alpha\beta) - (1 - \alpha)^2 \exp(-\alpha\beta)]} \quad (1)$$

$$\alpha = \sqrt{1 + \frac{4\delta}{n \cdot Pe} + \frac{24(1 - \epsilon)Sh}{Pe^2}} \quad (2)$$

$$\beta = \frac{n \cdot Pe}{2} \quad (3)$$

$$\chi = \frac{1}{1 + \frac{\delta \cdot Pe}{6n(1 - \epsilon)Sh}} \quad (4)$$

where n is the ratio of dust cake thickness to the diameter of the particle, L/D_p ; S_{in} is the saturation ratio of water vapor at the upstream of dust cake; δ is the ratio of pressure drop across the particle bed to the pressure at the upstream of the sampler, $\Delta P/P_0$; ϵ is the porosity of dust cake; S_h is Sherwood number; and Pe is Peclet number.

The evaporated mass of water, $m_{\text{ev},1}$, of the collected particles during the sampling period, Δt_A , can be found as:

$$m_{ev1} = \rho_e \cdot (S_{out} \cdot Q_{out} - S_{in} \cdot Q_{in}) \cdot \Delta t_A \quad (5)$$

where $Q_{out} = Q_{in}/(1 - \delta)$ is the flow rate at the downstream of dust cake; Q_{in} is the flow rate at the upstream of dust cake; and ρ_e is the saturation concentration of water vapor.

During filter sampling, water evaporation is calculated based on the pressure drop, ΔP , through the particle cake, which can be calculated as:

$$\Delta P = K_2 \cdot W \cdot V_f \quad (6)$$

$$K_2 = K_{2,st} \cdot R_{R-H} \quad (7)$$

where K_2 is the dust cake resistance constant; W is the mass area density of cake; and V_f is the face velocity. The flow resistance, K_2 , can be found by multiplying $K_{2,st}$, corrected by a correction factor R_{R-H} based on the Happel's cell model.

For the monitor exposed to the ambient air at field, the evaporation loss of particle-bound water also occurs when the sampling manifold is opened before β counting. The total evaporated water mass, m_{ev2} , of the collected particles during β counting, Δt_B , can be shown as⁵

$$m_{ev2} = \left(\frac{e^{2n\psi} - 1}{e^{2n\psi} + 1} \right) (1 - S_B) \frac{\rho_e D \psi}{D_p} A \Delta t_B \quad (8)$$

$$\psi = \sqrt{6(1 - \epsilon) S_h} \quad (9)$$

where S_B is the saturation ratio of water vapor; A is the filtration area; D is the diffusion coefficient of water vapor; and D_p is the particle diameter.

In the evaporation model, the evaporated water mass is the sum of m_{ev1} and m_{ev2} , which is deducted from the PM_{10} concentration determined by the thermodynamic model to obtain the theoretical β -gauge reading.

RESULTS AND DISCUSSION

Influence of RH on PM_{10} Readings

When both β -gauge monitors were not conditioned by water vapor, the PM_{10} readings of the two β -gauge monitors from May 19–22, 2002, were nearly the same, as shown in Figure 2. The difference in the PM_{10} readings averaged only $\pm 6.9\%$. During the test, ambient temperature ranged from 22.1 to 26.8 °C, and ambient RH ranged from 67.5 to 87.3%. However, when monitor 1 was conditioned with water vapor, its readings became different from those of monitor 2, as shown in Figure 3, for the data from May 24–25, 2002. The inlet RH of conditioned monitor 1 is 5.3–8.0% higher than that of monitor 2, and the highest RH occurred at 5:00–6:00 a.m., May 25, which is 89.3% for monitor 1 and 82.8% for monitor 2. The inlet temperature from 22.5 to 26.8 °C is nearly the same for the two monitors. Experimental data show that PM_{10} readings of the two monitors are nearly identical when the RH of monitor 1 is less than $\sim 82.1\%$ (12:00–1:00 a.m.) but higher than that of monitor 2. The difference of the PM_{10} readings of the monitors averages $\pm 1.5\%$ during

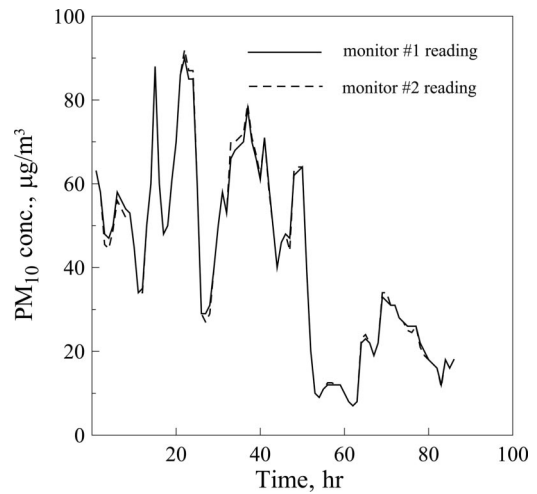


Figure 2. PM_{10} readings, RH, and temperature vs. time for two β -gauge monitors, May 19–22, 2002.

the test period. Higher PM_{10} readings of 9.2% are observed in monitor 1 when its RH is $>85.1\%$ at 2:00–3:00 a.m., and the difference increases to $16.8 \mu\text{g}/\text{m}^3$ (or 22.4% higher) at 5:00–6:00 a.m. when the RH of monitor 1 is peaked at 89.3%. The readings of both monitors become the same again as the RH of monitor 1 drops to 75.1%, although it is still 1.9% higher than the ambient RH (or RH of monitor 2). Similar results were obtained when the experiment was repeated from May 26–27, that is, differences in the PM_{10} readings only exist when the RH of monitor 1 is higher than ~ 80 –85%. Below that, no significant differences in PM_{10} concentrations between the two monitors are found.

When the RH of monitor 1 was raised to a value $>90\%$ by the ultrasonic atomizing generator, its PM_{10} readings became much higher than those of monitor 2 as shown in Figure 4 for the data obtained on June 23, 2002. Similar data were obtained on June 24, 2002. In Figure 4,

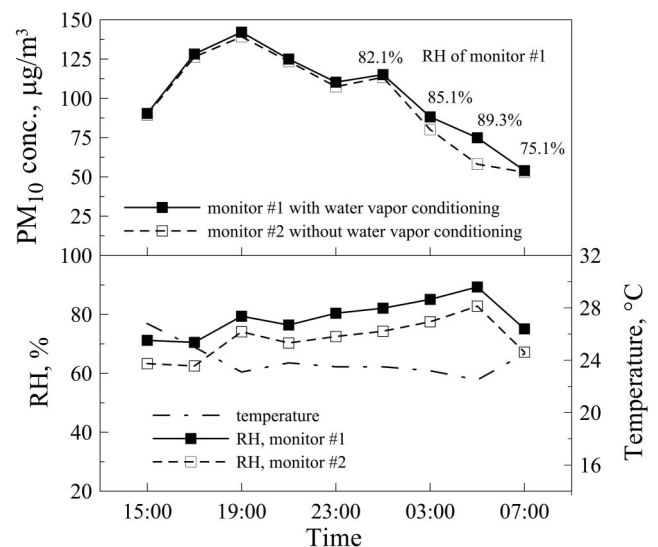


Figure 3. PM_{10} readings, RH, and temperature vs. time for the β -gauge monitors with or without water vapor conditioning, May 24–25, 2002.

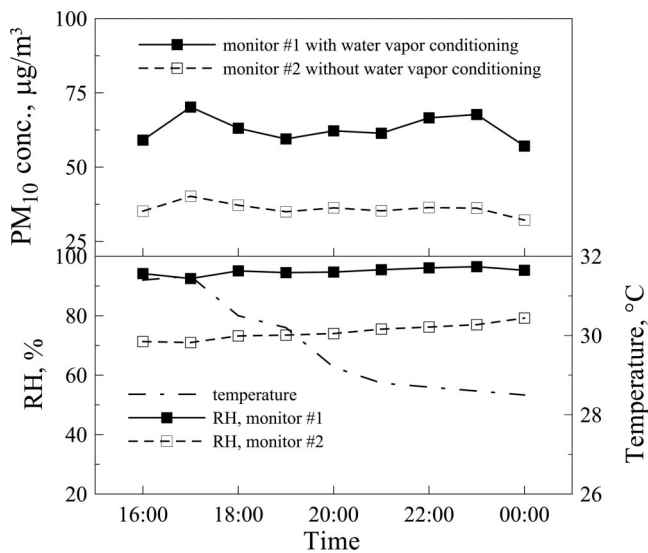


Figure 4. PM₁₀ readings, RH, and temperature vs. time for the β -gauge monitors with or without water vapor conditioning, June 23, 2002.

the RH of monitors 1 and 2 is from 92.5 to 96.5% and 71 to 79.2%, respectively. The temperature of the inlet air of these monitors is nearly the same at 28.5–31.5 °C. The PM₁₀ readings of monitor 1 ranges from 57.1 to 70.2 $\mu\text{g}/\text{m}^3$, which is 40.4 to 46.5% higher than that of monitor 2. The data obtained indicate the RH has a significant effect on the β -gauge readings only when it is greater than ~85%. The differences increase greatly with increasing RH when the RH is greater than ~85%.

To examine that water vapor absorption on the glass fiber filters does not give rise to the differences in β -gauge readings; the inlet of the two monitors were replaced by two 47-mm filter holders on June 26, 2002, and test results are shown in Figure 5. Before the filter holders were

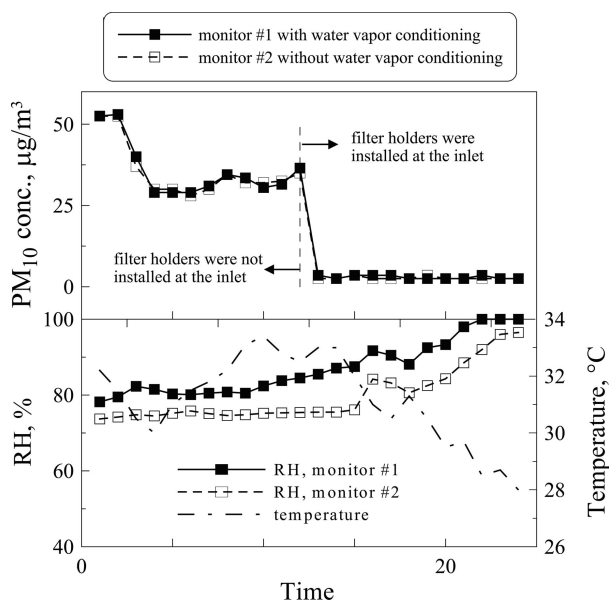


Figure 5. PM₁₀ readings, RH, and temperature vs. time for the β -gauge monitors, with or without aerosol filtering at the inlet, June 26, 2002.

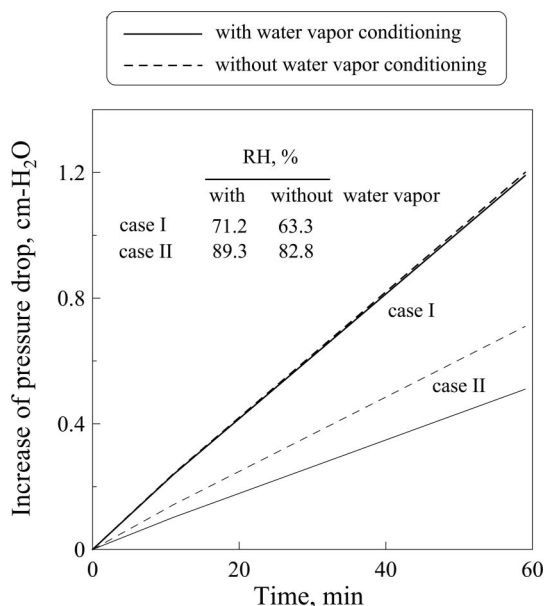


Figure 6. Increase of pressure drop vs. time. Case I: from 3:00 to 4:00 p.m. on May 24, 2002; Case II: from 5:00 to 6:00 a.m. on May 25, 2002.

installed to remove all of the particles coming into the two monitors (or before 3:00 p.m.), the two monitors had the same readings. With the filter holders in place while keeping the monitor 1 RH at 3.5–13.3% higher than monitor 2, the PM₁₀ readings of both monitors dropped to nearly zero. This indicates that the glass fiber filters do not affect the PM₁₀ readings, although they may absorb water vapor at high RH.

Influence of RH on Pressure Drop Across the Filter Deposit

During the test periods, the pressure drop across the filter cake increases as particles are collected on the filters. The increase of pressure drop with increasing sampling time was measured, and the results are shown in Figure 6. The increase of pressure drop of conditioned monitor 1 is found to be very close to that of monitor 2 when the RH of both monitors is <80% (monitor 1: 71.2%; monitor 2: 63.3%; Case I in Figure 6). However, when the RH of monitor 1 is high at 89.3% (6.5% higher than monitor 2), the increase of the pressure drop is found to be lower than that of monitor 2 (Case II in Figure 6). This is perhaps because of the more porous structure of the deposited particles on the filter tape of monitor 1 at high RH, which reduces the pressure drop. Similar influence of the RH on the pressure drop across the filter cake was also found in Gupta et al.¹⁰ Using all of the experimental data obtained in this study, the increase of pressure drop per unit of PM₁₀ concentration is plotted in Figure 7. It shows that the increase of pressure drop per unit of PM₁₀ concentration decreases slowly from 0.0147 to 0.012 cm-H₂O/ ($\mu\text{g}/\text{m}^3$) when the RH is increased from 67 to 81%. However, the decrease becomes sharper when the RH exceeds 80–85%, which is because of the more porous structure of the filter cake at higher RH. The smaller pressure drop across the filter deposits also results in less water vapor evaporation from the filter deposit and higher β -gauge

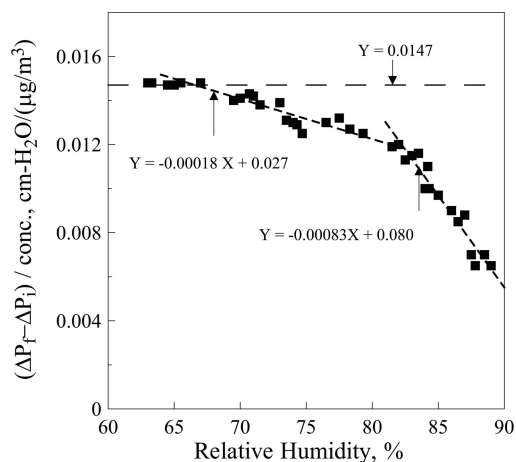


Figure 7. Increase of pressure drop per unit PM_{10} concentration vs. ambient RH, data from all periods (ΔP_f and ΔP_i are the pressure drop after and before sampling).

readings of monitor 1 when the RH is greater than ~80–85%, as is evident from the discussion in the previous section.

Comparison of β -Gauge Readings and Theoretical Predictions

Figures 8 and 9 show the comparison of the hourly β -gauge PM_{10} readings of monitor 1 and theoretical results of the evaporation model and ISORROPIA thermodynamic model⁴ from the period of May 24–25 and June 23, respectively. The theoretical water content of collected particles is calculated by the ISORROPIA model in the predictions. The water content that remained in the collected particles is further calculated by the evaporation model. The theoretical PM_{10} concentrations of the above two models are the sum of the PM_{10} readings of monitor 1 and the water content of the collected particles predicted by the two models. Both figures show that the evaporation model predicts the water content of collected particles more accurately than the thermodynamic

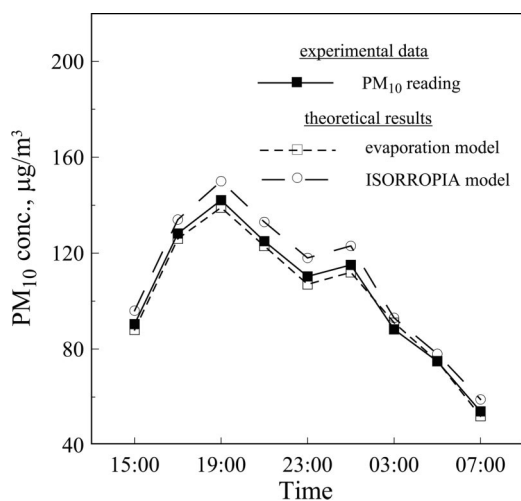


Figure 8. Comparison of PM_{10} readings and simulated concentrations of monitor 1, May 24–25, 2002 (ambient RH: $78.8 \pm 6.2\%$).

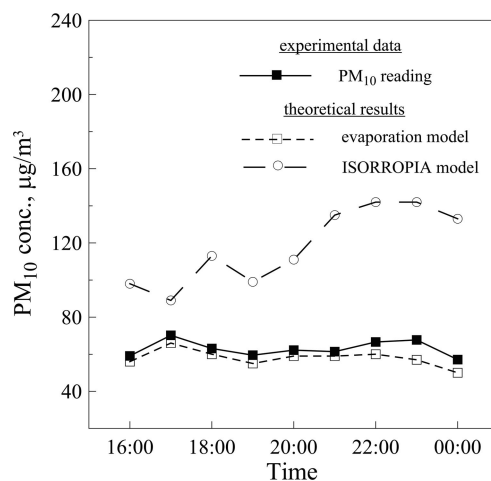


Figure 9. Comparison of PM_{10} readings and simulated concentrations of monitor 1, June 23, 2002 (ambient RH: $94.9 \pm 1.2\%$).

model. The PM_{10} concentration of monitor 1 is also predicted better by the evaporation model. When the average RH of monitor 1 is $<85\%$ (May 24–25, 2002), the thermodynamic model predicts a slightly higher PM_{10} concentration of monitor 1 as shown in Figure 8. Evaporation of water on the collected particles results in lower (but more accurate) PM_{10} concentrations than those predicted by the thermodynamic model. In comparison, Figure 9 shows that when the RH of monitor 1 is $>90\%$ (June 23, 2002), water content predicted by the ISORROPIA thermodynamic model is high, leading to a high PM_{10} concentration of monitor 1. In comparison, the evaporation model predicts the PM_{10} concentration more accurately. The remaining water on the filter explains why the concentrations of monitor 1 are still much higher than those of monitor 2, as shown in Figure 4. It is, therefore, very important to consider the water evaporation effect during β -gauge sampling and β -counting processes. The thermodynamic model can only predict water content on the airborne particles, not on particles that are collected on the filters.

CONCLUSIONS

In this study, two Wedding β -gauges monitors were collocated in the field with the inlet of one monitor conditioned by water vapor to examine the effect of RH on the β -gauge readings. The results show that PM_{10} readings of the two monitors are very close when the RH of both monitors are below ~80–85%, although the RH of one monitor is higher than the other. However, when the RH is >80 –85%, the results show the water content associated with particles collected on the filter tape cannot evaporate completely, resulting in higher β -gauge readings. In this case, the increase in the readings will increase with increasing RH; as more water is absorbed by particles, less evaporation occurs because of lower pressure drop through the filter cake.

The test results indicate that the thermodynamic model (such as ISORROPIA) can only predict the water content of particles when they are airborne. When particles are collected by the filters, pressure drop across the filter deposit occurs, which induces water vapor evaporation. At higher RH (>80 –85%), the remaining water on

the particles explains why the β -gauge readings are increased over those of the same PM_{10} particles in the lower RH (<80–85%) environment. An evaporation model has been developed to predict the β -gauge readings reasonably well.

To overcome the RH effect on the β -gauge readings, smart heaters were installed at the sampling inlet to remove moisture on aerosols when the RH was high. Test results of the β -gauge readings show good agreement with those of the Federal Reference Method samplers.¹¹ Results obtained in this study are helpful to the users of the β -gauge monitors to decide on the RH level to activate the heater.

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