A Prediction of the Indoor Air Movement and Contaminant Concentration in a Multi-Room Condition

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ABSTRACT: CFD simulation is a very useful tool to predict the concentration of contaminant generated from the building materials in a single room. However, there is a limitation on analyzing air movement and contaminant concentration in a multi-room when the door of each room is closed.

In this study, network based simulation was coupled with contaminant simulation for the multi-room condition, using an network simulation tool 'ESP-r'. The coupled simulation was first validated with experimental measurements which performed to define the characteristics of the analyzed space prior to the simulation, and indoor air flow and contaminant concentration between rooms were then analyzed when the door of each room was open and closed in the case of natural and forced ventilation.

1. Introduction

Quantitative experiments and survey methods have been used to analyze indoor air quality and the overall performance of ventilation system. However, the computer simulation is more convenient than such experimental methods in terms of design alternatives as well as time and cost. The computer simulation tool aforementioned can be divided into CFD based and network model based tools.

CFD (computational fluid dynamics) based tool is extensively used in the analysis of airflow, temperature and contaminant distributions.(1) The CFD simulation can provide detailed thermal environment and contaminant information. However, the application of CFD tool to multi-zone building simulation has a lot of limitations as it can not describe the discharge coefficient of opening and require excessive computer resources and long running time.(2)

The network based tool first solves a mass flow of each node connected to others and then calculates contaminant concentration for mass flow of nodes as scalar. Several programs based on network model, such as CONTAMW and COMIS(3), are currently available, but these programs focus only on the prediction of indoor air-quality and can not describe the energy performance.(4)

In this study, the network based simulation method was coupled with contaminant simulation, using an integrated network simulation tool 'ESP-r'. The coupled simulation was first validated with experimental measurement results. Indoor air flow and contaminant concentration between rooms were then analyzed when the door of each room was open and closed in the

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case of natural and forced ventilation.

2. Contaminant Simulation within ESP-r

2.1 Air- flow Network Modeling

Air flow between each room (i.e. node) can be described by air flow components such as crack, door, opening and fan under the mass balance principle. Air flow network modeling must decide boundary condition first and mathematical expression about air-flow of various fluids and relation of pressure difference should be clear.

Fig. 1 is an example of air flow network modeling. Each room consists of zone that use axis of coordinates(x, y). Outdoor air is flowed through crack and is moved through opening or crack between each room. Air current with ventilation system is defined by flow rate component.

- In ESP-r air flow network modeling is based on the following premise.[5]
- Mass flow is a function of pressure difference only.
- Transient pressure and density of air in a zone are taken to be a single value.
- Air and contaminants within a thermal zone are fully mixed.
- Intra-zone contaminant distribution cannot be appraised.
- There are no contaminant transportation delays.

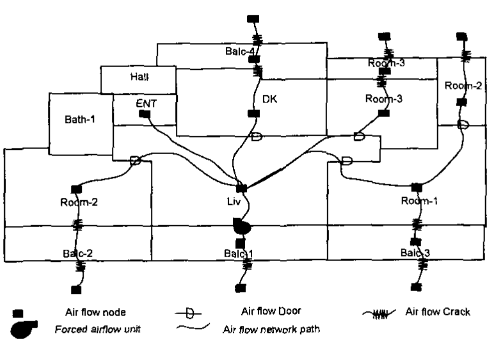

Fig. 1 Building modeling for network simulation.

- Particulate matter is treated just like gas, and there is no mechanism to address process like deposition, coagulation etc.
- Contaminants are considered to be 'trace' i.e. they do not affect the density of air and have negligible partial pressure.

2.2 Air-flow and Contaminant Concentration Module[6]

2.2.1 Air-flow Component

1) Air-flow crack component

Air flow through building fabric infiltration openings is described by a crack component. The relation is defined by equation (1), (2), (3).

$$m = \rho \times k \times \Delta P^{x} \quad (1)$$

$$x = 0.5 + 0.5 \times e^{(-500 \times W)} \quad (2)$$

$$k = L \times 9.7 \times \frac{(0.0092)^{x}}{1000} \quad (3)$$

Where

m : mass flow rate [kg/s],
W : Crack width[m],
L : Crack length[m],
P : pressure difference [kg/m^3],
Δk : flow coefficient [m^3/s/Pa^x],
x : flow exponent,
ρ : density of fluid [kg/m^3]

2) Air-flow opening component

A basic expression for turbulent flow through relatively large openings is the common orifice flow equation. Mass flow rate this is defined by equation (4).

$$\dot{m} = C_d \times A \times \sqrt{2 \times \rho \times \Delta P} \quad (4)$$

Where

m : mass flow rate [kg/s],
A : opening area [m^2],
C_d : discharge coefficient [0.65],
ΔP : pressure difference [kg/m^3],
ρ : density of fluid [kg/m^3]

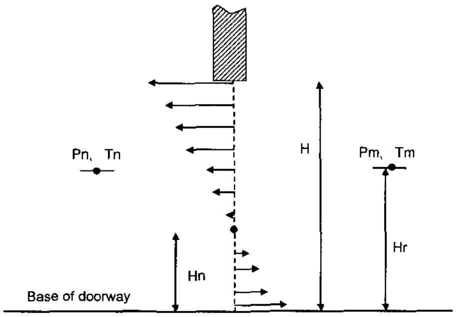

Fig. 2 Bi-directional air flow across doorway.

3) Air-flow door component

With large vertical openings, such as doorways, it is unlikely that unidirectional flow can be assumed. If a temperature difference exists across such an opening, then air flow can occur in both directions due to the action of small density variations over the door height causing a positive pressure at the bottom (or top) of the opening with a corresponding negative pressure difference at the top (or bottom). This situation is illustrated in Fig. 2.

The relation is defined by equation (5).

$$m^* = \rho(2/3)[C_d\, WH(2/\rho)^{1/2}(C_a^{3/2} - C_b^{3/2})/C_1] \quad (5)$$

Where

W: Opening width [m],

H: Opening height [m],

$r_P = H_r / H_{(-)}$,

g: acceleration due to gravity [9.81m/s^2],

P_a : atmospheric pressure [101325P_a],

R: gas constant for dry air [=287.1 J/kg·K],

Θ : node temperature [K],

C_d: discharge factor(-),

H_r : reference height above base of doorway [m]

In case the opening height is very small (< 0.01 m) or there is no or only a very small temperature difference (< 0.01K) a door component is treated as an ordinary air flow opening because in those cases the buoyancy effects may be disregarded.

4) Constant flow rate component

For many fluid flow network problem descriptions it is very convenient to have constant flow rate component types available.

$$m = \rho \times a \quad (6)$$

Where

m: mass flow rate [kg/s],

a: volume flow rate [m^3/s],

ρ: density of fluid [kg/m^3]

2.2.2 Contaminant Concentration Component

Contaminant concentration component is defined by equation (7).

$$m^*_{\alpha i} \approx m_{\alpha i} + \Delta t\Big[\sum_i F^*_{ji}\,(1-\eta_{\alpha ij})\, C_{\alpha i} + m^*_i \\ \sum_\beta K_{\alpha\beta}\, C_{\beta i} + G_{\alpha i} - \Big(R_{\alpha i} + \sum_i F^*_{ij}\Big) C_{\alpha i}\Big] \quad (7)$$

Where

m: quantity of matter,

Δt: time step,

F: volume flow rate,

η: Filter efficiency,

C: Mass ratio of contaminant,

K: The first chemical reaction ratio constant,

G: The occurrence rate,

R: Exclusion coefficient,

i: Target zone,

j: Among others zone,

α : Target contaminant,

β : Among others contaminant,

* : Step value next time,

3. Prediction of the Indoor Air Movement and Contaminant Concentration in a Multi-room Condition

3.1 Analyzed Model

A multi-residential house is located in Hwa-sung city, Korea was studied to show

how contaminant concentration varied with air movement through field measurement and network simulation. The analyzed house was newly built and elapsed 3 month after the completion. No one was occupied in the analyzed house at that time. Fig. 1 and Fig. 3 show the building modeling for network simulation and the analyzed house, respectively. The building was divided into 12 thermal zones : 5 balconies, 3 bed rooms, 2 bath rooms, dining & kitchen, living room (see Fig. 1 and Fig. 2). A detailed network model comprising 12 internal and 6 external nodes was made to describe various forced and unforced air flows. A balanced HVAC system was used to define intentional air flows for the building.

3.2 Measurement Outline

To analyze the indoor air quality with the change of ventilation rate and to define the characteristics of the analyzed space prior to the simulation, the filed measurement was conducted for 2 weeks(1 December 2004~14 December 2004). At that time, air temperature of outside varied from 10 ℃ to 15 ℃. The indoor temperature of target house was maintained between 24.5 ℃ and 26 ℃. A relative humidity of outside fluctuated between 22% and 36%, except on December 4th. Indoor relative humidity was showed about 30%.

To estimate the indoor air quality, HCHO emission rate was measured. The Indoor and outdoor temperature, wind velocity, and ventilation rates were also measured. The measurement method of IAQ was based on the MOE (Ministry of Environment Republic of Korea) measurement method. HCHO emission rate was measured two times every day. First measurement was conducted 30 minutes prior to operation of ventilation system and 30 minutes after quitting the ventilation system.

In case of infiltration only, HCHO emission rate was measured every day at the same time.

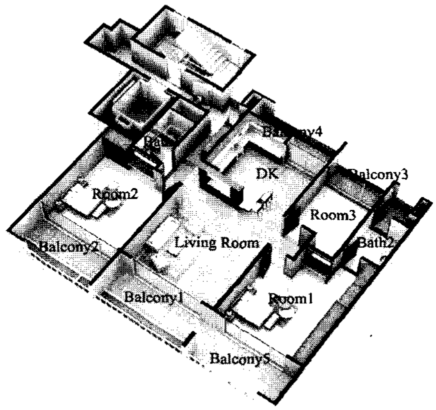

Fig. 3 Analyzed model.

Table 1 Measurement outline

Analysis Model	Multi residential building, 19/22F Location : Hwa-sung city, Korea Size : 125.4 m^2	
Measurement	*Item*	*Equipment*
	HCHO	Sampling 15l indoor air with Tenax -TA tube for 30 min using personal air sampler
	Indoor/outdoor temp. & RH	Data Logger (SK-SATO)
	Air-change rate	Multi-gas monitor, Constant concentration method (tracer gas : SF6)
	Indoor/outdoor wind speed measure	Anemometer
Sampling Condition	All openings(window, door etc)faced with the outdoor air were closed, while indoor openings were all opened. 1st : Measuring HCHO emission for 30 minutes under infiltration only. 2nd : Operating ventilation system for 5 hours 3rd : Measuring HCHO emission rate for 30 minutes under quitting ventilation system.	
Sampling Point	Height of sampling at the center of living room is 1.2-1.5m and detached more than 1m from the wall	

3.3 Simulation Conditions and Cases

Table 2 shows the simulation conditions used for the study. Simulation was performed based on the weather data of Seoul, which was made by the Society of Air-conditioning and Refrigerating Engineers of Korea (SAREK). Wind direction and velocity was set at south and 2 m/sec, which were the same as measurement condition.[7] The infiltration rate was fixed by 0.29 ACH with results of measurements. External HCHO concentration and indoor HCHO emission rate are based on results of measurements. Simulation time is 24 hours and the time step is five minute.

A total of six cases are analyzed in this study (see Table 3). Case 1 shows the results for the air current between rooms occurred by infiltration only, and Case 2 and 3 corresponds to the results for the ventilation system installed in living room and whole room respectively. Here, with the state of door opened and closed, the cases are divided into two sub-cases. The cases with -1 show the condition that the door between the rooms is opened. -2 represent the cases which the door is closed. Table 4. shows the air flow rate of ventilation system that is installed in each room. In whole rooms, the air change rate is set at 0.9 ACH constantly. It is based on the results of measurement.

Table 2 Simulation conditions

Weather data	30 years' weather data of Seoul with SAREK
Simulation period	24 hours, January 1
Outside wind direction	south
Outside wind speed	2 m/s constant
Infiltration rate	0.29 ACH (measurement data)
Outside HCHO concentration	0.004 mg/m^3 (measurement data)
Indoor HCHO emission rate	0.00001737 mg/m^{3}s

Table 3 Simulation Cases

	ventilation system		door state
	application	installed zone	
CASE 1-1	not applied		open
CASE 1-2	not applied		close
CASE 2-1	applied	living room	open
CASE 2-2	applied	living room	close
CASE 3-1	applied	whole room	open
CASE 3-2	applied	whole room	close

Table 4 Air change rate of ventilation system

zone	volume [m^3]	air flow rate [m^3/h]	air change rate [ACH]
Room 1	47.98	43.2	0.9
Room 2	39.96	36.0	
Room 3	26.28	23.7	
LDK	108.25	97.4	

3.4 Validation of Simulation Modeling

For the purpose of analytical validation for simulation modeling, the contaminant and air flow simulation results were compared with the measurement results. From the comparison between simulation and measurement results, the simulation modeling was modified to minimize the difference between the two, as results the crack length was adjusted mainly.

Measurement was accomplished in a condition that inner door were all opened.

Fig. 4 shows the contaminant (HCHO) concentration results with measurement and simulation at living room when the relatively fresh outdoor air is introduced by infiltration (0.29 ACH) only.

In Fig. 4, The 1st measurement was carried out at 3 : 35 PM and 2nd measurement was performed after 13 hours. Simulation conditions are the same as measurement condition.

As shown in Fig. 4, simulation results are

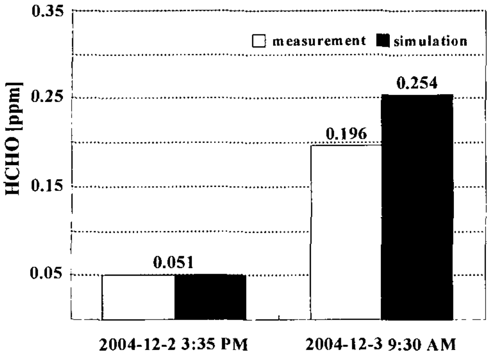

Fig. 4 HCHO concentration variation (Infiltration(0.29 ACH) only).

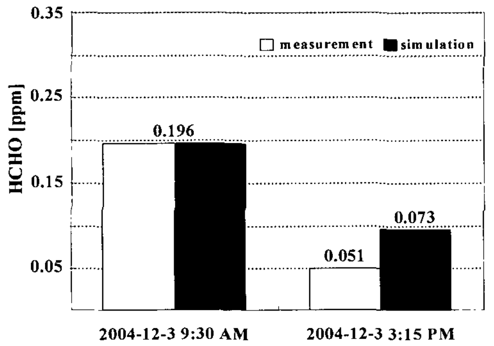

Fig. 5 HCHO concentration variation (with ventilation(0.9 ACH)).

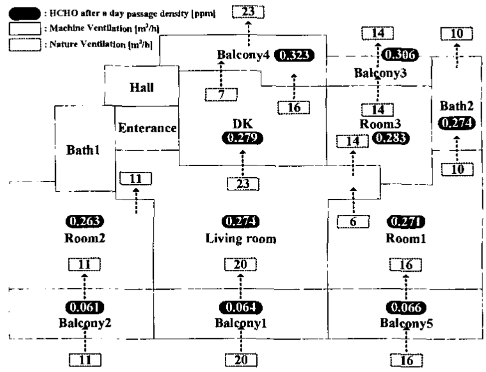

Fig. 6 Air flow and HCHO Concentration rate.

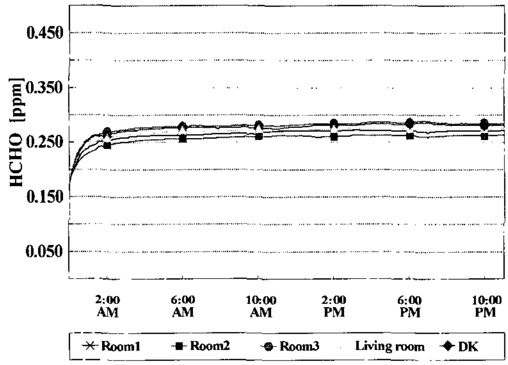

Fig. 7 HCHO concentration variation.

higher than measurement results. This difference is caused by the theoretical supposition of simulation that air and contaminants within a zone are fully mixed. However, in the case of actual measurement, contaminant distribution occurred according to the measurement points and different flow fields.

Fig. 5 shows the results of measurement and simulation for the change of HCHO concentration when ventilation systems were installed in whole room and operated with 0.9 times/h air-change rate.

In Fig. 5, the simulation results are somewhat higher than measurement results owing to the aforementioned reason. However, this difference is not high so much considering the measurement and analysis error. Moreover the variation pattern between simulation and measurement is similar. As results the simulation modeling which accomplished in this study were regarded as appropriate.

3.5 Simulation Results and Discussion

This paper presents the results of indoor air flow characteristics and change of contaminant concentration with the variation of air-change rate using network simulation method. And the difference of air flow whether inner door is open or not.

3.5.1 Air-flow between the Room and Change of HCHO Concentration with Infiltration only

1) Case 1-1 : Inner door open condition

Supposing that the contaminant generation

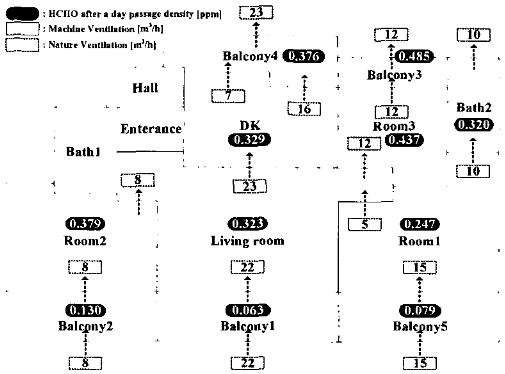

Fig. 8 Air flow and HCHO Concentration rate.

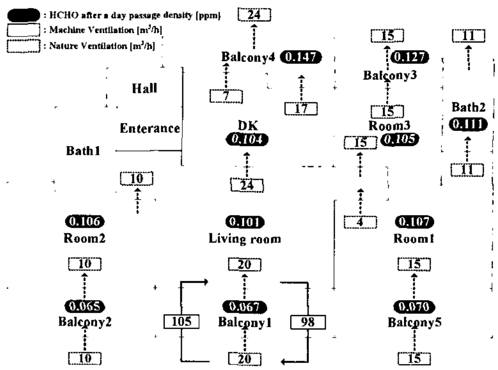

Fig. 10 Air flow and HCHO Concentration rate.

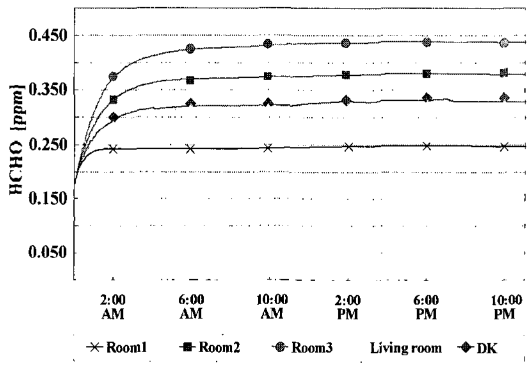

Fig. 9 HCHO Concentration variation.

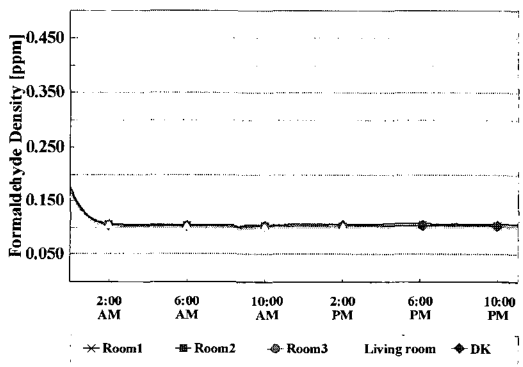

Fig. 11 HCHO concentration variation.

rate is set at constant in the whole room, the fresh outdoor air induced by infiltration only, and the concentration rate is almost equal in the whole room (see Fig. 6, Fig. 7).

2) Case 1-2 : Inner door closed condition

In this case, the contaminant generation rate and infiltration rate are the same as the case 1-1, in a condition that inner door is open, the characteristics of air flow and corresponding concentration rate of each room will be analyzed.

With a result that inner door is closed, the air flow rate is decreases than Case 1-1 and shows the tendency that each room contaminant concentration rising. Especially, in case of the room 2, as though contaminant generation rate is the same as another room, the contaminant concentration is higher than another room. This result can be explaining the pressure ascending in the room 2 close to the door and relatively small crack length than another room.

In case of the room 3, relatively contaminated air flows into room 3, the HCHO concentration higher than another room (see Fig. 8, Fig. 9).

3.5.2 Air-flow between the Room and Change of HCHO Concentration with Ventilation System in Living Room

1) Case 2-1 : Inner door open condition

The inflow rate of the air increased with the installation of a ventilation system (0.9 ACH) in the living room. Also, air flows smoothly as open the door of whole room. The contaminant concentration of the whole room is about 0.10

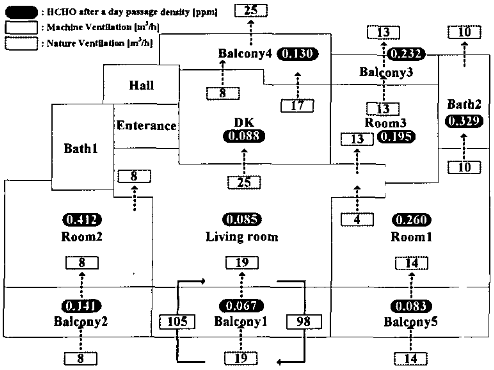

Fig. 12 Air flow and HCHO Concentration rate.

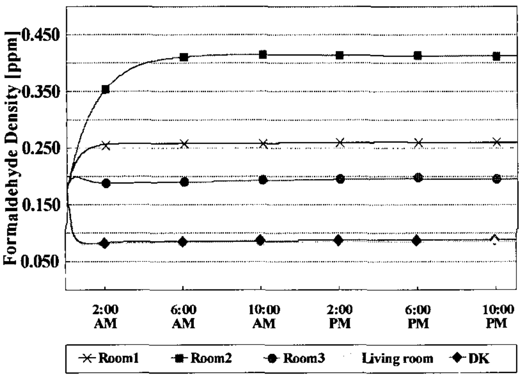

Fig. 13 HCHO Concentration variation.

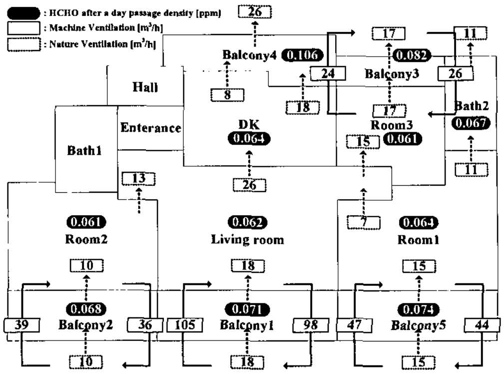

Fig. 14 Air flow and HCHO Concentration rate.

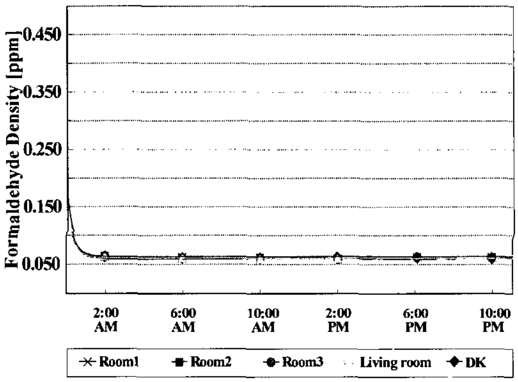

Fig. 15 HCHO concentration variation.

ppm. Compared with Case 1-1 the HCHO concentration is decreased below the half (see Fig. 10, Fig. 11).

2) Case 2-2 : Inner door closed condition

In this case, ventilation system is operated in living room only. As a result, the HCHO concentration of living room was decreased about 1/4 when compared with the results of Case 1-2 (infiltration only). While the concentration of room 1, room 2 was increased than that of Case 1-2. This is because that with operating ventilation system at living room the infiltration rate of Room 1, 2 was decreased according to the pressure rises of living room.

On the other hand, the concentration of room 3 was reduced as level of living room (see Fig. 12, Fig. 13).

3.5.3 Air-flow between the Room and Change of HCHO Concentration with Ventilation System in Whole Room

1) Case 3-1 : Inner door open condition

With installation of ventilation system in whole room, the inflow of outdoor air increases, about 0.9times/h air change rate.

Moreover all inner door were opened, the HCHO concentration shows the lowest value among the analyzed cases in this study (see Fig. 14, Fig. 15).

2) Case 3-2 : Inner door closed condition

Owing to the ventilation system operated in whole room, the HCHO concentration result in low level. From this result, the inner door condition could not affect the HCHO concen-

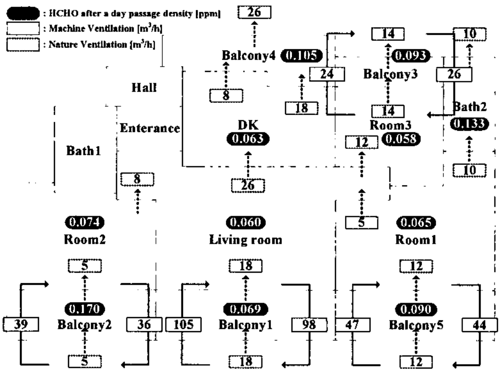

Fig. 16 Air flow and HCHO Concentration rate.

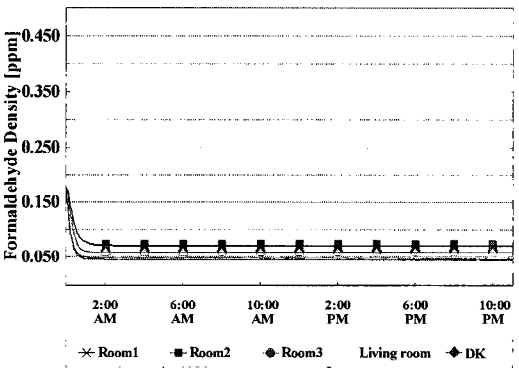

Fig. 17 HCHO Concentration variation.

tration in a state of operating the ventilation system in whole room.

Meanwhile, as seen from the Figure 16 the difference between inflow air and releasing air flow caused by the difference of air density (Fig. 16, Fig. 17).

4. Conclusions

In this study, the network based simulation method was coupled with contaminant simulation, using an integrated network simulation tool 'ESP-r'. The coupled simulation was first validated with experimental measurements. Indoor air flow and contaminant concentration between rooms were then analyzed when the door of each room was open and closed in the case of natural and forced ventilation. Integrated heating and cooling loads with indoor air flow and quality will also be presented in the near future.

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