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Effect of shifts from occupant design position on performance of ceiling personalized ventilation assisted with desk fan or chair fans

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ABSTRACT

Recently, personalized ventilation systems have gained popularity since they consist on localizing the occupant needs in terms of thermal comfort and indoor air quality (IAQ). Localized ventilation systems are designed on the basis of fixed occupant position. Since people move and do not remain in same position, it is of interest to study personalized ventilation system performance with respect to shifts from occupant design position. The aim of this work is to study and compare the performance of ceiling personalized ventilation (CPV) when aided with desk fans (DF) versus chair fans (CF) in crowded office spaces for shifts from seated occupant chair position with respect to the CPV jet. A computational fluid dynamics (CFD) model for particle transport and deposition was developed to simulate a two-station office ventilated by CPV system to predict particle transport and to assess ventilation effectiveness. The CFD model was coupled with a bio-heat model to predict segmental and overall sensation and comfort in addition to segmental skin temperatures. In this work, experiments were conducted to validate the CFD model accuracy in capturing the effect of the CF on particle transport.

The use of CF allowed the reduction of CPV flow rate by 22.72% resulting in energy savings of 14.87% for the case where the occupant was beneath the jet. Installing CFs allowed maintaining good performance of the system when chair shift due to movement of person occurred while installing DFs resulted in largely degrading the system performance at equal chair shift from the CPV center.

1. Introduction

Nowadays, a trend in heating ventilation and air conditioning (HVAC) design is emerging toward localizing the occupant needs in terms of thermal comfort and indoor air quality (IAQ) and hence deviating from mixing ventilation (MV) systems [1–3]. Localized airflow can result in both temperature and pollutant concentration segregations with limited mixing between adjacent occupant zones [3]. The evolution of ventilation systems' design is based on a compromise between satisfying good thermal comfort, ventilation effectiveness, and disease transmission between occupants while reducing the energy consumption.

Mixed ventilation (MV) is the conventional HVAC configuration based on maintaining uniform temperature and homogenous IAQ within the space by mixing fresh and return air before their delivery by ceiling mounted inlets [4,5]. Irrespective of the occupants' location, the space air temperature is nearly the same within the ventilated place since it is controlled by a single thermostat. MV had been widely used in buildings for its easy installation and simplicity. Nevertheless, this ventilation technique suffers from inefficient fresh air delivery to the occupants because of its mixture with recirculated air. In addition, MV mixing systems result in spreading airborne particles generated by occupants uniformly which in turn increase the potential of cross-infection among all occupants in a conditioned space unless large amount of fresh air is used to dilute contaminants. Furthermore, MV leads to an increase in the energy cost because it conditions both occupied and non-occupied zones. In contrast, localized ventilation controls the environmental conditions around the occupant and ensures minimal mixing between adjacent occupants' zones.

Recently, researchers were interested in air quality performance of localized systems that divided the space into microclimates around the occupants surrounded by a macroclimate [6,8]. They reported that localization of airflows caused segregations of temperature and particle concentration due to the low air mixing between the microclimates and macroclimate which allowed reducing the energy consumption while providing the occupant's comfort and fresh air needs [3]. Ceiling personalized ventilation

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Nomenclature

Symbols

C_b	CO_2 concentration at the breathing zone
C_f	CO_2 concentration of the fresh air
C_r	CO_2 concentration of the recirculated air
CF	chair fan
CFD	computational fluid dynamics
CPV	ceiling personalized ventilation
CPV + CF	ceiling personalized ventilation assisted by chair fans
CPV + DF	ceiling personalized ventilation assisted by desk fans
DF	desk fan
sd	shift distance from the CPV center
DFr	deposited fraction of particles at the vicinity of the exposed occupant
DRW	discrete random walk model
HVAC	heating ventilation and air conditioning
IAQ	indoor air quality
IF	intake fraction
MV	mixing ventilation
PSI-C	particle source in-cell scheme
u_τ	friction velocity
y	cell center distance from the wall
y^+	Y plus function

Greek symbols

ε_v	ventilation effectiveness
ρ	air density
μ	air dynamic viscosity
τ_w	wall shear stress

(CPV) constituted one integrated air delivery system which can be easily installed in the false ceiling of office buildings and was introduced by Yang et al. [6]. Makhoul et al. [7,8] enhanced the CPV design by using co-axial personalized ventilation (PV) nozzles with primary fresh air and secondary recirculated air jets providing good IAQ at the breathing level of the occupants with less air entrainment with the surrounding air at lower fresh air amounts. Nevertheless, shortcomings of the coaxial system were related to its non-practicality and difficulty of controlling equal velocities at the boundary separating the primary and secondary jets.

Melikov [9] highlighted the efficiency of controlling airflow interactions in the human body micro-environment for improved breathable air quality and thermal comfort. In the case of CPV systems, the rising human plumes oppose the fresh air delivery by the downward CPV jet. A practical design to control the convective plumes consisted of a CPV nozzle equipped with fans that could be mounted in the desk or the chair for suction of the thermal plumes emanating from the human body [10]. Makhoul et al. [10] and El-Fil et al. [11] showed that desk fans (DF) and chair fans (CF) assisting CPV led to significant enhancement in its performance. Their work was constrained with the assumption of fixed occupant position and restricted to one station office where the occupant was directly seated beneath the CPV jet and did not consider the effectiveness of these systems in reducing particle transport toward the occupant breathing zone. The CPV system assisted with DF assumed a fixed distance of occupant from the desk [10] which would not be the case based on human behavioral and desk activity. Current crowded office buildings [12,13] have higher pollutant concentrations leading to higher occurrence of respiratory cross-infection between workers through direct inhalation of contaminated particles generated by an infected occupant [14] or indirectly by hand- contaminated surface contact [15]. The shift in occupant design position might significantly degrade the CPV system performance. A seated occupant is most likely to move the chair position relative to the desk and will not always sit directly beneath the CPV jet. It is not clear how critical these shifts are on the CPV performance especially in crowded office spaces. A slight movement away from the desk would position the occupant breathing zone away from the CPV jet central clean air region. The performance of the CPV system assisted by DF or CF should be also evaluated for reduction of cross-contamination between occupants in addition to thermal comfort and ventilation effectiveness.

One of the primary concerns of this work is to compare the performance of CPV system assisted with DF and CF when shifts from occupant position occur with respect to the CPV jet. A CFD model for predicting species and particle transport was developed to investigate the IAQ associated with these systems. In addition, the CFD model was coupled with a bio-heat model to assess the thermal comfort by predicting segmental and overall sensation and comfort in addition to segmental skin temperatures. In this work, an experimental set-up was constructed with a main goal of assessing the ability of the CFD model in predicting the fans' effect (DF versus CF) on particle behavior. The validated CFD model was used to study the effect of several factors on thermal comfort and pollutants spread in crowded office spaces such as the relative position of occupant/desk/CPV jet and the fan type. An energy analysis was performed to determine the energy savings induced by the best performing CPV configuration when deviations take place in occupant position with respect to the CPV center.

Previous studies considered primarily the comfort and ventilation effectiveness performance of each type of fans (either DF or CF) [10,11]. The originality in this study is that it makes a holistic direct performance comparison between the two assisting fans not only in thermal comfort, ventilation effectiveness and energy consumption but also in the protection from infectious particles. In addition the comparisons consider shifts in the occupant position and possible changes in the relative distance between the occupant chair and the office desk.

2. Problem description

Since the tendency nowadays is toward increasing the occupancy density, the maximum possible density was selected at 8 m^2/person representing a crowded office space [12,13]. Three main ventilation configurations were compared under identical operating conditions: (1) Standalone CPV system; (2) CPV system assisted by DF (CPV + DF); and (3) CPV system assisted by CF (CPV + CF). Fig. 1 represents the conditioned space layout with the different ventilation configurations studied. Two CPV nozzles supplying fresh air at the center of slot diffusers recirculating air represented the inlets while four exhausts were present at the corners.

In accordance to the occupant preference (comfortable position, viewing distance, eye strain condition, etc.) [16–19] and performed office tasks (typing on the keyboard, reading a text from the screen, etc.) [17–20], the occupant might choose a certain distance from the office desk within his working area. Shifts in the right/left direction within the working area can also take place. However, the axial shift (close\away from the office desk) is more critical and for this reason it was considered. In fact, the expansion of the CPV jet in the axial direction is restricted by the computer plume from one side and the occupant plume from the other side reducing its axial covered area and limiting its effectiveness compared to the right/left direction in which the expansion of the CPV jet is relatively free. As the office working area is limited, reasonable and common shift distances from the desk were investigated close and away from the