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Review of underfloor air distribution technology

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ABSTRACT

Underfloor air distribution (UFAD) system, which is a relative new method of providing conditioned air and ventilation to the commercial buildings and data centers, is focused by researchers and designers for its potential advantages of better indoor thermal comfort (ITC) and indoor air quality (IAQ), layout flexibility, reduced life cycle costs, and energy saving. However, the application of UFAD system are still obstructed by the gap in the fundamental understanding of some new elements, such as the cooling load calculation, control of the thermal stratification, and evaluation of energy consumption. This paper reviews the current situation of UFAD technology, and the existing problems in recent researches are summarized. To improve the performance of UFAD system, several possible directions for the further studies are suggested.

1. Introduction

Heating, ventilation and air conditioning (HVAC) systems have been widely used in many parts of the world. The purposes of HVAC systems are mainly focused on the improvements of indoor thermal comfort (ITC) and indoor air quality (IAQ). However, the better ITC and IAQ usually mean more energy consumption. According to Enteria and Mizutani [1], almost 50% of the building energy is demanded to achieve the acceptable ITC and IAQ. Furthermore, the investigation conducted by Qi et al. [2] also shows that more and more attentions are paid to ITC and IAQ as the time of people stay indoors are up to 90%.

Underfloor air distribution (UFAD) systems are firstly used in the data centers of high heat and fewer people, and the processing capacity of cooling load is up to 200–1000 W/m^2 [3]. In 1970s, UFAD systems are employed in the commercial buildings for the first time in Germany [4]. In these buildings, the ITC and IAQ are improved. And then, the individual control and task air conditioning (TAC) are also promoted [5–7]. Recently, the intelligent building has become the trend of the next generation buildings, which integrates the functions of building automation, office automation, and communication automation [8,9]. The intelligent building requires more freshness, effectiveness, and comfortable indoor environment [10], which also results in higher requirements to the air conditioning systems. As a method to resolve this problem, the underfloor supply air plenum is adopted as the space to accommodate the cables and pipes for the intelligent buildings [11]. What's more, for a well-designed UFAD system, the employed of underfloor supply air plenum not only produces the indoor thermal stratification that improves ITC and IAQ [12–15], but also achieves the facilities layout in the room flexibly [16]. Therefore, the increasing attentions are paid to the UFAD system by the researchers and designers from USA [17], Sweden [18], Poland [19], Korea [20], and China [21], etc.

UFAD is an ancient technology because of this technology has been proposed many years ago (since 1950s) [22]. However, UFAD is also an innovative technology account for the widely employed only in recent years [23,24]. Although UFAD technology has been developed for many years, the problems on the system setting and operation still commonly exist in the field [24,25]. To resolve these problems, many efforts have been paid to investigate the technology of UFAD system. In these studies, a series of achievements are acquired by the Center for the Built Environment (CBE) [16,26,27]. The first book guiding for the application of UFAD system is published by ASHRAE [28], and the standards relevance to the UFAD system are also revised [29]. In China, the book focuses on the principle and design of UFAD system is published in 2006 [30], in which the fundamental understanding of UFAD system is discussed. Additionally, five application cases are also introduced in this book. Recently, the model of the cooling load calculation for UFAD is proposed by Bauman et al. [31]. This model has been integrated in the software EnergyPlus [32], which can be used to analyze the energy consumption of UFAD system. As the first validated UFAD system tools of their kind, this model is widely employed at present [33–35]. To provide assistance in the design, construction,

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Nomenclature

C	empirical coefficients
CL_{OZ}	cooling load in the occupied zone (W)
i	type of the heat sources
j	effects of the different parameters, such as floor level and zone orientation
Q	load of the heat sources (W)
X	empirical coefficients
T	pulse time
v	coefficients of the transfer function
w	coefficients of the transfer function

Greek letters

α	correction coefficient
δ	pulse of the sample

and operation of UFAD systems, UFAD GUIDE is also published by ASHRAE [36] recently, which is great helpful for the application of UFAD systems.

Although a few studies have been done on the UFAD technology from the above, the researches about the control of thermal stratification and higher energy consumption in the humid climate are insufficient. Moreover, the method of cooling load calculation for UFAD system is very different to the conventional overhead air conditioning (OH) system, which still unfamiliar to the designers. This paper reviews the current situation of UFAD system, and the existing problems in recent researches are summarized. To improve the performance of UFAD system, several possible directions for the further studies are suggested.

2. System overview

In UFAD system, the conditioned air is supplied to the occupied zone (OZ) directly [37]. The thermal plumes generated by the heat sources introduce the conditioned air to absorb the heat and humidity, and then bring the contaminants air to the ceiling level [38,39]. On the basis of continuity, the airflow of heat and contaminants is returned to the upper zone (UZ) partly while the airflow rate is greater than the supply air at the ceiling level. At a certain plane in the room, the airflow rate returned to the UZ is equal to the supply air [40]. Then, the room is divided into OZ and UZ by the plane, which causes the thermal stratification [41]. The heat and contaminants air is concentrated in the UZ, and the air in the OZ is cool and fresh. The schematic diagram of UFAD system is shown in Fig. 1.

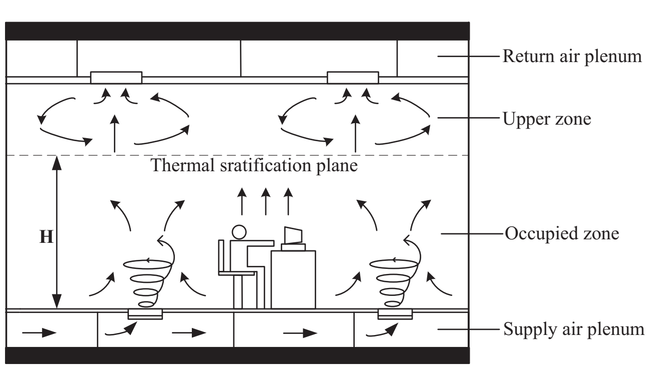

Fig. 1. The schematic diagram of UFAD system.

Compared to the OH system, UFAD system adopts a higher supply air temperature, an underfloor supply air plenum, floor-to-ceiling airflow pattern, localized air distribution, and solutions used for the perimeter system [42]. Nevertheless, the equipments used in UFAD system, such as cooling and heating plants and air-handling unit (AHU), are similar to the OH system. There are commonly three approaches to configure the UFAD system [43]:

- With a pressurized underfloor supply air plenum, the conditioned air handled by the AHU is delivered to the OZ through the plenum and the floor mounted diffusers by a relative lower pressure of 12.5–25 Pa [28].
- With a zero pressure underfloor supply air plenum, the local fan-powered diffusers are used to supply the conditioned air to the OZ.
- The conditioned air vent from the supply air diffusers through the underfloor ductworks rather than the underfloor supply air plenum.

The first approach can be configured easily, which also has great potential benefits of energy saving for eliminating the underfloor ductworks and fan-powered terminal devices [44]. The advantage of the second and the third approaches is that there is no risk of uncontrolled air leakage to the OZ [45]. However, the most common configuration for UFAD system is the integrated approach, and the decision is determined by the cost-saving purpose firstly.

A large number of smaller floor mounted diffusers are used in UFAD system, and many of them are closed to the occupants [43]. The floor mounted diffusers not only can be adjusted by the occupants conveniently, but also can be installed flexibly. Furthermore, the employing of raised floor and floor mounted diffusers are more feasible for the configuration of TAC [46].

2.1. *Benefits of UFAD system*

The benefits of a well-designed UFAD system are listed below:

- Reduced the energy consumption: In UFAD system, only the OZ is air-conditioned, as well as the convection thermal loads in the UZ are not considered to the supply air calculation. In application, the supply and return air temperature of UFAD system are commonly 4–7 °C and 1–6 °C higher than that in the OH system, respectively [43]. Thus, the energy use of chiller plants is reduced account for the higher supply air temperature. On the other hand, the increasing of return air temperature extends the period of economizer operation, which also causes the reducing of energy consumption [47,48]. Additionally, the energy consumption is reduced because of the decreasing of the airflow rate and pressure for fans. The investigation on the comparison of the variable air volume (VAV) system is conducted by Webster et al. [45]. The results show that the supply fan used in UFAD system only consumes about 48% energy for average to the OH system. According to Lian and Ma [30], the total energy consumption of UFAD system can be reduced by 25–50% to the OH system.
- Improved the ITC, IAQ, ventilation efficiency, occupant productivity, and health: In UFAD system, the local thermal environment is depended on the individual comfort preferences to some extent. According to Tsuzuki et al. [46], a sizable range (5 °C for floor-based outlets) for achieving a satisfied microclimate is acquired in a TAC system with fan-driven supply outlets. Other studies conducted by Bauman et al. [7] show that the adjustable range of swirl diffusers for the individual microclimate is lower than the TAC fan-driven outlets, but still has a range of 2–3 °C. A