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An experimental study on a full-scale indoor thermal environment using an Under-Floor Air Distribution system

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ABSTRACT

Characteristics of thermal environment in a full-scale indoor space utilizing an Under-Floor Air Distribution (UFAD) system are investigated by conducting and analyzing experimental measurements. The indoor air stratification of different locations in the steady state for three supply flow rate options is presented. This research focuses on the influence of supply air flow rate, and its corresponding momentum and buoyancy fluxes, on the vertical temperature profile in the indoor environment. Temperature measurements show that the indoor vertical temperature profile is influenced highly by the distance away from the supply diffuser position. Experimental results also show that the supply air flow rate has a strong effect on the vertical temperature profile. When the supply air flow rate of a given diffuser increases, and then the supply air momentum flux increases as well, the gradient of the vertical temperature profile becomes gentler. The stratification height in the indoor environment ascends with a higher total flow rate. The almost same throw height at the supply diffuser is observed for the identical flow rate option in two sets of experiments with different total flow rates.

1. Introduction

Ventilation (cooling and heating) in buildings consumes a large amount of energy nowadays. Particularly, air conditioning systems have become increasingly popular. Such systems consume a huge amount of energy. According to Refs. [1,2], non-industrial buildings contribute 30–50% of all primary energy consumption in Organization for Economic Cooperation & Development countries, and ventilation operation consumes as much as 50% of the amount attributed to the non-industrial buildings section.

The Under-Floor Air Distribution (UFAD) system originally was introduced in the 1950s. Its main purpose was to remove high heat loads in the spaces. In the 1970s, UFAD system was introduced into office buildings, in West Germany, to remove heat load in the office. Recently UFAD systems have achieved considerable acceptance in Europe, South Africa, Japan and North America.

UFAD systems differ from a traditional overhead ventilation system. UFAD systems usually use an under-floor supply plenum and a raised access floor system to supply the conditioned air through floor supply diffusers. The conditioned air is delivered into the occupied zone of the indoor environment directly (mostly near the floor level). Room air is extracted through return vents (mostly on the ceiling and sometimes on the floor), and then returns to the air conditioner.

Alajmi and El-Amer [3] investigated the energy consumption of UFAD systems in commercial buildings for various types of application and at different air supply temperatures in a hot climate. Their EnergyPlus simulation results show that UFAD systems have a significant energy saving compared to ceiling-based air distribution (CBAD, i.e. overhead ventilation system), especially for high ceiling buildings.

Bauman and Webster [4] showed that UFAD has several benefits, such as reduced life cycle building costs, improved thermal comfort, improved ventilation efficiency and indoor air quality (IAQ), reduced energy use, reduced floor to floor height in new construction and improved productivity and health. A design guide book by Bauman [5] provides very comprehensive information on UFAD systems.

Webster et al. [6] showed the impact of air flow rate and supply air temperature on the thermal stratification for UFAD systems. As the air flow rate increases, room air stratification decreases. When the supply air temperature is varied, the temperature profile almost keeps the same shape, but the temperature profile moves to higher or lower temperature.

Lin and Linden [7] presented a study on the steady-state flow driven by a heat source and an UFAD cooling diffuser in a ventilated space having a ceiling vent. The model was based on plume theory for the heat source and a fountain model for the diffuser flow

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A_e	opening area of the supply diffuser (m^2)
D	distance away from the supply diffuser (m)
F_0	buoyancy flux of the supply jet at the source ($m^4\,s^{-3}$)
g	gravitational acceleration ($m\,s^{-2}$)
g'_0	reduced gravity of the supply jet at the source ($m\,s^{-2}$)
K_t	proportional constant for estimating the throw height
l_m	thermal length scale of the supply air jet (m)
M_0	momentum flux of the supply jet at the source ($m^4\,s^{-2}$)
Q_0	volumetric flow rate of the supply jet at the source ($m^3\,s^{-1}$)
Q_i	flow rate option, i = 1, 2, 3
S.H.	stratification height (m)
T.H.	throw height (m)
T_0	temperature of the supply jet at the source (°C or K)
T_r	reference temperature for normalization (°C or K)

Greek symbols

Δ	magnitude of the difference
ρ_0	density of the supply jet at the source ($kg\,m^{-3}$)
ρ_r	reference density for normalization ($kg\,m^{-3}$)

and assumed a steady-state two-layer stratification in the room. The control parameters are the buoyancy flux of the heat source, the volume flux and the momentum flux of the cooling diffuser. The results showed that when the vertical momentum is small, the entrainment mechanism at interface is not significant. When the vertical momentum increases, the interface is raised above the height obtained by the displacement case and lower layer temperature increases. The interface height is controlled by the ventilation rate and momentum flux, and the temperature contrast between the two layers is set by the momentum flux. The heat load determines the temperature in the space for given ventilation condition. This simple model was extended by Liu and Linden [8] to consider more general conditions.

Wan and Chao [9] found that the temperature stratification in the enclosure with UFAD systems highly depended on the thermal length scale of the floor supply jet issued from the supply diffuser. When the thermal length scale is greater than 1, temperature stratification is minor for all tested heat densities and air distribution methods. When the thermal length scale is less than 1, there is a significant vertical temperature gradient.

Kong and Yu [10] showed that the combination effect of three parameters, i.e. heat load, supply air flow rate and supply air velocity, on room air temperature stratification would be expressed by the length scale of the floor supply jet, which is the same as that shown in [9]. Their numerical simulation results, by using computational fluid dynamics, show that there is an interface formed, when there is only one local heat source in the room. The interface height is about 1.42 times the length scale. The maximum height of the supply air jet is about 1.56 times the length scale.

Wang et al. [11] investigated the thermal stratification characteristics in a full-scale UFAD experimental space. Their results show that 4 zones are considered to compose the vertical thermal stratification. They are bottom cooler zone, lower narrow zone, transitional zone, and upper warmer zone. In the bottom cooler zone, the temperature gradient is relatively unclear. In the lower narrow zone, the temperature changes abruptly and increases linearly. In the transitional zone, it can be considered as the transitional region between the lower cooler zone and the upper warmer zone. In the upper warmer zone, the temperature is much higher than other zones.

Characteristics of thermal environment in a test chamber utilizing an UFAD system are investigated through experimental measurements in this research. The research examines the influence of supply air flow rate, or its corresponding momentum and buoyancy fluxes, on the vertical temperature profile in the indoor environment. The paper presents experimental results of a full-scale indoor thermal environment in a test chamber. We focus on the connections between temperature stratification and supply air conditions, and neglect the role of humidity in this paper. Dimensions of the experimental space, measuring instruments and experimental arrangements are introduced in Section 2. Experimental results of measured velocity and temperature are presented and discussed in Section 3. Section 4 summarizes the findings in this research.

2. Full-scale experiments

2.1. The test chamber

Measurements are conducted in a full-scale test chamber on the sixth floor of Taiwan Building Technology Center (T.B.T.C.) building, which is located in the campus of National Taiwan University of Science and Technology (NTUST) in Taipei. Taipei is in a monsoon-influenced humid subtropical climate. Using air-conditioners to cool the indoor air temperature is common from May to October in Taipei.

The measurement space comprises the Main area and the area in front of Display stand, and is marked in Fig. 1(a). The space of the Main area is 810 cm (length) × 625 cm (width) × 325 cm (height) and the space of the area in front of Display stand is 190 cm (length) × 230 cm (width) × 325 cm (height). The total floor area of the space is 55 m^2 and the measurement space is empty of furniture.

The conditioned air is delivered into the space through floor supply diffusers. The room air exits by two square return vents on the ceiling, then moves to the space behind the return air wall and finally comes back to the air conditioners which are placed beneath the floor. Either of the return vents has the size of 60 cm × 60 cm. The air motion is cyclic as shown in Fig. 1(b).

The conditioned cool air is delivered by 8 rectangular supply diffusers for the CAC & WAC set and 4 diffusers for the CAC set. Here CAC and WAC denote the central and the western air conditioners respectively. Each diffuser has the same size of 40 cm (length) × 20 cm (width) on the floor and is located in the perimeter zone of the measurement space as shown in Fig. 1. Each diffuser with linear bar grilles is a passive type and is connected to an air conditioner via a duct. Two sets of temperature measurements, the CAC & WAC and CAC sets, are presented in this paper, and their arrangements are described in Section 2.3.

2.2. Experimental instruments

The measuring instruments include a hot-wire anemometer for measuring the air supply velocity, DICKSON TK550 thermistors for measuring the outdoor weather temperature and the supply conditioned air temperature, and T-type thermocouples for measuring the indoor temperature at different vertical levels.

A separate temperature measurement experiment was carried out to calibrate the DICKSON TK550 thermistors and the thermocouples by using a testo Pt100 probe as a benchmark. Measurement deviations from this benchmark were all less than 0.5 °C, and mostly 0.3 °C, for the DICKSON TK550 thermistors and the thermocouples used in this research.