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An autonomous hierarchical control for improving indoor comfort and energy efficiency of a direct expansion air conditioning system

Jun Mei[a,*], Xiaohua Xia[a], Mengjie Song[b]

[a] Centre of New Energy Systems, Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0028, South Africa
[b] Energy Research Institute at NTU (ERI@N), Research Techno Plaza, Nanyang Technological University, 50 Nanyang Drive, Singapore 637553, Singapore

HIGHLIGHTS

- We propose a novelty control strategy to save more energy consumed and cost.
- The results validate the proposed method for improving comfort levels.
- The proposed hierarchical control method is easy to implement in practice.
- Performance of designed control strategy is better than the previous strategies.
- The designed control method is not very sensitive to the system parameters.

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Autonomous hierarchical control
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ABSTRACT

This paper presents an autonomous hierarchical control method for a direct expansion air conditioning system. The control objective is to maintain both thermal comfort and indoor air quality at required levels while reducing energy consumption and cost. This control method consists of two layers. The upper layer is an open loop controller that allows obtaining tradeoff steady states by optimizing the energy cost of the direct expansion air conditioning system and the value of predicted mean vote under the time-of-use price structure of electricity. On the other hand, the lower layer designs a model predictive controller, which is in charge of tracking the tradeoff steady states calculated by the upper layer. Control performance of the proposed control method is compared to a conventional control strategy. The results show that the proposed control strategy reduces the energy consumption and energy cost of the direct expansion air conditioning system by 31.38% and 33.85%, respectively, while maintaining both the thermal comfort and indoor air quality within acceptable ranges, which validate the proposed methodology in terms of both comfort and energy efficiency.

1. Introduction

It is well known that the building sector is responsible for almost 40% of the global total energy consumption, costing $350 billion per year. Since energy management of building air conditioning (A/C) systems is a key factor in improving the energy efficiency and reducing the energy cost of buildings, optimal control of the A/C systems has increasingly attracted research attention. Energy efficiency improvement of buildings can also be performed at different levels of time scale and building subsystems such as ambient intelligence [1–3], energy balance [4–8], building portfolio management and planning [9–14] and energy-water nexus [15,16].

Since people spend much time indoors, thermal comfort and indoor air quality (IAQ) are important issues in A/C control. Thermal comfort has been accomplished by regulating temperature and relative humidity of indoor air. In view of air quality, CO_2 concentration is used as an indicator because carbon dioxide is the main fluid waste from occupants in a building. The indoor air temperature, humidity and CO_2 concentration are affected by A/C systems, lighting, the number of occupants and natural ventilation. They are also affected by outdoor environment, including the outside temperature, humidity, CO_2 concentration and solar irradiation. The A/C system needs to provide a comfortable environment for occupants with the minimum energy consumption and cost. There are strong interactions of energy cost and energy consumption with thermal comfort and IAQ. This crucial fact has been recognised by industrial and academic researchers.

Researchers proposed various control strategies to improve energy efficiency and comfort temperature [17–20]. In [21], the authors

* Corresponding author.
E-mail address: junmei027@gmail.com (J. Mei).

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Nomenclature

A_1	heat transfer area of the DX evaporator in the dry-cooling region, m^2
A_2	heat transfer area of the DX evaporator in the wet-cooling region, m^2
A_0	total heat transfer area of the DX evaporator, m^2
A_{win}	total window area, m^2
C_c	CO_2 concentration of conditioning space, ppm
C_s	CO_2 concentration of supply air, ppm
C_z	specific heat of air, kJ kg^{-1} °C^{-1}
G	amount of CO_2 emission rate of people, m^3/s
h_{fg}	latent heat of vaporization of water, kJ/kg
h_{r1}	enthalpy of refrigerant at evaporator inlet, kJ/kg
h_{r2}	enthalpy of refrigerant at evaporator outlet, kJ/kg
k_{spl}	coefficient of supply fan heat gain, kJ/m^3
k_P,k_I	proportional and integral gains of PI controller
m_r	mass flow rate of refrigerant, kg/s
M_{load}	moisture load of conditioned space, kg/s
$Occp$	number of occupants
Q_{load}	sensible heat load of conditioned space, kW
Q_{rad}	solar radiative heat flux density, W/m^2
Q_{spl}	heat gain of supply fan, kW
T_d	air temperature leaving the dry-cooling region on air side, °C
T_s	temperature of supply air from the DX evaporator, °C
T_w	temperature of the DX evaporator wall, °C
T_z	air temperature of conditioned space, °C
T_0	temperature of outside, °C
v_a	air face velocity for DX cooling coil, m/s
v_f	air volumetric flow rate, m^3/s
V	volume of conditioned space, m^3
V_{h1}	air side volume of the DX evaporator in the dry-cooling region on air side, m^3
V_{h2}	air side volume of the DX evaporator in the wet-cooling region on air side, m^3
W_s	moisture content of supply air from the DX evaporator, kg/kg dry air
W_z	air moisture content of conditioned space, kg/kg dry air
W_0	air moisture content of outside, kg/kg dry air
α_1	heat transfer coefficient between air and the DX evaporator wall in the dry-cooling region, kW m^{-2} °C^{-1}
α_2	heat transfer coefficient between air and the DX evaporator wall in the wet-cooling region, kW m^{-2} °C^{-1}
ε_{win}	transmissivity of glass of window
ρ	density of moist air, kg/m^3

proposed an optimization method on room air temperature to improve both thermal comfort and energy efficiency. In [22], Cigler et al. presented an MPC to minimize the energy consumption and the value of predicted mean vote (PMV) index simultaneously. The simulation results showed that it would save 10–15% energy while keeping the comfort temperature within a level defined by standards. A hierarchical control method was proposed to improve the energy efficiency while maintaining the indoor temperature equal to a value such that the PMV index will be equal to zero reported in [23]. The results showed that it would reduce more energy consumption in comparison with previous work [24]. An economic model predictive control (MPC) method for optimising the building demand and energy cost under a TOU price policy under given bounded comfort temperature is studied in [25]. It demonstrated that this strategy is capable of reducing more energy cost and shifting the peak demand to off-peak hours while keeping the temperature at comfort bounded. In [26,27], the authors presented an MPC that minimises the expected energy cost and bounds of temperature comfort violations. One can note that all the above contributions focus on improving the energy efficiency of buildings by heating, ventilation and air conditioning (HVAC) temperature control. However, ensuring the indoor humidity at an appropriate level is also a crucial problem since it directly affects building occupants' thermal comfort and the operating efficiency of building A/C installations [28]. In fact, in cities with high humid climates, such as Cape Town or Hongkong, high humidity may still adversely impact indoor thermal comfort level and energy efficiency of building A/C systems even when indoor air temperature has been maintained at a desired value.

In recent years, a model-based predictive control algorithm proposed for HVAC system to control indoor temperature and humidity simultaneously taking into account energy efficiency was reported in [29]. In the study, the indoor air temperature and humidity are considered in two separate control loops. However, the control method remained inadequate fundamentally. A multi-input-multi-output (MIMO) control strategy is proposed for controlling the indoor air temperature and humidity simultaneously by varying the speeds of the compressor and the supply fan in an experimental direct expansion (DX) A/C system in [30]. In the research, the authors considered the coupling effect between indoor air temperature and humidity; so that the control accuracy and sensitivity can be improved. However, the control strategy was carried out based on the linearized system around a particular operational point, i.e., fixing the supply air temperature and moisture content. For a DX A/C system, its inlet air temperature and humidity affect its output cooling capacity directly [31]. The development of a physical model-based controller for a variable speed DX A/C system, aiming at controlling indoor air temperature and humidity simultaneously should be within its entire possible working range. An artificial neural network (ANN)-based modeling and control for an experimental variable speed DX A/C system was proposed to control the indoor air temperature and humidity simultaneously [32]. A real-time neural inverse optimal control for the simultaneous control of indoor air temperature and humidity using a DX A/C system was reported in [33]. A three-evaporator air conditioning system for simultaneous indoor air temperature and humidity control was studied in [34]. In [35], a fuzzy logic controller was developed for temperature and humidity control. The results demonstrated that the fuzzy logic controller developed can achieve the simultaneous control over indoor air temperature and humidity, with a reasonable control accuracy and sensitivity.

Nowadays, the indoor air quality (IAQ) is also an important issue for users, especially in office buildings, since a poor IAQ has a direct effect on work efficiency. In [36,37], Zhu et. al., studied indoor air temperature, humidity and CO_2 concentration control simultaneously without considering their coupling effects. However, these coupling effects cannot be ignored in many cases. In fact, the experimental investigation [38] suggested that the indoor CO_2 concentration affected indoor air temperature. Furthermore, indoor humidity was correlated with CO_2 concentration according to measurement results reported in [39]. Indoor air temperature, relative humidity and CO_2 levels assessment in academic buildings with different HVAC systems was studied in [40]. In [41], this study aimed to establish an optimal occupant behavior that can reduce total energy consumption and improve the thermal comfort, IAQ and visual comfort simultaneously by an energy simulation and optimization tool. In [42], an energy-optimised open loop controller and a closed-loop regulation of the multi-input-multi-output (MIMO) MPC schemes for a DX A/C system were proposed to improve both thermal comfort and IAQ, while minimizing energy consumption. The results showed that the energy savings were achieved and thermal comfort and IAQ were improved. However, the setpoints of thermostats