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Simultaneous control of indoor air temperature and humidity for a chilled water based air conditioning system using neural networks

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ABSTRACT

Conventional chilled water based air conditioning systems use low temperature chilled water to remove both sensible load and latent load in conditioned space, and reheating devices are usually installed to warm the overcooled air, which leads to energy waste. Alternatively, this paper proposes a neural network (NN) model based predictive control strategy for simultaneous control of indoor air temperature and humidity by varying the speeds of compressor and supply air fan in a chilled water based air conditioning system. Firstly, a NN model has been developed to model the system dynamics, linking the variations of indoor air temperature and humidity with the variations of compressor speed and supply air fan speed. Subsequently, the NN model is experimentally validated and used as a predictor. Based on the NN model, a neural network predictive controller is proposed to control the indoor air temperature and humidity simultaneously. The experimental results demonstrate the effectiveness of the proposed scheme compared with conventional PID controllers. Moreover, it has been proven that it is practical to simultaneously control indoor air temperature and humidity by varying the compressor speed and the supply air fan speed without adding any other devices to the chilled water based air conditioning systems.

1. Introduction

Nowadays, HVAC system has been widely used in commercial buildings and industrial manufactories to provide comfort environment with suitable air temperature and humidity. The energy consumed by HVAC accounts for about 50% of the total energy in buildings [1]. So the effective operation of HVAC systems has attracted numerous interests in recent years.

In conventional chilled water based air conditioning systems, the indoor sensible load and latent load are handled by chilled water cooling coil at the same time [2]. That means the chilled water temperature should be lower than the dew point temperature in order to control the air temperature and humidity, respectively. However, two control loops for air temperature and humidity are highly coupled. Since the compressor speed in chiller and the supply air fan speed are constants, conventional chilled water based air conditioning systems can hardly accommodate large variances in sensible load and latent load in many scenarios. Normally, additional devices would be added to a chilled water based air conditioning system to assist the control of both temperature and humidity. For example, dedicated outdoor air systems (DOAS) [3] have been proposed in the United States, and different devices have been adopted for humidity control and temperature control. These systems connect sensible cooling terminals with low-temperature air supply devices, where the outdoor air is processed to a sufficiently dry state to remove the indoor latent load [4]. Conventional chillers are still utilized as the cooing source of low-temperature air supply devices, limiting further improvement in energy saving performance in DOAS. Radiant cooling terminals are appearing in Europe [5,6]. These devices can remove the sensible cooing load through radiant heat exchange and natural convention with appropriate chilled water imported. Radiant cooling terminals have been shown to be a good choice for low-temperature heating systems and high temperature cooling systems [7–9]. In most areas of Europe, the climate is dry enough to alleviate any concern on condensing on the surface of radiant terminals in summer. In most areas of China, the outdoor air is humid in summer, which makes the humidity control a more challenging task than it is in Europe [10]. Temperature and humidity independent control (THIC) systems, which consist of temperature control

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Nomenclature

A, B, C, A', B', C'	PID controllers parameters
f_c	compressor speed
f_{sf}	supply air fan speed
H_r	relative humidity
$\hat{H}_r$	predicted relative humidity
J	total number of neurons in the output layer
n_u	control horizon
N	total number of the data sets in training/testing/validation
o	neural network output
p	prediction horizon
R	mean ration of the experimental results to the corresponding results predicted by the NN model during tests
t	time step
T_{db}	dry bulb temperature
U	input vector
M	desired system output vector
W_u	weight vector of squared control increments
W_y	weight vector of squared tracking errors
y	output from a system
$\hat{Y}$	predicted outputs of neural network
ξ	control weight vector
σ	standard deviation of the rations of the experimental results to the corresponding results predicted by the NN dynamic model during tests

Abbreviations

ARE	average relative error
MRE	maximum relative error
LGU	load generating unit
NN	neural network
OPC	object linking and embedding for process control
A/C	air conditioning
VSD	variable speed driver

and humidity control subsystems, have been developed in China in recent years [11]. A high temperature cooling source device is utilized for temperature control and processed air with relative low humidity is used to cover the latent load in the conditioned space [12,13]. However, high temperature chiller and new air handling unit should be made especially for THIC systems, which makes the renovation cost great for buildings equipped with conventional air conditioning systems.

With the rapid development of variable speed drive technology, it becomes possible for the chilled water based air conditioning systems to have the compressor speed and supply fan speed varied, so as to achieve simultaneous control over both indoor air temperature and relative humidity. The system sensible heating ratio (SHR) and total cooling capacity of a direct expansion (DX) air conditioning (A/C) system can be altered by varying the speeds combinations of compressor and supply air fan [14]. That means the cooling capacity can be distributed to cover different sensible load and latent load by simultaneously varying the compressor speed and the supply air fan. To this end, several model and control strategies have been introduced to handle the interaction between the indoor air temperature and the humidity using DX A/C systems [15–17].

Theoretically, it is possible to implement the simultaneous control of air temperature and humidity for a chilled water based air conditioning system by appropriately adopting and modifying the control algorithms which have been validated for DX A/C systems. However, for DX A/C system, the cooling and dehumidifying mainly occur at the two phase flow section of the evaporator, in which the temperature of the refrigerant keeps constant. For chilled water based air conditioning system, the chilled water temperature distribution in the cooling coil is more complex than that of the refrigerant in DX A/C systems. Moreover, the chilled water temperature control and flow rate control are independent, while in DX A/C systems, compressor speed has influence on both evaporation temperature and mass flow rate of refrigerant. The chilled water based air conditioning systems are also equipped with multi air handling units, while the DX A/C systems are usually equipped with a single evaporator. Therefore, the inner interaction in chilled water based air conditioning system is more complex than DX A/C systems. To the best knowledge of the authors, no reported studies can be identified in open literature for the simultaneous control of indoor air temperature and relative humidity by varying the compressor speed in chiller and the supply air fan for chilled water based air conditioning systems.

The complexity of simultaneous indoor air temperature and relative humidity control stems from the fact that it is composed of several interconnected subsystems which mutually influence one another, and there exist nonlinear dynamics between system inputs and outputs. To verify the possibility of simultaneous control of indoor air temperature and humidity by varying the compressor speed and supply air fan speed of a chilled water based A/C system, this paper mainly focuses on the dynamic operation characteristics of a chilled water based A/C system when speeds of compressor and supply air fan vary, while the interaction between the air handling units is neglected. In other words, this work tries to model the dynamic operation characteristics of a chilled water based air conditioning system with a single air handling unit.

To address the coupling effect between two control loops of air temperature and humidity, physical models have been proposed to describe the dynamics based on the principles guiding heat exchange behavior [18,19]. This kind of model will result in large number of differential equations and limit the online implementation of physical model based controller, since solving the differential equation requires huge computation resources. On the other hand, neural network (NN) has been proven to be an excellent alternative modeling nonlinear MIMO systems [20]. Using an artificial neural network, the coupling effect of DX A/C system has been well handled in [15], and the NN model exhibits a good approximating result. Moreover, different controllers have been proposed based on neural network models, such as inverse-model-based control which includes internal model control method and direct inverse control method, model predictive control and optimal control [21–23], which leads to easy development of online controller. Therefore, in this paper, NN model is chosen to simulate the nonlinear dynamic characteristics of the chilled water based air conditioning system and a NN model based adaptive controller is developed by taking the advantages of the neural network.

In this paper, an experimental rig of a chilled water based air conditioning system is firstly introduced and the experimental conditions at which the experiments are carried out for the dynamic modeling and controller testing are specified. Secondly, the development of the nonlinear dynamic model for the air conditioning system considering the coupling effect between output indoor air temperature and relative humidity is presented. The developed model is then validated by comparing the actual experimental data with the values predicted using the developed model. Finally, command following tests are carried out to exam the controllability of a developed predictive controller based on the nonlinear dynamic model. Controlling results have been compared with those of conventional PID controllers to further validate the performance of the developed scheme.