Journal of Environmental Science International
24(10); 1273~1283; October 2015

pISSN: 1225-4517 eISSN: 2287-3503
http://dx.doi.org/10.5322/JESI.2015.24.10.1273

ORIGINAL ARTICLE

Temporal Characteristics of Selected Volatile Organic Compounds in Urban High-Stories Urban Apartments

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Abstract

In present study, the temporal characteristics of nine selected volatile organic compounds (VOCs), including four alcohol, 2 aldehyde, and 3 ketone compounds, in high-stories urban apartments over a 2-y period were investigated. The indoor VOC concentrations had generally a decreasing trend over the 2-y follow-up period. For examples, the 2E1H indoor concentration decreased from 10.8 $\mu g/m^3$ for the first two months to 5.1 $\mu g/m^3$ for the last two months. In addition, the DCA and ACT indoor concentrations decreased from 5.0 and 14 $\mu g/m^3$ for the first two months to 2.2 and 6.4 $\mu g/m^3$, respectively, for the last two months. The indoor-to outdoor concentration ratios over the 2-y period were much greater than 1, indicating that indoor VOC concentrations were higher than the outdoor VOC concentrations. Similar to those of the individual VOCs, the indoor-to-outdoor concentration ratios of all three VOC groups were higher than 1 over the 2-y follow-up period, suggesting higher indoor concentrations of the three VOC groups than outdoor concentrations. In consistence with the results of VOC indoor concentrations, the VOC emission rates decreased gradually as time passed, due to the decreased VOC emission strengths of indoor sources. Finally, there was an initial sharp decrease in the indoor VOC concentrations followed by a slower decrease, indicating a multi-exponential decay model for the target VOCs, which was demonstrated by comparison of the residuals and the adjusted coefficient of determination associated with the one and two-exponential fits of each data set.

Key words : Temporal characteristics; Decay compartment model; Consumer product; High story; VOC source

1. Introduction

Individual exposure to volatile organic compounds (VOCs) is a crucial environmental problem because of the harmful health effects and ubiquity of these pollutants in various indoor environments. The VOC exposure is closely associated with symptoms of Sick Building Syndrome, which is denoted as a group of symptoms, such as irritability, sleepiness, nausea, and other health effects (Cakmak et al., 2014; Langer et al., 2015; Ongwandee et al., 2011; Takigawa et al., 2012). The ubiquity of indoor VOCs is ascribed to a range of emissions sources, including construction finishing materials (floor, ceiling and wall coverings, etc.), furniture, and consumer products (household cleaners, air fresheners, deodorizers, waxes, etc.) (Bari et al., 2015; Liang et al., 2014; Shin and Jo, 2013; Wang et al., 2015). Especially, the construction finishing and furnishing materials in newly-built buildings are primary indoor sources of a great deal of VOCs (Liang et al., 2014; Shin and Jo, 2013). Therefore, high VOC concentration levels are more typically measured in new residential buildings than established ones (Wang et al., 2015).

Received 21 September, 2015; **Revised** 17 October, 2015;
Accepted 19 October, 2015
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It should be noted that the concentrations of VOCs in many new residential buildings decrease as time passes because the emission strength of construction finishing and furnishing materials decrease with time. This assertion is supported by previous studies (Shin and Jo, 2013; Wang et al., 2015), that reported the long-term variation of indoor VOC concentrations in new buildings after the resident moved in. In those studies, indoor VOC measurements were repeated over a 2-y period. The results revealed that most VOC concentrations in new buildings did not exhibit levels similar to those of older building until two years. In addition, Järnström et al., (2006) repeated their VOC concentrations in newly-built buildings over a one year period and found that the VOC concentrations generally showed the greatest dec -rease most definitely during the first six months. These time-interval VOC data might be associated with a VOC decay model to predict VOC concen -trations over time. Typically, a more reliable expon -ential decay model can be obtained with more measurement values. Therefore, the VOC measure -ment data collected from the previous studies are insufficient for establishing exponential decay models. As such, long-term observations with shorter observation time intervals are necessary to supply new and more reliable results regarding the indoor VOC concentration dependency on time. Neverth -eless, such studies have rarely reported to date, even though limited studies have determined short-term indoor VOC decay models to predict short-term concentrations on an hourly basis (Deng et al., 2012; Li and Niu, 2007; Yan et al., 2009).

Moreover, past indoor VOC data regarding new buildings is likely inappropriate because of variations in emission strength of many VOCs and differences in ventilation conditions. Recently built-buildings are more tightly sealed for energy savings, leading to low ventilation conditions. This indicates that new information pertaining to VOC levels in recently constructed houses is required to update the rela -tionship between exposure and health risk for residents of new buildings. Consequently, this study was performed to examine the temporal charac -teristics of selected VOCs (focusing on alcohol, aldehyde, and ketone groups) in new apartments every month over a 2-y period after the residents had moved in. In addition, the emission strength of indoor VOCs according to the survey period were estimated. One- and two-compartment exponential decay models were also developed to evaluate long-term (two year) time dependence on indoor VOC concentrations after moving into new residential buildings were cons -tructed. Ultimately, the present study provides up -dated longitudinal indoor VOC concentration data after moving-into new apartments, emission infor -mation, and long-term VOC decay models.

2. Experimental methods

2.1. Experimental design

A 2-y time-series investigation of indoor and outdoor VOC concentrations was performed in 25 new homes in selected high-story apartment buildings (declared as 10 or more stories). Air sampling was carried out in the selected apartments within one month of when the residents moved in and then every month over a 2-y period. During the survey, five apartments were switched by their neighborhood ones due to the residents moving or complaints about their inconvenience. The buildings were located in Daegu with about 2.5 million inhabitants. Residents of 25 homes in 37 apartment buildings that satisfied the experimental criteria were asked for permission to measure the air concentration levels inside their apartments. The criteria for apartment selection were as follows: the buildings should be located at least 150 meters away from major roadways to reduce the impact of motor vehicle exhausts; the age of the apartments should be less than one month (counting

from the date on which heating fuel was supplied); and the apartments should have two to three bed -rooms, one living room, and two bathrooms. All investigated apartments were constructed with con -crete and iron frames, while liquid petroleum gas was supplied as the main cooking and heating fuel for the apartments. The apartment floor was covered with parquet, polyvinyl chloride (PVC), and/or marble. Interior wall was covered with marble and/or PVC, while ceiling was covered with PVC. Even though there was one fan in the kitchen and bathroom in the investigated apartments, the inhabitants were asked not to run them during air sampling.

VOC sampling was carried out inside the apart -ments in the morning (09:00—12:00) or afternoon (14:00—17:00). Before air sampling, all doors and windows were left open for 0.5 h to equilibrate the indoor VOC levels to the ambient levels. External doors and windows were then left closed for 2 h, but the room doors were left open. Subsequently indoor sampling was carried out for 1 h at a height of 1.5 m from the floor in the middle of the living room. For the cold sampling months, both the inhabitants and one technician stayed inside one bedroom, during which time both the door and the window were closed. However, they stayed outside the apartments during the sampling hours for the other measurement months to reduce the effects of occupants and their activities on indoor VOC levels. Either smoking or cooking activities were not observed during the measurements. Additionally, outdoor air sampling was concurrently carried out at the outdoor balcony of each apartment.

2.2. VOC measurements

The target compounds were collected by drawing air through a 0.64-cm-outside diameter and 10-cm length stainless steel trap containing Tenax TA using a sampling pump (Model 224-PCXR8, SKC Inc.). The air flow rates were determined before and follo -wing the collection of each sample using a digital flow meter. The average of the two air flow rates was utilized as the sampling flow rate for sample volume calculations. Flow rates of 25—30 and 35—40 mL min^{-1} were adjusted for indoor and outdoor samples, respectively, on the basis of the relative expected concentrations for each experimental condition.

The target compounds collected in the SS traps were analyzed using a gas chromatograph (HP 5890 II)/mass spectrometer (HP MSD5973) (GC/MS) unit or a GC/flame ionization detector (FID) system (HP 7890) combined with a thermal desorbing unit (TD, Perkin Elmer ATD 400). As displayed in Table 1, the target compounds included 11 chemicals, which are listed in the Japanese indoor air standard mixture (JP-4M7537, Supelco). These chemicals consisted of four alcohols, two aldehydes, and three ketones. The GC/FID system was utilized for VOC analyses, while the GC/MS was employed for confirmation of the GC/FID results. Identification of each chemical was carried out based on its retention time and/or Wiley 275 software library.

For the quality control program, laboratory and field blank traps and spiked samples were utilized. Specified portions of duplicate measurements of integrated samples were carried out during field sampling periods. The laboratory and field blank traps were investigated daily for trap contamination. To determine the quantitative response, known VOC standards were infused into an adsorbent trap to transfer the target chemicals to the analytical instrument. If the instrumental response differed by more than ± 15% from that estimated by a specified calibration curve, a new calibration curve was pre -pared. Seven traps spiked with known amounts of the target chemicals were utilized to prepare the calibration curve. Analyses of 41 duplicate sampling traps (23 and 18 for indoor and outdoor sampling traps, respectively) displayed the relative standard deviations <15% for the target chemicals.

Table 1. Mean values of monthly indoor and outdoor concentrations ($\mu g/m^3$) obtained in apartments over a 2-y period*

Group	Compounds	Type	Month											
			1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24
Alcohols	2-Ethyl-1-Hexanol (2E1H)	In	10.8	10.3	9.1	8.5	8.1	7.6	7.6	6.4	5.7	5.2	5.1	5.1
		Out	1.5	1.6	1.7	1.3	1.3	2.0	1.2	1.6	1.5	1.2	1.2	1.6
	Ethanol (EOL)	In	27	24	18	16	14	13	12	11	11	11	11	11
		Out	ND	1.6	1.3	1.3	1.6	1.6	1.6	1.7	1.4	1.4	1.3	1.5
	1-Propanol (1POL)	In	15	14	11	10	9.4	8.5	7.2	6.3	5.6	5.3	5.4	5.3
		Out	3.1	2.5	2.5	2.4	3.1	1.7	3.8	2.8	2.3	2.1	2.4	2.1
	2-Propanol (2POL)	In	8.6	8.0	7.7	6.9	6.2	5.6	5.3	5.3	5.3	5.2	5.3	5.3
		Out	3.9	2.4	1.9	3.8	3.8	3.7	4.4	2.2	1.7	1.7	3.8	2.5
Aldehydes	Decanal (DCA)	In	5.0	4.1	3.9	3.5	3.3	2.7	2.4	2.3	2.3	2.3	2.1	2.2
		Out	1.0	1.1	1.1	1.0	0.9	0.8	1.0	0.8	0.9	1.1	0.9	1.1
	Nonanal (NNA)	In	8.3	8.0	7.7	7.6	7.0	6.2	5.7	5.3	5.0	5.2	4.7	4.7
		Out	1.1	1.1	1.1	0.9	0.8	0.8	1.0	0.8	1.1	0.8	0.8	0.8
Ketones	Acetone (ACT)	In	14	12	12	11	9.9	9.8	9.0	7.9	6.9	6.7	6.5	6.4
		Out	2.8	2.6	2.7	2.3	2.3	3.0	2.2	2.6	2.5	2.2	2.2	2.6
	2-Butanone (2BT)	In	13	12	11	10	9.8	9.0	8.6	7.7	6.5	5.9	5.8	5.6
		Out	2.1	1.7	1.7	3.1	3.7	3.6	3.9	2.8	2.3	1.3	3.1	2.7
	4-Methyl-2-pentanone (4M2P)	In	8.8	8.0	7.4	7.6	6.7	6.4	5.9	5.2	4.8	4.8	4.8	4.6
		Out	2.4	2.4	2.3	2.2	2.4	2.5	2.0	1.9	1.5	1.3	2.2	2.4

*Abbreviation of each VOC is displayed in parenthesis; ND, not detected.

2.3. Estimation of emission rates

Emission rates were estimated using the measured VOC concentrations and a mass balanced relationship:

$$ER = Q(C_{in} - C_{out}) \quad (1)$$

where ER is the VOC source emission rate ($\mu g/h$), C_{in} is the measured VOC concentration ($\mu g/m^3$), C_{out} is the outdoor VOC concentration, and Q is the ventilation rate (m^3/h), which was determined by multiplying apartment volume (m^3) by air exchange rate (ACH, h^{-1}). ACHs were determined by the tracer CO_2 gas decay method, when main doors and windows were left closed, but the room doors were left open to maintain better air mixing among rooms within the apartment. Major assumptions made in this study are as follows: perfect mixing within the houses and no net loss of target chemicals from the air due to other effects, such as adsorption on the inner surface of the houses or chemical reactions.

2.4. Development of exponential decay model

The indoor VOC concentrations and their measure -ment times were stood for the following equations:

$$Y = A\,e^{-Bt} \text{ and } Y = C\,e^{-Dt} + E\,e^{-Ft} \quad (2)$$

which matched to a single- and a double-type expon -ential decay model, respectively. In these models, Y is the VOC concentration determined at any time t, A, C, and E are constants, and B, D and F are the

exponential constants that are associated with the rate of decay. Curve fitting was carried out by the nonlinear curve fitting program (Sigma Plot software, Jandel Scientific Software).

3. Results and Discussion

3.1. Temporal characteristics of selected VOCs

The indoor and outdoor concentrations of nine selected VOCs were investigated in newly-construc -ted apartments over a 2-y period to assess the temporal characteristics of VOCs in the residences. For many cases, the VOC concentration values were greater than the median values, suggesting the non-normal distribution of VOC concentrations. However, a normality test (Shapiro-Wilk) showed that the dis -tribution of VOC concentrations was log normal. The temporal variations in indoor VOC concentra -tions measured in the survey apartments, along with VOC abbreviations, are displayed in Table 1. Here -after, the VOC abbreviations denoted in this table were utilized for brevity.

As displayed in Table 1, the indoor VOC concen -trations had generally a decreasing trend over the 2-y follow-up period. For examples, the 2E1H indoor concentration decreased from 10.8 $\mu g/m^3$ for the first two months to 5.1 $\mu g/m^3$ for the last two months. In addition, the DCA and ACT indoor concentrations decreased from 5.0 and 14 $\mu g/m^3$ for the first two months to 2.2 and 6.4 $\mu g/m^3$, respectively, for the last two months. This descending tendency was ascribed to time-series decrease in VOC emissions of major indoor sources, including building finishing materials and furniture with time pass (Järnström et al., 2007; Liu et al., 2013; Langer et al., 2015). Furthermore, the indoor air concentrations of the 9 VOCs were statistically higher than the outdoor air concentra -tions, suggesting the influence of various indoor sources, including building finishing materials and furniture, for the target VOCs. In contrast to indoor VOC concentrations, the outdoor VOC concentration did not significantly vary with time. Specifically, the 2E1H outdoor concentration was 1.5 $\mu g/m^3$ for the first two months and 1.6 $\mu g/m^3$ for the last two

Table 2. Ratios of indoor to outdoor concentrations of selected VOCs measured in apartments over a 2-y period

Group	Compounds	Month											
		1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24
Alcohols	2-Ethyl-1-Hexanol (2E1H)	14	6.3	5.5	6.5	6.1	3.8	6.6	4.1	3.8	4.4	4.2	3.2
	Ethanol (EOL)	16	15	14	12	8.9	8.2	7.4	6.4	8.5	8.2	9.0	8.0
	1-Propanol (1POL)	4.9	5.7	4.5	4.2	3.1	5.2	1.9	2.2	2.4	2.6	2.3	2.5
	2-Propanol (2POL)	2.2	3.4	4.1	1.8	1.6	1.5	1.2	2.4	3.2	3.0	1.4	2.2
Aldehydes	Decanal (DCA)	5.0	3.7	3.6	3.4	3.7	3.6	2.3	2.8	2.7	2.0	2.3	2.0
	Nonanal (NNA)	7.8	7.0	7.4	8.5	8.8	7.5	5.8	6.6	4.6	6.2	6.0	5.5
Ketones	Acetone (ACT)	5.1	7.8	7.7	8.5	7.3	4.9	7.8	5.0	4.5	5.6	5.5	4.1
	2-Butanone (2BT)	6.1	7.1	6.4	3.3	2.6	2.5	2.2	2.7	2.9	4.4	1.8	2.0
	4-Methyl-2-pentanone (4M2P)	3.7	3.3	3.2	3.4	2.8	2.6	3.0	2.8	3.2	3.6	2.2	1.9

months. Additionally, the DCA and ACT outdoor concentrations were 1.0 and 2.8 $\mu g/m^3$ for the first two months to 1.1 and 2.6 $\mu g/m^3$, respectively, for the last two months. These results indicated that outdoor VOC source strengths did not substantially vary with time pass.

Outdoor VOC concentrations can affect the indoor VOC concentrations of residences by the penetration from outdoor environments into building interiors (Shin and Jo, 2013). As such, Table 2 shows the ratios of indoor to outdoor concentrations of indi -vidual 9 VOCs measured in apartments over a 2-y period. The indoor-to outdoor concentration ratios over the 2-y period were much greater than 1, indi -cating that indoor VOC concentrations were higher than the outdoor VOC concentrations. Specifically, the indoor-to outdoor concentration ratios ranged from 3.2 to 14 for 2E1H, from 2.0 to 5.0 for DCA, and from 4.1 to 5.1 for ACT. These findings suggest that outdoor VOCs do not significantly influence the indoor VOC concentration levels and that indoor VOC sources are primary cause for the indoor VOC concentrations (Bari et al., 2015).

Figure 1 was also prepared to examine the relation -ships between indoor VOC concentrations standar -dized to outdoor VOC concentrations (indoor-to-outdoor concentration ratios) of three selected VOC groups (alcohols, aldehydes, and ketone groups) versus their measurement months. Similar to those of the individual VOCs, the indoor-to-outdoor concent -ration ratios of all three VOC groups were higher than 1 over the 2-y follow-up period, suggesting higher indoor concentrations of the three VOC groups than outdoor concentrations. Furthermore, the ratios of these VOC groups exhibited a descending trend over the 2-y follow-up period, while there was an initial sharp decrease in the ratios followed by a slower decrease over the rest follow-up period, indicating a multi-exponential decay model. Consistently, other research groups (Park and Ikeda, 2006; Tuomainen et al., 2003) observed that certain VOC indoor concent -rations decreased gradually over 3-y follow-up periods. In addition, a great deal of research groups reported that indoor VOC concentrations were typically higher than outdoor VOC concentrations in residential, school, hair salon, and office buildings (Cometto-Muñiz and Abraham, 2015; de Gennaro et al., 2014; Do et al., 2015; Gokhale et al., 2008; Mishra et al., 2015; Su et al., 2013; Uchiyama et al., 2015; Wangchuk et al., 2015).

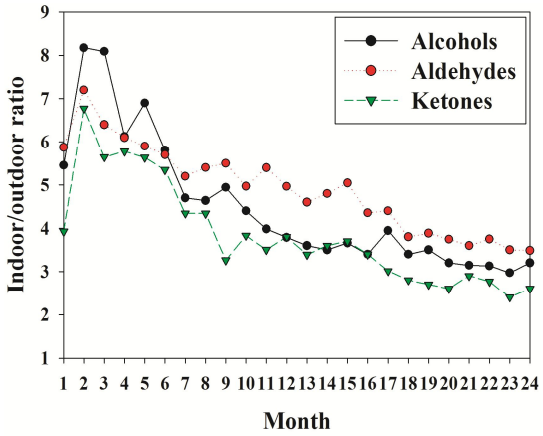

Fig. 1. Temporal variations in ratios of indoor to outdoor concentrations of selected VOC groups (alcohols, aldehydes, ketones).

Table 3 reveals the emission rates of 9 selected VOCs (2E1H, EOL, 1POL, 2POL, DCA, NNA, ACT, 2BT, and 4M2P) estimated for the investigated apartments according to survey period. Generally, EOL displayed the highest emission rates for the first two months with a value of 2162 $\mu g/h$, followed by 1POL (1046 $\mu g/h$), ACT (988 $\mu g/h$), 2BT (911 $\mu g/h$), 2E1H (854 $\mu g/h$), NNA (615 $\mu g/h$), 4M2P (546 $\mu g/h$), 2POL (401 $\mu g/h$), and DCA (341 $\mu g/h$). Although some exceptional cases, this pattern was applicable to the rest follow-period results. In consistence with the results of VOC indoor concentrations, the VOC emission rates decreased gradually as time passed,

Table 3. Emission rates (μg/h) of selected VOC groups standardized to the number of VOC species according to survey period

Group	Compounds	Month											
		1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24
Alcohols	2-Ethyl-1-Hexanol (2E1H)	854	735	635	615	576	478	547	407	358	345	329	297
	Ethanol (EOL)	2162	1956	1447	1238	1043	951	865	779	890	862	857	866
	1-Propanol (1POL)	1046	1007	735	651	536	586	285	296	280	278	256	275
	2-Propanol (2POL)	401	479	491	257	208	164	180	264	309	298	127	242
Aldehydes	Decanal (DCA)	341	253	240	214	206	165	115	128	122	98	103	32
	Nonanal (NNA)	615	586	568	570	527	458	404	381	332	367	334	325
Ketones	Acetone (ACT)	988	941	943	836	720	671	669	535	458	466	455	410
	2-Butanone (2BT)	911	870	788	598	515	461	402	415	362	389	223	243
	4-Methyl-2-pentanone (4M2P)	546	473	435	454	366	331	335	288	281	291	223	191

due to the decreased VOC emission strengths of indoor sources (Chen et al., 2014; Han et al., 2011; Wang et al., 2015).

The indoor concentrations of total VOCs and ACH values measured in ten selected apartments during are shown in Table 4. For the apartments, the total VOC concentration for the first two months were higher than those for the rest follow periods. As mentioned previously, these findings are attributed to additional emissions of total VOCs from building finishing materials, furniture, and consumer products since residents have moved into the apartments (Chen et

Table 4. Indoor concentrations ($\mu g/m^3$) of total VOCs and air exchange rates (ACH, h^{-1}) estimated in apartments

Apartment ID	ACH	Indoor concentration of total VOCs											
		Month											
		1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24
1	0.41	136	127	97	99	93	97	92	76	54	72	64	52
2	0.44	132	122	96	90	79	73	56	52	49	38	53	40
3	0.42	78	84	76	70	69	70	59	54	49	58	51	43
4	0.38	95	98	90	77	72	59	56	51	57	48	41	40
5	0.42	103	106	85	74	77	64	67	51	49	60	44	55
6	0.42	99	100	89	76	79	64	59	63	56	49	59	47
7	0.37	156	141	126	115	104	100	97	86	80	75	71	62
8	0.41	109	95	79	74	67	69	64	50	65	43	46	43
9	0.43	134	92	97	76	75	56	51	55	57	47	53	56
10	0.60	116	124	94	79	82	74	69	61	60	51	50	53

Table 5. Modeling values of one- and two-exponential models for VOC concentrations determined in apartments monthly over a 2-y period[a]

Group	Compounds	Single- exponential model				Double-exponential model					
		A	B	Adj. R^2	F-test[b]	C	D	E	F	Adj. R^2	F-test
Alcohols	2E1H	11(0.1)	0.04(0.0009)	0.99	1871	11(9.8)	0.04(0.03)	0.7(9.9)	~0(0.2)	0.99	566
	EOL	26(1.3)	0.05(0.005)	0.83	99	21(3.3)	0.2(0.05)	11(3.9)	~0(0.02)	0.97	227
	1POL	17(0.4)	0.06(0.003)	0.96	544	14(7.2)	0.1(0.06)	3.7(7.6)	~0 (0.06)	0.98	302
	2POL	8.5(0.2)	0.03(0.002)	0.85	136	4.8(2.2)	0.1(0.07)	4.8(2.4)	~0 (0.02)	0.95	147
Aldehydes	DCA	4.9(0.2)	0.04(0.003)	0.91	205	3.7(0.9)	0.1(0.05)	2.0(1.0)	~0(0.02)	0.98	278
	NNA	9.0(0.2)	0.03(0.0015)	0.95	449	8.3(17)	0.04(0.05)	0.8(17)	~0(0.3)	0.95	136
Ketones	ACT	45(0.8)	0.04(0.002)	0.97	933	40(40)	0.05(0.03)	5.6(40)	~0(0.1)	0.97	229
	2BT	14(0.2)	0.04(0.001)	0.98	1271	6.4(0.19)	0.04(0.003)	7.3(0.03)	0.04(~0)	0.98	385
	4M2P	9.1(0.1)	0.03(0.001)	0.96	612	7.0(11)	0.05(0.06)	2.2(11)	~0(0.09)	0.96	204

[a] The numbers in parenthesis are the standard error values; A, C, and E are constants, and B, D and F are the exponential constants that are associated with the rate of decay.
[b] F-test value.

al., 2014; Liang et al., 2014; Ye et al., 2014). Similar to individual VOCs, the total VOC concentrations showed a descending trend from one month to 24 months after the residents moved into their homes. The highest total VOC concentration measured over the 2-y period was observed in Apartment 7, with a value of 156 $\mu g/m^3$ for the first two months. These results are attributed to ACH values and total VOC emission strengths in the surveyed apartments, which are two important parameters for IAQ (Deng et al., 2012). The lowest ACH value, which reflects low ventilation conditions (Chen et al., 2014; Han et al., 2014; Rackes and Waring, 2013), was obtained from the apartment 7, with a value of 0.37. Although data are not presented in this paper, the apartment sizes were all comparable each other and the ceilings of all apartments were covered with paper-containing finishing materials. Notably, the walls of Apartment 7 were repainted, which could have increased total VOC concentrations due to strong VOC emissions from paints (Schieweck and Bock, 2015; Xiong et al., 2013). However, in other cases, the indoor VOC concentrations did not display a definite correlation with ACH values. For example, the indoor VOC concentration for the first two months in the apartment 10 (116 $\mu g/m^3$) was higher than that for the apartment 4 (95 $\mu g/m^3$), although the ACH value in the apartment 10 (0.60 h^{-1}) was greater than that for the apartment 4 (0.38 h^{-1}). These results suggest that the indoor VOC concentrations in apartments might be determined the complicated interactions of venti -lation conditions and indoor source characteristics in the apartments, rather than simple ventilation effects (Chen et al., 2014).

3.2. VOC decay modeling

Regarding the 9 VOCs that showed distinguishable decreasing tendencies, the indoor concentrations were correlated with exponential decay models to assess their temporal dependence. Table 5 reveals the empirical values of single- and double-exponential models for the indoor VOC concentrations deter -mined over a 2-y period. Both the single- and double

-exponential equations were statistically significant with p less than 0.05. There was an initial sharp decrease in the indoor VOC concentrations followed by a slower decrease, indicating a multi-exponential decay model for the target VOCs. This result was explained by finding that the two-exponential fits were better, as demonstrated by comparison of the residuals and the adjusted coefficient of determina -tion (Adj. R^2) associated with the one and two-exponential fits of each data set. The adjusted coeffi -cients were 0.95—0.99 for the double-exponential model, while they were 0.83—0.99 for the single-exponential model, depending on target VOCs. These prepared models can be utilized to predict time-dependent indoor VOC concentrations in high-story apartments buildings. However, it is noteworthy that the model uses for the prediction of indoor VOC concentrations in apartments are restricted to apart -ment buildings that display indoor conditions compar -able to those of the apartments investigated in the current study, because residential indoor VOC concen -trations could vary with a range of indoor parameters, including source emission strength, residents' activi -ties, humidity, temperature, and ventilation rates (Järnström et al., 2006; Park and Ikeda, 2006; Tuo -mai-nen et al., 2003).

4. Conclusions

The present was performed to examine the tem -poral variations in indoor VOC concentrations, VOC emission rates, and VOC decay characteristics in sele -cted apartments over a 2-y period. The indoor VOC concentrations revealed a descending trend over the surveyed period. The selected VOCs related to building finishing materials and furniture emissions exhibited a descending trend. Specifically, the indoor 2E1H concentration assumed to be emitted from a range of building finishing materials, such as vinyl floor and wall coverings, decreased gradually with time. In most cases, the decreasing tendency for VOC concentration is attributed to the decrease in the emission strength of building finishing materials. Similar to the results of VOC indoor concentrations, the VOC emission rates decreased gradually as time passed, due to the decreased VOC emission strengths of indoor sources. The VOCs revealed definite descending trends and their indoor concentrations could be fit to exponential decay models to assess their temporal dependence.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MEST) (2011-0027916).

REFERENCE

Bari, M. A., Kindzierski, W. B., Wheeler, A. J., Héroux, M. -È, Wallace, L. A., 2015, Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada. Build. Environ., 90, 114-124.

Cakmak, S., Dales, R. E., Liu, L., Kauri, L. M., Lemieux, C. L., Hebbern, C., Zhu, J., 2014, Residential exposure to volatile organic compounds and lung function: results from a population-based cross-sectional survey, Environ. Poll., 194, 145-151.

Chen, W., Persily, A. K., Hodgson, A. T., Offermann, F. J., Poppendieck, D., Kumagai, K., 2014, Area-specific airflow rates for evaluating the impacts of VOC emi -ssions in U.S. single-family homes, Build. Environ., 71, 204-211.

Cometto-Muñiz, J. E., Abraham, M. H., 2015, Compila -tion and analysis of types and concentrations of airborne chemicals measured in various indoor and outdoor human environments, Chemosphere, 127, 70-86.

de Gennaro, G., de Gennaro, L., Mazzone, A., Porcelli, F., Tutino, M., 2014, Indoor air quality in hair salons: Screening of volatile organic compounds and indica -tors based on health risk assessment, Atmos. Environ., 83, 119-126.

Deng, Q., Yang, X., Zhang, J. S., 2012, Key factor analysis of VOC sorption and its impact on indoor concen -trations: the role of ventilation, Build. Environ., 47, 182-187.

Do, D. H., Walgraeve, C., Amare, A. N., Barai, K. R., Parao, A. E., Demeestere, K., van Langenhove, H., 2015, Airborne volatile organic compounds in urban and industrial locations in four developing countries. Atmos. Environ., 119, 330-338.

Gokhale, S., Kohajda, T., Schlink, U., 2008, Source apportionment of human personal exposure to volatile organic compounds in homes, offices and outdoors by chemical mass balance and genetic algorithm receptor models, Sci. Total Environ., 407, 122-138.

Han, K. H., Zhang, J. S., Knudsen, H. N., Wargocki, P., Chen, H., Varshney, P. K., Guo, B., 2011, Develop -ment of a novel methodology for indoor emission source Identification, Atmos. Environ., 45, 3034-3045.

Han, K., Zhang, J. S., Guo, B., 2014, A novel approach of integrating ventilation and air cleaning forsustainable and healthy office environments, Energy Build., 76, 32-42.

Järnström, H., Saarela, K., Kalliokoski, P., Pasanen, A. -L., 2006, Reference values for indoor air pollution concentrations in new residential buildings in Finland, Atmos. Environ., 40, 7178-7191.

Järnström, H., Saarela, K., Kalliokoski, P., Pasanen, A. -L., 2007, Reference values for structure emissions measured on site in new residential buildings in Fin -land, Atmos. Environ., 41, 2290□2302.

Langer, S., Bekö, G., Bloom, E., Widheden, A., Ekberg, L., 2015, Indoor air quality in passive and conventional new houses in Sweden, Build. Environ., 93, 92-100.

Li, F., Niu, J., 2007, Control of volatile organic com -pounds indoors-development of an integrated mass-transfer-based model and its application, Atmos. Environ., 41, 2344-2354.

Liu, Z., Ye, W., Little, J. C., 2013, Predicting emissions of volatile and semivolatile organic compounds from building materials: a review, Build. Environ., 64, 7-25.

Liang, W., Yang, C., Yang, X., 2014, Long-term concen -trations of volatile organic compounds in a new apartment in Beijing, China. Build. Environ., 82, 693-701.

Mishra, N., Bartsch, J., Ayoko, G. A., Salthammer, T., Morawska, L., 2015, Volatile organic compounds: characteristics, distribution and sources in urban schools, Atmos. Environ., 106, 485-491.

Ongwandee, M., Moonrinta, R., Panyametheekul, S., Tangbanluekal, C., Morrison, G., 2011, Investigation of volatile organic compounds in office buildings in Bangkok, Thailand: Concentrations, sources, and occupant symptoms, Build. Environ., 46, 1512-1522.

Park, J. S., Ikeda, K., 2006, Variations of formaldehyde and VOC levels during 3 years in new and older homes, Indoor Air, 16, 129-135.

Rackes, A., Waring, M. S., 2013, Modeling impacts of dynamic ventilation strategies on indoor air quality of offices in six US cities, Build. Environ., 60, 243-253.

Schieweck, A., Bock, M. -C., 2015, Emissions from low-VOC and zero-VOC paints valuable alternatives to conventional formulations also for use in sensitive environments?, Build. Environ. 85, 243-252.

Shin, S. H., Jo, W. K., 2013, Longitudinal variations in indoor VOC concentrations after moving-into new apartments and indoor source characterization, Envi -ron. Sc. Poll. Res., 20, 3696-3707

Su, F.-C., Mukherjee, B., Batterman, S., 2013, Determi -nants of personal, indoor and outdoor VOC concen -trations: an analysis of the RIOPA data, Environ. Res., 126, 192-203.

Takigawa, T., Saijo, Y., Morimoto, K., Nakayama, K., Shibata, E., Tanaka, M., Yoshimura, T., Chikara, H., Kishi, R., 2012, A longitudinal study of aldehydes and volatile organic compounds associated with subjective symptoms related to sick building syndrome in new dwellings in Japan, Sci. Total Environ., 417-418, 61 -67.

Tuomainen, M., Tuomainen, A., Liesvuori, J., Pasanen, A. -P., 2003, The 3-year follow-up study in a block of flats-experiences in the use of the Finnish indoor climate classification, Indoor Air, 13, 136-147.

Uchiyama, S., Tomizawa, T., Tokoro, A., Aoki, M., Hishiki, M., Yamada, T., Tanaka, R., Sakamoto, H., Yoshida, T., Bekki, B., Inaba, Y., Nakagome, H., Kunugita, N., 2015, Gaseous chemical compounds in indoor and outdoor air of 602 houses throughout Japan in winter and summer, Environ. Res., 137, 364-372.

Wang, J., Smedje, J., Nordquist, T., Norbäck, D., 2015, Personal and demographic factors and change of

subjective indoor air quality reported by school children in relation to exposure at Swedish schools: A 2-year longitudinal study, Sci. Total Environ., 508, 288-296.

Wangchuk, T., Mazaheri, M., Clifford, S., Dudzinska, M. R., He, C., Buonanno, G., Morawska, L., 2015, Child -ren's personal exposure to air pollution in rural villages in Bhutan, Environ. Res., 140, 691-698.

Xiong, J., Wang, L., Bai, Y., Zhang, Y., 2013, Measuring the characteristic parameters of VOC emission from paints, Build. Environ., 66, 65-71.

Yan, W., Zhang, Y,m Wang, X., 2009, Simulation of VOC emissions from building materials by using the state-space method, Build. Environ., 44, 471-478.

Ye, W., Little, J. C., Won, D., Zhang, X., 2014, Screening-level estimates of indoor exposure to volatile organic compounds emitted from building materials, Build. Environ., 75, 58-66.