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What is This?
Energy Benefit of the Underfloor Air Distribution System for Reducing Air-Conditioning and Heating Loads in Buildings

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\textbf{Key Words}
under floor air distribution system · UFAD · HVAC · building energy · energy performance

\textbf{Abstract}
Although there have been continuing efforts recently for low-energy buildings as parts of the low-carbon green growth movement, particular attention has been paid to architectural design, the elective control of façades, and the efficiency of Heating, Ventilation, and Air Conditioning (HVAC) mechanical systems. To maximize the gains from these efforts, it is essential to consider the energy distribution approach and its layout during the design stage of the building. To this end, air distribution principles in HVAC have grown in popularity in buildings. The method to deliver the energy is strongly associated with increasing concerns about indoor environmental quality on occupants’ well-being, as well as rising energy costs for space heating and cooling. This paper identifies types of air distribution systems for heating and cooling in buildings and addresses the potential energy benefit of an underfloor air distribution (UFAD or UAD) system over the conventional ceiling air distribution system. A series of EnergyPlus simulations shows performance differences between the two distribution systems. One result is that the potential benefits of an UFAD are clearly demonstrated for a large space with a high ceiling.

\textbf{Introduction}

Current trends in the area of architecture clearly show more energy, not less, will be required to sustain our quality of life. The top priority in building design is generally placed on maximizing the productivity of the space and occupants’ satisfaction. In leased commercial buildings, in particular, where many unspecified people...
are responsible for paying for the energy used, a building would be designed in that way and would therefore consume more energy compared to other types of buildings. As buildings become larger and higher, in addition, this energy demand increases dramatically, and the efficiency of energy-consuming building systems becomes more important.

Most people think of insulation or mechanical systems when they consider energy demand and efficiency in air-conditioning of buildings. There have been continuing efforts recently to develop quality-based air-conditioning equipment that is both low in cost and high in efficiency and with smarter envelope systems with enhanced insulation and air tightness. To maximize the gains from these efforts, these systems should be related to all elements that could contribute to higher energy efficiency in actual operation of buildings. In particular, an energy distribution approach and its physical layout should be incorporated in the design stage of the building as a whole.

Air distribution principles in HVAC have a strong influence on indoor environmental quality and the energy costs for space heating and cooling. It also has a direct impact on space organization, floor height planning, interior layout, and the cost of construction. In a heating and cooling system utilized by the air, the type of air distribution system plays a much more decisive role in the performance, especially within a large space with a high ceiling.

In Korea, there has been a rapid economic growth since the 1980s, along with a rising national income, which has led to people’s greater desire for a higher quality of life. One means of pursuing this goal would be a focus on cultural life, and because this mostly occurs within buildings, currently construction of gymnasiums, concert halls, and theatres are booming in Korea. However, these cultural facilities are mostly composed of large spaces and natural ventilation through windows would be almost impossible; and would generally require a high level of dependency on mechanical ventilation with conditioned air.

Since these large cultural facilities have high ceilings, furthermore, when conventional ceiling air distribution system is used in these buildings, a great amount of energy would be required to maintain the optimal indoor temperature for a comfortable indoor environment. There have been literature reports asserting the advantages of an underfloor air distribution (UFAD) system for these cultural facility spaces, over the conventional ceiling air distribution system in terms of both energy reduction and thermal comfort [1–7]. The energy consumption and environmental performance of demand control ventilation system typically used in multi-zone high-rise buildings have been discussed [8]. An UFAD system is an air-conditioning distribution system that uses the underfloor plenum as the path for the conditioned air to be delivered. For facilities with high ceilings, an UFAD system would be more appropriate to enhance thermal comfort and reduce energy consumption and would allow individual control of ventilation volume and distribution of air only to occupied zones.

This paper presents an analysis on whether the application of an UFAD system for a large space could result in energy consumption reduction. The amount of energy saving and the alternatives to reduce energy consumption were estimated by a computer simulation program, EnergyPlus, when an UFAD system was applied to a large space with a high ceiling in a cultural facility.

**Underfloor Air Distribution System**

The heating and cooling system for a space consists of a space conditioning unit and the associated air distribution system. The primary distinctions that affect the performance of air conditioning systems are rooted in the configuration of the distribution system. As illustrated in Figure 1, a conventional HVAC design would typically be based on a regular overhead (OH) air distribution system with the conditioned air being both supplied and returned at ceiling level through an array of evenly spaced ceiling diffusers connected to extensive networks of ducting. This method of the mixed flow air distribution would produce relatively uniform temperatures throughout the space by the high-level mixing of space air into the supply air [9–12]. However, a considerable amount of the ceiling plenum is needed to house the network of both supply and return ducts.

As illustrated in Figure 2, an UFAD is an air distribution system where the conditioned air is delivered from the ‘bottom up’ rather than the ‘top down,’ as in the conventional OH air distribution, which thus allow individual control of ventilation volume and distribution of air only to the occupied zones [3].

To date, there have been numerous publications in the literature which focus on verifying the advantages of the UFAD for conventional spaces. Stanke provided a brief review of UFAD which identifies the advantages and difficulties of applying this system [13]. Often cited as an initial cost benefit of UFAD, the total building
height could reduce slab-to-slab distance as much as 10 percent by removing the supply ducts, terminals, and the diffusers [1].

Indoor air quality (IAQ), one of the primary concerns for an air-conditioning system, relates to the contaminant concentrations in the breathing zone. Some studies report lower breathing-zone concentrations for UFAD systems than for OH variable air volume (VAV) systems [14]. Bauman also suggests that a 5%–10% reduction in floor-to-floor height is possible, compared to conventional ceiling-based OH air distributions [1]. In addition, Bauman et al. reported a modelling study that investigated the primary pathways for heat to be removed from a room with an UFAD system under cooling operation with implications for the design and operation of UFAD systems [15].

Fukao et al. also measured and evaluated thermal environments, indoor air quality and the ventilation effectiveness of an UFAD system in an actual office building with comparison to an OH system in the same building with an identical floor plan [16]. Xu demonstrated that the indoor air temperature stratification with an

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**Fig. 1.** Conceptual view of a traditional overhead air distribution system.

**Fig. 2.** Conceptual view of an underfloor air distribution (UFAD) system.
UFAD system could offer an opportunity for cooling load reduction in the occupied zone, as compared with the conventional mixing system [17].

According to Barba’s work, some designers use UFAD systems to achieve higher scores in the Leadership in Energy and Environmental Design (LEED – by USGBC) rating system through enhancing the energy optimization score and individual control of supply diffusers [18]. Modern office buildings make growing use of UFAD for thermal comfort, energy efficiency, and flexibility of the space. Thanks to the practical UFAD benefits enumerated above, Stanke predicted that as many as 35% of future’s office buildings will include UFAD systems [13]. Karvonen also estimated that raised floor installation in North America will double to 20% of new office building construction in the near future [19].

System Definition and Analysis

Analysis Tool: EnergyPlus

For the energy simulation of a target space with a high ceiling, a computer program, EnergyPlus, has been selected as the main tool [3]. EnergyPlus includes a number of innovative simulation features – such as variable time steps and user-configurable modular systems that are integrated with a heat and mass balance-based zone simulation – and input and output data structures tailored to facilitate third-party module and interface development [20].

UFAD system modules, jointly developed by the Center for the Built Environment (CBE) laboratory and Lawrence Berkeley National Laboratory (LBNL), can model the entire building using EnergyPlus. Table 1 describes the input and output of the EnergyPlus UFAD System Module.

Model Construction of the Target Space

As a model of a large space with a high ceiling, the multiplex theatre “C” in a huge department store recently built in South Korea was selected for energy simulation in this study, using an UFAD. In terms of the total floor area (294,853m²), the building complex is in the Guinness Book of Records as the largest department store in the world, and houses theatres, duty free shops, an aquarium and hot springs and so forth. Figure 3 illustrates the interior view of the theatre, which is located in the centre of the building.

Table 1. EnergyPlus underfloor air distribution system module inputs and outputs

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Supply conditions</td>
<td>• Supply plenum temperature</td>
</tr>
<tr>
<td>– Supply plenum configuration</td>
<td>• Room occupied zone temperature</td>
</tr>
<tr>
<td>– Air temperature</td>
<td>• Room upper zone temperature</td>
</tr>
<tr>
<td>• Room conditions</td>
<td>• Surface temperatures</td>
</tr>
<tr>
<td>– Thermostat setting/height</td>
<td>• Airflow rate</td>
</tr>
<tr>
<td>– Heat sources</td>
<td></td>
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<tr>
<td>• Diffusers</td>
<td></td>
</tr>
<tr>
<td>– Type (swirl or VA)</td>
<td></td>
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<td>– Number</td>
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Fig. 3. Real view of the target interior space with high ceiling.
complex, surrounded by walls without a window to the outdoors. The theatre complex hosts a total of eight screens and the target interior space is located on the eighth floor and can be regarded as a representative configuration. The space has seating accommodation for 278 and the ceiling is 12 m high.

To easily input the geometric information into the space model, the OpenStudio plugin for SketchUp was used to define the zones, materials and properties. As shown in Figure 4, the distinctive features of the theatre were included in the consideration; taking into account the physical dimension and both ceiling and floor plenums that were input for the modelling.

Results

The Effect of an UFAD System

A series of simulations were carried out to analyze the energy consumption level, the current distribution and the thermal environment of the large interior space of the theatre with either a regular ceiling air distribution system or an underfloor air distribution system. The comfort level from actually applying the UFAD system was also evaluated.

The EnergyPlus simulation was used to calculate not only the total amount of the annual heating and cooling loads but also the temperature of the thermostat, the occupied zones and the unoccupied zones, when an UFAD is utilized. Figure 5 shows the daily temperature data acquired by the simulation.

At first, the simulated temperature on the thermostat seems to be almost the same as the set-point temperature. The highest temperature in cooling was 28.4°C and the lowest was 23.5°C, and the average temperature was 25.4°C, which was almost the same as the set-point temperature. In cooling, the average temperature in the occupied zone was 25.2°C, whereas the unoccupied zone was 26.8°C on average, showing a temperature difference of 1.5°C.

In heating, the average temperature in the occupied zone was 21.9°C, whereas in the unoccupied zone it...
was 24.5°C on the average, showing a temperature difference of 2.52°C. The reason of the bigger temperature difference in heating was due to the stratification by the buoyancy effect of the supply air. The buoyancy is directly proportional to the density of a fluid and the volume of the air increases and its density decreases when it becomes warmer. Temperature change with different height was 0.31°C/min cooling, which was relatively bigger as compared with the change of 0.54°C/m during heating.

Figure 6 shows the demanded air volume for heating and cooling the screen zone as analyzed by EnergyPlus. The required air volume for cooling with the UFAD was 1.99 m³/s, and the air velocity was 0.42 m/s, considering the area of the diffuser.

Energy Consumption with Different Air Distribution Systems
The potential of UFAD systems to reduce energy consumption for air-conditioning was highlighted when

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**Fig. 5.** Daily temperature interpretation results depending on area (°C/KWh).

**Fig. 6.** Mechanical ventilation air volume projection results.
comparing UFAD to conventional OH systems. Figure 7 shows the comparison of energy consumed at the multiplex theatre when using the OH or the UFAD system. The total amount of the annual air-conditioning load with the OH system was shown to be about 2,904 KWh, while with the UFAD system was about 2,331 KWh. During the summer season from May to September, in particular, the OH system would consume 2,472 KWh of energy for cooling, while the UFAD system would use about 2,039 KWh. In brief, applying the UFAD system would use about 18% less energy for air conditioning in the space. The energy reduction effect was due to the relatively higher cooling ventilation temperature and lower ventilation speed of the UFAD system. Since the UFAD system would supply conditioned air only to the required zones, it would require relatively lower energy, as compared to the ceiling-based OH system which would need to cover the entire space.

The energy used for the supply and return air fans were likewise found to be significantly lower when using the
UFAD system. The amount of the energy for supply air fans would decrease by 511.4 KWh and the energy for return air fans would decrease by 372.5 KWh during the cooling season. In particular, the energy saving ratio for return air fans (55.7%) would be more noticeable than that of supply air fans (27.9%); due to factors such as the relatively higher temperature and smaller amount of air volume of the supply air for cooling than for the OH system.

The analysis also reveals the potential energy benefit of the UFAD system which would be expected to be greater for large spaces with a high ceiling, compared to conventional buildings. In order to verify the relationship between the energy consumption and ceiling height, another theatre with a ceiling height of 17 m was simulated with identical conditions of the afore-discussed simulation. As Figure 8 shows, lighting and human loads was increased associating with the increase in the volume of the space and the number of seats.

As the volume of the space and its cooling load increased, the amount of energy consumption generally also increased. The increment in the case of the OH system was 388 KWh, whereas with the UFAD system, the increase was 239 KWh. That means the increment in the cooling load when using the UFAD would be relatively less than that of the OH taking into account the ceiling height.

**Conclusion**

It is well-known that an HVAC system with an UFAD system could deliver many benefits, such as energy efficiency, occupancy satisfaction, space flexibility, individual controls and so forth. This paper investigated whether these advantages can be delivered in large public spaces with a high ceiling such as in theatres. An interior space of a recently-built multiplex located on the eighth floor of a megamall was selected for the performance evaluation. The target space with seating for 278 and with a ceiling height of 12 m was investigated. EnergyPlus was used to simulate the large space with two different air distribution systems. The results show that the application of an UFAD system for large spaces has the potential to significantly improve energy performance, in addition to its other inherent benefits.

In comparison to a conventional ceiling air distribution system, applying the underfloor system for the target space would use about 18% less energy for air-conditioning. The energy used for supply and return air fans was found to be significantly lower with the UFAD system than the conventional system. The potential energy benefit of using an UFAD system would be expected to be greater for large spaces with high ceilings, as compared to the conventional buildings. When the air environment was assumed to be normal, the application of an UFAD system clearly showed that a pleasant temperature could be satisfactorily maintained only in the occupied zones and that there would be a clear temperature difference between occupied zones and unoccupied zones.

A building with the UFAD system has the potential to reduce the floor level by about 5%–10% as compared to a building with the ceiling-based system. The ceiling space for installing a large air supply duct can be replaced with the ceiling space for exhaust ventilation and other equipment installation. Because of the increase in the screen size, the movie theatre floor height would also increase. Hence, the application of the underfloor air distribution system would be advantageous in terms of floor height reduction.

**Acknowledgments**

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