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A novel hybrid steady-state model based controller for simultaneous indoor air temperature and humidity control

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ABSTRACT

Due to the strong coupling between two control loops, it is always a challenge to develop appropriate control algorithm for simultaneously controlling indoor air temperature and humidity using a direct expansion (DX) air conditioning (A/C) system, making it an engineering application where no expert experience is available. Although the control performance of a steady state model based controller (SSMBC) was normally regarded to be not comparable to that of a dynamic model based controller, the successful development of a SSMBC may provide new insights of the control mechanism. In this paper, a SSMBC was developed based on a previous developed steady state model of a DX A/C system. Its control performance was theoretically analyzed and experimentally tested. It was proven that by utilizing a specific activating method, the SSMBC could achieve much better control performance than that of a traditional On-Off control method. However, the SSMBC could be further improved. Based on the theoretical analysis of the interaction between the changes of system operating states and those of indoor air thermal states, a hybrid SSMBC, which consisted of a SSMBC and a stabilizing controller, was further developed. The accuracy and sensitivity of the novel hybrid SSMBC are experimentally validated.

1. Introduction

To a layman, air conditioning (A/C) may simply mean "the cooling and heating of air". This simple understanding of A/C is neither sufficiently useful nor accurate. As pointed out by Edward [1], A/C is in fact a process of treating air in an internal environment to establish and maintain the required air state in terms of temperature, humidity, cleanliness and motion. In buildings, therefore, controlling indoor humidity at an appropriate level is important since this directly affects building occupants' thermal comfort, indoor air quality and the operating efficiency of building A/C installations [2–6].

In small- to medium-scaled buildings, direct expansion (DX) air conditioning (A/C) systems are widely applied. They are simpler in system configuration, more energy efficient and generally cost less to own and maintain when compared to chilled water-based central A/C installations. However, the compact system configuration of DX A/C systems also makes it challengeable to simultaneously control indoor air temperature and humidity. Indoor air humidity is often uncontrolled in the space served by a traditional On-Off controlled single speed DX A/C system.

The introduction of variable-frequency inverters has made the speed control of compressor and supply fan more practical and paved a new way to meet the challenge of simultaneous control of indoor air temperature and humidity by DX A/C systems [7–13]. However, due to the complex dynamic characteristics of heat and mass transfer taking place in a variable speed DX A/C system and the strong cross-coupling between two control loops for controlling temperature and humidity respectively, it is hard to develop a corresponding control algorithm, which could not only successfully decouple two control loops, therefore achieving required control accuracy, but also have reasonable control sensitivity. For example, if using a conventional PID controller, the transient performances of two feedback loops would be inherently poor due to the strong coupling [9]. An empirical model based controller [10] can control simultaneously indoor air temperature and humidity only within a certain range near the operating point where the model was linearized. This is because empirically based models do not allow to accurately extrapolate beyond the range of the data used for training/estimating the model parameters [14].

On the other hand, a fuzzy logic controller (FLC) that make use of the common sense of people and their experiences, may not require a specific system model and appears very useful when the processes are too complex to be analyzed by conventional quantitative techniques or when the available sources of information are interpreted qualitatively, inexactly, or uncertainly. However, there is no systematic procedure for designing an FLC and it is often

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Nomenclature

A	area (m^2)
C	compressor speed (rpm)
DP	dew point (K)
F	supply fan speed (rpm)
H	enthalpy (kJ/kg)
m	mass flow rate (kg/s)
P	pressure (Pa)
QL	latent cooling capacity (W)
QS	sensible cooling capacity (W)
Qt	total cooling capacity (W)
SHR	sensible heat ratio
T	temperature (K)
ΔT	temperature difference (K)
W	moisture content (kg/kg)

Greek symbols

α	convective heat transfer coefficient (W/(m^2 K))
ρ	density (kg/m^3)

Subscripts

a	air
c	compressor
e	evaporator
hu	heating up
i	inlet/inner
l	liquid
max	maximum
min	minimum
o	outlet/outside
r	refrigerant
$ratio$	area ratio
s	saturation
sh	superheated
tp	two-phase
v	vapor
wa	air side wall

difficult to express human experience exactly using linguistic rules in a simple format. Due to the coupling and complexity as discussed above, the use of a variable speed DX A/C system to simultaneously control air temperature and humidity is one of the engineering applications where no expert experience is available for directly developing fuzzy control rules.

For those model based controllers, no matter which modeling approach was applied, a control oriented model for HVAC applications was normally a dynamic one [15–17]. A steady state model may be regarded as insufficient for controller development since it cannot reflect the dynamic behavior of the system. Utilizing a steady state model for controller development requires more profound understanding of the interaction between indoor cooling loads and output cooling capacities from the HAVC systems, which may be covered by the automatic control process of a dynamic model based controller. Thus, although the control performance of a steady state model based controller (SSMBC) was regarded to be not comparable to that of a dynamic model based controller, the successful development of a SSMBC may provide new insights of the control mechanism for a specific HVAC application, especially for that being lack of related expert experience.

For example, the sensible heat ratio (*SHR*), which was defined as the ratio of sensible cooling load to the total cooling load, is an integrated variable relating to both indoor cooling sensible load and latent cooling load. By recognizing that *SHR* could indirectly simultaneously affect indoor air temperature and humidity, Li and Deng [12,13] built up a steady-state model for predicting the total output cooling capacity and the Equipment *SHR* under various operating conditions, and thus successfully developed a DDC-based (Direct Digital Control-based) capacity controller for a DX A/C system for the simultaneous control of both indoor air dry-bulb temperature and humidity. However control sensitivity of this controller was poor and the interaction between indoor cooling loads and output cooling capacities from the DX A/C system was not fully interpreted by these experimental researches.

In this paper, a controller was developed based on a previous developed steady state model of a DX A/C system for simultaneous controlling indoor air temperature and humidity. Preliminary controllability tests not only validated the feasibility of the SSMBC, but also suggested that the SSMBC could be further improved. Theoretical analysis of the control process for simultaneous control of temperature and humidity using a SSMBC was then carried out. Finally, based on a revealed new control mechanism, a hybrid controller, which consisted of a SSMBC and a stabilizing controller to stabilize as soon as possible the thermal states of indoor air after being subject to disturbance, was further developed. The accuracy and sensitivity of the novel hybrid SSMBC is experimentally validated.

2. Experimental station

An experimental station was set up to resemble a typical DX A/C system. It mainly consisted of two parts, i.e., a DX refrigeration plant and an air-distribution sub-system. The schematic diagram of the experimental station is shown in Fig. 1.

The major components in the DX refrigeration plant included a variable-speed rotor compressor, an Electronic Expansion Valve (EEV), an air-cooled tube-plate-finned condenser and a high-efficiency louver-fin-and-tube DX evaporator. The evaporator was placed inside the air-distribution sub-system, to work as an air cooling and dehumidifying coil in the air side of the DX A/C system. The design air face velocity for the DX cooling coil was 2.5 m/s. The nominal output cooling capacity from the DX refrigeration plant was 9.9 kW (∼2.8 RT). The actual output cooling capacity from the DX refrigeration plant can however be modulated from 15% to 110% of the nominal capacity. Both condenser fan and compressor were driven by variable-frequency drives (VFD). The EEV was used to maintain the degree of refrigerant superheat at the evaporator exit. Working refrigerant in the DX plant was R22.

The air-distribution sub-system included an air-distribution ductwork with return air dampers, an air filter, a variable-speed centrifugal supply air fan and a conditioned space. The size of the conditioned space was 7.8 m (*L*) × 3.8 m (*W*) × 2.8 m (*H*). A supply diffuser is located at the center of the conditioned space's ceiling and two return dampers are located at the foot of a wall. Inside the space there was a sensible heat and moisture load generating unit (LGU), which was intended to simulate the cooling load inside the conditioned space. The regulatory range of the LGU is 0∼12 kW for sensible heat load and 0–9.6 kW for moisture load.

The station was fully instrumented for measuring all of its operating parameters, which may be classified into three types: temperature, pressure and flow rate. All measurements were computerized. A computerized data acquisition unit was provided in this experimental station. It provided 48 channels for monitoring various types of operating parameters. The direct current signal obtained from various measuring devices and sensors can be scaled into their real physical values of the measured parameters using a logging and control supervisory program. The logging and control supervisory program enabled the PC to act as a central supervisory control unit in the experimental station and provided also