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On the Effect of Tube Attenuation on Measuring Water Vapor Flux Using a Closed-path Hygrometer

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폐회로 습도계를 이용한 수증기 플럭스 관측시 관의 감쇠 효과에 관하여

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ABSTRACT

Eddy covariance method is widely used in measuring vertical fluxes of mass and energy between the atmosphere and the biosphere. In this method, scalar concentration is measured with either open-path or closed-path sensors. For the latter, fluctuations of scalar concentration are attenuated as the sample travels through a long tube, resulting in flux loss. To quantify this tube attenuation, water vapor concentrations measured with both closed-path and open-path sensors were analyzed. Our statistical analysis showed that the power spectral density obtained from the closed-path sensor was different from that from the open-path sensor in the frequency range of > 0.5 Hz. The loss of water vapor flux due to tube attenuation was < 5% during midday. At nighttime, however, the flux loss increased significantly because of the low wind speeds and the weak turbulence sources. Theoretical calculation for the tube attenuation showed a small bias in high frequency range probably because of the interaction of sticky water vapor with a tube wall.

Key words **: eddy covariance, hygrometer, tube attenuation, flux loss**

I. INTRODUCTION

Biosphere-atmosphere interactions play an important role in the climate change and weather (Pielke *et al*., 1998). Various methods have been used to quantify the mass and energy exchanges between the land surface and the atmosphere, of which the eddy covariance method is widely used. This method provides a direct measurement and does not require many assumptions compared to other micrometeorological methods (e.g., Choi *et al*., 1999). The vertical flux equation is based on the conservation law and may be simplified as:

$$Fc = \overline{w'\rho_c'} + \text{correction terms} \quad (1.1)$$

where w is the vertical wind speed; ρ_c is the concentration of a scalar quantity such as carbon dioxide, water vapor and methane; overbar is time averaging operator; and prime denotes the fluctuation

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from the mean. Some corrections are necessary for air density variation (Webb *et al.*, 1980) and inadequate frequency response (e.g., Moore, 1986; Massman, 2000), for instance. The measurement system is usually optimized such that the overall corrections are minimized (e.g., Hong *et al.*, 1997; Choi *et al.*, 1999). Typically, three-dimensional sonic anemometer is used for capturing the fast movement of wind, whereas fast-response open-path or closed-path sensors are used to measure the scalar concentration fluctuations.An open-path hygrometer measures *in situ* water vapor concentration in the atmosphere. A closed-path hygrometer draws the air sample through a tube to an infrared gas analyzer. Although open-path hygrometers are easier to manage, closed-path hygrometers do have some advantages in field operation. Firstly, frequency response correction can be minimized for the finite path and sensor separation. Secondly, flow distortion by the physical presence of the sensor near the sonic anemometer is minimized. Thirdly, the correction for air density variation for sensible heat flux can be removed (e.g., Leuning and Moncrieff, 1990). This density correction could be significant when the background concentration of a scalar is relatively larger than the magnitude of the vertical scalar flux. For example, CO_2 flux may change its sign after the correction (e.g., Suyker and Verma, 1993). Finally, open-path sensors for trace gases (e.g., CH_4, N_2O) are much more expensive or not even available for some gases. The signals from the sonic anemometer are processed on real time whereas it takes time for air to come to analyzers for closed-path sensors. Unless this delay time is considered in computing covariance, scalar fluxes are underestimated. A high-performance pump is required to maintain the stable flow rate. Otherwise, delay time may change from time to time, causing the flux calculation more difficult. In addition, spatially non-uniform scalar concentration results in diffusion process inside the tube and attenuates fluctuations of the scalar concentration, thereby underestimating turbulent scalar fluxes. In order to quantify the effect of tube attenuation, water vapor concentrations measured with both closed- and open-path hygrometers were analyzed. Covariance values obtained from these two different sensors were examined statistically for a given frequency domain using a spectrum analysis. These measurement results were also compared with theoretical results produced by models of Massman (1991) and Lee and Gill (1977, 1980).

II. Theoretical Background

2.1. Statistical test for tube attenuation

To quantify the difference in measured water vapor fluxes between the open-path and closed-path hygrometers, we applied a statistical test in which the probability distribution of the spectrum in a frequency domain must be known. The probability distribution follows the χ^2 distribution if time series is stationary Gaussian and satisfies with the weakly dependence assumption :

$$\sum_{m=-\infty}^{\infty} |m||R_x(m)| < \infty \qquad (2.1)$$

where R_x (m) is the autocovariance function at lag, m (x'(t)x' (t+m)) (Bendat and Piersol, 1986; Shumway, 1988). Then, the periodogram, P(f) in a frequency domain is approximately an unbiased estimator for the power spectrum, S(f) (Shumway, 1988). It can be used to derive 100(1-α) % confidence interval for the power spectrum as:

$$\frac{2P(f)}{\chi_n^2(\alpha/2)} \le S(f) \le \frac{2P(f)}{\chi_n^2(1-\alpha/2)} \qquad (2.2)$$

where χ_n^2 is chi-square distribution with n degrees of freedom. Degrees of freedom depend on the smoothing method in a frequency domain. In our study, the number of averaged power spectral density was increased exponentially in a frequency domain to increase the degree of freedom of chi-square distribution with increasing frequency.

The above assumptions were checked and then the null hypothesis (H_o) that the water vapor fluxes measured with the closed-path hygrometer is statistically same as those with the open-path sensor ($PSD_{open\ path}/PSD_{closed\text{-}path} = 1$) was tested. Because the probability distribution of the ratio of two χ^2 distributions follows the F distribution, H_o can be tested statistically using the F-test.

2.2. Calculation of delay time

When a closed-path sensor is used, the wind speed and the water vapor concentration are not measured at the same time. It is because of the traveling time for air sample to arrive at the analyzer. To compute this time lag, the cross-correlation between the vertical wind speed and the water vapor concentration was calculated. Generally, cross-correlation function has the peak at the time when the two variables are measured simultaneously. With a given flow rate in a tube with known tube length and diameter, the time lag can be analytically calculated by simple mathematics. Results of delay time computation will be discussed later. The mean flow velocity and Reynolds number, $Re = 2au_t/\nu$ (where *a* is the tube radius, u_t is the mean flow velocity in a tube, and ν is the kinematic viscosity of air) are computed from this time lag, and whether the flow in a tube is turbulent or laminar can be examined thereafter.

2.3. Theoretical prediction for the tube attenuation

When a closed-path sensor is used and the delay time is quantified, the attenuation in a tube remains to be the main concern for accurate flux measurement. The theory for the tube attenuation has been well established (e.g., Taylor, 1954; Philip, 1963; Lenchow and Raupach, 1991; and Massman, 1991, 2000). The tube attenuation effect can be explained by the transfer function such as:

$$T(f) \equiv \rho_{c-out}/\rho_{c-in} = e^{4\pi f^2 \Lambda L a u_t^{-2}} \tag{2.3}$$

where $\rho_{c\text{-}out}$ and $\rho_{c\text{-}in}$ denote the scalar concentration at the entrance and at the end of a tube, respectively; f is natural frequency (Hz); L is the tube length, and Λ is the attenuation coefficient which depends on the flow situation in a tube. Philip (1963) obtained the attenuation coefficient for the laminar flow ($Re < 2100$):

$$\Lambda = 0.0104\nu \ Re \ D^{-1} \tag{2.4}$$

where D is the molecular diffusivity of the scalar (e.g., water vapor). For a turbulent flow in a tube (i.e., $Re > 2300$), Massman (1991) obtained the attenuation coefficient by solving the diffusion equation numerically.

$$\Lambda = 0.5\nu \ Re \ |\lambda_i|\Omega^{-1}D_{max}^{-1} \tag{2.5}$$

where λ_i is the imaginary part of a eigenvalue of the diffusion equation, D_{max} is the maximum value of D, and $\Omega \equiv 2\pi f\alpha^2/D_{max}$.

2.4. Effect of air density variation

Webb *et al.* (1980) suggested that the simultaneous transfer of sensible and latent heat fluxes results in the variations in air density, thereby violating the assumption barw $\overline{w} = 0$. Most open-path sensors measure the density of the scalar in air rather than the mixing ratio, hence the total vertical flux of a scalar is given as:

$$F_c = \overline{w'\rho'_c} + \mu(\overline{\rho_c}/\overline{\rho_a})\overline{w'\rho'_v} + (1+\mu\sigma)(\overline{\rho_c/T})\overline{w'T} \tag{2.6}$$

where ρ_v and ρ_a are the densities of water vapor and dry air, respectively; μ is the ratio of molecular weights of water to dry air, $\sigma = (\overline{\rho_v}/\overline{\rho_a})$; and T is the temperature.

When a closed-path sensor is used to measure the water vapor fluxes, the density correction can be removed. Temperature fluctuations can be reduced fully by controlling the tube length and its material. If the ambient air is brought to the analyzer of a closed-path sensor to a constant temperature, constant pressure, and constant humidity (especially $\rho_v \cong 0$), the vertical scalar flux is given as:

$$F_c = (\overline{P}/\overline{P_I})(\overline{T_I}/\overline{T})\overline{w'\rho'_{cI}} \tag{2.7}$$

where subscript, *I* denotes values in the cell (analyser).

III. Materials and Method

Data used in this study were collected in a micrometeorological experiment made over a rice paddy in Hari, Kanghwa island in northwestern Korea during the summer of 1999. Rice canopy was about 0.2 m high with a standing water column of approximately 0.1 m and the leaf area index <1.0. The eddy covariance systems (1.95 m and 2.6 m above the water surface) were mounted on a 3 m tower. The system consisted of an open-path Krypton hygrometer (KH20, Campbell Scientific Inc., Utah, Logan, USA), a closed-path CO_2/H_2O infrared gas analyzer (LI-6262, LI-COR Inc., Lincoln, Nebraska, USA), three-dimensional sonic anemometers (CSAT3, CSI, USA), and fine wire thermocouples (see Fig 1). The details of the measurement theory and the specifications of LI-6262 are available in the literature (LICOR publication #9003-59). The eddy covariance data measured at 2.6 m were used for this study. The sampling rate was 10 Hz and more detailed information can be found in Kim *et al.* (1999).

The tube length was approximately 3 m. The pressure in a cell was maintained at 56 kPa in LI-6262 closed-path analyzer and the air was drawn at the intake at the rate of 12 LPM (standard liter per minute) using a vacuum pump. The sensor separation between the sonic anemometer and the open-path Krypton hygrometer was 0.13 m and the separation between the sonic anemometer and the intake tube for closed-path LI-6262 analyzer was 0.15 m.

All the necessary corrections were made, following Moore (1986) and Webb *et al.* (1980), and then the water vapor fluxes from the closed- and open-path sensors were compared. In this study, the attenuation coefficient for the turbulent flow in a tube was obtained from the data given in Lee and Gill (1977, 1980) by fitting the nonlinear regression:

$$\Lambda = \frac{a + \mathrm{Re}}{b + c \cdot \mathrm{Re}} \tag{3.1}$$

where $a = 144.5$, $b = -1375$, $c = 0.6742$, and $R^2 = 0.997$. The model of Lee and Gill (1977, 1980) seemed most realistic in parameterizing the turbulent diffusivity (Massman, 1991).

IV. Results and Discussion

4.1. Statistical analysis

In order to test our null hypothesis, H_o (no statistical difference in water vapor flux between open- and closed-path sensors), the criteria for the x^2 distribution must be examined. First, to examine the stationarity of the data, the nonstationarity factor was calculated following Mahrt (1998). This factor was in general less than 2 for the data used in this study, indicating that the stationary condition was met. Next criterion was the Gaussian time series. Our data were collected in a relatively homogeneous and flat surface and therefore followed the Gaussian distribution by yielding the third momentum, skewness to be near zero and the fourth momentum to be about 3. Third criterion was weak dependence. The autocorrelation function $(\overline{x'(t)x'(t+m)}/\sigma_x^2)$ of the atmospheric turbulence can be expressed as an exponential function. Then, the integration of the lag-weighted auto-covariance function must be bounded and the upper bound of this integration is the variance of the variables. The area of frequency-weighted power spectral density is finite because of the molecular dissipation at the high frequency. The random and uncorrelated molecular motion becomes more dominant at high frequency, thereby satisfying the weak dependence condition. In reality, third criterion can be violated when aliasing or white/blue noise occurs. In this study, high-quality data were selected through the spectrum analysis, and the probability distribution of the power spectral density followed the chisquare distribution (Fig. 2).

The null hypothesis, H_o was then tested using the F-test. Our statistical analysis showed that the power spectral density obtained from the closed-path sensor was statistically different from that from the open-path sensor in the frequency range of >0.5 Hz at the 95% confidence level. Hence, the null hypothesis was rejected above 0.5 Hz. During midday, the water vapor fluxes were underestimated approximately 5% above 0.5 Hz with the closed-path hygrometer. Total water vapor flux measured by the closed-path sensor appeared slightly greater than that measured by the open-path sensor (Fig. 3). It should be noted, however, that the difference resulted from the different contributions in energy containing range and is within the range of random error.

The water vapor fluxes measured by the closed-path sensor were underestimated up to 20% under the stable conditions with weak wind, but the actual magnitude of the flux was small (Fig. 3). At night, for example, cospectra shifts toward higher frequency and the contribution of smaller eddy becomes greater under stable conditions.

4.2. Theoretical analysis of tube attenuation

For the tube length of 3 m and the flow rate of 12 LPM, the mean flow velocity in a tube was 25.3 ms^{-1}. It corresponds to $\mathrm{Re} \sim 5500$ and hence the flow in a tube was turbulent. In this experimental setting, delay time due to a tubing alone was estimated as 0.1 second. The delay time calculated using the cross-correlation between the vertical wind speed and the water vapor concentration measured using the closed-path sensor was 0.7 second, however (Fig. 4). Fig. 5 shows comparison among the measured normalized cospectra $fC_{w\rho_c}/\overline{w'\rho'_c}$ using the closed-path and open-path sensors and the the-

Fig. 1. The eddy covariance system used in measuring the water vapor flux.

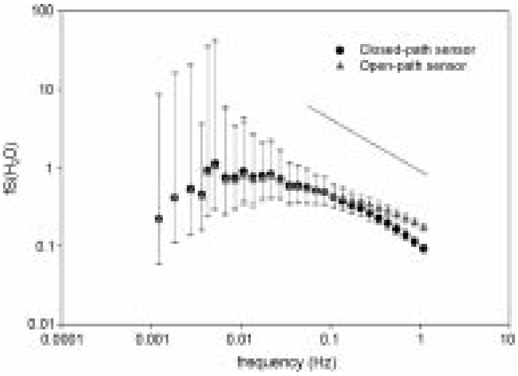

Fig. 2. The power spectral density of water vapor measured with the closed- and open-path sensors.

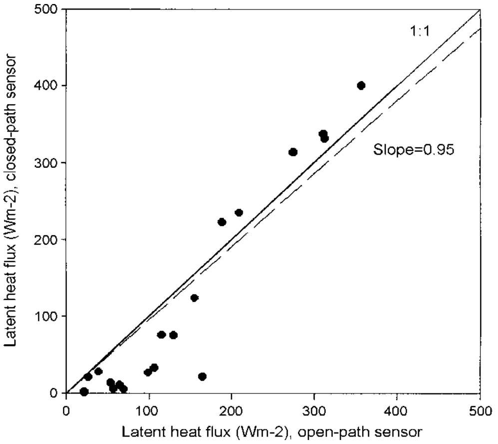

Fig. 3. Comparison of the latent heat flux measured with closed- and open-path sensor eddy covariance systems.

ore-tical cospectra. The theoretical cospectra compared reasonably with the measured cospectra

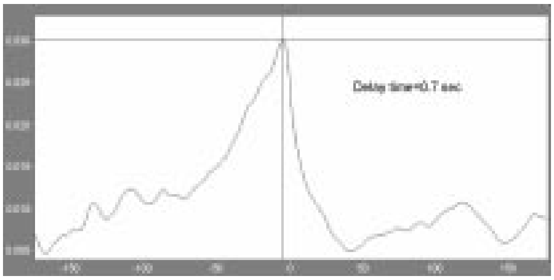

Fig. 4. The cross-correlation between the vertical wind speed and the water vapor concentration measured with the closed-path sensor. The peak of the cross-correlation occurred at 0.7 s.

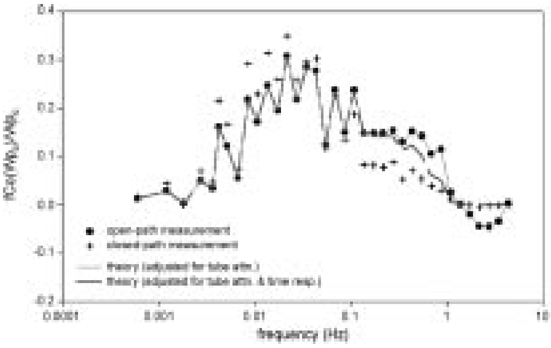

Fig. 5. Normalized cospectra of water vapor and vertical wind speed. Cospectra predicted by the model for the tube attenuation are also shown.

except in the high frequency domain.

This small discrepancy between the measured and theoretical results may be explained by considering the assumptions used in the theoretical models for the tube attenuation. First possibility is the reduced flow rate along the tube due to the effect of several bends in the tubing. As Massman (1991) had pointed out, however, the scalar concentration would be asymmetric with respect to travel time and distance down the tube in the entrance of a tube, so the bend actually improve the frequency response for both turbulent and laminar flows. Lenchow and Raupach (1991) showed that the effect of bends in the tubing was similar to the intake section because in both cases the flow had a more uniform velocity profile across the tube, which diminished the effect of differential advection. Therefore, these effects cannot account for the discrepancy in our study. Also, the condition that the edge effect can be neglected in the turbulent flow was satisfied in our experimental setting. That is,

$$L/a > 0.25\nu \ \mathrm{Re} \ D_m^{-1} \tag{4.1}$$

where D_m is the mean of the turbulent diffusivity profile in a tube.

Second possibility is the interaction between solute and a tube wall. Zeller *et al.* (1989) showed that even relatively small interaction velocity ($|\upsilon_d| \approx 0.03$ cm s^{-1}) was sufficient to cause the observed lengthening of the response time. And the major impact of this interaction is to significantly reduce the amplitude of the signal (Massman, 1991). In our study, delay time between the vertical wind speed and the CO_2 concentration measured using the same tubing setting for water vapor measurement was 0.3 second. Water vapor is stickier than CO_2. Therefore, the difference of delay time between H_2O and CO_2 may be mainly induced by the interaction of water vapor with a tube wall. It is natural that the model can predict the measured results better when delay time was given as 0.7 second in this study (Fig. 4). More detailed and organized experiment to further investigate the effects of the interaction on the flow attenuation may be needed.

Third possibility is the response time of the closed-path sensor. The response time of the gas analyzer can be estimated by introducing the step changes in concentration at the instrument inlet. Although this process was not done in our experiment, Suyker and Verma (1993) showed that the response time of LI-6252 was 0.05 second, where their maximum flow rate through the analyzer was 10 LPM (LI-COR Manual publication number: 9003-59). A little more damping might have occurred inside the closed-path sensor due to the response time of LI-6262. Finally, possibility of leakage in the tubing system could also affect the time delay. The spectra and cospectra from the two different systems were, however, very similar, suggesting no significant leakage in our closed-path sampling system.

V. SUMMARY AND CONCLUSION

Turbulent fluxes of water vapor were measured with the closed-path infrared gas analyzer (LI-6262) using the eddy covariance system installed at the height of 2.6 m above the water surface in a rice canopy. The results from the closed-path sensor system were compared against those from open-path sensor system (using KH20). The former was on average 5% smaller in the magnitude of water vapor during midday. Such a small flux loss was likely resulted from the fact that the flow rate in closed-path system was fast enough to maintain turbulent flow in a tube. Our statistical analysis showed that the power spectral density obtained from the closed-path sensor was different from that from the open-path sensor in the frequency range of >0.5 Hz. The model for the flow attenuation in a tube produced a reasonable comparison with those from the measurement. We speculate that the interaction of water vapor with a tube wall might have resulted in small biases in the modeled results. In conclusion, both closed-path and open-path sensors can be successfully used in water vapor flux measurement with 5% uncertainty except under stable conditions when care must be exercised for the contribution of high frequency eddies in flux estimation.

요 약

에디 공분산 방법은 생태계와 대기간의 질량과 에너지 교환을 측정하는데 널리 사용되고 있다. 이 방법은 다른 미기상학적 방법과는 달리 많은 가정을 필요로 하지 않는 직접 측정으로서, 스칼라의 농도 변화를 측정하기 위해 고속 반응의 개회로 또는 폐회로 기기를 필요로 한다. 후자를 사용할 경우, 흡입된 공기가 관을 통과하면서 스칼라의 농도 변동의 감쇠가 일어난다. 이러한 관 감쇠 효과는 측정하고자 하는 난류 플럭스를 과소 평가하게 한다. 난류 흐름의 감쇠 효과를 정량화하기 위해서 개회로 기기와 폐회로 기기로 측정된 수증기 농도를 각각 분석하였다. 통계적 분석에 의하면, 폐회로 기기에서 얻어진 스펙트럼이 0.5 Hz 이상의 영역에서 개회로 기기에서 얻어진 스펙트럼과 서로 다름을 보였다. 낮에는 관 감쇠에 의한 수증기 플럭스의 손실이 5% 이내였으나, 밤에는 풍속이 작고, 난류의 강도가 약하여 플럭스 손실이 상대적으로 크게 나타났다. 이론적으로 계산된 플럭스 손실은 관측 결과와 고주파수 영역에서 약간의 차이를 보였는데, 이것은 수증기가 관의 벽과 상호 작용하면서 플럭스 측정에 영향을 주었기 때문인 것으로 추정된다. 결론적으로, 개회로나 폐회로 기기 모두 5% 오차 내에서 수증기 플럭스 관측에 사용할 수 있다. 그러나 대기가 안정할 때는 플럭스 산출시 고주파수에서의 영향을 신중히 고려해 주어야 한다.

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