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Energy-efficient predictive control of indoor thermal comfort and air quality in a direct expansion air conditioning system

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HIGHLIGHTS

- An open loop controller optimises energy consumption of a DX A/C system.
- Indoor air temperature, humidity and CO_2 concentration are maintained using MPC.
- Both open loop and MPC can potentially lead to 27.2% energy savings.
- MPC robustly deals with disturbances present in the system.
- The control strategy maintains proper indoor thermal comfort and air quality.

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ABSTRACT

Generally, conventional controllers for comfort are designed by using on/off control or proportional-integral (PI) control, with little consideration of energy consumption of the system. This paper presents a multi-input-multi-output (MIMO) model predictive control (MPC) for a direct expansion (DX) air conditioning (A/C) system to improve both indoor thermal comfort and air quality, whereas the energy consumption is minimised. The DX A/C system is modelled into a nonlinear system, with a varying speed of compressor and varying speed of supply fan and volume flow rate of supply air being regarded as inputs. We first propose an open loop controller based on an optimisation of energy consumption with the advantage of a unique set of steady states. The MPC controller is proposed to optimise the transient processes reaching the steady state. To facilitate the MPC design, the nonlinear model is linearised around its steady state. MPC is designed for the linearised model. The advantages of the proposed energy-optimised open loop controller and the closed-loop regulation of the MIMO MPC scheme are verified by simulation results.

1. Introduction

Nowadays, approximately 30–40% of all primary energy in the world is consumed by the building sector, where a significant portion is used to improve indoor air quality and thermal comfort, accounting for a large amount of greenhouse gas emissions. When energy is overused, it would result in a shortage of energy. Meanwhile, the global temperature has steadily increased due to greenhouse effects, which in turn makes the use of air conditioning grow. Therefore, reducing the energy consumption in buildings is a key factor in reducing national greenhouse gas emissions. Energy management of building air conditioning systems becomes fundamentally necessary to improve the energy efficiency and reduce the energy cost of buildings. Energy efficiency improvement of buildings can also be made through other means of interventions [1,2] such as hybrid energy supplies [3–9], appliances operation scheduling [10–15], facility retrofitting and maintenance [16–21], envelope retrofitting [22], lighting retrofitting [23,24] and energy-water nexus [25,26].

Reducing energy consumption does not necessarily sacrifice user welfare or equipment performance [27]; in some aspects, user health is in accordance with energy efficiency. For example, more and more people are spending a substantial amount of time indoors, therefore improving thermal comfort and indoor air quality for the occupants would contribute to productivity and efficiency. In buildings, controlling indoor humidity at an appropriate level is crucial since this directly affects building occupants' thermal comfort and the operating efficiency of building air conditioning installations [28]. Various humidity control strategies applied to large-scale central air conditioning (A/C) systems, such as heat pipe technology and pre-conditioning outdoor air [29,30], or

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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
C_a	specific heat of air, kJ kg^{-1} $°C^{-1}$
V_f	air volumetric flow rate, m^3/s
$M_{h,load}$	moisture load in the conditioned space, kg/s
M_{rmf}	mass flow rate of refrigerant, kg/s
Q_{load}	sensible heat load in the conditioned space, kW
T_e	temperature of air leaving the DX evaporator, °C
T_{cs}	air temperature in the conditioned space, °C
T_d	air temperature leaving the dry-cooling region on air side, °C
T_w	temperature of the DX evaporator wall, °C
V	volume of the conditioned space, m^3
V_{com}	swept volume of the rotor compressor, m^3
W_e	moisture content of air leaving the DX evaporator, kg/kg dry air
W_{cs}	moisture content of air-conditioned space, kg/kg dry air
α_1	heat transfer coefficient between air and the DX evaporator wall in the dry-cooling region, kWm^{-2} $°C^{-1}$
α_2	heat transfer coefficient between air and the DX evaporator wall in the wet-cooling region, kW m^{-2} $°C^{-1}$
ρ	density of moist air, kg/m^3
h_{fg}	latent heat of vaporisation of water, kJ/kg
h_{r1}	enthalpy of refrigerant at vaporisation inlet, kJ/kg
h_{r2}	enthalpy of refrigerant at vaporisation outlet, kJ/kg
k_{spl}	coefficient of supply fan heat gain, kJ/m^3
v_s	specific volume of superheated refrigerant, m^3/kg
V_{sc}	speed of compressor, rpm
k_{fan}	coefficient of supply fan speed, m^3/r
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
λ	compressor's displacement coefficient
BESTEST	building energy simulation test
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers

chemical dehumidification desiccant mechanisms [31,32] and mechanical dehumidification desiccant mechanisms [33,34] are not applicable to direct expansion (DX) A/C systems. Compared to central chilled water-based A/C systems, DX A/C systems are simpler in system configuration, more energy efficient [35] and cost less to own and maintain. Therefore, DX A/C systems have been widely used over recent decades in buildings, especially in small to medium scaled buildings. However, most DX A/C systems currently are equipped with single-speed compressors and supply fans by on/off cycling compressors as a low-cost approach only to maintain indoor air temperature, and this leads to either space overcooling or uncontrolled equilibrium indoor air humidity. Therefore, on/off cycling leads to a degraded level of thermal comfort for occupants. With the advancement of variable speed drive technology, it becomes possible for DX A/C systems with the varying speeds of compressors and supply fans to achieve simultaneous control of indoor air temperature and humidity [36].

Various control strategies designed and employed for DX A/C systems are to control indoor air temperature and humidity simultaneously. An experimental investigation indicated that a conventional PID control method proposed to maintain indoor air temperature by varying compressor speed, and indoor air humidity by varying supply fan speed, separately, may be controlled simultaneously [37]. Since the strong cross-coupling between two decoupled feedback loops (i.e., the control loop for temperature by varying compressor speed and that for humidity by varying supply fan speed), the transient performance of the two feedback loops was inherently inferior. Consequently, this control strategy remained inadequate.

To overcome the difficulties of the coupling effect, more advanced control strategies have been reported. A novel direct digital (DDC)-based capacity controller for a variable speed DX A/C system to control indoor air temperature and humidity simultaneously has been developed in [38,39]. In [40], Qi and Deng presents a multivariable dynamic model of the variable speed DX A/C system taking into account the coupling effects among multiple variables. The state-space representation was linearised at a particular operational point, to facilitate developing a multi-input multi-output (MIMO) controller which is capable of addressing couplings and is more effective in simultaneously achieving multiple control objectives, such as temperature, humidity, capacity and efficiency. The model was experimentally validated. Besides, Qi and Deng [41] proposed MIMO Linear Quadratic Gaussian (LQG) control strategy for simultaneously controlling indoor air temperature and humidity by regulating the varying speeds of the compressor and supply fan in an experimental DX A/C system. The MIMO controller developed can effectively control indoor air temperature and humidity simultaneously, with command following and disturbance rejection capability tests. However, these papers did not discuss indoor CO_2 concentration control. In [42], an artificial neural network (ANN)-based controller is proposed for a variable speed DX A/C system to control indoor air temperature and humidity simultaneously. In [43], a novel hybrid steady-state model based controller (SSMBC) is proposed to control indoor air temperature and humidity simultaneously. The experiment shows that the novel hybrid SSMBC is accurate and sensitive. In [44], a novel Proportional-Derivative (PD) law based fuzzy logic controller for a variable speed DX A/C system is designed to control indoor air temperature and humidity simultaneously.

In recent years, indoor air quality is more and more regulated by A/C system design and control. The CO_2 concentration, air temperature and humidity have become three major indicators of indoor comfort and air quality. In [45,46], Zhu et. al., studied indoor air temperature, humidity and CO_2 concentration control simultaneously, but without consideration the coupling effect. Three coupling effects cannot be ignored in many cases. In fact, the experimental investigation [47] 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 [48]. To our best knowledge, very little work exists in the literature to study indoor air temperature, humidity and CO_2 concentration control simultaneously with consideration of coupling effects and energy efficiency. This paper studies the optimisation of DX A/C systems that strikes a balance of indoor comfort, air quality as well as energy efficiency.

Nonlinear control systems for indoor air temperature, humidity and CO_2 concentration in DX A/C system have been modelled with considering the coupling effects of indoor air temperature, humidity and CO_2 concentration. The energy consumption model for the DX A/C system is given. The open loop optimal method is used to optimise the energy consumption model for the DX A/C system, such that there would be a unique and optimal steady state for