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Experimental study on the characteristics of supply air for UFAD system with perforated tiles

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ABSTRACT

Underfloor air distribution (UFAD) system is widely used in commercial buildings and data centers for its potential advantages of superior thermal comfort and indoor air quality, etc. In UFAD system, conditioned air is directly supplied to the occupied zone from a pressurized plenum, which causes temperature stratification from the lower zone to the upper zone. The airflow distribution is determined by the pressure decay and flow pattern in the plenum, which is affected by the size of plenum, the open area of the diffusers, air leakage, and the obstructions under raised floor. This paper summarizes the results of an experimental study of airflows through plenum and perforated tiles in a plenum test facility, and the governing equations and boundary conditions on the distribution of velocity and pressure in the plenum are deduced. The linear models of the lost coefficient of air leakage and the velocity ratio of outlet and inlet of the plenum are proposed to simplify the measurement and calculation of the distribution of velocity and pressure in the plenum. The results show that the calculated results coincide with the experimental results, and the models will help to understand the design and operation for the UFAD system.

1. Introduction

Underfloor air distribution (UFAD) system is a relative new method of providing conditioned air and ventilation to commercial buildings and data centers for its potential advantages of superior thermal comfort and indoor air quality (IAQ), layout flexibility, reduced life cycle costs and energy saving [1,2]. UFAD system adopts an underfloor supply air plenum between the structural concrete slab and a raised access floor system to supply conditioned air directly into the occupied zone through floor diffusers or perforated tiles, which causes temperature stratification from the lower zone to the upper zone [3]. The control of thermal stratification is critical for the design and operation of a UFAD system [4]. What is more, the airflow distribution from diffusers is determined by the pressure decay and flow pattern in the plenum, which is affected by the size of plenum, the open area of the diffusers, air leakage, and the obstructions under raised floor [5,6]. Thus, to ensure the thermal environment, the cold air from diffusers must be distributed properly [7,8].

Recently, the UFAD system was found to be energy saving [9–11], but the application of UFAD system were still has problems because of misunderstanding of some new elements, such as the control of thermal stratification, performance of supply air plenum and air leakage [12]. In order to explore the effects of control parameters on UFAD system, Lin and Linden [13] developed an UFAD ventilation model, and was verified by the salt-bath technique experiments. The results showed that airflows had a greatly impact on the thermal stratification, which was determined by the volume flux and momentum flux of the cooling diffuser. However, the studies still should be performed in a full-scale building for practical application.

To predict the thermal distribution in the UFAD system, the models for cooling load calculation were developed [14–16], and a series of full-scale experiments were conducted to verify the models. Their studies proposed that the performance of stratification must be carefully considered to improve thermal comfort and reduce energy consumption. Webster et al. [17] analyzed the influence factors on the temperature stratification in the UFAD system. The results showed that the diffuser type and operating characteristics had a secondary impact on the stratification performance, as well as the overall performance were greatly impacted by the range of airflows on the design and operation. Wan and Chao [18] found that the performance of stratification was highly depended on the thermal length scale, and significant thermal stratification was produced by a minor jet thermal length scale. Chao and Wan [19] reported that the desired thermal comfort can be controlled

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Nomenclature

A_e	open area of the perforated tiles (m^2)
B_0	initial specific jet buoyancy flux of pure plume (m^4/s^3)
C_p	air specific heat capacity at constant pressure (J/kg K)
d_h	hydraulic diameter (m)
f	friction coefficient
g	gravitational acceleration (m/s^2)
K	pressure lost factor
K_{open}	specific lost factor of pressure for actual open area
K_A	specific lost factor of pressure for actual open area with the effect of air leakage
l_m	length scale
L	length of the plenum (m)
M_0	initial specific jet momentum flux of pure jet (m^4/s^2)
p	pressure in the plenum (Pa)
p_0	pressure in the space above the raised floor (Pa)
Δp	local pressure drop across the perforated tile (Pa)
Q_0	initial jet volume flux of the supply air (m^3/s)
S	enclosure heat load (W)
T_r	reference air temperature (K)
ΔT_0	difference of temperature between the air in the plenum and the air above the raised floor (K)
u	velocity in the plenum (m/s)
u_{in}	inlet velocity of the plenum (m/s)
v	outlet velocity from the plenum (m/s)

Greek letters

ε	velocity ratio of outlet and inlet of the plenum
ζ	lost coefficient of air leakage
η	ratio of the total area of perforated tiles and the cross-sectional area of plenum
ρ	air density (kg/m^3)
φ	fractional open area of the perforated tile

by designing the supply air conditions properly in the UFAD system with fan-powered floor air unit, and more researches should be conducted to investigate on characteristics of supply air. The experiments on thermal comfort and IAQ in hot and humid climate were performed by Sekhar and Ching [20]. Their studies revealed that the satisfied IAQ in UFAD system was produced by a reasonably supply air, nevertheless the inefficiency in supplying air to the occupied zone deteriorated the thermal comfort.

Compared to the overhead air conditioning (OH) system, the supply air plenum using in UFAD system had a significantly benefits for flexible cable management and distribute conditioned air conveniently. However, the distribution of temperature and airflows in the room was difficult to predict because of the undesirable decay of thermal and pressure in the plenum. In this regard, Bauman et al. [21] proposed a simple first-law model to estimate the primary pathways on heat transfer in UFAD system under cooling operation. Surprisingly, only about 60% of cooling load was exhausted by the return air, the remaining up to 40% was transferred into supply air plenum. Karki et al. [22] investigated the influences factors on pressure decay in the supply air plenum, and a computational fluid dynamics (CFD) model was developed to calculate the airflows through perforated tiles in raised floor data center. In their studies, the outflow velocity was related to local pressure drop across the perforated tiles, which was determined by a corresponding pressure loss coefficient.

Further studies were conducted to investigate the effect of supply air plenum on supply air in UFAD system. Jin et al. [23] illustrated the effect of inlet parameters on the plenum using a validated CFD model. To achieve a better thermal environment in the buildings, the velocity and jet direction must be considered carefully. Samadiani et al. [26] argued the effects of pipes in the plenum and open area of perforated tiles on the airflows in a raised floor data center. Comparison between plenum with pipes and empty showed that the maximum change of airflows was up to 35%. The results also indicated that the pressure resistances closed to tiles was greatly impact by the neighboring tiles. Despite the fact that a significant amount of UFAD system has been employed in the field, the fundamental understanding of several key performance features still is needed to be improved. The effect of the control parameters, such as the size of plenum, the open area of the diffusers, air leakage, and the obstructions under raised floor, is essential to be studied further for achieving the better airflow distribution.

The objective of this paper is to investigate the characteristics of supply air through the plenum and the perforated tiles. Several experiments were performed in a plenum test facility to analyze the influences of control variables on the airflow distribution, and the governing equations and boundary conditions on the distribution of velocity and pressure in the plenum are deduced. The linear models of the lost coefficient of air leakage and the velocity ratio of outlet and inlet of the plenum are proposed to simplify the measurement and calculation on the distribution of velocity and pressure in the plenum.

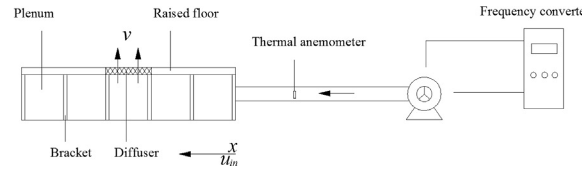

Fig. 1. The schematic diagram of the plenum test facility.

2. Methodology

2.1. Physical situation

As shown in Fig. 1, a plenum test facility with dimension of 3 m in length, 3 m in width and 0.45 m in height was constructed to investigate the characteristics of supply air. The steel cement access floor (raised floor) with the dimension of 0.6 m × 0.6 m was installed above the plenum, and was supported by the brackets. The perforated tile sized of 0.6 m × 0.6 m was mounted in the center of the raised floor.

The plenum test facility was served by a supply fan, which was connected to the plenum with a round duct, and the diameter of the duct was 0.25 m. The flow rates of supply air can be adjusted by a frequency converter to meet the experimental requirements. The thermal anemometer with an accuracy of ±3% and range of 0–30 m/s was set up in the duct to measure the velocity of supply air, and the outflow was measured manually by a flow measuring hood with an accuracy of ±3% and range of 40–4300 m^3/h. The local pressure drop across the perforated tile was measured by a differential pressure transmitter with an accuracy of ±0.25% and range of 0–100 Pa.

2.2. Theoretical background

The characteristics of a pure jet or a pure plume were determined by its momentum flux M or buoyancy flux B, respectively. The fluxes at the source were defined as [24]:

$$M_0 = \frac{Q_0^2}{A_e} = v^2 A_e \quad (1)$$