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Design charts for sizing *CC/DV* system aided with personalized evaporative cooler to the desired thermal comfort

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ABSTRACT

This work extends chilled ceiling displacement ventilation (*CC/DV*) design charts to a wider operation range of *DV* supply temperatures and flow rates when aided with personalized evaporative cooler (*PEC*) at typical office of peak load of 70 W/m^2. The overall thermal comfort (*OTC*) of the occupant can be read off from the chart at different operating conditions of *DV/CC-PEC* system. The charts simplify the sizing procedure of the *CC/DV-PEC* system by specifying the operational design parameters which include temperatures of *DV* supply and *CC* surface, *PEC* airflow rate, the ratio of total load over *DV* airflow rate named displaced air parameter (*P*), and the *CC* cooling load. In producing the charts, extensive simulations were performed using a multilayer space thermal model to determine the human microenvironment conditions and local comfort models to determine occupant thermal comfort.

The use of the charts is demonstrated through case studies. It is found that the addition of *PEC* at flow rate of 10 l/s provided acceptable thermal comfort up to *DV* supply temperature of 26 °C. In such conditions, the *CC/DV* heat removal is about 83% of the space baseline load in design conditions which leads to energy savings while maintaining comfort.

1. Introduction

Most conventional mechanical cooling systems provide uniform thermal environment in the building. Combined chilled ceiling (*CC*) and displacement ventilation (*DV*) system is known to be an effective system [1,2]. Energy saving of 21 percent has been reported by Ghali et al. [3] compared to a conventional cooling system for the same air quality and thermal comfort.

The challenge in design of this integrated system is sizing of the two subsystems (*CC* & *DV*) to deliver the required load removal while providing a good level of indoor air quality and thermal comfort. This complex design process was initially addressed by Behne [2] and Tan et al. [1], who successfully implemented design diagrams for cooling loads below 100 W/m^2, indicating the applicability boundaries of *CC/DV* operative combination. For a room cooled with a combined *CC/DV* system, stratification height (the elevation at which the density gradients disappear in the rising air and its plume spreads horizontally) shows the level of the clean air zone and if the level is above 1.1 m, good indoor air quality is achieved. Nonetheless, this parameter was not clearly included in the works of Behne [2] and Tan et al. [1].

Ghaddar et al. [4] and Keblawi et al. [5] introduced new operational design charts that permit the user to select supply conditions, chilled ceiling temperature, the ratio of *CC* sensible load to the total sensible load of the combined system and also read off the value of the stratification height. The *CC/DV* design charts were developed for six load ranges from 40 to 100 W/m^2 at increments of 10 W/m^2. They considered range of values of supply air and chilled ceiling temperatures between 15 °C and 22 °C. The supply air temperature range is constrained to avoid the risk of cold drafts in the occupied region. The supply mass flow rate was constrained by the fresh air minimum requirement for acceptable *IAQ* with the condition that air velocity is less than 0.15 m/s to reduce draft for thermal comfort [11]. The design parameters, appearing in each of Keblawi et al. charts, are the supply temperature T_s, the chilled ceiling temperature T_c, load ratio *R* which is the fraction of the chilled ceiling ratio to the total sensible load, the displaced air parameter ($P = Q_s/\dot{m}_s$) which is the ratio of the total sensible load ratio to the supply air mass flow rate, the stratification height *H* and the vertical temperature gradient dT/dZ. The Keblawi et al. design chart for the cooling sensible load range 60–70 W/m^2 is shown in Fig. 1 since it will be used in this work as Ref. [5]. The shaded grey top region in the chart depicted in Fig. 1 represented conditions where the vertical temperature gradient dT/dZ is above comfort constraint of 2.5 K/m [5].

These charts (see sample chart shown in Fig. 1) were a step forward for determining the operating conditions of *CC/DV* systems

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Nomenclature

A	area
CFD	computational fluid dynamics
DV	displacement ventilation
$F_{j\rightarrow c}$	view factor from surface j to the chilled ceiling surface
h	enthalpy (kJ/kg)
h_c	convective heat transfer coefficient between ceiling and adjacent air layer (W/m^2 K)
h_{ci}	internal wall convection coefficient (W/m^2 K)
H	stratification height (m)
$\dot{H}$	enthalpy rate of air (kJ/(kg s))
$\dot{H}'_P$	enthalpy rate of the mixture of PEC and plume flow (kJ/(kg s))
IAQ	indoor air quality
J	number of wall surfaces in the space
$\dot{m}$	air flow rate (kg/s)
n	number of heat sources
OTC	overall thermal comfort
P	ratio of total sensible space load to total space supply air mass flow rate ($P = Q/\dot{m}_s$) (kJ/kg)
PEC	personalized evaporative cooler
PV	personalized ventilation
q_{PEC}	volumetric flow rate of the personalized evaporative cooler (l/s))
Q	cooling load (W)
R	ratio of sensible load removal by the chilled ceiling to total space sensible load
RH	relative humidity
T	temperature (°C or K)
$T_{C\text{-}PEC}$	corrected temperature of the evaporative cooler jet at the interface of the plume (°C)
w	humidity ratio (kg H_2O/kg dry air)
Z	vertical coordinate or height from the floor (m)

Greek

ε	emittance of the surface
σ	Stefan–Boltzmann constant (W/K4 m^2)

Subscripts

a	air
c	chilled ceiling
ac	air layer adjacent to ceiling and exhaust
e	exit
i	inlet
p	plume associated with heat source
s	supply air
w	wall

for sizing purposes. However, they do not quantify the level of thermal comfort and can only be used when *DV*'s supply temperature and *CC*'s temperature are both below 21 °C. Ghaddar et al. [4] reported the combination of *DV* supply temperatures below 21 °C and *CC* temperatures below 20 °C that result in comfortable condition. Moreover, the objective of these charts was to use them in sizing the *CC*/*DV* chiller capable of removing the load generated in the space.

Recent studies have proved that addition of a personalized evaporative cooler (*PEC*) to 100% fresh air ventilation system increases the level of thermal comfort, perceived air quality, health, and self-estimated productivity [6–8]. In a study about human response to local exposure, Zhang and Zhao [9] reported that thermal comfort can improve by face cooling; accordingly, the upper boundary of

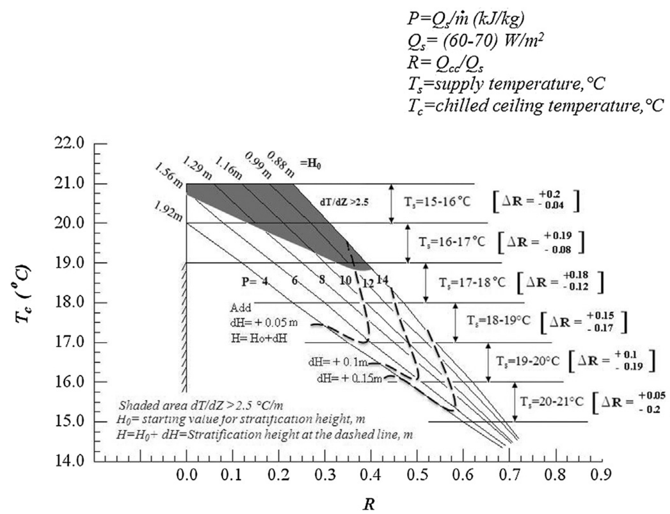

Fig. 1. Design chart of *CC*/*DV* system developed by Keblawi et al. [5] for sensible load range of 60–70 W/m^2.

acceptable room air temperature can shift from the conventional design value of 24 °C up to 30.5 °C. Using this idea, Chakroun et al. [10] studied that combination of *CC*/*DV*-*PEC* aiming the *PEC* jet toward the face. This combined system could shift the acceptable threshold of *DV* supply air temperature by 3 to 4 °C above 21 °C. Subsequently, findings of Makhoul et al. [11] and Chakroun et al. [10] show that energy savings of up to 20% can be achieved over systems that do not use personalized coolers while maintaining same comfort level.

The combination of *CC*/*DV*-*PEC* is shown to offer comfortable microenvironment and would result in less energy consumption since supply air flow rate can be set at higher temperature [10]. The integrated system has also been reported as a method to reduce the need for oversized air conditioning devices to cover transient load and reduce discomfort of people move from extreme outdoor climate to conditioned indoor environment [12]. This can also be helpful when actual load exceed building design load due to many factors that have to do with construction, system inefficiencies, and people use of space, particularly in office buildings [13,14]. Nevertheless, *CC*/*DV*-*PEC* requires a complex design procedure and if not properly performed, occupants may then experience local and overall thermal discomfort. In addition, excessively high *PEC* airflow rates and low *PEC* airflow temperatures compared to the surrounding environment can cause draught and thermal discomfort, respectively. Achieving acceptable design of *CC*/*DV*-*PEC* system is much easier if early design guidance is offered; consequently, in this work we are proposing to generate extended operational design charts for the *CC*/*DV*-*PEC* system for heavy load range of office building where such system would be most applicable for stationary occupants [14,15].

In general, integration of *PEC* with 100% fresh air convective cooling systems and more specifically with *CC*/*DV* system has been recently studied [14–23]. However, the following issues have not been tackled:

1. Providing design charts to simplify the complexity of downsizing process of *CC*/*DV* aided with *PEC* for typical cooling load of a conventional office (70 W/m^2)
2. The impact of *PEC* flow rate on comfort, when *PEC* is combined with *CC*/*DV* and is operated at room air temperatures above 26 °C and *DV* supply temperatures above 21 °C