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Research Paper

Humidity control of liquid desiccant membrane ceiling and displacement ventilation system

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HIGHLIGHTS

- Mixed supply air was proposed as a dehumidification strategy in LDMC-C/DV system.
- A transient boundary layer model was developed and validated experimentally.
- A case study was conducted on a typical office space in Beirut's climate.
- Mixed supply air reduced indoor humidity by 8.72% while maintaining IAQ.
- Mixing saved 24% of energy compared to conventional system for same supply air.

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ABSTRACT

The liquid desiccant membrane cooled ceiling (LDMC-C) and displacement ventilation (DV) system removes humidity directly from the space. However, LDMC-C/DV system does not control humidity in the lower occupied zone. In this work, a method for humidity control is proposed where fraction of the dehumidified cool dry air adjacent to the LDMC ceiling is extracted from the exhaust stream and mixed with the DV supply air stream. This leads to re-establishing of the thermal comfort; reducing the DV cooling requirements, and saving energy. A time-dependent mathematical model of the LDMC-C was developed and validated experimentally. The LDMC-C transient model was then integrated to the mixed DV space model and was applied to a case study. When mixing strategy was applied, the relative humidity dropped by an average of 8.72% in the occupied zone within 12 min and energy saving of 24% was achieved compared to in-duct conventional dehumidification.

1. Introduction

Chilled ceilings (CC) have recently attracted attention due to their unique features in providing cooling that results in thermal comfort of occupants at low noise while using less energy compared to conventional cooling systems [1–3]. However, two main concerns are presented in such systems: the indoor air quality and the limit on the minimum ceiling temperature. The first concern is due to the absence of a ventilation system while the second concern is attributed to the risk of condensation. Therefore, it is preferable to equip the CC system with an additional ventilation system such as the displacement ventilation (DV) [4]. The DV system removes additional sensible and latent load as well as pollutants from the indoor air [5]. So, the latent load removal and humidity control in the CC/DV conditioned space is completely reliant on the DV supply airflow conditions to deliver a comfortable environment with good indoor air quality [6,7].

Although the DV system has solved the first drawback of the CC system but the risk of condensation remains if the temperature of ceiling is not simultaneously controlled with the humidity content of the DV supply air [8,9]. In order to prevent any risk of condensate formation on the ceiling, researchers have considered the use of liquid desiccant with hydrophobic membranes to dehumidify the air without

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Nomenclature

A_c	cross-sectional area of the dehumidifier (m^2)
$A_{c\text{-}BDL}$	cross-sectional area of the boundary layer (m^2)
C	concentration of water per desiccant (kg of H_2O/kg $CaCl_2$)
CC	chilled ceiling
C_p	specific heat (J/kg·K)
COP	coefficient of performance
DV	displacement ventilation
h_{fg}	latent heat of vaporization of the water (J/kg)
H_m	thickness of the desiccant solution (m)
IAQ	indoor air quality
L_p	length of the dehumidifier panel (m)
$LDMC\text{-}C/DV$	liquid desiccant membrane chilled ceiling with displacement ventilation
$\dot{m}$	mass flow rate (kg/s)
$\dot{m}_{entrained}$	entrained air mass flow rate per unit length (kg/s·m)
q	rate of heat transfer (W)
RH	relative humidity (%)
t	time (s)
T	temperature (°C)
U_c	overall heat transfer coefficient of the membrane ($W/m^2\cdot K$)
U_m	overall mass transfer coefficient of the membrane (m/s)
V	velocity of supply air (m/s)
W_{th}	width of the membrane (m)
ω	humidity ratio (kg of H_2O/kg of dry air)
x	horizontal distance from the inlet of the membrane (m)
c	CO_2 concentration in air (ppm)
f	fraction of exhaust air mixed with supply air

Greek letters

δ	boundary layer thickness (m)
μ	dynamic viscosity ($kg/m^2\cdot s$)
ρ	density (kg/m^3)

Subscripts

a	room air
BDL	boundary layer
CO_2	carbon dioxide
electric	electric appliances
ex	exhaust
latent	latent heat generated by people
light	lighting equipment
outside	outside air
people	sensible heat generated by people
s	supply air conditions
sol	solution
w	wall

direct contact with the desiccant [10–13]. This dehumidification method has been recently used in conventional air-conditioning systems and known as liquid-to-air membrane energy exchangers (LAMEEs) which proved to be capable of achieving significant energy savings when integrated with conventional air-conditioning systems [14–20]. In the ceiling membrane system, the desiccant solution entered at a relatively low temperature to provide cooling while picking up the moisture from the vicinity of the membrane [19,20]. The integrated desiccant membrane cooled ceiling and displacement ventilation system (LDMC-C/DV) resolved the problem of condensation and allowed lower ceiling operating temperatures [20]. Such low ceiling temperature cannot normally be used in conventional CC/DV systems due to the condensation risk. The LDMC-C/DV system succeeded in providing comfortable indoor conditions for a certain range of DV supply air temperature and humidity [20]. However, the dehumidification in the membrane system occurred at the ceiling level only. Thus, if the system is not equipped with a control strategy for the humidity content of the DV supply air, moisture accumulation can build up in the occupied zone jeopardizing the thermal comfort of the occupants. An indoor relative humidity that exceeds 70% can lead to a sensation that the skin is "wet and sticky" [21]. Moreover, elevated moisture levels within the occupied zone can induce mold growth, respiratory problems, corrosion and chemical deterioration of the building materials [22,23]. Therefore, it is of interest to find a strategy that allows the integrated LDMC-C/DV system to control the indoor humidity in order to extend its applicability to cover the extreme outdoor environmental conditions.

Researchers have used various strategies to dehumidify the air outside the space. A typical dehumidification method in DV systems is to cool the supply air to below its dew point temperature to remove the moisture via condensation [23,24]. The air is subsequently re-heated to the desired supply temperature to the occupied zone [25]. This method is an energy intensive technique [26]. Another well-known dehumidification strategy is the use of solid desiccant in the DV supply stream [27,28]. However, this technique adds complexity to the system and requires energy. Liquid desiccant systems tower beds have also been considered to efficiently dehumidify the supply air outside the space [29,30]. The liquid desiccant system is often integrated with a sustainable energy source which reduces the system energy demand [31]. However the problem with liquid desiccant tower beds is the direct contact between the supply air and the hazardous desiccant that can lead to potential health issues [32].

In LDMC-C/DV systems, the dehumidification takes place near the ceiling and has no direct effect on the humidity in the lower zone since the cool dry adjacent to the ceiling is exhausted. To take advantage of this fact, a fraction of the dry and cool exhaust air could be mixed with the DV supply air when outdoor conditions are humid. This simplified technique can result in reducing the humidity in the supply stream which subsequently would lead to a drop in the relative humidity in the occupied zone inside the space. The main advantage of this technique is basically the reduction in energy consumption and the compactness of the system compared to other dehumidifying techniques [33,34]. Chakroun et al. [35] used this procedure of mixing exhaust cool air with outdoor supply air in conventional CC/DV and reported energy savings of up to 20.6% compared to the case of the 100% fresh air DV supply. However, this technique is constrained by the maximum allowed CO_2 concentration needed for good IAQ in the occupied zone [36] which must not exceed the recommended ASHRAE standards [37]. Consequently, for non-humid conditions, no mixing is needed between the exhaust and supply air, and the IAQ would be maintained by the DV system, while in extreme humid conditions, a fraction of the dry and cool exhaust air are mixed with the supply air in LDMC-C/DV system.

Therefore, the objective of this work is to propose a humidity control strategy based on mixing the exhaust dry cool air with the supply fresh air in LDMC-C/DV conditioned spaces. A transient model of the integrated LDMC-C/DV system is developed based on Hout et al. steady state model [20]. The model incorporates the changing supply and exhaust conditions during the implementation of the mixing strategy and is composed of the space model and the membrane boundary layer model. The transient membrane boundary layer model is validated experimentally. The integrated model is applied to a case study of an office space in Beirut during humid summer conditions. The effectiveness of the humidity control strategy in LDMC-C/DV system and the associated energy savings are then evaluated in comparison with the