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A Practical Comparison of Capture Efficiencies of Cooker/Range Hood under Real Conditions and by Applying the ASTM Standard—An Experimental Assessment

Hyusan Jang
Hyunsoo Kim
Donghyun Rim
Seongjun Park
Seungkil Son
Myoung Souk Yeo
Shinhye Lee
Dong Hwa Kang

ABSTRACT

The purpose of this study is to compare capture efficiencies of cooker/range hood (CEs) under various conditions to verify that there can exist a difference between a CE by applying a pressure difference across the building envelope made in a real environment of residence, and the CE of the American Society for Testing and Materials (ASTM) standard. This experiment was conducted in the field and in a laboratory. We developed grounds of conditions of pressure difference via field measurements and then estimated the CEs by applying the conditions in a laboratory experiment. Through the experiment, we verified that the CE based on the actual environments was outside the range of the CE of the ASTM standard to some extent under the condition of specific pressure differences.

INTRODUCTION

The use of cooker/range hoods is one effective method in which contaminants generated by cooking are exhausted before they can mix into the room air (Singer et al., 2012). Furthermore, it can be said that the use of cooker/ range hoods during cooking is essential because the various pollutants generated by cooking adversely affect our health (Sun et al., 2018). The capture efficiency (CE) serves as an indicator of cooker/ range hood performance, and the American Society for Testing and Materials (ASTM) suggested that CEs are subjected to be obtained under a specific condition to compare and rate them (ASTM 2018). However, the conditions of operating cooker/range hoods in a real house environment are different from those described in the ASTM standard (Kalamees et al., 2010; Leivo et al., 2015). Kalamees et al. (2010) found that the air pressure difference across the building envelope measured in apartments ranged from 7 Pa to 11 Pa on average each day, and in the case of unbalanced ventilation, the room depressurized up to even 30 Pa. Therefore, the CE applying the ASTM standard can be different than in a real environment, and in such a case,

Hyusan Jang is a master's course student in the Interdisciplinary Program in Urban Design, Graduate School of College of Engineering, Seoul National University. **Shinhye Lee** is a master's course student in the Department of Architectural Engineering, Seoul National University. **Seongjun Park** is a doctor's course student in the Department of Architectural Engineering, The Pennsylvania State University, Pennsylvania. **Hyunsoo Kim** is a research and development engineer at Kyungdong Navien Co., Ltd. **Seungkil Son** is a director of research and development center at Kyungdong Navien Co., Ltd. **Dong Hwa Kang** is a PhD professor in the School of Architecture and Architectural Engineering, University of Seoul. **Donghyun Rim** is a PhD professor in the Department of Architectural Engineering, The Pennsylvania State University, Pennsylvania. **Myoung Souk Yeo** is a PhD professor in the Department of Architecture and Architectural Engineering, Seoul National University.

it can be said that the CE described in the ASTM standard is more helpful for comparing the performance of cooker/range hoods themselves under standardized conditions rather than for rating CEs in a real environment.

The purpose of this paper is to estimate CEs and compare them under several conditions to identify the difference between CEs. To identify the typical cooking environment in South Korea, a questionnaire and field measurements were conducted regarding the conditions of the pressure difference. Through these investigations, we recognized that the conditions in an actual environment and those described by the ASTM standard are different. Thus, experiments were performed by paying attention to the system resistance (the pressure differences across the envelop). In this study, we confirmed the correlation between CEs and the air flow rate and the direction, which indicates that the system resistance and the makeup-air direction could have an effect on the CEs.

MATERIALS AND METHODS

Questionnaire

To understand the Korean cooking environment, 127 practitioners of cooking in their 20s–60s were surveyed regarding the conditions of cooking activities. The questions are as follows: 1) How many times do you use all the burners at the same time in a week when cooking? 2) Do you use a cooker/range hood while cooking? 3) Are both the windows and doors (not the front door) open or closed, or is each of them open or closed while the hoods are operating? Question 3 was asked only to those who answered that they used hoods for cooking in question 2.

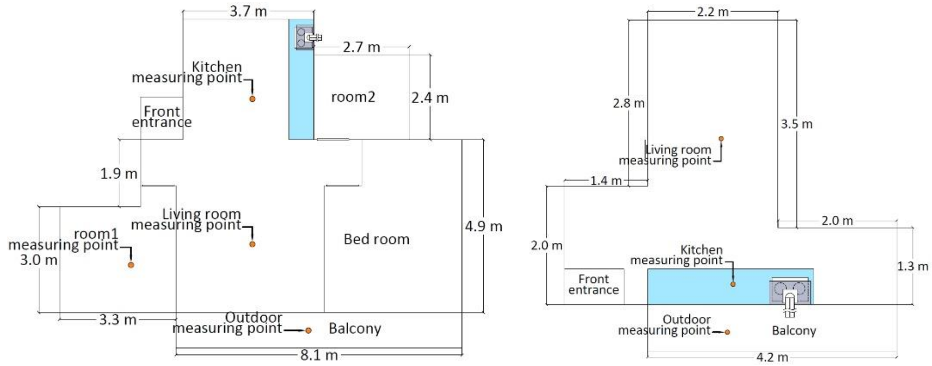
Pressure measurements

With reference to the aforementioned questionnaire, pressure measurements were performed to grasp the pressure differences between the indoor and outdoor environment based on Korean cooking patterns. These measurements were conducted in two typical residences in Korea: an apartment and a studio built in 2018 and 2017 respectively, with both the windows and doors closed and the hoods running. Their airtightness was not measured because there was not a comparative experiment of the apartment and the studio, and our purpose was to confirm the Korean environment of cooking in these residences. Also, it was difficult to measure their airtightness because of real dwelling environment. Figure 1 displays the floor plans of these two sites: The floor area is 66.4m^2 in the apartment and 15.9 m^2 in the studio. Wall- mounted cooker/range hoods were used in both measurements. The apartment was located on the 15th floor above the ground, and the studio apartment was located on the 2nd floor above the ground. The pressure differences were calculated by measuring the absolute pressure. The results of the pressure differences are shown in Table 2.

A laboratory experiment for estimating CE

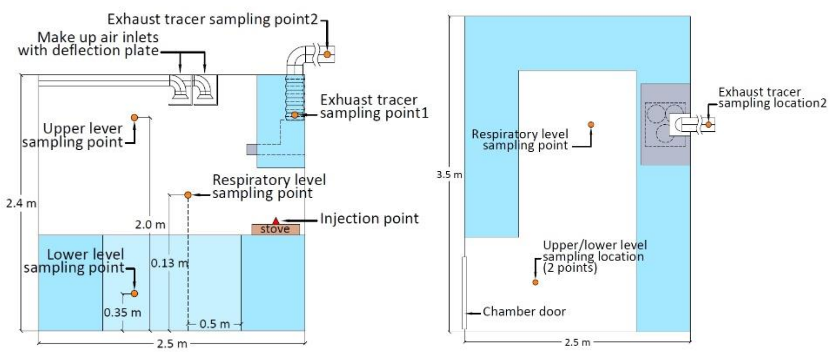
Study laboratory. A schematic of the laboratory layout is displayed in Figure 2. Almost all the experimental conditions performed in the laboratory, save for pressure difference conditions, followed the standards written in the ASTM to equally compare CEs, as described in Table 1. Also, during the experiments, the pressure differences across the envelop was created by adjusting the fan speed of cooker/range hoods.

Instruments. For field measurements, the absolute pressures were recorded using a PTB220 Series Digital Barometers (VAISALA). For laboratory experiments, the temperature and RH were recorded continuously during the sampling period at 1 min intervals using MCH-383SD (Lutron Electronic). A multifunction transmitter (C310, KIMO) was used as the differential pressure measuring instrument. The partial air flow rate of the hood was measured using a Testo 420. Contaminants were generated using tracer gas techniques for convenience, with sulfur hexafluoride (SF_6) as the tracer gas, a photoacoustic infrared gas monitor (Innova 1412i, Lumasense Technologies), and a multipoint sampler and doser (Innova 1303, Lumasense Technologies). In Korea, the use of SF_6 for a laboratory experiment is currently allowed. Finally, SF_6 was injected at ambient pressure at multiple locations at a constant 440 mg/s.



(a) The floor plan of the apartment (b) The floor plan of the studio

Figure 1 The floor plans for pressure measurements



(a) The section of the test chamber (b) The floor plan of the test chamber

Figure 2 The laboratory layout

Table 1. The Verifying of the ASTM Standard in the Test Chamber

Classification	ASTM Standard	The Test Chamber
The chamber size	2.5 m x 3.5 m x 2.4 m	2.5 m x 3.5 m x 2.4 m
The temperature	15℃ to 30℃	16.0℃ to 23.3℃
The specification and size of the hood	Less than 340 CMH and 0.91 m width	170 CMH and 0.90 m width
The burner size	Diameter for each plate: 250 mm, thickness for each plate: 13 mm, the gap: 13mm, and the top of the plates has 30 holes	Diameter for each plate: 250 mm, thickness for each plate: 13 mm, the gap: 13mm, and the top of the plates has 30 holes
The temperature of the burner	160±10℃	175±25℃
The inlet size and velocity	Depressurizing the chamber by less than 5 Pa using airflow rate and the velocity is less than 0.5 m/s	The average velocity is 0.47 m/s
Tracer gas generation rate	A constant rate	440 mg/s constantly

Table 2. The Conditions of the Pressure Difference During the Experiment [ΔP]

Classification	Case 1	Case 2	Case 3	Case 4
The pressure difference across the chamber	4	15	33	Natural ventilation

Measurements. As presented in Table 2, 4 Pa was selected as the condition of the ASTM standard, and three conditions (Case 2-4) were also selected as representative conditions based on Korean cooking patterns from the results of the pressure measurement. The experiment was conducted under the specific conditions described in Table 2. Each case of the experiment was repeated four times, and as presented in Figure 2, the tracer gas concentrations were measured at five locations. Here, the height difference of the sampling point such as the upper level and lower level, was to observe the well-mixed state of the test chamber. Upon completing one case, we ventilated through the chamber door for at least 10 minutes before proceeding to the subsequent case. We confirmed that the concentration of each point was reset to the initial state, and then proceeded with the next experimental case. During the experiment, highlight was used as a cooking stove with three burners.

Analysis

Time of steady state. As one criterion for the determination of steady state, the ASTM recommends the time required to reach steady state (T_{ss}) by applying Equation 1 (ASTM 2018). In addition, we regarded T_{ss} as steady state when a condition was satisfied by observing that the CE estimated in each case was less than 10% compared with the previous CE data for longer than 10 minutes. Moreover, it satisfied the conditions for which a minimum of 10 tracer gas measurements at each location for at least 10 minutes was needed (Kim et al., 2018; ASTM 2018).

$$T_{ss} = 4000 * \frac{V}{Q_{hood}} \tag{1}$$

Capture Efficiency. Equation 2 was used to calculate the CE provided by the ASTM. However, in the experiments, since SF_6 was used as a tracer gas, the SF_6 concentration in the internal chamber would be almost zero (C_{inlet}). Here, C_{exh} was applied to the concentration sampled from exhaust2, and C_{cha} was the concentration that was sampled at the respiratory level.

$$CE = \frac{C_{exh} - C_{cha}}{C_{exh} - C_{inlet}} \tag{2}$$

We defined temporal errors and precision errors based on ASTM standards to identify uncertainties in estimating the CEs. The temporal error is the standard error in the mean recorded values: δ_{exh}, δ_{cha}. For the test chamber, the precision error shall be 1.25%, and for the exhaust concentration, it shall be zero (ASTM, 2018). Therefore, the uncertainty in the CEs was calculated using Equation 4.

$$\delta(C_{exh}) = \sqrt[2]{(\delta_p(C_{exh}))^2 + (\delta_{se}(C_{exh}))^2} \tag{3}$$

$$\delta CE = CE[\sqrt[2]{\frac{(\delta(C_{exh}))^2 + (\delta(C_{cha}))^2}{(C_{exh} - C_{cha})^2} + \frac{(\delta(C_{exh}))^2 + (\delta(C_{amb}))^2}{(C_{exh} - C_{amb})^2}}] \tag{4}$$

RESULT AND DISCUSSION

Questionnaire

Figure 4 presents the results of the questionnaire. For question 3, we allowed the respondents to select multiple answers. First, in the lower graph of Figure 4 (a), the frequency of using all the burners more than four times was the highest. This indicates that the condition of the number of burners according to the ASTM standard when estimating CE does well to imitate a real residence environment. In the upper graph of Figure 4 (a), it can be seen that a number of households operate cooker/range hoods while cooking. In particular, according to Figure 4 (b), most of the respondents open the windows and operate cooker/range hoods while cooking at the same time. This indicates that they adopt mechanical and natural ventilation simultaneously.

Pressure measurements

Table 3 displays the results of the absolute pressures and the pressure differences measured with the windows and doors closed and the hoods operating within the two typical residences in Korea: an apartment and a studio. For ΔP in the rightmost column, it can be seen that the range of the pressure differences at the apartment and studio is mostly 20 Pa or higher. This was found to be outside the pressure difference conditions given in the ASTM standard in a real environment and served as the basis for determining the conditions of pressure difference in the laboratory experiment.

A laboratory experiment for estimating CE

Based on Figure 5, cases 1–3 revealed a similar tendency, whereas case 4 represented a significantly low concentration at respiratory level. First, for cases 1–3, it can be seen that the higher the pressure difference, the higher the concentration at the exhaust and respiratory level. For case 4 with natural ventilation, the main differences with respect to cases 1–3 occurred in the concentration at the exhaust and respiratory level. Both decreased, and in particular, the concentrations at respiratory level dropped by more than 85%. The respiratory concentrations can be expected to not be sampled due to the effect of escaping through the chamber door. Instead, the concentration at the upper level was similar to that of case 1, and it can be estimated that the SF_6 that did not enter the hood and was not sampled at the respiratory level affected the upper level.

Table 4 and Figure 6 present the average CEs by using each sampled concentration. Based on Table 4 and Figure 6, since we verified that the experiment was unable to build a well-mixed condition, applying only Equation 2 is likely not to be suitable. Therefore, although CE is essentially subjected to be estimated with the concentration at the respiratory level, we attempted to apply not only the term of C_{cha}, but also the term of C_{up} and C_{avg} to Equation 2, where C_{cha} is the concentration at the respiratory level, C_{up} is the concentration at the upper level, and C_{avg} is the average concentration of C_{cha}, C_{up}, and C_{lower}. The CEs in Table 4 are applied to the upper level, the respiratory level, and the average concentration

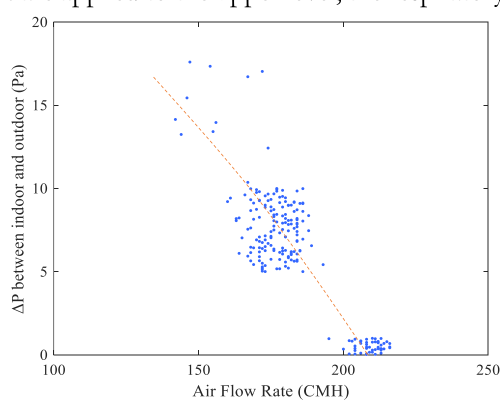
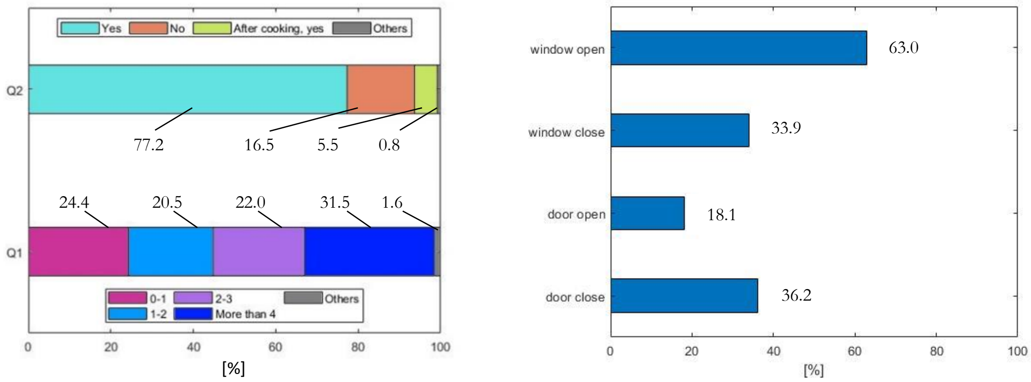


Figure 3 Fan curve of the cooker/range hood

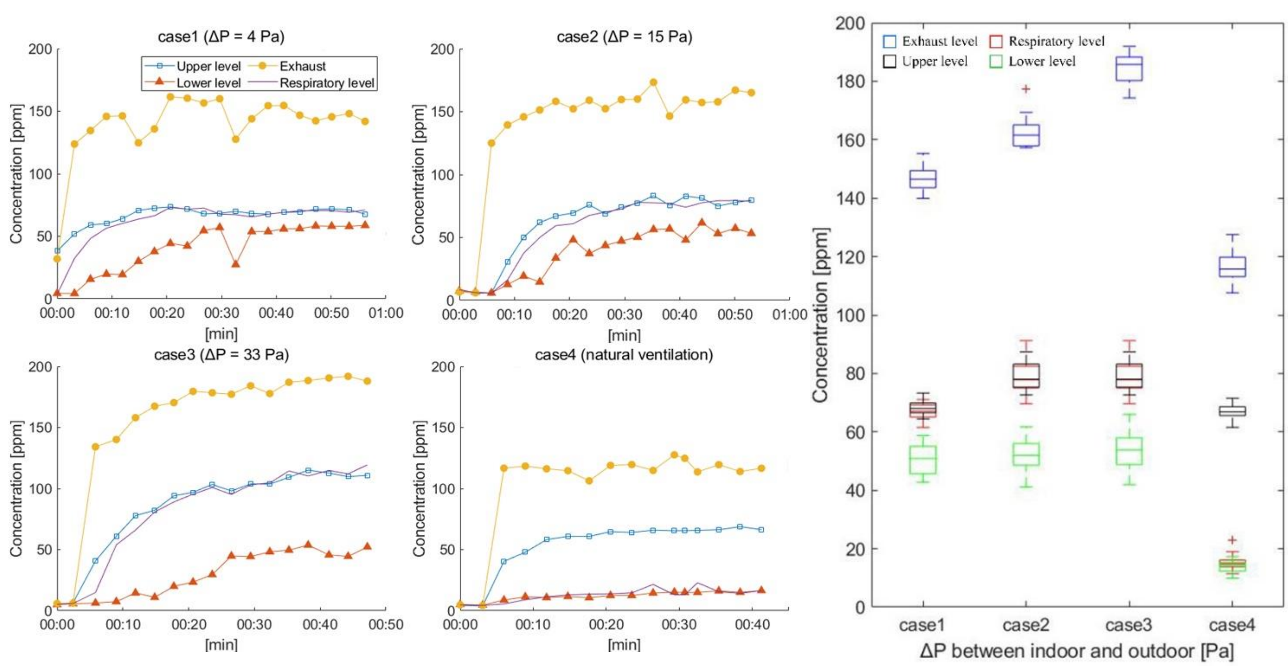
Table 3. The Result of the Field Measurements [Pa]

Classification	Fan speed	Kitchen	Living room	Room	Outdoor	ΔP
Apartment	1	101906	101910	101908	101929	23
	2	101892	101892	101895	101929	37
	3	101879	101883	101885	101929	50
Studio apartment	1	100930	100936	-	100941	9
	2	100914	100920	-	100941	27
	3	100905	100912	-	100941	36



(a) The result of the question 1, 2 (b) The result of the question3

Figure 4 The result of the questionnaire

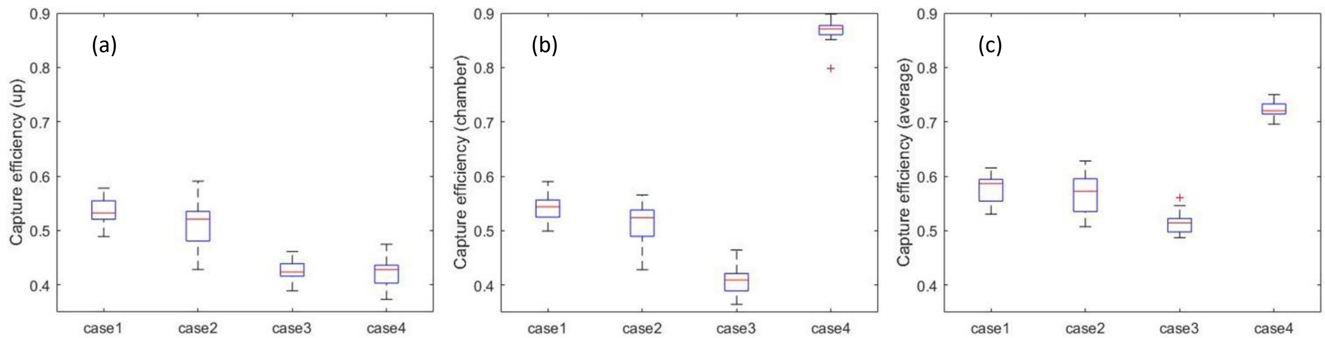


(a) The typical raw data of the laboratory experiments (b) The distribution at steady state in each case

Figure 5 The tendency of the concentrations and the distribution in each case

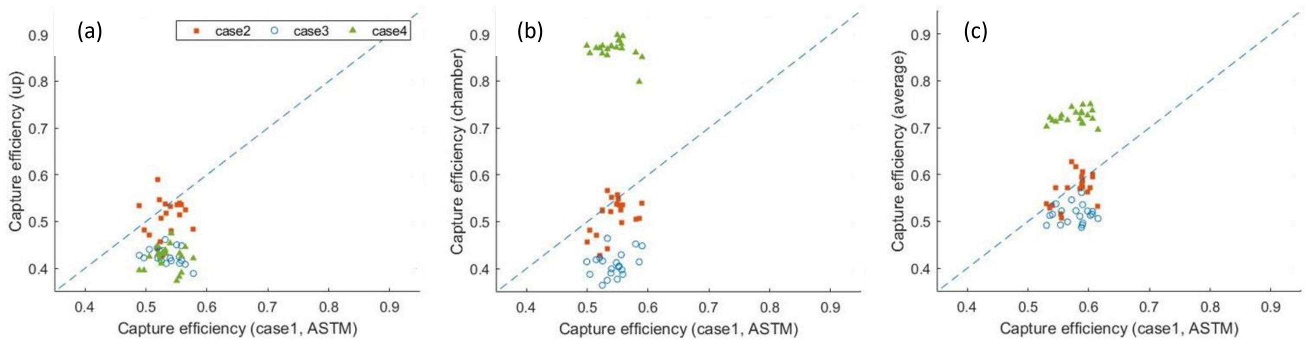
Table 4. Average CEs for each case [%]

Classification	case1 (ΔP = 4 Pa)			case2 (ΔP = 15 Pa)			case3 (ΔP = 33 Pa)			case4 (natural vent.)		
	up.	cha.	avg.	up.	cha.	avg.	up.	cha.	avg.	up.	cha.	avg.
1st experiment	51.4 (1.25)	51.4 (1.15)	54.3 (1.13)	46.6 (1.06)	45.6 (1.27)	52.5 (1.07)	43.0 (1.30)	40.4 (1.45)	50.7 (1.31)	42.1 (1.12)	86.6 (1.01)	71.7 (0.96)
2nd experiment	54.2 (1.30)	56.1 (1.37)	58.6 (1.17)	54.4 (2.09)	53.4 (2.02)	59.3 (2.02)	43.8 (1.88)	44.1 (2.05)	52.5 (2.16)	41.5 (2.47)	86.6 (2.93)	72.6 (2.61)
3rd experiment	54.1 (2.05)	54.6 (2.07)	59.3 (2.03)	53.1 (1.41)	54.3 (1.47)	59.8 (1.49)	42.8 (1.23)	39.5 (1.35)	51.3 (1.26)	42.2 (1.29)	88.4 (1.43)	73.1 (1.10)
4th experiment	54.1 (2.10)	55.0 (1.99)	58.5 (2.06)	50.8 (1.74)	51.7 (1.64)	56.2 (1.62)	41.0 (1.06)	39.6 (1.22)	51.6 (0.94)	43.4 (2.10)	86.0 (2.75)	72.0 (2.24)



(a) The CE distribution applying upper term (b) The CE distribution applying respiratory term (c) The CE distribution applying average term

Figure 6 The CE distribution applying each term



(a) The correlation of CE between upper term and ASTM (b) The correlation of CE between respiratory term and ASTM (c) The correlation of CE between average term and ASTM

Figure 7 The correlation of CE between each term and ASTM

from the left, and we represented the standard errors below in brackets, as well. Figure 6 (b) illustrates that when natural ventilation(case4) occurred, the CE was high, due to the concentration at the respiratory level being significantly low rather than due to the efficiency of cooker/range hood itself. As mentioned above, in effect, the comparison with CEs could be difficult for the case with natural ventilation(case4) since dilution of pollutants affected on CE. Figure 3 presents that when the pressure difference increases, air flow rate of cooker/range hood decreases. This is why for cases 1–3, we confirmed that the CEs decreased as the air flow rate through the cooker/range hood decreased (Singer et al., 2012; Delp et al., 2012; Lunden et al., 2015; Dobbin et al., 2018; Sun et al., 2018). Figure 7 displays graphs that compare the CE estimated under conditions that can occur in a real environment (cases 2–4) and the CE estimated under the conditions provided by the ASTM standard(case1). It can be said that this suggests the importance of makeup-air and airflow direction. In order to increase CE, the resistance of the system must be low, and even if there is no system resistance as in case 4, if makeup-air is not formed in the cooker/range hood direction, contaminants cannot be properly captured and can spread to other rooms. Figure 7 reveals that although most CEs do not align with the CEs based on the ASTM in the cases of higher pressure differences and natural ventilation, the CEs might be similar to the ASTM in the case of lower pressure differences, suggesting that ΔP defined in the ASTM coincides to some extent with the range of 4 Pa to 15 Pa in this experiment.

CONCLUSION

The purpose of this study was to compare and estimate the CEs under various system resistance conditions to confirm that a difference exists between the CEs under various conditions. Since the test chamber was unable to create a well-mixed state, the CEs were estimated by applying not only C_{cha}, but also C_{up} and C_{avg}. In cases 1–3, the CEs decreased as the air flow rate through the cooker/range hood decreased. Finally, we confirmed the importance of makeup-air and airflow direction. In order to increase CE, the resistance of the system must be low, and makeup-air must be formed in the cooker/range hood direction, otherwise contaminants cannot be properly captured and can spread to other rooms. Also, it can be said that although most CEs do not align with the CEs estimated based on the ASTM in the cases of higher pressure differences and the natural ventilation, the CEs might be similar to the ASTM in the case of lower pressure differences, suggesting that ΔP defined in the ASTM coincides to some extent with the range of 4 Pa to 15 Pa in this experiment.

In this study, we paid attention to the makeup-air and the air flow direction that affect the CE. The further study will investigate factors such as room size, presence of occupants in the kitchen, and conditions of the pressure differences between the inside and outside, in hopes that this study will expand the boundary of the ASTM standard.

ACKNOWLEDGMENTS

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NOMENCLATURE

T = time [s]

V = volume [m^3]

Q = air flow rate of the cooker/range hood [L/s]

C = concentration [ppm]

δ = error

Subscripts

ss = steady state

exh = exhaust

cha = chamber

amb = ambient

avg = average

p = precision error

se = standard error

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