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Evaluation of four control strategies for building VAV air-conditioning systems

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ABSTRACT

It is necessary to adopt appropriate control strategies to save energy and improve the indoor air quality (IAQ). On the validated TRNSYS simulation platform, four different control strategies are investigated to examine the indoor air temperature, energy consumption, CO_2 concentration and predicted mean vote (PMV) for the variable air volume (VAV) systems in an office building in Shanghai. As an original scheme, Strategy A using constant outdoor air intake fraction shows high energy consumption, low CO_2 concentration and acceptable thermal comfort. By using minimum outdoor air ventilation based on dynamic occupancy detection, Strategy B can provide more than 15% energy saving, acceptable PMV value but high CO_2 concentration in breathing zone. By using indoor air temperature reset, Strategy C presents the most energy savings beyond 20% reduction, low CO_2 concentration but poor thermal comfort. In mild seasons, combining enthalpy-based outdoor airflow economizer cycle with supply air temperature reset, Strategy D can achieve 9.4% energy savings and the lowest CO_2 concentration. Taken together, each strategy covers some strengths as well as some weaknesses. How to comprehensively assess a control strategy for all specific objectives should be considered in future studies.

1. Introduction

Since the ventilation control at zone level is one of the key factors affecting energy usage and indoor air quality, VAV systems are used for many large buildings to deliver an appropriate amount of supply air. The energy consumption for VAV system is chiefly associated with the thermal loads (cooling or heating) and the power to deliver these loads. Of course, the waterside power energy determined by the airside thermal load will indirectly influence the chiller energy consumption. For saving energy and improving IAQ, some strategies are developed to achieve the minimum outdoor air ventilation, to increase the supply air temperature, or to raise the indoor air temperature set point. More than six categories of strategies have been proposed in the recent works.

1.1. Fixed outdoor air damper

Fixed outdoor air damper with a minimum position is commonly used to meet the requirement of minimum outdoor air flow rate in VAV systems. With the decrease of supply air flow rate, however, outdoor air flow rate will drop directly because of a fixed outdoor air damper position. Effects of supply air flow rate on outdoor air flow rate are approximately linear [1]. Since the heating, ventilation and air-conditioning (HVAC) system in large buildings operates at part-load conditions frequently, the ventilation strategy of maintaining a constant outdoor air intake fraction always leads to far lower outdoor air flow rates than the minimum demand stipulated in ASHRAE standard. By using outdoor air intake based on the unfavorable zone requirement [2], a strategy was proposed to apply in VAV systems. This strategy is different from the constant outdoor air flow rate based on total outdoor air requirement and on constant air intake fraction.

1.2. Minimum outdoor air flow rates

Cho and Liu [3] proposed an applicable terminal-box control algorithm using minimum airflow reset to avoid inappropriate operation control functions associated with occupant discomfort and energy wasting in conventional strategies. Also, the dedicated minimum ventilation damper with pressure control is a recommended method to dynamically control the minimum outdoor air flow rates in VAV systems [1].

1.3. Demand controlled ventilation (DCV) methods

Although CO_2-based DCV has been proposed and investigated in many literatures [4–6], there are several problems in practical application. As an energy-saving strategy, in some cases, CO_2-based DCV may sacrifice other core design objectives including occupant health, productivity and even the threats to building structure's long-term integrity. Energy benefits can be realized by implementing a DCV strategy, if the number of occupants and the actual

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Nomenclature

Symbols

A	total occupied floor area (m^2)
C	CO_2 concentration (ppm)
E	energy consumption (kWh)
h	specific enthalpy (kJ/kg)
P	total number of occupants (person)
Q	cooling loads (kW)
R	outdoor air flow rate ($m^3/(s\,m^2)$)
RE	relative energy consumption
S	CO_2 generation rate per person (10^{-6} m^3/(s person))
t	dry-bulb temperature (°C)
v	air flow rate (m^3/s)
V	total net occupied floor volume (m^3)
W	humidity ratio (kg water/kg dry air)
Z	zone outdoor air fraction
Δt	sampling interval (s)

Greek letters

ρ	air density (kg/m^3)

Subscripts

a	area
i	zone number
min	minimum
o	outdoor air
oz	outdoor air for a zone
p	primary
pz	primary air for a zone
P	person
r	return air
s	supply air
set	set point

Superscripts

i	current sampling time
$i-1$	previous sampling time

Acronyms

AHU	air handling unit
DCV	demand controlled ventilation
HVAC	heating, ventilation and air-conditioning
IAQ	indoor air quality
PMV	predicted mean vote
VAV	variable air volume

ventilation rate can be determined with a reasonable degree of accuracy; and if building pressure can be maintained simultaneously [7]. Furthermore, CO_2-DCV application should be limited to those spaces with high-density, unpredictably, variable or intermittent occupancy. In addition, CO_2-DCV strategy can be used only in the presence of a reliable method to maintain a continuous base ventilation rate while preserving a minimum pressurization flow. To overcome these difficulties when DCV control is combined with economizer control, Wang and Xu [8] developed a robust control strategy with “freezing”, gain scheduling, integral term reset and feedback transition control for different transition processes.

1.4. Minimum static pressure drop

Discharge and recirculation air dampers always keep fully opening during the occupied times. For the economizer with outdoor, discharge and recirculation air dampers, an improved operating strategy called split-signal damper control strategy [9], can provide minimum static pressure drop in economizer dampers and be extremely effective at reducing the energy consumption of return and supply fans. Compared with the existing three-couple and two-couple dampers, the improved economizer damper can save 5% annual energy at least. Another example is a method of the integrated damper and pressure reset [10]. For static pressure set point reset according to the zone demand, however, the control logic is difficult to implement because of the highly interactive relationship between duct static pressure and damper position [11]. Also, it was found that Trim and Respond logic is a more effective approach in comparison with PID logic [11].

1.5. Supply air temperature reset

The supply air temperature reset applications [12–15] showed some favorable benefits in reducing power energy, reheating of cold primary air, outdoor air flow rates and the consequent humidification. By collecting occupants' requests for the air temperature from their own personal computers and by balancing occupants' requirements and energy consumption, an interactive system using a variety of feedback to control air-conditioning system can save beyond 20% energy at a constant indoor air temperature set point of 26 °C during the summer cooling period [12]. The risk of great increase in power requirement is relatively small if supply air temperature is lower than the optimum. On the contrary, higher supply air temperature may result in relatively higher power consumption.

1.6. Combining strategies

Mossolly et al. [16] proposed two strategies. One was to adjust supply air temperature and outdoor air flow rate to ensure the acceptable IAQ. The other was to modulate supply air temperature, supply air flow rate and outdoor air intake fraction to provide an acceptable thermal comfort and IAQ in each zone. Compared with the conventional control strategy based on the fixed supply air temperature, the proposed strategies not only enhanced the thermal comfort and IAQ, but also reduced the operational cost by 11% for the first strategy and 30.4% for the second.

Xu et al. [17] presented a strategy with two schemes. One dynamically corrected the total outdoor air flow rates by utilizing the unpolluted outdoor air from the over-ventilation zone. The other optimized the temperature set point for the critical zones to reduce the variation of the required outdoor air fractions among all zones. Two schemes were combined to reduce the total outdoor air volume for energy conservation.

1.7. Other strategies or methods

There are three other strategies or methods. One is based on CO_2 or other pollutants emission. The ventilation rates, which are mostly determined by pollution emission, have substantial effects on the annual building loads. Thus, it is very important to reduce the pollution emission from building material and other sources [18]. Chao and Hu [19] developed a dual-mode control ventilation strategy, namely CO_2 sensor control and non-occupant-related indoor contaminants control, to decrease CO_2 or other pollutants emission. The other strategy adopted free cooling such as natural ventilation. Outdoor air flow rates during the evening and early morning hours are higher than those of the occupied hours [20]. This free cooling strategy could increase the chilled water temperature and result in approximate 20% savings in energy consumption. The third strategy used high air velocity to improve the thermal comfort. From the thermal comfort concept, it can be seen that if higher air velocity is provided, less cooling power is required to maintain PMV values in the desired range [21].