available at www.sciencedirect.com

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

Multivariable control-oriented modeling of a direct expansion (DX) air conditioning (A/C) system

Qi Qi, Shiming Deng*

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR

ARTICLE INFO

Article history:
Received 28 June 2007
Received in revised form
17 October 2007
Accepted 18 October 2007
Published online 9 January 2008

Keywords:
Cooling system
Air conditioning
Direct expansion
Modelling
Simulation
Comparison
Experiment

ABSTRACT

A dynamic mathematical model for a DX A/C system has been developed. The dynamic model, written in state-space representation which was suitable for designing multivariable control, was linearized at steady state operating points. The linearized model has been validated by comparing the model simulation results with the experimental data obtained from an experimental DX A/C system. The simulated results agreed well with the experimental data, suggesting that the model developed was able to capture the transient characteristics of the DX A/C system modeled. It is expected that the model developed can be useful in designing a multi-input multi-output (MIMO) controller to simultaneously control indoor air temperature and humidity in a space served by a DX A/C system.

Modélisation aux variables multiples axée sur la régulation d’un système de conditionnement d’air à détente directe

Mots clés : Système frigorifique ; Conditionnement d’air ; Détente directe ; Modélisation ; Simulation ; Comparaison ; Expérimentation

1. Introduction

Direct expansion (DX) air conditioning (A/C) systems are widely used in small- to medium-scaled buildings in recent decades. Compared to central chilled water-based A/C systems, the use of DX A/C systems is advantageous since they are simpler in configuration, more energy efficient and generally cost less to own and maintain. In the US, according to Department of Energy, packaged rooftop DX A/C systems accounted for approximately 60% of the total installed cooling capacity (Bordick and Gilbridge, 2002).

Residential buildings are most likely served by DX A/C systems, but controlling indoor humidity at an appropriate level using a DX A/C system is both challenging and important since this directly affects occupants’ thermal comfort and indoor air quality (IAQ) (Fanger, 2001). Most DX A/C units are

* *Corresponding author*. Tel.: +852 2766 5859; fax: +852 2765 7198.
E-mail address: besmd@polyu.edu.hk (S. Deng).

0140-7007/$ – see front matter
doi:10.1016/j.ijrefrig.2007.10.009

Nomenclature

A, B, C	coefficient matrices (in Eq. (18))
A_1	heat transfer area of the DX evaporator in dry-cooling region, m^2
A_2	heat transfer area of the DX evaporator in wet-cooling region, m^2
C_p	specific heat of air, $kJ\,kg^{-1}\,K^{-1}$
f	air volumetric flow rate, m^3/s
M	moisture load in the conditioned space, kg/s
M_{ref}	mass flow rate of refrigerant, kg/s
Pr	Prandtl number
Q_{load}	sensible heat load in the conditioned space, kW
Q_{spl}	heat gain of supply fan, kW
SH	super heat of refrigerant, °C
T_1	temperature of air leaving the DX evaporator, °C
T_2	air temperature in the conditioned space, °C
T_3	air temperature leaving the dry-cooling region of the DX evaporator, °C
T_w	temperature of the DX evaporator wall, °C
V	volume of the conditioned space, m^3
V_{h1}	air side volume of the DX evaporator in dry-cooling region on air side, m^3
V_{h2}	air side volume of the DX evaporator in wet-cooling region on air side, m^3
V_{com}	swept volume of the rotor compressor, m^3
W_1	moisture content of air leaving the DX evaporator, kg/kg dry air
W_2	moisture content of air-conditioned space, kg/kg dry air
α_1	heat transfer coefficient between air and the DX evaporator wall in dry-cooling region, $kW\,m^{-2}\,{}^\circ C^{-1}$
α_2	heat transfer coefficient between air and the DX evaporator wall in wet-cooling region, $kW\,m^{-2}\,{}^\circ C^{-1}$
ρ	density of moist air, kg/m^3
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
j_{e1}, j_{e2}	Colburn factors
k_{spl}	coefficient of supply fan heat gain, kJ/m^3
v_s	specific volume of superheated refrigerant, $m^3\,kg^{-1}$
e	rotor eccentricity, m
l	stroke of cylinder, m
r	radius of rotor, m
s	speed of compressor, rpm
λ	compressor's displacement coefficient
λ_{sys}	eigenvalue (in Eq. (23))
ε	rotor relative eccentricity
Superscript	
w	evaporator wall

currently equipped with single-speed compressors and supply fans, relying on on–off cycling compressors as a low-cost approach to maintain only indoor air dry-bulb temperature, resulting in either space overcooling or an uncontrolled equilibrium indoor relative humidity (RH) level.

Recent developments in variable speed drive (VSD) technology offer tremendous opportunities for improving indoor thermal comfort and energy efficiency for DX-based space air conditioning. Compressor speed can be continuously varied to modulate the output cooling capacity to match the actual thermal load. The supply fan speed can be also altered to affect both sensible heat and latent heat transfer rate across heat exchangers. Therefore it is possible to improve indoor thermal comfort control using DX A/C systems equipped with variable speed compressor and supply air fan.

In the open literature available, a considerable number of previous investigations have focused on the dynamic modeling of vapor compression refrigeration cycles. He et al. (1997) developed an overall dynamic model for a vapor compression refrigeration cycle, and the simulation results indicated that there were strong cross-couplings among system inputs and outputs. Linear Quadratic Gaussian (LQG) technique was then used to design a multi-input multi-output (MIMO) controller with guaranteed stability and robustness (He et al., 1998). The possibility of using a model-based nonlinear controller was also investigated numerically for a vapor compression refrigeration system (Tao et al., 2004, 2005). Rasmussen and Alleyne (2004) presented a reduced order dynamic model of a transcritical vapor compression cycle. It was demonstrated that the reduced order model was adequate for predicting the dominant system dynamics. Therefore the reduced order model with minimal loss in accuracy was very useful for designing an MIMO controller. Shah et al. (2004) developed a model for the vapor compression refrigeration cycle in an automotive air conditioning system with a variable speed compressor, and applied the multivariable adaptive control strategy to the air conditioning system to improve its capacity control and system efficiency. Lin and Yeh (2007) developed a low-order linear model for an air conditioning system through system identification. Experimental results indicated that an MIMO-based controller can both achieve satisfactory transient responses in indoor air temperature and improve energy efficiency at steady states. However, the model established through system identification was only valid for certain particular systems.

In mechanical cooling based on A/C systems, dehumidification is less straightforward because of the dual function of cooling and dehumidification taking place in cooling coils. This has led to the controlled variables of air temperature and humidity becoming coupled, which was confirmed by experimental investigations (Li and Deng, 2007a). Krakow et al. (1995) suggested that space air temperature and relative humidity could be controlled by varying compressor speed and varying evaporator fan speed, separately, using a proportional–integral–derivative (PID) control method. However, the study focused on the feasibility of such a PID control method, without looking at the coupling effect of air temperature and humidity by treating the two controlled variables separately. A DDC-based control algorithm developed by Li and Deng (2007b,c) considered the coupling effect of air temperature and humidity and used space sensible heat ratio (SHR) as a controlled variable to simultaneously control space