APPLICATION OF COUPLED SIMULATION BETWEEN BES-CFD FOR NATURALLY VENTILATED RESIDENTIAL BUILDINGS

Hyungkeun Kim[1], Jung Haw[1], Taeyeon Kim[1] and Seung-Bok Leigh[1]

[1]Center for Sustainable Buildings, Department of Architectural Engineering, Yonsei University, Seoul, Republic of Korea

ABSTRACT

Natural ventilation performance can be assessed with computer simulation. Generally, there are two types of computer simulation methods: BES (Building Energy Simulation) and CFD simulation. In order to supplement each simulation's weaknesses, the integration of energy simulation and the CFD program was recommended. Through the integration of BES and CFD simulation, this study analyzes the thermal environment of apartment housing to which natural ventilation is applied. The efficiency of the coupling method is analyzed by comparing the results of coupling with those of BES. Also examined is the utility of the airflow rate, set as the transfer element greatly influencing the results of coupling interpretation under certain conditions.

Due to certain natural ventilation conditions that make it impossible for BES to perform an accurate calculation of airflow rates, the results were compared with the airflow rate taken into account as an important factor. Under the condition with higher airflow rates, since heat transfer due to airflow is dominant, the convective heat transfer coefficient does not have a significant influence.

Key-word : Building Energy Simulation(BES), Computational Fluid Dynamics(CFD), Coupled simulation, Natural ventilation

INTRODUCTION

Natural ventilation is one of the core elements of green buildings. It aims to secure a wholesome indoor air quality and enhance cooling efficiency in summer. Natural ventilation strategies are often formed with a focus on indoor air quality, but their application, when expanded to cooling efficiency, can help create a pleasant thermal environment with less energy consumption for cooling. Natural ventilation performance can be assessed with experimentation and computer simulation. In recent years the latter method has been used in numerous studies, since field experiments tend to incur high costs. Generally, there are two types of computer simulation methods: BES (Building Energy Simulation) and CFD simulation.

BES is a tool to assess building energy performance. Natural ventilation performance is calculated to assess the indoor thermal environment, which is needed to measure energy consumption. With each room set as a node, the natural ventilation rate per room is computed on the basis of the airflow network model in which one room is connected to another. However, given BES, it is impossible to achieve an interpretation of airflow that accurately reflects each room's shape, which is simplified in the process of calculating natural ventilation performance. Moreover, it is difficult to make an accurate analysis of the indoor thermal environment since heat transfer cannot be analyzed in detail(Zhai et al. 2002).

On the other hand, CFD simulation enables a precise interpretation of airflow through a governing equation with the generation of in-building fluid domain. A more detailed analysis of airflow can be attained with such a precise interpretation. This simulation will yield results regarding detailed indoor and outdoor airflow, temperature, contaminant distribution, and heat transfer. Much research has recently been done on the indoor and outdoor air environment. Compared to BES, however, an interpretation based on CFD simulation takes a longer time as fluid domain grows larger. Another shortcoming of this method lies in its difficulty with defining the boundary conditions needed for interpretation (Negrão 1998).

In order to supplement each simulation's weaknesses, the integration of energy simulation and the CFD program was recommended (Clarke and Tang 1990). Simulation integration makes it possible to achieve an interpretation reflective of more realistic conditions by exchanging information between simulations that run coupling on the values that were interpreted contingent upon each separate simulation (Djunaedy et al. 2003). With this coupling of simulations, an interpretation can be made by utilizing the results of CFD interpretation at each timestep of interpretation even without interpreting an unsteady state. Consequently, this integration offers the advantage of reducing a substantial amount of time considering the degree of accuracy required in interpretation (Zhai et al. 2001).

First, energy simulation can provide information on the boundary conditions needed for CFD, including weather data and wall surface temperature. A CFD tool can in turn send accurate airflow conditions and the convective heat transfer coefficient to the energy simulation with a more precise interpretation of numerical values and the calculation of a turbulence model that are based on these boundary conditions received from the energy simulation (Zhai and Chen 2004). This iterative process facilitates an analysis of the thermal environment for more accurate interpretation space.

However, methods are needed to determine an efficient timestep in accordance with the interpretation results, since the integration still takes a long period of simulation. Z. Zhai and Q. Chen divided coupling methods largely into static and dynamic coupling (Zhai and Chen 2005). Coupling became more efficiently applied with a variety of simulation strategies.

In addition, integration study of multi-zone model and CFD simulation were performed for the evaluation of natural ventilation in a building. (Tan and Glicksman 2005) Then, study of internal coupling method was performed to analyze indoor air distribution and thermal condition.(Wang and Wong 2008) In recent years, natural ventilation performance was analyzed through the BES and CFD simulation that is connected to the coupling interface to perform with external coupling method.(Wang and Wong 2009)
Eventually, energy performance of the buildings can be predicted more accurately using BES-CFD coupled simulation.(Fan and Ito 2012)

Through the integration of BES and CFD simulation, this study analyzes the thermal environment of apartment housing to which natural ventilation is applied. The efficiency of the coupling method is analyzed by comparing the results of coupling with those of BES. Also examined is the utility of the airflow rate, set as the transfer element greatly influencing the results of coupling interpretation under certain conditions.

SIMULATION STRATEGIES

BES model

In order to analyze the thermal performance of apartment housing, this study utilizes EnergyPlus developed by the US DOE(Department of Energy).

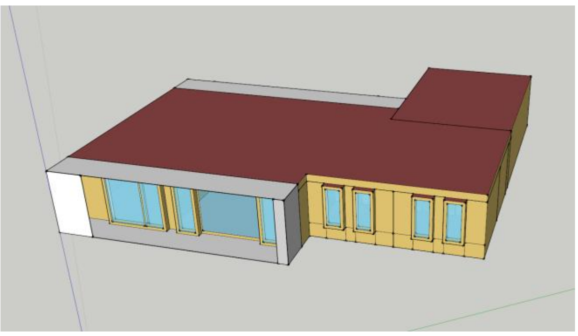


Figure 1. Simulation modelling for BES

Table 1. Analysis parameters of BES

PARAMETER	VALUE
Solar distribution	Full Interior And Exterior
Heatbalance Algorithm	Conduction Transfer Function
Timestep	5 min
Run Period	Summer : Aug 21st~22nd(2days) Fall : Oct 13th~14th(2days)
Internal Gains	Living room : 115 W Room 2 : 60 W Room 3 : 60 W

Table 2. Description of materials

LOCATION	MATERIAL	THICKNESS
Outer wall	Finishing coat	10
	Mineral wool	110
	Concrete	200
	Air gap	
	Gypsum board	9.5
Inner wall	Gypsum board	12.5
	Air gap	
	ALC	150
	Air gap	

As for the analysis of its indoor thermal environment, the airflow network model of EnergyPlus is put to use. The sample building, divided into several zones, is assessed in terms of ventilation and thermal performance.

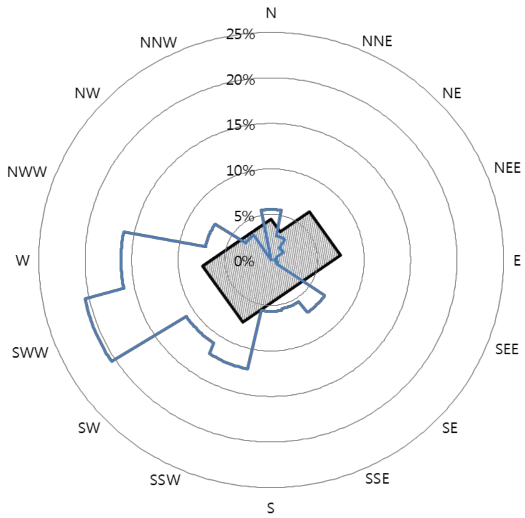
Figure 1 illustrates the modeling designed to interpret the energy of the subject apartment housing, located in the city of Incheon, Korea. The weather data of the area for the study reflects field measurement values. Each room is marked as a separate zone, the ceiling plenum distinguished from each room. The balcony space, without the installation of outside windows, is not counted as a separate zone. Only in consideration of sun screening are exterior awnings installed in it.

The interpretation of simulation is conducted two days in summer and in fall, respectively. The indoor space is tested under the condition of non-occupancy, and thus the simulation does not require an additional internal heat load besides a device for field measurement. Table 1 lists the conditions for BES interpretation and Table 2 shows the materials and details of each building part. Each window has a different degree of insulation performance due to double glazing.

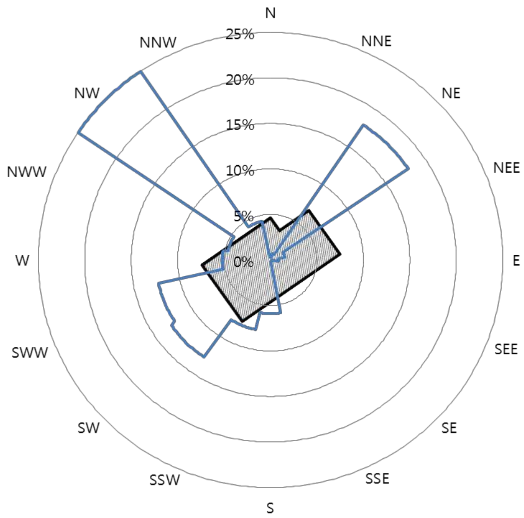
$$\sum_{i=1}^{N} q_{i,c}A_i + Q_{Vent} + Q_{other} - Q_{heat-extraction} = \frac{\rho V_{room} C_p \Delta T}{\Delta t} \quad (1)$$

$$q_{i,c} = h_c(T_i - T_{room}) \quad (2)$$

EnergyPlus allows the interpretation of indoor thermal performance by calculating both surface heat transfer and heat transfer via other factors such as ventilation. The following equation (1) is the energy



(a) Summer



(b) Fall

Figure 2. Wind data

balance equation used in BES. The first term represents convective heat transfer on the surface, the rate of which is calculated from the following equation (2).

Since this study intends to analyze the indoor thermal environment depending on the degree of natural ventilation, heat transfer driven by natural ventilation becomes an important factor. In this case the airflow rate and indoor and outdoor temperature differences have an impact on the thermal environment. Heat transfer through natural ventilation is formulated in the following equation (3).

$$Q_{Vent} = \dot{m}_{vent} C_p (T_{out} - T_{room}) \qquad (3)$$

Here it should be noted that the airflow rate has a great influence. In BES simulation, the airflow rate is computed on the basis of pressure differences among separate zones. The calculation of the airflow rate and pressure differences of a building are made in the following equations (4) and (5).

$$\dot{m}_i = C_i \rho \frac{\Delta P_i}{\mu} \qquad (4)$$

$$\Delta P = \left(P_n + \frac{\rho V_n^2}{2}\right) - \left(P_m + \frac{\rho V_m^2}{2}\right) + \rho g (z_n - z_m) \qquad (5)$$

According to the equations shown above, pressure differences greatly influence the computation of a building's airflow rate. In the case of energy simulation, it may be difficult to calculate the airflow rate under certain conditions. Figure 2 indicates the wind data of the subject site. The orientation of the building is to the southeast. In the test for fall, the main wind blows from the northwest, perpendicular to the building. However, the main wind, changing to a southwesterly direction in summer, blows parallel to it. In energy simulation, a building is construed as a simple rectangular shape, which makes it hard to calculate the pressure differences between a building's front and rear surfaces. In this case, therefore, a coupled simulation that takes the airflow rate into account needs to be done.

CFD model

This study analyzes indoor airflow and the thermal environment with the application of CFD simulation. CFD modeling involves simulating the entire building and obstacles in the vicinity, as well as apartment interior space, in order to simulate the introduction of natural ventilation varying with the outdoor wind environment. Despite requiring a lot of time and computer resources, the interpretation of indoor and outdoor integration is known to provide more reliable results. The entire fluid domain is modeled in a way that the surface of inlet and outlet boundary conditions is separated from the outermost obstacle by 10 times the height of the studied building and the surface of the upper symmetry boundary conditions is apart from the building's uppermost part by four times its height. For the analysis, the grid of exterior space is generated coarsely, while that of interior space requiring a precise heat analysis is created densely.

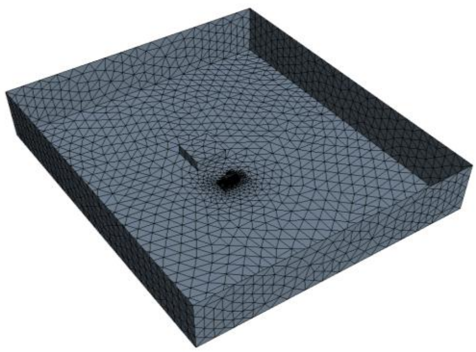


Figure 3. The CFD model of residential building

Table 3. Boundary condition of CFD

Turbulence model	Standard k-ε low Reynolds number model
Total cell number	Summer : 883,508 Fall : 1,055,808
Domain size	435m × 508.5m × 90m
Convergence tolerance	10E-03
Wind profile	$\mathrm{U} = U_0 \times \left(\frac{Z}{Z_0}\right)^{\alpha}$ α = 0.22

Figure 3 shows a mesh model of the space to be analyzed.

In order to conduct a precise analysis of the indoor thermal environment, the standard k-ε low Reynolds number model is used that allows a more precise interpretation of heat transfer on the surface. The low Reynolds number model is a method by which the effect of surface viscosity is more accurately analyzed with the dense generation of a surface grillage. Compared to the high Reynolds number model that computes an approximate surface grid by the wall function at the surface, it takes a longer computation time but assures a more precise heat analysis calculation. Table 3 lists other conditions applied to CFD simulation.

Coupling strategies

The coupled simulations of BES and CFD are performed in order to analyze the indoor thermal environment affected by natural ventilation. As mentioned earlier, BES requires detailed information on the airflow and thermal condition of a building's surroundings that can be computed in CFD simulation, in order to achieve a more accurate analysis of the indoor thermal environment. Simulations are created with BES at the center, so that the CFD program can provide information needed for the former. Coupled simulations are conducted with the quasi-dynamic coupling method designed for their efficient implementation.

Table 4. Case analysis

CASE	APPROACH	TRANSFER ELEMENTS
Case 1	BES	-
Case 2	BES-CFD coupled	h_c, airflow rate
Case 3	BES-CFD coupled	airflow rate

With the timestep of BES set at 5 minutes, a coupled simulation of BES and CFD is run every hour at the time when natural ventilation takes place. It is the moment that BES provides CFD simulation with information on the wind direction and speed in the surroundings of the building, the outdoor temperature, and the surface temperature of each indoor wall. The CFD program then conducts analysis by applying this information to the boundary conditions. Once the simulation results are converged, CFD simulation imparts the airflow rate and convective heat transfer coefficient. In the course of this process, BCVTB (Building Controls Virtual Test Bed) (July 17, 2008), the integration interface program created by the Lawrence Berkeley National Lab in the US, is used.

As stated before, the airflow rate is a factor crucial to the analysis of the indoor thermal environment in the cases examined in this study. The speed of indoor airflow tends to increase as natural ventilation is smoothly achieved. In that case, heat transfer by wind-driven force may have a greater effect than surface heat transfer. Therefore, it is assumed that computing the convective heat transfer coefficient in BES itself and transferring only the indoor ventilation could be more efficient. Under this assumption, this study carries out three cases of simulation. Case 1, energy simulation, compares the accuracy of coupled simulation. Analysis is

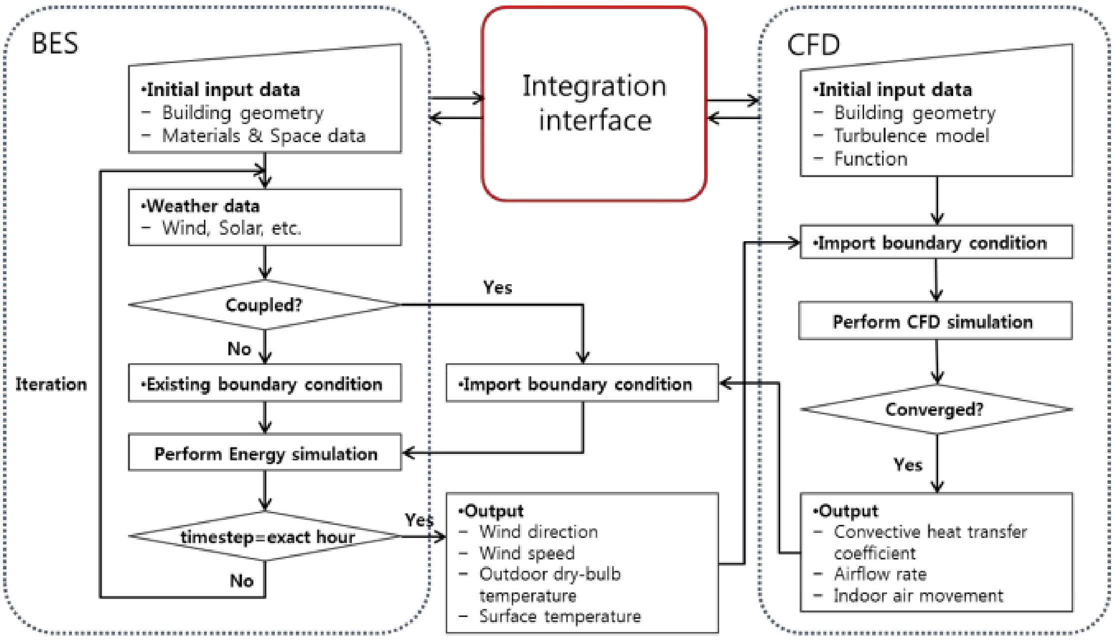


Figure 4. Coupling strategies

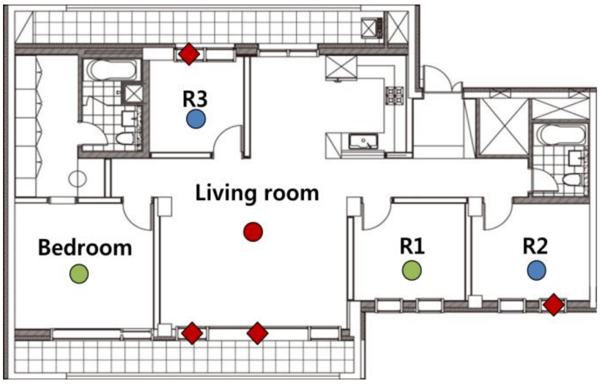


Figure 5. Location of measuring points

performed to find out the impact of ventilation with coupled simulation classified into two types. In Case 2 the convective heat transfer coefficient and ventilation are both transferred, while in Case 3 the convective heat transfer coefficient is set and executed as a BES internal value and only ventilation is transferred.

Field Measurement

Field measurement was conducted in this study to validate the simulation results. A living room and room 2 that is located close to the front of the apartments are selected for the study, and the indoor and radiant temperatures and the surface temperatures of walls, ceilings, floors, and window glass are measured. For the rooms installed with double windows, the temperature of the cavity space is additionally measured. Relative humidity and airflow speed are measured only in the living room. For an additional analysis, a hot wire anemometer is installed in bedrooms 2 and 3 in the same direction as the main wind. Figure 5 shows the measurement points.

In order to analyze the indoor thermal environment of an intermediate season, this study conducts field

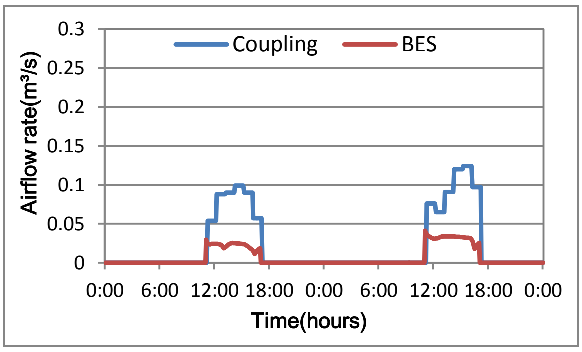


Figure 6 Airflow rate in fall condition

measurement by selecting 2 days in mid-October during which the outdoor temperature is distributed close to the lower limit of the indoor thermal comfort zone. The operation of windows is carried out largely in the daytime and at night, and the windows are kept open from 10:30 a.m. to 5 p.m., a time period when natural ventilation is expected to occur. In this case all the awnings are taken down to augment the sun's radiation.

To assess the indoor thermal environment of summertime, field measurement is done with the selection of two scorching summer days when the sun's radiation is greatest and outdoor temperature is high. Field measurement is carried out in two steps: a day with the indoor space tightly sealed and another one under maximum ventilation. The sealing of indoor space, done with all the windows and entrances closed and the awnings put up, is aimed at evaluating changes in the indoor thermal environment depending on the availability of natural ventilation. The condition for maximum ventilation is secured with the venetian blinds pulled aside, since the blinds can hinder the maximization of natural ventilation.

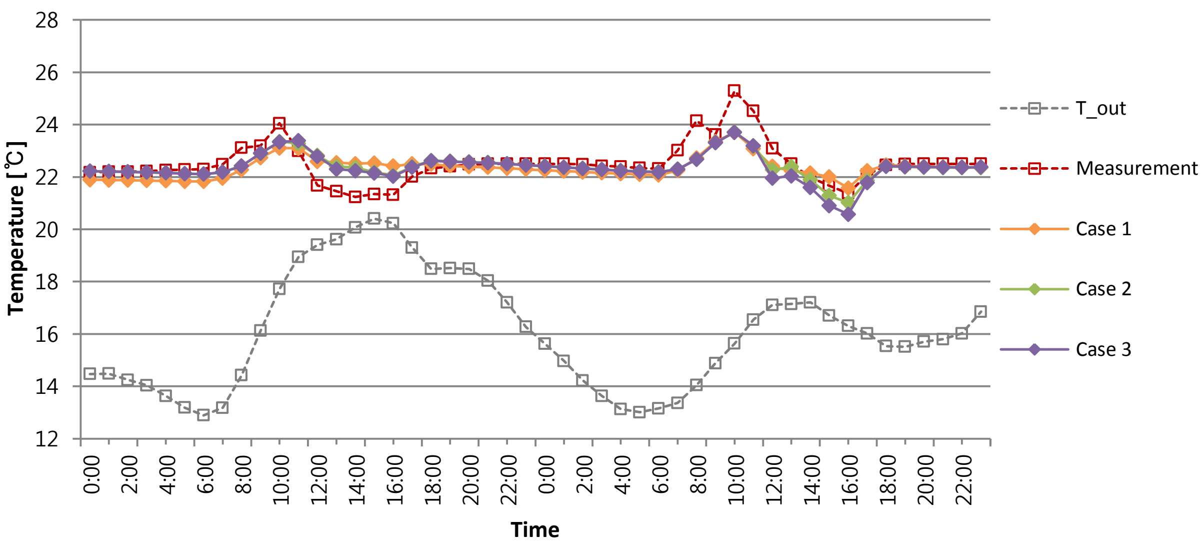


Figure 7. Indoor air temperature of room 2 in fall condition

SIMULATION RESULTS

Fall condition

The comparison of the simulation results is made by examining the results of room 2, in which natural ventilation has occurred relatively smoothly. Figure 6 shows a graph comparing the indoor airflow rates in fall under the coupling method with those under BES. According to the graph, the airflow rate in the coupled simulation is in the neighbourhood of 0.1m^3/s. Although BES records a lower airflow rate than the coupling method, it is expected that airflow will not have much influence because of the low airflow rates.

Figure 7 shows the indoor temperatures of each case. From the examination of Case 1 (the BES results) and Cases 2 and 3 (both the coupled simulation results), it is learned that the latter two cases indicate results closer to the field measurement findings than the former case. It is ascertained that the results of Case 1 are generally similar to the others. The BES results, however, take on a pattern disparate from the field measurement results gained at the time of natural ventilation, whereas the coupled simulation results exhibit a pattern comparatively similar to those of field measurement.

The comparison between Case 2 (where the airflow rate and convective heat transfer coefficient are both provided) and Case 3 (where only the airflow rate is set as a transfer factor) shows that both cases record similar values at most timesteps. The BES results, though not deviating to a great extent from the field measurement results, are found to not have their impact clearly reflected at the time when natural ventilation occurs.

In fall condition, however, it is difficult to conclude that coupled simulation is better prediction than BES, because the difference among 3 cases are not quite noticeable.

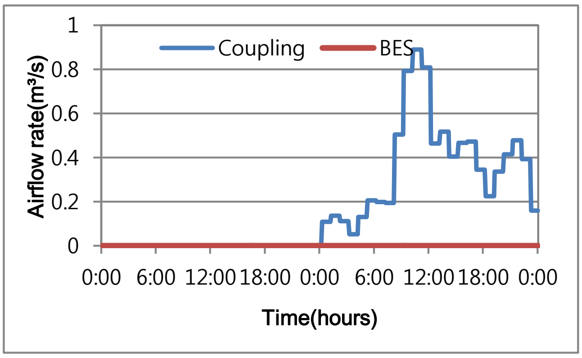


Figure 8. Airflow rate in summer condition

Summer condition

As mentioned earlier, it was expected that with BES simulation an accurate calculation of airflow rates for summer would not be achieved due to the building orientation. Figure 8 below indicates the airflow rates of BES and of coupled simulation in summer. The graph confirms BES results that are indicative of airflow rates hovering around 0. As stated above, this lack of clear reflection of airflow rate can be attributed to the wind direction being parallel to open windows. The airflow rates in summer are greater than those in fall, reaching a maximum of 0.8m^3/s. As a result, the airflow rate can be viewed as a more important factor.

Figure 9 shows the summertime indoor temperatures of each case. An examination of Case 1 (BES results) and Cases 2 and 3 (coupled simulation results) indicates the results of the latter cases to be closer to the field measurement results than those of the former case. The margin of error is larger than in fall. There appears a particular time of ventilation when the difference between Case 1 and the field measurement results is greater than 2℃.

A comparison between Case 2 (where the airflow rate and convective heat transfer coefficient are both provided) and Case 3 (where only the airflow rate is

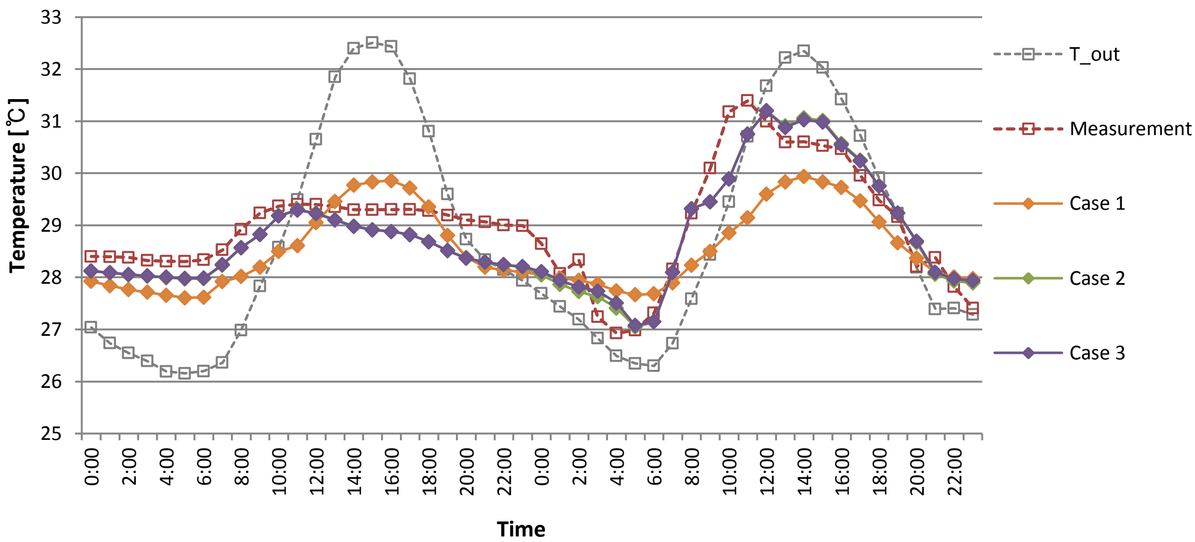


Figure 9. Indoor air temperature of room 2 in summer condition

set as a transfer factor) shows that both cases have similar results at most timesteps. Except for certain periods that exhibit results different from the field measurement findings, the results gained at the time of ventilation assume nearly similar patterns. It is also found that the margin of error for Cases 2 and 3 is not greater than in fall, a finding attributed to the great influence on the indoor thermal environment of heat transfer driven by ventilation.

CONCLUSION

In order to analyze the utility of the coupling method, this study conducted field measurement and compared BES and coupled simulation results. Due to certain natural ventilation conditions that make it impossible for BES to perform an accurate calculation of airflow rates, the results were compared with the airflow rate taken into account as an important factor. The conclusions are stated in the following:

1. With BES it is difficult to accurately assess natural ventilation performance. Therefore, coupled simulation is needed to calculate the indoor thermal environment under natural ventilation conditions.
2. It is difficult to assess airflow rates with BES when the building orientation is parallel to the main wind direction.
3. Under the condition with higher airflow rates, since heat transfer due to ventilation is great, the convective heat transfer coefficient does not have a significant influence.

NOMENCLATURE

q = heat transfer
Q = Heat load
A = Area of surface
V = Volume
C = specific heat
T = Temperature
h = heat transfer coefficient
m = mass flow rate
ρ = density
P = Pressure
μ = air viscosity
z = height

Subscripts, superscripts and indices

c = convection
i = index of the zones or surfaces
$vent$ = ventilation

ACKNOWLEDGEMENT

This research was supported by a grant (11 High-tech Urban G03) from High-tech Urban Development Program funded by the Ministry of Land, Transport and Maritime Affairs of Korean government

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST) (No.2005-0049406)

REFERENCES

BCVTB, July 17, 2008. Building Controls Virtual Test Bed. Lawrence Berkeley National Laboratory.

Clarke, J. A. and D. Tang. 1990. An Investigation of the Functional Conflation of Building Energy Simulation and Computational Fluid Dynamics. University of Strathclyde.

Djunaedy, E., J. L. M. Hensen, and M. G. L. C. Loomans. 2003. Toward external coupling of building energy and airflow modeling programs. Pages 771-787, Kansas City, MO.

Fan, Y. and K. Ito. 2012. Energy consumption analysis intended for real office space with energy recovery ventilator by integrating BES and CFD approaches. Building and Environment 52:57-67.

Negrão, C. O. R. 1998. Integration of computational fluid dynamics with building thermal and mass flow simulation. Energy and Buildings 27:155-165.

Tan, G. and L. R. Glicksman. 2005. Application of integrating multi-zone model with CFD simulation to natural ventilation prediction. Energy and Buildings 37:1049-1057.

Wang, L. and N. H. Wong. 2008. Coupled simulations for naturally ventilated residential buildings. Automation in Construction 17:386-398.

Wang, L. and N. H. Wong. 2009. Coupled simulations for naturally ventilated rooms between building simulation (BS) and computational fluid dynamics (CFD) for better prediction of indoor thermal environment. Building and Environment 44:95-112.

Zhai, Z. and Q. Chen. 2004. Numerical determination and treatment of convective heat transfer coefficient in the coupled building energy and CFD simulation. Building and Environment 39:1001-1009.

Zhai, Z., Q. Chen, P. Haves, and J. H. Klems. 2002. On approaches to couple energy simulation and computational fluid dynamics programs. Building and Environment 37:857-864.

Zhai, Z., Q. Chen, J. H. Klems, and P. Haves. 2001. Strategies for coupling energy simulation and computational fluid dynamics programs.in Proceedings of 9th IBPSA Conference, Rio de Janeiro, Brazil.

Zhai, Z. J. and Q. Y. Chen. 2005. Performance of coupled building energy and CFD simulations. Energy and Buildings 37:333-344.