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Effectiveness of intermittent personalized ventilation assisting a chilled ceiling for enhanced thermal comfort and acceptable indoor air quality

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ABSTRACT

In this work, the performance of an intermittent personalized ventilation system coupled with a chilled ceiling was evaluated based on its ability to provide comfort and protect occupants from passive contaminants. A 3-D computational fluid dynamics model was used to predict the airflow fields in the space (velocity, temperature, and concentration). The model's predictions were experimentally validated in a climatic chamber equipped with a chilled ceiling and a personalized ventilation. Good agreement was found between experimental results and the computational fluid dynamics model.

A case study was then conducted for different chilled ceiling and personalized ventilation configurations at an average personalized ventilation flow rate of 7.5 L/s, It was found that at lower chilled ceiling temperatures (16 °C), it is recommended to operate the personalized ventilation under steady flow since the intermittent personalized ventilation doesn't bring any enhancement in comfort and air quality. However, for conventional chilled ceiling temperatures at 20 °C, an intermittent personalized ventilation operated at 0.5 Hz improved comfort compared to steady personalized ventilation. Moreover, the intermittent personalized ventilation was able to achieve 7.52% and 15.04% energy savings compared to a steady system and standalone chilled ceiling respectively, under similar comfort conditions.

1. Introduction

The productivity of occupants in office spaces is highly dependent on their satisfaction with their thermal environment or in other words their state of thermal comfort [1,2]. Providing occupants with comfortable conditions through the adequate implementation of heating ventilation and air conditioning (HVAC) systems is crucial [3]. To fulfill these requirements, many HVAC systems have been suggested such as the conventional mixing and displacement ventilation systems that condition the space by supplying cool fresh air [4,5]. Other emerging HVAC systems include radiant cooling systems such as the chilled ceiling (CC) system which utilizes both convective and radiative heat exchange with heated surfaces.

The CC is a popular system easily integrated within office spaces [6]. It is characterized by a metal panel installed at the ceiling level and cooled by chilled water pipes [7]. CC systems assure comfort mainly through radiative heat transfer cooling between the cold ceiling and different hot surfaces in the space such as occupants, walls and computers. This allows for a higher cooling efficiency than conventional systems and better thermal comfort [8]. In addition, CC systems reduce air motion and produce a more thermally uniform environment which minimizes draught discomfort [9]. Many studies have been conducted to investigate the performance of CC systems. Catalina et al. [10] used computational fluid dynamics (CFD) to model a test room equipped with a CC to investigate thermal comfort. Results showed that small temperature gradients (1 °C/m) were present in the space as well as low velocities and uniform values of thermal comfort. Another advantage of CCs is that they are energy-friendly systems. In fact, the heat removed from occupants by radiation allows the CC to maintain higher room air temperatures than conventional systems for the same levels of comfort. This reduces the cooling load and allows for considerable reduction in energy consumption [11]. In a recent study, Carbonnier et al. [12] performed numerical simulations and showed that the CC systems were able to reduce energy consumptions by 10% compared to conventional systems. Moreover, CCs are characterized by their quiet operation which decreases noise discomfort; unlike conventional systems where higher noise levels can cause disturbance to some occupants [13].

Even though the CC system is a superior system, it has two main drawbacks. Standalone CC systems are not efficient when high heat loads are present in the space [14,15]. Additionally, CC systems compromise indoor air quality (IAQ) since they only condition the space without a fresh air supply to dilute pollutants. This is not the case for

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Nomenclature

HVAC	Heating ventilation and air conditioning
CC	Chilled ceiling
CFD	Computational fluid dynamics
CCPV	Personalized ventilation assisting chilled ceiling
IAQ	Indoor air quality
PV	Personalized ventilation
$\overline{m}_{PV,supp}$	Average PV supply flow rate (kg/s)
f	Frequency (Hz)
A	Amplitude
HEPA	High efficiency particulate air
BZ	Breathing zone
t	Time (s)
$V_{PV}(t)$	Instantaneous PV velocity (m/s)
V_{min}	Minimum PV velocity (m/s)
V_{max}	Maximum PV velocity (m/s)
ε_v	Ventilation effectiveness
C_{ex}	Species' concentration at the exhaust grill (ppm)
C_{BZ}	Species' concentration at the breathing zone (ppm)
C_{fr}	Species' concentration in the fresh air supply (ppm)
$T(t)$	Instantaneous temperature (K)
$C(t)$	Instantaneous concentration (ppm)
$\overline{T}$	Average temperature (K)
$\overline{C}$	Average concentration (ppm)
OTS	Overall thermal sensation
OTC	Overall thermal comfort

conventional HVAC systems where supplying cool fresh air is an inherent attribute. For example, in mixing ventilation systems, IAQ can be easily enhanced by increasing the fraction of supply fresh air compared to recirculated air. In displacement ventilation system, IAQ and hence stratification height; can be increased by supplying higher amounts of fresh air. In CC systems, the lack of air renewal can lead to contaminants' build up and deteriorate IAQ [16,17]. Actually, there are many types of contaminants present in office spaces that can be emitted from human respiration, computers, and office furnishing. These pollutants' negatively affect occupants' health, wellbeing and thus their work efficiency by causing sick building syndromes (nausea, eye irritation, dizziness and headaches) [18]. In such cases, the CC cannot operate as a standalone system. It needs to be assisted by another HVAC system that can compensate its shortcomings by delivering cool fresh air towards the occupants to provide good IAQ and maintain comfort.

A promising HVAC system that can assist the CC; is the personalized ventilation (PV) system. This compact and adjustable air distribution system delivers cool fresh air directly towards the occupants [19–21]. Therefore, it can improve the quality of the inhaled air by supplying high IAQ towards the occupant's breathing zone (BZ) [22]. Moreover, by allowing adjustment of its different supply parameters, PV can respond to different thermal preferences and thus; enhance comfort [23]. In addition, PV is a cheap system that can assist other HVAC systems and reduce energy costs while still assuring comfort and protecting occupants from pollutants [24]. There are many configurations of PV that have been thoroughly studied in literature (computer mounted, desk fans, ceiling integrated, chair fans). In an experimental study, Lipczynska et al. [25] investigated the performance of a standalone desk mounted PV system assisting CC; in terms of IAQ and comfort. Their results showed that the CC/PV system was able to enhance the inhaled air quality in the occupant BZ by 89.6% compared to mixing ventilation systems and reduce cross contamination. The PV system also improved thermal comfort by reducing draught sensation by 79% compared to mixing ventilation systems [25].

In more recent PV applications, the supplied cool fresh air from the PV nozzle was varied to enhance thermal comfort and improve energy performance. In other words, the supply flow rate accelerated and decelerated between a minimum and a maximum at a characteristic frequency. This can create a highly turbulent jet, especially with increasing frequency and fluctuations, leading to enhancement of comfort compared to steady PV; mostly in warm indoor environments [26,27]. However, PV intermittency may deteriorate IAQ in the occupant breathing zone due to increased turbulence and entrainment of pollutants from the surrounding environment into the jet. The surrounding environment in the vicinity of the occupant is also affected by the turbulence levels of the intermittent PV jet which may affect IAQ in case the occupant shifts the head position. In previous work, researchers were able to find an operating PV frequency that was a good compromise between thermal comfort and IAQ in which both requirements were acceptable. Al-Assaad et al. [28,29] studied intermittent PV when assisting mixing and displacement ventilation systems using CFD and mathematical modeling, respectively. They reported that as frequency increased, comfort improved while IAQ deteriorated. A compromise between comfort and IAQ was found at frequencies of 0.94 Hz and 0.5 Hz respectively while attaining energy savings of 16.1% and 15.7% compared to steady PV. Therefore, it is worth investigating the performance of intermittent PV integrated with the CC system.

However, in rooms equipped with CC; the ceiling is characterized by temperatures ranging between 16 °C and 20 °C depending on the latent load and possibility of replacing the CC with a desiccant cooled membrane ceiling [30–33]. The temperature difference between the cold ceiling and the hot surfaces in the room (occupant, walls, equipment) induces significant buoyant forces. These forces increase with lower ceiling temperatures and can create unstable room air stratification in the space and increase turbulence intensity [34–36]. Combined with the turbulent intermittent PV jet which acts as the only source of fresh air; IAQ might be highly compromised. To the authors' knowledge, no studies in literature have combined the intermittent PV and CC systems and compared their performance with steady PV/CC systems based on thermal comfort, IAQ and energy savings.

This study considers an office space equipped with CC and assisted by an intermittent PV system. The aim is to study the performance of this system and find the compromise intermittent PV operating frequency for enhanced thermal comfort as well as occupant protection from passive contaminants at minimal energy costs. The performance of steady and intermittent PV assisting a CC system will be assessed in terms of thermal comfort, IAQ and energy consumption. To achieve these objectives, a transient 3-D computational fluid dynamics (CFD) model of an office space equipped with a CCPV model with intermittent PV is employed to predict the airflow field variables. The CFD model predictions of temperatures and species' concentrations were validated experimentally in a climatic chamber on a thermal manikin representing an occupant in an office space.

2. Methodology

2.1. System description

This study considers a typical office space conditioned by CC system and a desk-integrated horizontal PV system. Fig. 1 illustrates the conditioned space equipped with the intermittent CCPV systems as well as the seated occupant and workspace. The CC is characterized by a metal panel cooled by chilled water indirectly. The chilled water cools the ceiling which exchanges radiant energy with the different office surfaces (computer, walls, occupant and floor). The PV supplies cool fresh air from a rounded outlet horizontally towards the occupant's face in a sinusoidal manner as seen in Fig. 1. The airflow downstream from the