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Numerical Analysis of Ventilation System Performance by COMIS Model

Hiroshi Yoshino, Dr.Eng.
Member ASHRAE

Jing Liu

Helmut E. Feustel, Ph.D.
Member ASHRAE

Jean-Robert Millet, P.E.

Lars-Goran Månsson, P.E.
Member ASHRAE

ABSTRACT

This research evaluated the performance of four kinds of ventilation systems for dwellings under various conditions by means of numerical simulation. The total number of combinations of various parameters for the calculation was 174.

Calculations were performed hourly for indoor air pollutant concentration, humidity and condensation, indoor-outdoor pressure difference, airflow rate, and heat energy by ventilation, etc., through the heating season.

A multizone infiltration and pollutant transport model (COMIS) was used to perform the simulation. A new term, "acceptable ratio," is introduced in this study to evaluate the performance of ventilation systems from the point of view of CO_2 level and energy consumption. In addition, by means of statistical methods, the effect of various factors on ventilation system performance is discussed. A set of predictive equations for ventilation systems are derived in this paper to try to evaluate ventilation system performance in an easy way under any conditions.

INTRODUCTION

It is well known that most people spend most of their time within buildings. Moreover, numerous studies have shown much stronger pollution indoors than outdoors. Thus, today, ventilation plays an important role in residential buildings because it can provide fresh air and dilute indoor air pollutants to ensure adequate indoor air quality. However, because domestic ventilation will represent 10% of the total energy use in the near future (Månsson 1994), the increase of air exchange rates may lead to excessive energy consumption. So the good selection of a ventilation system should depend on whether it can provide adequate indoor air quality with minimum energy consumption.

This study is part of a research project of Subtask 2 of Annex 27, Evaluation and Demonstration of Domestic Ventilation Systems, which is one of the ongoing international collaborative projects within the International Energy Agency (IEA) program Energy Conservation in Buildings and Community Systems (Millet et al. 1997). The purpose of this study was to evaluate the performance of four kinds of ventilation systems for dwellings under various conditions by means of numerical simulation.

In this paper, a multizone infiltration and pollutant transport model (COMIS) was used to do the simulation work. This Fortran code was developed in 1989 during a one-year international workshop at a U.S. national laboratory. Further development took place between 1990 and 1996 within the framework of IEA Annex 23, Multi-Zone Airflow Modeling (Phaff 1996).

This program is capable of doing sophisticated multizone airflow and pollutant transport simulations. Several airflow components, such as cracks, ducts, fans, large vertical openings, and pressure coefficients of facades, can also be modeled. In a COMIS model, each zone and boundary condition is represented by a single node, and each flow path is represented by a link. By performing a mass balance at each zonal node, a set of nonlinear algebraic equations is obtained. Solution of these equations through iterative methods is used to evaluate the indoor air pressure induced by wind, thermal buoyancy, mechanical ventilation, or a combination of these factors. Then airflow rate and distribution and indoor air pollutant concentration and distribution can be calculated by pressure nodes. In addition, various schedules can be defined

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Hiroshi Yoshino is a professor and **Jing Liu** is a graduate student in the Graduate School of Engineering, Tohoku University, Sendai, Japan. **Helmut Feustel** is a staff scientist at Lawrence Berkeley National Laboratory, Berkeley, Calif. **Jean-Robert Millet** is chef de division, CSTR, Champs-sur-Marne, France. **Lars-Goran Månsson** is president of LGM Consult AB, Tullinge, Sweden.

for the outdoor climate, indoor air temperatures, pollutant sources and sinks, opening of windows, and fan operations, etc. (Feustel and Raynor-Hoosen 1990).

ASSUMPTIONS

Model House and Climatic Conditions

A single-family house (D4a) and four-story multifamily house (D4c) were chosen to represent different dwelling types. The total areas of D4c and D4a were 83 m^2 and 80 m^2, respectively. Room height was 2.5 m and the living room always faced south. Their floor plans are shown in Figure 1 and Figure 2. Leakage for 1.0, 2.5, and 5.0 ACH at 50 Pa was assumed to be concentrated in two parts on each exterior wall, one-half located at 0.625 m and the other half at 1.875 m above the floor. For leakage of 10 ACH at 50 Pa, additional cracks were located in the floor and ceiling. The standard living schedule, corresponding to family composition, is based on European statistics (Villenave et al. 1995). Indoor air temperature was assumed uniformly as 20°C. Except for the door between the kitchen and the hall, all the others were considered closed. The equivalent area of cracks at the bottom of interior doors was 100 cm^2 for habitable rooms and 200 cm^2 for the bathroom.

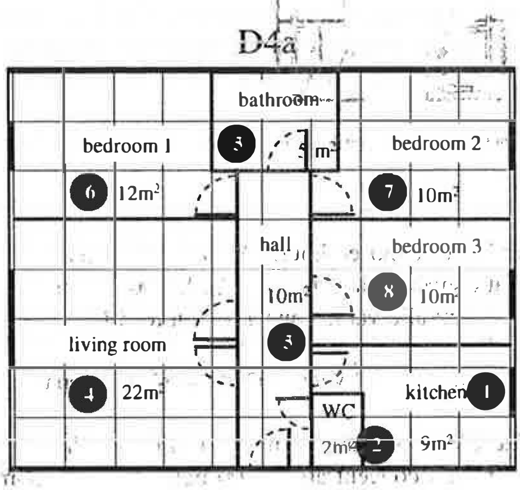


Figure 1 *Floor plan of a multifamily house.*

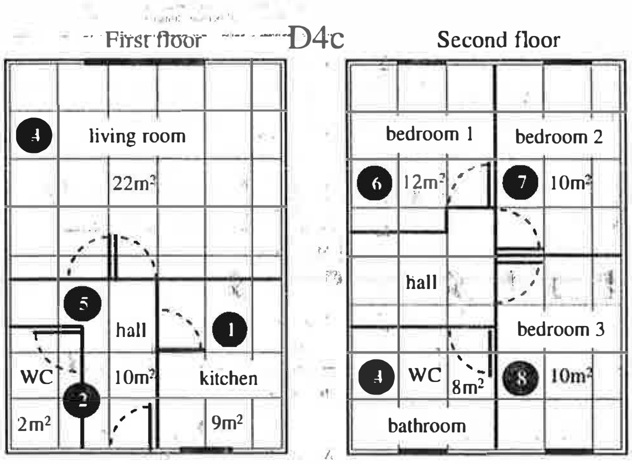


Figure 2 *Floor plan of single-family house.*

TABLE 1
Climatic Characteristic of Three Regions

Climate	Cold (Ottawa)	Moderate (London)	Mild (Nice)
Heating Season	2 Oct.-20 May	24 Sept.- 20 May	13 Nov.- 27 Apr.
Average Temperature (°C)	1.44	7.51	10.1
Average Humidity (g/kg)	2.97	5.22	5.31
Average Wind Speed (m/s)	4.44	1.97	4.34
Prevailing Wind Direction (°)	186.8 (S)	182.1 (S)	264.9 (SW)

This simulation was performed using weather data for three cities representative of different climatic zones. Table 1 illustrates their main meteorological parameters. The duration of window openings in bedrooms was only assumed as four hours (8:00 - 12:00) during weekdays.

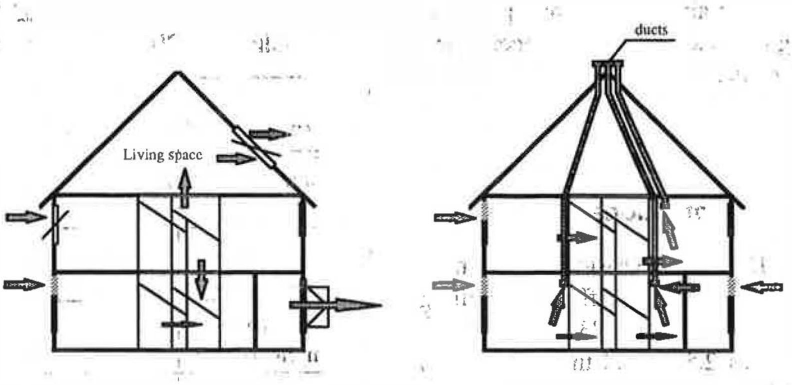
Ventilation System

Four typical ventilation systems (shown in Figure 3) were selected for simulation: natural, natural passive stack, mechanical exhaust, and mechanical central supply and exhaust system (represented as systems 1 to 4, respectively, in this paper). The bathroom fan was assumed to operate at 6:00-8:00 on weekdays and 9:00-11:00 on weekends. The operation of the kitchen hood was assumed to be one hour a day (17:00-18:00). The natural supply openings were located 2.3 m above the floor. There are no natural supply openings for the case of a mechanical central ventilation system. The assignment of a mechanical exhaust airflow rate corresponding with systems 3 and 4 was assumed as 1/2 kitchen, 1/3 bathroom, and 1/6 toilet. The assignment of fresh air into the building was assumed as 2/5 for the living room and 1/5 for each bedroom for system 4. The wind pressure values are subject to different wind directions. The window-opening position depends on the outdoor temperature and wind speed, varying with time.

Evaluation Indexes

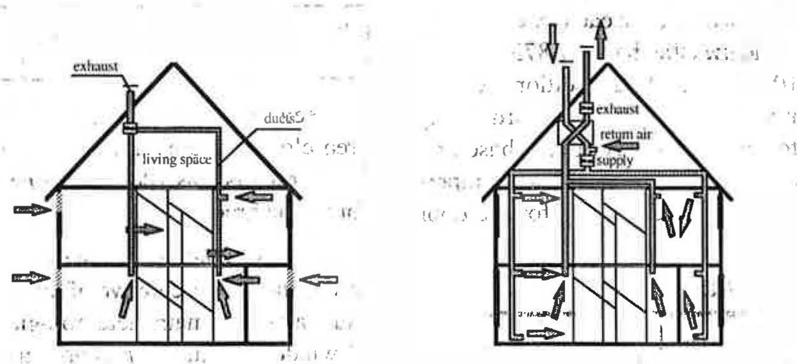
In order to evaluate the performance of the ventilation system, the following results were simulated as evaluation indexes in this study.

Indoor Air Pollutants. Some specific contaminants were selected as indicators of indoor air quality. They are the following:



System 1 : Natural window ventilation

System 2: Natural stack ventilation



System 3: Natural supply and mechanical central exhaust

System 4: Mechanical central supply and exhaust

Figure 3 Four kinds of ventilation systems.

1. *Plt1*: the pollutant is assumed to be generated from the rooms themselves; its emission is related to the floor area of each room, 1 mg/(m^2·h).
2. *Plt2*: CO_2 based on human metabolism.
3. *Plt3*: the pollutant related to cooking activities, which is considered to be proportional to the water evaporation during cooking.
4. *Plt4*: the pollutant related to passive smoking, which is assumed as 20g/h for the housewife when she is in the living room between 12:00 and 24:00.

The metabolic CO_2 and water vapor (including showering and cooking) production of a family with two adults is given as an example in Figure 4. The outdoor concentrations of all pollutants were neglected.

The chemical reactions among all the pollutants are assumed to be negligible. Because many kinds of indoor air pollutants are at low concentration but have large toxicological effects during a long-term exposure, a special index was introduced by Villenave et al. (1995) in terms of *CV* (cumulated value) to show the cumulative effect of a pollutant on occupants during the heating season. The highest *CV* is chosen for evaluation among all occupants on the basis of the number of exposed hours, *Nh*, above a certain indoor air pollutant concentration, C_i: $Nh(C_i)$. If 700 ppm is defined as the maximum allowable concentration for CO_2,

$$CV_{CO_2(700)} = \int Nh(C_i)dC_i \quad \text{for } C_i \geq 700 \text{ ppm.} \qquad (1)$$

The *CV* values are calculated from 0 for Plt1, Plt3, and Plt4. For CO_2 concentration, 700 ppm and 1000 ppm were both selected as setpoints.

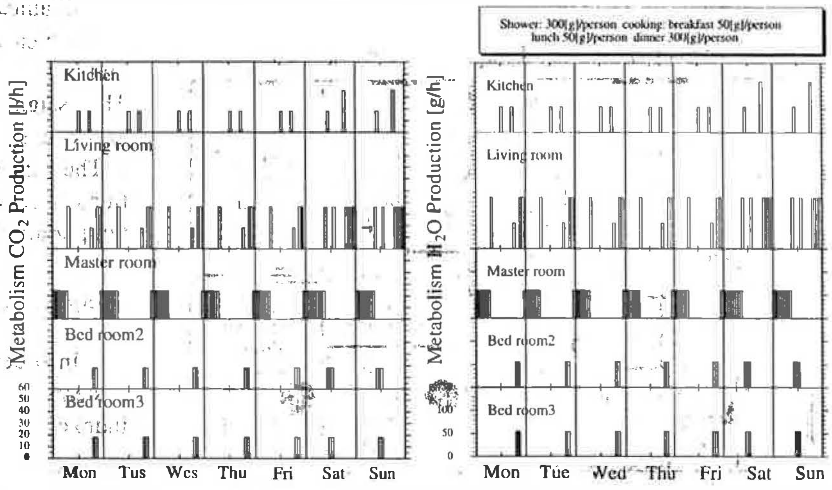


Figure 4 Metabolic CO_2 and water vapor generation schedule.

Indoor Humidity

1. *Feeling of dryness*: the highest value of exposed hours among occupants when indoor relative humidity is less than 30% during the heating season.
2. *Condensation*: the number of hours when concealed condensation and visual condensation occurred in "wet rooms" (kitchen, toilet, and bathroom) and "habitable rooms" (bedrooms and living room), respectively. The heat-transfer coefficient is assumed to represent a single-pane window.

Airflow and Energy Need

1. *Equivalent air change rate*: weighted mean by indoor-outdoor temperature difference of the whole building per hour to make an attempt to associate airflow with energy need, which is expressed below.
2. *Airflow rate*: average air exchanges between each room and outdoors.
3. *Energy need*: cumulative values up to the outdoor temperature above 17°C as a threshold value for the need of heating. Only for system 4, the heat recovery coefficient is assumed as 0.6.

Combination of All Simulation Parameters

The related parameters for sensitivity studies, as mentioned above, are summarized in Table 2. Because of the large number of extreme combinations—approximately 17,000—a selection of critical combinations, 174 cases, has been made based on mathematical statistics.

EVALUATION FROM THE POINT OF VIEW OF AIRFLOW CONTROL

Airflow Distribution. Figure 5 is an example, coded as N105, to show the detailed airflow rates in rooms with system 3 at two typical times. The simulation conditions are shown in Table 3. At 9:00 the window is opened, while at 17:00 the kitchen fan is on. From Figure 5, it can be seen that due to the window opening, airflow rates through bedrooms 1 and 2 increase up to 232.4 m^3/h and 199.4 m^3/h compared to only 73.5 m^3/h and 71.5 m^3/h for the case at 17:00. But because of the operation of the kitchen fan, the infiltration rate into the living room is about two times as much as that for the case at 9:00.

Average Air Change Rate. Figure 6 shows the average airflow rates through the rooms (fresh air goes into the bedrooms and living room, indoor air goes out from the kitchen, toilet, and bathroom) and the average equivalent air change rate of the dwelling for all 174 cases. The equivalent air change rate through each room is higher than the 0.35 ACH minimum recommended ventilation rate of *ANSI/ASHRAE Standard 62-1989* (ASHRAE 1989) for providing an acceptable indoor environment in residential buildings. Because local fans and passive stacks are installed in the kitchen, toilet, or bathroom, it is obvious that the equivalent air change rates through these rooms are much higher than through other rooms. This situation is very helpful for preventing the risk of condensation, etc. With system 2, in most cases the average airflow rates are higher than for the other systems due to passive stacks. Because of the use of mechanical supply, with system 4, air change rates within bedrooms look a little higher than with the other systems.

EVALUATION FROM THE POINT OF VIEW OF INDOOR AIR QUALITY AND HUMIDITY

Indoor Air Pollutant Concentration and Humidity Variation

Figure 7 shows the indoor air pollutant concentration variation in the living room and the total fresh airflow rate during a certain period (1 Jan.~7 Jan.) of N105. Referring to

TABLE 2
Parameters for Simulation

Parameter	Level		
Dwelling Type	**Single-Family House**	**Ground Floor in 4-Story Multifamily House**	**Top Floor in 4-Story Multifamily House**
Leakage (systems 1,2,3)	10 (ACH @5 0 pa)	5 (ACH @ 50 pa)	2.5 (ACH @ 50 pa)
(system 4)	5 (ACH @ 50 pa)	2.5 (ACH @ 50 pa)	1.0 (ACH @ 50 pa)
Occupancy	5 (Crowded)	4 (Average)	2 (Spacious)
Window Airing	Climate Dependent	50% Climate Dependent	Closed
Climate	Cold (Ottawa)	Moderate (London)	Mild (Nice)
Supply Area (systems 2,3)	400 cm^2	100 cm^2	0 cm^2
(system 1)	410 cm^2	101 cm^2	
Flow Rate (systems 3,4)	45 L/s	30 L/s	15 L/s
Local Fan Kitchen	ON(100 L/s)	—	OFF
Local Fan Bath	ON(25 L/s)		OFF

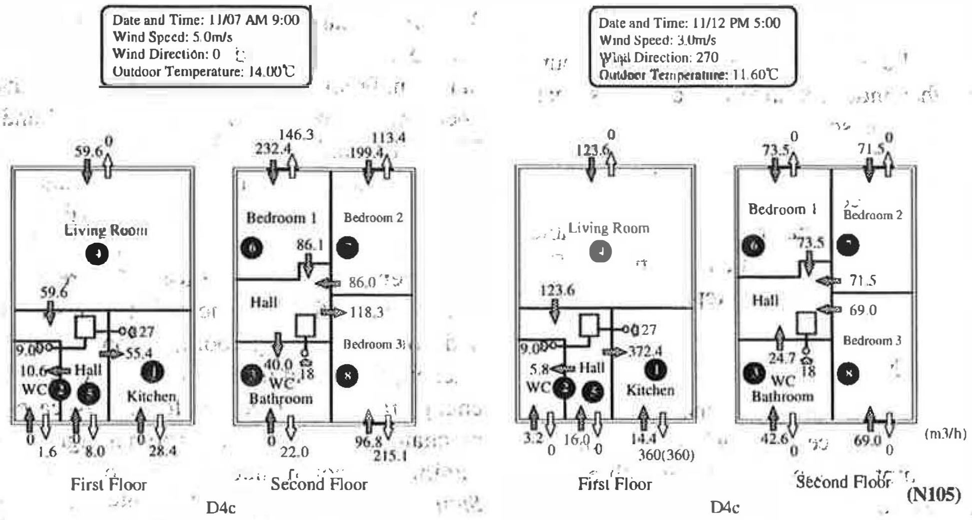


Figure 5 Airflow distribution of an example.

TABLE 3
Detailed Description of an Example

Case No.	Dwelling Type	Leakage (ACH@50pa)	Occupancy (persons)	Window Airing	Climate	Supply Area (cm^2)	Flow Rate (L/s)	Local Fan	
								Kitchen(L/s)	Bathroom(L/s)
N105	D4c	2.5	2	Open	Nice	400	15	100	25

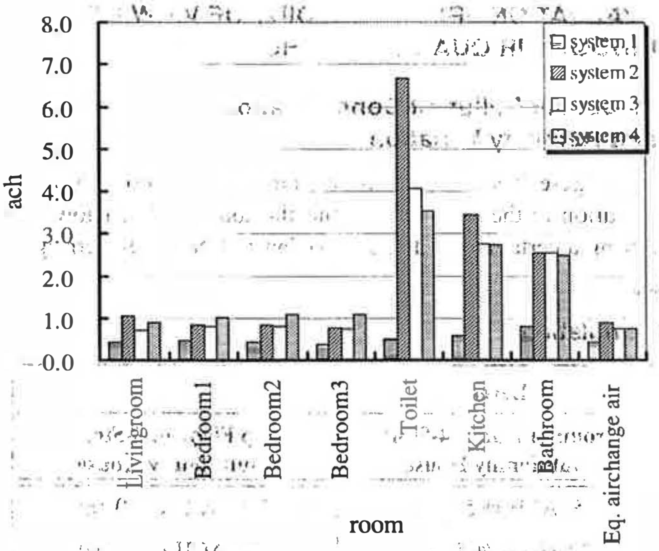


Figure 6 Average air change rate of each room.

Figure 5, it is clearly shown that, owing to window airing and local fan, airflow rates vary considerably. Especially when windows are opened, the fresh air rate reaches 171 m^3/h, more than five times the rate when windows are closed. The pollutant level increases steadily from 18:00 until 24:00 when the living room is being occupied continuously. The CO$_2$ concentration during this period is below 1000 ppm except for the peak values in the case of systems 1 and 3. The average concentrations with all the systems are at or below 500 ppm.

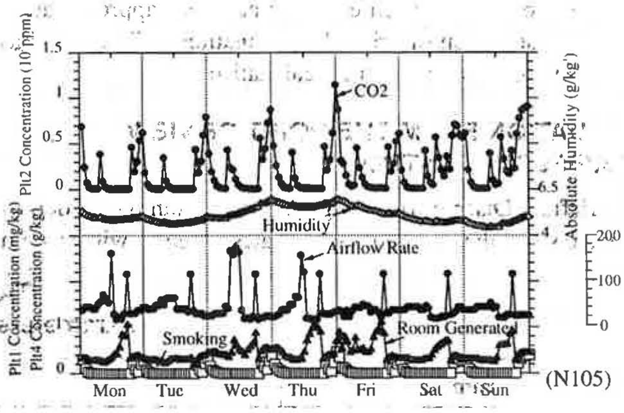


Figure 7 Variation of pollutant concentration and airflow rate.

The absolute humidity in the living room is in a range between 4.2 g/kg and 6.1 g/kg during this period. The results show that the humidity variation is slightly relative because most moisture is exhausted by the kitchen and bathroom fans.

Overall Distribution of Indoor Air Pollutant and Humidity

The maximum, minimum, and average values and standard deviations for all the cases were calculated. Figure 8 shows the results of indoor air pollutant concentration (expressed by the *CV* value) and dryness and condensation.

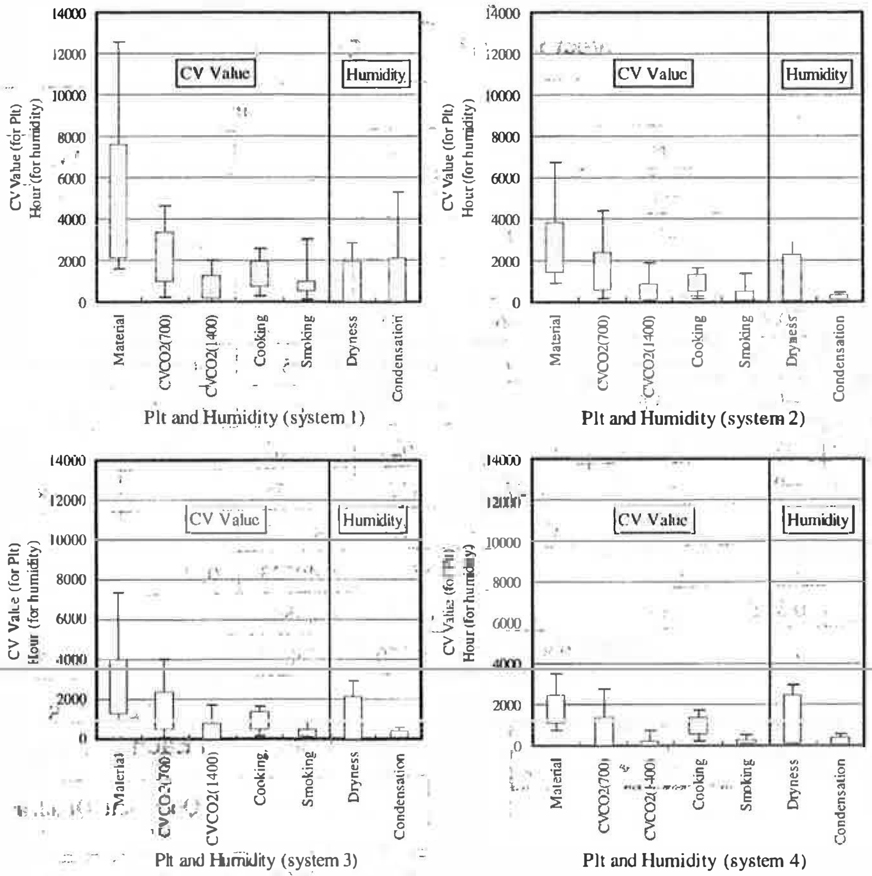


***Figure 8** Mean and SD of Plt and humidity.*

The average levels of pollutant concentrations with system 1 are about 1.5 to 4.5 times higher than those with other systems. The range (Max.– Min.) and the standard deviation value show that using system 4 can keep a stable and relatively low indoor air pollutant concentration level due to the control of mechanical force. There seems to be no distinctive difference between systems 2 and 3 although the former looks a little more effective in lowering the possibility of condensation.

SYNTHETIC EVALUATION

Use of Principal Component Analysis Method

For this paper, the Principal Component Analysis method was used to evaluate the overall performance of the ventilation system combined with all the evaluation indexes mentioned before (Manly 1986).

Nine evaluation indexes were selected to do this analysis: four kinds of pollutants, humidity including dryness and condensation, heat need, and equivalent air change rate. After normalization to eliminate the impact of parameters' different units, principal components were calculated on the basis of a variance-covariance matrix. Some results are summarized in Table 4. Because the cumulative proportion of PC0 and PC1 (Principal Components 0 and 1) is more than 0.75 and the proportions from PC2 to PC8 are too low, only PC0 and PC1 were taken into account and the others were neglected. Studying the absolute values of eigenvectors for PC0 and PC1 in Table 4, PC0 can represent the synthetic effect of pollutants, condensation, and air change rate, while PC1 can represent the synthetic effect of dryness and energy need. Using these eigenvectors as coefficients, the following estimated formulae were obtained:

$$F_i = 0.409x_1 + 0.399x_2 + 0.399x_3 + 0.286x_4 + 0.391x_5 - 0.172x_6 + 0.282x_7 - 0.213x_8 - 0.354x_9$$

$$G_i = -0.178x_1 - 0.166x_2 - 0.168x_3 - 0.106x_4 - 0.165x_5 - 0.616x_6 - 0.103x_7 - 0.654x_8 - 0.37x_9$$

where F_i and G_i represent the principal component scores of PC0 and PC1 for case i, respectively. The scores of all the 174 cases are shown in Figure 9. Higher pollutant concentration, condensation, or lower air change rate results in a higher F value, while a higher level of energy need or dryness results in a lower G value. Thus, the coordinates of two-dimensional plots (F_i, G_i) determine the alternative influence of these two components for every case. The line $F = 0$ and $G = 0$ (the average level for F and G) divide the figure into four parts. The meaning of each quadrant is presented in Table 5. Then a ratio of the number of cases at each quadrant for every system was

TABLE 4
Eigenvectors of Principal Components

	Eigenvector								
	PC0	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
$CV_{Material}$ x1	0.409	−0.178	0.036	0.134	0.080	−0.164	0.324	0.770	0.225
$CV_{CO2(700)}$ x2	0.399	−0.166	−0.091	0.288	−0.075	0.467	−0.121	−0.319	0.618
$CV_{CO2(1400)}$ x3	0.399	−0.168	0.043	0.339	−0.130	0.249	−0.386	0.114	−0.674
$CV_{Cooking}$ x4	0.286	−0.106	−0.646	−0.551	−0.417	−0.086	−0.052	0.009	−0.043
$CV_{Smoking}$ x5	0.391	−0.165	0.137	0.145	0.059	−0.768	-0.046	−0.431	0.012
Dryness x6	−0.172	−0.616	−0.154	−0.212	0.601	0.004	−0.388	0.078	0.056
Condensation (Wet Room) x7	0.282	−0.103	0.691	−0.623	−0.067	0.193	−0.007	−0.046	0.004
Heat Need x8	−0.213	−0.654	0.027	0.112	−0.255	0.114	0.598	−0.204	−0.191
Air Change Rate x9	−0.354	−0.237	0.224	0.115	−0.603	−0.215	−0.467	0.238	0.266
Eigenvalue	5.24468	1.60249	0.64679	0.63934	0.49523	0.19522	0.08011	0.07367	0.02249
Proportion	0.58274	0.17805	0.07187	0.07104	0.05503	0.02169	0.00890	0.00819	0.00250
Cumulative Proportion	0.58274	0.76080	0.83266	0.90370	0.95872	0.98042	0.98932	0.99750	1.00000

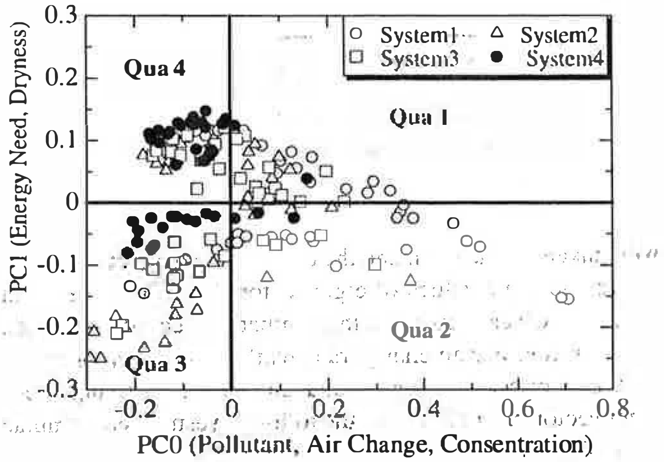


***Figure 9** Distribution of principal component scores.*

derived. The results are presented in Figure 10. More than half of the cases can be considered to be the "best" (in Quadrant 4) and only 7% to be the "worst" (in Quadrant 2) with system 4. It means that both indoor air quality and air distribution are good due to the force of the central mechanism, and energy need is less than in other systems because of heat recovery. The number of cases in Quadrant 4 for systems 2 and 3 is almost the same. But in the case of system 2, the ratio of the cases in Quadrant 3 is up to 35%. It means that energy conservation is not good when compared to other systems. System 1 is not very efficient in satisfying the requirement for acceptable indoor environment because the ratio at Quadrant 2 is up to 47%.

TABLE 5
Meaning of Each Principal Component

	Quadrant 1	Quadrant 2	Quadrant 3	Quadrant 4
PC0 (Plt, Air Change, Condensation)	Bad	Bad	Good	Good
PC1 (Energy Need, Dryness)	Good	Bad	Bad	Good

Use of "Acceptable Region" Method

As noted before, the Principal Component Analysis method is a very interesting and useful statistical method to illustrate all the impacts of evaluation indexes synthetically, but it looks complex and a little hard to use. In practice, because the total energy consumption (due to both ventilation heat loss and fan's electrical need) during the heating season and CO_2 concentration (represented as $CV_{CO2(700)}$ here) are the most important evaluation indexes associated with indoor environment, combining them may be a more effective and simple method to evaluate the synthetic performance of the ventilation system.

Figure 11 shows that $CV_{CO2(700)}$ of all the 174 cases is mainly in the range of 0 to 5000 (10^3 ppm × h) while the energy consumption is within the range of 0 kWh to 15000 kWh. To achieve an acceptable CO_2 level and energy conservation, the maximum values at 1100 (10^3 ppm × h) and 2800 kWh were derived to represent their threshold values, respectively. The limit values were obtained from the average level of all 174 cases. Then a rectangle is enclosed, as shown in Figure 11, using these two limit values. Within this region, both CO_2 level and energy consumption are lower than the average level of the total cases. Thus, this region can be considered as an "acceptable region" for occupants. Then a new term, "acceptable ratio," was derived for this paper as the ratio of the number of cases in the "acceptable region" to the total cases for a ventilation system. As shown in Table 6, when other

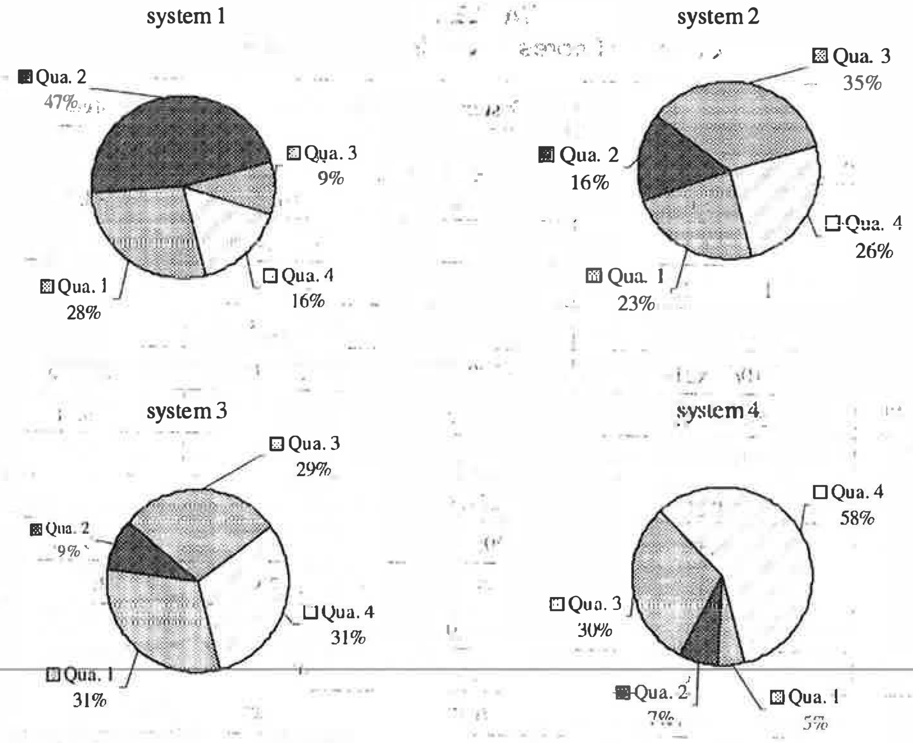


***Figure 10** Ratio at each quadrant vs. ventilation system.*

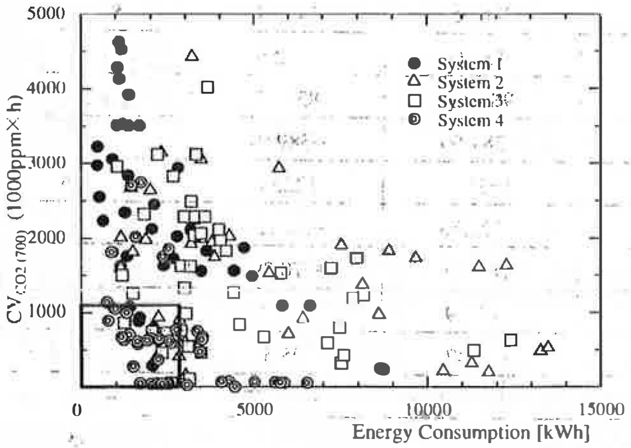


***Figure 11** Energy vs. $CV_{CO2(700)}$ taking "acceptable region" into account.*

TABLE 6
"Acceptable Ratio" for Various Systems

System	1	2	3	4
Acceptable Ratio	0.19	0.12	0.13	0.52

parameters are assumed the same, the "acceptable ratio" of system 4 is the highest, about 52%. Apparently, using system 4, the CO_2 level and energy consumption are the most acceptable for occupants.

EVALUATION OF RELATED PARAMETERS

Predictive Formulae

As indicated in Table 2, the related parameters and their corresponding categories are all represented by qualitative data. According to multivariate statistical theory, the Quantification I Analysis method (Arima and Ishimura 1987) is available to quantify the relationship between these parameters and the evaluation indexes. From Table 7, the predictive equations of ventilation systems for $CV_{CO2(700)}$ can be obtained taking category scores as coefficients of items in the equations. Equation 2 shows the predictive equation of a natural ventilation system (system 1) as an example:

$$CV_{CO2(700)} = 1904.64 - 275.46x_{11} + 510.1x_{12} + 419.6x_{13} - 708.23x_{21} + 299.65x_{22} + 549.59x_{23} + 295.19x_{31} - 36.4x_{32} - 275.93x_{33} + 30.57x_{41} - 137.61x_{42} + 42.27x_{43} - 80.55x_{51} + 1087.99x_{52} - 495.43x_{53} - 765.29x_{61} + 163.65x_{62} + 678.65x_{63} - 122.48x_{81} + 72.58x_{82} - 59.37x_{91} + 35.19x_{92} \tag{2}$$

Because the adjusted R-squared values in Table 7 are all relatively large, the CO_2 level can be approximately predicted with any combination of the aforementioned parameters by use of these predictive equations.

Evaluation of Item Range

According to the Quantification I Analysis method, the higher value of the item range in Table 7 means that the corresponding parameter strongly influences the CO_2 level and energy need. In accordance with the relationship among these

TABLE 7
Category Scores of Ventilation Systems

Item/Category		System 1	System 2	System 3	System 4
		$R'=0.83$ $\alpha<0.0001$	$R'=0.81$ $\alpha<0.0001$	$R'=0.62$ $\alpha<0.0001$	$R'=0.81$ $\alpha<0.0001$
Dwelling Type	D4c (x11)	-275.46	−16.11	−8.7	52.72
	D4agf (x12)	510.1	−390.45	15.83	−41.97
	D4atf (x13)	419.6	444.8	20.96	−135.94
	Range	785.56	835.25	29.66	188.66
Leakage Area The Value before '/' is for Systems 1, 2, 3; the Value after '/' is for System 4 (n50)	10/5 (x21)	−708.23	−384.18	−340.73	−218.55
	5/2.5 (x22)	299.65	-307	253.11	51.33
	2.5/1 (x23)	549.59	546.7	206.74	191.38
	Range	1257.82	930.88	593.84	409.93
Family Number	5 (x31)	295.19	532.96	449.46	391.28
	4 (x32)	−36.4	−257.98	−308.29	141.47
	2 (x33)	−275.93	−396.39	−286.25	−466.17
	Range	571.12	929.35	757.75	857.45
Window Airing	Open (x41)	30.57	−30.47	−24.76	4.78
	Half open (x42)	−137.61	207.35	−76.22	51.72
	Closed (x43)	42.27	−79.3	65.12	−32.17
	Range	179.88	286.65	141.34	83.89
Climate	Cold (x51)	−80.55	−132.64	-51.56	78.04
	Moderate (x52)	1087.99	983.42	833.87	248.21
	Warm (x53)	−495.43	−387.99	−389.91	−209.45
	Range	1583.4	1371.4	1223.8	457.66
Supply area The Value before '/' is for Systems 2, 3; the Value after '/' is for System 1 (cm^2)	400/410 (x61)	−765.29	−528.38	−334.19	
	100/101 (x62)	163.65	161.09	−70.29	
	0 (x63)	678.65	443.09	371.4	
	Range	1443.94	971.47	705.59	
Mechanical Flow Rate (L/s)	45 (x71)			−476.47	−785
	30 (x72)			164.55	−536.95
	15 (x73)			389.36	1069.27
	Range			865.83	1854.27
Kitchen Fan	On (x81)	−122.48	38.48	87.83	−61.7
	Off (x82)	72.58	−22.81	−51.99	36.57
	Range	195.06	61.29	139.72	98.27
Bathroom Fan	On (x91)	−59.37	0.57	−99.54	−42.05
	Off (x92)	35.19	−0.34	58.99	27.5
	Range	94.56	0.91	158.53	69.55
Constant		1904.64	1208.56	788.02	−66.85

TABLE 8
Impact of Related Parameters on Evaluated Indexes

	$CV_{CO2(700)}$				Energy Need			
	System 1	**System 2**	**System 3**	**System 4**	**System 1**	**System 2**	**System 3**	**System 4**
Dwelling Type	++	++	+	+	++	++	++	+
Leakage Area	+++	++	++	+	++	++	++	++
Family Number	++	++	+++	++	+	+	+	+
Window Airing	++	+	+	+	+	+	+	+
Climate	+++	+++	++++	++	+++	++++	++++	++++
Supply Area	+++	++	++		++	+++	+	
Mechanical Flow Rate			++	+++			++	++
Kitchen Fan	+	+	+	+	+	+	+	+
Bathroom Fan	+	+	+	+	+	+	++	+

parameters, a single classification was given in a four-grade scale, from the strongest influence (++++) to indifference (+).

The converted results are shown in Table 8. Because the $CV_{CO2(700)}$ and energy need are all cumulative values during the heating season, the climate can be taken into account as the most determining parameter, especially in the case of energy need. In addition, it appears that leakage and supply area have a major influence on both $CV_{CO2(700)}$ and energy need for all the systems. But the mechanical airflow rate becomes the dominate parameter in influencing $CV_{CO2(700)}$ with system 4. Although window airing and local fans can cause remarkable changes to the instantaneous airflow, no strong influence can be found during the entire heating season.

CONCLUSIONS AND DISCUSSION

The air change rates in the kitchen, toilet, and bathroom are much higher with system 2 than with the other systems due to passive stacks. But system 4 can offer more air change rates to the bedrooms and living room.

Using the Principal Component Analysis method and "acceptable ratio" method, the same conclusion can be drawn: a more sophisticated system can be confirmed to give an acceptable and stable indoor environment to occupants. The "acceptable ratio" of system 4 is about 52%, the highest among all the systems.

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