Optimal control strategy of air-conditioning systems of buildings requiring strict humidity control

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ABSTRACT

This paper presents a model-based optimal control strategy for multi-zone air-conditioning systems with strict humidity control. An adaptive full-range decoupled ventilation strategy is adopted for optimizing the set point of the outdoor air flow rate to minimize the energy cost as well as to achieve the temperature and humidity controls. Tests were conducted to evaluate the energy performance of the proposed control strategy. The results show that the proposed optimal control strategy can reduce energy consumption significantly, while maintaining a satisfactory indoor thermal environment.

KEYWORDS

Dedicated ventilation, adaptive full-range decoupled ventilation, strict humidity control, optimal control, air-conditioning system.

1 INTRODUCTION

The energy consumption of buildings has increased rapidly in recent years, which is responsible for approximately 40% of the total world annual energy consumption (Omer, 2008). For the buildings with strict space temperature and humidity control, such as hospitals, manufacturing facilities, pharmaceutical clean rooms, semiconductor factories, etc., the energy intensities of heating, ventilation, and air conditioning (HVAC) systems can be 4-50 times greater than the average commercial building(Khoo, Lee, & Hu, 2012; Kircher, Shi, Patil, & Zhang, 2010; Mills et al., 2008). In such applications, appropriate ventilation strategy of HVAC system is very important, since it can directly influence both the environmental control performance and the energy performance.

Latent load accounts for 30-50% of the total thermal load in buildings(Jiang, Ge, Wang, & Huang, 2014). So far, the most common method to remove indoor humidity is to employ counteraction processes(Wu, Johnson, & Akbarzadeh, 1997), named as "interactive control"(IR), which handle latent load by cooling down the air below its dew point (12-15°C) and then reheat supply air to the required air temperature. A large amount of energy is wasted during the counteraction processes. The most popular solution is to fully decouple the dehumidification and cooling process, also named as "dedicated outdoor air ventilation strategy" (DV) , adopting the strategies, such as combined use of make-up air-handling units (MAUs) and air-handling units (AHUs) (Li, Lee, & Jia, 2016), the two-chilled water temperature system(Tsao, Hu, Chan, Hsu, & Lee, 2008), desiccant technologies(Xiao, Ge, & Niu, 2011), etc. Nevertheless, these control strategies may need high energy consumption for outdoor air treatment or higher initial costs. The co-authors of this paper proposed a "partially decoupled control strategy" (PD) (Shan & Wang, 2017), which treats outdoor air with the minimum set-point of the required outdoor airflow, and achieves 69.6% of electricity and 87.8% of town gas consumptions savings.

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Though many studies investigated the control strategies for simultaneous temperature and humidity control, existing ventilation strategies still have their limitations under dynamic load and weather conditions. In this study, an "adaptive full-range decoupled ventilation strategy" (ADV strategy), which incorporates the advantages of the DV strategy and PD strategy with superior energy performance under different load and weather conditions, is proposed and validated in a pharmaceutical factory in Hong Kong.

2 CONCEPT OF ADAPTIVE FULL-RANGE DECOUPLED VENTILATION STRATEGY

As described and compared above, all three most updated existing ventilation strategies have different limitations in applications. A novel "adaptive full-range decoupled ventilation strategy" (ADV) is therefore developed to overcome these limitations and minimize the energy consumption by compromising properly "inducing more outdoor air" and "sub-cooling and reheating process with minimum outdoor airflow" under high internal latent load conditions. A typical air-conditioning subsystem configuration, i.e. a blow-through type MAU and a draw-through AHU served for multi zones, is selected as shown in Fig. 1. The MAU consists of filters, a centrifugal fan and a cooling coil for treating the outdoor air. The AHU contains filters, a cooling coil, a heater and an axial fan for conditioning the total supply air. The chilled water is supplied by a chiller plant to both MAU and AHU cooling coils.

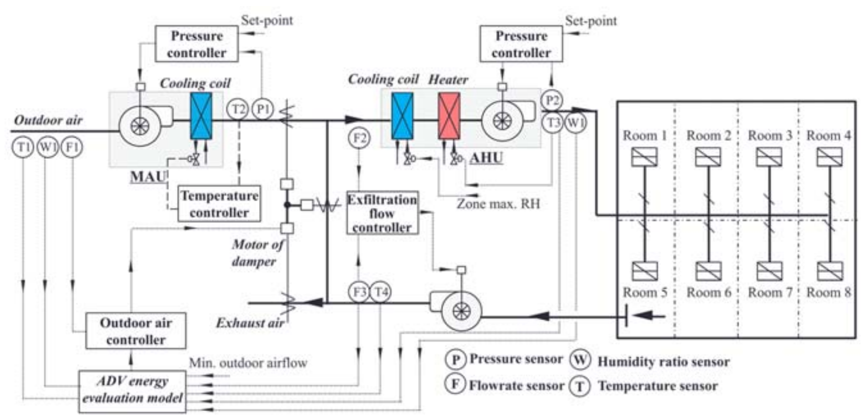

Fig. 1 System configuration of a typical air-conditioning system

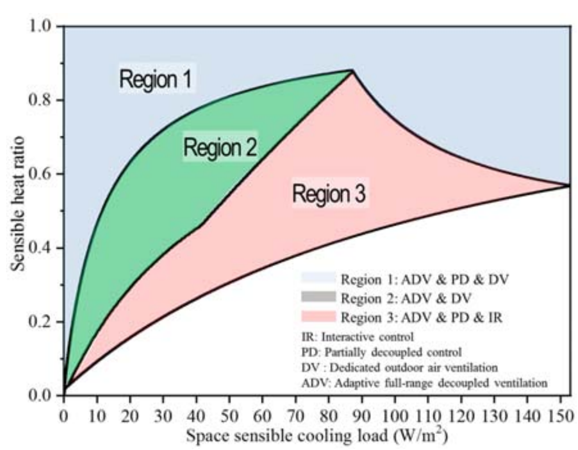

Fig. 2 Preferred ventilation mode/strategies in different internal load regions under Hong Kong design weather condition

The energy performance of different strategies is compared under Hong Kong design weather condition (i.e., 29.1 °C, 84.4%)(ASHRAE Handbook, 2015). As shown in Fig. 2, in Region 1, the proposed ADV strategy, as well as the PD and DV strategies, have the superior energy performance compared with the IR strategy, where space has comparatively high sensible heat ratio. In Region 2, the proposed ADV strategy and the DV strategy have the superior energy performance compared with the other two strategies, where space has medium sensible heat ratio. In Region 3, the proposed ADV strategy, as well as the IR and PD strategies, are the superior options, where space has a low sensible heat ratio.

3 TEST SYSTEM SET-UP

A dynamic simulation platform is built to test the ventilation strategy using TRNSYS 18. This test platform employs detailed physical models including the building envelope and major components (e.g. hydraulic network, MAUs, AHUs, etc.) of a multi-zone air-conditioning system. The dynamic processes of heat transfer, hydraulic characteristics, flow balance, energy conservation and controls among the whole system are simulated (Wang, 1999). An adaptive outdoor airflow controller is used for optimizing the set point of the outdoor air flow rate by using the ADV energy evaluation models.

3.1 Incremental source terms of all the zones

In the optimization process, both the building sensible cooling load and latent load are needed to know in advance to predict the air state of the indoor space for system performance prediction. These loads cannot be measured directly. However, they can be estimated based on measurements. For each zone, the heat and moisture balance can be expressed as Eqs. (1)–(2), respectively. Sensible heat load ($Q_{sen,\,i}$) and moisture load (D_i) are also called source terms since they are the driving forces in these equations. In a prediction period, these three source terms can be considered to be constant and can be computed during a sampling step as Eqs. (3)–(4).

$$M_i c_p \frac{dT_i}{dt} = m_{s,i} c_p (T_s - T_i) + Q_{sen,i} \tag{1}$$

$$M_i \frac{dG_i}{dt} = m_{s,i} (G_s - G_i) + D_i \tag{2}$$

$$Q_{sen,i}^k = M_i c_p \frac{T_i^k - T_i^{k-1}}{\Delta t_{smp}} - m_{s,i}^k c_p (T_s^k - T_i^k) \tag{3}$$

$$D_i^k = M_i \frac{G_i^k - G_i^{k-1}}{\Delta t_{smp}} - m_{s,i}^k (G_s^k - G_i^k) \tag{4}$$

where M is the air mass of one space, T is temperature, G is the moisture content, D is the moisture, respectively, c_p is air specific heat, Δt_{smp} is the sampling interval, k indicates the current sampling time.

3.2 Energy evaluation models

With the predicted total supply air state, the energy evaluation models are then predicted according to the working principles of the ADV strategy.
The energy evaluation models include the sum of energy consumption of the coil, heater and fan as shown in Eqs.(5)-(8). The energy uses of the air-side components are evaluated using the enthalpy difference between the inlet and outlet.

$$W_{cc,MAU} = \frac{m_{outdoor,set}{}^{k}(H_{outdoor}{}^{k} - H_{outlet,MAU}{}^{k})}{COP_c} \quad (5)$$

$$W_{cc,AHU} = \frac{m_{sup}{}^{k}(H_{inlet,cc,AHU}{}^{k} - H_{outlet,cc,AHU}{}^{k})}{COP_c} \quad (6)$$

$$W_{heater,AHU} = \frac{m_{sup}{}^{k}(H_{outlet,cc,AHU}{}^{k} - H_{outlet,hc,MAU}{}^{k})}{COP_h} \quad (7)$$

$$W_{fan} = c_0 + c_1 \cdot m_{outdoor,set} + c_2 \cdot m_{outdoor,set}^2 + c_3 \cdot m_{outdoor,set}^3 \quad (8)$$

Where W is energy use, H is enthalpy, COP is the overall coefficient of performance including the pump and the chiller/heat pump, the parameters c_0-c_3 were obtained using the fan performance data.

The COP of chillers/heat pumps can be modeled as Eqs. (9)-(10) since the effect of condenser temperature change can be neglected when simulating the effects of control setting within a prediction period. The reference COP_{ref} is obtained from the measured cooling load and the chiller power consumption. $T_{w,ref}$ is the measured supply chilled water temperature at a sampling instant used as a reference temperature.

$$COP = COP_{ref}[1 + \Phi(T_{w,in} - T_{w,ref})] \quad (9)$$

$$COP_{ref}^{k} = COP_{chil/hp}^{k} / W_{chil/hp}^{k} \quad (10)$$

A pharmaceutical factory building located in Hong Kong, a humid sub-tropical city, is selected for the case study. It has 4 floors with a total height of around 23 m and a gross floor area of about 9000 m^2. All production areas are Class ISO 8 cleanrooms based on ISO 14644-1 cleanroom standards(International Organization for Standardization (ISO): Geneva & Switzerland, 2015). The cleanrooms have strict requirements on dry bulb temperature (20 ±3°C), relative humidity (55 ±10%) and air change per hour (>20ACH).

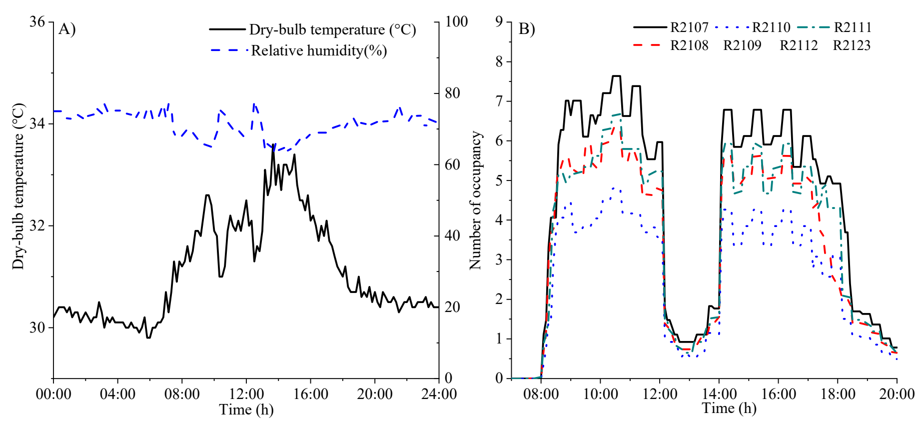

Fig. 3. A) Weather condition B) occupancy profiles of zones of the selected day

Fig. 3(A) shows the outdoor air dry-bulb temperature and relative humidity in a selected summer day (11 Aug 2017). The air temperature on the day varied between 29.8 and 33.6 ℃ while the relative humidity varied between 63% and 78%. This is a typical hot and humid summer day in Hong Kong. The occupancy profiles of all zones are presented in Fig. 3(B). The number of occupancy in the zones varied significantly to generate dynamic sensible and latent heat to the cooling and ventilation systems.

4 RESULTS

Fig. 4 illustrates the outdoor air flowrate adopting PD, DV and ADV strategies. From 8:30 to 10:00 when the energy estimator estimated that inducing more outdoor airflow to remove all indoor moisture load is economical, the outdoor airflow of adopting ADV strategy follows the same trend as DV method. From 10:00 to 12:00 when the energy estimator estimated that inducing more outdoor airflow to remove all indoor moisture load may consume more energy than 'overcooling and reheating process' with minimum outdoor airflow, the outdoor airflow of adopting the ADV strategy follows the same trend as the PD strategy. It can be found the ADV strategy can successfully and smoothly shift from one mode to another while all room temperature and relative humidity can also be controlled in the required range as shown in Fig. 5.

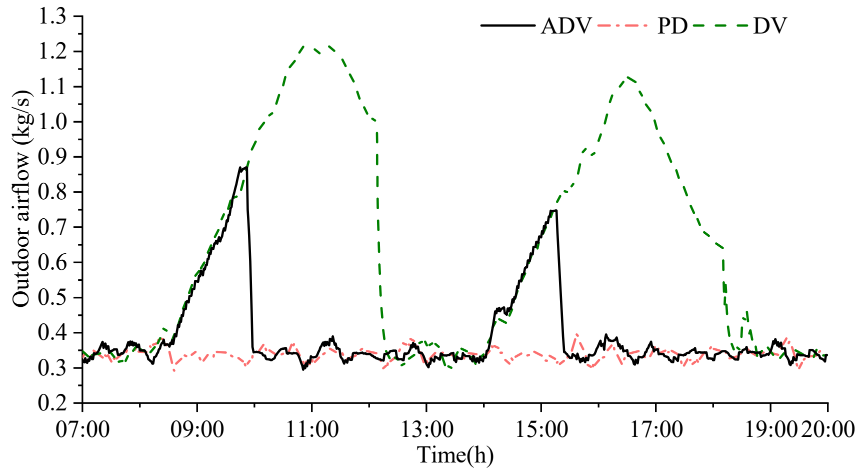

Fig. 4. Outdoor airflow rate using PD, DV and ADV strategy

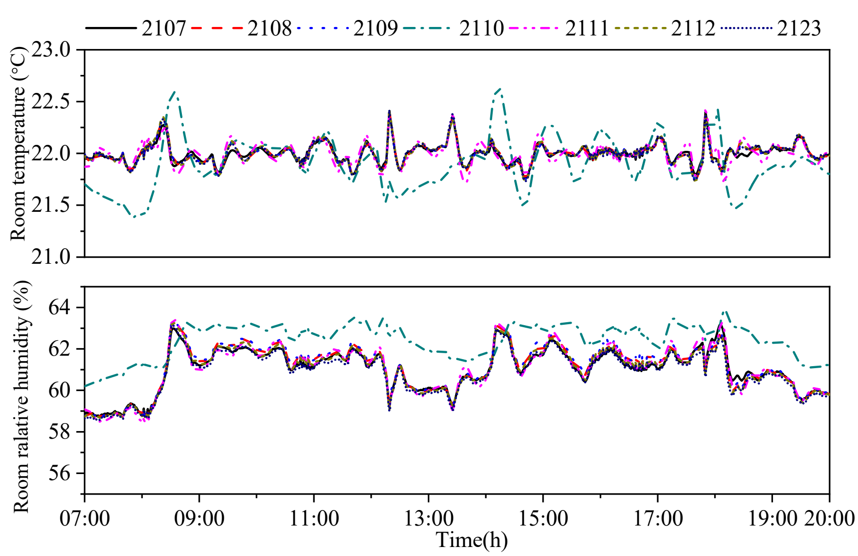

Fig. 5. Room temperature and relative humidity using ADV strategy

The energy consumptions when using the PD, DV and ADV strategies are compared in Table 1. The table shows the energy consumptions of the cooling coils, fans and the heater, as well as the total energy consumption of the entire air-conditioning system. Compared with that using PD strategy and DV strategy, the percentage saving of the system total energy consumption adopting ADV strategy was 2.84% and 13.57% respectively. It should be noted that the energy performance of different ventilation strategies was compared under a typical summer day, if the outdoor weather enthalpy decreases, the energy saving rate of using the ADV strategy is expected to achieve a higher energy saving rate compared with PD strategy.

Table 1: Energy consumptions when using different strategies in a typical summer day

Energy use results	**PD**	**DV**	**ADV**
Supply fan consumption (kWh)	166.70	166.69	166.73
Return fan consumption (kWh)	144.22	155.10	147.80
Make-up Fan consumption (kWh)	64.38	142.72	76.79
Cooling coil consumption of PAU(MJ)	266.81	763.09	436.11
Cooling coil consumption of AHU(MJ)	728.08	400.26	548.25
Heater consumption of AHU(kWh)	152.43	0.00	44.94
Overall energy consumption (kWh)	528.19	593.77	513.18
Overall percentage saving (%)	**-2.84%**	**-13.57%**	**-**

5 CONCLUSIONS

An adaptive full-range decoupled ventilation strategy(ADV) is tested and evaluated in a simulated platform under dynamic load and weather conditions. Compared with conventional strategies (i.e., dedicated outdoor air ventilation strategy(DV), partially decoupled control strategy(PD)”), results showed the proposed strategy can achieve significant energy saving while maintaining an acceptable indoor environment for the air-conditioning system requiring strict humidity control.

6 ACKNOWLEDGEMENTS

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