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Optimal control of combined air conditioning system with variable refrigerant flow and variable air volume for energy saving

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ABSTRACT

An optimal control strategy for minimizing the energy consumption of variable refrigerant flow (VRF) and variable air volume (VAV) combined air conditioning systems was presented. The combined system was proposed to take advantages of VAV systems to solve the ventilation problem of VRF systems. The VAV part consists of an outdoor air processing unit and air supply and distribution devices. To determine set-point of the optimal control variable, i.e. outdoor air supply temperature, this paper proposed an optimal control strategy based on adaptive predictive model and recursive least squares estimation technique. Typical days in summer and winter were selected to test the strategy. Results indicated that the optimal control strategy reduces energy consumption of the combined system by 32.17% in summer and 2.47% in winter. The overall energy efficiency is enlarged by 12.18% in summer and 3.37% in winter, compared with the benchmark operation strategy.

Régulation optimale d'un système de conditionnement d'air combiné avec débit variable de frigorigène et volume d'air variable pour économiser l'énergie

Mots clés : Système de conditionnement d'air combiné ; Débit variable de frigorigène ; Volume variable d'air ; Régulation optimale ; Facteur de charge

1. Introduction

As people spend more and more time in buildings today, thermal comfort and indoor air quality (IAQ) are becoming essential requirements of the heating, ventilating and air-conditioning (HVAC) systems. However, comfortable indoor environment is paid by large quantity of energy. On the other hand, the energy crisis arouses worldwide attentions to

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Nomenclature

HVAC	Heating, ventilating and air-conditioning
VRF	Variable refrigerant flow
VAV	Variable air volume
IDU	Indoor unit
OAP	Outdoor air processing
IAQ	Indoor air quality
DX	Direct expansion
OA	Outdoor air
EEV	Electronic expansion valve
PLR	Part load ratio, W W^{-1}
RTF	Run time fraction
PLF	Part load factor
EIR	Energy input ratio, W^{-1} W
COP	Coefficient of performance, W W^{-1}
LR	Load ratio, W W^{-1}
M	Mass, kg
m	Mass flow rate, kg s^{-1}
V	Volume, m^3
v	Volumetric flow rate, m^3 s^{-1}
T	Temperature, °C
$\dot{Q}$	Heat, W
D	Humidity load, kg s^{-1}
w	Humidity ratio, kg kg^{-1} (dry air)
c_p	Specific heat capacity, J kg^{-1} K^{-1}
C	CO_2 concentration, ppm
G	CO_2 emission rate of people, L s^{-1}
P	Number of occupants
n	Compressor speed, rpm
W	Input power, W

Greeks

η	Efficiency of the reheater
τ	Time, s

Subscripts

com	compressor
fan	supply fan
sys	combined system
i	ith air conditioned zone
s	supply air
c	condensing
e	evaporating
db	dry bulb
wb	wet bulb
meas	measurement
set	set-point
ref	reference value

develop methods for reducing energy consumption of the HVAC systems, which are reported to consume as much as 40% of the energy consumption of the buildings (Chua et al., 2013). HVAC engineers have spent many efforts for designing new types of air conditioning systems, or developing advanced control strategies to reduce energy consumption while maintaining acceptable thermal comfort and IAQ (Freire et al., 2008; Sun et al., 2011; Lu et al., 2011). Among all the endeavors, variable refrigerant flow (VRF) air conditioning system has earned a wide popularity in both commercial and residential buildings, due mostly to the better part-load efficiency and the individualized thermal comfort control capability (Zhou et al., 2007; Liu and Hong, 2010; Aynur et al., 2009). Several studies about the VRF systems, from designing and field testing, to steady state and dynamic modeling, to energy and control simulation, have been conducted in recent years. Readers are encouraged to consult (Afify, 2008; Kwon et al., 2012; Shi et al., 2003; Shao et al., 2008; Li et al., 2009; Shen and Rice, 2012; Chen et al., 2005; Shah et al., 2004; Elliott et al., 2011) for a more detailed discussion of these topics. HVAC system designers who are used to adopt water-source heat pump loops, two- or four-pipe fan-coil networks and other all air systems, are now considering VRF systems. However, one of the shortcomings having not been solved thoroughly is that the VRF system cannot ensure IAQ since it does not induce outdoor air (OA) (Goetzler, 2007; Aynur et al., 2010). However, a number of studies have demonstrated the importance of ventilation to health outcomes (sick building syndrome symptoms, respiratory illnesses), absence rates, and perceived indoor air quality (Seppanen et al., 1999; Wargocki et al., 2002). Therefore, the VRF system should be innovated to be able to provide ventilation air. However, it should be noticed that ventilation is also an important contributor of energy consumption particularly in highly occupied spaces. When one considers these factors together -the importance of ventilation on occupancy, the energy consumption of ventilation, and the evidence of ventilation deficiencies in VRF systems, it is very clear that there is a need to develop and promote better energy efficient systems for providing ventilation while simultaneously taking advantages of the VRF systems. Energy recovery ventilators are often used in conjunction with the VRF systems (Aynur et al., 2008a, 2008b; Li and Wu, 2010) aiming at overcoming the shortcoming. A schematic drawing of an energy recovery ventilator can be found in literature (Aynur et al., 2008a). This type of system provides OA while recovering energy from the exhaust air in order to reduce the ventilation loads (Quazia et al., 2007). However, the Energy recovery ventilator usually is not controllable for the OA flow rate (Abe et al., 2006), thus fixed rather than suitable OA flow rate is supplied to the air conditioning zone, and it often results in energy consumption increasing in parallel VRF system. Recently, a new air conditioning system combining VRF and VAV with continuous OA flow control (Zhu et al., 2014a, 2014b) is introduced to take advantages of VAV systems to solve the ventilation problem. In this combined system, the VAV part mainly consists of an outdoor air processing (OAP) unit and air supply and distribution devices. The OA is cooled and dehumidified in cooling mode while heated in heating mode before supplying into air conditioning spaces. Preliminary investigations found that the combined system could maintain all the air conditioning zones at their specific set-points within small errors no matter their set-points are the same or different, and no matter the number of operating indoor units changes or not (Zhu et al., 2014a). In addition, the combined system was found having