ELSEVIER

Evaluation on sampling point densities for assessing indoor air quality

K.W. Mui*, L.T. Wong, W.L. Ho

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

Abstract

In Hong Kong, the Environmental Protection Department (HKEPD) has launched an indoor air quality (IAQ) certification scheme to promote an acceptable IAQ in workplaces. However, the associated uncertainties and measurement efforts have not been detailed for practical measurement in indoor spaces. In this study, indoor carbon dioxide (CO_2) concentration is selected as an indicator of the IAQ to investigate the probable errors and measurement efforts in different sampling schemes regarding the sampling point density. In particular, a one-year measurement for sample-spatial average indoor CO_2 concentration at 17 sampling locations in a typical large office (floor area = $1200\,m^2$) has been used to evaluate the probable errors of the sample-spatial average concentrations using different sampling point densities. The result shows that the measured concentration at a single sampling point could not be representative for the space and more than one sampling locations would be required in order to increase the measurement accuracy. Mathematical expressions for the sample-spatial average concentration at a confidence level at certain sampling point densities are proposed. When doubled the required measurement points, it was found that the probability of obtaining a measured CO_2 concentration at the confidence level of 95% could be increased from 70% to 90%, as compared with the current sampling practice. It is recommended to specify the measurement uncertainties in future codes so that effort for IAQ measurements in indoor spaces could be determined for practical strategies.

1. Introduction

Measuring the spatial dependence of pollutant concentrations in an indoor environment is useful for pollutant monitoring and exposure assessment. In order to maintain an acceptable indoor air quality (IAQ), strategies and guidelines on achieving the required IAQ have been developed worldwide. In 1999, the Hong Kong Environmental Protection Department (HKEPD) specified such requirements in a brief guideline [1]. Since 2003, the HKEPD has launched an IAQ certification scheme for offices and public places. This scheme

provides certification steps, including the details of measurement, to determine the IAQ [2].

In IAQ measurement, carbon dioxide (CO_2) concentration is commonly used as a surrogate indicator for assessing the IAQ and ventilation efficiency. Research confirmed that the measurement and analysis of indoor CO_2 concentration could be useful for understanding IAQ and ventilation [3–9]. There are a number of relationships that could be implied in discussing CO_2 and IAQ; these include the health effects of elevated CO_2 concentrations, the impact of CO_2 on occupant perceptions of the indoor environment, the relationship between CO_2 concentrations and concentrations of other contaminants, and the association between CO_2 and outdoor air ventilation rate [10–12].

A short-term 8-h testing is proposed in the HKEPD IAQ certification scheme, for a balance between

*Corresponding author. Tel.: +852 2766 5835; fax: +852 2765 7198.

E-mail addresses: behorace@polyu.edu.hk (K.W. Mui), beltw@polyu.edu.hk (L.T. Wong).

measurement effort and accuracy. It provides a good measurement of the average concentration of contaminants, assuming that building related contaminants (e.g. Radon) normally peak in the morning (if the HVAC system is shut down at night) and occupant related ones (e.g. CO_2) normally peak in the afternoon. It is engrossed to find out the uncertainties in using the sampling methods for pollutant concentration measurement, the differences between the collected results and the year-round pollutant profile due to seasonal variations [13–15]. Rapid locating and the rational method are presented to determine the sampling locations within a building where the highest average concentration of contaminants may occur [16,17].

Measurement errors have been reviewed for some air contaminants [18–20]. These errors are critical as they can lead to a bias in the exposure-effect relationship. Uncertainties of the measured quantities must be quantified [21]. Several expressions for the standard error of the measured mean concentration have been proposed and used in varying degrees in atmospheric chemistry literature [19,22]. If the uncertainty of the sampling methods can be identified, then policymakers can make better judgment in resources and manpower management in pollutant testing and the inappropriate level of reliance on the test results can be avoided [21–23].

In response to the concern about IAQ, policymakers need the best obtainable information and resources to develop a full range of policy responses ranging from no action standards. Although all were developed for the same indoor pollutants, these responses are non-uniform in their approach, choice of acceptable levels and impact on affected populations. In this paper, using spatial average of indoor CO_2 concentration as a reference, a study between the different sampling point densities and the long-term measurement in an open-plan office was performed, in order to determine the confidence level and error distribution for different sampling scenarios. This paper also highlights the significance of sampling point densities for assessing the IAQ level, as compared with the existing scheme adopted in Hong Kong.

2. Sampling for average indoor CO_2 level

In Hong Kong, the HKEPD recommendation of a measurement period of 8 h has been generally adopted in current practice [2]. In a typical mechanically ventilated indoor environment, the concentration of a pollutant at an arbitrary sampling point i would be measured, and the sample-time average concentration of the pollutant $\langle \Phi \rangle$ in the time domain τ would be used to describe the environmental condition in the space [24,25], where, t_a and t_b are the start time and end time

of a measurement.

$$\langle \Phi_i \rangle = \frac{1}{t_a - t_b} \int_{t_b}^{t_a} \Phi_i(t)\,dt, \quad t \in t_b - t_a = \tau,\ 0 \leqslant \Phi_i \leqslant \infty,$$
(1)

The sample-time average concentration would be taken as the time-mean concentration at the sampling point i, if the sampling period is 'practically' long, where, the concentration Φ_i would be normally distributed with the mean $\mu_{\tau,i}$ and the standard deviation $\sigma_{\tau,i}$ in the time domain τ.

$$\langle \Phi_i \rangle \to \mu_{\tau,i}, \quad \tau \to \infty.$$
(2)

The distribution $\hat{\Phi}_i$ of the concentration is given by

$$\hat{\Phi}_i = \int_0^\infty \frac{e^{-(\Phi_i - \mu_{\tau,i})^2 / 2\sigma_{\tau,i}^2}}{\sigma_{\tau,i}\sqrt{2\pi}}\,d\Phi_i,$$
$$\sigma_{\tau,i} > 0,\ 0 \leqslant \Phi_i \leqslant \infty,\ 0 \leqslant \mu_{\tau,i} \leqslant \infty.$$
(3)

For large indoor spaces, measurement at one sampling point is deficient in representing the overall environmental conditions. The measurements at certain sampling points would be taken to evaluate the sample-spatial average concentration $\{\Phi\}$, where, r is the number of sampling points in the space.

$$\{\Phi\} = \frac{1}{r} \sum_{i=1}^r \langle \Phi_i \rangle = \frac{1}{r} \sum_{i=1}^r \mu_{\tau,i}, \quad \tau \to \infty.$$
(4)

And $\{\Phi\}$ would be taken as the spatial mean $\mu_{\Re}$ for the space if the number of measurement points is 'sufficient',

$$\{\Phi\} \to \mu_{\Re}, \quad r \to \infty.$$
(5)

However, in realistic measurement of the space, only a finite maximum number of sampling points could be taken. In most of the circumstances in large spaces, a smaller number of sampling points would be taken in order to save the measurement efforts and time with a balance of measurement accuracy. The required sampling points in a space r is specified by Eq. (6), where, A_f (m^2) is the floor area of the space and A_s (m^2) is the sampling point density that the floor area requires for one sample point.

$$r = \frac{A_f}{A_s}, \quad A_s < A_f.$$
(6)

One sampling point for an area of $500\,\text{m}^2$ has been adopted for current practice in Hong Kong [2]. The sample-spatial average concentration in a measurement would be taken from any one of the combinations of r sampling points, and from a maximum number of m sampling points. The r-combination C from the set of m sampling points is given by Kokoska and Zwillinger [25]

$$C(m,r) = \frac{m!}{r!(m-r)!} \quad m > r.$$
(7)