UNCERTAINTY AND SENSITIVITY ANALYSIS OF NATURAL VENTILATION IN HIGH-RISE APARTMENT BUILDINGS

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ABSTRACT

Quantification of natural ventilation rates is an important issue in HVAC system design. Natural ventilation in buildings depends on many parameters whose uncertainty varies significantly, and hence the results from a standard deterministic simulation approach could be unreliable. This study performed uncertainty analysis to predict natural airflow rates. The paper presents relevant uncertainty in model parameters such as meteorological data, building properties (leakage areas of windows, doors, etc.), etc. Uncertainties of the aforementioned parameters were quantified based on data available from literature and on-site visits. The Monte-Carlo method with Latin Hypercube Sampling (LHS) was used for uncertainty propagation. The CONTAMW was chosen to simulate natural ventilation phenomena in a high-rise apartment building that is typical of residential buildings in Korea. It is shown that the uncertainty propagated through this process is not negligible and may significantly influence the prediction of the airflow rates. In the paper, the result of a sensitivity analysis is also addressed.

KEYWORDS

Uncertainty, sensitivity, natural ventilation

INTRODUCTION

The demands and expectations of occupants in regards to a ventilation system include good indoor air quality, low investment and maintenance costs, low energy use, and a minimum level of noise and draft. A new ventilation code (KMOCT 2006) was enacted in Korea in 2006 to ensure a healthy environment for occupants. The code specifies a minimum 0.7 Air Changes per Hour (ACH, h-1) in multi-family apartment buildings. For the authorities to approve a new building design, the design team should prove by experiment or simulation that the new apartment buildings are capable of providing at least 0.7 ACH either by natural or mechanical ventilation or a combination of the two. Thus, it is important to estimate the natural ventilation rate on which the design of the ventilation system is based.

But, due to the following challenges, estimating natural ventilation rate is difficult.

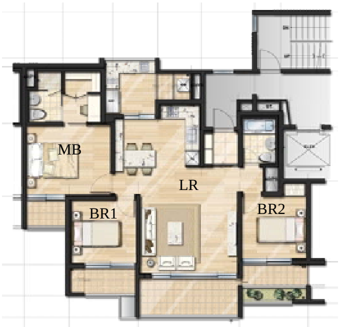
- *Stochastic nature of weather*: Natural airflows have two driving forces: buoyancy and wind. Since wind speed and direction change quickly and the temperature difference between indoor and outdoor also fluctuates diurnally as well as annually, it is difficult to quantify such influences on natural ventilation.
- *Occupant's behavior*: An occupant's schedule in opening/closing windows and doors has a significant role in controlling the natural airflow rate. Unfortunately, widely varying occupant influences have not been measured or investigated directly. Simply assuming that natural ventilation occurs only through infiltration (when all the doors and windows are closed) is not realistic and measures only the minimum airflow rate.
- *Building components*: Each dwelling has different types of doors, windows, exhaust fans, etc. In addition, each dwelling has a different local environment, such as the surroundings, the distance from the ground, etc.
- *Uncertainties in simulation parameters*: Simulation parameters such as discharge coefficient, flow coefficient, etc., used to simulate airflow phenomena inside and around the building cannot be predicted accurately.

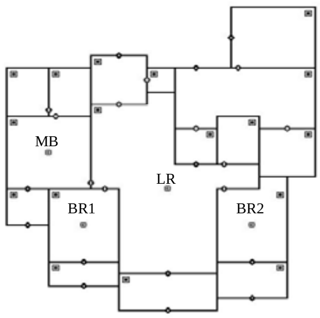
The aforementioned issues lead to difficulty in evaluating the natural ventilation rate. Hence, the paper presents a probabilistic approach to estimate natural ventilation rate in multi-family apartment buildings using uncertainties in relevant parameters. Uncertainty propagation is introduced to treat the parameters which are not 'deterministic' but 'probabilistic'. In the paper, significant parameters in the influence on natural ventilation are identified, and the probabilistic range of parameters is then estimated based on the literature and on-site visits. Finally, through the Latin Hypercube Sampling

(LHS) method, natural ventilation rates are predicted. The paper addresses the fact that uncertainty in modeling natural ventilation phenomena is significant and without introducing the stochastic nature of the ventilation phenomena the deterministic prediction of the natural airflow rate in residential buildings may lead to false conclusions.

VENTILATION SIMULATION

A 15-story residential building in Seoul, Korea was selected for simulation of natural ventilation phenomena. The building is typical of residential buildings in terms of size and floor plan. Fig. 1 shows the floor plan with a master bedroom (MR), two bedrooms (BR1, BR2), a living room (LR) and a kitchen. To simulate airflow entering the building, CONTAMW 2.4 developed by the National Institute of Standards and Technology (Walton and Dols 2005) was selected. The reason for CONTAMW is as follows: if a computationally intensive approach (e.g., Computational Fluid Dynamics, CFD) is selected for a large number of simulation runs required for uncertainty analysis, this will become a hindrance. CONTAMW 2.4 is not the most detailed approach compared to the calculation of flow patterns, but accurate enough and suited for assessing ventilation rates in a building. CONTAMW, based on nodal flow network modeling, predicts time histories of the airflows between nodes and concentration of indoor pollutants. In the CONTAMW model, the living room and kitchen were modeled as a single space (Fig.1(b)). Indoor temperature was assumed to be 18℃ in the winter, 21℃ in the spring/autumn and 24℃ in the summer.

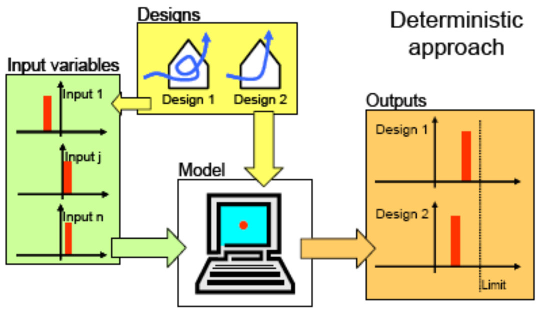




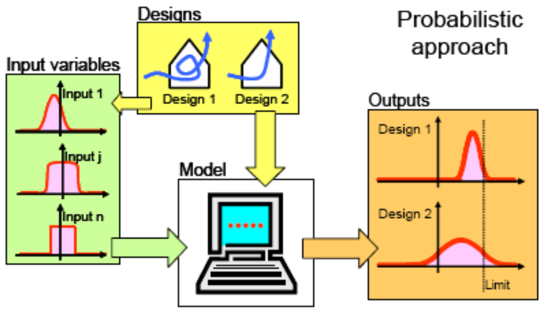
(b) CONTAMW model
Figure 1 Floor plan and CONTAMW model

UNCERTAINTY ANALYSIS

This section discusses the uncertainty analysis briefly mentioned in the previous section. In estimating the airflow rate, various simulation results can be obtained in the deterministic approach (where only one simulation is carried out, Fig. 2), depending on the chosen value of input parameters which are of a stochastic nature. In addition, with a favorable set of assumptions and parameters, the design team may present to the authorities the best value for the code check ('evil' approach) and vice versa ('decent' approach using a conservative set). Moreover, in comparing different design alternatives, the probabilistic approach delivers more meaningful information than the deterministic approach. In the deterministic approach, design 2 is better than design 1 since the output is further from the limit (Fig. 2). But, if the design is evaluated based on a probability not exceeding the limit, design 1 is considered better than design 2. With this in mind, to avoid the aforementioned problem as well as to reflect the 'probabilistic nature of the reality', uncertainty propagation is introduced as follows.



(a) Deterministic approach



(b) Probabilistic approach
Figure 2 Deterministic approach vs. probabilistic approach (Wouters et al, 2004)

Based on the literature (ASHRAE 2001, 2005; Walton and Dols 2005; Moon 2005; Kim 2002; Lee 1997) and on-site interviews with questionnaires, uncertain parameters influencing the natural ventilation are identified as shown in Table 1. Such parameters include building components, simulation parameters, meteorological data and the occupant's behavior. The minimum, maximum and base values of the selected parameters are then identified. Due to a lack of explicit information on the parameter distribution, normal distributions were assumed for all parameters. The occupant's behavior was also obtained from the on-site interview and questionnaires conducted for 32 families. It should be noted that the leakage through cracks in exterior walls and between wall and slab is not considered in this study since the majority of high-rise multi-family apartment buildings in Korea are of cast-in-place concrete construction and it is reported that in such buildings the measured leakage through exterior cracks accounts for 2-3% of total leakage of an apartment unit and is thus negligible (Lee 1997).

The Latin Hypercube Sampling (LHS) method was then utilized for uncertainty propagation. The LHS method, one of the Monte Carlo simulation techniques (Wyss and Jorgensen 1998), has proved suitable for complex, non-linear models and has been demonstrated in building simulation (De Wit and Augenbroe 2002). The LHS is a form of stratified sampling. The domain of each parameter was subdivided into N disjoint intervals with equal probability mass. In each interval, a single sample was randomly drawn from the associated probability distribution. Application of this technique provides good coverage of the parameter space with relatively few samples compared to simple random sampling (De Wit and Augenbroe 2002). Parameter samples were generated using an LHSNORM function in MATLAB 7.0 Statistics Toolbox. A total of 30 simulation cases were generated and propagated through the mixed simulation toolset. The number of generated samples is well above the minimum required value (4 k /3 =17.33 where k is the number of parameters, k=13). In this study, a total of 270 simulations were run (30 cases in each season (winter, summer, spring/fall) for different floors (1F, 8F, 15F).

Table 1 Uncertain parameters and their minimum, maximum and base values

PARAMETERS			MIN	BASE	MAX	REFERENCES
Flow exponent			0.6	0.65	0.7	Walton and Dols 2005
C_d, Discharge coefficient			0.6	0.675	0.75	Kim 2004; Moon 2005
C_p, wind pressure coefficient			0	0.5	1	Moon 2005
Wind velocity profile exponent			0.33	0.33	0.4	Walton and Dols 2005; Moon 2005
Local terrain constant			0.28	0.28	0.40	Walton and Dols 2005; Moon 2005
Wind velocity (m/s)			0	2.5	17.7	Korea Meteorological Administration
Outdoor temperature (℃)	W		-14.0	-2.8	11.1	Korea Meteorological Administration
	Sp		-6.5	13.3	30.8	
	Su		15.5	24.4	35.0	
Front door leakage area (cm^2/EA)			24	41.8	248.6	Lee 1997; KS 2003; ASHRAE 2001
Shaft area ratio			0.5	1	1.5	Kim 2004; ASHRAE 2001
Roof fan leakage area (cm^2/EA)			320	942	1512	ASHRAE 2001
The number of occupants (persons)	MR		0	1.50	2.80	On-site interview and questionnaires
	BR1		0	1.50	4.00	
	BR2		0	1.50	2.80	
	LR		0	1.60	4.90	
Window opening area (m^2) by occupants	MR	W	0	0.10	0.54	
		Sp	0	0.15	0.55	
		Su	0	0.28	0.84	
	BR1	W	0	0.11	0.71	
		Sp	0	0.24	1.00	
		Su	0	0.41	1.39	
	BR2	W	0	0.09	0.64	
		Sp	0	0.21	0.79	
		Su	0	0.36	1.30	
	LR	W	0	0.26	1.51	
		Sp	0	0.53	1.96	
		Su	0	0.80	2.54	
	Kitchen	W	0	0.11	0.40	
		Sp	0	0.20	0.58	
		Su	0	0.25	0.84	
Door opening area (m^2) by occupants	MR	W	0	0.62	1.68	
		Sp	0	0.72	2.08	
		Su	0	1.00	2.20	
	BR1	W	0	0.50	1.43	
		Sp	0	0.63	1.83	
		Su	0	0.85	2.00	
	BR2	W	0	0.41	1.23	
		Sp	0	0.52	1.59	
		Su	0	0.69	1.78	
	Bathroom	W	0	0.36	0.89	
		Sp	0	0.53	1.22	
		Su	0	0.34	1.42	

* Su=Summer, W=Winter, Sp=Spring/Fall

COMPARISON BETWEEN MEASURED AND SIMULATED INFILTRATION RATES

Unfortunately, no literature for the measured natural ventilation rate reflecting the schedule of occupant presence and operation of openings (door, windows) has been reported. Multi-family high-rise apartment buildings in Korea differ from western residential dwellings in construction, building components and living patterns, and thus foreign data cannot be used. All that is available from domestic literature are the measured infiltration rates using a blower door test (Lee et al 2007), tracer gas (Lee et al 2000; Ahn T.K. 2005; Choi et al 2006) and pressure measurements (Park et al 2001). The aforementioned measurements (Ahn T.K. 2005; Choi et al 2006; Lee et al 2007, Lee et al 2000; Park et al 2001) were conducted in apartments similar to the selected floor plan as shown in Fig. 1.

Hence, a tentative comparison has been made to test the approach that was developed. For the purpose of comparison, 30 additional simulations were run to simulate infiltration phenomena. The simulation results (dashed line in red) are shown in Fig.3 with the measured infiltration rates, which vary widely from 0.18 to 0.62. The minimum, average and maximum ACH of the 30 simulation runs are 0.02, 0.22, 0.63 respectively which confirms strong uncertainty. As shown in Fig.3, the uncertainty propagation generated by the LHS method covers the measured infiltration rates reasonably.

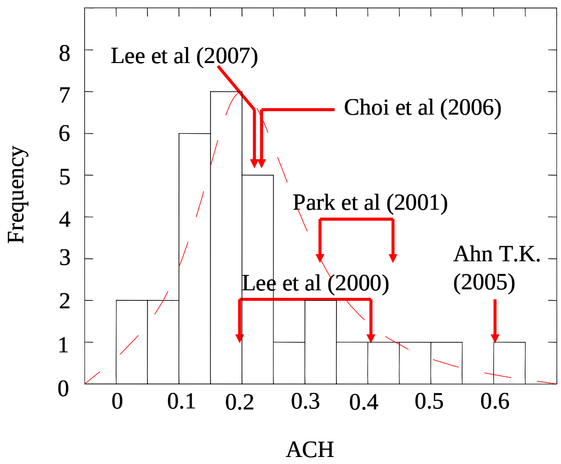


Figure 3 Comparison between the simulated and measured infiltration rates

SIMULATION RESULTS

Table 2 shows the simulated ACH from 270 simulation runs. The calculated ACH is defined as the outdoor airflow rate directly into each floor divided by its volume. Natural ventilation rates increase in the order of winter, spring/autumn, summer, and in proportion to the distance from the ground. Even though high stack and wind effects exist in winter, the ACH in summer is greater than that in winter (Table 2) since occupant behavior has a larger impact. It should be noted that there is a significant gap between the maximum and the minimum ACH, and the calculated standard deviation is greater than the average. This means that estimation of the natural ventilation rates can be biased due to the aforementioned uncertainties in simulation parameters, weather, building components and occupant behavior.

Table 2 Air Changes per Hour in different floors
(a) winter

FL.	MIN	BASE	MAX	AVERAGE OF 30 SAMPLES	STANDARD DEVIATION
1F	0.10	0.50	5.95	1.26	1.31
8F	0.02	0.72	11.72	2.15	2.71
15F	0.19	0.85	14.95	2.65	3.42

(b) spring/autumn

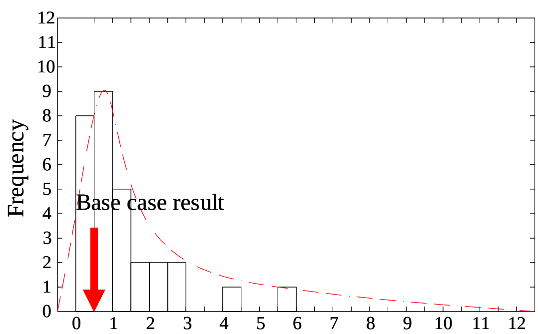
FL.	MIN	BASE	MAX	AVERAGE OF 30 SAMPLES	STANDARD DEVIATION
1F	0.10	0.69	8.63	1.70	1.91
8F	0.02	1.22	17.52	3.30	4.02
15F	0.13	1.48	22.43	4.15	5.11

(c) summer

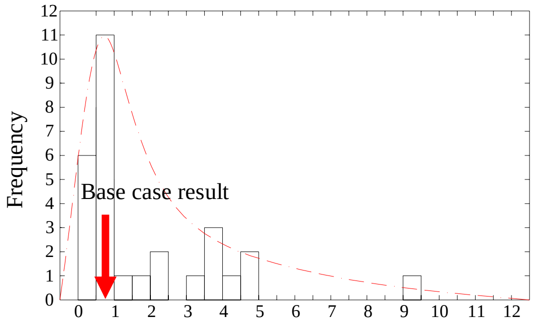
FL.	MIN	BASE	MAX	AVERAGE OF 30 SAMPLES	STANDARD DEVIATION
1F	0.05	0.73	11.70	2.16	2.61
8F	0.01	1.48	23.72	4.36	5.47
15F	0.04	1.83	30.37	5.48	6.91

Fig.4 shows the simulated ACH and distribution (dotted line) of the airflow rates for each floor in winter. The distribution curve in winter has a narrow spread compared to other seasons. In winter, the highest frequency of occurrences for 1F, 8F, 15F is around the base case result and its ACH is less than 1.0 ACH. The distribution curve becomes wider as a floor gets higher, which means that the aforementioned uncertainties are more influential for a higher floor. In other words, more uncertainty exists in estimating the natural ventilation rate for a higher floor. It should be noted that since a higher floor has a more ACH than a lower one, as shown in Table 2 and Fig. 4, a different type and sizing of mechanical ventilation system could be introduced according to the distance from the ground.

For want of space, the profiles of the distribution curve in spring/fall and summer are not included here, but those are similar to that in winter and the simulated ACHs in spring/fall and summer are greater than that in winter (Table 2).



(a) ACH(1F)



(b) ACH(8F)

(c) ACH(15F)

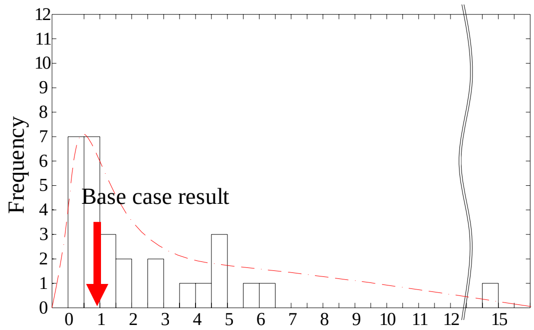
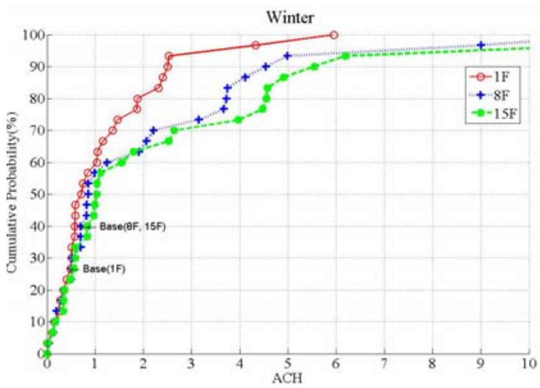
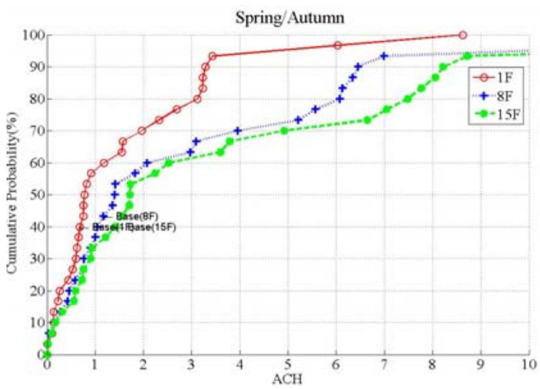


Figure 4 Air Changes per Hour (ACH) in winter

Fig. 5 shows the cumulative probability of natural airflow rates. In winter, more than 50% of total samples meet the code requirement, 0.7 ACH. During seasons other than winter, occupants utilize modest outdoor air when available, and thus more than 70% of total samples in spring/autumn and 80% of total samples in summer meet the code requirement. This shows that the required ventilation rate (0.7 ACH) is supplied to a large extent by natural ventilation, without using mechanical ventilation.





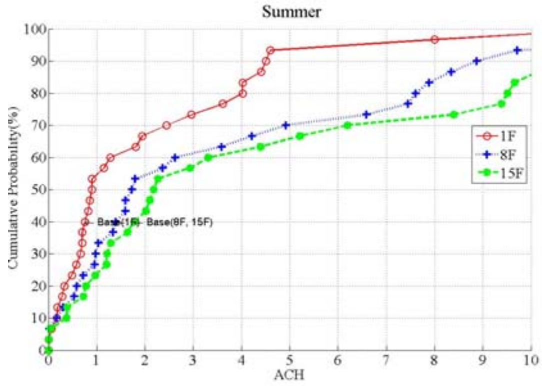


Figure 5 Cumulative probability of natural airflow rates

So far natural airflow rates under uncertainty have been discussed. What follows is an investigation of IAQ with simulated natural airflow rates. For a measure of IAQ, CO2 concentration is selected since it is a typical contaminant generated primarily by occupants and, in addition, measurement of CO2 in occupied spaces has been used widely to evaluate the sufficiency of outdoor air supplied to indoor spaces (ASHRAE 2005). For CO2 calculation, an adult is assumed to generate 0.31 liter per minute (ANSI/ASHRAE 2004). As a threshold of CO2 concentration, 1,000 ppm, a non-mandatory but recommended value of the code (KMOCT 2006) is chosen. The number of occupants in each room (Fig. 1) was obtained through on-site interview and questionnaires (Table 1). In the simulations, the schedule of occupants and windows remains static until state variables reach a steady-state condition. The outdoor CO2 concentration is assumed to be 380 ppm (Korea Meteorological Administration).

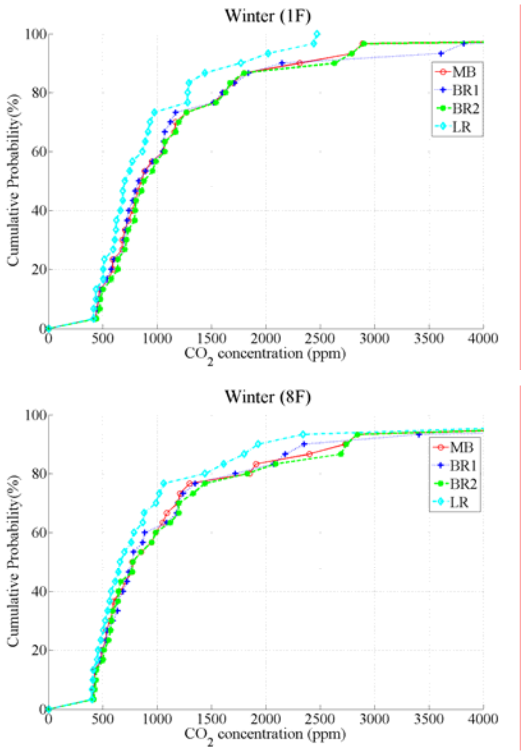
Based on the CONTAMW simulations, the probability of exceeding 1,000 ppm of CO2 concentration is tabulated as shown in Table 3. The average of the probabilities exceeding 1,000 ppm in each room is 33.1% in winter, 25.3% in spring/autumn, and 21.9% in summer respectively. This seasonal difference is caused by different natural ventilation rates in each season (Table 2). In addition the probability of exceeding 1,000 ppm gets higher in winter for a lower floor, and vice versa (Table 3).

Table 3 Probability of exceeding 1,000 ppm of CO2 concentration

		WINTER	SPRING /AUTUMN	SUMMER
1F	MB	40.0%	40.0%	36.7%
	BR1	40.0%	30.0%	30.0%
	BR2	40.0%	33.3%	30.0%
	LR	23.3%	26.7%	23.3%
8F	MB	36.7%	30.0%	23.3%
	BR1	36.7%	26.7%	16.7%
	BR2	36.7%	26.7%	23.3%
	LR	26.7%	16.7%	16.7%
15F	MB	33.3%	23.3%	23.3%

	BR1	33.3%	16.7%	16.7%
	BR2	33.3%	20.0%	13.3%
	LR	16.7%	13.3%	10.0%
Average		**33.1%**	**25.3%**	**21.9%**

Fig. 6 shows the cumulative probability of CO2 concentration in each room for 1F, 8F, 15F in winter and summer seasons. As shown in Fig. 6, the lower floor (1F) is most disadvantageous in winter in terms of CO2 concentration. The living room has the lowest CO2 concentration level since it is well ventilated through cross-ventilation and air movement to/from other zones in the plan (Fig.2). On the other hand, the master bedroom is the worst zone because of the comparatively small size of windows. The gradient of the cumulative probability in summer is steepest, which indicates 'low CO2 concentration'. The probability of having CO2 concentration lower than 1,000 ppm in the living room is almost 90% in summer. Fig.5 shows that a higher floor is well-ventilated with outdoor air in summer without an occupant's deliberate intervention with openings or need of mechanical ventilation. For want of space, the cumulative probability of CO2 concentration in spring/fall is not included here.



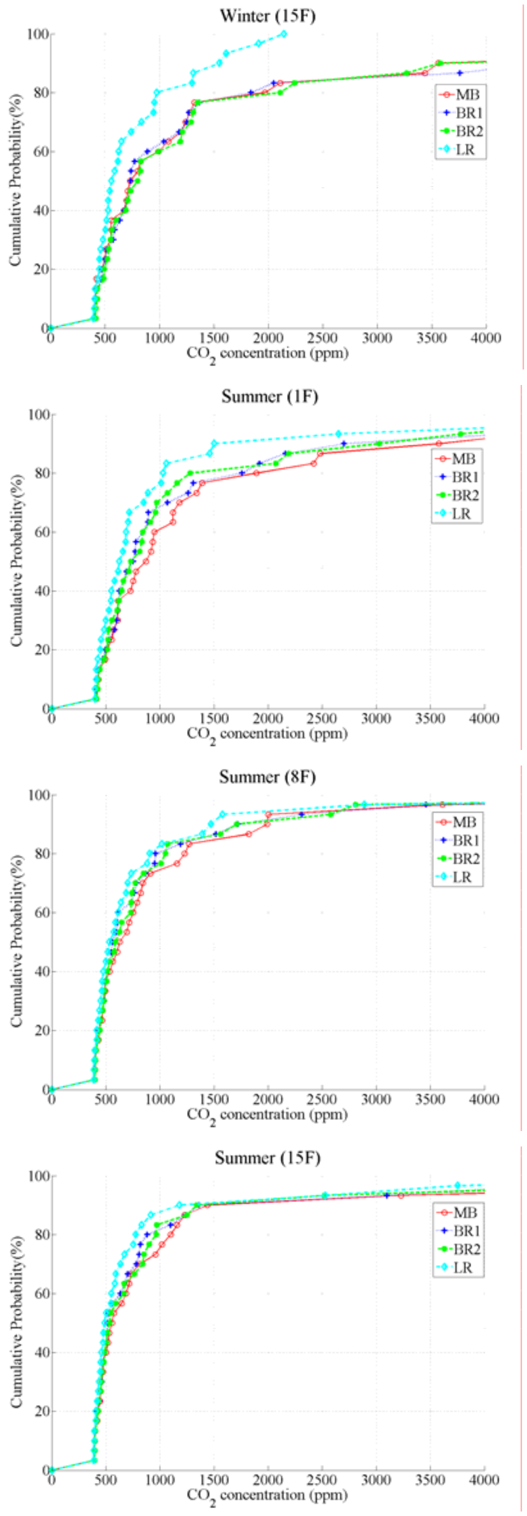


Figure 6 Cumulative probability of CO2 concentration

COMPARISON BETWEEN EXPERIMENT AND SIMULATION

A comparison has been made between the simulated and measured CO2 concentration and cumulative probability. For this purpose, an in-situ experiment was done from 9:51 p.m. (01/25/2007) to 10:17 p.m. (01/29/2007) for about 4 days, or 96.6 h with a sampling time of 1 min. A portable Graywolf CO2 sensor was used to measure indoor CO2 concentration. The experiment was conducted in bedroom1 on the 17th floor in a selected 22-story apartment building (Fig.1). The number of recorded data points is 5796 and Fig. 7 shows the measured CO2 concentration. During the experiment, the occupants were allowed to open/close windows (doors) "freely" as they wanted. The measured minimum, average and maximum CO2 concentration were 315, 840, 1,492 ppm respectively. The notably low CO2 concentration occurred when the occupants were out with windows wide open.

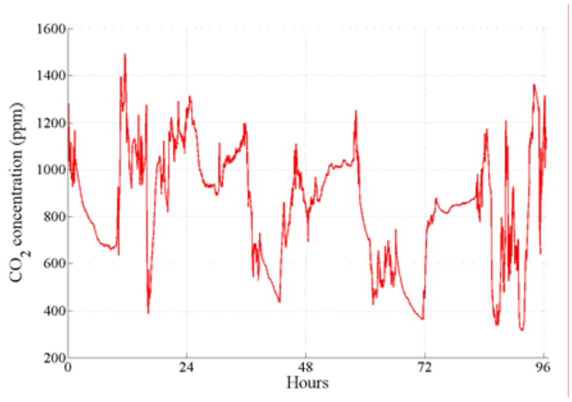


Figure 7 Measured CO2 during the in-situ experiment (01/25/2007-01/29/2007)

Fig. 8 shows the comparison between measured CO2 concentration and the simulated result for BR1 in 8F in winter (Fig. 6). Under 1,000 ppm, the measured probability curve is surprisingly similar to the simulated one. Over 1,000 ppm, the gap between measurement and simulation grows. It is speculated that this is caused by the occupant's active intervention when indoor CO2 concentration is high due to under-ventilation.

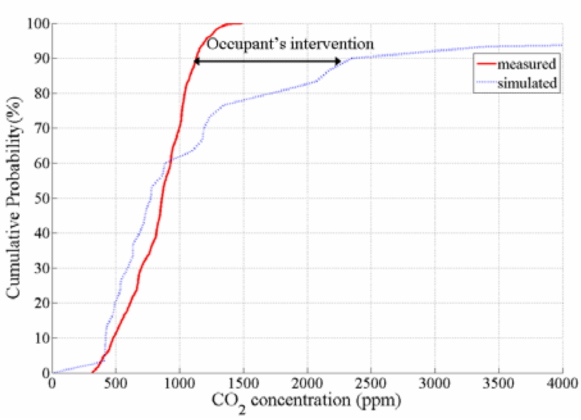


Figure 8 Comparison between measured and simulated

SENSITIVITY ANALYSIS

This section discusses the identified dominant parameters using a parameter screening technique suggested by Morris (1991). The Morris method can be used to determine a set of parameters which account for the uncertainty in the model output (de Wit 2002; Saltelli et al, 2005).

In our study, the 13 parameters (Table 1) were discretized on a 6-level grid (p=6) and a total of 140 simulations were run. Table 4 shows the 7 most important parameters identified in the sensitivity analysis in decreasing order of importance for 8F in winter. Two immediate conclusions can be drawn. First, four parameters (local terrain constant, flow exponent, discharge coefficient, wind velocity profile exponent) out of 7 parameters are relevant simulation inputs, all of which are usually decided by simulationist's qualitative judgment. This indicates that the variability in predicting the ACH by different simulation experts might be substantial. Secondly, the second dominant parameter is window opening area by occupants. This means that natural ventilation cannot be accurately simulated without introducing a reliable model of user behavior.

Table 4 dominant parameters in decreasing order of importance (winter, 8F)

RANK	PARAMETERS	UNCERTAINTY IN
1	Wind velocity	Weather
2	Window opening area by occupants	Occupant
3	Local terrain constant	Simulation parameters
4	Flow exponent	
5	Discharge coefficient	
6	Outdoor temperature	Weather
7	Wind velocity profile exponent	Simulation parameters

CONCLUSIONS AND FUTURE WORK

A probabilistic approach has been discussed that is capable of capturing the stochastic characteristics of natural ventilation phenomena in high-rise apartment buildings in Korea. The approach generates a probability curve of ventilation rates and indoor CO2 concentration through uncertainty propagation by means of the Monte Carlo method. It is shown that the 'uncertain nature' in natural ventilation is not negligible (Table 2, Fig.4) and may significantly influence the prediction of airflow rates.

Following the successful application of uncertainty propagation to natural ventilation phenomena, future study may include:

- *Techno-economical optimal design of mechanical ventilation and its control*: This looks at techno-economical type of ventilation, and the optimal location and sizing of diffusers/registers in a typical floor plan. Performance criteria for design decision-making will include initial and maintenance costs, indoor air quality, energy use and comfort. This will introduce multi-objective optimization with Pareto optimality.

- *Integrated control of ventilation systems with central heating/cooling systems*: This extends a local ventilation control problem to a whole-building control problem in which room environmental control and ventilation control are dealt with simultaneously. It will be investigated whether the integrated control significantly outperforms the suboptimal ventilation control based only on local state information.

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