SIMULATION-BASED PERFORMANCE ASSESSMENT OF SLIT-TYPE VENTILATION SYSTEM FOR DOMESTIC BUILDINGS IN KOREA

I. Yook [1], D. Kim [1], Y. Jung [2], J. Kang [2], S. Lee[2] and J. Kim [3]

[1]Department of Research and Development, DASS, Seoul, Korea
[2]Department of Building and Urban Research, Korea Institute of Construction Technology, Kyeonggi, Korea
[3]Energy Systems Research Unit, University of Strathclyde, Glasgow, UK

ABSTRACT

The airtight window system adopted in highrise residential buildings or residential-commercial complexes recently in Korea gives rise to poor ventilation, deterioration of Indoor Air Quality (IAQ) and the overloading of cooling systems during the summer season. To address these problems, a slit-type ventilation system has been developed. This study is to investigate the performance of the slit-type ventilation system using computer simulation. A thermal model coupled with an air flow network model which represents an apartment with an under-floor heating system was created. This thermal model was used to predict the energy demand and to obtain CFD boundary conditions for the evaluation of ventilation efficiency. Coupling detailed thermal simulation with CFD gave practical advantages in conducting a preliminary analysis to assess energy saving and ventilation effectiveness of the proposed slit-type ventilation system.

KEYWORDS

Slit-type ventilation, performance assessment, simulation, air-flow model, CFD

INTRODUCTION

Buildings and residential-commercial complexes in Korea are well-insulated, with double glazing and air tight window frames. Air tight window systems are likely to give rise to poor ventilation, Indoor Air Quality (IAQ) deterioration and an overload of cooling systems in the summer season. In order to address these problems, a slit-type ventilation system has been proposed. The slit-type ventilation system was designed to use natural ventilation by allowing outside air to enter through small slits in the window frames. It is based on the idea that by utilising wind pressure, a natural air flow inside the apartment can be created if an air path is properly established from the window. As can be seen in Figure 1, the prototype slit-type ventilation system uses slit-type openings (2~3 cm in height) in the external window frames. Internal doors also include similar slits or holes to facilitate the flow of air.

The aims of the slit-type ventilation system are as follows:

- to guarantee good IAQ by inducing a natural air flow based on pressure differences between the external and internal spaces;
- to minimize the load on mechanical ventilation systems; and
- to reduce the heating/cooling load.

The purpose of this study is to identify energy saving effects and ventilation performance of the proposed system using a computer simulation. Detailed thermal simulation and CFD were used to assess the energy saving performance, ventilation efficiency and air flow strategy of the system.

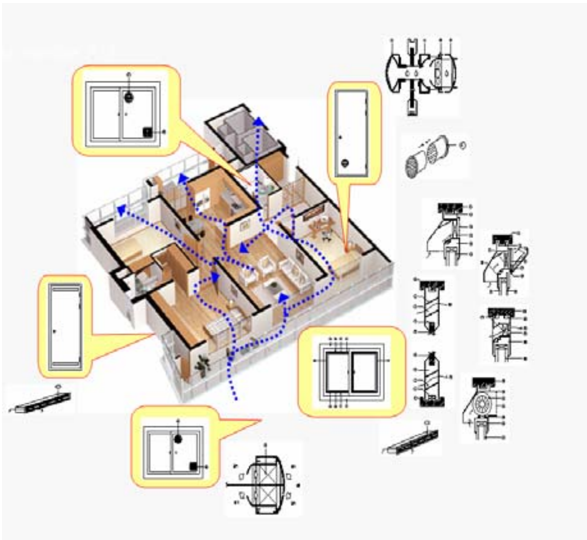

Figure 1 Concept and components of slit-type ventilation system

THERMAL AND AIR FLOW NETWORK MODEL

Simulation context

The climate data of Seoul was used for the simulation. The simulation period focused on the heating season. A typical apartment was selected for the geometric model shown in Figure 2.

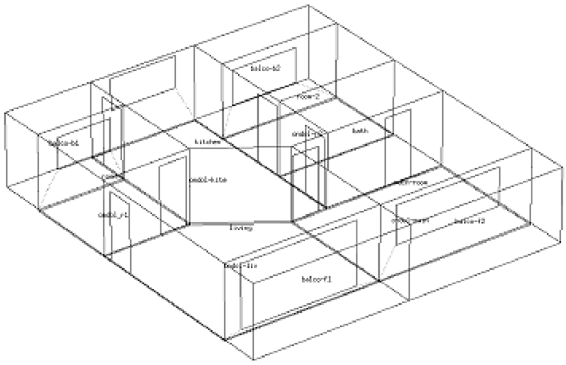

Figure 2 Geometric model for ESP-r analysis

Analysis procedure

This study examines the validity of the model during the heating period and analyzes the heating load and ventilation performance of the slit-type system. The analysis procedure is as follows.

- Heating load analysis of the under-floor heating system.
- Heating analysis according to the air change rate.
- Ventilation performance analysis on the Air Flow Network.
- Air distribution analysis inside rooms in the CFD simulation.

The CFD simulation was carried out on the basis of the external coupling method (Djunaedy et al. 2005).

'Ondol' (under-floor heating) model

The 'Ondol' model comprises two zones: a room and a virtual zone which represents the heat supply layer underneath the room between the construction layers of the floor. The control system (defined using the multi-sensor option in ESP-r) is equipped with two sensors located within the room and virtual zone. The control system actuates the water heating system in response to variations in the room temperature. The water supply temperature to the virtual zone can also be adjusted by users. The heating/cooling loads are obtained by calculating the heat flux required by the virtual Ondol zone to maintain stated room conditions. The conventional Ondol system, used as a reference model, was modelled in relation to a typical Korean apartment construction as illustrated in Figure 3.

To simulate the thermal characteristics of the analyzed model during the heating period, we assumed that there was a heat generating layer within the virtual zone under the residential space. Using the ESP-r multi-zone control method, the hot water (supplying temperature assumed to be 50℃) flow rate is adjusted to meet a temperature setting of 22℃ in the rooms.

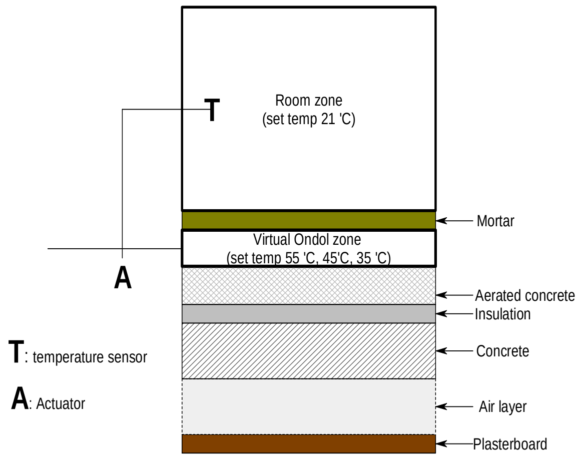

Figure 3 Ondol control model and structure of conventional Ondol layer

Table 1 Material and property of Ondol floor construction

Materials	Thermal conductivity (W/m℃)	Density (kg/㎥)	Specific heat (J/kg℃)
Plasterboard	0.210	910.0	1130.0
Mortar	1.510	2000.0	790.0
Glass wool	0.042	24.0	840.0
Concrete	1.400	2200.0	882.0
Aerated Concrete	0.175	600.0	1092.0

Figure 4 shows that the model represents the behaviour of the Ondol system well in terms of the thermal inertia of the floor construction, radiant heat exchange, convective heat transfer, etc. as judged against the experimental data seen in Figure 5. This modelling method was tested in a previous experimental study (Achermann and Zweifel, 2003).

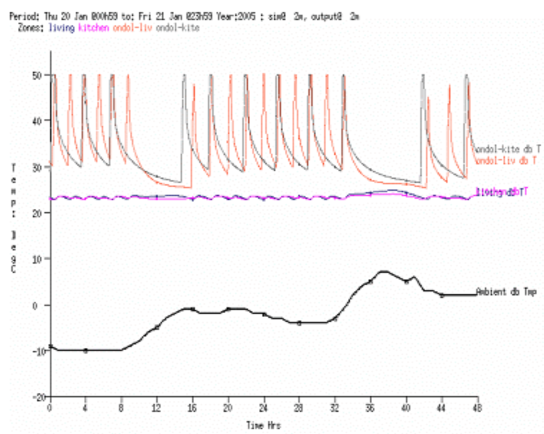

Figure 4 Temperature profile of Ondol model

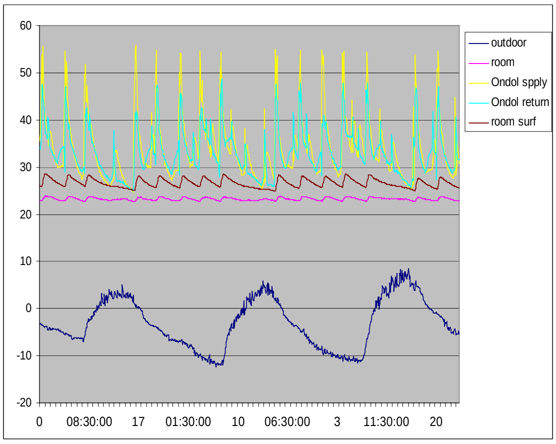

Figure 5 Temperature profiles of typical Ondol measured data

In Table 2, heating loads are compared with respect to the air change rate. This will be used as a reference to evaluate the efficiency and performance of the slit-type ventilation system.

Table 2 Comparing heating loads and energy consumption with respect to the air change rate

		living room	main room	room 1	room 2	kitchen	monthly sum
0.0 times	sum	188.98	660.5	78.8	242.7	407.2	1578.3
	avg	0.25	0.89	0.11	0.33	0.55	0.42
	max	2.17	2.12	0.84	1.04	2.39	2.39
0.2 times	sum	252.5	716.9	100.3	271.4	457.2	1798.3
	avg	0.34	0.96	0.13	0.36	0.61	0.48
	max	2.33	2.18	0.85	1.04	2.34	2.34
0.5 times	sum	347.7	798.77	131.1	314.5	535.6	2127.8
	avg	0.47	1.07	0.18	0.42	0.72	0.57
	max	2.50	2.18	0.89	1.06	2.32	2.50
1.0 times	sum	503.45	933.72	182.3	383.4	666.8	2669.9
	avg	0.68	1.26	0.25	0.52	0.90	0.72
	max	2.76	2.17	0.90	1.07	2.47	2.76

Air flow network model

To simulate the natural ventilation created by the outside wind pressure, the ESP-r air flow network model was made to examine the air change rate and energy consumption of each space with the change of ambient air pressure. The simulation period lasted one week from January 20th to January 26th. Wind velocity and wind direction data are used without consideration of external air pressure decreasing factors (building height, wind velocity change due to surroundings). Table 3 illustrates components and equations available in the ESP-r (ESRU, 2000). Figure 6 shows the airflow network model for this study.

Table 3 Components of airflow network model

	ESP-r code	Equations
Crack	120	$\dot{m} = \rho \cdot k \cdot \Delta P^{x}$ $x = 0.5 + 0.5\exp(-500 \cdot W)$ $k = L \cdot 9.7 \cdot (0.0092)^{x}/1000 \ (m^3/s \cdot Pa^{x})$
Opening	110	$\dot{m} = C_d A \sqrt{2\rho\Delta P}$, $C_d = 0.65$
Door	130	$\dot{m} = \dfrac{2\rho\left[\dfrac{C_d W H (\frac{2}{\rho})^{0.5} \cdot (C_a^{3/2} - C_b^{3/2})}{C_t}\right]}{3}$ $C_a = (1 - r_p) C_t + (P_n - P_m)$ $C_b = (P_n - P_m) - r_p C_t$ $C_t = g P_o H / R (1/\theta_m - 1/\theta_n)$
fan	30	$\dot{m} = \rho a$,

a	flow rate (m^3/s)	L	crack length (m)
$\dot{m}$	mass flow (kg/s)	C_d	discharge factor
ρ	density (kg/m^3)	P_o	standard air pressure (101325 Pa)
W	crack width (m) opening width (m)	R	gas constant (287.1 J/kgK)
H	opening height (m)	θ	point temperature (K)
r_p	H_r/H	H_r	height from the floor (m)
g	gravity acceleration (m/s^2)	H_n	the middle point height from the floor (m)

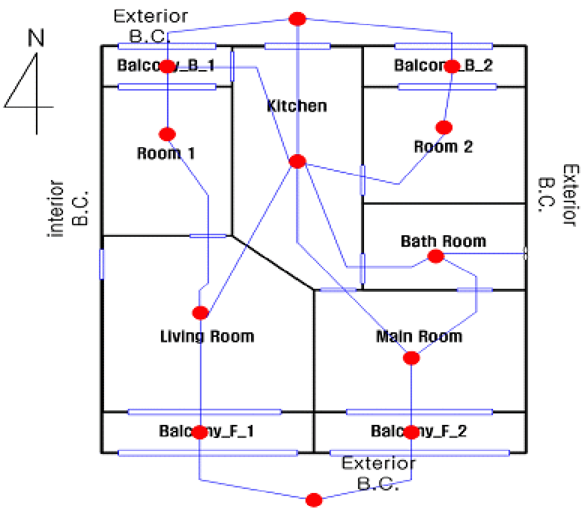

Figure 6 Airflow network model

Figures 7 and 8 show the air change rate of the slit-type ventilation system during the one-week period. In the case of natural ventilation, the air change rate is from 0.05 to 0.5 AC/hour and is largely affected by external wind speed. In the case of mechanical ventilation, the air change rate is from 0.2 to 0.4 AC/hour which is relatively constant. The air change rate in the main room is the lowest. It implies that a ventilation strategy is needed to guarantee a certain degree of air change rate throughout all spaces.

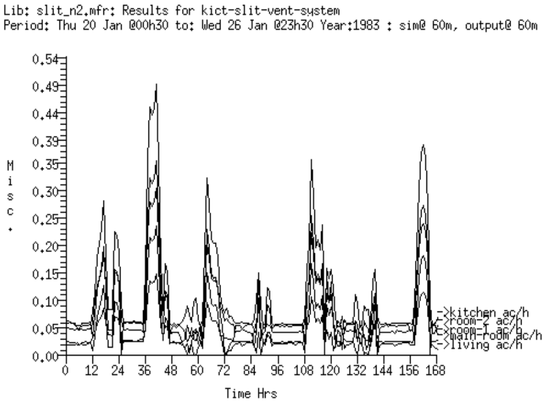

Figure 7 Air change rate of the slit-type ventilation system in the case of the natural ventilation

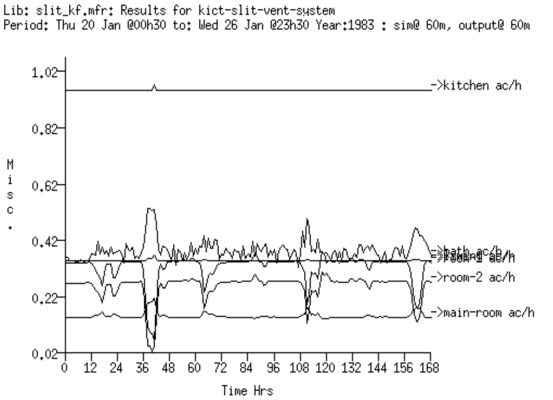

Figure 8 Air change rate of the slit-type ventilation system in the case of the mechanical ventilation

Tables 4 and 5 indicate the heating load and energy consumption changes with respect to the air change rate in the kitchen or bathroom. It is shown that energy consumption increases in proportion to the air change rate. The increasing rate is, however, relatively trivial and both fans in the kitchen and bathroom give similar results.

In Table 6, the air change rates of each room are defined by various conditions. From these results, the average air change rate of each room is dependent upon the fan location as well as the fan capacity.

Table 4 Energy load and consumption with respect to the change of fan capacity in the kitchen (slit height 20 mm, opening area 0.25 m^2)

air change rate	KWh /KW	living room	main room	room 1	room 2	Kitchen	Sum
0.2AC/h	sum	33.17	142.31	147.1	158.6	174.9	656.2
	avg	0.20	0.85	0.88	0.94	1.04	0.78
0.5AC/h	sum	32.35	144.92	148.4	159.8	177.9	663.4
	avg	0.19	0.86	0.88	0.95	1.06	0.79
1.0AC/h	sum	36.68	148.1	150.3	161.8	182.7	679.8
	avg	0.22	0.88	0.89	0.96	1.09	0.81

Table 5 Energy load and consumption with respect to the change of fan capacity in the bathroom (slit height 20 mm, opening area 0.25 m^2)

air change rate	KWh /KW	living room	main room	room 1	room 2	kitchen	sum
0.2AC/h	sum	32.66	142.2	146.7	158.4	174.0	654.2
	avg	0.19	0.85	0.87	0.94	1.04	0.78
0.5AC/h	sum	32.02	144.6	147.1	158.9	174.9	657.7
	avg	0.19	0.86	0.88	0.95	1.04	0.78
1.0AC/h	sum	32.02	147.7	147.2	159.5	176.0	662.7
	avg	0.19	0.88	0.88	0.95	1.05	0.79

Table 6 Air change rate subject to various conditions

			living room	main room	bath room	room 1	room 2	kitchen
bath-room fan capacity	0.2 AC/h	avg	0.07	0.05	0.20	0.09	0.04	0.13
		max	0.29	0.18	0.20	0.27	0.23	0.46
		min	0.03	0.01	0.20	0.00	0.00	0.07
	0.5 AC/h	avg	0.11	0.06	0.50	0.10	0.05	0.24
		max	0.31	0.19	0.50	0.22	0.19	0.52
		min	0.05	0.00	0.50	0.00	0.00	0.20
	1.0 AC/h	avg	0.17	0.08	1.00	0.15	0.10	0.44
		max	0.33	0.21	1.00	0.21	0.16	0.61
		min	0.10	0.04	1.00	0.01	0.00	0.42
kitchen fan capacity	0.2 AC/h	avg	0.08	0.05	0.16	0.11	0.07	0.22
		max	0.20	0.13	0.33	0.40	0.34	0.38
		min	0.05	0.03	0.05	0.00	0.00	0.20
	0.5 AC/h	avg	0.19	0.09	0.23	0.17	0.12	0.51
		max	0.28	0.17	0.44	0.29	0.25	0.63
		min	0.18	0.07	0.12	0.01	0.00	0.50
	1.0 AC/h	avg	0.37	0.16	0.41	0.34	0.27	1.00
		max	0.38	0.22	0.56	0.40	0.32	1.00
		min	0.37	0.15	0.34	0.08	0.03	1.00

CFD SIMULATION

As presented above, the detailed thermal simulation provided a prediction of the impact of the slit-type ventilation system on energy demand and air change rate. Another issue affecting the adoption of the system is thermal comfort and air movement in rooms. For example, during the winter season, cold air entering through the slit may cause cold drafts and make occupants feel uncomfortable. In order to test this possible problem, a CFD simulation was carried out to examine the indoor thermal environment (temperature and velocity distributions).

Model and boundary conditions

The geometric model for CFD simulation is based on that of the ESP-r. Figure 9 shows this CFD geometric model. To define the boundary conditions for the CFD simulation, the results of the ESP-r thermal simulation were used. As the boundary conditions can be obtained at any time through the year, the thermal environment affecting occupants can be simulated for any circumstances. Tables 7 and 8 present examples of CFD boundary conditions gained from the ESP-r thermal simulation. By using the outcomes of thermal simulation, it is expected that the dynamic thermal environment inside the rooms can be represented in the CFD model with more accuracy. CFD simulation results are shown in Figures 11 to 15, focusing on the distribution of air temperature and velocity inside.

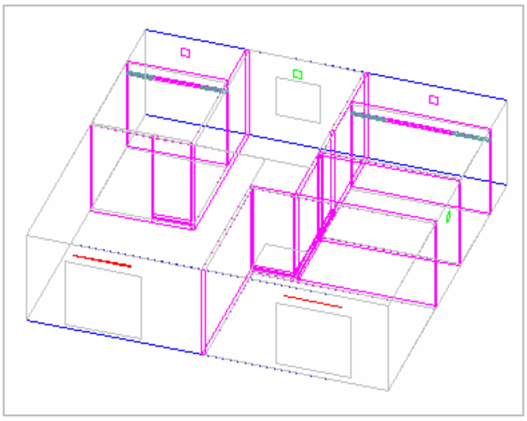

Figure 9 CFD model (3d view).

Table 7 Boundary conditions for CFD simulation (Temperatures)

LOCATION	TEMPERATURE (℃).
living room	20.58
main room	21.40
bathroom	18.53
room 1	20.68
room 2	21.14
kitchen	21.51
southern balcony 1	3.98
southern balcony 2	4.57
northern balcony 1	2.29
northern balcony 2	2.29
southern outside air	-10.00
northern outside air	-10.00

Table 8 Boundary conditions for CFD simulation (Velocity of air entering through the slits).

ENTRANCE CONDITION	WIND VELOCITY (m/s)
Slit 1 (living room windows)	0.0957
Slit 2 (main room windows)	0.043

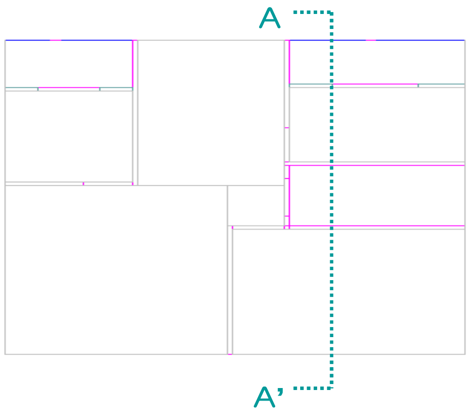

Figure 10 Cross-section position.

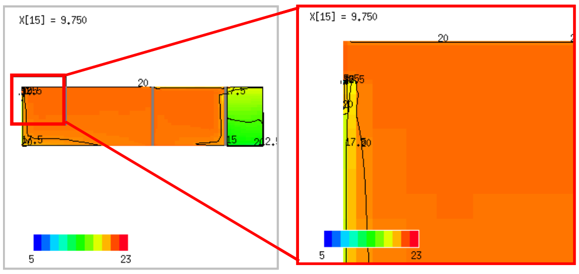

Figure 11 Local temperature distributions around the slit (A-A’ cross section)

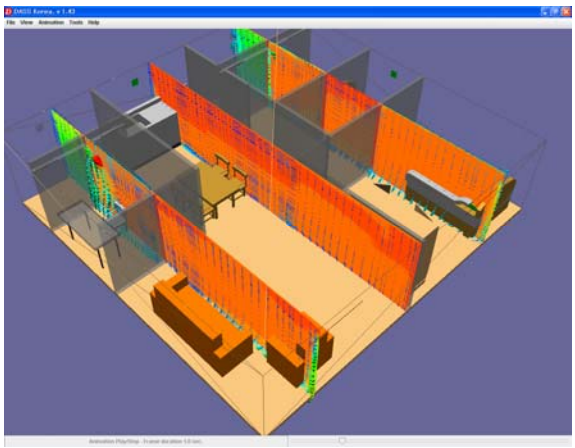

Figure 12 Local temperature distribution in 3D model

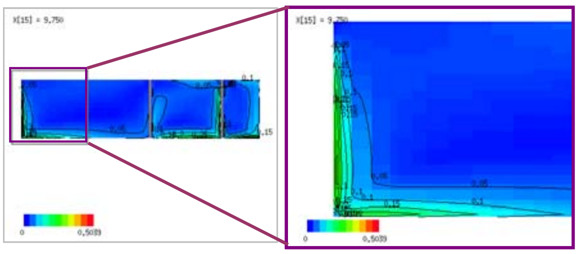

Figure 13 Local velocity distribution around slit

(A-A’ cross section)

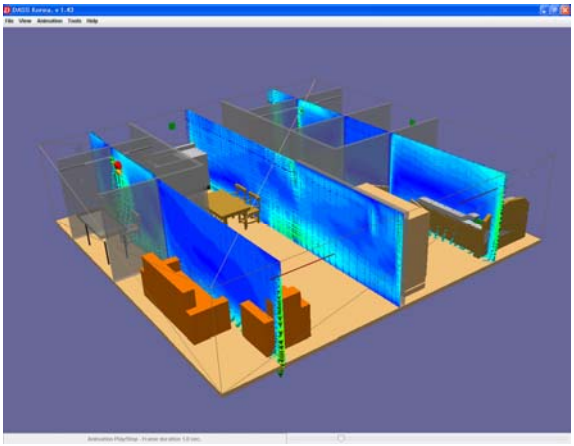

Figure 14 Local velocity distribution in 3D model

Analysis of local air temperature and velocity characteristics

The main purpose of the CFD simulation is to test any impact of the slit-type ventilation system on occupants in terms of thermal comfort. Figure 11 illustrates the temperature distribution around the slit while Figure 12 shows the temperature distributions in three vertical sections. The temperature of the air entering from the balcony is around 4℃ (according to ESP-r simulation) with the outside temperature being -10℃. As can be seen, due to the small volume of external air, it does not affect the internal air temperature distribution significantly.

Meanwhile, the velocity distributions in the space are illustrated in Figures 13 and 14. The air velocity in the space is mostly less than 0.1m/s. This indicates that the air movement caused by the slit opening is minimal and occupants in the rooms may not feel much air movement.

It implies that the air movement and temperature change caused by the slit doesn't make a significant impact on thermal comfort. In addition, with an under-floor heating system, the occupants thermal comfort is more associated with floor surface temperature.

CONCLUSION

This study was conducted to evaluate slit-type ventilation system performance and efficiency. The following results were found:

- In the case of natural ventilation, the range of air change rates were from 0.05 AC/hr to 0.5 AC/hr. The air change rates can be affected by the location and surroundings of the building where the slit-type ventilation system is installed.
- With mechanical ventilation, the location of fans is important as well as their ability to balance air change rates between rooms. In order to make the slit-type ventilation system more energy efficient, it is required to design an air flow strategy when installing the system, especially, in a house with many rooms.
- In terms of thermal comfort, no significant impact has been found. It is expected that the small volume of air change (i.e. convective heat exchange) is tolerable. However, experimental study is also necessary to make sure the impact on the occupants' thermal comfort is minimal.

It was found that the simulation procedure of coupling a thermal model with a CFD model provided technical advantages in handling the CFD simulation. For example, the slit-type opening generates tiny mesh elements which results in a huge number of cells. This created a problem in the amount of time needed to perform the necessary calculations. By taking the environment results simulated from the ESP-r, the CFD simulation could be carried out much more efficiently.

REFERENCE

Achermann, M., Zweifel, G. (2003), RADTEST - Radiant Heating and Cooling Test Cases:a report of Task 22, subtask C, Building Energy Analysis Tools Comparative Evaluation Test, IEA.

Clarke, J. A. (2001), Energy Simulation in Building Design 2nd, Butterworth-Heinemann, pp. 256-261.

Hensen, J. L. M (1999), A comparison of coupled and decoupled solutions for temperature and air-flow in a building, in ASHRAE Transactions, vol. 105:2, pp 962-969

Hensen, J. L. M. (2004), Integrated building airflow simulation, in Advanced Building Simulation, A. Malkawi &G. Augenbroe, eds., Spon Press, New York, pp. 87-118.

Djunaedy, E., Hensen, J. L. M., & Loomans, M. (2005). External coupling between CFD and energy simulation: implementation and validation, ASHRAE Transactions, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, vol. 109, pp. 612-624

ESRU, (2000), 'ESP-r: A Building and Plant Energy Simulation Environment, User Guide Version 9 Series', ESRU Publication, University of Strathclyde, Glasgow.

DASS, (2005), Cflo3 User manual