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Thermal comfort prediction of an underfloor air distribution system in a large indoor environment

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ABSTRACT

The use of air distribution in HVAC has grown in popularity in buildings, and, to this end, the method chosen to deliver the conditioned air is strongly associated with increasing concerns about indoor environmental quality and its effect on occupants' well-being. In the underfloor air distribution (UFAD) system, air is directly supplied to the base of the occupied zone, which causes temperature stratification from the lower to the upper layer of the zone. This flow pattern gives UFAD the advantage of using less energy while providing better thermal comfort than overhead air distribution (OHAD) system. This paper investigates the effectiveness of UFAD in a large space with a higher ceiling for various velocities of supply air and locations of diffusers at an identical air supply temperature. In particular, the goals of providing satisfactory comfort conditions for the occupants and its practical application to buildings have been examined. Computational fluid dynamics (CFD) software was used to simulate the thermal environment, along with the control variables for a huge theater space equipped with a UFAD system. Results show that the UFAD is capable of creating smaller vertical variations of air temperature and a more comfortable environment than conventional OHAD systems

1. Introduction

The top priority in building design is generally placed on maximizing the productivity of the space while creating a comfortable, healthy environment for its occupants, using available technology that consumes the least amount of energy. The issues of comfort and space quality in buildings have gained in importance ever since environmental concerns have shifted construction toward so-called "sustainable" or "healthy" building practices. Although there are many factors that affect the indoor environmental quality, the monitoring of thermal conditions represents the pre-eminent task for the aim of ensuring suitable living spaces for occupants.

The importance of reducing building energy consumption has increased ever since global warming became a serious issue. For space heating and cooling, air distribution strategies in HVAC have a strong influence not only on indoor environmental quality and but on energy costs. Air distribution also has a direct impact on space organization, floor height planning, interior layout, and the cost of construction. A relatively new approach to air distribution, the underfloor air distribution (UFAD) system, has been widely used in new commercial buildings. This technique is simply accomplished by supplying air through a raised floor using different types of distribution configurations and outlets. UFAD systems that make use of the under floor plenum for conditioned air distribution will therefore increase in popularity as they extend the flexibility of building services and take advantage of the raised floor to accommodate the HVAC system.

In UFAD, air is directly supplied to the occupants' area, causing occupants' plumes and zone heat load to stratify to the upper layer of the zone, which is later extracted from return points at that high level. This flow pattern gives UFAD the advantage of using less energy than a conventional overhead air distribution system (OHAD) due to the lower pressure drop and lower airflow rate. Previous research has suggested that atop return type underfloor system can save a significant amount of energy, since the supply air temperature can be higher. However, temperature non-uniformity can also lead to thermal discomfort [1].

In a heating and cooling system that utilizes air, the type of air distribution system plays a decisive role in the performance, especially within a large space with a high ceiling. The potential energy benefit of using a UFAD system would be expected to be greater for large spaces with high ceilings, as compared to conventional buildings. Previous findings show that UFAD leads to significant energy savings compared to OHAD [2].

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One advantage, which is often cited as an initial cost benefit of underfloor air distribution, is that the slab-to-slab distance (and, therefore, the total building height) could be reduced by as much as 10% by removing the supply ducts, terminals, and the diffusers [3].

Rapid economic growth has led to a greater desire for a higher quality of life. One means of pursuing this is a focus on a population's cultural life, and thus, there is currently a boom in construction of gymnasiums, concert halls, and theaters in Korea. Since most of these cultural facilities are composed of large spaces, they generally require a high level of dependency on mechanical ventilation with conditioned air.

Furthermore, since these large cultural facilities have high ceilings, a great amount of energy could be required to maintain the optimal indoor temperature for a comfortable environment. There have been reports in the literature that assert the advantages of a UFAD system, over a conventional ceiling air distribution system, for these cultural facility spaces, in terms of both energy reduction and thermal comfort [3,5–10]. For facilities with high ceilings, a UFAD system would be more appropriate to enhance thermal comfort, and would also allow both individual control of ventilation volume and distribution of air only to occupied zones [4].

This paper presents an analysis on whether the application of a UFAD system for a large cultural facility space could result in higher satisfaction levels for indoor thermal comfort with optimal control of supply air volume. First, the characteristics of UFAD are reviewed, based on citations in the literature, as well as the HVAC which has been adapted to an already-built large theater space in Korea. Next, the appropriateness of a UFAD application to the huge space has been verified in terms of the indoor thermal quality and comfort. Different locations for the diffusers and velocities of the supply air were varied to determine what produces a better performance for UFAD systems.

2. Underfloor air distribution system

Access floors are a modular system of architectural floor panels installed on pedestals above the structural floor to create an easily accessible underfloor space. With the arrival of IT systems in the office environment, demand for these floors has risen rapidly. A UFAD system uses the open space between the slabs and access floor as paths for air distribution through diffusers installed on the surfaces of the floors. As illustrated in Fig. 1, a UFAD is an air distribution system where the conditioned air is delivered from the "bottom up" and not the "top down," as in the conventional overhead air distribution and which thus allows individual control of ventilation volume and distribution of air only to the occupied zones [6].

To date, there have been numerous publications in the literature that focus on verifying the advantages of UFAD for conventional spaces. Stanke provided a brief review of UFAD which identified the advantages and difficulties of applying this system [11]. Barba discussed that some architects prefer UFAD systems since they can help to achieve a higher score in the LEED (Leadership in Energy and Environmental Design, by the USGBC) rating system through enhancing the energy optimization score and individual control of supply diffusers [12].

3. Thermal comfort in UFAD

Energy efficient building concepts and technologies require an intense approach to occupant satisfaction with respect to overall building performance. It is also important to understand how and under what environments the occupants can achieve comfort. Jaakkola concluded that allowing individuals to control the room temperature was the most effective means to improve thermal comfort and decrease sick building syndrome (SBS) symptoms [13]. Yun reported the evidence to link the indoor and outdoor temperatures along with past thermal experience with comfort temperatures [14].

Recently, Djongyang has presented a literature review of thermal comfort, which included an overview of the human body thermoregulatory system as well as the mathematical modeling of heat exchanged between a human body (both sleeping and awake) and its environment [15]. Ghaddar developed a modeling methodology to assess thermal comfort and sensation for active people in transitional spaces. The work studied how air movement can create comfort, and incorporated human thermal response, thermal sensation, and comfort as variables. The model was also validated and agreed well with subjective surveys [16]. Our work is largely inspired by these papers, and we borrow heavily from Ghaddar, in particular.

Multiple studies have insisted that the UFAD system has an advantage in higher occupant satisfaction in terms of indoor air quality and thermal comfort. UFAD stratifies the air and prevents mixing, so that concentrated pollutants are removed via exhaust at the highest points in room, and, thus, occupants located in the clean zone constantly breathe uncontaminated air. The underfloor approach allows personal control of the local environment and satisfies up to 100% of occupants, reducing complaints.

Alajmi investigated the effectiveness of UFAD systems in commercial buildings for various types of applications and at different air supply temperatures. Their findings show that UFAD demonstrates a significant energy savings (30%) compared to conventional air distribution systems, particularly for buildings with high ceilings, as well as providing satisfactory comfort conditions for the occupants [17]. Zukowski presented a method of designing thermal comfort conditions in a room with a UFAD system. An example of a thermal comfort calculation for a typical room in a single-family house with a UFAD system was introduced [18]. Chung clarified details of the thermal stratification due to UFAD, which is crucial to system design, energy efficient operation, and comfort performance, with an aim of examining the impact of mean radiant temperature (MRT) on thermal comfort [4].

Wan tested the thermal performance of a floor return type underfloor system by varying the heat load densities and supply air temperatures. They found that both the vertical temperature differences and air velocities were found within the standard comfort limits [1]. Xu also showed that a UFAD system could produce indoor air temperature stratifications that led to cooling load reductions in the occupied zone, as compared with conventional mixing systems [19]. However, in order for a UFAD application to supply these improvements in individual thermal comfort, the design of the system must incorporate multiple relevant parameters, including vertical load distribution, diffuser throw, and floor temperature [11].

4. Research methodology

4.1. Analysis tool: CFD Star-CD

For the analysis of the thermal environment of a target space with a high ceiling, a computer program, Star-CD by CD-adapco, has been selected as the main tool. Computational fluid dynamics (CFD) analyzes fluid flows using numerical algorithms. Over the past few decades, CFD tools have rapidly evolved so that they can accurately create complex simulations of turbulent flows, thermal distribution, air velocity, diffusion of contaminants, convection around buildings, and the behavior of smoke in large spaces.