OPERATION STRATEGIES FOR AN OFFICE BUILDING INTEGRATED WITH MULTI-STORY DOUBLE SKIN FACADES IN THE HEATING SEASON

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ABSTRACT

In this paper, heating energy saving strategies for winter are proposed for office buildings with a multi-story double skin façade. Based on a model that was validated with measured data, two alternative operation strategies were analyzed.

A model that introduces heated air in the cavity to the indoors by openable windows control(Case 2) and a model that combines it with HVAC by using a cavity as a preheating space(Case 3) were compared with the conventional model(Case 1). The results of the comparison showed that the Case 2 and 3 reduced the heating energy by about 3.4 and 37.9 % respectively.

INTRODUCTION

The double-skin façade (DSF) system is popular as an alternative to reduce the high energy demand in the existing curtain wall façade system. Despite the popularity of DSF, however, there have been few constructed buildings that report their real implementations, resulting in the lack of quantitative studies on its actual performance. In particular, compared to the relatively active research on single-story DSF buildings, there has been minimal research on multi-story DSF buildings due to the difficulty of constructing the test cell and the lack of actual construction cases. Some studies on the field measurement of multi-story DSF buildings (Hens et al., 2008; Pasquay, 2004; Gertis, 1999) were not only limited to the European climate but also monitored only some stories and not all the floors of the buildings. Moreover, while some performed a miniaturized-model test (Ding et al., 2005), it was conducted under a strictly controlled environment.

As the behavior of DSF differs by climate, it is essential to consider the operation strategy based on the region and season. The seasonal control strategy based on the mild European climate was studied by Gratia et al. (2004a; 2004b). Saelens et al. (2006) also studied the control strategy of DSF combined with mechanical ventilation, and particularly proposed the possibility of heating energy reduction using the supply window during winter.

DSF's passive technology should be suitable for the climate of the region where the target building is located, and therefore, the past studies cannot be easily generalized to South Korea's climate, which changes greatly by season. This study and a series of other research to follow will propose seasonal control strategies for office buildings with multi-story DSF under the climate of South Korea.

In this study, two operation strategies that could be used in winter were compared: one for controlling the openings between the cavity and a conditioned zone using an Erl (EnergyPlus Runtime Language) algorithm of EnergyPlus, and the other two for using the cavity as a preheating space for the HVAC system.

SIMUATION ALGORITHM

The numerical method used in this study for airflow is the airflow network algorithm. EnergyPlus integrated an algorithm of AIRNET(Walton, 1989) with heat balance model. Airflow occured when there is difference in pressure. Based on Bernoulli's equation, when the two consecutive nodes are called n and m, airflow can be expressed as the following:

$$\Delta P = \left(P_n + \frac{\rho v_n^2}{2}\right) - \left(P_m + \frac{\rho v_m^2}{2}\right) + \rho g(z_n - z_m) \quad \text{(Eq. 1)}$$

The pressure difference that crosses two nodes is determined by Equation 1. Considering the effect of wind pressure, the above equation may be written in the format used by the airflow network model:

$$\Delta P = P_n - P_m + \Delta P_s + \Delta P_w \quad \text{(Eq. 2)}$$

Airflow through closed openings, doors or cracks can be determined using a power law equation as in Equation 3, which is an empirical formula showing the relation between pressure difference and airflow.

$$\dot{m} = C(\Delta P_c)^n \quad \text{(Eq. 3)}$$

Such a nonlinear airflow equation is repetitively calculated using the Newton-Raphson method. The relative convergence tolerance was set to 0.0001, and the relaxation factor for convergence acceleration was set to -0.5.
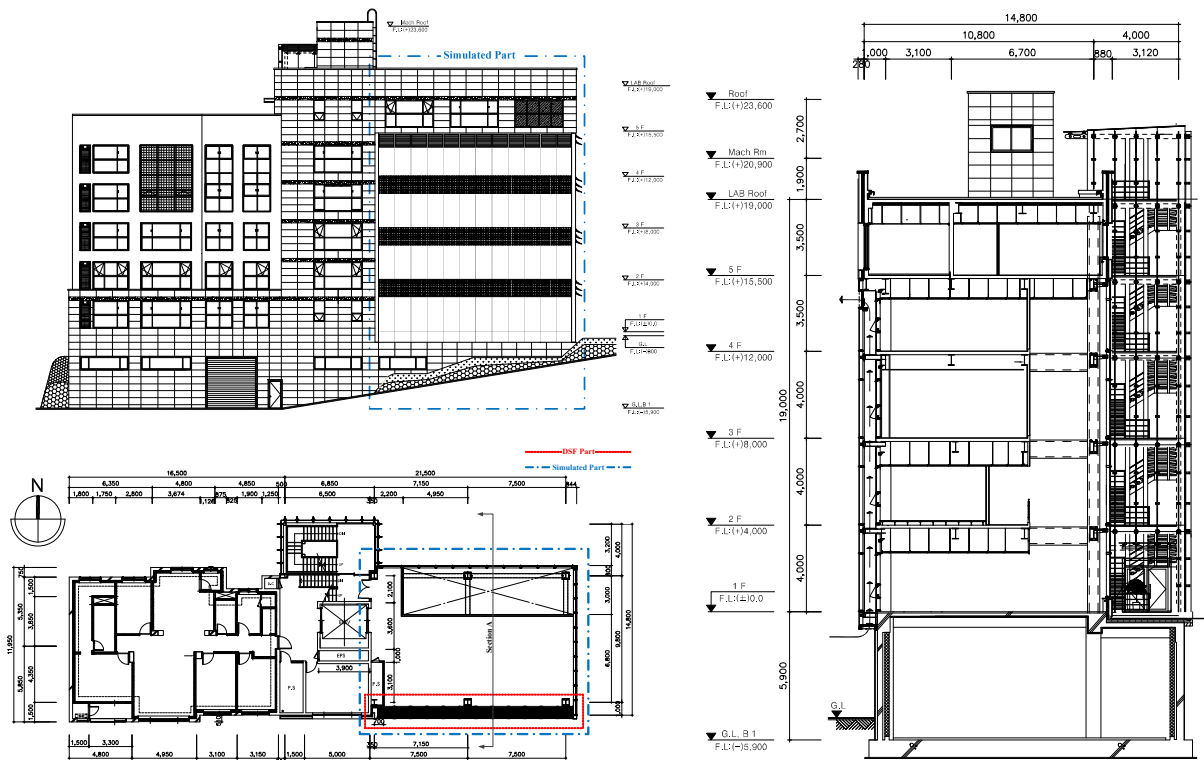
Figure 1 Front Elevation, Plan and Cross Section of Target Building

EXPERIMENT AND VALIDATION

The target building is located in Yongin, Korea and used by the office and research center. The multi-story DSF is applied to its southern façade. The building' drawings are shown in Figure 1. The optical and thermal properties of its windows are shown in Table 1.

From February 20 to April 30, 2011, the air temperature (2.3 m of vertical spacing) and surface temperature (3rd floor) of cavity were measured. At the same time, the weather station located on the rooftop measured the temperature, humidity, direct solar radiation, global solar radiation, wind speed and wind direction.

The poly-crystal BIPV (Building Integrated Photovoltaic) modules were installed on 1/3 from the top of the cavity on each floor, which blocks the solar radiation penetrating into the cavity. This façade feature was reflected in the cavity modelling on each floor by separating the zone with and without BIPV. To simulate the airflow and stack effect between vertical zones of the cavity, virtual horizontal windows were created. These horizontal windows are linkage where uni-directional or bi-directional airflow occurs.

Figure 2 shows the result of the validation. Figure 2(a) shows the temperature at the measured point on each floor and the average temperature at the cavity zone under simulation. Cv(RMSE) is about 18.97%, and

*Table 1 Thermal and Optical Properties of Windows*

Properties		Single Glazing (Clr8)	Double Glazing (Clr6-Air12-Loe6)
Visible	Transmittance	0.86	0.58
	Reflectance	0.08	0.15
Solar	Transmittance	0.71	0.27
	Reflectance	0.07	0.18
U-value (W/m²·K)		5.72	1.76
SHGC		0.77	0.38

MBE about 8.35%. The BIPV zone on the first floor was excluded due to the absence of the measuring point. Figure 2(b) compares the measured and simulated surface temperatures on the 3rd floor cavity. Cv(RMSE) was about 29.69% and MBE about 4.87%. Such a degree of accuracy is within the Cv(RMSE) and MBE value (30%, ±10%, respectively) proposed by US DOE Measurement & Verification Guidelines as acceptable calibration tolerances.
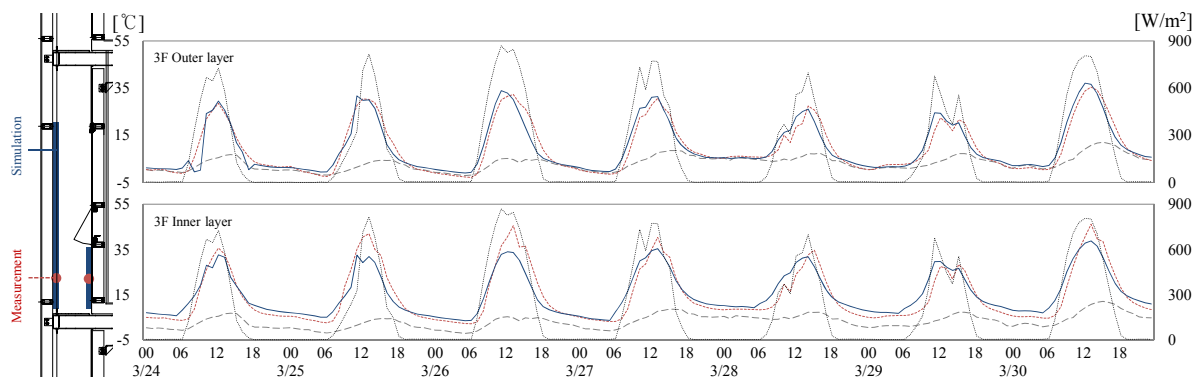
$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_{sim,i}-T_{mea,i})^2}{n}} \qquad \text{(Eq. 4)}$$

$$Cv(RMSE) = \frac{RMSE}{T_{mea,avg}} \times 100 \qquad \text{(Eq. 5)}$$

$$MBE = \frac{\sum_{i=1}^{n}(T_{sim,i}-T_{mea,i})}{n} \qquad \text{(Eq. 6)}$$
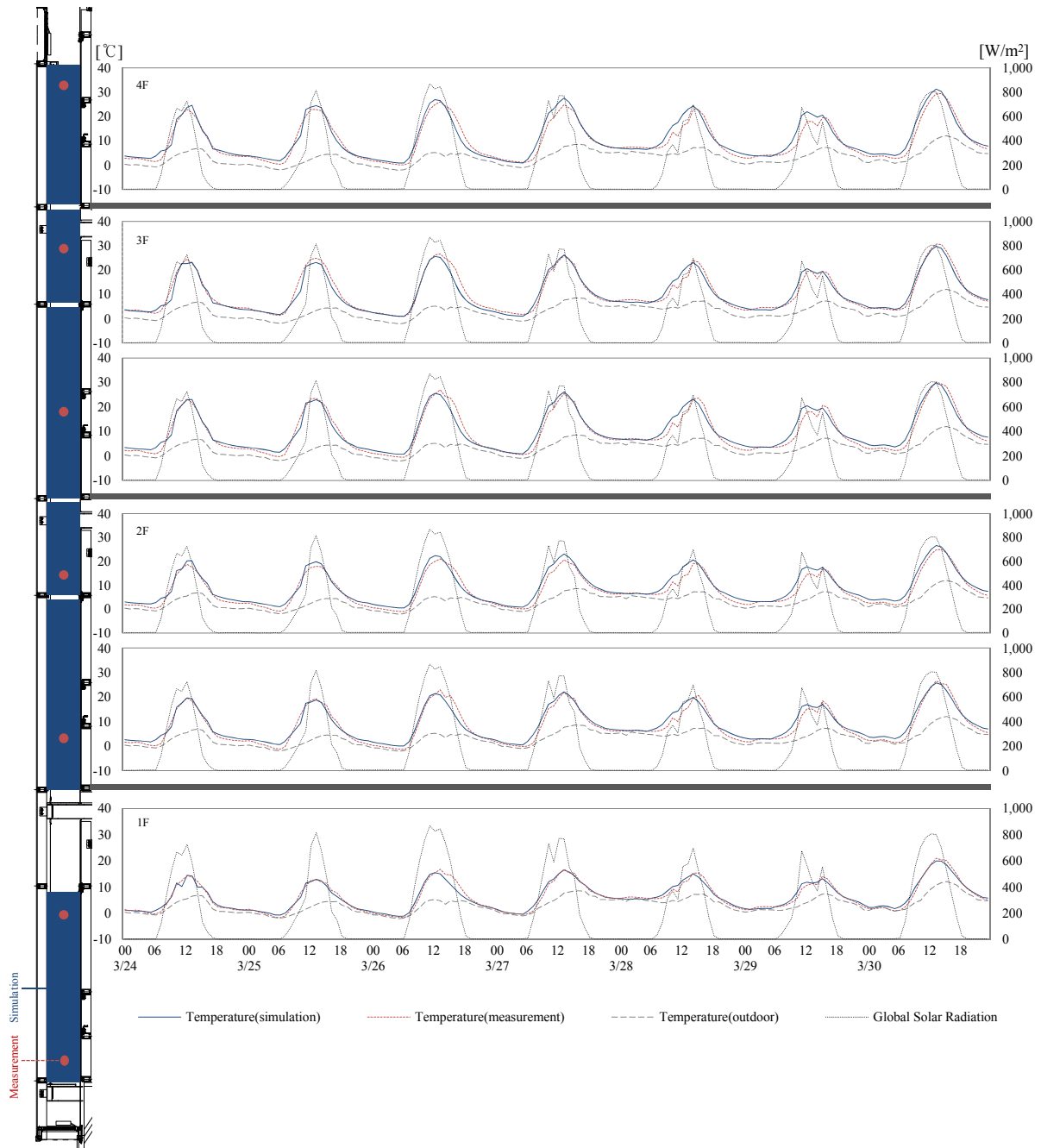
(a) Air Temperature of Cavity

(b) Surface Temperature of 3rd Floor Cavity

Figure 2 Comparison of Measured and Simulated Temperature

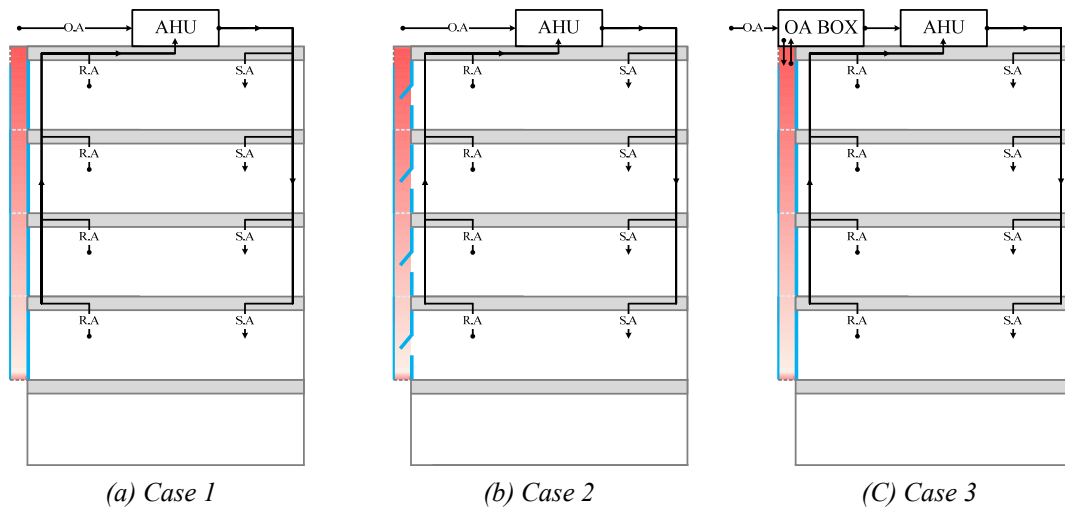*(a) Case 1*   *(b) Case 2*   *(C) Case 3*

Figure 3 Schematic Illustration of Simulation Cases

CASE STUDY

The case study model, which is newly created based on the validated model excludes the BIPV module, and modelled the cavity as four discretized zones. As shown in Figure 3, there are two alternative models presented (Case 2, 3) to the basic model (Case 1). Compared to the other cases, Case 1 is the basic model to which no control strategy was applied. In Case 2, if air temperature in the cavity heated by solar radiation exceeds 21ºC, the heated air is introduced to indoor through openable windows at the inner layer. In Case 3, the cavity is combined to the HVAC system to be used as a preheating space. The heated air from the 4th floor cavity and air from outdoor are mixed in an additional outdoor air mixing box. The relief node of this mixing box is connected to the inlet node of the existing AHU mixing box. In the simulation, the air in the 4th floor cavity and the air in the outdoor air mixing box are circulated by air loop. The air properties of both air are identical.

  In all cases, DSF is installed on the south of the building. On other sides of the building (east, west, and north), low-e glasses with 30% of the window area ratio were installed. Table 2 and Table 3 show indoor heat gain and HVAC operation, respectively. The weather data(Kwanho, 2010) used in the simulation is generated by using ISO TRY method. The climate data were collected for thirty years by the Korean Meteorological Association(KMA). During the simulation period, the upper and lower openings of cavity were closed. Outdoor air flow rate that enters into AHU is set to 0.55 m^3/s in all cases, which satisfies the minimum air change rate per hour of 0.7 in all rooms.

Figure 4 shows how much heating coil energy is consumed in winter in each case. Compared to Case 1, which functions only as the thermal buff among the cases, other two cases demonstrated a reduction in heating coil energy by 3.4 and 37.9 %, respectively. Compared to Case 1, Case 2 which applied the control algorithm on the inner layer windows, shows similar monthly heating energy consumption, while Case 3, which combine heated air in cavity with HVAC system, show considerably higher heating coil energy reduction. Compared to Case 1, the cavity temperature dropped in Case 3 due to an airflow of 0.55 m^3/s travels to AHU. The maximum range of the temperature drop by floor between January 15 and 19 is 12ºC on the fourth floor, 1.4ºC on the 3rd floor in Case 3.
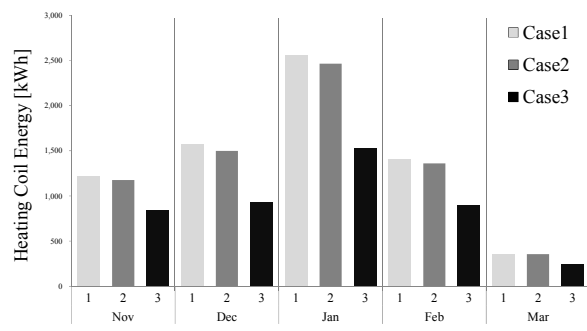

Figure 4 Heating Coil Energy Consumption

Table 3 HVAC Operation

Set Point Temperature	Heating 21℃
	Cooling 26℃
Period	November ~ March
Operation Time	08:00 ~ 18:00
HVAC	Packaged Direct Expansion

Table 2 Indoor Heat Gain

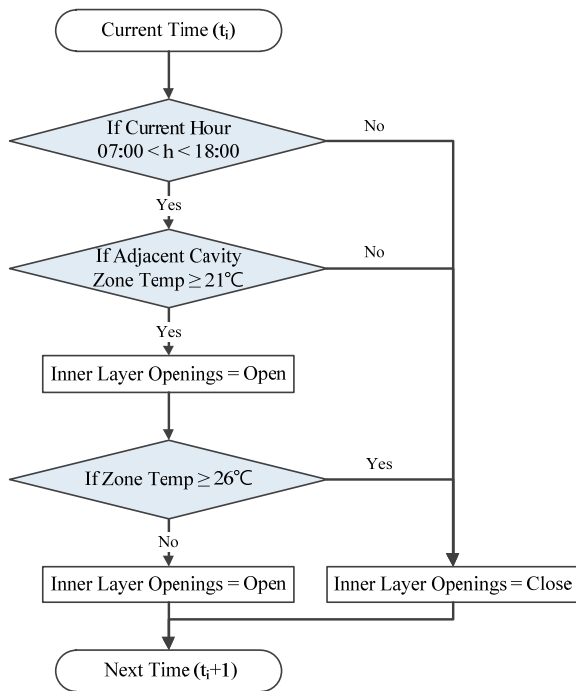| People	0.1 person/m^2
Equipment & Lighting	10 W/m^2

Figure 5 Openable Windows Control Logic (Case 2)

This shows that compared to the case in which there is no integration with an active system, the direct introduction of outdoor air through the cavity causes a considerable temperature drop. But the marked degradation of the heating coil energy demand sufficiently offsets the heat loss through the DSF inner layer, which increased accordingly.

Case 2: Introducing cavity air using openable windows

The basic airflow network opening control algorithm of EnergyPlus considers only the natural ventilation in which there is an opening when the outdoor temperature or enthalpy is lower than setpoint. Thus, the control of introducing heated cavity air to indoor cannot be simulated by using only the basic setting.

Thus, in this study, an opening control algorithm was created using an EMS (Energy Management System) class, which extends the degree of control freedom within EnergyPlus using Erl (EnergyPlus Runtime Language). As shown in Figure 5, if the temperature of the cavity facing each conditioned zone exceeded 21ºC, the windows at the inner layer are opened, and if the zone temperature exceeded 26ºC (cooling set-point temperature), the windows at the inner layer are closed. Figure 6 shows the relation between the time the windows were opened and the amount of heating coil energy reduction between January 15 and 19. The horizontal axis is time while the vertical axis is the amount of time the windows were opened by floor. The full bar represents when the windows were opened for one hour, and the half bar, for half an hour. The number of opened minutes increases by floor. This means that as the thermal stratification is created in the cavity, the air temperature in the upper level increases. The amount of heating coil energy reduction was generally high when the opened minutes increases, except at noontime when heating energy is not required.
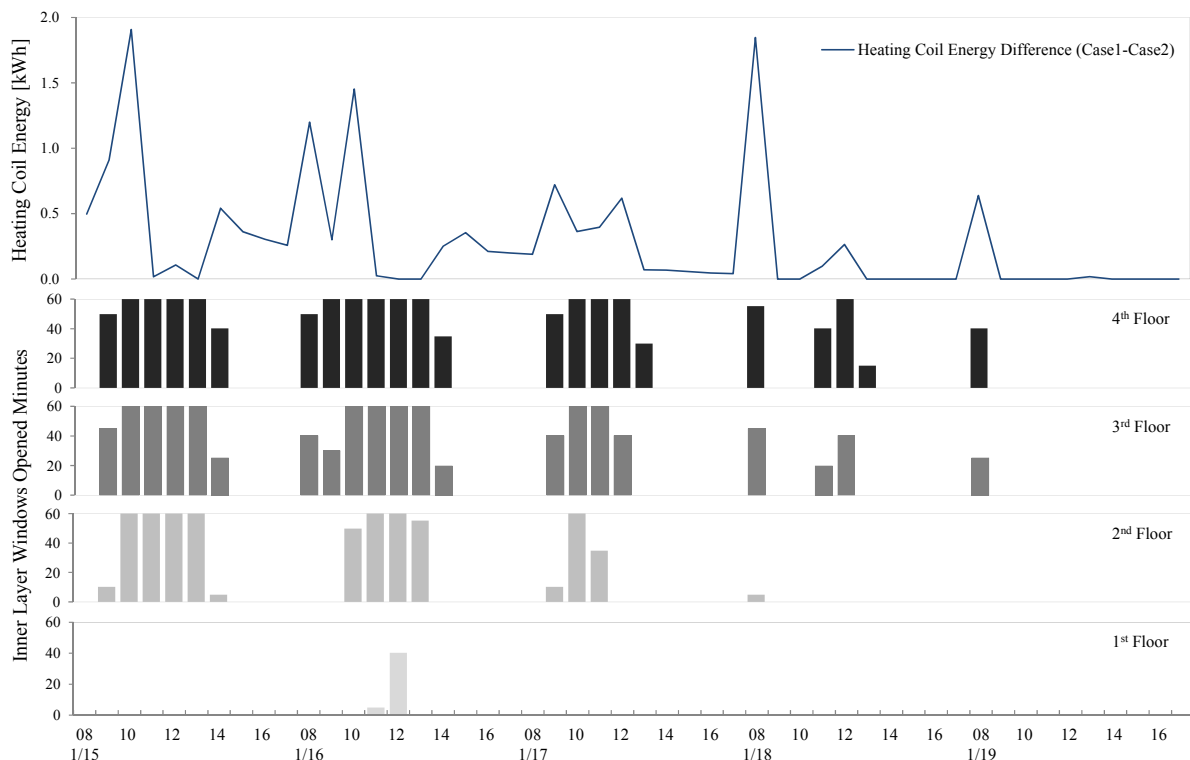

Figure 6 Heating Coil Energy Difference by Inner Layer Windows Opened Minutes
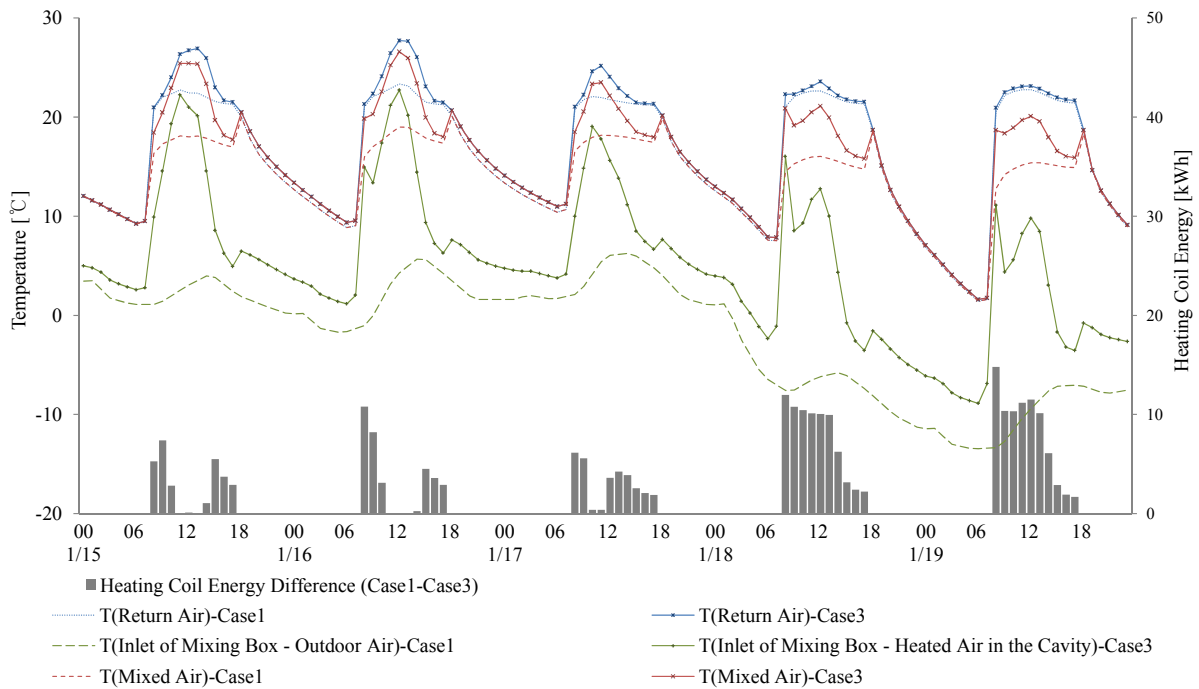
Figure 7 Heating Coil Energy Difference by Mixed Air Temperature Difference

Case 3: DSF integrated with HVAC system

In Case 3, the outdoor air is introduced to AHU through the cavity after it is mixed with the heated air in the 4th floor cavity. Therefore, as shown in Figure 7, the temperature of the inlet to the mixing box becomes relatively higher than that in Case 1. The relatively warmer air enters into AHU, reducing the load that the heating coil has to cover. The temperature difference of the mixed air between Case 1 and Case 3 becomes greater during the day when the temperature of the cavity goes up, and accordingly, the heating coil energy difference between Case 1 and Case 3 also increases.

CONCLUSIONS

This study verified the simulation model by using measured data, and based on the model, proposed a heating energy saving strategies in winter for office buildings with multi-story DSF under winter climate of Korea. The study compared and analyzed the basic model (Case 1) without control, the model that introduces indoors the heated air in the cavity (Case 2), and the models that combine with HVAC the cavity by using it as a preheat space (Case 3). The study reached the following conclusions:

1. Upon comparing with Case 1, the heating coil energy reductions of Case 2 and 3 were at 3.4% and 37.9%, respectively;
2. Despite that Case 2 automatically controlled the window at the inner layer, it did not greatly reduce energy, compared to that of Case 1. Thus, it is believed that such a control strategy does not significantly affect the heating load reduction during heating seasons;
3. Case 3 showed a huge reduction in heating coil energy by using the temperature of the heated cavity, compared to the cold outdoor air used in Case 1; and

Further research will continue to verify the model during the intermediate and cooling seasons, which utilizes natural ventilation, and to investigate various operating strategies.

NOMENCLATURE

ΔP: total pressure difference between nodes n and m [Pa]

$P_{n,m}$: pressure at nodes n and m [Pa]

ρ: air density [kg/m^3]

$v_{n,m}$: air velocity at nodes n and m [m/s]

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

$z_{n,m}$: height at nodes n and m [m]

ΔP_s : pressure difference due to the difference of density and height [Pa]

ΔP_w: pressure difference due to the wind [Pa]

$\dot{m}$: mass flow rate [kg /s]

C: air mass flow coefficient

ΔP_c: total pressure loss across the element [Pa]

n: flow exponent

T_{sim}: simulated temperature [ºC]

T_{mea}: measured temperature [ºC]

$T_{mea,avg}$: average of measured temperature [ºC]

n: a number of data

ACNKOWLEDGEMENT

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