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Performance analysis of a new design of office diffuse ceiling ventilation system

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ABSTRACT

This paper aims to document and analyse performance of a new design of diffuse ceiling ventilation system in a typical office room. A full scale measurement is carried out in a climate chamber with an office setup at the Technical University of Denmark. Indoor air temperatures, air speeds, wall surface temperatures, pressure loss of the ceiling and ventilation effectiveness are measured for an air change rate of 3.5 h^{-1} and 5.1 h^{-1} respectively. A computational fluid dynamics model of the office with the diffuse ceiling ventilation system is built and validated by the full scale measurement. The measurements of pressure loss across the ceiling show a low pressure drop between the plenum and the occupied zone. Ventilation effectiveness is measured to be close to 1 on average under the tested conditions. It is shown that the diffuse ceiling ventilation system is able to remove indoor pollutant in an efficient way. The draught risk is found to be insignificant by both experimental and theoretical investigations. A design chart based on "flow element" method is created for the diffuse ceiling ventilation system by calculations with the validated CFD model. The design chart serves as a guideline for design and dimension of the investigated diffuse ceiling terminals as an air distribution system.

1. Introduction

A good design of an air distribution system requires not only supplying clean air with appropriate temperature and flow rate to the occupants, but also that the system is designed in an energy efficient and cost effective way so that the occupants are able to experience high air quality and thermal comfort in the occupied zone with minimum energy consumptions. Major air distribution principles used in mechanical ventilation are mixing ventilation (MV) [1] and displacement ventilation (DV) [2]. Indoor pollution concentration is diluted in a room with mixing ventilation, while with a displacement ventilation, fresh air is supplied from the lower level of the occupied zone to separate stale air from fresh air in the room. An alternative ventilation principle for room air distribution system is downward ventilation or diffuse ceiling ventilation (DIFCV). The design principle of DIFCV is that air is supplied through ducts or direct openings from façade into a pressurized plenum. As there is a small pressure difference between the plenum and the occupied zone, the air penetrates through the entire ceiling into the occupied zone.

Numerous studies have been carried out to investigate ceiling radiant cooling system without/with ventilation. Chakroun [3] investigated the air quality in rooms conditioned by chilled ceiling and mixed displacement ventilation. The energy saving of such a system is evaluated. Taki [4] and Keblawi [5] investigated the performance of a combination of chilled ceiling and displacement ventilation systems. Tian et al. [6,7] investigated the performances of a chilled ceiling panel system with/without mechanical ventilation for a typical office room in both cooling model and heating model. The thermal environment and thermal comfort in the room were fully measured and evaluated. It is found that ceiling ventilation improves the general thermal comfort and reduces the risk of local discomfort in the combined mode.

The research on diffuse ceiling ventilation system for office environment is limited. In Denmark, DIFCV is extensively used in livestock buildings [8]. However in terms of indoor space occupied by human being, the results are preliminary. The design of the diffuse ceiling ventilation system such as the shape and distribution of the air passages, the porosity of the ceiling, etc. has a significant influence on performance of the ventilation system. Diffuse ceiling ventilation systems with different designs were investigated in the literature [9–14]. Nielsen [9–11] carried out experimental work with an aim to evaluate the ventilation performance of a ceiling mounted low-impulse textile terminal and a diffuse ceiling in comparison with DV and MV systems. The diffuse ceiling was made of 60 cm × 120 cm painted mineral wool plates suspended from the ceiling, impenetrable to air, i.e., air was supplied through cracks in the suspension system hypothetically forming small microjets. Consequently, the ceiling installation determines the cracks, their locations and the microjets, which potentially affects

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Nomenclature

ACH	air change
CFD	computational fluid dynamics
DIFCV	diffuse ceiling ventilation
DR	draught rating
DV	displacement ventilation
IAQ	indoor air quality
MV	mixing ventilation
PMV	predicted mean vote
PPD	predicted percentage dissatisfied
RNG	re-normalized group k–ε model
C_e, C_{outlet}	contaminant concentration in the exhaust air (ppm)
C_i	contaminant concentration in the occupied zone (ppm)
C_b, C_{BG}	contaminant concentration in the intake air (ppm)
Q	heating load (W)
Tr,	exhaust air temperature (°C)
Ti	supply air temperature (°C)
$T_{a,l}$	local air temperature, in degrees Celsius (°C)
T_u	local turbulence intensity (%). If unknown, 40% may be used
u_{rm}	upper limit of air movement in the occupied zone, 0.2 m/s
v_a	the displayed reading of air speed measurement (m/s)
$\overline{V_{a,l}}$	local mean air velocity (m/s)
ΔT	temperature difference (K)
ε_{exp}	personal exposure index (–)
ε_{occ}	ventilation effectiveness in the occupied zone (–)
ε_v	ventilation effectiveness (–)

the performance negatively. To reduce the uncontrolled leakages, another design with perforated suspended ceiling plates penetrable to air was experimentally investigated by Hviid [12]. The plates had perforation percentages of 16–17% and 17–64% of the supplied air entered through cracks in the suspension system. Both Nielsen and Hviid claim that DIFCV is superior to creating draught free environment in the traditional design range.

Application of full scale experiments of diffuse ceiling ventilation was investigated by Jacobs [13,14] in a Dutch classroom. The measurement showed that even at extreme condition with high ventilation flow rate and large temperature difference (11 dm^3/s per child, ΔT = 18 K), there was no draught problem and air quality in the classroom is significantly improved. Furthermore the results showed modest investment costs and very low fan power use due to low pressure loss compared to conventional diffusers.

The objective of this paper is to experimentally and theoretically investigate performance of a new design of office diffuse ceiling product with controlled microjets. It is generally interesting to investigate whether the new design of diffuse air distribution system is able to provide occupants a high air quality and a comfort environment in the occupied zone. Based on calculations by validated CFD models, a design chart will be developed for the investigated DIFCV system as room air distribution device.

2. Experimental investigations

The experiments are carried out in a climate chamber located at the Department of Civil Engineering, Technical University of Denmark. The objective of the experiments is to measure ventilation effectiveness and thermal comfort in an office room equipped with the new type of acoustic ceiling as the air distribution terminals. Tracer gas experiment based on constant dosing method is carried out to evaluate the ventilation effectiveness. Indoor air temperature, surface temperature and air velocity are measured to evaluate thermal environment under the tested conditions. Furthermore predicted mean vote (PMV) and predicted percentage dissatisfied (PPD) rate are calculated both for seated and standing person in the occupied zone. Local thermal comfort is evaluated by draught rate which derives from the measurements.

Fig. 1. Photo of the test climate chamber with an office layout.

2.1. *The experiment apparatus*

2.1.1. *The climate chamber*

The test chamber has an inner dimension of 3.6 m × 6.0 m × 3.5 m (length × width × height). The chamber is set up to reproduce an office layout, which consists of two tables, two chairs, two heated dummies and two stationary PCs in a symmetrical placement in the occupied zone, see Fig. 1. The test chamber is thermally insulated. The heating effect of solar radiation inclusive the heating effect by the window in a summer weather is considered to be 242 W. The heating effect is simulated by an electrical heating foil with a total effective area of 1.44 m^2 (2.0 m × 0.72 m) attached on the wall opposite to the supply air terminal device. The acoustic ceiling is installed at a height of 2.9 m. The acoustic ceiling consists of suspension profiles, acoustic plates and aluminium lamellas. The suspension profile consists of the steel bar and horizontal aluminium profile. Air in the plenum enters into the lamellas channels through holes in the suspension profiles and flows into the room at both ends of the lamellas, in effect creating linear microjets. The design of the ceiling can be seen in Fig. 2. The supply air duct inlet is located above the acoustic ceiling, slightly off-centre to the right while the outlet is located below the ceiling, slightly off-centre to the left. The inlet air comes from a temperature controlled room around 5 m away from the test chamber. The room acts like a cooling unit regulating temperature of the air entering the chamber. The exhaust air of the chamber is directly discharged to a large hall. The temperature in the hall is not controlled but it is kept at a rather constant temperature around 21 ± 0.5 °C during the experiments.

2.1.2. *Air speed and temperature measurement*

Air speed transducer Type MM0038 of Indoor Climate Analyser (Brüel & Kjær model 1213) is used to measure air speed at a height of 0.1 m, 1.1 m and 1.7 m respectively. Thermocouple Type T is used to measure air temperature at the inlet, at the exhaust and at different levels of the room along a wooden stand. Six thermocouples are mounted at different heights of the stand to measure air temperatures at different levels (0.1 m, 0.6 m, 1.1 m, 1.4 m, 1.7 m and