Impacts of Thermal Decay on the Energy Performance Degradation in UFAD (Underfloor Air Distribution) System

Byeong Ho Yu#1, Byeong-Mo Seo*2, Jung-Eun Son*3, Kwang Ho Lee#4

#1Graduate School, Hanbat National University
125, Dongseo-daero, Yuseong-gu, Daejeon 305-719, Republic of Korea
#4Department of Architectural Engineering, Hanbat National University
125, Dongseo-daero, Yuseong-gu, Daejeon 305-719, Republic of Korea
1hoya0824@naver.com
4kwhlee@hanbat.ac.kr

*Graduate School, Hanbat National University
125, Dongseo-daero, Yuseong-gu, Daejeon 305-719, Republic of Korea
2sbm7470@naver.com
3sarahjung92@naver.com

Abstract
The room air stratification, a zone is divided into two regions which are the occupied region near the floor and the non-occupied region near the ceiling, is the core principle of energy performance in UFAD (Underfloor Air Distribution) system. Through the principle, air conditioning is only needed in the occupied region in cooling mode. Therefore, the building is able to realize energy saving. However, the thermal decay, defined as the supply air temperature rise due to the heat gain into supply plenum, is able to decrease the energy saving. Therefore, in this study, the cooling load and energy consumption of UFAD system were analyzed in an office building. Especially, fundamental impacts of thermal decay on energy performance degradation were analyzed. As a result, UFAD system consumed relative higher energy due to the thermal decay, despite the lower cooling load according to the stratification, and the thermal decay leads to the increase of the supply air flow rate and the decrease of density difference between zone air and supply air. Finally the stratification disappearance caused by those factors decreases the energy performance of UFAD system. Those indicate that the thermal decay needs to be resolved for the optimized performance of UFAD system.

Keywords – UFAD system; Thermal decay; Room air stratification; Supply plenum;

1. Introduction
UFAD (Under Floor Air Distribution) system is one way to control the indoor environment for comfort. In UFAD system, the supply air provided into the zone through the supply plenum located between the structural concrete slab and a raised access floor panel. A building equipped with UFAD system has several benefits compared to conventional ducted system such as improved indoor air quality [1], reduction of the floor-to-floor height [1], thermal comfort [1], layout flexibility [1-2], reduction of life cycle costs [2] and improved energy efficiency in suitable climates [2]. Due to the benefits mentioned above, many research on the UFAD system were
conducted. The energy analysis on the UFAD system in hot climate condition was carried out by Ali F. Alajmi et al. [3]. The result is that the HVAC demand of UFAD is lower than CBAD by 37–51%. Also similar research was conducted by Son H. Ho et al. [4]. In their study, it was mentioned that UFAD system gives better performance than CBAD system in contaminant removal and significantly in energy saving while maintaining the same thermal comfort condition. However, several study on the energy saving performance differed with expected. The analysis on the cooling energy consumption in UFAD system compared with CBAD System in cooling period was carried out by B. Yu et al. [5]. The result is that the UFAD system consumed relative higher energy due to the thermal decay defined as the temperature rise of conditioned air caused by the heat gain in the supply plenum from upper the raised floor and under the slab, despite the lower cooling load according to the principle of room air stratification. And the simplified calculation method for design cooling loads in UFAD system was developed by S. Schiavon et al. [1]. In their study, the supply and return plenums were included as one of cooling load. These results indicate that actually the cooling load is occurred not only the occupied zone also the supply plenum caused by the heat transfer into the plenum although the building equipped with UFAD system has the cooling load of only occupied region in theory. And F. Bauman et al. [6] reveal that about 30-40% of cooling load in whole interior zone is transferred into the supply plenum and about 60-70% of cooling load in whole interior zone was occurred in UFAD system. Therefore, in UFAD system, it is a necessary research for the operation of optimized energy performance to describe several phenomena caused by thermal decay. As the same reason, the influence of thermal decay on the performance in UFAD system was carried out by K. Lee et al. [7]. In their study, they confirm that the heat transfer into the supply plenum from both side the upper the raised floor and under the slab significantly increase the supply air temperature and the temperature rise is considerable. In addition, the annual HVAC energy consumption in UFAD system with thermal decay is greater than an idealized ducted UFAD system without thermal decay about 23% at chiller. Therefore this study aims to investigate what phenomena connected to the thermal decay is occurred through observing the cooling load, energy consumption, thermal decay, heat transfer, air flow rate, temperature difference between occupied and non-occupied region and the Phi value representing the room air stratification [8]. In order to eliminate degradation of energy performance, it is very important to describe the interaction among the each phenomenon in the entire space including supply plenum. According to those results, the best solution for the optimized energy performance in UFAD system would be suggested.

2. Method

The purpose of this study is to investigate what phenomena connected to the thermal decay is occurred in a zone conditioned by UFAD system. For that, three-story building equipped with supply and return plenum and UFAD system was simulated through EnergyPlus. The time-step is set 15 minute and the average output during every hour is used. Also the climatic condition of the Incheon referred to EnergyPlus is used. And the others used in this study is reported below.
2.1 Simulation software

The energy simulation program, EnergyPlus, was used for this study. EnergyPlus is a combination of the DOE-2 and BLAST which are the conventional major simulation program [9-10]. The accurate simulation is conducted to analyze various heat transfers through application of the heat balance method recommended by ASHRAE [9, 11]. In addition, the fully integrated modeling of major building components such as zone, surface, air heat balance, system and plant is conducted at each time-step. By those features, EnergyPlus is able to describe the interactive connection of each component [9]. Especially, EnergyPlus must be used, when evaluating the UFAD system. The reason is that the heat gain into the underfloor supply plenum and the room air stratification should be captured by the simulation program [1]. Thus EnergyPlus can perform a full heat balance including the underfloor supply plenum and calculates the temperature rise of the conditioned air inside the plenum during each time-step.

2.2 Description of office building

A three-story prototype office building with a rectangular shape (75m × 51m) and aspect ratio of 1.5 was chosen. The floor plate size is 3,720 m² (total floor area is 11,200 m²) and each floor is composed of four perimeter zones and an interior zone which represent approximately 28% and 72% of the floor area, respectively (see Fig. 1). The floor to floor height is 3.96 m, and the return and supply plenum height are 0.6 m and 0.4 m. strip windows are evenly distributed in the walls and the baseline window-to-wall ratio (WWR) is 30% [7]. The constructions and the thermal properties of windows change based on Table 5.5 of ASHRAE 90.1-2004 [12]. When doing the design day simulation, ASHRAE 0.4% summer and 99.6% winter design conditions were assumed [13].

![Floor plan of the simulated building](image)

Fig. 1 Floor plan of the simulated building [7].

2.3 Internal temperature, ventilation and infiltration rate, and HVAC system

From 5:00 till 19:00 the system controls the internal air temperature to dead-band between 24C and 21 C. During the other time, the dead-band is altered to 27C and 18C for set-back. The infiltration was assumed equal to 0.000333 m³/(s m²) (flow per exterior surface area). The minimum outdoor air flow rate was set to 0.762 L/(s m²) (flow per gross area) and was provided from 5:00 until 19:00. Regarding the airflow
outlets of each zone, the air is distributed through swirl diffusers in interior zones and linear bar grilles in the perimeter zones [7]. Variable-speed fan coil units (FCU) shuts off when zone temperatures are in the dead-band. In cooling mode, the fan and the heating coil is off, and in heating mode, the fan and the heating coil are on. The building is served by a single variable-speed central station air handling unit (AHU) including an economizer, chilled water cooling coil, hot water heating coil and supply fan. The AHU fan is controlled with a static pressure reset strategy. The central plant tow-speed cooling tower. A gas fired boiler provides hot water to all heating coils [7]. Table 1. shows details of system and plant inputs.

| **Table 1. Summary of HVAC system configuration [7].** |
|-----------------------------------------|-----------------|
| AHU supply temperature                  | 15.6°C          |
| AHU fan design static pressure          | 750 Pa          |
| AHU fan efficiency                      | 63%             |
| AHU part load shutoff                  | 125 Pa          |
| Minimum outside air rate                | 7.62E-04 m³/s/m² |
| Zone minimum air flow                   | 7.62E-04 m³/s/m² |
| FCU design static pressure              | 125 Pa          |
| FCU design efficiency                   | 15%             |
| Chiller design COP                      | 5.5             |
| Boiler design efficiency                 | 78%             |

*a* Designates low shutoff pressure associated with static pressure reset.

2.4 Internal heat gains and occupancy

The fraction of the design value is defined as the ratio of the actual load to the peak or maximum load in Fig. 2. The occupants’ presence in the building varied according to Table 2. and Fig. 2. Three levels of internal cooling load were simulated and they are summarized in Table 2. Internal loads follow the schedules shown in Fig. 3 [7].

![Figure 2 Occupancy, lighting, equipment schedule [7].](image)
Table 2. Summary of HVAC system configuration [7].

<table>
<thead>
<tr>
<th></th>
<th>W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead lighting</td>
<td>9.1</td>
</tr>
<tr>
<td>Peak occupancy</td>
<td>9.3</td>
</tr>
<tr>
<td>Equipment</td>
<td>14.4</td>
</tr>
<tr>
<td>Total</td>
<td>31.4</td>
</tr>
</tbody>
</table>

2.5 Gamma-Phi formulation

The Gamma-Phi formulation is entered into EnergyPlus to describe the room air stratification. As shown in Fig. 3, the Gamma-Phi formulations could be inferred.

![Gamma-Phi correlations](image)

Fig. 3 Interior zone (Swirl) Gamma-Phi correlations [8]

The value of Gamma (Γ), defined in (1), is a dimensionless number representing the ratio of momentum to buoyancy forces [8], which is computed through the experimental measured value. When equipped with a swirl diffuser in interior, the value of Gamma (Γ) used in Fig. 3 is equal to (1). The lower values of Gamma indicate increased stratification, higher values less. Generally the values should be between 2 and 30 [14].

\[
\Gamma = \frac{(Q \cdot \cos \phi)^3}{m \cdot \left(\frac{n}{m} A_{eff}\right)^{5/6} \cdot (0.0281 \cdot W)^{1/2}}
\]  

(1)

Where,

- Q total room airflow [m³/s]
- \( \cos(\phi) \) discharge angle from vertical [°]
- n number of diffusers [1]
- m number of plumes (i.e., workstations) [1]
- \( A_{eff} \) effective diffuser area of single diffuser [m²]
- W room convective heat extraction (i.e., cooling load) [kW]

The value of Phi, defined in (2), is a dimensionless number between 0 and 1 representing the stratification in the room; lower values mean more stratification.

\[
\Phi I = \frac{T_{oz-avg} - T_{SAT}}{T_R - T_{SAT}}
\]  

(2)

Where,
\( T_R \) return air temperature \(^{\circ}F\)

\( T_{oz-avg} \) occupied zone average temperature \(^{\circ}F\), calculated as average temperature between heights of 4 inches and 67 inches in room

\( T_{SAT} \) diffuser supply air temperature \(^{\circ}F\)

3. Results and discussion

3.1 Analysis on the thermal decay

Fig. 5 shows the profile on supply plenum air temperature of each zone on August 11\(^{th}\). The temperature difference between AHU supply air and supply plenum air defined as thermal decay could be confirmed through Fig. 5. As a result, the thermal decay was occurred as significant level in plenum. In detail, the thermal decay which occurred in perimeter plenum was greater than the interior plenum since the supply path is set to series configuration. Therefore, the AHU supply air is delivered into the interior plenum first, and the air temperature is increased by the thermal heat gain from the surrounding materials, and after, the heated air is delivered into the perimeter plenums, and the heated air is heated again.

![Fig. 5 The profile on supply plenum air temperature of each zone on August 11\(^{th}\)](image)

Also the going down of thermal decay level is confirmed when schedules are changed to the occupied schedule in Fig. 5. It is due to the fact that the load such as people, machines, lights, solar irradiation, thermal heat transfer, etc. is increased during the occupied time, therefore in order to achieve the thermal comfort, the air flow must be increased as shown in Fig. 6 (the air flow of interior plenum is illustrated on the left side, the perimeter plenums right side), and which means that the heat gain rate per unit supply air volume is decreased. That is why the thermal decay level is decreased during occupied time rather than before. And due to the supply air path which is set to series configuration, the air flow rate of interior plenum is about 5 times of other plenum. This will have influence on heat transfer into plenum due to dynamic changes in various temperatures and convective heat gain coefficients. And the dynamic changes is due to the fact that in a building equipped with UFAD system, the absence of duct system incurs decrease of the thermal performance. In Fig. 7, the heat gain rate into plenum of each zone on August 11\(^{th}\) is illustrated. As confirmed in Fig. 7 (the heat gain rate of interior plenum is illustrated on the left side, the perimeter plenums the right side), the
highest heat gain was confirmed in interior zone among all zones. In addition, the interior plenum heat gain was greater than the sum of perimeter plenums heat gain. The reason is the air flow rate difference between interior and perimeter plenums, and that the non-heated air delivered directly from AHU makes the temperature difference more between surfaces and air rather than the perimeter plenum in which the once-heated air is supplied from the interior. Except for the interior plenum, the analysis on the heat gain rate of each perimeter plenum was conducted to observe the effect of solar irradiation on heat transfer into plenum, and the black points on lines were marked as the peak value of the heat gain. As a result, the peak value of heat gain was occurred at 10:00 in east plenum, at 13:00 in south plenum, at 16:00 in west plenum and north plenum. Except for the north plenum which has few or no effect of solar irradiation, the peak value was observed depending on the solar location. The result indicates that the solar irradiation is a major factor of deciding the heat transfer quantity in perimeter plenum. But the effect of solar irradiation was negligible in north and interior plenums, and the heat gain into interior plenum was greater than the sum of others. Therefore it is assumed that to decrease the heat transfer (or thermal decay), the improvement of thermal performance in plenum should be given as a higher priority rather than decreasing the effect of solar irradiation.

Fig. 6 The profile on supply plenum air flow rate of each zone on August 11th

Fig. 7 The profile on supply plenum heat gain rate of each zone on August 11th
3.2 Correlations between thermal decay and room air stratification

Fig. 8 shows the Phi value of each zone, the value of interior zone is illustrated. As shown in Fig. 8, except for 20:00, the interior zone maintains the room air stratification stably. The reason of sharp rise is due to the increased set-point temperature switched to 27 C after occupied time. In addition, the interior zone could achieve the thermal comfort despite the heat exchanging between the occupied region and non-occupied region. Simultaneously, the temperature difference is getting closer to 0 due to the heat exchanging. On the other hand, the unstable patterns were observed in each perimeter zone. The ATU (Air Terminal Unit) discharge temperature is increased by heat gain as the conditioned air passes along plenums, and the increased temperature is a cause of air flow rise. Consequently, this affects the Phi value through the gamma value computed by (1), because the air flow is a numerator in (1), and thus the increase of gamma value lead to the increase of phi value as shown in Fig. 3. And after 05:00, the building is operated with occupied schedule, and thus the air flow rate is increased to handle the increased cooling load, which is normal phenomena. However, the air flow rate is increased more again due to the thermal decay. In addition, as mentioned earlier, the air flow rate is increased once again due to the solar irradiation. As a result, the phi value is getting closer to 1.0 when the solar irradiation faces the window of each zone, which means there is few or no room air stratification. Then the stratification degradation incurs decrease of energy saving performance in UFAD system because the system would control thermal comfort of whole region including occupied and non-occupied region.

![Graph](image)

Fig. 8 The profile on Phi value of each zone on August 11th

3.3 Analysis on the energy consumption

In Fig. 9, the cooling load and energy consumption of each component in the system is illustrated. As a result, the cooling load was less than 1.5 times that of the chiller energy despite the high design COP which is set to 5.5. In other words, the system handled larger load than that presented in Fig. 9. The reason is assumed to be due to the fact that the cooling load presented in Fig. 9 does not consider the heat gain into underfloor supply plenum. Therefore the plenum should be considered a kind of controlled zone which is maintained to 15.6 C which is the same as the given AHU set-
point temperature, and the heat gain should be calculated for the accurate design of UFAD system. In addition, another reason is due to the fact that the air flow rise affected by the several factors mentioned thus far makes the stratification degradation incurred in the controlled zone, and thus the stratification degradation finally incurs the thermal control throughout the whole region including occupied and non-occupied region.

![Graph showing cooling load and energy consumption](image)

**Fig. 9 The profile on cooling load and energy consumption of each component during cooling period**

### 4. Conclusions

This study aimed to analyze on the cooling load and energy consumption in an office building equipped with the UFAD system. Especially, impacts of thermal decay on energy performance degradation were analyzed. For that, analysis on the thermal decay, air flow rate and heat gain rate were carried out on representative day in which the pattern was enough to recognize clearly. Also an analysis on the correlations among those factors was carried out. Major findings from this study are:

- The energy consumption in UFAD system was greater than the calculated cooling load based on only occupied region. Therefore it is required to calculate the cooling load including the supply plenum.
- It was found that the energy consumption in UFAD system was varying significantly depending on the interaction among the thermal decay level, air flow rate, heat gain rate and phi value.
- The heat gain incurs thermal decay, which, in turn, incurs the increase of air flow rate and finally the phi value. As a result, those phenomena have negative synergy effect on the energy consumption throughout whole system.
- In supply plenum, there is no insulation, which is a major cause of the heat gain, and thus the degradation of energy performance was observed.
- Although the solar irradiation had strong influence on the system performance in perimeter plenums, the thermal performance of plenums affects not only perimeter zones but also interior zone and the heat gain in interior plenum was greater than the sum of others. Therefore, the improvement of thermal performance in supply plenum should be
considered as the higher priority than decreasing the effect of solar irradiation for the maintaining the optimal performance of UFAD system.

Acknowledgment

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References