Field measurement on the particle concentrations and exposures in five residential buildings in Korea

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Abstract. This study measured five apartments in the Daejeon. There is higher fluctuation for ambient air particle conditions. The average PN (particle number) concentrations was 5.2x10⁸/m³. There are differences between five sites because of fluctuation for ambient air conditions. Particle concentration has different each occupant schedule. I/O ratios were different by occupancy schedules. Indoor particles exceeded 0.7 µm was significant emitted indoor activities. This result comes from two reasons. 1) Penetration by envelopes. 2) Indoor sources by occupants’ activities. PN decay rate (a+k) were 0.49-4.29 h⁻¹ during indoor peak events. Total emitted particles (σ) was 0.01-36.15 x 10¹³ particles per events. The cooking generated PN were wide range because of different event conditions. The ventilation rate is not enough to remove particles.

1. Introduction
In recent years, outdoor particle concentrations in Korea become reached dangerous levels. This phenomenon hurts health. Ambient particle (PM₁₀) in Korea is one of the highest countries (35µg/m³) in OECD (Organization for Economic Cooperation and Development) [1]. Furthermore, the ambient level of Korea exceeded the Korea guidelines of PM₂.₅(50 µg /m³), PM₁₀(100 µg /m³) [2]. High level of ambient particle level comes for different reasons. The secondary aerosols and emission from vehicles made particles. Seasonal dust event so-called yellow dust became a major source of ambient particulate matters[3-5]. This phenomenon seriously affects indoor particle level. The particles from ambient air increase indoor particle levels by building envelope including to penetration or ventilation [6, 7]. The indoor particle is changed consistently by deposition, dispersion, ventilation [8-10].

Most types of Korean residence were 75.6% apartments[11]. Korea government forced the setting ventilation system up to new apartments building. However, this regulation was enforced no more than ten years. Most apartments are naturally ventilated without filtration. Natural ventilation has been difficult in maintaining indoor air quality by worse ambient air.

For the past, many studies have investigated the relationship between indoor and outdoor particle concentrations. Park et al. studied the effect of ventilation types between mechanical ventilation with balance and natural ventilation on I/O ratio[12]. They concluded that mechanical ventilation decreases the I/O ratio. Nasim et al. analysed ultrafine particle in elementary school rooms and concluded the indoor particle concentrations and daily exposure[13]. Eileen founded that particles size-distribution data collected for indoor and outdoor in Boston[14]. They suggested that the proportion of indoor and outdoor sources. Despite many studies for particles, few researchers have investigated the studies for indoor and outdoor particles concentrations in residential under different air conditions.
The objective of this paper is an investigation for the indoor/outdoor particle concentrations and the impact of outdoor particles in naturally ventilated apartments. We measured the size-resolved (0.3-10 μg) particle number (PN) concentrations in five residential buildings in different ambient conditions.

2. Method

2.1. Sampling site
This study measured five apartments in the Daejeon (Table 1 presents a summary of sampling sites.) in winter seasons between Nov and Dec 2017. The population density of Daejeon is 2,852/km²[15]. The city is the major city in Korea. Two expressways through the city and 13 big bridges connecting the Kum river was in the city. All apartments have reinforced concrete and multi-story buildings. The heating system is a radiant floor heating system without other combustion or air conditioning.

| Sampling site | Build year | Floor area (m²) | Floors | Occupants | Nearest major roadway |
|---------------|------------|----------------|--------|-----------|----------------------|
| B1            | 1975       | 64             | 5      | 2         | -                    |
| B2            | 2016       | 64             | 21     | 3         | -                    |
| B3            | 1991       | 130            | 13     | 3         | -                    |
| B4            | 1991       | 102            | 12     | 2         | 700m, 26,000         |
| B5            | 1991       | 100            | 12     | 2         | 2.3km, 95,000        |

2.2. Measurement
We measured particle concentrations using optical particle counter (OPC; TSI, Model 3330, USA) in six-channel sizes: 0.3-0.5, 0.5-0.7, 0.7-1.0, 1.0-2.5, 2.5-5.0, 5.0-10.0 μm. We investigated the size-resolved indoor and outdoor particles simultaneously for concentration and exposure levels and sources.

2.3. Data analysis
We investigated the duration of exposure and particle concentrations by the occupant schedules and monitoring data. There are various parameters for the indoor particle concentrations. Mass balance equation (equation 1) was used for the spaces in steady state conditions.

\[
\frac{dC_{in}}{dt} = aP C_{out} - (a + k)C_{in} + \frac{S}{V} \tag{1}
\]

Where, \(V\) is volume of the space(m³), \(C_{in}, C_{out}\) is PN concentrations, \(a\) is air exchange rate (AER, h⁻¹), \(P\) is penetration factor (-), \(k\) is particle deposition rate (h⁻¹), \(S\) is emission rate (h⁻¹) by indoor spaces. Based on equation 1:

\[
\frac{I/O}{Ratio} = \frac{aP}{a+k} + \frac{S}{(a+k)C_{out}} \tag{2}
\]

Using equation 2, net indoor sources (\(C_{in,net}\)) can be investigated in indoor peak events (equation 3). Episodic indoor sources were studied two parameters: the theoretical peak incremental PN emitted by indoor peak events (\(\sigma/V\)) including to indoor activities and particle decay rate (\(a+k\)) by ventilation.

\[
C_{in,net}(t) = C_{in}(t) - f \times C_{out}(t) \tag{3}
\]

\[
\frac{\sigma}{V} = \int \frac{S(t)}{V} dt = (a + k) \int C_{in,net}(t) dt \tag{4}
\]
3. Result

3.1. Indoor and outdoor particle concentrations

![Figure 1. Outdoor particle number concentrations. (The error bars indicate one standard deviation)](image)

Figure 1 shows total PN concentrations for total outdoor PN concentrations (0.3-10.0 µm) in five residential. Box plots denote 1st quartile, 3rd quartile, median value, and outliers for 1.5 interquartile range (IQR) of lower and higher quartile. The average PN concentrations were 5.2x10^8/m^3. There are differences between five sites. Fluctuation of ambient air pollution occurred by characteristics of cites including to population density, on-vehicle density[16, 17]. However, the main factor of fluctuation is the external factor by the inflow of northern air pollution during winter in Korea [18-20].

Figure 2 indicates size-resolved PN concentrations. Most of the time in the occupied period, occupants did not ventilate indoor spaces. So, higher PN concentrations in ambient air penetrated indoor spaces through building envelopes such as unidentified crack[6, 7, 21-24]. Indoor PN did not emit in the unoccupied period. However, Indoor emission in the occupied period influenced the higher PN concentrations in the unoccupied period. PN concentrations in occupants awake period were higher than other conditions. This result comes from indoor emissions by occupants’ activities. Certain PN concentrations (0.7-10.0 µm) were higher than different period. The difference between occupants awake period and unoccupied period was statically significant (P-value < 0.01)

![Figure 2. Size-resolved indoor particle number concentrations](image)
Figure 3. Indoor and outdoor (I/O) ratio of indoor particle number concentrations

I/O ratios mean the relationship between outdoor and indoor conditions. Figure 3 indicated the average I/O ratios in each building. High PN levels and high I/O ratios corresponded with periods when occupants are awake in the house. Otherwise, I/O ratios in the unoccupied period and asleep period, PN levels are lower, and I/O ratios are constantly lower than 1.

Figure 4 shows size-resolved average I/O ratios in different occupant conditions. I/O ratio in all size is higher than 1 in occupants’ awake period. On the other hand, I/O ratio in all size is lower than 1 in unoccupied and asleep period. This phenomenon comes from indoor sources. Cooking, cleaning and natural ventilation increased particle concentrations[21, 25-27]. There were less indoor emission particles in asleep and unoccupied period.

Figure 4. Size-resolved I/O ratio

3.2. Indoor peak events

The indoor peak events were conducted 7 times (cooking:6, cleaning:1). Cooking-generated particle is major indoor sources in Korea[28]. Indoor particle was removed by range hood or natural ventilation. PN decay rate \((a + k)\) were 0.49-4.29 h\(^{-1}\). Total emitted particles \((\sigma)\) was 0.01-36.15 x 10\(^{13}\) particles per events. According to emission PN, ventilation was not enough. The ventilation system needs
improvements. The cooking generated PN were wide range because of different event conditions [29-32]. The removal rate \((a+k)\) significantly affect the PN concentrations. Furthermore, the emission rate of cooking-generated particles determined the indoor PN concentrations.

### Table 2. Summary of total emitted particle and decay rate in indoor peak events.

| Sampling Building ID | \(a+k\) (h\(^{-1}\)) | \(\sigma\) \((10^{13})\) | Indoor | Time | Vent. |
|----------------------|--------------------------|--------------------------|--------|------|-------|
|                      | 0.3-0.5 | 0.5-0.7 | 0.7-10 | 0.3-0.5 | 0.5-0.7 | 0.7-10 |
| B1 a                 | 1.29    | 1.45    | 1.59   | 19.41   | 3.74     | 1.81 |
| B2 b                 | 1.41    | 1.44    | 1.11   | 1.07    | 0.14     | 0.03 |
| B3 c                 | 2.23    | 0.70    | 0.49   | 0.95    | 0.04     | 0.01 |
|                      | 3.50    | 4.05    | 4.29   | 36.15   | 17.42    | 12.81 |
| B4 e                 | 0.77    | 0.88    | 1.02   | 0.29    | 0.04     | 0.29 |
|                      | 1.21    | 1.08    | 0.97   | 1.21    | 0.12     | 0.04 |
| B5 g                 | 2.26    | 2.55    | 2.80   | 2.60    | 0.52     | 1.99 |
|                      | 0.80    | 1.05    | 1.19   | 1.82    | 0.47     | 0.27 |
|                      | 0.9     | C       | H/H    | H/NV    | H/-      | H/-  |

C: Cooking, Cl: Cleaning with natural ventilation.
H/H means turning on range hood during cooking, turning off hood after cooking. H/NV means turning on range hood during cooking, opening window after cooking. – means closed indoor spaces.

### 4. Conclusion
We measured indoor and outdoor PN concentrations in five residential buildings. The average outdoor PN concentrations were \(5.2 \times 10^8\)/m\(^3\). Outdoor PN concentrations fluctuated by different reasons including to external factor and difference of population density, on-vehicle density. Outdoor PN influences indoor PN concentrations.

Indoor particle concentrations have different by occupants’ conditions as occupied and unoccupied period. I/O ratio in all size is higher than 1 in occupants awake period. Whereas, I/O ratio in all size in lower than 1 in unoccupied and asleep period because of the difference of indoor particle emissions. Cooking, cleaning with natural ventilation made higher indoor PN concentrations (seven indoor peak events) in this study. PN decay rate \((a+k)\) were 0.49-4.29 h\(^{-1}\) from outbreak of indoor peak event to decrease particles. Total emitted particles \((\sigma)\) was 0.01-36.15 \(\times 10^{13}\) particles per events. According to emission PN, ventilation was not enough. The cooking generated PN were wide range because of different event conditions, including to ventilation or cooking methods.

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