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Ceiling personalized ventilation combined with desk fans for reduced direct and indirect cross-contamination and efficient use of office space

Carine Habchi [a], Kamel Ghali [a], Nesreen Ghaddar [a,*], Walid Chakroun [b], Sorour Alotaibi [b]

[a] Mechanical Engineering Department, Faculty of Engineering and Architecture, American University of Beirut, P.O. Box 11-0236, Beirut 1107-2020, Lebanon
[b] Mechanical Engineering Department, College of Engineering & Petroleum, Kuwait University, Khaldiya, P.O. Box 5969, Safat 13060, Kuwait

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ABSTRACT

Crowded offices with short distances separating workers' stations increase the probability of respiratory cross-infection via two different paths. One path is the contaminant transmission through air by direct inhalation and the other is through the body contact of contaminated surfaces and walls. Mixed ventilation principles used today reduces the probability of cross contamination by increasing the distance between the stations challenging the efficient use of the space or by supplying more fresh air in the space which is energy inefficient.

In this work, new cooling and ventilation configuration is studied by modeling using computational fluid dynamics with consideration of space occupancy density while providing good indoor air quality. The configuration considers a ceiling personalized ventilation system equipped with desk fans. The ability of the computational fluid dynamics model in computing the thermal, velocity and concentration fields was validated by experiments and published data. The main objective of the performed experiments was to ensure that the developed computational fluid dynamics model can capture the effect of the desk fan flow rate on particle behavior.

The studied system is found to provide acceptable indoor air quality at shorter distance between the occupants compared to the mixing system at considerable energy savings. By optimizing the design of the proposed personalized ventilation system, the occupancy density in an office is enhanced to 8 m^2 per occupant compared to 12 m^2 per occupant for conventional mixing system while maintaining better indoor air quality at significant decrease in the energy consumption.

1. Introduction

Suspended aerosol particles may present risks to the human health [1] and are regarded as an essential contaminant in the air [2,3]. Epidemiological studies revealed significant relation between dangerous human diseases and particle pollution where increased particle concentration increased the risk of cardiovascular problems [4], lung cancer [5], asthma and a variety of respiratory infections [6]. Literature studies have mainly focused on outdoor air pollution, but more attention has recently been directed to indoor particles' exposure [7,8] where people spend the majority of their time [9]. Offices in particular are one of the critical indoor spaces where the likelihood of their exposure to airborne pathogens is very high [10]. With the increase of energy consumption for indoor environmental quality enhancement [11,12], there is a need to use ventilation configurations that are effective [13,14] while maintaining good IAQ.

Cross-infection between workers can take place via different paths: direct inhalation and by contact of contaminated surfaces. Infected persons release droplets that probably contain viruses or bacteria that expose healthy persons to infection by either direct inhalation [15] or indirectly via a contaminated surface-to-hand-to-mouth contact [16]. Researchers' studies on cross-contamination investigated mainly the probability of infection due to the direct inhalation. However, few studies considered the indirect path via the contact of contaminated surfaces. Reducing locally contaminants' concentration within the air inhaled by occupants does not necessarily indicate a clean non-infectious environment for the office occupants. Pathogens such as bacteria and viruses are able to survive on surfaces for long periods [17] resulting in a higher probability of being transmitted to susceptible occupants [18,19].

In designing a multi-station office space, the distance between the work-stations constitutes one of the main factors affecting

* Corresponding author. Tel.: +961 1 350000x3594.
E-mail address: farah@aub.edu.lb (N. Ghaddar).

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Nomenclature

CFD	computational fluid dynamics
CPV	ceiling personalized ventilation
DF	desk fan
d	distance between the occupants
d_p	particle diameter
D	peripheral ceiling diffuser
DSN	single nozzle system at the center of a peripheral ceiling diffuser with direct jet
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
PV	personalized ventilation
Q_f	desk fan flow rate
SN	single nozzle

direct and indirect cross-contamination. Crowded office spaces with short distances separating occupants' stations increase the probability of respiratory cross-infection. In conventional mixing ventilation systems (*MV*), the possibility of cross infection is controlled by increasing the distance between stations which would result in inefficient use of the space. Furthermore, a strong relationship exists between the airflow pattern, airflow interaction within the occupied zone and particle distribution within the space [20,21]. The airflow pattern widely affects particles' spread and surface deposition. Thus, the careful design of the heating, ventilation, and air conditioning (HVAC) system can prevent cross contamination between the occupants. On the other hand, efficient use of the space is important for economic and energy efficiency reasons. Therefore, when considering the layout of office spacing, a designer must minimize cross-infection while using space efficiently and reducing dead space areas. Efficient cooling and ventilation strategies should also be implemented to reduce cross-contamination between close work stations in comparison with conventional *MV* system.

Personalized ventilation is an effective system in localizing the occupant needs for thermal comfort and air quality [22]. One possible configuration is the ceiling personalized ventilation (*CPV*) systems which are practical to use since they don't require additional installation cost and can be retrofitted to spaces ventilated by *MV* systems of ceiling supply type. Recently, Makhoul et al. [23] proposed a new ceiling-mounted personalized ventilation system characterized by high energy savings while insuring high breathing air quality and thermal comfort in the microclimate of occupants [24,25]. The system consisted of ceiling coaxial *PV* jets delivering clean air effectively by lengthening the potential core region at the center of a peripheral angled diffuser creating a canopy localizing the flow around the occupant. However, coaxial nozzles presented the disadvantage of requiring additional ducting system and difficulty of control of two jets of equal velocities. To overcome the constraints of the coaxial system, Makhoul et al. [26] proposed to aid the single ceiling *PV* jet of Yang et al. [27] with desk fans which were able to control the convective plumes emanating from the human body allowing the personalized air to reach the breathing level more effectively. Nevertheless, the ability of Makhoul et al. system [26] in reducing cross-contamination between occupants was not investigated. In this work, the performance of the *CPV* system assisted by desk fans will be studied and compared to conventional *MV* technique to identify the design parameters that will decrease direct and indirect cross-contamination of airborne particles at minimal distance between the workstations.

One of the primary goals of the current study is to minimize both the number of particles reaching the breathing zone of the exposed person and the number of particles deposited on surfaces at occupant's vicinity that contribute significantly to the cross-infection through the physical contact. The objective of the study is to optimize the ventilation configuration to reduce the required distance between occupants and hence increase occupancy density while maintaining good IAQ. A 3-D simulation model, using commercial computational fluid dynamics (CFD) software, is developed to predict accurately the particle transport and deposition and assess the performance of different ventilations systems (*MV*, *PV*, and *PV* aided with desk fans). The accuracy of the developed CFD model in computing velocity, thermal and concentration fields was validated experimentally and by comparison to published data. The main purpose of the conducted experiments was to ensure that the developed CFD model can capture the effect of the desk fan flow rate on particle behavior.

A parametric analysis is then performed to study the effect of the following parameters: (i) the distance between the occupants; (ii) the ventilation system type; and (iii) the desk fan flow rate on direct and indirect cross contamination. The optimal configuration will be recommended for ensuring high IAQ and clean surfaces in the immediate occupant surrounding even in crowded office spaces.

2. Problem description

The occupancy density of the studied office is taken as 12 m^2/person which is the standard value recommended [28]. Over recent years, offices became more crowded posing a challenge to the constraint of 12 m^2 per occupant [28,29]. Since one of the main concerns of this study is to decrease the probability of cross-contamination (direct and indirect) with minimal distance between the occupants, the performance of the studied ventilation and cooling configuration is investigated for three distances between the occupants: ($d1$ = 4.0 m (long distance); $d2$ = 3.0 m (medium distance); $d3$ = 2.0 m (short distance)) (Fig. 1). A minimum distance of 1.35 m between the edge of a desk and a wall behind it is recommended to permit the opening of a door behind the seated occupant [30]. Therefore, a distance of 1.4 m was adopted in this work resulting in a maximum separating distance between the occupants of 4 m for the office occupancy density of 12 m^2/person. On the other hand, the distance of 2.0 m is the minimum distance possible between the occupants since the desks become very close and interaction would occur for distances less than 2.0 m between the angled diffusers jets. If the separating distance can be decreased from 4.0 to 2.0 m, the occupancy density can be increased from 12 to 8 m^2/occupant. In fact, typical floor area of one station office is 3.4 m $\times$ 3.4 m [26] and for two stations office, the corresponding dimensions are 6.8 m $\times$ 3.4 m with conventional mixing ventilation (Fig. 1b). Hence, the maximal distance between occupants for an occupancy density of 12 m^2/person is 4.0 m for an office having a length of 6.8 m and excluding the distance between the wall and the desk (6.8–2 $\times$ 1.4 m). If the