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Technical note

Temporal/seasonal variations of size-dependent airborne fungi indoor/outdoor relationships for a wind-induced naturally ventilated airspace

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Abstract

With the use of published temporal/seasonal size characteristics of fungal spores and meteorological data in the subtropical climate, we estimated the airborne fungal concentration indoor/outdoor (I/O) ratios in a wind-induced naturally ventilated home. We expanded previous size-dependent indoor air quality model based on a hygroscopic growth factor as a function of relative humidity (RH) on aerodynamic diameter and concentration of fungal spores. The average geometric mean diameters of airborne fungi decreased from outdoor 2.58 ± 0.37 to indoor $1.91 \pm 0.12\,\mu m$ in summer, whereas decreased from outdoor 2.79 ± 0.32 to indoor $1.73 \pm 0.10\,\mu m$ in winter, resulting from the effect of hygroscopicity of airborne fungi. The higher indoor airborne fungal concentrations occurred in early and late afternoon in which median values were 699.29 and 626.20 CFU m^{-3} in summer as well as 138.71 and 99.01 CFU m^{-3} in winter, respectively, at 2 a.m. and 8 p.m. In the absence of indoor sources, summer has higher mean I/O ratios of airborne fungal concentration (0.29 – 0.58) than that in winter (0.12 – 0.16). Parsimoniously, our proposed RH-corrected I/O ratio model could be used to estimate the indoor source concentrations of bioaerosols provided that the actual measured fungus-specific I/O ratios are available.

Keywords: Airborne fungus; Bioaerosol; Deposition; Hygroscopic; Humidity; Natural ventilation

1. Introduction

Fungus allergen is one of the predominant allergens in Taiwan. The main source of airborne fungi in indoor air is usually from outdoor air (Wu et al., 2000). Su et al. (2001) reported that human exposure to airborne fungal spores might cause adverse health effects, especially respiratory symptoms. As most time of 70–90% is spend indoors, information on the indoor and outdoor relationships of airborne fungal concentrations is important.

Burge et al. (1995) indicated that the extent of airborne fungi is closely related to indoor relative humidity (RH), while above 70% RH conditions may be optimal for fungal growth. The hygroscopic growth, which means increase of a particle diameter by condensation or water absorption, influences the kinetics of aerosol. Therefore, we expanded previous size-dependent indoor air quality model (Liao et al., 2003) based on a hygroscopic growth factor. The objectives of this paper were set to predict the airborne fungi indoor/outdoor relationships with variations of seasonal, temporal and meteorological effects.

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2. Materials and methods

2.1. Reanalysis of outdoor fungal spores data

We adopted the research results of Lin and Li (1996) as our major database to appraise the temporal/seasonal variations of size-dependent airborne fungi indoor/outdoor relationships in a wind-induced naturally ventilated airspace. Box and whisker plots are used to demonstrate the seasonal variation of wind speed, temporal/seasonal variations of indoor/outdoor RH and outdoor airborne fungal concentrations data (Figs. 1A–D). Furthermore, we employed an opening effectiveness model to predict the flow through a sidewall opening (Liao et al., 2003) depending on wind speed and window/door openings to estimate air exchange rates.

2.2. Effects of relative humidity on fungal spores

We developed a relative humidity versus aerodynamic equivalent diameter (RH–AED) growth coefficient profile and a RH-concentration profile for airborne fungi to correct the proposed indoor/outdoor (I/O) ratio model by Liao et al. (2003). Our approach applied the research findings obtained from Reponon et al. (1996), Johnson et al. (1999), and Lee et al. (2002) to derive a RH–AED profile so as to determine the specific growth coefficient versus AED of airborne fungi (Fig. 1E). Fig. 1E indicates that specific growth coefficient (g, dimensionless) and RH (%) has a linear relationship as: $g(\mathrm{RH}) = 0.0027\ \mathrm{RH} + 0.84$ ($r^2 = 0.80$, $p < 0.05$) for RH ranging from 10% to 100%. Based on Fig. 1E, we could obtain a corrected factor for AED of airborne fungi due to RH changes as

$$\mathrm{RH}_{\mathrm{dp}} = \frac{g(\mathrm{RH_i})}{g(\mathrm{RH_o})}, \tag{1}$$

where $\mathrm{RH}_{\mathrm{dp}}$ is the AED corrected factor due to RH changes, $g(\mathrm{RH_i})$ is the specific growth coefficient due to indoor RH ($\mathrm{RH_i}$, %), and $g(\mathrm{RH_o})$ is the specific growth coefficient due to outdoor RH ($\mathrm{RH_o}$, %). Thus, AED-corrected I/O ratio model due to RH changes can be expressed as

$$\frac{C_{\mathrm{I}}(k')}{C_{\mathrm{o}}(k')} = \frac{\lambda_{\mathrm{n}}}{\lambda_{\mathrm{n}} + \lambda_{\mathrm{d}}(k')}, \tag{2}$$

where $k' = k \times \mathrm{RH}_{\mathrm{dp}}$ is the AED-corrected size range number, in which k is the size range number; $C_{\mathrm{I}}(k')$ is the indoor concentration of fungal spores in the k'th size range (CFU m^{-3}); $C_{\mathrm{o}}(k')$ is the outdoor concentration of fungal spores in the k'th size range (CFU m^{-3}); λ_{n} is the air exchange rate of natural ventilation through open windows and doors (h^{-1}) in which $\lambda_{\mathrm{n}} = \mathrm{Q_n}/\mathrm{V}$, $\mathrm{Q_n}$ is the natural ventilation rate ($\mathrm{m}^3\,\mathrm{h}^{-1}$); V is the volume ($\mathrm{m}^3$); and $\lambda_{\mathrm{d}}(k')$ is the deposition rate of indoor fungal spores due to Brownian and turbulent diffusive deposition and gravitational sedimentation in the k'th size range (h^{-1}). The particles are divided into geometrically equal sized bins in the size range of interest.

We analyzed the available data from Lin and Li (1996) regarding the relationship between concentrations and RH to derive a region-specific seasonal variation RH-concentration profile in order to correct the indoor concentration of airborne fungi due to RH changes in northern Taiwan region (Figs. 1F,G). Figs. 1F and G show that linear RH-concentration relationships prevailed for both summer and winter in that specific concentration correction factors due to RH in summer and in winter are $\log C_{\mathrm{s}}(\mathrm{RH}) = 0.0314\,\mathrm{RH} + 1.36$ ($r^2 = 0.80$, $p < 0.05$) and $\log C_{\mathrm{w}}(\mathrm{RH}) = 0.0165\,\mathrm{RH} + 1.73$ ($r^2 = 0.74$, $p < 0.05$), respectively. The concentration correction factor ($\mathrm{RH_c}$), for example, in summer has the form as

$$\mathrm{RH_c} = \frac{C_{\mathrm{I}}(k')^{[\log C_{\mathrm{s}}(\mathrm{RH_i})/\log C_{\mathrm{s}}(\mathrm{RH_o})]}}{C_{\mathrm{I}}(k')}. \tag{3}$$

The corrected indoor airborne fungal concentration, $C_{\mathrm{i}}(k')$, in summer can be written as

$$C_{\mathrm{i}}(k') = C_{\mathrm{I}}(k') \times \mathrm{RH_c} = \left(C_{\mathrm{o}}(k')\frac{\lambda_{\mathrm{n}}}{\lambda_{\mathrm{n}} + \lambda_{\mathrm{d}}(k')}\right)^{[\log C_{\mathrm{s}}(\mathrm{RH_i})/\log C_{\mathrm{s}}(\mathrm{RH_o})]}. \tag{4}$$

In this basic model, the impact of RH effect on airborne fungal concentration is almost completely captured by a simple expression for I/O ratio in the absent of indoor sources.

3. Results and discussion

Table 1 gives the measured and predicted mean values of the total concentrations and geometric mean diameter (GMD) with geometric standard deviation (GSD) of particle size distribution for indoor/outdoor airborne fungi in summer/winter at different time periods. Airborne fungi in summer have higher indoor/outdoor concentrations than that in winter at selected time periods. There were major RH fluctuations being observed in winter ($\Delta\mathrm{RH} = 16.59 \pm 2.63\%$ in winter ($\mathrm{RH_o} > \mathrm{RH_i}$), and $9.94 \pm 6.63\%$ in summer ($\mathrm{RH_o} < \mathrm{RH_i}$) (Figs. 1C,D) result in a larger difference in outdoor/indoor airborne fungal concentrations than that in summer. The average GMDs airborne fungi decrease from outdoor $2.58 \pm 0.37\,\mu\mathrm{m}$ to indoor $1.91 \pm 0.12\,\mu\mathrm{m}$ in summer, whereas decrease from outdoor $2.79 \pm 0.32\,\mu\mathrm{m}$ to indoor $1.73 \pm 0.10\,\mu\mathrm{m}$ in winter (Table 1). The results suggest that the hygroscopicity of airborne fungi as a function of RH significantly affect their AED in a wind-induced naturally ventilated airspace (Chen et al., 2003).

The predicted indoor airborne fungal concentrations are presented in Figs. 2A and B, in that box and whisker

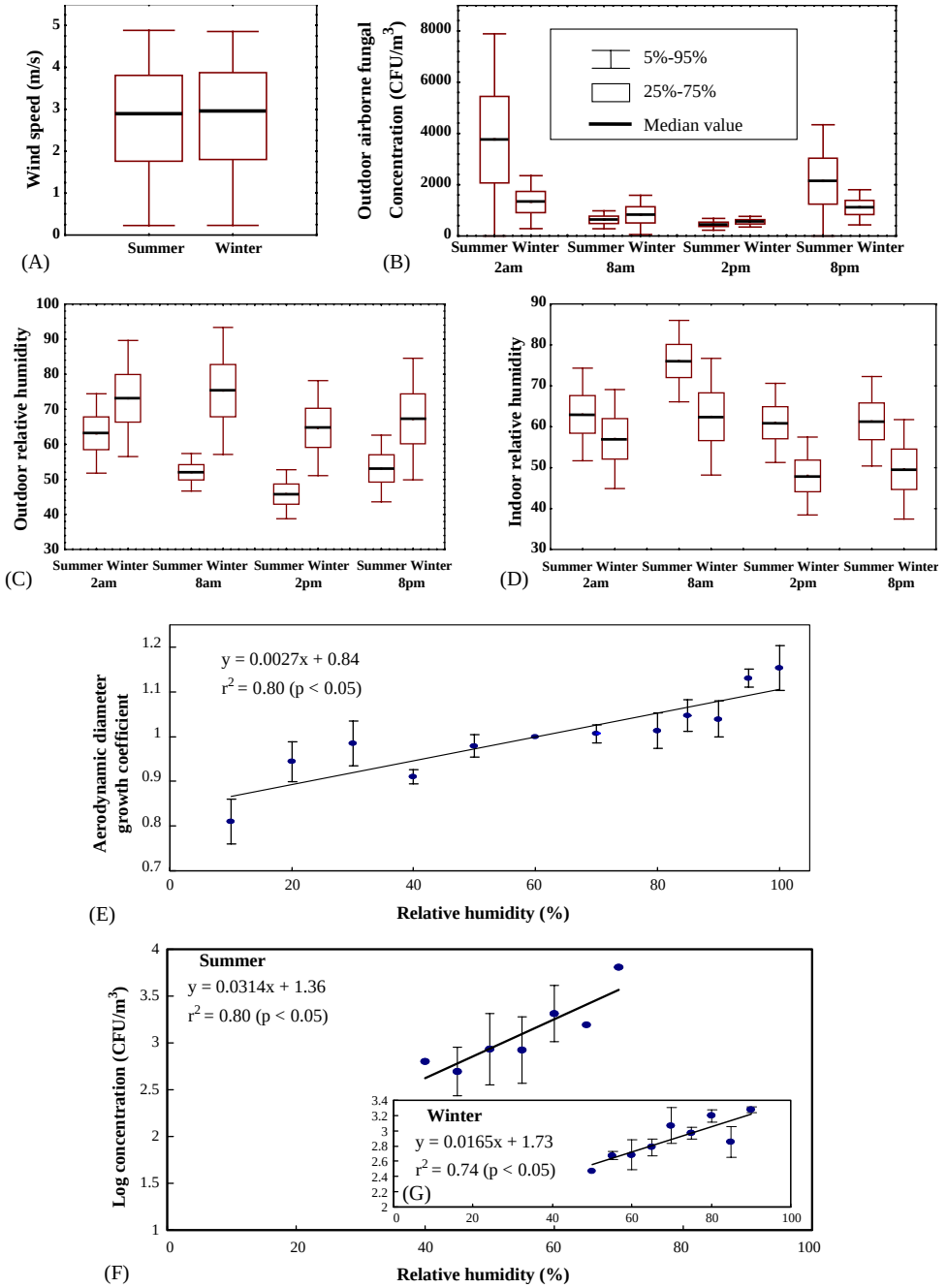

Fig. 1. Box and whisker plot representations of seasonal variation on (A) wind speed, (B) outdoor airborne fungal concentrations, (C) outdoor relative humidity, (D) indoor relative humidity analyzed from the measured data by Lin and Li (1996), (E) the correction factor profiles of hygroscopic changes on aerodynamic diameter and concentration of airborne fungi, (F) a relative humidity-aerodynamic diameter growth coefficient profile and a relative humidity–concentration profile in summer and (G) in winter. The error bars represent one standard deviation from the mean.

plots are used to represent uncertainty. The predicted mean values all fall within the interquartile. The higher indoor airborne fungal concentrations occurred in early and late afternoon in which median values were 699.29 and 626.20 CFU m^{-3} at 2 a.m. and 8 p.m., respectively, in summer; whereas 138.71 and 99.01 CFU m^{-3} at 2 a.m. and 8 p.m., respectively, in winter. Fig. 2A indicates that the 95th-percentile predictions of indoor airborne fungal

Table 1
Measured and predicted mean value of the total concentration (CFU m^{-3}), GMD (μm) and GSD of particle size distribution of outdoor/indoor airborne fungi in summer/winter at different time periods

	Summer				Winter			
	Outdoor		Indoor		Outdoor		Indoor	
	LN(gmd, gsd)	Measure Mean	LN(gmd, gsd)	Predicted Mean	LN(gmd, gsd)	Measure Mean	LN(gmd, gsd)	Predicted Mean
2 a.m.	(2.28, 1.45)	3768 (2506)[a]	(1.80, 1.10)	1105	(2.62, 1.63)	1326 (627)[a]	(1.72, 1.24)	204
8 a.m.	(2.76, 1.60)	633 (213)	(1.96, 1.18)	367	(3.01, 1.68)	824 (465)	(1.79, 1.51)	122
2 p.m.	(3.09, 1.80)	454 (140)	(1.79, 1.27)	192	(3.16, 1.72)	557 (127)	(1.84, 1.45)	66
8 p.m.	(2.18, 1.48)	2139 (1339)	(2.09, 1.16)	736	(2.36, 1.62)	1118 (417)	(1.58, 1.27)	175

[a] Parentheses represent the one standard deviation from the mean.

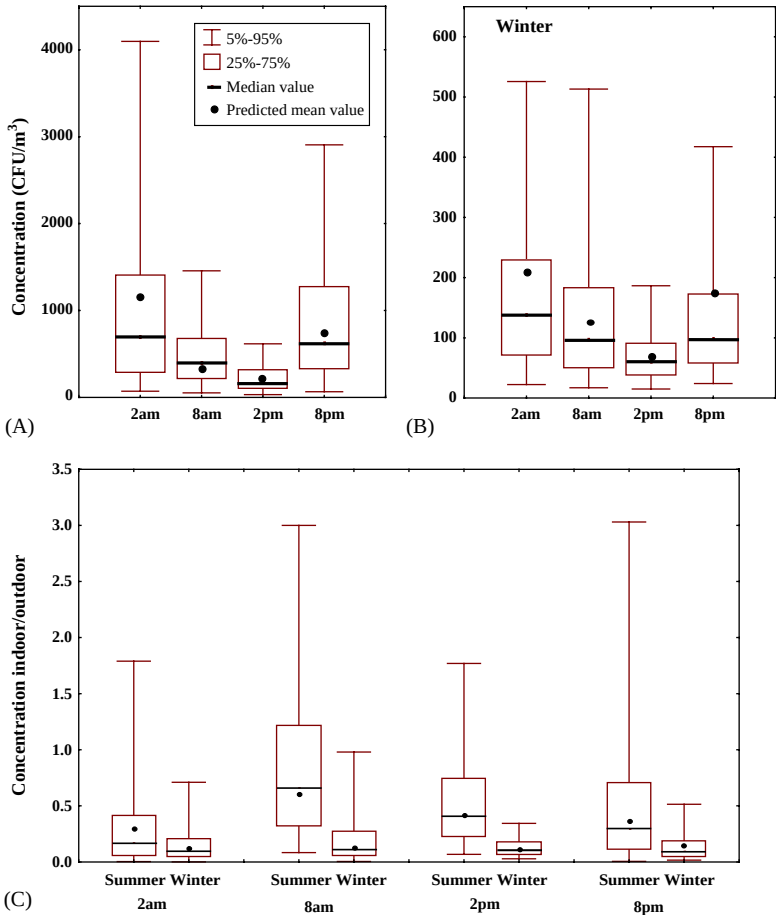

Fig. 2. Box and whisker plot presentations of (A) predicted indoor airborne fungal concentrations in summer and (B) in winter at certain time periods, and (C) the temporal/seasonal variations of calculated concentration I/O ratios of airborne fungi.

concentrations in summer are far above 1000 CFU m^{-3} at 2 a.m. and 8 p.m., indicating the indoor environment needs investigation and improvement. The variation in the total airborne fungal concentrations at 2 p.m. was lower than that at other time periods for both summer and winter. Strength of higher indoor airborne fungal concentrations in summer is partly explained by higher outdoor concentrations (Fig. 1B), and higher slope of the fitted relationships between concentration and RH in summer (Fig. 1F).

In the absence of indoor sources of bioaerosol, summer has higher I/O ratios of airborne fungal concentration (mean ranging from 0.29 to 0.58) than that in winter (mean ranging from 0.12 to 0.16) (Fig. 2C). Fig. 2C shows that the variation in the concentration I/O ratio for summer was higher than that in winter partly due to the variation of outdoor concentrations in summer is greater than that in winter (Fig. 1B). The 95th percentile I/O ratios are all greater than 1 in summer, whereas in winter all 95th percentile I/O ratios are less than 1. Generally, the I/O ratios of interquartile are all less than 1.

4. Conclusions

We have successfully coupled a well-defined size-dependent indoor air quality approach with a hygroscopic growth factor as a function of relative humidity in aerodynamic diameter and concentration of fungal spores. Our results demonstrate the importance of knowing the information of temporal/seasonal- and particle size distribution of outdoor bioaerosol for understanding residential exposure to airborne fungi of outdoor origin. More importantly, this research illustrates that an exposure assessment based on total bioaerosol measured outdoors may obscure the actual causal relationships to indoor fungal spores of outdoor origin without considering the hygroscopic growth effect.

References

Burge, H., Chew, G., Muilenberg, M., Gold, D., 1995. Role of fungi in-house dust ecosystems. Journal of Allergy and Clinical Immunology 95, 167.

Chen, L.Y., Jeng, F.T., Chen, C.C., Hsiao, T.C., 2003. Hygroscopic behavior of atmospheric aerosol in Taipei. Atmospheric Environment 37, 2069–2075.

Johnson, D.L., Pearce, T.A., Esmen, N.A., 1999. The effect of phosphate buffer on aerosol size distribution of nebulized *Bacillus subtilis* and *Pseudomonas Fluorescens* bacteria. Aerosol Science and Technology 30, 202–210.

Lee, B.K., Kim, S.H., Kim, S.S., 2002. Hygroscopic growth of *E. coli* and B. *subtilis* bioaerosols. Journal of Aerosol Science 33, 1721–1723.

Liao, C.M., Chen, J.W., Huang, S.J., 2003. Size-dependent PM_{10} indoor/outdoor/personal relationships for a wind-induced naturally ventilated airspace. Atmospheric Environment 37, 3065–3075.

Lin, W.H., Li, C.S., 1996. Size characteristics of fungus allergens in the subtropical climate. Aerosol Science and Technology 25, 93–110.

Reponon, T., Willeke, K., Ulevicius, V., Reponen, A., Grinshpun, S.A., 1996. Effect of relative humidity on the aerodynamic diameter and respiratory deposition of fungal spores. Atmospheric Environment 30, 3967–3974.

Su, H.J., Wu, P.C., Chen, H.L., Lee, F.C., Lin, L.L., 2001. Exposure assessment of indoor allergens, endotoxin, and airborne fungi for homes in southern taiwan. Environmental Research A 85, 135–144.

Wu, P.C., Su, H.J., Lin, C.Y., 2000. Characteristics of indoor and outdoor airborne fungi at suburban and urban homes in two seasons. The Science of the Total Environment 253, 111–118.