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Chilled ceiling and displacement ventilation aided with personalized evaporative cooler

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ABSTRACT

This paper aims at studying the energy impact of a chilled ceiling displacement ventilation *CC/DV* system aided with a personalized evaporative cooler (*PEC*) directed towards the occupant trunk and face. A simulation model is developed for integrating the personalized cooler with the ascending thermal plume. The thermal model of the conditioned room air around the person is integrated with a segmental bioheat and thermal comfort model to predict the human thermal comfort.

The model is validated with experimental data on the vertical temperature distribution in the room, and the recorded overall comfort perceived by surveyed subjects. Experimental results agreed well with predicted values of temperature and comfort level. When using personalized cooling, the *DV* supply air temperature can be as high as 24 °C while the *PEC* at flow rates of 3–10 l/s achieved similar comfort with a *DV* system at supply temperature of 21 °C. At equal thermal comfort level, the integrated *CC/DV* system, *PEC* model resulted in up to 17.5% energy savings compared to the *CC/DV* system without a *PEC*. When mixed air is used in the *CC/DV* system additional 25% savings in energy is realized when compared with energy used for the 100% fresh air without the *PEC*.

1. Introduction

The continuing rise in energy demand, costs and the associated environmental problems, notably climate change, are causing increased emphasis on the design of energy efficient air conditioning systems for both industrial and comfort applications. Buildings in Kuwait are an example and account for more than 50% of all energy use in the country [1]. In the summer, the HVAC systems represent 70% of peak load. With building codes in effect, building heat gain through envelopes and infiltration is minimized. Given that Kuwait climate is characterized by high outdoor temperature that exceeds indoor comfort conditions by 20–30 °C, ventilation air conditioning represents a major contributor to increased cooling load. Targeting energy cost associated with providing indoor air quality (*IAQ*) in HVAC systems while maintaining thermal comfort is a strategic intervention to reduce building energy consumption [2].

The chilled ceiling displacement ventilation (*CC/DV*) provides high *IAQ* by introducing 100% fresh supply close to the floor level displacing warm air into exhaust and creating clean occupied lower zone in the space. Many researchers have adopted the "stratification height" in the *CC/DV*-conditioned spaces to be the measure of the *IAQ* [3–6]. The stratification height is defined as the elevation at which the density gradients disappear in the rising air and its plume spreads horizontally. It is determined from mass balances at the height when air supply flow rate is equal to the thermal plumes total flow rate and it is recommended not be less than a desired minimum, normally the height of a seated person, for acceptable *IAQ* [6,7]. The 100% fresh air in the occupied zone of the *CC/DV* conditioned room exceeds the ANSI/ASHRAE Standard 62.1 [8] minimum acceptable ventilation requirements of the space. The energy consumption cost of conditioning ambient air to appropriate supply condition of the *DV* system is substantial. Several researchers [2,9–12] reported that although the *CC/DV* system consumed 53% less cooling energy than the conventional system at 100% fresh air system, it did not offer energy savings with mixed conventional systems. Kanaan et al. [9] developed a contaminant transport model for CO_2 transport in rooms conditioned by *CC/DV*. Their transport model accounted for contaminant buoyant convection within the plumes using Mundt model [13] and room air layers and contaminant lateral and vertical diffusion inside and outside the plumes of high concentration of contaminant. They assessed indoor air quality at steady state conditions of room load was between 40 and 70 W/m^2 and used the model to determine the maximum fraction of return air that maintains acceptable the contaminant concentration in the breathing zone. Chakroun et al. [14] extended contaminant transport model of Kanaan et al. [9] for

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Nomenclature

D_o	outlet diameter of the personalized evaporative cooler jet (m)
C_p	specific heat of air, J/kg K
CC	chilled ceiling
DV	displacement ventilation
HVAC	heating, ventilation, and air conditioning
$\dot{H}$	enthalpy rate, W
IAQ	indoor air quality
N	number of room air horizontal layers
PEC	personalized evaporative cooler
PV	personalized ventilator
q	mass flow rate, kg/s
T	temperature (°C)
x	distance from the outlet of the *PEC*
z	plume height, m
z_v	plume virtual source point height, m

Subscripts

o	plume centerline
s,sp	source plume
w,wp	wall plume

CC/*DV*-conditioned spaces and reported that substantial energy savings of up to 20% can be achieved with mixed *CC*/*DV* systems when part of the return air is mixed with the supply air without violating *IAQ* standard within the occupant lower zone in the room. Thermal comfort is ensured in the *CC*/*DV* conditioned space when the vertical temperature gradient in the occupied zone is less than 2.5 °C/m [15]. If the *CC*/*DV* system is integrated with personalized cooling and mixing of air return fraction, it might make the system more attractive and superior to other air conditioning system.

Researchers have used personalized cooling equipment such as cooling jackets that are either passively cooled by phase change materials [16] or actively cooled by connecting the cooled jacket to external cooling system [17]. Both techniques offer upper cooling for the human body and the potential of localizing occupant comfort and energy savings. However, the two techniques have their limitations: the comfort provided by the passive technique is limited to the quantity of *PCM* used and the duration at which melting of the phase change material occurs and the active technique limits the motion of the occupant and it requires special jacket. It is important to provide localized cooling without requiring special clothing from people. More innovative means can be adopted to reduce the *DV* system energy consumption caused by the conditioning load associated with fresh air ventilation requirement. Fresh or clean air can be supplied at the breathing zone level of occupants using personalized ventilators (*PV*) that are commonly used in air cabins and office spaces. Kaczmarczyk et al. [18] reported the improvement in perceived air quality when using a personalized ventilation system. The use of low turbulent *PV*s according to Melikov [19] not only reduces airborne infectious disease transmission, but also reduces HVAC system energy consumption. Melikov [19] reported that high efficiency *PV* system performs well (no draught discomfort) at room temperatures between 23 °C and 26 °C with a *PV* jet temperature that is equal or 3–4 °C less than room air while ensuring the penetration of the jet into the occupant thermal plume. The air quality in the vicinity of the occupant breathing zone was not considered. Cermak et al. [20] studied experimentally the performance of *PV* at flows ranging from 7 l/s to 15 l/s in conjunction with mixing and displacement ventilation (*DV*) and showed that *PV* will always increase inhaled air quality but it may also carry pollutants from a source located in its vicinity if not carefully designed. Khalifa et al. [21] investigated the design and performance characteristics of personalized ventilation systems that, in combination with general ventilation, to deliver high quality air to the breathing zone with no more clean air supply than indicated by ANSI/ASHRAE 62.1 [8]. Their new *PV* nozzle supplied clean air at 2.4 l/s with ventilation effectiveness close to 7 versus less than 2 for a conventional nozzle delivering the same amount of clean air.

In a recent study, Halvonova and Melikov [22] explored the idea of using ductless *PV*s in an office air conditioned by *DV* system by utilizing the lower clean air of the *DV* system. They reported that supplying cool and clean air at the breathing level of the occupants while maintaining an elevated room temperature improve the occupants' thermal comfort, the air quality they perceive as well as the inhaled air quality compared to a standalone operating *DV* system. Makhoul et al. [23] developed a model of room convective heat transfer with *DV* assisted by personalized ventilation system based on seperate plume and surrounding air temperatures while accouting for the *PV* effect on the thermal plumes. Their experimentally validated thermal model was used to estimate energy savings that resulted from using higher supply air temperature in the *DV* system aided with cooler *PV* while maintaing thermal comfort. The *PV* supply flow rates used by Makhoul et al. [23] ranged from 4 l/s to 7 l/s. They have not addressed how the *PV* flow rate affects air quality in the breathing zone. Liden and Waher [12] extended the thermal model of Makhoul et al. [23] to account for contaminant transport when the *DV* system is assisted by a *PV* and validated the simplified model predictions of CO_2 level in the breathing zone with detailed 3-D *CFD* simulations using commercial software. Chakroun et al. [24] assessed air quality experimentally in rooms conditioned with mixed-air *CC*/*DV* system aided with personalized evaporative cooler (*PEC*) by measuring the level of CO_2 concentration at selected locations in the room inside and outside the human plume using a high *PEC* flow at 20 l/s. Their findings show that the occupant plume is shifted towards the back of the human when running the *PEC* and the breathing zone had some what similar air quality as the room at that level. They also reported that increasing the ceiling temperature reduces CO_2 concentration whereas increasing the supply temperature had an opposite effect outside the plume.

It is clear that the *CC*/*DV* system energy consumption has the potential of reducing its energy consumption if supply air in the *DV* system is introduced at a higher temperature without causing discomfort to the occupants and fresh cooler air is provided at the breathing while maintaining *IAQ* (manifested by CO_2 concentration). This might be achieved through the use of a *PEC* instead of a *PV*. The *PEC* will cool only the area around the person while consuming a small amount of energy for the fan while air cooling is done due to water evaporation that can cause 3–4 °C reduction in relatively dry supply air temperature. The *PEC* cooler will be energy efficient because by directing the cool air to the upper region of the human body, the overall comfort of the occupant is improved without the need for having homogenous cool air temperature in the occupant microclimate permitting the use of elevated supply air temperature. Zhang [25] showed that upper body segments such as back and chest have dominant impact on the overall sensation during cooling. Zhang and Zhao [26] reported that face cooling could improve thermal acceptability and the upper boundary of the acceptable room temperature range could be shifted from 26 °C to 30.5 °C when face cooling is provided. Similar findings are also reported by Ghaddar et al. [27] with air movement targeting upper body segments to enhance comfort. They incorporated data on segmental ventilation of clothed human under different external wind conditions and thermal comfort and segmental discomfort models of Zhang [25] into the bioheat model of Othmani et al. [28]. What we are proposing in this work is to use evaporative cooler instead of a *PV* taking advantage of the dry air supply conditions that ensure that no condensation takes place on the *CC*. The *PEC*