Thermal Decay and Energy Consumption Depending on Location of Slab Insulation in Underfloor Air Distribution System

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ABSTRACT
Generally, Underfloor Air D1istribution (UFAD) system commonly applied to office buildings has many advantages over Ceiling Based Air Distribution (CBAD), including improvement of indoor air quality and energy saving. However, the thermal decay which is defined as the increase of the supply air temperature due to heat gain into underfloor supply plenum, can adversely affect the energy savings. Therefore, in this study, a thermal insulation was installed on the slab to prevent thermal decay and to improve cooling performance, and the effect of the insulation installation on the cooling energy consumption was analyzed. The result showed that the thermal decay was reduced by the installation of the insulation on the slab, and different effects were observed in individual cases. The energy consumption was reduced in the case where the insulation was installed on the slab, while no energy saving effect was found in the case where the insulation was installed under the slab. This indicates that an appropriate insulation installation location should be taken into account.

KEYWORDS
Underfloor air distribution, Thermal decay, Supply plenum, Insulation, Convective heat gain

1. INTRODUCTION
In contrast to CBAD system where air-conditioning is performed through the duct space of the ceiling, the UFAD system, commonly applied to office and business buildings, directly supplies air-conditioned air through the floor diffuser positioned on the floor panel in the supply plenum formed between the upper concrete slab and the lower floor panel. The UFAD system has many advantages over the conventional CBAD system, including comfortable thermal environment, improvement of indoor air quality, reduction of building life-cycle cost, and story height reduction due to the absence of ducts (Bauman, FS 2003). The most outstanding characteristic of the UFAD system is the stratification of indoor air which is caused by the density difference between the cold supply air diffused from the floor diffuser during the cooling in summer and the relatively hot air inside the space. The stratification of indoor air divides an indoor space into an occupied zone and an non-occupied zone, enabling the UFAD system to be in charge of only the load on the occupied zone which affects the occupants to save energy (Bauman, F. and Webster, T 2001, Daly, A 2006). However, since the cold air

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is provided during the cooling through the supply plenum without a separate duct, the supply plenum temperature is increased by the heat from the indoor space and the heat transfer from the return plenum, which is the lower part of the supply plenum (Lee, K.H et al. 2012). Such heat gain may have a negative effect on energy saving, since it causes an increase of the air supplied to the inside, causing an increase of the supply air flow rate for maintaining the indoor temperature as well as destroying the indoor stratification (Bauman, F et al. 2006). Many studies have been conducted on the thermal decay of the supply plenum (Woods, JE and Novosel, D 2008, Schiavon, S. et al. 2010). In a previous study conducted in South Korea, an insulation was installed on the floor panel for the purpose of reducing the increase of the thermal decay, and the result showed that the thermal decay was reduced by the installation of the insulation, which also caused an adverse effect on energy saving as the cooling load on the indoor space was greatly increased (Lee, K. H et al. 2016). Therefore, the present study was conducted to install an insulation not on the floor panel but on the slab to minimize the effect on the indoor space and to prevent the heat gain from the return plenum, which is the lower part of the supply plenum. The energy consumption was also analyzed on the basis of the temperature of the supply plenum, the flow rate of the supplied air, and the cooling load.

2. RESEARCH METHODS

2.1 Simulation software

The present study was conducted with a prototype office building to which the UFAD system was applied to install an insulation on the slab, which is the lower part of the supply plenum, to analyze the supply plenum temperature and the energy consumption. As the analytical tool, the Heat Balance method recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), was employed to utilize the EnergyPlus simulation software for the detailed analysis of the heat transfer by the convention, radiation, and conduction through building skin (Winkelmann, F 2001). In addition, the EnergyPlus software enables to analyze the thermal environment of the supply plenum, the indoor cooling load and the degree of stratification needed for the analysis of a building to which the UFAD system is applied (Webster, T et al. 2010).

2.2 Simulation modeling

The analysis subject of this study was a large three-story office prototype model having an aspect ratio of 1.5 (52.8 m x 35.2 m) and a story height of 3.9 m (supply plenum 0.4 m, return plenum 0.8 m). Each story included one interior zone and four perimeter zones. The area of the interior zone was 1137.48 m^2, that of the east and west perimeter zones was 140.069 m^2, and that of the north and south perimeter zones was 220.561m^2. The window area ratio was 40%. According to the ASHRAE 90.1 standards, the indoor heat gains included occupants of 9.3 m^2/person, lighting of 9.1 W/m^2, and electronic device of 14.4 W/m^2. The analysis was performed under the climatic conditions of Daejon on the basis of the IWEC meteorological data provided by ASHRAE. The analyzed data were for a representative date (July 30) and summer season (June, July, and August). The detailed conditions of the analysis are shown in Table 1.

Table 1. *Input condition of simulation*

General	Program	EnergyPlus v6.0
	Floorplate area	53 (m) × 35 (m)

	Site/Weather	Daejeon(South Korea)
Zone	Terminal unit	VAV with Reheat
	Cooling/Heating Set-Point(℃)	Cooling : 25℃ Heating : 20℃
	Diffuser Type	Interior : Swirl Exterior : Linear Bar
System	AHU Discharge Temperature	15.6℃
	AHU Fan Efficiency	63%
Plant	Chiller design COP	5.5
	Boiler design Efficiency	78%

2.3 Simulation cases

The objective of the present study is to analyze the energy consumption depending on the temperature of the supply plenum, the indoor cooling load, and the supply air flow rate by installing a thermal insulation on the slab of an UFAD system. The simulation conditions are shown in Table 2. The simulation cases were the base case where no insulation was installed, and Cases 2 and 3 where an insulation having a heat transmission coefficient of 0.516 W/m^{2}K was upon a slab and below a slab, respectively. Except the location of the insulation installation, all the conditions were equal.

Table 2. *Simulated cases (Insulation location)*

	Slab	Raised Floor
Base Case	None	None
Case 1	Above	None
Case 2	Below	None

3. SIMULATION ANALYSIS

In this study, the results were analyzed with respect to the interior zone and the west perimeter zone, which is greatly affected by the external air, of the middle floor. The representative date was decided as July 30 of which temperature corresponds to the average temperature. With respect to that date, the data about the heat gain and thermal decay, and the supply air flow rate were analyzed in detail for each hour from 06:00 to 17:00 when the system was operated. In addition, the cooling load and the energy consumption during summer (June, July, and August) when the cooling performance is noticeable were analyzed and compared between the cases.

3.1 Diffuser discharge temperature

Figure 1 shows the temperature of the air supplied through the floor diffusers of the interior zone and the west perimeter zone of the middle floor in each case on the representative date. The supplied air temperature was increased in both the interior zone and the perimeter zone in comparison with the AHU supply air temperature (SAT= 15.6℃), but the temperature increase was different between the cases. The increase of the supplied air temperature was less in Cases 1 and 2 than in the base case in both the interior zone and the west perimeter zone. This may be because the installation of the insulation on the slab reduced the heat gain from return plenum, which is the lower part of the supply plenum.

The temperature in the interior zone was higher by the maximum of 0.38℃ in Case 1 and by the maximum of 0.17℃ in Case 2 in comparison with the base case. The temperature in the perimeter higher by the maximum 0.40℃ in Case 1 and by the maximum of 0.18℃ in Case 2 in comparison with the base case. Despite a secondary temperature increase in the perimeter zone, the temperature increased was similar between the cases, indicating that the difference in the quantity of the heat gained through the insulation in the perimeter zone was negligible.In addition, it may be noted that the temperature was increased immediately after starting up the system operation and then gradually decreased in all the zones. This is because the flow rate was low due to the relatively low cooling load in the morning but the flow rate was increased as the cooling load was increased, resulting in decrease of the temperature.

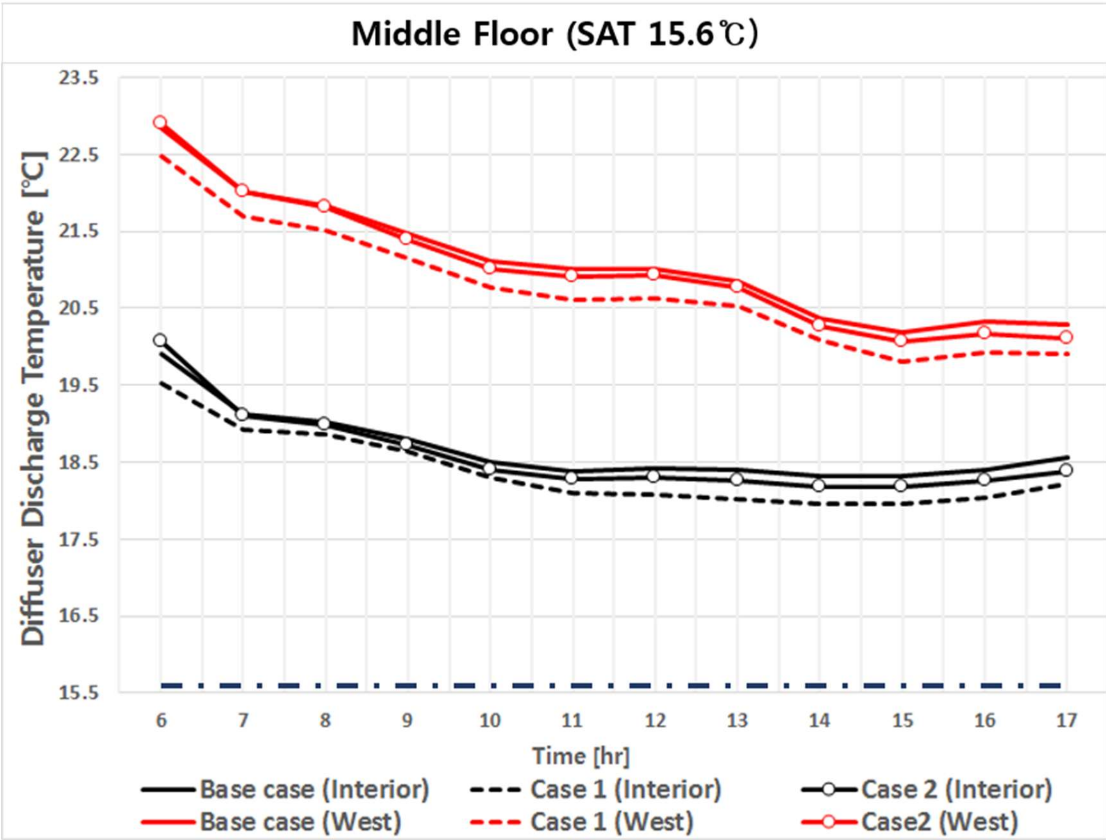

Figure 1. *Diffuser discharge temperature for the interior and west zone*

3.2 Supply airflow rate

Figure 2 shows the supply airflow rate through the floor diffuser in the interior zone and the west perimeter zone, and Figure 3 shows the overall supply airflow rate from the air handing unit (AHU) through the supply plenum of the interior zone on the middle floor. As shown in Figure 2, the difference between the cases was negligible and a constant flow rate was maintained in the interior zone, indicating that the cooling load generated inside the space was maintained in a constant pattern. In the perimeter zone, the flow rate was low in the morning but it was gradually increased in the afternoon when the solar radiation was increased, and the flow rate in the base case was similar to that of Case 2, whereas the flow rate was relatively lower in Case 1. As can be known from Figure 1, the required flow rate was decreased since thermal decay was reduced. Figure 3 shows that the overall flow rate into the supply plenum in Case 2 was similar to that of the base case, while that of Case 1 was lower than that of the base case. This difference may be because of the difference of the flow rate required in the perimeter zone.

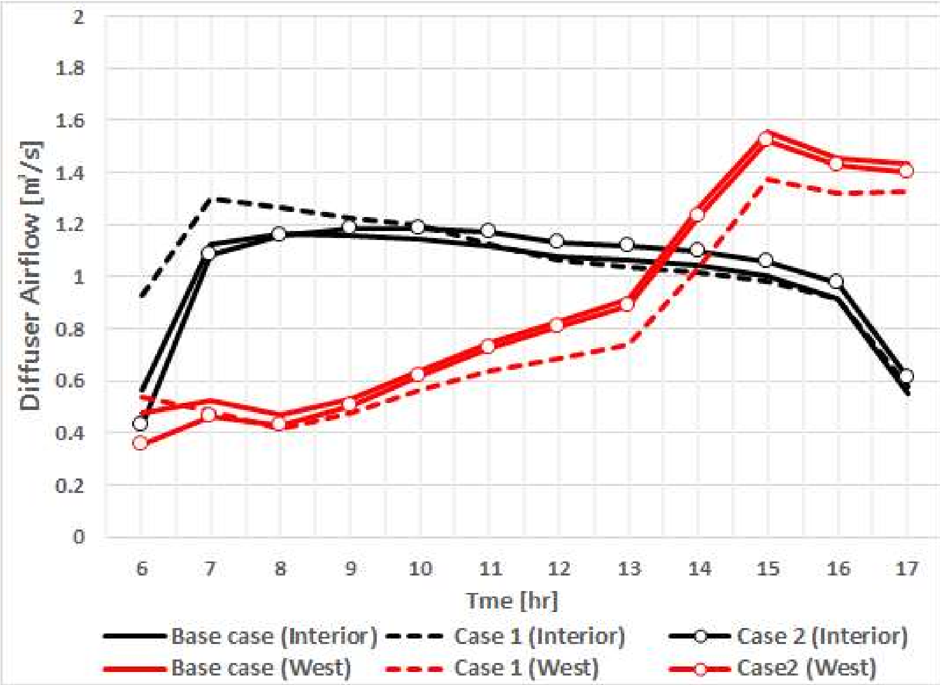

Figure 2. *Supply airflow rate for the interior and west zone*

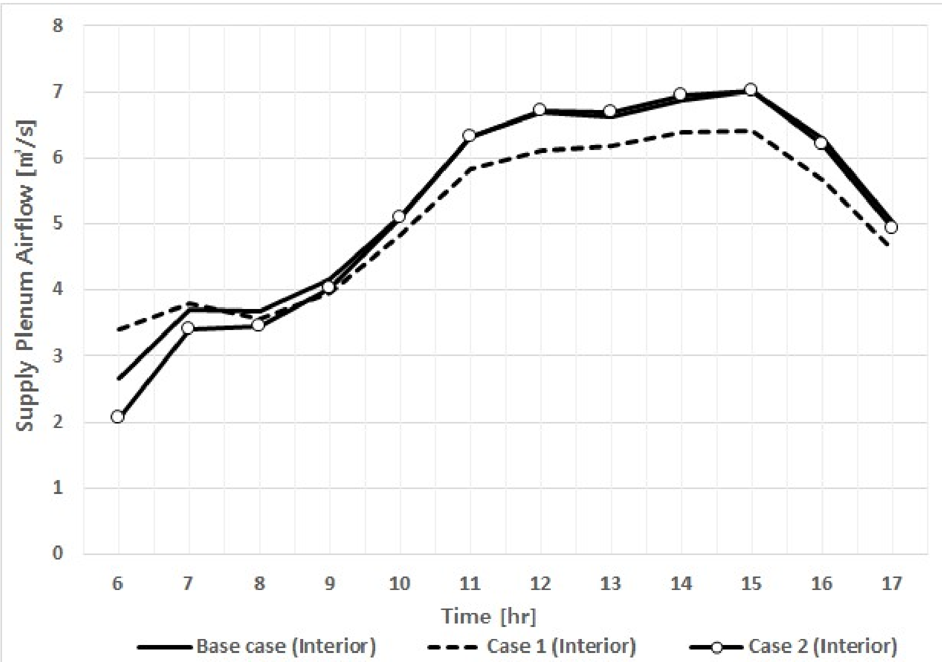

Figure 3. *Supply airflow rate for the supply plenum (middle floor, interior)*

3.3 Convective heat gain and deltaT

Figure 4 shows the heat flow in the supply plenum of the interior zone, where the plot on the left represents the temperature difference between the ceiling surface of the supply plenum and the air in the supply plenum and between the bottom surface of the supply plenum and the air in the supply plenum, and the plot on the right shows the heat gain from the ceiling of the supply plenum and from the floor. With regard to the heat flow on the bottom of the supply plenum, the temperature difference was small in the order of Case 1, Case 2, and the base case. The heat gain caused by the temperature difference was less by a maximum of 1.4 times in Case 1 and by a maximum of 1.25 in Case 2 in comparison with the base case. With regard to the heat floor on the ceiling, the temperature difference was negligible between the cases. The heat gain was relatively small in Case 1 in comparison with the other cases, which may be because the flow rate in Case 1 was lower than in other cases due to the overall flow rate in the supply plenum, as shown in Figure 3, and thus the heat transfer by convention was less in Case 1.

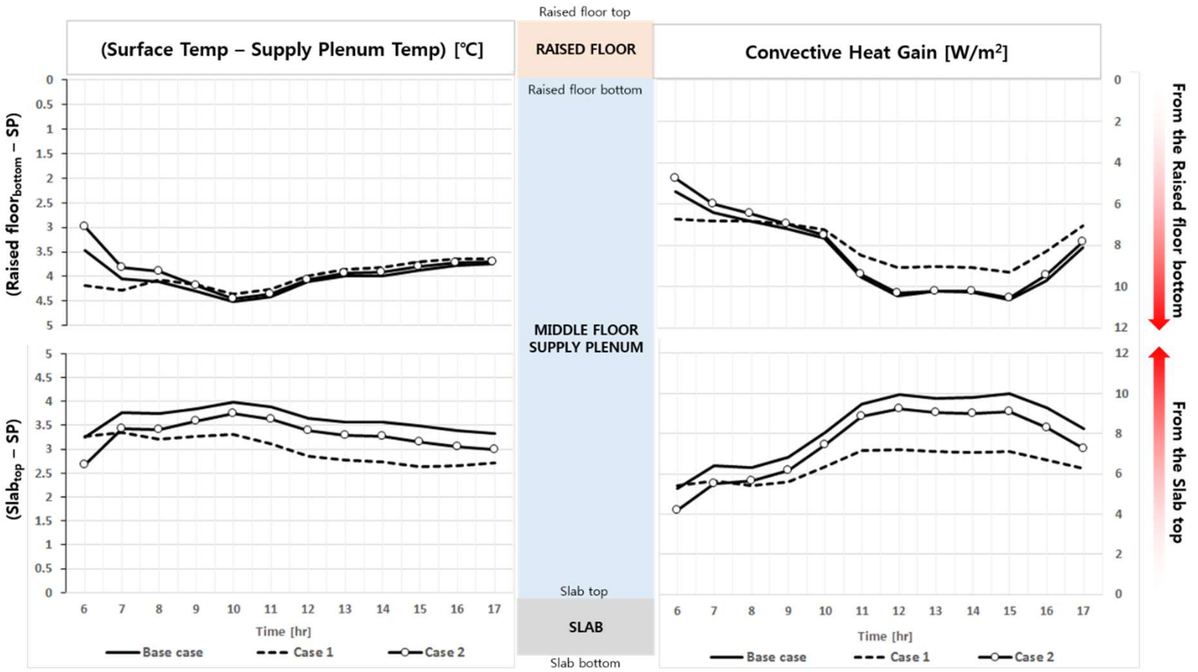

Figure 4. *Convective heat gain and DeltaT between surface and plenum in the supply plenum (middle floor, interior, SP = supply plenum)*

3.4 Cooling load and energy consumption

Figure 5 shows the indoor cooling load and the energy consumption by fans and chiller in respective cases during summer (June, July, and August). The cooling load was higher by 8.6% in Case 1 and 4.4% in Case 2 than in the base case. This result may be because the installation of the insulation on the slab prevented the heat transfer from return plenum to the supply plenum, resulting in the temperature increase in return plenum which in turn affected the indoor space. The comparison of the energy consumption in the base case and Cases 1 and 2 showed that the energy consumption by fans was decreased by 4.72% and 3.12% in Cases 1 and 2, respectively. The energy consumption by chillers was decreased by 3.44% in Case 1, whereas it was increased by 0.11% in Case 2.

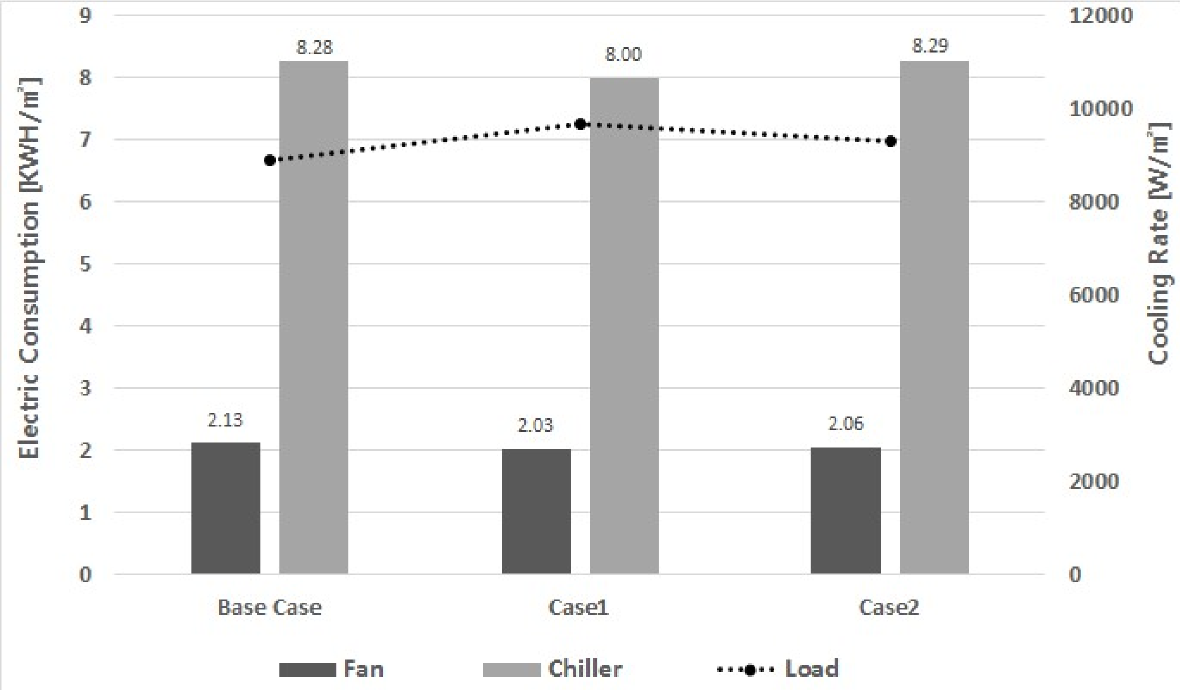

Figure 5.*Cooling load for the interior zone and electric energy consumption*

CONCLUSION AND IMPLICATIONS

The present study is about the thermal decay of the UFAD system. An insulation was installed on the slab, which is the bottom of the supply plenum, for the purpose of reducing the thermal decay, and the energy consumption in summer (June, July, and August) was analyzed on the basis of the variation of the supply plenum temperature caused by the insulation installation and the indoor cooling load. The conclusions of the present study are as follows:

(1) The heat gain was less in the case where the insulation was installed on the slab than in the case where no insulation was installed, because the heat transferred from return plenum, which is the lower part of the supply plenum, was not introduced. The comparison of the location of the insulation installation showed that the heat gain was less in the case where the insulation was installed upon the slab than in the case where the insulation was installed below the slab.

(2) The insulation installation on the concrete slab, which is the bottom of the supply plenum, reduced the thermal decay due to the difference of the heat gain (a maximum of 0.38℃ reduced in Case 1 and a maximum of 0.18℃ reduced in Case 2). With regard to the supply plenum temperature of the west perimeter zone, the temperature difference between the cases was similar to that of the interior zone, indicating that the effect of installing the insulation on the slab in the perimeter zone was negligible.

(3) The supply airflow rate into the indoor space of the interior zone was similar between the cases. The supply airflow rate to the west perimeter zone was lower in the case where the insulation was installed upon the slab than in other cases.

(4) The energy consumption (fans + chillers) was reduced by 3.7% in Case 1 where the

insulation was installed upon the slab and by 0.55% in Case 2 where the insulation was installed below the slab in comparison with the base case. Despite the insulation installation, the energy saving effect was negligible because the reduction of the thermal decay was small and the indoor cooling load was increased.

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