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Laboratory testing of a displacement ventilation diffuser for underfloor air distribution systems

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ABSTRACT

Underfloor air distribution (UFAD) systems use the underfloor plenum beneath a raised floor to provide conditioned air through floor-mounted diffusers, which typically discharge cool air with both horizontal and vertical momentum components. These systems usually create a vertical temperature stratification when in cooling mode and this has an impact on energy, indoor air quality and thermal comfort. The purpose of this study was to characterize the stratification performance of a previously unstudied type of floor diffuser that discharges air horizontally, with almost no vertical velocity component, and that aims to combine the benefits of both UFAD and displacement ventilation (DV) strategies.

We performed 19 full scale laboratory experiments in which we varied the number of diffusers and the internal loads over a range of values typically found in office spaces. We quantified the amount of thermal stratification by measuring the dimensionless temperature at ankle height and found a degree of stratification that is typical of DV systems – higher than is typical in UFAD systems. We developed a model based on these results that can be used to simulate these systems in whole building energy simulation tools, such as EnergyPlus, and simplified UFAD design tools.

1. Introduction

Underfloor air distribution (UFAD) is an innovative method of providing space conditioning and ventilation to buildings. UFAD systems use an underfloor supply plenum located between the structural concrete slab and a raised access floor system to supply conditioned air through floor diffusers directly into the occupied zone [1].

UFAD and displacement ventilation (DV) systems are based on many of the same principles in cooling operation as they both deliver cool air into the room at or near floor level and return it at or near ceiling level. Thermal plumes that develop over heat sources in the room play a major role in driving the overall floor-to-ceiling air motion by entraining air from the surrounding space and drawing it upward. Properly controlled UFAD and DV systems in cooling mode produce temperature stratification in the conditioned space resulting in higher temperatures at ceiling level and cooler conditions in the occupied zone.

The primary difference between UFAD and DV systems is in the manner by which they supply air to the space. In the classic definition of a DV system, which is applied only for cooling purposes, air is supplied at very low velocity, thereby limiting the amount of mixing, through larger area diffusers often located in low sidewall positions. With this arrangement, finding enough available wall space for diffusers can be a challenge, particularly in open plan office settings. For UFAD systems, (1) air is supplied at higher velocity through smaller-sized floor diffusers, creating greater mixing, and (2) local air supply conditions are under the control of the nearby occupant by adjusting the UFAD floor diffuser. By using a raised access floor system to serve as the supply plenum, the entire floor surface area is available for placing supply diffusers, allowing great flexibility.

Stratified air distribution systems (DV and UFAD) are known to provide improved ventilation efficiency (increased fresh air in the breathing zone) when operated as 100% outdoor air systems, and also to provide improved contaminant removal efficiencies when contaminants are associated with heat sources. ASHRAE Research Project RP-1373 found air distribution effectiveness values for DV systems and UFAD systems using low throw height diffusers that were higher than those for conventional mixing systems and UFAD systems using diffusers with higher throw heights [2,3]. These

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Nomenclature

T	temperature [°C]
Φ	dimensionless temperature [–]
Γ	gamma, a non-dimensional parameter representing the ratio of buoyancy to vertical momentum forces in the zone [–]
Ar	Archimedes number, a non-dimensional parameter representing the ratio of buoyancy to momentum forces in the zone [–]
A_d	experimentally determined effective area [m^2]
A_c	floor area of the chamber [m^2]
β	volume expansion coefficient [K^{-1}]
H_c	height of the chamber [m]
Θ	diffuser discharge angle, measured from vertical [°]
N	number of open diffusers [–]
M	number of thermal plumes (i.e. heat sources) [–]
W	zone cooling load [W]
Q	airflow rate [l/s]

Subscripts

P	measurement at the exit of the duct as the air enters the supply plenum (supply air)
S	measurement at the discharge of the diffuser (the room supply), averaged across all open diffusers.
F	measurement at the upper surface of the concrete raised floor
0.1, 0.4, . . ., 2.2, 2.95	measurement in the room at the height noted by the subscript, in meters
OZ	represents the occupied zone, an average of measurements at 0.1 m, 0.6 m, 1.1 m & 1.7 m
R	measurement at the entrance to the ceiling-level exhaust duct as the air leaves the room (return air)

research findings have been incorporated into ASHRAE Standard 62.1-2013,[1] which assigns a value of 1.2 for air distribution effectiveness for DV and UFAD with low throw diffusers in cooling mode, thereby allowing a potential reduction in the required minimum outside air rates to the space.

Further evidence of the ventilation efficiency benefits of stratified systems is provided by a laboratory experiment reported by Jung and Zeller [4] that compared the stratification and air change effectiveness (ACE) performance of DV, UFAD, and overhead mixing systems. For the 100% outside air conditions of these tests, local ACE for the UFAD system ranged from 1.2 to 2.0 with average ACE values of 1.2–1.3. Some of the local ACE values for the UFAD system were even higher than the corresponding local ACE values for the DV system, a surprising finding. These findings are relevant to the current study because the smaller-sized UFAD floor diffusers delivered only about 9.4 l/s with a vertical throw height of about 1.1 m, a value that is lower than typical throw heights (1.2–1.8 m) for most UFAD swirl diffusers being installed today. This resulted in a rather dense diffuser layout with just about any point in the test room being quite close to a nearby diffuser. In fact, it is this distribution of supply diffusers across the floor that proves to be an advantage for UFAD compared to DV, which has its supply outlets located along the base of one end wall of the test room. These findings suggest that UFAD systems can be configured to achieve ventilation performance comparable to pure DV systems using a larger number of diffusers, diffusers that deliver air with less mixing (lower throw height), or both. The DV diffusers of the current study match these criteria. The most similar previous study that we identified.

2. Fundamentals of stratification in DV and UFAD systems

We describe thermal stratification in the zone using a dimensionless temperature, Φ_H (phi), at a height '*H*' in the room, defined by:

$$\Phi_H = \frac{T_H - T_S}{T_R - T_S} \tag{1}$$

where T_H is the air temperature measured at a particular height '*H*' in the room; T_S is the air temperature measured at the diffuser discharge (the supply air); and T_R is the air temperature measured at the room exhaust (the return air temperature, typically located at ceiling level). Thus, lower values of Φ in the occupied zone (from floor to 1.7 m height) indicate increasing stratification – that the air temperature at that height is lower relative to the temperature at the exhaust. For example, a value of $\Phi_{0.1} = 0.2$ indicates that a space is highly stratified. Higher values of Φ in the occupied zone indicate decreasing stratification. For example a value of $\Phi_{0.1} = 1$ indicates that a space is not at all stratified, and that the air is fully mixed.

In this paper, we also calculate the average temperature in the occupied zone, T_{OZ}, according to:

$$T_{OZ} = \frac{T_{0.1} + T_{0.6} + T_{1.1} + T_{1.7}}{4} \tag{2}$$

Which is then used to calculate the dimensionless stratification in the occupied zone, Φ_{OZ}, according to:

$$\Phi_{OZ} = \frac{T_{OZ} - T_S}{T_R - T_S} \tag{3}$$

For displacement ventilation systems according to Chen and Glicksman [5] $\Phi_{0.1}$ varies between 0.2 and 0.7 and according to Skistad et al. between 0.3 and 0.7 [6]. Mundt [7] developed a model for the prediction of $\Phi_{0.1}$ for displacement ventilation systems that is a function of the airflow rate and is based on a heat transfer model between the ceiling and the floor. Mundt's equation is used in a cooling airflow design modeling tool developed by Chen and Glicksman [5]. Most UFAD diffusers (e.g. swirl, linear bar grille, VAV directional, etc.) create less stratification than a DV system due to the vertical velocity component of the supply air as it leaves the floor diffuser, which causes increased mixing. Thus, $\Phi_{0.1}$ for UFAD systems is typically higher than for DV systems. Underfloor displacement ventilation diffusers differ from other UFAD diffusers in that they discharge air almost horizontally. It is expected, but yet not proven, that underfloor displacement ventilation diffusers may generate stratification similar to that generated by typical wall displacement diffusers.

Lin and Linden [8] and Liu and Linden [9] theoretically developed and experimentally tested (in a small-scale salt-tank model) a prediction of Φ for underfloor air distribution systems as a function of the non-dimensional parameter, Γ (gamma) (see Eq. (4)). Webster et al. [10] then used this model to develop stratification predictions based on full-scale experiments. The obtained Γ–Φ_{OZ} equations obtained by Webster et al. were then implemented in the EnergyPlus UFAD module [11,12]. The Γ–$\Phi_{0.1}$ and Γ–$\Phi_{1.7}$ equations have been implemented in the online CBE UFAD design tool [13,14].

Gamma, Γ, describes the ratio of buoyancy forces to vertical momentum forces and is commonly used in the analysis of UFAD systems. For a typical UFAD diffuser, a large value indicates that mixing dominates in the zone, and a small value indicates that stratification dominates in the zone. In the case of an interior zone, with

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[1] ASHRAE 62.1-2013 defines low throw slightly differently from those studies – it is defined as where the air velocity from the supply jet decays to less than 0.25 m/s (50 fpm) at a height of 1.4 m above the floor [1].