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Flow characteristics in occupied zone – An experimental study with symmetrically located thermal plumes and low-momentum diffuse ceiling air distribution

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ABSTRACT

Airflow interaction between thermal plumes and vertical air distribution may cause significant effects on airflow characteristics such as velocity and temperature fields, turbulence intensity and fluctuation frequency. The flow interaction creates a random flow motion, vortical structures and turbulent mixing that can further yield a draught discomfort in an occupied zone. The main objective was to investigate large-scale airflow patterns and fluctuations as a result of interaction of buoyancy flows and diffuse ceiling flow. Experiments were performed in a test room of 5.5 m (length) x 3.8 m (width) x 3.2 m (height) with symmetrical set-up of cylindrical heat sources that gave a thermal load of 40–80 W/floor-m^2. The ventilation air was supplied through a diffuse ceiling with 0.5% degree of perforation. The observations indicate that the mean air speed and the airflow fluctuation increase with thermal load. Furthermore, the results show that a range of length scales increases with thermal load and with mean air speed. The results indicate that it can be difficult to fulfill the standard air velocity criteria for highly occupied spaces, where the maximum allowable mean air velocity is relatively low, i.e. 0.15–0.20 m/s. This is because the buoyancy flows from heat sources accelerate locally the flow field.

1. Introduction

A healthy, energy-efficient and comfortable indoor environment is the key objective of air distribution. In accordance with the European standard 13182:2002 (E) [1], the main characteristics of airflow patterns in occupied zone are usually in the range of 0.1–0.5 m/s for the mean air speed, 20–80% for the turbulence intensity, 0–1 Hz for the frequency of velocity fluctuations and 18–35 °C for the temperature. However, the mean air speed is usually below 0.35 m/s and the temperature below 26 °C in occupied zone. In field surveys, draught has been identified as one of the biggest problems in commercial buildings [2]. To maintain comfortable thermal conditions is especially challenging in the office buildings because of high cooling demand. In those cases, even when the whole body thermal sensation is neutral, the increased local heat loss due to high velocity and/or low temperature may cause a local discomfort due to draught. In addition, air distribution is difficult to control in occupied zone [3].

Turbulence is a chaotic and a random flow motion that involve a wide range of scales [4–6]. Turbulent kinetic energy grows up from the mean flow into the largest eddies from where the turbulent kinetic energy is further transferred to the smaller and still smaller eddies until the turbulent kinetic energy is dissipated into the heat. This process is usually fast. Thus, a transfer occurs within short distance. Turbulence improve transport of energy, but requires continuous supply of energy against the turbulent stresses [7]. In addition, turbulence increases flow disturbances and interaction between the vorticity and the velocity gradients. Consequently, turbulence may have a significant effect on airflow characteristics.

The risk of draught increases when the airflow temperature decreases and the mean velocity and the turbulence intensity increase. Earlier studies have shown that the energy spectrum is proportional to the mean velocity; the fluctuation energy increases when the mean velocity increases [8–10]. In addition, Fanger et al. [11] proposed that the turbulence intensity has a significant effect on the sensation of draught. In a subsequent study, Melikov et al. [12] showed that also temperature fluctuation increases draught sensation. Furthermore, the

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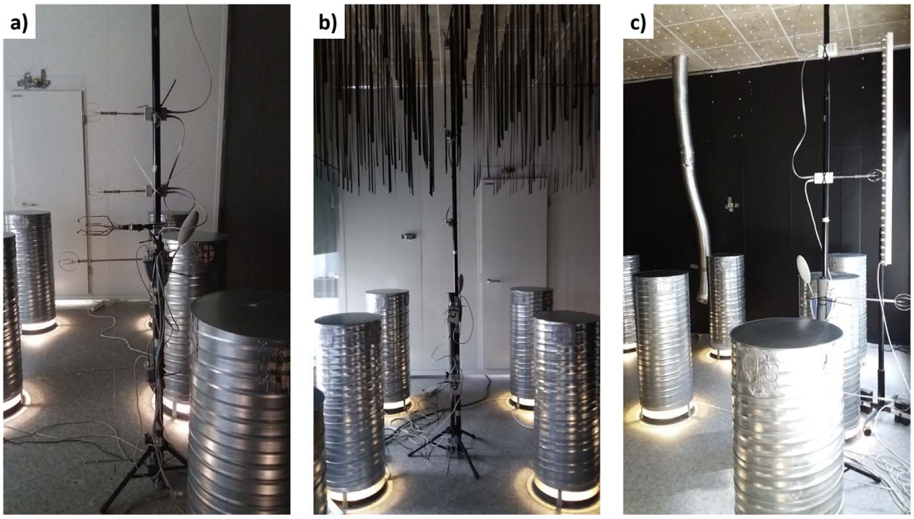

Fig. 1. Test room: a) cylindrical thermal loads and measuring mast with hot-sphere anemometers and ultrasonic anemometer, b) low-weight ribbons for detecting large-scale flow motions at the upper zone, c) exhaust air duct at the wall and led-light mast with equipment.

airflow direction and the flow fluctuation can also have a substantial effect on local thermal sensation, e.g. the rising natural convection flow may interact with downward supply airflow and hence reduce the cooling of skin [13,14]. In this way, the discomfort due to draught at vertical downward airflows can be reduced. For draught sensation, the experiments have shown that individuals are more sensitive to the airflow variations with the equivalent frequency between 0.2 and 0.6 Hz than the other frequency levels if the average air velocity is higher than 0.1 m/s [15,16].

The restriction of draught rate (*DR*) model in the European standard EN ISO 7730:2005 [17] is that the model includes only the terms for local air temperature and local air speed as well as for turbulence intensity. The model does not take into account e.g. the airflow direction and interactions that have been shown to affect the sensation of draught [18]. In addition, an uncertainty of measurements should be known in order to carry out the reliable assessment and validation. Melikov et al. [19] proposed that 5% uncertainty of draught rate can be realistically achieved.

Natural convection flows seem to dominate in highly occupied indoor environments, if the momentum flow of air jets is small [20]. Nielsen [21] represented that the driving force for the airflow field depends on the Archimedes number, which describes a ratio between buoyancy and inertial forces. Furthermore, Kosonen et al. [22] showed that a heat source strength and a thermal load distribution have a significant effect on air velocity field in a room. Generally, thermal load distribution has been shown to have a remarkable effect on thermal conditions [23,24], and airflow patterns [25,26].

Kandzia [27] studied the transient flow behavior of large-scale flow structures under natural and forced convection with symmetrical set-up of thermal loads and air distribution. The author found that a low-momentum supply airflow and high internal thermal loads cause an unstable airflow structure in a room. When the supply air velocity was increased, the airflow structures had more stable and two-dimensional behavior. This indicates more unstable airflow characteristics with the buoyancy-driven flows than with the momentum-driven flows. In addition, Müller et al. [18] demonstrated a significance of airflow interaction in indoor environments. The authors emphasized remarkable effects on airflow characteristics, such as mean air speed, turbulence intensity, fluctuation frequency and airflow direction.

Fourier transform can be conducted to investigate indoor airflow field [5,12,28]. Recently, Cheng and Lin [29] showed a difference in energy spectrums with several air distribution methods. Zhang et al. [30] in turn emphasized that a power spectrum may reflect the amount of turbulent kinetic energy in the flow motion of turbulent thermal convection. In addition, Wang et al. [31] represented the turbulent scales in a cabin mock-up, i.e. in a highly occupied thermal environment. The authors found that a range of spatial scales are on the order of 0.1 m … 8×10^{-4} m and the time-scales correspondingly 0.8 s … 0.01 s that characterize vortices in mixing region under opposing jets. In an earlier study, Chen and Srebric [32] stated that the smallest spatial scales, i.e. the Kolmogorov length scales, can be around 0.001 m–0.01 m for the most indoor airflows.

The diffuse ceiling ventilation is a vertical air distribution method in which the supply air is distributed evenly through the perforated suspended ceiling down to the occupied zone [21,33,34]. The method has been shown to produce rather promising results compared to other ventilation methods [35–38], e.g. the diffuse ceiling ventilation can cool down higher thermal loads without draught than other common methods [39,40]. However, the cooling capacity reduces towards increasing room height [41]. Furthermore, the diffuse ceiling ventilation can act as a radiant cooling ceiling [42] when the supply airflow decreases the ceiling temperature.

The main objective of the current study was to investigate airflow conditions, air speed fluctuation and turbulence scales with increasing thermal loads in a case where low-momentum diffuse ceiling air distribution and thermal loads are installed symmetrically in a test room. The symmetrical set-up was chosen, because the evenly distributed thermal loads and air distribution offer a good opportunity to observe average effects on airflow field. The novelty of this study is the extended airflow characteristics with gradually increased thermal load in a simplified indoor environment.

2. Methods

2.1. Test room

The measurements were carried out in a test room (Fig. 1) of internal dimensions of 5.5 m (length) x 3.8 m (width) x 3.2 m (height). The test room was located inside a laboratory hall such that the outer environment was also stable. The thickness of the envelope wall element was 80 mm in which the U-value was 0.3 W/m^2,K. The vertical air distribution was introduced by discharging supply air through a diffused ceiling into the occupied zone. The depth of the suspended ceiling was 0.35 m. The suspended ceiling was made of perforated Ecophon Advantage A glass-wool-plate elements with the dimensions of $600 \times 600 \times 20$ mm^3 [43]. The degree of the open area of the perforation was around 0.5%. The diameter of the supply air nozzles in the diffused ceiling was 14 mm. Two Ventiduct VSR duct-diffusers [44] were installed sequentially above the suspended ceiling. The combined duct diffuser of diameter 0.2 m extended the entire length of the upper