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Model-based optimal control of a dedicated outdoor air-chilled ceiling system using liquid desiccant and membrane-based total heat recovery

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ABSTRACT

This study presents a model-based control strategy for a novel dedicated outdoor air-chilled ceiling (DOAS-CC) system with the aim of optimizing the overall system performance. The DOAS-CC system incorporates liquid desiccant dehumidification and membrane-based total heat recovery technologies. Simplified but reliable models of major components in the DOAS-CC system are firstly developed to predict the system performance. A cost function is then constructed to minimize total energy consumption while properly maintaining thermal comfort reflected by indoor air temperature and relative humidity. Genetic algorithm is used to search for optimal set-points of the supply air temperature and humidity ratio of the dedicated outdoor air subsystem as well as the supply water temperature. The performance of this strategy is tested and evaluated with different control settings in a simulated multi-zone space served by the DOAS-CC system under various weather conditions. The results show that optimized control variables produced by the optimal strategy can improve the system energy performance and maintain indoor thermal comfort.

1. Introduction

Dedicated outdoor air-chilled ceiling (DOAS-CC) system, as an alternative air conditioning manner, has been widely investigated and successfully utilized in Europe [1,2], America [3,4], Asian countries [5–7] and other places [8] in the last decade. There are increased interests in this system in recent years, since it can achieve independent control of indoor air temperature and humidity, provide more effective ventilation, prevent virus and bacteria transmission among different zones, etc. Compared with conventional air-conditioning schemes, the DOAS-CC system can improve indoor thermal comfort and indoor air quality as well as save energy, especially when adopting some new technologies, such as total heat recovery [9,10] and liquid desiccant dehumidification [11,12]. This paper proposes a novel DOAS-CC system incorporating liquid desiccant dehumidification and total heat recovery technologies.

Robust control is prerequisite for reliable operation of air-conditioning systems besides proper design and maintenance. It also has significant impacts on energy use as well as occupants' comfort, healthy and productivity. During the last decade, a great deal of research has been carried out on the control issues of the DOAS-CC systems or similar systems. For instance, Lim et al. [13] presented two control methods for indoor temperature control in a single room served by a radiant cooling system, i.e. modulation of the supply water temperature and of the supply water flow rate in the radiant cooling panels respectively. Mumma and Jeong [14,15] investigated the control method for a single-zone DOAS-CC system. In the research, dual wheels (i.e. enthalpy wheel and sensible wheel) and a cooling coil in the DOAS subsystem were adopted for indoor air humidity control, while the supply water flow rate of chilled ceiling was regulated for indoor air temperature control. Liu et al. [11] employed a liquid desiccant system for independent control of the supply air humidity in an air-conditioning system. Capozzoli et al. [16] presented two hybrid air-conditioning systems with chemical dehumidification for supply air humidity control in supermarket applications. Xiao et al. [17] studied control strategies and control performance of a liquid desiccant system for independently supply air temperature and humidity control. Most of previous studies on control of DOAS-CC systems and liquid desiccant based air-conditioning systems focused on local control, i.e. how to effectively maintain a variable at its set-point; but rarely concerned about the selection of set-points to achieve optimal performance of the entire system. This may be attributed to the limited understanding of characteristics of the entire system even though individual components in such a system is well understood. Projects adopting DOAS-CC systems integrated with liquid desiccant dehumidification increase rapidly in recent years. It is the critical time to study optimal control of such systems during their operations.

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Nomenclature

c_p	air specific heat (kJ/kg °C)
c_{pw}	specific heat of water (kJ/kg °C)
C	solution concentration (%)
D	moisture load (kg/s)
h	enthalpy (kJ/kg)
J	cost function
m	mass flow rate (kg/s)
M	air mass (kg)
P	pressure of water vapor (Pa)
Q	heat transfer rate (kW)
Q_{CC}	heat flow extracted by the chilled ceiling panel (kW)
RH	relative humidity (%)
t	time (s)
T	temperature (°C)
UA	heat transfer coefficient (kW/K)
v	air volumetric flow rate (m^3/s)
w	air humidity ratio (kg/kg)
W	power consumption (kW)
Greek symbols	
α	weighting factor or mass transfer effectiveness
β	heat transfer effectiveness
ε	effectiveness
λ	model parameter
φ, γ	coefficients
Δ	interval
Superscripts	
k	current sampling step
$k-1$	previous sampling step
Subscripts	
a	air
deh	dehumidifier
ex	exhaust air
E	energy
f	outdoor air
i	the *i*th zone
in	inlet
L	latent
max	maximum
out	outlet
rgn	regenerator
s	solution
sen	sensible
S	sensible
w	water

Optimal control has been widely studied in conventional air-conditioning systems. Wang and Jin [18] proposed a model-based optimal control strategy for variable air volume (VAV) systems. In the study, three variables, i.e. supply air temperature of air handling unit, outdoor ventilation flow rate and chilled water temperature, were optimized by genetic algorithm (GA). The results showed that the optimal strategy was capable of optimizing the system overall performance. Xu et al. [19] presented an optimal ventilation control strategy for a multi-zone VAV air-conditioning system. The temperature set-point of the critical zone was optimized to reduce the required outdoor air fraction, hence to reduce the total outdoor air flow rate and the system energy consumption. The results illustrated that the optimal strategy could achieve about 4% of energy saving and maintained acceptable thermal comfort and indoor air quality. Chow et al. [20,21], Ma and Wang [22], Chang [23], etc. studied the system-based optimization approaches for chiller plant implementations. For instance, Chow et al. [20] introduced a new concept of integrating neural network and genetic algorithm in the optimal control of absorption chiller system. The chilled and cooling water mass flow, the chilled water supply temperature, and the cooling water return temperature were optimized in the system. It was concluded that more energy saving could be achieved when more control variables were brought in the optimal control strategy. The results obtained from above mentioned studies demonstrate that system overall performance can be improved when optimal control is implemented in the air-conditioning systems, since the set-points of control variables are optimized and reset during operation to follow dynamic operating conditions. Meanwhile, model-based optimization method is effective.

Considering that reliable models, either complicated numerical models or simplified models, of the major components including chilled ceiling [2,24], liquid desiccant dehumidifier and regenerator [25–27] as well as the membrane-based total heat exchanger [10] are available at present, this study develops a model-based optimal control strategy for the integrated DOAS-CC systems to optimize the overall system energy performance and indoor thermal comfort. The performance of this strategy is tested and evaluated in a simulated multi-zone space under various operating conditions.

2. Description of the air-conditioning system and testing facility

The prototype of the investigated building is a commercial building located in South China. The usable floor area is about 302 m^2. It is divided into five zones. Four of them, i.e. Zone 1–3 and Zone 5, are perimeter zones and Zone 4 is an interior zone, as shown in Fig. 1. The function and area of each zone are shown in Table 1.

Thickness of the external wall of the building is 163 mm and the heat transmission coefficient U-value for the opaque part of the façade is 1.506 W/(m^2 K). Insulating glazing windows having a U-value of 2.83 W/(m^2 K) is used. Blinds are installed for shading. The floor to ceiling height of the conditioned space is 2.7 m and the area ratio of window to wall is 40% for external walls. In the open space, about 50% of the ceiling is covered by chilled ceiling panels. The design occupant numbers of the five zones are 5, 2, 1, 13, and 56 persons, respectively.

Fig. 2 shows the schematic of the whole DOAS-CC system studied. In the integrated system as illustrated in Fig. 2a, the DOAS subsystem is responsible for satisfying ventilation demand and removing the moisture load of the conditioned space. The outdoor air flow rate from the DOAS can be either fixed or regulated by demand controlled ventilation strategy. A membrane-based total heat exchanger is employed to recover the energy of exhaust air and improve the system energy efficiency, since such heat exchangers have a number of advantages, including higher effectiveness, no cross contamination, no moving parts, and lower pressure drops [28,29]. A liquid dehumidifier is used to dehumidify the humid outdoor air to the supply air humidity ratio set-point ($\omega_{sup,sp}$), which can be constant or determined by optimization strategy. The dry cooling coil after the dehumidifier is used to cool down the supply air to a comfort level, i.e. 19 °C in this study. The supply fan and the return fan run at variable speeds. The supply fan is modulated to maintain the supply air static pressure, and the