Concentration of Formaldehyde, Acetaldehyde, and Five Volatile Organic Compounds in Indoor Air: The Clean-Healthy House Construction Standard (South Korea)

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Abstract
The authors evaluate indoor air quality in apartments built according to the South Korean Clean-Healthy House construction standard. The evaluation includes three types of residential units with differing gross floor areas. Indoor air was analyzed for formaldehyde (observed range 52.0–99.2 µg/m³), acetaldehyde (14.6–61.0 µg/m³), benzene (0.6–1.3 µg/m³), toluene (161.8–371.0 µg/m³), ethylbenzene (6.5–17.0 µg/m³), xylene (14.7–45.0 µg/m³), and styrene (37.7–112.5 µg/m³). The concentrations of all analyzed substances were within the South Korean guidelines. The findings confirm that the Clean-Healthy Homes initiative has led to a greatly improved indoor air environment compared to existing newly built apartment blocks in South Korea. However, this construction standard is applied only to large apartment developments comprising 1,000 or more units, and it seems that further effort should be made to extend the standard to stand-alone residences and small-scale apartment blocks in order to ensure that indoor air quality is maintained more widely.

Keywords: indoor air quality; formaldehyde; acetaldehyde; volatile organic compounds; housing

1. Background and Purpose
Modern lifestyles can result in people spending more than 90% of each day indoors. Indoor air quality therefore has a strong effect, not only on personal health, but also on comfort and productivity (Klepeis et al., 2001; Brown et al., 1994; Mølhave, 1991; Salthammer et al., 2010; Nielsen et al., 2007; Wolkoff and Nielsen, 2001). Volatile organic compounds (VOCs) such as formaldehyde, acetaldehyde, acetone, toluene, benzene, ethylbenzene, styrene, and xylene, are hazardous chemicals that commonly pollute the indoor environment. As such, they have been studied by many researchers (Du et al., 2014; Zhu et al., 2005; Park and Ikeda, 2004; Sawant et al., 2004; Lai et al., 2004; Kim et al., 2001; Guo et al., 2003).

Hazardous chemicals are released indoors by construction materials such as wallpaper, flooring, paint, and glue, as well as by furniture such as sofas, closets, and desks (Risto, 1997; Guo et al., 2000; Bouhama et al., 1997; Plaisance et al., 2014; Ye et al., 2014). Gas stoves, cassette-gas burners, and other heating devices used indoors have been reported to greatly increase the concentration of VOCs in indoor air (Gou et al., 2009; Lee et al., 2002; Garrett et al., 1997; Jia and Yao, 1993). The homes of smokers have also been found to have significantly higher concentrations of VOCs compared to non-smoking households (Edward et al., 2001; Guerin et al., 1992).

Indoor pollution by hazardous chemicals is a contributory factor to the social problem known as “sick building syndrome,” an issue that is also encountered in South Korea (WHO, 1983; Mølhave et al., 1997; Mendell, 1993). In 2003, the South Korean Ministry of Environment promulgated the Indoor Air Quality Management Act (IAQ Act. Ministry of Environment, 2003) for newly built apartment blocks, and in 2005 the guidelines for indoor air quality in newly built apartment blocks were revised (Ministry of Environment, 2005). The South Korean guidelines on indoor air quality in apartment blocks cover formaldehyde, benzene, toluene, ethylbenzene, xylene, and styrene (IAQ Act Revised, 2005). Moreover, to enable construction contractors and consumers to select building materials with low emissions of formaldehyde, the guidelines recommend attaching a Healthy Building Mark in accordance with the formaldehyde emission rate (South Korea Air Cleaning Association, 2005).

However, despite these efforts on the part of the South Korean government, there has not been much change in the indoor air quality in several newly built apartment blocks (Pang et al., 2008; Yoon, 2013). Accordingly,
the South Korean Ministry of Land, Infrastructure, and Transport took steps to resolve the issue by issuing the Clean-Healthy House construction standard in May 2010, effective from December of the same year (Ministry of Land, Infrastructure, and Transport, 2010).

The Clean-Healthy House building standard is designed to ensure a certain level of indoor air quality and ventilation in order to provide residents with a healthy, comfortable indoor environment. Newly built or renovated apartment developments of 1,000 or more residences are required to be based on the standard.

Construction companies must create a Clean-Healthy House Building Standard Evaluation Report themselves and submit it to a government office. The report is divided between the minimum standard and the recommended standard. Newly built apartment blocks should apply all of the minimum standard items, and if at least three of the seven recommended standard items are applied, then the building is recognized as a Clean-Healthy House.

In this study, the authors measured indoor air concentrations of formaldehyde, acetaldehyde, and five VOCs in apartments that comply with the Clean-Healthy House.

2. Method

2.1 Overview

Table 1. shows an overview of the Clean-Healthy House to be measured. The subject apartment blocks were flushed-out for approximately eight days, which is one of the minimum standards, after which indoor air quality was measured. Flush-out is conducted by the construction company before residents move in. In addition to opening all windows and internal doors, the doors of interior furniture, etc., are also opened in order to ventilate all hazardous chemicals to the outside. Three types of residence (termed A, B, and C) were measured prior to occupancy. The measurements for evaluating the indoor air quality were conducted under two scenarios: with and without ventilation. All of the measured residences were equipped with heat recovery ventilators with differing ventilation volume based on gross floor area. Operation of the heat recovery ventilator was adjustable with three settings: low, medium, and high. With the ventilators set at low, the subject residences met the South Korean Ministry of Land, Infrastructure and Transport air exchange rate of 0.7 h⁻¹ for newly built apartment blocks (Ministry of Land, Infrastructure, and Transport, 2006). The ventilation volume was calculated based on the specification sheet of the heat recovery ventilator supplied by the construction company and the construction plans, rather than via a directly measured value. To evaluate indoor air quality in the ventilation scenario, the heat recovery ventilators were operated at low setting with air exchange rates of 0.74, 0.88, and 0.77 h⁻¹ in the A, B, and C residences, respectively. The A-and C-type residences were 18-story buildings and the B-type was a 17-story building.

2.2 Measurement Methods

Fig.1. shows the measurement schedule. Table 2. shows the indoor air sampling devices and samplers and the volume of air sampled. In accordance with the official experimental method published by the South Korean Ministry of Environment (2004), indoor air quality for each type of residence was measured over two days: without ventilation (day 1) and with ventilation (day 2). Before collecting indoor air samples, all windows and doors connecting with the outside were opened. In addition, all internal doors and furniture doors were also opened, and the residence was left to ventilate for 30 minutes. Next, all the windows and doors connecting with the outside were closed while the furniture doors and kitchen under-sink cupboards were left open and the residence was left in this state for five hours. During this five-hour period in which the residence was sealed, indoor air was sampled for 30 minutes under the two conditions: ventilated/ unventilated. Formaldehyde and acetaldehyde were sampled using a 2, 4- dinitrophenylhydrazine (DNPH) cartridge, with an ozone scrubber attached to the front section to remove ozone from the sample. The air-sampling device was a SIBATA (Japan) MP-Σ100H. VOCs were sampled using a Tenax TA tube with a

| Table 1. Overview of Clean-Healthy House Apartment Blocks Measured |
|---------------------------------------------------------------|
| **Type** | **Floor area [m²]** | **Volume [m³]** | **Ventilation volume [m³/h]** | **Air exchange rate [h⁻¹]** | **Ventilation condition** | **Temperature [°C]** | **Relative humidity [RH%]** |
| A  | 65 | 149.5 | 110 | 0.74 | Off | 20.2, 43 |
| B  | 84 | 193.2 | 170 | 0.88 | Off | 21.5, 41 |
| C  | 96 | 220.8 | 170 | 0.77 | Off | 22.1, 42 |

*: Total ventilation volume inside the residence with a heat recovery ventilator operated at low setting
**: Average values measured at five-minute intervals using a memory-type thermo-hygrometer.

| Table 2. Indoor Air Sampling Devices, Samplers and Air Sample Volumes |
|---------------------------------------------------------------|
| **Measurement item** | **Sampling device, sampler used** | **Sampled air volume [L]** |
| Formaldehyde, acetaldehyde | MP-Σ100H (SIBATA, Japan) Ozone scrubber + DNPH cartridge | 15 L (0.5 L/min) |
| Volatile Organic Compounds (VOCs) | MP-Σ30H (SIBATA, Japan) Tenax TA tube (Gerstel) | 6 L (0.2 L/min) |
SIBATA (Japan) MP-Σ30H. The measurement position was in the center of the living room at a height of 1.2 - 1.5 m above the floor. A travel blank was used to check for contamination of the sampler.

2.3 Method of Analyzing Target Chemicals

The chemicals analyzed included indoor pollutants, which are listed in the South Korean Ministry of Environment’s indoor air quality guidelines (2005) for newly built apartments and the World Health Organization (WHO) guidelines (1999). The chemicals analyzed were formaldehyde, acetaldehyde, benzene, toluene, ethylbenzene, xylene, and styrene. Formaldehyde and acetaldehyde were recovered from the DNPH cartridge by solvent extraction with acetonitrile and extracts were analyzed via high-performance liquid chromatography (HPLC). VOCs collected by the Tenax TA tube were analyzed using a gas chromatography/mass spectrometer (GC/MS). Tables 3. and 4. show the conditions for HPLC and GC/MS analysis, respectively.

3. Results

3.1 Concentrations of Formaldehyde and Acetaldehyde

Table 5. shows the observed concentrations and respective guideline concentrations for formaldehyde and acetaldehyde. The concentrations of formaldehyde in the three types of residence ranged between 52.0μg/m$^3$ and 99.2μg/m$^3$, all of which are within the guidelines proposed by South Korea and the WHO. Moreover, it was confirmed that the concentration of formaldehyde in indoor air decreased when the ventilation equipment was operated. The rates of decline in formaldehyde concentration differed for each type of residence. In the C-type residence, indoor formaldehyde concentration declined by 22.6% when the ventilation equipment was operated. Acetaldehyde concentration did not vary significantly by residence type. When the ventilation equipment was non-operational, acetaldehyde concentration was lowest (15.5μg/m$^3$) in the A-type residence. In the B-type residence, acetaldehyde concentration (61.0μg/m$^3$) exceeded the Japanese and WHO guidelines. However, under ventilation the acetaldehyde concentration (32.4μg/m$^3$) was within both of the guidelines. The rate of decline in acetaldehyde under ventilation ranged from 5.4% to 58.5% between the residence types.

3.2 Concentrations of five VOCs in Indoor Air

Table 6. shows the observed concentrations and respective guideline concentrations for five VOCs in indoor air. None of the five VOC concentrations exceeded the indoor air quality guideline for South Korea. With the exception of ethylbenzene measured

| 30 min | 5 hours | 30 min |
|--------|---------|--------|
| 1      | 2       | 3      |

① External windows and doors are opened, and interior, furniture and kitchen under-sink cupboard doors are opened for 30 minutes to allow sufficient ventilation.

② External windows and doors are closed and sealed for five hours while interior, furniture, and kitchen under-sink cupboard doors are left open. During this time, ventilation is turned on or off in accordance with measurement conditions.

③ After 5 hours, indoor air samples are collected for 30 minutes.

![Fig.1. The Measurement Schedule](image)

Table 3. HPLC Conditions

| Method | Column | Mobile phases | UV detector | Injection volume | Oven temp. | Detection wavelength |
|--------|--------|---------------|-------------|------------------|------------|---------------------|
| HPLC   | Agilent 1100 | GL Science/Inertsil Acrolein C18 4.6 x 150 mm (5μm) | Water/Acetonitrile = 60:40 | 10 μL (1.2 mL/min) | 40°C | 360 nm |

Table 4. GC/MS Conditions

| ATD                | PerkinElmer Turbo Matrix ATD |
|-------------------|-----------------------------|
| Desorption temp. (Time) | 260°C (10 min) |
| Second desorption Temp. (Time) | 5°C→280°C (45 min) |
| GC/MS             | Agilent GC/MS 6890N/5973inert |
| Chromatographic column | HP-VOC 60 m x 0.32 mm, df = 1.8μm |
| GC oven temp.    | 35°C (2 min)→15°C/min→95°C→2.5°C/min→105°C→5°C/min→250°C (5 min) |
| Split ratio      | 7:1 |
| MS analysis mode | SCAN |
| MS range         | m/z 35 (low) – 550 (high) |
| Ion source temp. | 250°C |
in the B-type residence, the concentration of pollutants indoors was found to decline with ventilation. Benzene concentration was 0.6 - 1.3ug/m^3. The highest concentration of toluene was 371.0ug/m^3, observed in the C-type residence without ventilation. Ethylbenzene concentration ranged from 6.5ug/m^3 to 17.0ug/m^3. Xylene concentration was between 14.7ug/m^3 and 45.0ug/m^3, which is between approximately 15 and 48 times lower than the guidelines for South Korea. Finally, styrene concentration was between 37.7ug/m^3 and 112.5ug/m^3, with the highest measured value of 112.5ug/m^3 occurring in the C-type residence without ventilation. However, the indoor air styrene concentration with ventilation was measured at 55.0ug/m^3, falling to half the level observed without ventilation. Although the reduction rate of indoor chemical concentration decreased by ventilation system it was measured differently in each type, and the results were not clearly explained by this study. Thus, subsequent research needs to investigate whether the ventilation rate in each room is uniformly ventilated.

4. Discussion

4.1 Evaluation of Indoor Air Quality in Clean-Healthy Houses

Table 7. compares indoor air pollutant concentrations and results from the literature. Many researchers have investigated to evaluate hazardous substances polluted in offices, schools, public buildings and houses; however, the results in this study were compared only with those drawn by the studies on housing. The mean formaldehyde concentration is 80.2ug/m^3 in the present study, which compared highly with previous studies in other countries. Nevertheless, the level is within the guidelines of both South Korea and the WHO. In the case of newly built apartment blocks that were constructed prior to enforcement of the Clean-Healthy House construction standard, Yoon (2013) reported indoor air formaldehyde concentration of 527.3ug/m^3, exceeding the guideline for South Korea, while Kang et al. (2010) measured pre-bake-out formaldehyde concentration at 180ug/m^3. Compared with these kinds of result, the apartment blocks built to the Clean-Healthy House standard have much lower levels of formaldehyde contamination.

Table 5. Observed Concentrations of Formaldehyde and Acetaldehyde in Indoor Air and Guideline Values [ug/m^3]

| Chemicals          | Type | Ventilation off | Ventilation on | Pollutant reduction in indoor air by ventilation (%) | Guideline          |
|--------------------|------|----------------|---------------|------------------------------------------------------|--------------------|
| Formaldehyde       | A type | 63.3           | 52.0          | 17.9                                                 | 210 (South Korea*) |
|                    | B type | 99.0           | 90.5          | 10.9                                                 | 100 (WHO**, Japan***)|
|                    | C type | 99.2           | 76.7          | 22.6                                                 | 260 (South Korea), 260 (Japan) |
| Acetaldehyde       | A type | 15.5           | 14.6          | 5.4                                                  | 50 (WHO)          |
|                    | B type | 61.0           | 32.4          | 46.9                                                 | 48 (Japan)        |
|                    | C type | 43.1           | 17.9          | 58.5                                                 |                    |

*: Ministry of Environment, South Korea (2005)  
**: World Health Organization (1999)  
***: Ministry of Health, Labour, and Welfare, Japan (2002)

Table 6. Observed Concentrations of Five VOCs in Indoor Air and Guideline Values [ug/m^3]

| Chemicals    | Type | Ventilation off | Ventilation on | Pollutant reduction in indoor air by ventilation (%) | Guideline          |
|--------------|------|----------------|---------------|------------------------------------------------------|--------------------|
| Benzene      | A type | 1.3           | 0.6           | 51.9                                                 | 30 (South Korea)   |
|              | B type | 1.2           | 1.0           | 19.2                                                 |                    |
|              | C type | 1.0           | 1.0           | 0                                                    |                    |
| Toluene      | A type | 181.6         | 161.8         | 10.9                                                 | 1000 (South Korea, WHO) |
|              | B type | 266.0         | 170.0         | 36.1                                                 | 260 (Japan)        |
|              | C type | 371.0         | 183.0         | 50.7                                                 |                    |
| Ethylbenzene | A type | 9.8           | 6.5           | 34.0                                                 | 360 (South Korea, WHO) |
|              | B type | 10.7          | 13.2          | -23.3                                                |                    |
|              | C type | 17.0          | 9.2           | 45.9                                                 | 3800 (Japan)       |
| Xylene       | A type | 29.3          | 22.2          | 24.4                                                 | 700 (South Korea, WHO) |
|              | B type | 18.2          | 14.7          | 19.3                                                 | 870 (Japan, WHO)   |
|              | C type | 45.0          | 25.3          | 43.7                                                 |                    |
| Styrene      | A type | 54.6          | 37.7          | 31.1                                                 | 300 (South Korea, WHO) |
|              | B type | 78.3          | 58.0          | 26.0                                                 |                    |
|              | C type | 112.5         | 55.0          | 51.1                                                 | 220 (Japan, WHO)   |
Average acetaldehyde concentration in this study was 30.7 μg/m³, which again is slightly higher than studies in other countries but is within Japanese and WHO guidelines. South Korea does not have a guideline to limit acetaldehyde, and few previous studies have reported indoor air concentrations of acetaldehyde in newly built apartment blocks in South Korea. Aside from these, the indoor air concentrations of benzene, toluene, ethylbenzene, xylene, and styrene all satisfied the South Korean guidelines. Kang et al. (2010) reported indoor toluene concentration of 1,286.7 μg/m³ in a newly built apartment block, which exceeds the South Korean guideline; however, the average concentration of toluene measured in the Clean-Healthy House was 222.2 μg/m³, which is approximately 6 times lower than in existing newly built apartment blocks. Moreover, the average indoor air concentrations of xylene and styrene were 25.8 and 66.0 μg/m³ respectively, which are similar to those of previous studies.

One major difference between existing newly built apartment residences and Clean-Healthy House residences is the implementation of a flush-out, which is slightly different from a bake-out. The bake-out method used in South Korea uses the hot-water under-floor heating system to heat the interior of the residence to a temperature of 35–40 degrees, before opening the windows and doors to ventilate. The result
is a reduction in the volume of pollutants released from the construction materials, which reduces the indoor air pollutant concentration (Kang et al., 2010). Also according to Kang et al. (2010; see Table 7.), bake-out provides an excellent improvement in indoor air pollutant concentrations. However, such a bake-out is not conducted directly by the construction company, but by the resident of the newly built apartment upon first occupancy. Flush-out must be conducted by the construction company following interior construction and installation of fitted furniture and before the resident takes up occupancy. During the flush-out, continuous ventilation was operated with all doors of installed furniture and rooms open; and the volume of air change (400m$^3$/m$^2$) was secured.

The Clean-Healthy House residences surveyed in this study had undergone a flush-out period of approximately eight days. However, the improvement in indoor air quality following flush-out is yet to be accurately evaluated, and therefore requires further research.

Finally, the Clean-Healthy House building standard is applied only to the construction of large housing blocks containing 1,000 or more residences, but is not applied to small-scale apartment blocks and stand-alone residences. Therefore, the standard should be applied more widely in order to ensure good indoor air quality in other types of residences in South Korea.

5. Conclusions
This research evaluated the indoor air quality of apartment blocks built to the Clean-Healthy House construction standard, which took effect in South Korea from December 2010. Indoor concentrations were measured for formaldehyde, acetaldehyde, benzene, toluene, ethylbenzene, xyylene, and styrene. In all types of residence, indoor pollution levels were within the guidelines for South Korea. Moreover, concentrations were lower than those measured in existing newly built apartment blocks in South Korea. Looking ahead, there is a need to investigate how effective the flush-out operation is for improving indoor air quality, and there needs to be an effort to apply the Clean-Healthy House construction standard not only to large-scale apartment blocks, but also to small-scale apartment blocks and stand-alone residences.

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