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Occupant behavior regarding the manual control of windows in residential buildings

Bongchan Jeong [a], Jae-Weon Jeong [b], J.S. Park [b,*]

[a] Department of Architectural Engineering, Graduate School of Hanyang University, South Korea
[b] Department of Architectural Engineering, College of Engineering, Hanyang University, 222 Wangsimni-ro Seongdong-gu, 133-791, Seoul, 133-791, South Korea

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ABSTRACT

The objective of this study was to identify the relation between occupants' daily activities and window control and also to quantify the influence of environmental variables on occupants' window opening and closing behavior. A field measurement was carried out during non-heating period, from February to May 2015, and heating period December 2014 to February 2015 in twenty occupied housing units. Window state, indoor and outdoor environmental conditions were continuously monitored during the measured periods. From the results of the field measurements, it was found that the control of window is strongly related to occupants' daily activities. Cooking, cleaning and getting fresh air accounted for 27%, 40%, and 33% of total openings, respectively. Window openings in relation to the activities occurred at the specific time during the day. The daily average opening frequency and opened hours were varied from 0.5 to 1.8 numbers/day and from 0.4 to 0.6 h/day respectively depending on outdoor temperature. The proportion of opened windows steeply changed when outdoor temperature exceeded 12.7 °C. Window closing was associated with the degree of drop in indoor temperature after windows were opened. The results of this study can help developing a complete model inferring occupants' window opening behavior in residential buildings.

1. Introduction

Residential buildings account for a large portion of energy consumption and have significant energy saving potential. Due to this energy saving potential, governments have enhanced regulations related with the energy performance of the residential buildings. The residential buildings have become more tightly sealed and insulated to minimize heat loss. And mechanical ventilation systems with heat recovery units have been installed, because infiltration or natural ventilation is often insufficient to meet the minimum requirement for ventilation.

The mechanical ventilation systems are commonly equipped with filters to remove particles from outdoor air and re-circulate air. Park et al. [1] showed that mechanical ventilation systems with filters can reduce indoor levels of airborne particles by 26% for submicron particles and 65% for fine particles when compared with naturally ventilated residential buildings. In terms of energy saving, several studies show that mechanical ventilation with heat recovery can reduce energy consumption to provide a minimally acceptable amount of outdoor air [2–4]. However, it was found from Park and Kim's study [5] that 68.3% (95 of 139) of occupants did not use mechanical fans for ventilation at all, and the occupants frequently used windows for ventilation more than the mechanical fan. The results indicate that natural ventilation by opening windows is still the predominant way occupants control the indoor environment in residential buildings.

Opening windows is the most common and preferable natural ventilation method [6]. The two main parameters that are influenced by opening windows are air change rate and indoor temperature. Iwashita found that 87% of the total air change rate was attributed to window and door opening [7]. Also Wallace et al. found that window and door opening produced the greatest increase in air change rates [8]. Opening windows is not only useful for ventilation, but also provide a benefit for thermal comfort. Brager et al. shows that there is a 1.5 °C difference in the neutral temperature felt between occupants with high and low degree of window control [9]. Paciuk found that there is a significant relation between the possibility of personal control and satisfaction [10]. These findings suggest that the understanding of the occupants' interactions with windows is important to ensure a good performance of naturally as well as mechanically ventilated residential buildings. And the energy simulation based on the actual behavior

* Corresponding author.
E-mail address: junpark@hanyang.ac.kr (J.S. Park).

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Table 1
Characteristics of the sample housing units.

Sample ID	Complex	Floor area [m^2]	Floor level[a]	Location		Number of occupants[b]	Period of residence [year]	Smokers	Participated period[c]
				Of the building	Within the building				
a	A	109	4/20	Border	Inner	3 (M, F, m)	6.5	0	H/NH
b		109	8/20	Border	Outer	4 (M, F, f, f)	6.8	0	H/NH
C		171	8/20	Border	Outer	4 (M, F, f, f)	6.6	1	H/NH
d		109	16/24	Border	Inner	4 (M, F, f, f)	7.0	0	H/NH
e		109	5/24	Border	Inner	3 (M, F, f)	6.6	0	NH
f		129	14/26	Border	Outer	4 (M, F, m, f)	7.0	0	H
g	B	163	12/14	Border	Outer	4 (M, F, m, f)	2.3	0	H/NH
h		163	4/15	Border	Outer	4 (M, F, m, f)	2.0	0	H/NH
i		163	6/14	Border	Inner	4 (M, F, m, f)	2.3	1	NH
j		163	10/15	Border	Outer	4 (M, M, F, F)	2.0	0	NH
k		163	5/14	Border	Inner	4 (M, F, m, f)	2.4	1	NH
l		136	2/19	Border	Inner	4 (M, F, m, m)	2.8	0	H
m		145	4/19	Border	Outer	4 (M, F, f, m)	3.0	0	H
n		145	13/19	Border	Inner	4 (M, F, f, f)	1.2	0	H
o	C	72	14/21	Border	Inner	4 (M, F, f, f)	6.7	0	H/NH
p		80	7/23	Border	Outer	4 (M, F, m, f)	9.5	1	H/NH
q		108	9/25	Center	Outer	4 (M, F, f, f)	4.5	0	H/NH
r		80	6/20	Border	Outer	4 (M, F, m, m)	1.4	0	H/NH
s		163	15/25	Center	Outer	4 (M, F, m, f)	2.0	0	NH
t		79	19/25	Center	Outer	4 (M, F, m, m)	16	0	H

[a] Floor number/Total Number of floors.
[b] M, male adult; F, female adult; m, male below 18 years; f, female below 18 years.
[c] H/NH, both heating and non-heating period; NH, non-heating period only; H, heating period only.

Table 2
Measurement parameters and the specifications of devices used for measurement.

Parameter		Device	Accuracy	Interval [minutes]
Outdoor	Dry-bulb temperature	Data Logger[a] (TR-72ui	±0.3 °C	10
	Relative humidity	and RS-11, T&D)	±5% RH	
Indoor	Dry-bulb temperature	Humidity, Temperature	±0.8 °C	10
	Relative humidity	and CO_2 monitor	±4% RH	
	CO_2 concentration	(MCH-383SD, Lutron)	±40 ppm	
	Particle number concentration	Optical Particle Count (Aerotrack 9306, TSI)	±5% flow	60
	Particle mass concentration	Aerosol monitor (Dusttrak 8532, TSI)	±5% flow	60
Window opening	Window opening status	State Logger[b] (UX90-001, Onset Computer)	–	Event

[a] The sensors were radiation-shielded.
[b] Binary window status was measured, opened or closed.

of occupants can provide reliable operational energy use which will lead to more successful design of sustainable buildings.

Early studies used environmental parameters as input variables to predict the windows opened. As early as 1951, Dick and Thomas [11] found that outdoor temperature was the most important variable affecting the number of windows opened. Raja et al. found a change in opened windows started occurring at an outdoor temperature of 15 °C [12]. Few windows were opened when the outdoor temperature was below 15 °C, but increased steeply with an outdoor temperature above 15 °C. The results of Nicol are consistent with these findings [13]. The results of surveys for naturally ventilated office buildings through different countries showed that opened windows tends to increase significantly as the outdoor temperature rises above 10 °C. Recently, stochastic models for control of windows in office buildings have been proposed to reveal affecting factors on window opening and closing behavior [14–18]. Window opening and closing behavior indicate change of window state from closed to opened and from opened to closed respectively. The main argument is that indoor and outdoor temperatures are likely to be the key stimuli for opening windows, and building characteristics may also affect the probability of windows being opened.

In residential buildings, only a few studies have been made. Levie et al. showed through the questionnaire survey that household characteristics, such as disposable income, house size, age and gender of the occupants, and insulation level, are significantly associated with window opening behavior in residential buildings [19]. Shi et al. showed that outdoor temperature is the most important explanatory variable affecting the proportion of windows opened in 8 residential apartments in China [20]. Andersen et al. studied the probability of opening and closing windows in 15 Danish residential buildings and concluded that indoor CO_2 concentration and outdoor temperature are the two single most important variables in determining the probability of opening and closing windows respectively [21]. The result of Schweriker et al. showed that both indoor and outdoor temperature are significant variables affecting both opening and closing window probability [22]. Another important finding was that specific calibration was required for buildings equipped with an air-conditioning unit. These studies have considered environmental factors only to analyze occupants' interaction with windows control. The window opening behavior in residential buildings, however, can be strongly related to daily activities of occupants, such as sleeping, cooking, and cleaning. The occupants' activities vary during a day, and they can play an important role in determining window opening and closing behavior. Thus window opening frequency, opening hours, and time of day are clearly influenced not only by indoor and outdoor temperatures but also the daily patterns of the occupants' activities.

Based on the previous literature reviews with regard to window control, a field study was carried out in order to expand the understanding of occupant interaction with window control in residential buildings. The main objective of this study is to identify the relation between daily activities and window control, and also to quantify the influence of environmental variables on occupants'