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Thermal environment and air quality in office with personalized ventilation combined with chilled ceiling

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ABSTRACT

The thermal environment and air quality conditions provided with combined system of chilled ceiling and personalized ventilation (PV) were studied in a simulated office room for two occupants. The proposed system was compared with total volume HVAC solutions used today, namely mixing ventilation and chilled ceiling combined with mixing ventilation. The objective of the study was to evaluate whether PV can be the only ventilation system in the rooms equipped with chilled ceiling. The room air temperature was 26 °C in cases with traditional systems and 28 °C when PV was used. PV supplied air with the temperature of 25 °C. PV improved thermal conditions and was up to nearly 10 times more efficient in delivering clean air at workstations than mixing ventilation systems, which resulted in strong protection of occupants from the cross-infection. In the room space outside workstations no substantial differences in thermal environment were found between studied systems. The room air mixing with PV working alone was at the same level as with mixing ventilation. No substantial differences in contaminants' concentration distribution and air-change effectiveness were found between the studied systems in the occupied zone outside workstations.

1. Introduction

Thermal environment and indoor air quality in offices affect health, comfort and performance of occupants [1–3]. HVAC systems often consume more than 40% of total building energy needs. Thus creating comfortable conditions in spaces at low energy use becomes an important challenge for HVAC engineers and requires development of new solutions. Centrally controlled total volume ventilation systems (e.g. mixing ventilation or displacement ventilation), which are typically used in offices, aim to create uniform indoor environment in the occupied zone of rooms which cannot satisfy all occupants. In the case of mixing ventilation air is supplied far from occupants and is mixed with polluted room air before reaching people's breathing zone. With the displacement ventilation cool and clean air is supplied at low level, near the floor and is moved upward by the buoyancy flows present in the room. Thus air should be cleaner in the lower (occupied) zone. However, in many practical applications the air cleanness is lower than assumed during design process [4,5]. The air cleanness especially decreases when the pollution source is located close to the occupant. In such situation the human boundary layer is transporting contaminated air to the breathing zone. Also movements created by walking people disturb the pollution stratification and decrease the cleanness of the air [6]. Moreover due to risk of draught at the feet its' cooling capacity is limited. The performance of total volume air distribution systems is discussed in Ref. [7].

Promising air distribution is achieved by personalized ventilation. It delivers clean air directly to occupants' breathing zone and provides possibility for individual control of the microenvironment at each workstation [8]. Therefore personalized ventilation has potential to improve inhaled air quality compared to total volume ventilation [9–11]. Previous studies showed also that personalized ventilation decreases intensity of some Sick Building Syndrome symptoms in comparison with mixing ventilation [9,12]. However, due to smaller airflow rates and limitation of the lowest supply air temperature personalized ventilation

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Nomenclature

ACE	Air-Change Effectiveness
ADPI	Air Distribution Performance Index
CC	chilled ceiling
MV	mixing ventilation
PV	personalized ventilation
TV	total-volume ventilation
WS	workstation
q	flow rate, L/s
t_a	air temperature, °C
t_{acn}	corrected time-averaged air temperature at *n*-point, °C
t_{eq}	manikin based equivalent temperature, °C
t_o	operative temperature, °C
t_w	cooling water temperature, °C
v_a	air velocity, m/s
ε^c	Contaminant Removal Effectiveness
τ_r	time-averaged air temperature in the reference point, °C
τ_i	local age of air, min
ϕ_n	effective draft temperature, °C

Subscripts

E	exhaust
exh	exhaled
i	in the *i*-location
inh	inhaled
n	in the *n*-point
S	supply

systems are not able to remove substantial amount of sensible heat load generated in spaces. In such cases additional cooling system is needed.

The chilled ceiling is a popular hydronic radiant cooling solution used in different type of buildings. It has higher cooling efficiency than traditional total air systems and is easy to maintain [13]. Radiant ceiling cooling provides "cool head and warm feet" environment which is preferred to "warm head and cool feet" environment often created by total volume air systems. Nevertheless, the chilled ceiling requires installation of additional ventilation system to provide fresh air into spaces. Typically chilled ceiling is installed with mixing ventilation. However, it is suggested that displacement ventilation combined with chilled ceiling has increased cooling capacity and may provide environment with high air quality and acceptable thermal comfort conditions [14–18]. Loveday et al. [19] reported that the stratification flow, typical for displacement ventilation, can be disturbed because of chilled ceiling use. Air cooled under the ceiling creates downward convection flow, which increases the warm and contaminated upper region. Additionally chilled ceiling cools walls due to increased radiant heat exchange, which can increase downward convection flow near walls, causing transport of pollutants from the mixing contaminated region into the supply air and occupied zone [20]. Reduced chilled ceiling temperature increases the air velocity at height of 0.1 m and 1.1 m indicating mixing in the stratified zone, which can cause additional decrease of the air quality [19].

Combined system of chilled ceiling and displacements ventilation was also studied with integrated personalized evaporative cooler [21,22]. Personalized evaporative cooler is installed at workstations and explores the idea of "ductless" personalized ventilation [23,24]: air is drawn from the floor level and supplied toward occupant's face and upper body parts. Difference compared to "ductless" personalized ventilation is that air passes through saturated water sponge in the cooler and is cooled by 3–4 K. This combined system is proposed for hot and dry climate, where problematic are peak loads resulting in oversized HVAC systems. An aim of personalized evaporative cooler is to improve thermal conditions locally at the workstations during peak hours when chilled ceiling combined with displacement ventilation is not capable of maintaining design room temperature. Benefits of the personalized evaporative cooler for occupants are temporary and are focused only on the thermal comfort.

Hitherto performed studies have not considered personalized ventilation as the only ventilation system operating in the room when combined with radiant cooling. Personalized ventilation ensures convective cooling to the upper body parts of occupants, which can be controlled according to their individual preferences. Thus combining it with chilled ceiling should be in addition to improved perceived air quality also an effective way to improve thermal comfort in rooms at temperature higher than the upper limit of 26 °C recommended in the standards [25]. It has been reported that increasing the maximum allowed air temperature in the room and implementing personalized ventilation system together with mixing ventilation may be an effective energy-saving strategy [26]. It may be expected that under certain operating conditions combining chilled ceiling with personalized ventilation instead of mixing ventilation will also lead to reduction of the energy consumption. Moreover, change in air distribution strategy from total volume air distribution to localized air distribution should bring benefits in improving perceived air quality at workstations. The proposed combined system of chilled ceiling and personalized ventilation is novel and its performance needs to be studied.

The objective of the presented research was to identify the thermal environment and air quality conditions in an office room for two occupants equipped with personalized ventilation combined with chilled ceiling and to compare them with room conditions created by solutions used today such as mixing ventilation and combined system of chilled ceiling and mixing ventilation. An important part of the study was to evaluate whether mixing ventilation can be replaced by personalized ventilation as the only ventilation system in the rooms with chilled ceiling considering the environment at the workstation and in the occupied zone.

2. Methods

a) Experimental facilities

Experiments were performed in a climate chamber (L × W × H: 4.12 m × 4.2 m × 2.89 m) arranged as an office with 2 workstations (Fig. 1). The chamber was equipped with total volume mixing ventilation (MV), personalized ventilation (PV) on each desk and with a chilled ceiling (CC). The round movable panel was used as a PV diffuser because of high efficiency in delivering clean air to occupants at low turbulence intensity of the supplied personalised flow [27]. Three linear diffusers mounted at the centre of the ceiling were used for MV. Exhaust diffusers were located in the ceiling corners, as indicated in Fig. 1. Eighteen radiant cooling panels (1.19 m × 0.59 m) were built-in the suspended ceiling and covered 75% of its area.