Impact of the Perimeter Zone Diffuser Slot Angle on Room Air Stratification and Energy Performance in Underfloor Air Distribution System

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ABSTRACT
Recently tendency to introduce an underfloor air distribution (UFAD) system for environmentally friendly buildings as an alternative to OH systems clearly increased. Also LEED which is a green building certification system developed by the U.S. Green Building Council proposes UFAD to be the system having improved control and efficiency. This study, by using the Phi-Gamma formula, aims at assessment of the energy performance and temperature stratification according to the variation of a diffuser slot angle from vertical in perimeter zones. Through the EnergyPlus simulation which is validated by both bench-scale and full-scale experiment, the analysis on the energy consumption depending on the diffuser slot angle was conducted in the three-story office building. As a result, stratification was improved with an increase in the vertical angle of the diffuser and thus cooling load was reduced during the summer. However, it showed an increase in energy consumption in the boiler. The reason is that the mixed air temperature is increased despite the reduction of AHU supply air volume. Therefore the energy saving effect was insignificant.

KEYWORDS
UFAD, Room air stratification, Energy performance, Discharge angle from vertical, EnergyPlus

INTRODUCTION
The underfloor air distribution (UFAD) system, which is a building energy consumption saving technology, is an air conditioning system that enables to maintain the indoor temperature with a relatively small supply-return air temperature gap at a low supply air flow rate (Jang et al. 2012). In the U.S., the Leadership In Energy & Environmental Design (LEED), which is a green buildling certification system, suggests the UFAD system as an environment-friendly system with respect to system controllability and ventillation efficiency. The Intelligent Building Certification System supervised by Intelligent Building Society of Korea gives the significant points for the certification to the UFAD system among all the air conditioning methods in the area of mechanical equipment. Internationally, research on the UFAD system has been actively conducted to develop the cooling load calculation method and analyze the performance of the UFAD stratification (Sam Cmh et al. 2015, Webster T et al. 2002). In addition, a dimensionless number, gamma-phi, has been introduced to quantitatively represent the degree of stratification (Webster T et al. 2008). In South Korea, Yu et al. (2004) analyzed and compared the properties of the UFAD system and ceiling-based air conditioning system, indicating that occupants' satisfaction with the UFAD system was high in winter but low in summer. In addition, it was found that the ventilation efficiency was higher in the UFAD system than in the ceiling-based air conditioning system. However, the study by Yu et al. (2004) was a simple comparative experiment, not dealing with the details of the UFAD system. Kim

et al. (2007) studied the tendency of temperature stratification in summer depending on the number of diffuser.The result indicated that the flow rate and type of air supply inlet and the heat storage performance of the ground should be considered in the design of appropriate temperature startifcation in the UFAD system. Like these examples, several studies have been conducted in South Korea with regard to the UFAD system. However, the stratification, which is a key factor to the UFAD system, has not been studied sufficiently. In the present study, an office building was described through EnergyPlus simulation and the formulation for gamma-phi, which is the stratification coefficient, was used to analyze the change of the stratification in the west zone depending on the increase of the angle from the vertical diffuser as well as the energy performance.

1. RESEARCH METHODS

1.1 Simulation program

The present study employed EnergyPlus which was developed by the U.S. Department of Energy (DOE) for the analysis of cooling and heating energy in buildings and enables the mathematical verification of thermal environment (Crawley et al. 2014). EnergyPlus is the software program developed by integrating only the advantages of DOE-2 and BLAST. EnergyPlus uses the heat balance recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), and enables to the dynamic analysis of unsteady-state heat transfer through heat conduction, radiation, and convention as well as the mathematical verification of cooling and heating load in buildings on the basis of the building skin and the indoor and outdoor environmental conditions. In particualr, EnergyPlus enables to realize the stratification by means of a room air model and the gamma-phi formulation and reflect the temperature increase through supply plenum in the UFAD system. Therefore, EnergyPlus was employed as an appropriate tool for the simulation of the UFAD system in the present study (U.S. DOE. 2010).

1.2 Simulation model

The subject building was assumed to be a three-story office building prototype having a rectangular shape of 53 m X 35 m and strip windows are evenly distributed in the walls and the window-to-wall ratio is 40%, and the floor to floor height is 3.9 m (supply plenum 0.4 m and return plenum 0.8m). The modeling was performed with respect to one interior zone and four perimeter zones per each floor. The weather data of Incheon, the built-in data of EnergyPlus, were used. The representative date was decided as July 28 when the cooling load is drastically increased in summer. In addition, the office building schedule of ASHRAE Standard 90.1 was applied. Table 1 shows the system input conditions for simulation. The variable of the present study was the diffuser slot angle from the vertical in the gamma formulation, and the value is shown in Table 2. CASE 1 indicates the initial value of the diffuser slot angle from the vertical, and the angle was increased by 15°, starting from CASE 2. In addition, the maximum value was set to be 75°, since the variation of the estimated data was negligible from the angle of 75°.

Table 1*Simulation condition*

Fixed Value	
AHU Discharge Temperature	15℃
AHU Fan Design Static Pressure	875Pa

AHU Fan Efficiency	63%
Supply Plenum Configuration	Series
Interior Zone Reheat	No
FCU Fan Design Static Pressure	125Pa
FCU Fan Design Efficiency	15%
Chiller Design COP	5.5

Table2*Diffuser Type and Simulation Case*

Case	Diffuser Slot Angle from Vertical (°)	
	Swirl (Interior)	Linear Bar grille (Perimeter)
CASE 1	28	15
CASE 2	28	30
CASE 3	28	45
CASE 4	28	60
CASE 5	28	75

2. Theoretical Background

2.1 Room Air Stratification

The stratification of the UFAD system is a key factor to the system, since it plays a critical role in determining the heat, ventilation, and energy performance (Bauman, 2003). The stratification of the UFAD system refers to the inconsistent vertical temperature distribution from the bottom to the ceiling due to the buoyant effect of air (Son et al., 2016). As shown in Figure 1, the stratification forms a temperature layer at the level of a person's head (1.7 m) which divides the air-conditioned indoor space into a lower occupied zone and an upper non-occupied zone. A larger temperature difference between the occupied zone and the non-occupied zone means better stratification. In addition, the stratification may save the cooling energy, because the stratification removes the need to consider the cooling load occurring in the upper non-occupied zone.

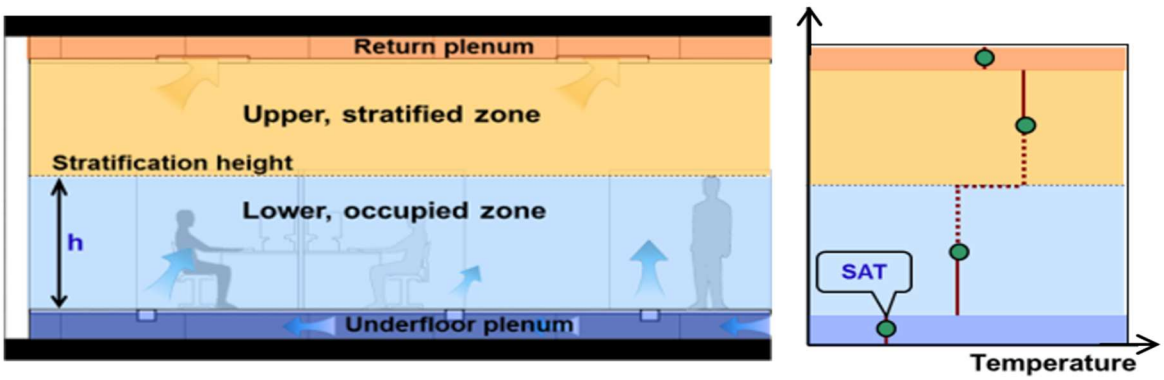

Figure 1. Room Air Stratification

2.1 Phi(ø)-Gamma(Γ) formulation

Phi is a dimensionless coefficient representing the temperature stratification and has a value in a range from 0.0 to 1.0. A smaller phi value means better stratification. The phi value is defined as Equation (1) (Webster T et al. 2013):

$$\mathrm{PHI} = \mathrm{T_{oz-a}} - \mathrm{T_{SAT}}/\mathrm{T_R} - \mathrm{T_{SAT}} \quad (1)$$

where T_{oz-av} means occupied zone average temperature (˚F), calculated as average temperature between heights of 4 inches and 67 inches in room. and T_{SAT} is diffuser supply air temperature (˚F). and T_R is return air temperature (˚F).

Gamma is a dimensionless coefficient representing the ratio of buoyancy to momentum. Equation (2) describes the gamma value for the perimeter zone (Webster T et al., 2013). The general value of gamma is in a range from 2 and 30, and a smaller gamma value means better stratification (EnergyPlus Input Output Reference, 2010).

$$\Gamma_{\mathrm{L}} = (\mathrm{Q} \cdot \cos\varphi)/(\mathrm{n} \cdot \mathrm{A_{eff}}) \cdot (0.0281 \cdot \mathrm{W_L})^{\frac{1}{3}} \quad (2)$$

where Γ_L means Gamma, a dimensionless number representing the ratio of momentum to buoyancy forces. And Q is total zone air flow (m^3/s). Also $\cos\theta$ is discharge angle from vertical (°). n is number of diffuser, A_{eff} is effective diffuser area (m^2). and W_L is zone extraction rate per unit length of zone (kW/m).

3. Simulation Analysis

3.1 Phi(ø)

The gamma value is determined by the air flow rate, the diffuser slot angle from the vertical, and the area of the diffuser slot, and the phi value is determined by the gamma value. Figure 2 shows the phi value of the west zone, and Figure 3 shows the supply air flow rate in the west zone. As can be seen from Figure 2, as the diffuser slot angle from the vertical increased, the phi value pattern was improved. Figure 3 shows that the stratification was destroyed as the ATU supply air flow rate at 05 o'clock in CASES 4 and 5 was increased due to the increased external air temperature and solar radiation as time passed. The stratification was destroyed in CASE 1,which is the base case, from 10 o'clock as the phi value became 1, whereas the the stratifcation was destroyed at 13 o'clock in CASE 2 and at 15 o'clock in CASE 3. The stratification was not destroyed in CASES 4 and 5. This result indicates that the stratification was dependent on the magnitude of cosθ, where θ is the diffuser slot angle from the vertical. As the angle, θ, was increased, the direction of the air flow was gradually changed from a vertical direction to a horizontal direction, providing advantageous conditions for the stratification. In addition, it is thought that the flow rate was also increased as the magnitude of cosθ was increased. According to Equations (2) mentioned in Section 2.1 Phi (ø)-Gamma (Γ) formulation, as the diffuser slot angle from the vertical, θ, was increased (and thus the cosθ was decreased), the gamma value was decreased. Therefore, in view of the increase of the Gamma value due to the increased air flow rate, it is determined that the stratification is not destroyed but maintained and improved. The effect of the increased air flow rate was dependent on the θ value. The pattern of the maintained stratification was improved as the θ value was

increased in individual cases. For example, the average phi value in CASE 5 where the θ value was the greatest was 0.7, which indicates that the stratification was improved and maintained. Figure 3. shows the stratification pattern that the flow rate was high initially at 05 o'clock in CASES 4 and 5 where the θ value was large, but the flow rate was later decreased as time passed. The air-conditioning up to the stratification height of 1.7 m was relatively easy in CASES 1, 2, and 3 where the θ value was equal to or less than 45°, since the diffuser slot angle was close to the vertical. On the contrary, in CASES 4 and 5 where the θ value was equal to or greater than 60° and thus the direction of the air-conditioning was near to the horizontal direction, the flow rate was increased to reach the stratification height of 1.7 m. As time passed, the stratification was destoryed in CASES 1, 2, and 3 due to the increased flow rate. However, the flow rate was decreased in CASES 4 and 5 where the stratification was maintained and improved, because the air-conditioning was performed only up to the occupied zone, as described in Section 2.1 Room Air Stratification.

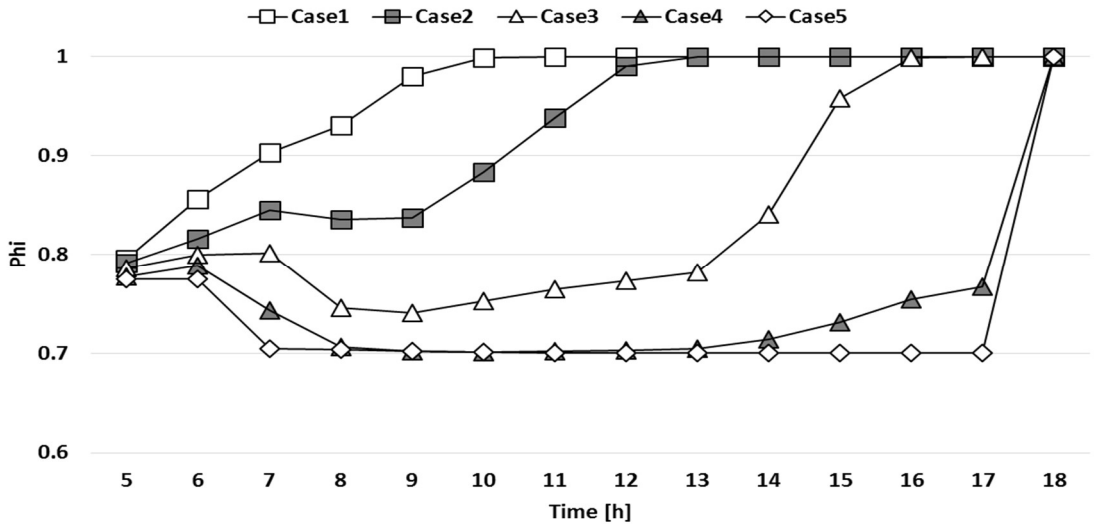

Figure 2. Phi of West Zone

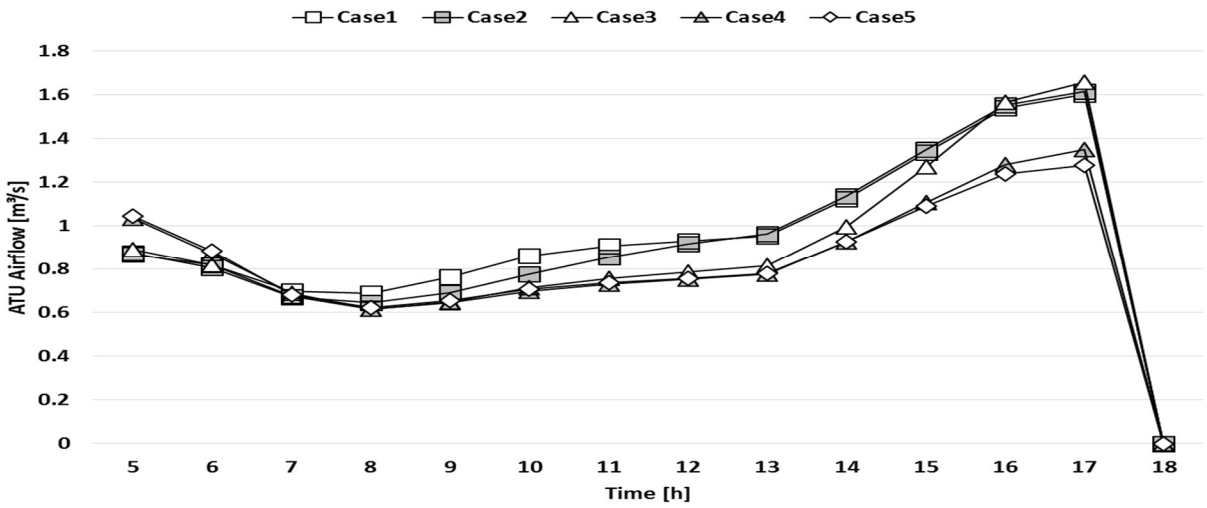

Figure 3. ATU Airflow of West Zone

3.2 Energy Consumption

Figure 4 shows the annual energy consumption by chillers, towers, fans, and auxiliary pumps. As the diffuser slot angle from the vertical, θ, was increased, the stratification in the perimeter zone was improved but the reduction of the annual energy consumption was negligible. The annual energy consumption by chillers was the highest as 11.24 kW/m² in the basic case, CASE 1, and the lowest as 11.05 kW/m² in CASE 5 where the diffuser slot angle from the vertical was the greatest, but the difference was as small as 1.69%. There was almost no difference between the cases in the annual energy consumption by towers and auxiliary pumps. With respect to the cooling coil rate, as the diffuser slot angle from the vertical is increased and thus the stratification is improved, the total flow rate is decreased. However, since the air-conditioning is performed only up to the occupied zone due to the stratification, the temperature of the non-occupied zone is increased, resulting in an increased return air temperature. As the return air at the increased temperature and the high-temperature external air are mixed, the temperature of the mixed air is increased, resulting in a negligible difference in the cooling coil rate. Hence, the difference of the annual energy consumption by chillers, towers, and auxiliary pumps was very small between the cases. The annual energy consumption by fans was the highest in CASE 1 as 5.05 kW/m², and the lowest in CASE 5 where the diffuser slot angle from the vertical was the largest, indicating that the difference was 4.9%. The annual energy consumption by fans was reduced as the diffuser slot angle from the vertical increased, which resulted in improved stratification in the perimeter zone as well as decreased supply air flow rate to the perimeter zone. Although the stratification in the perimeter zone was improved as the diffuser slot angle from the vertical increased, the annual energy consumption in the interior zone was not dependent on the perimeter zone stratification. This indicates that the overall annual energy consumption was not greatly changed by the stratification in perimeter zones because the interior zone which accounted for about 60% of the entire area was not affected by the stratification.

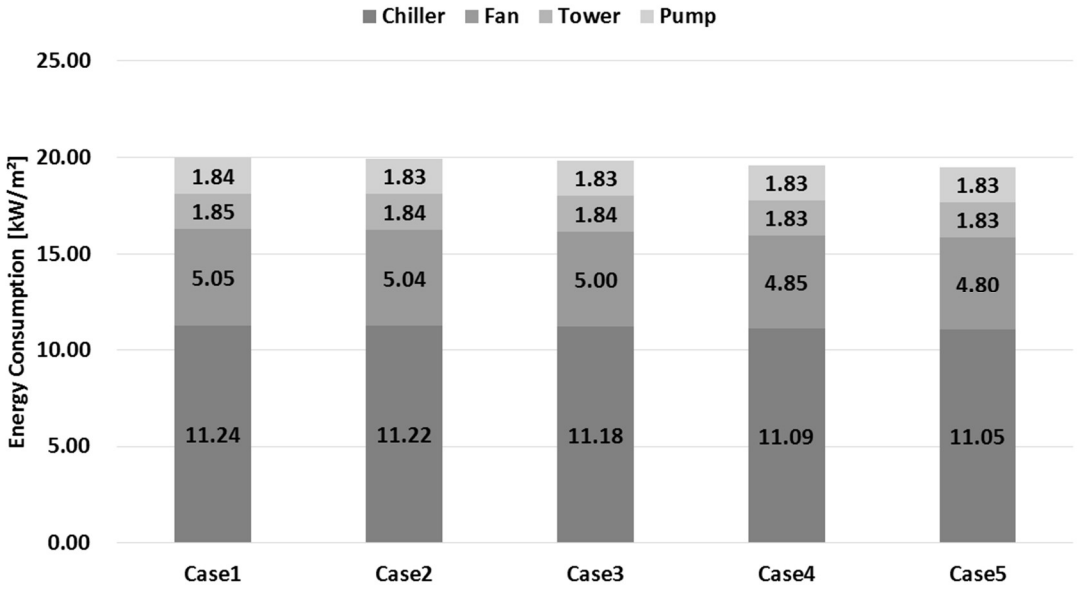

Figure 4. Annual Energy Consumption

5. CONCLUSIONS

In this study, an office building was simulated by using EnergyPlus. Among the stratification

factors included in the gamma-phi formulation, the diffuser slot angle from the vertical was chosen as a variable in this study. The diffuser slot angle from the vertical was increased only in the perimeter zone, because the effect of the diffuser slot angle from the vertical was negligible in the interior zone. Through this, the change of the stratification was investigated and the energy performance was evaluated with respect to the west zone.

(1) As the diffuser slot angle from the vertical was increased, the phi value of the west zone was decreased and stratification was improved. According to Equations (2) mentioned in Section 2.1 Phi (ø)-Gamma (Γ) formulation, as the diffuser slot angle from the vertical, θ, was increased (and thus the cos θ was decreased), the gamma value was decreased. Therefore, in view of the increase of the Gamma value due to the increased air flow rate, it is determined that the stratification is not destroyed but maintained and improved. The stratification was better maintained and improved as the θ value was greater.

(2) As the diffuser slot angle from the vertical was increased, the stratification of the perimeter zone was improved and thus the air flow rate was decreased. However, since the temperature of the mixed air was increased due to the temperature increased in the non-occupied zone, the decrease of the cooling coil rate was negligible in comparison with the decrease of the overall flow rate. Hence, the difference in the energy consumption by chillers, towers, and auxiliary pumps was small. The maximum decrease in the energy consumption by fans due to the decreased flow rate was 4.9% in the perimeter zone. This indicates that the overall annual energy consumption was not greatly changed by the stratification in perimeter zones because the interior zone which accounted for about 60% of the entire area was not affected by the perimeter zone stratification.

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