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# Estimation of NO₂ Source Generation and Ventilation rate in Residence by Multiple Measurements

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## 1. 서 론

Indoor air quality is the dominant contributor to total personal exposure because most people spend a majority of their time indoors. Especially when indoor environments have sources of contaminants, exposure to indoor air can potentially pose a greater threat than exposure to ambient air. Indoor air quality is affected by outdoor air pollution, indoor generation of pollutants, pollution depletion mechanisms (surface deposition and chemical decay), ventilation, and volume of the indoor space. Although technologies exist to measure these factors directly, it is not practical to directly measure all the factors in field studies. Various indoor and outdoor combustion sources make nitrogen dioxide (NO₂) the most ubiquitous pollutant in the indoor environment. NO₂ is a by-product of high temperature fossil fuel combustion. Despite the wide distribution of sources, indoor NO₂ concentration is an important factor for personal exposure. Indoor NO₂ concentration was responsible for 75% of the variation in the total personal exposure of office workers. The purposes of this study were to characterize indoor air quality using multiple NO₂ measurements, to estimate ventilation rate and NO₂ source strength, and to compare the indoor air quality characteristics in Brisbane, Australia to those in Seoul, Korea. The two cities have many different characteristics such as house type, weather, industry and ambient pollution levels.

## 2. 본 론

To estimate the ventilation rate and NO₂ source strength in indoor environments, daily indoor and outdoor NO₂ concentrations for 30 houses in Brisbane were measured over 30 consecutive days between April and May in 1999. In Seoul, daily indoor and outdoor NO₂ concentrations in 40 houses were measured for 21 consecutive days between June and August in 2000. In addition, information on house characteristics was collected by identical questionnaires in the two cities. All NO₂ concentrations were measured using passive filter badges.

A mass balance model is often used to explain indoor air quality. Indoor air quality models using mass balance are a useful tool to quantify the relationship

between indoor air pollution levels, ambient concentrations, and explanatory variables. Models of indoor air quality describe the transport and dispersion of pollutants throughout a structure and the variation of indoor air pollutants as a function of source strengths, air change rates, removal mechanisms, and other factors. Considering a residence as a single chamber (one-compartment), a mass balance in the chamber provides,

$$\frac{dC_i}{dt} = mIC_o + S - mIC_i - \frac{R}{V} \qquad (1)$$

Where, Ci= indoor concentration ($\mu$g/m$^3$), Co= outdoor concentration ($\mu$g/m$^3$), I= ventilation rate (hr$^{-1}$), S= source strength ($\mu$g/m$^3 \cdot$ hr) = emission rate ($\mu$g/hr)/volume of the space (m$^3$), R= decay rate ($\mu$g/hr), m= mixing factor (unitless), and V= volume of the space (m$^3$).

The removal rate, R, is a function of a deposition constant (K, hr$^{-1}$) and the volume of pollutant present indoor (VCi).

$$R = KVC_i \qquad (2)$$

Assuming that the indoor environment is completely mixed (m=1), equation (1) becomes.

$$\frac{dC_i}{dt} = IC_o + S - IC_i - KC_i \qquad (3)$$

Assuming that indoor level is in a steady-state condition (dCi/dt=0), the equation (4) can be obtained.

$$C_{i(ss)} = \frac{IC_o}{I+K} + \frac{S}{I+K} \qquad (4)$$

where, Ci(ss) = average steady-state indoor NO$_2$ concentration.

Substituting I/(I+K) for A and S/(I+K) for B, rearranging terms allow the average concentration of the house to be written as a linear regression equation.

$$C_{i(ss)} = (\frac{I}{I+K})C_o + (\frac{S}{I+K}) \qquad (5)$$

Because we measured indoor and outdoor concentrations simultaneously, linear regression analysis provided A and B of equation 5. In equation 5, the penetration factor, A, should be between zero and 1. The source strength factor, B, should be greater than or equal to zero because S is greater than or equal to zero.

## 3. 결 론

A total of 30 participants were recruited in Brisbane. Daily NO₂ measurements from two participants were excluded from the following analysis because they refused to participate after 2 weeks of measurements. The mean number of family members was 3.4 and 21 houses were single family homes. Twelve houses had gas ranges without a pilot light. None of the houses had kerosene or coal heaters. The NO₂ measurements are shown in Table 1. Daily NO₂ concentrations were measured in 28 houses for 30 consecutive days in Brisbane. Geometric means of indoor and outdoor daily NO₂ concentrations in Brisbane were 22.6 $\mu g/m^3$ and 29.3 $\mu g/m^3$, respectively. The mean ratio of indoor to outdoor (I/O) NO₂ concentrations was 0.82 ± 0.41.

Table 1. Measured NO₂ concentrations of indoor and outdoor for daily 30 days

| | | Indoor NO₂ ($\mu g/m^3$) | Outdoor NO₂ ($\mu g/m^3$) |
|---|---|---|---|
| Brisbane (n= 28) | GM (GSD) | 22.6 (1.77) | 29.3 (1.54) |
| | Mean ± SD | 26.2 ± 14.1 | 31.8 ± 12.2 |
| | Median | 24.8 | 29.3 |
| | Range | 5.1~61.9 | 7.8~61.6 |
| | Indoor/outdoor | 0.82 ± 0.41 | |
| Seoul (n= 37) | GM (GSD) | 58.9 (1.52) | 71.0 (1.54) |
| | Mean SD | 63.7 ± 24.2 | 77.2 ± 30.1 |
| | Median | 61.5 | 73.2 |
| | Range | 18.5~111.6 | 27.5~140.4 |
| | Indoor/outdoor | 0.88 ± 0.32 | |

- GM : Geometric mean
- GSD : Geometric standard deviation

Daily NO₂ measurements were completed in 37 houses for 21 consecutive days in Seoul. Geometric means of indoor and outdoor daily NO₂ concentrations in Seoul were 58.9 $\mu g/m^3$ and 71.0 $\mu g/m^3$, respectively. The mean ratio of indoor to outdoor NO₂ concentrations was 0.88 ± 0.32. The indoor and outdoor NO₂ concentrations measured in Seoul were significantly higher than those in Brisbane ($p < 0.05$). Indoor and outdoor NO₂ concentrations in both cities were log-normally distributed. Indoor and outdoor NO₂ levels were analyzed to determine significant factors of exposure. Penetration factor (ventilation rate divided by the sum of ventilation rate and deposition constant) and source strength factor (source strength divided by the sum of ventilation rate and deposition constant) were calculated using equation (5) and

multiple daily indoor and outdoor $NO_2$ concentrations (Table 2). Mean coefficients of determination ($R^2$) between daily indoor and outdoor $NO_2$ measurements in both cities are also shown in Table 2. Coefficients of determination for houses with electric ranges was were significantly higher than those for houses with gas ranges ($p<0.05$). Penetration factors were between zero and 1 except for one house in Brisbane and the source strength factors were more than zero in all houses in Brisbane and Seoul. The house in Brisbane with a penetration factor of 1.10 was excluded in the following analysis. Penetration factors in Brisbane were $0.59 \pm 0.14$. Source strength factors in Brisbane were $1.49 \pm 1.25$ in homes with electric ranges and $5.77 \pm 3.55$ in homes with gas ranges and the two were significantly different ($p<0.05$). In Seoul, penetration factors and source strength factors were $0.58 \pm 0.12$ and $9.12 \pm 4.50$, respectively. While penetration factors were not significantly different between the two cities, source strength factor in Seoul was significantly higher than that in Brisbane ($p<0.05$).

Table 2. Penetration factor, source strength factor and coefficient of determination ($R^2$) by equation (5) using daily indoor and outdoor $NO_2$ concentrations

|  |  | Penetration factor (Slope : A) | | Source strength factor (Intercept : B) | | $R^2$ |
|---|---|---|---|---|---|---|
|  |  | Mean±SD | Range | Mean±SD | Range | Mean±SD |
| Brisbane | Electric .range (n= 16) | 0.65±0.18 | 0.44~0.72 | 1.49±1.25 | 0.09~4.35 | 0.70±0.13 |
|  | Gas range (n= 12) | 0.56±0.12 | 0.46~1.10 a | 5.77±3.55 | 2.38~10.23 | 0.57±0.21 |
| Seoul | Gas range (n= 37) | 0.58±0.12 | 0.26~0.82 | 9.12±4.50 | 2.13~19.40 | 0.52±0.20 |

a : One house with penetration factor of 1.10 in Brisbane was excluded from the following analysis.

The relationship between the coefficient of determination ($R^2$) of equation (5) and source strength factor were plotted in Figure 1. Mean $R^2$ with an electric range was significantly higher than that with a gas range ($p<0.05$). Mean $R^2$ with a gas range in Brisbane and Seoul were $0.52 \pm 0.20$ and $0.57 \pm 0.21$, respectively, and mean $R^2$ with an electric range in Brisbane was $0.70 \pm 0.13$. The high correlation with low source strength suggests that the $NO2$ concentrations inside the houses with electric ranges were more likely influenced by outdoor sources than indoor sources. The houses with electric ranges are located in left-upper part of plot and the houses using gas ranges are sporadically located in right-lower part of plot. High sporadic

distribution in gas range houses may indicate the variability in the amount of gas range usage.
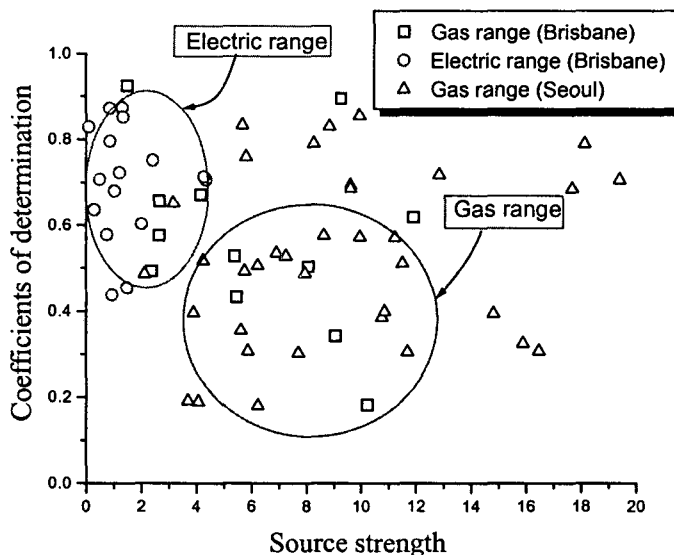


Fig. 1. Relationship between coefficients of determination ($R^2$) and calculated source strength factors in 64 houses in Brisbane and Seoul.

Ventilation rate can be estimated from penetration factor and source strength can be estimated from source strength factor, if the deposition constant is known. A $NO_2$ deposition constant of 1.05 $hr^{-1}$ was assumed for Brisbane, based on several references for Western countries. Using this deposition constant, the geometric mean ventilation rate was 1.44 ACH with a geometric standard deviation of 1.51 and subsequently, the source strength of $NO_2$ was 15.8 ± 18.2 $\mu g/m^3 \cdot hr$. $NO_2$ source strength for houses with electric ranges was 6.6 ± 6.3 $\mu g/m^3 \cdot hr$ and for those with gas ranges, the $NO_2$ source strength was 29.1 ± 21.8 $\mu g/m^3 \cdot hr$, as shown in Table 3.

4. 요  약

Indoor air quality can be affected by indoor sources, ventilation, decay and outdoor levels. Although technologies exist to measure these factors, direct measurements are often difficult. The purpose of this study was to develop an alternative method to characterize indoor environmental factors by multiple indoor and outdoor measurements. Daily indoor and outdoor $NO_2$ concentrations were measured for 30 consecutive days in 28 houses in Brisbane, Australia, and for 21 consecutive days in 37 houses in Seoul, Korea. Using a mass balance model and regression analysis, penetration factor (ventilation rate divided by the sum of ventilation rate and deposition constant) and

Table 3. Estimated ventilation rate and NO$_2$ source strength in Brisbane and Seoul

| | | Ventilation rate (ACH) | | NO2 source strength (ug/m$^3$ hr) | |
|---|---|---|---|---|---|
| | | Mean±SD (GM, GSD) | Range | Mean±S.D. | Range |
| Brisbane[a] | Electric range (n= 16) | 1.56±0.64 (1.44, 1.51) | 0.71~2.66 | 6.6±6.3 | 0.6~21.9 |
| | Gas range (n= 11) | | | 21.9±21.8 | 9.1~75.2 |
| Seoul[b] | Gas range (n= 37) | 1.58±0.95 (1.36, 1.73) | 0.36~4.36 | 44.7±38.1 | 8.5~95.9 |

- GM : Geometric mean

- GSD : Geometric standard deviation

a: estimated with NO$_2$ deposition constant of 1.05 hr$^{-1}$

b: estimated with NO$_2$ deposition constant of 0.94 hr$^{-1}$

source strength factor (source strength divided by the sum of ventilation rate and deposition constant) were calculated using multiple indoor and outdoor measurements. Subsequently, the ventilation rate and NO$_2$ source strength were estimated. Geometric means of ventilation rate were 1.44 ACH in Brisbane, assuming a residential NO$_2$ deposition constant of 1.05 hr$^{-1}$, and 1.36 ACH in Seoul, with the measured residential NO$_2$ deposition constant of 0.94 hr$^{-1}$. Source strengths of NO$_2$ were 15.8 ± 18.2 μg/m$^3$ · hr and 44.7 ± 38.1 μg/m$^3$ · hr in Brisbane and Seoul, respectively. In conclusion, indoor environmental factors were effectively characterized by this method using multiple indoor and outdoor measurements.