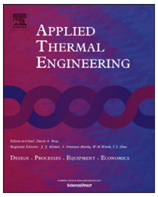
Applied Thermal Engineering 80 (2015) 87–96

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng



Research paper

Online optimal control of variable refrigerant flow and variable air volume combined air conditioning system for energy saving

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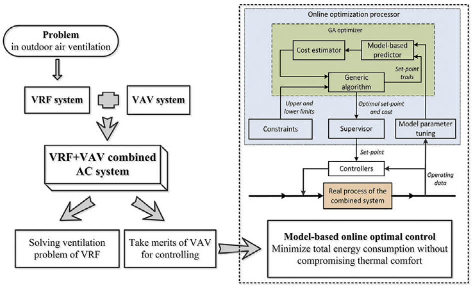
HIGHLIGHTS

- A VRF and VAV combined system is proposed.
- A model-based online optimal control strategy is proposed for the combined system.
- The strategy can reduce energy consumption without sacrificing thermal comfort.
- Novel simplified adaptive models are firstly developed for the VRF system.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 June 2014
Accepted 12 January 2015
Available online 21 January 2015

Keywords:
Combined air conditioning system
Variable refrigerant flow
Variable air volume
Optimal control
Adaptive model

ABSTRACT

The variable refrigerant flow (VRF) and variable air volume (VAV) combined air conditioning system can solve the problem of the VRF system in outdoor air ventilation while taking advantage of its high part load energy efficiency. Energy performance of the combined air conditioning system can also be optimized by joint control of both the VRF and the VAV parts. A model-based online optimal control strategy for the combined air conditioning system is presented. Simplified adaptive models of major components of the combined air conditioning system are firstly developed for predicting system performances. And a cost function in terms of energy consumption and thermal comfort is constructed. Genetic algorithm is used to search for the optimal control sets. The optimal control strategy is tested and evaluated through two case studies based on the simulation platform. Results show that the optimal strategy can effectively reduce energy consumption of the combined air conditioning system while maintaining acceptable thermal comfort.

1. Introduction

It is widely known that conventional central heating, ventilating and air-conditioning (HVAC) systems contribute large part, as much as 40% [1], to the total energy use of commercial buildings. And the energy demand is expected to continuously rise due to population growth. HVAC engineers are devoting more and more efforts in order to reduce energy use without compromising thermal comfort and indoor air quality (IAQ) [2–4]. These efforts include retrofitting operation and management of installed systems, developing advanced control strategies, and designing alternative HVAC systems. Recently, energy system assessment and optimization from the life cycle point of view [5,6] also earned much attention. On the other hand, among all the alternative HVAC systems, VRF systems have been attracting wide attentions since early 1980s. The VRF system owes benefits in installation, maintenance and

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http://dx.doi.org/10.1016/j.applthermaleng.2015.01.030
1359-4311/

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
COP	coefficient of performance
M	mass, kg
m	mass flow rate, kg/s
V	volume, m^3
v	volumetric flow rate, m^3/s
T	temperature, °C
Q	heat load, W
D	humidity load, kg/s
w	humidity ratio, kg/kg (DA)
c_p	specific heat capacity, J/kg K
C	CO_2 concentration, ppm
G	CO_2 emission rate of people, m^3/s
P	number of occupants
W	input power
t	time
Δt	time interval, s
N	estimation steps
Y	variable value
e	filter factor
UA	heat transfer coefficient,
Greeks	
$\alpha, \beta, \theta, \psi$	fitting factors
λ	forgetting factor
ε	weighting factor
Superscripts	
j	jth estimation step
k	kth prediction step
Subscripts	
a	air
i	ith air conditioned zone
s	supply air
w	input power
fan	supply fan
pred	prediction
crt	correction
est	estimation
meas	measurement
ref	reference value
cond	condensation
sen	sensible
in	inlet
out	outlet

commissioning due to the relatively simple structure. Duct losses in the VRF systems can be minimized due to the in-space installation of the indoor units (IDUs) [7]. Many studies about the VRF systems, including designing and field testing [8,9], steady state and dynamic modeling [10–13] and energy and control simulation [14,15], have been conducted in recent years. The VRF system was found having high energy efficiency under part load conditions, due partly to the modulation of the compressor speed to adapt to the load changing [16–18]. However, the shortcoming that the VRF system cannot provide outdoor air (OA) for ventilation has not been solved thoroughly [7], which presents a striking contrast to the wide application of the VRF systems. More attentions should be paid on solving this shortcoming nowadays since many studies [19,20] have demonstrated that ventilation has great impacts on health outcomes (e.g. sick building syndrome symptoms, respiratory illnesses), absence rates and productivity. On the other hand, ventilation is also an energy use contributor for processing and delivering the air especially in highly occupied spaces. When one considers these factors together – the importance of ventilation for occupants, the deficiency of ventilation in VRF systems, and the energy consumption of ventilation, it is very clear that there is urgent need to develop higher energy efficiency systems for providing ventilation while simultaneously taking advantages of the VRF systems.

However, still very few investigations can be retrieved about integration of VRF system with appropriate ventilation system up to date. Heat recovery ventilators are ventilation devices frequently adopted in combining with the VRF systems [21–23]. The OA flow rate usually is not controlled [24] though part of the energy can be recovered from the exhaust air. It often results in energy consumption increasing in the parallel VRF system particularly when the occupant number fluctuates dynamically. Recently, Jiang et al. [25] proposed a solid desiccant heat pump and VRF combined air conditioning system to form a temperature and humidity independent control system. The research mainly focused on the adsorption and dis-adsorption performance of the solid desiccant heat pump under different weather and load conditions while control performances of the combined system were not involved. In practice, a good example of combining VRF system with ventilation system is the renovated ASHRAE Headquarters building in Atlanta, U.S. [26], which has been awarded a LEED Platinum Certification. In the “Living Lab” in first floor of the headquarters building, a dedicated outdoor air system supplies sufficient quantity of outdoor air based on the demand of the spaces, while a VRF system accommodates the remaining loads. Again, the two systems are separately operated. No studies about joint control of the two systems have been released up to date. In our previous investigations [27,28], a VRF and VAV combined air conditioning system (noted as combined system hereinafter) with continuous OA flow control was proposed and simulated. In this combined system, the VAV part mainly consists of an outdoor air processing (OAP) unit and VAV boxes. The OA is cooled and dehumidified in cooling mode (only heated in heating mode) before supplying to air conditioning spaces. Preliminary studies found that the combined system could maintain all the air conditioning zones at their specific set-points no matter their set-points are the same or different [27], and no matter the number of operating indoor units changes or not [28]. The proposed combined system can eliminate the conflict between demanding and supplying of the “fresh” air, which is commonly seen in conventional VAV systems as they fulfill IAQ requirements and zone cooling/heating loads using the same terminal (VAV box). Results also showed that the combined system has potential to minimize energy consumption without compromising thermal comfort and IAQ by intelligent (optimal) control. However, the