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A field study of thermal comfort with underfloor air distribution

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ABSTRACT

Field measurements and questionnaires based on the ASHRAE RP-921 project protocol were used to assess thermal comfort in a cold climate office environment with underfloor air distribution. All male and 90% of female participants ranked the thermal environment at their desk areas acceptable at the time of the survey. The median operative temperature was about 23 °C and ranged from 22 °C to 24 °C. The median average mean vote was −0.5, slightly cooler than neutral. Despite only 21% of participants voting warmer than neutral and only 15% expressing a preference for cooler conditions, 32% indicated that they would prefer more air movement. About 18% responded that they experienced some discomfort in body regions.

1. Introduction

"Stratified ventilation" was initially used to refer to displacement ventilation [1], but includes underfloor air distribution (UFAD). UFAD has gained popularity, because many believe it provides 1) better effectiveness at removing CO_2 exhaled by occupants, 2) reduced energy use, 3) improved occupant satisfaction with thermal comfort (TC), and 4) easier reconfiguration relative to conventional overhead mixing ventilation (MV) systems [2]. Woods [3] presented a typology of UFAD system types in 2004. He concluded that "valid and reliable field data from UFAD systems are not available to conclude that…UFAD performance is superior to" MV. Since that time, the number of published field studies is still small. While laboratory studies, with greater control over variables, may have internal validity, they may lack external validity for application to real-life conditions, due to the differences in contexts [4,5]. The field study reported here addressed TC with UFAD in terms of both occupant responses and measured conditions. The type of system studied was an unducted pressurized plenum ("push") supply system with ceiling return [3], deployed in an open plan office environment with cubicle workstations and passive swirl diffusers. Push UFAD is the prevalent type [6].

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2. Literature review

The articles discussed here are limited to those that addressed systems reasonably similar to the system that was studied. Displacement (low velocity) systems, floor return systems (e.g. [7],), perforated floor tile systems ([8]) and UFAD with supplementary air flow systems (e.g. [9],) were types of systems excluded from the review because the air flow patterns were so different from those in the study building.

Comfort conditions with UFAD have been investigated using a few methods: experimental room tests, numerical simulation, and field studies. The literature review sections address each of these categories. ASHRAE Standard 62 [10] differentiates floor-level air supply systems by velocity and temperature. UFAD systems typically supply "cool air", under which there are two subdivisions: 1) systems with a supply jet of 0.8 m/s or more reaching 1.4 m or more above the floor and 2) systems with "unidirectional flow and thermal stratification", which are considered displacement ventilation systems, ASHRAE/ANSI Standard 55 [11] specifies 0.1, 0.6, and 1.1 m above floor level as standard heights to measurement measure thermal comfort parameters for seated occupants. In the literature, measurement at these heights is so common that this will be referred to as 55-h for conciseness. The standard also recommends a head-foot (0.1 and 1.1 m above the floor) vertical air temperature difference (VATD) limit of 3 °C, which will be referred to as VATD-L.

2.1. Laboratory studies on thermal comfort with underfloor air distribution

Bauman et al. [12] evaluated the performance of an unducted "pull" (fan-powered diffusers) UFAD system in a test room mocked up as an open plan office. A portable instrument stand was used to measure temperatures and air velocities at 55 h and 1.7, 2.0, and 2.35 m above the floor. They found that VATD-L could be satisfied with a wide range of air flows. They recommended that diffusers be located 1-1.5 m from occupants to avoid drafts. Based on measurements with thermal manikins, they also found that adequate whole-body heat exchange could be achieved in the stratified environment "under certain operating conditions".

Matsunawa et al. [13] conducted lab, numerical and field tests of a UFAD pull system, the results of which will be discussed in the corresponding section of this paper. The experimental chamber was about 9 m^2. With a passive swirl diffuser, the head-foot VATD was as large as 3.7 °C, 0.7 °C higher than VATD-L. The fan-powered diffuser reduced the temperature difference to 2.5 °C. With the fan-powered diffuser, the air velocity only exceeded 0.2 m/s within a distance of about 300 mm from the diffuser.

Webster et al. [14] found that head-foot VATD remained below VATD-L with swirl diffusers tested in a 25 m^2 experimental chamber.

Lee et al. [15] used both experimental chamber measurements and CFD simulation to investigate UFAD design parameters. Their findings are reported in section 2.2.

2.2. Simulation studies of thermal comfort with underfloor air distribution

The computation fluid dynamic (CFD) analysis conducted by Matsunawa et al. [13] determined a head-foot VATD of 2 °C or less, supporting the adequacy of the comfort conditions assessed in an experimental chamber (discussed in 2.1. above).

Zhou and Haghighat [16] developed an optimization method for UFAD diffuser placement and air flow. They illustrated the various tradeoffs among fan power, PMV and ventilation efficiency, showing that all parameters could be improved relative to test setups in experimental rooms.

Ho et al. [17] used two dimensional computer modelling to compare overhead and underfloor ventilation systems. In terms of thermal comfort, they found head-foot VATD less than VATD-L. For typical diffuser installations, they found air velocity around 0.2 m/s from floor to ceiling.

Aghakhani and Eslami [18] reported use of CFD modelling to compare UFAD and overhead systems. They found that, while both systems met thermal comfort criteria, the foot area was cooler than the head area with UFAD and the reverse for the overhead system.

Lee et al. [15] found that swirl diffusers created the largest thermal stratification, but the maximum head foot was less than VATD-L for a standing person.

2.3. Field studies on thermal comfort with underfloor air distribution

Hedge et al. [19] conducted a mail questionnaire survey to evaluate occupant responses to UFAD systems that had been in place for at least 6 mo. They concluded that the occupants were satisfied with the heating, ventilation and indoor air quality [IAQ], believing that UFAD had a positive effect on their health and productivity. The post-occupancy evaluation conducted by Matsunawa et al. [13] found a head-foot VATD of 2 °C or less, supporting the adequacy of the comfort conditions assessed in an experimental chamber (discussed in section 2.1. above) and by numerical methods (discussed in section 2.2. above). Matsuna et al. conducted a questionnaire survey with 80 male and 31 female respondents. A few respondents reported draft in the foot region, which was subsequently alleviated for some occupants by adjustment of their diffusers. Discomfort persisted for a few occupants, predominantly female.

Fukao et al. [20] compared the performance of the environmental control systems in a corresponding 260 m^2 test area on each of two floors of a building, one equipped with an overhead mixing system and the other with a push UFAD system with swirl diffusers. Thermal conditions at three locations in each test area were measured continuously for 1 week in each of summer and winter. Measurements were also made 3 times per day at 23 other locations. A questionnaire regarding comfort was distributed to occupants six times over two days. A thermal manikin was also used to assess body heat loss conditions. VATD for the centre of the test area was 0.8 and 1.3 °C for summer and winter, respectively, well within VATD-L. Fukao et al. provided a single value for predicted mean vote (PMV) per season with the UFAD system of 0.1 and 0.0 for summer and winter, respectively. It was unclear whether this was based on an average of the continuous measurements, of the spot measurements or some other data set; most likely it was for the centre of the test area, as for VATD. The mannikin showed that the cool area was at and below the thighs. The questionnaire survey found that 90% and 75% of respondents considered the thermal environment acceptable in summer and winter, respectively.

Fisk et al. [21] evaluated a pressurized plenum UFAD system with swirl diffusers in a LEED-certified building. The main objective

Fig. 1. City of Calgary Water Centre west and south façades.