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A PD Law Based Fuzzy Logic Control Strategy for Simultaneous Control of Indoor Temperature and Humidity Using a Variable Speed Direct Expansion Air Conditioner

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ABSTRACT

In small to medium scale buildings located in the subtropics, such as Hong Kong, direct expansion air conditioning (DX A/C) systems are widely applied. This is because, as compared to chilled water based central air conditioning systems, DX A/C systems are compact, flexible for multi-room services, energy efficient and cost less to maintain and operate. However, traditionally, a DX A/C system is equipped with a single-speed compressor and supply air fan, and employs ON / OFF control strategy to maintain indoor air temperature only, leaving the indoor moisture content (or relative humidity) uncontrolled. With the introduction of variable speed technology, the speeds of compressor and supply air fan can be varied continuously so as to realize the simultaneous control of the indoor temperature and humidity. In this paper, the development of a novel control strategy based on PD law and fuzzy logic is reported. The compressor speed was adjusted directly according to the indoor air moisture content and supply air fan speed according to the indoor air dry-bulb temperature, respectively, to realize the simultaneous control of indoor air temperature and humidity. Controllability tests for the novel control strategy were carried out and the test results suggested that, although two control loops for temperature and humidity were significantly coupled, the simultaneous control of indoor temperature and humidity was achieved with respect to control accuracy and sensitivity.

1. INTRODUCTION

In small- to medium-scaled buildings, direct expansion (DX) air conditioning (A/C) systems are widely applied. Compared to large-scaled chilled water based central air conditioning systems usually seen in large scaled buildings, DX A/C systems are more compact, flexible for multi-room services, energy efficient and cost less to maintain and operate. For an air conditioned space served by a DX A/C system, to maintain the required indoor air temperature and humidity requires matching not only the system's total output cooling capacity (TCC) with the space cooling load, but also the sensible heat ratio of the DX A/C system (E SHR) with the application sensible heat ratio of the conditioned space (A SHR) at all time (Li *et al.*, 2007a). This is hardly possible with a single-speed compressor DX A/C system as its E SHR is very often between 0.7 and 0.8 which can well be larger than the A SHR of a conditioned space at 0.6 to 0.7 and even below 0.5 in wet seasons in sub-tropics (Li *et al.*, 2006; Xu *et al.*, 2008). A simple control strategy such as ON / OFF control has been considered inadequate as uncontrolled indoor air humidity will degrade occupants' perceived thermal comfort (Toftum and Fanger, 1999) and impact indoor air quality as well as the energy efficiency of the system.

With the introduction of variable-frequency inverters, continuous speed variation for compressor or supply fan is practically possible, which helps pave the way to simultaneously control indoor air temperature and humidity using a variable speed (VS) DX A/C system. Andrade *et al.* (2001) investigated the influence of varying both airflow rate and refrigerant flow rate in a variable-speed split-type air conditioner equipped with a compressor and air blower on its output sensible and latent cooling capacities, which directly affected indoor thermal environmental control. Besides Andrade, extensive experimental studies have been carried out, revealed the operating characteristics of a VS DX A/C system (Li and Deng, 2007c; Xu *et al.*, 2010; Li *et al.*, 2014), paving the way for developing control strategies for simultaneous control of indoor air temperature and humidity. Therefore, based on variable speed driven compressor and supply fan, plenty of controllers for simultaneous control of indoor air temperature and humidity have been developed during the past two decades (Krakow *et al.*, 1995a, 1995b; Li and Deng, 2007a, 2007b; Qi and Deng, 2008, 2009; Xu *et al.*, 2008; Li *et al.*, 2013).

Generally speaking, conflict between the complexity of the control system and the control performance arose among those current developed controllers. Satisfactory performance can be achieved by the physical model based controller (Li and Deng, 2007a, 2007b; Qi and Deng, 2008, 2009) and empirical model based controller when online updating was adopted (Li *et al.*, 2013). However, due to the extreme complexity of the heat and mass transfer between air and refrigerant inside the evaporator of a VS DX A/C system, the development of a dynamic model, no matter physical or empirical, is difficult, making the associated control systems and hardware both complicated and costly. On the other hand, a simple control algorithm, such as the simple PID controller (Krakow *et al.*, 1995) or H-L control proposed by Xu *et al.* (2008), cannot meet a strict requirement of the indoor air temperature and humidity. Therefore, novel control strategies considering the compromise between complexity of control system and controllability should be developed to realize simultaneous control of indoor air temperature and humidity using VS DX A/C system.

Fuzzy logic, rather than a certain logic or machine logic, is promising for achieving improved control of heating, ventilation and air conditioning (HVAC) systems (Huang and Nelson, 1991). Fuzzy logic controllers (FLCs) are based on a set of fuzzy control rules that make use of the common sense of people and their experiences. Basically, the use of FLCs provides an effective means of capturing the approximate and inexact nature of the real world (Lee, 1990a; 1990b). The methodology of the FLCs 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.

Therefore, in this paper, a novel control strategy based on fuzzy logic is proposed that the compressor speed was adjusted directly according to the indoor air wet-bulb temperature and supply air fan speed according to the indoor air dry-bulb temperature, respectively, to realize the simultaneous control of indoor air temperature and humidity. The organization of this paper is as follows. Firstly, the controller development is presented. Secondly, the experimental setup where all controllability experiments were carried out is described. This is followed by presenting the results of controllability experiments. Finally, conclusions are given.

2. THE DEVELOPMENT OF THE NEW CONTROLLER

With extensive experimental studies been carried out, the operating characteristics of a VS DX A/C system have been revealed (Li and Deng, 2007c; Xu *et al.*, 2010; Li *et al.*, 2014). The operating characteristics can be applied as the basis for developing some advanced controller for the VS DX A/C system.

2.1 Novel control principle

The operating characteristics represent the characteristics of the output cooling capacities (including the sensible and latent part) when the DX A/C system is operated under variable speed conditions. The control strategy proposed in this paper is based on a general influence pattern of different speeds combination of compressor and supply fan of a VS DX A/C system shown in Figure 1 and 2, reported by Li and Deng (2007). Figure 1 illustrates the output sensible cooling capacity at different compressor speed and supply fan speed combinations. As seen, although varying either C or F will influence both the sensible and latent part of the output cooling capacity, the rate of decrease for sensible component was more noticeable when the supply fan speed was reduced, meaning that, the influence caused by varying supply fan speed on the output sensible cooling capacity is more considerable than that caused by varying compressor speed. On the other hand, the output latent cooling capacity will be influenced more by varying compressor speed than by varying supply fan speeds, as shown in Figure 2. Since the sensible part of the cooling capacity only affect the T_{db}, it is proposed in this paper that vary the supply fan speed according to T_{db} while compressor speed according to T_{wb}. When T_{db} and T_{wb} are fixed, the indoor air humidity is also fixed. Therefore, the simultaneous control of T_{db} and T_{wb} is equivalent to the simultaneous control of indoor air temperature and humidity.

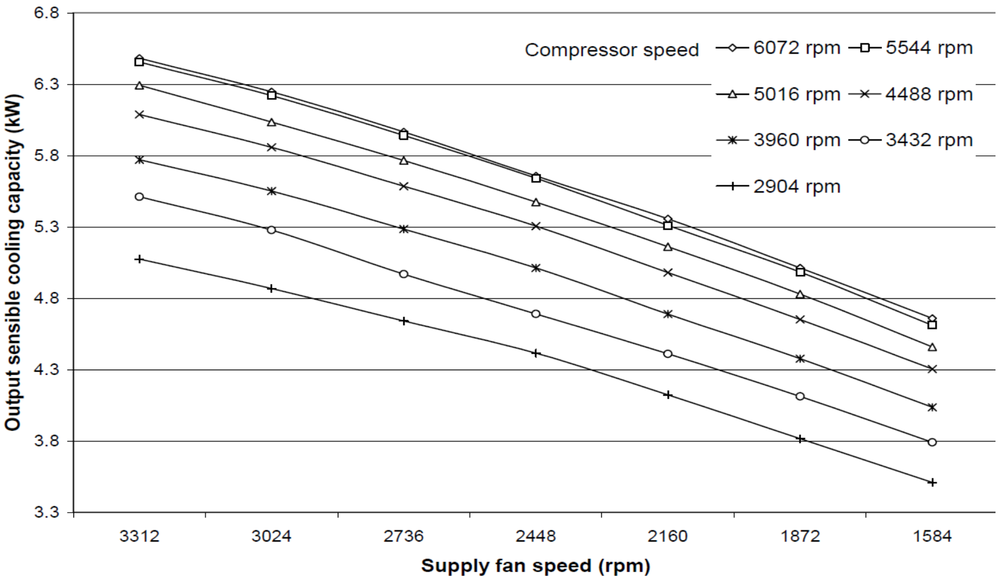


Figure 1: Output sensible cooling capacity at different speeds combination (Li and Deng, 2007)

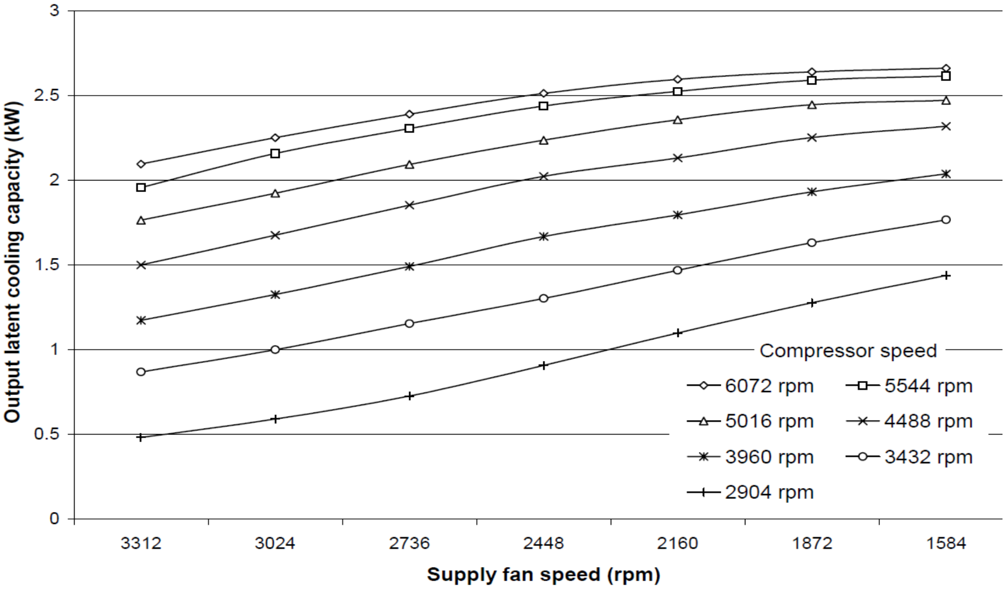


Figure 2: Output latent cooling capacity at different speeds combination (Li and Deng, 2007)

Krakow *et al.* (1995b) had proposed PID controllers with similar control loops. However, determining the gain factors for a traditional PID controller can well be difficult due to the difficulties of building a dynamic physical model for the heat and mass transfer process in the DX evaporator for a VS DX A/C system. Therefore, two PID-law-combining fuzzy logic sub-controllers (PFCs) are proposed in developing the control algorithm.

2.2 Development of the control algorithm

In general, a PFC has two parts: the PID law and a fuzzy rule-based system. The fuzzy rule-based system consists of a fuzzifier, a fuzzy reasoning unit and a defuzzifier. A fuzzifier uses several fuzzy sets and the corresponding membership functions to convert its input data into suitable linguistic values which may be viewed as labels of fuzzy sets. Furthermore, a fuzzy reasoning unit consists of certain fuzzy rules, which are based on expert experience. The fuzzy reasoning unit would establish a fuzzy reasoning matrix to signify the relationship between the fuzzy inputs and fuzzy control output. Finally, a defuzzifier converts the fuzzy control output to a real control signal.

The size of the fuzzy reasoning matrix is determined by the number of the fuzzy sets in the fuzzifier. For example, if there are *k* fuzzy sets for tracking absolute error, *m* fuzzy sets for integral error and *n* fuzzy sets for derivative error, then, there would be $k \times m \times n$ inputs to a PFC, thus forming a $k \times m \times n$ fuzzy reasoning matrix. Therefore, a small increase in the number of fuzzy sets would significantly enlarge the size of a fuzzy reasoning matrix. On the other hand, more fuzzy sets result in a more precise representation of the controlled system. Therefore, an appropriate balance between control accuracy and calculation complexity should be established. This was reflected in Huang's study (Huang and Nelson, 1991) where a PD (proportional-derivative) law, instead of a PID law, was used in a PFC to simplify the calculation. However, using a PD law could simplify not only calculation but a PFC's structure. This is explained below:

The output from a PFC is normally the absolute value of a control signal. For each input to the PFC, there should be a corresponding fuzzy rule. Taking the room air temperature control using a DX A/C system controlled by a PFC as an example, if defining both eleven linguistic variables for the proportional error between *T* and its set-point (see Table 1), and eleven linguistic variables for the derivative error, there would be a fuzzy reasoning matrix with totally 121 (11×11) fuzzy rules in a conventional fuzzy reasoning unit. Such an arrangement, however, overlooks the inherent physical relationship between the proportional error and derivative error. The former represents the absolute difference between the current *T* and its set point, and the latter the rate of change of the absolute difference. The two are hence inter-related. Very often, even with different inputs to the PFC, the required output can be the same. For example, when *T* is 5 ℃ above its setting, but at the same time, is decreasing at a rate of 0.5 ℃/min, or when *T* is 3 ℃ below its setting, but at the same time, is increasing at a rate of 0.3 ℃/min, then for both cases, although the inputs to the PFC are different, *T* will eventually arrive at its setting in 10 minutes. Consequently, the current outcomes from the DX A/C system for both cases can remain unchanged. Therefore it is not necessary to establish a fuzzy rule for each of the 121 inputs. Rather, as shown in Table 1, a weight may be assigned to each of the linguistic variables. Then the outputs from the PFCs will be the degrees of the change in *C* or *F*, presented as dx, evaluated by the following equation:

$$\mathrm{dx}=\sum\left[f(n)_t \bullet \mathbf{W}\right] \tag{1}$$

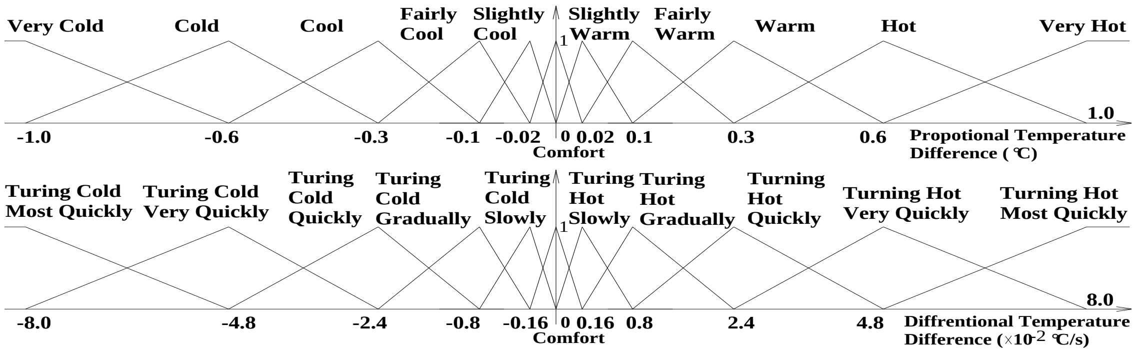
where $f(n)_t$ is the grade of membership for the input error signals, calculated using the membership function as shown in Figure 3. **W** is the weight assigned to each linguistic variable listed in Table 1.

Table 1: Linguistic variables and their corresponding weights for indoor air temperature and humidity control

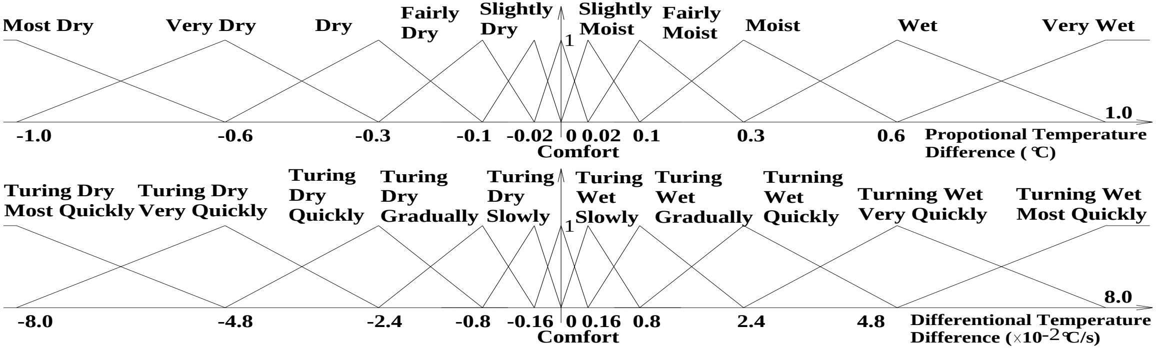
Inputs	Linguistic Variables and Weights										
ΔT_{db}	VH*	H	W	FW	SW	Com	SC	FC	Cool	Cold	VC
	5.0	1.8	1.0	0.6	0.1	0	-0.1	-0.6	-1.0	-1.8	-5.0
$\mathrm{d}T_{db}/\mathrm{dt}$	THMQ	THVQ	THQ	THG	THS	Com	TCS	TCG	TCQ	TCVQ	TCMQ
	5.0	2.0	1.5	0.8	0.1	0	-0.1	-0.8	-1.5	-2.0	-5.0
ΔT_{wb}	VW	Wet	Moist	FM	SM	Com	SD	FD	Dry	VD	MD
	5.0	1.8	1.0	0.6	0.1	0	-0.1	-0.6	-1.0	-1.8	-5.0
$\mathrm{d}T_{wb}/\mathrm{dt}$	TWMQ	TWVQ	TWQ	TWG	TWS	Com	TDS	TDG	TDQ	TDVQ	TDMQ
	5.0	2.0	1.5	0.8	0.1	0	-0.1	-0.8	-1.5	-2.0	-5.0

*Note: abbreviations of linguistic variables shown in Table 1

VH: very hot; H: hot; W: warm; FW: fairly warm; SW: slightly warm; Com: comfort; SC: slightly cool; FC: fairly cool; VC: very cold; THMQ: turning hot most quickly; THVQ: turning hot very quickly; THQ: turning hot quickly; THG: turning hot gradually; THS: turning hot slowly; TCS: turning cold slowly; TCG: turning cold gradually; TCQ: turning cold quickly; TCVQ: turning cold very quickly; TCMQ: turning cold most quickly; VW: very wet; FM: fairly moist; SM: slightly moist; SD: slightly dry; FD: fairly dry; VD: very dry; MD: most dry; TWMQ: turning wet most quickly; TWVQ: turning wet very quickly; TWQ: turning wet quickly; TWG: turning wet gradually; TWS: turning wet slowly; TDS: turning dry slowly; TDG: turning dry gradually; TDQ: turning dry quickly; TDVQ: turning dry very quickly; TDMQ: turning dry most quickly.



(a) Membership Function for controlling T_{db}



(b) Membership Function for controlling T_{wb}

Figure 3: Structure of Membership functions for the PFCs

With the degrees of the change in *C* and *F*, the required compressor and supply fan speeds can be evaluated by following equations:

$$C(t+1)-C(t)=\left(C_{\max}-C(t)\right)/10\times dC,\quad dC\geq 0 \tag{2a}$$

$$C(t+1)-C(t)=\left(C(t)-C_{\min}\right)/10\times dC,\quad dC\leq 0 \tag{2b}$$

$$F(t+1)-F(t)=\left(F(t)-F_{\max}\right)/10\times dF,\quad dF\geq 0 \tag{3a}$$

$$F(t+1)-F(t)=\left(F_{\min}-F(t)\right)/10\times dF,\quad dF\leq 0 \tag{3b}$$

where *t* is the current time point and *t*+1 the next time point, the maximum and minimum value for *C* and *F* are set at 90% and 25% for safely operating the system. Therefore, the speed signals of *C* and *F* are sent to the system to regulate the compressor and supply fan, realizing simultaneous control of indoor air temperature and humidity. The complete block diagram is shown in Figure 4.

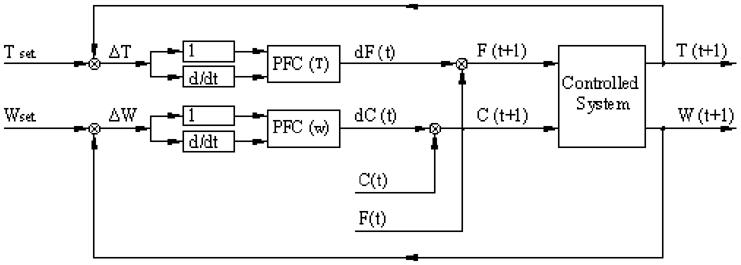


Figure 4: Schematic diagram of the complete PD-law-combining fuzzy logic controller for a VS DX A/C system

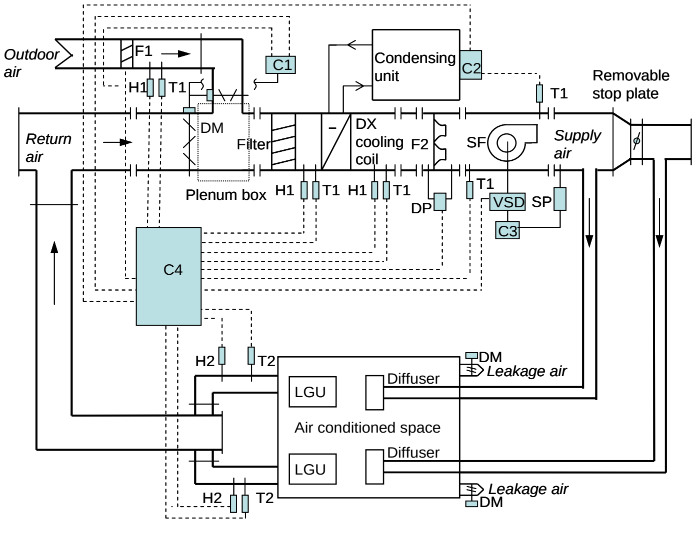
3. EXPERIMENTAL SETUP

3.1 The experimental VS DX A/C system

All the experimental works were carried in an experimental VS DX A/C system which was previously setup and used in previous related studies (Li and Deng, 2007; Xu *et al.*, 2008; Li *et al.*, 2014). As shown schematically in Figure 5, the experimental DX A/C system was made of two main parts, a DX A/C refrigeration plant and an air distributed sub-system. For the refrigerating plant, there was a variable-speed scroll compressor, an electronic expansion valve (EEV), a high efficiency louver-finned tube DX evaporator and an air-cooled plate-finned tube condenser. The variable-speed scroll compressor had a nominal cooling capacity of 9.9 kW, with a total charge of 5.3 kg refrigerant R22. With the variable-speed operation, the output cooling capacity of the compressor could be modulated from 15% to 110% of its nominal cooling capacity. The evaporator was placed in the supply air duct to function as a DX air cooling and humidifying coil. The EEV can be manually or PID controlled to regulate the refrigerant flow rate based on the degree of superheat setting at the exit of evaporator. The condenser fan can also be variable-speed operated. Besides, an electrical heater was used to control the temperature of the cooling air entering the condensing unit so that different operating conditions of the condensing temperature for different experimental purposes may be maintained.

The air distribution sub-system consisted of an air-distribution duct work and a simulated conditioned space of 7.6 m (L) × 3.8 m (W) × 2.8 m (H). A variable-speed centrifugal fan was used as a supply fan of the DX A/C system. Load generation units (LGU) were placed inside the conditioned space to simulate sensible and latent load for the space, up to 12 kW and 4 kW for sensible and latent load, respectively.

This experimental VS DX A/C system was fully instrumented with high precision sensors and transducers for measuring operating parameters including temperatures, air and refrigerant flow rates, and operating pressures in the DX refrigeration plant, etc., and all the measurements were computerized. Air humidity was indirectly measured by measuring air dry-bulb and air wet-bulb temperature. The temperature sensors for both air and refrigerant were of platinum Resistance Temperature Device (RTD) type with a pre-calibrated accuracy of ±0.1 ℃. The supply air flow rate to the conditioned space was measured by the apparatus constructed in accordance with ANSI / ASHRAE Standard 41.2, consisting of a set of nozzles of different sizes, diffusion baffles and a manometer with a measuring accuracy of ±0.1% of the full reading scale. A computerized data acquisition system used in the experimental VS DX A/C system provided 48 channels to record all measured operating parameters, based on which the developed controller was conveniently integrated into it by self-programming.



C1-controller of outdoor/return air damper
C2-controller of condensing unit
C3-controller of supply fan
C4-data acquisition and control unit
DM-damper
DP-differential pressure transducer
F1-hot film anemometer
F2-supply airflow rate measuring apparatus
H1-air wet-bulb temperature sensor
H2-air humidity meter
LGU-load generating unit
SF-supply fan with motor outside duct
SP-static pressure measuring device
T1,T2-air dry-bulb temperature sensor
VSD-variable speed drives

Figure 5: Schematic diagram of the complete experimental VS DX A/C system

3.2 Experimental conditions

For validating the controllability of the proposed PD-law-combining fuzzy logic controller for a VS DX A/C system, two kinds of controllability tests were carried out:

(1). The command following test: to test controller's ability of reacting to the changes of set points. During this type of test, the set points of indoor air dry-bulb and wet-bulb temperatures were both altered from 23 ℃ and 16 ℃ to 25 ℃ and 18 ℃, respectively. The controller was expected to response so that the indoor air temperature and moisture content can be maintained at their respective new set points.

(2). The disturbance rejection test: to test the controller's ability of resisting the disturbance caused by the variation of indoor cooling load. The output variables of the VS DX A/C system, i.e., indoor air dry-bulb and wet-bulb temperatures were to be maintained at their respective set points, 23 ℃ and 16 ℃, when space sensible and latent cooling loads were altered from 5.26 kW and 1.42 kW to 3.97 kW and 1.15 kW, respectively.

During all experiments, the condenser cooling air flow rate remained constant at 3100 m^3/h with a fixed condenser cooling air inlet temperature of 35 ℃. The degree of refrigerant superheat was also fixed at 6 ℃. The detailed experiment results will be reported in Section 4.

4. PD-LAW-COMBINING FUZZY LOGIC CONTROL FOR THE VS DX A/C SYSTEM

After developing the PD-law-combining fuzzy logic controller for the experimental VS DX A/C system, the controllability tests to examine its control performance were carried out using the experimental VS DX A/C system. When carrying out the tests, the controller was digitally implemented in the form of a computer program, with suitable interfaces for collecting data and outputting control signals such as varying speeds of compressor and supply fan via variable-frequency inverters.

4.1 Command following test

Figure 6 shows the results of command following test for the PD-law-combining fuzzy logic controller, with changes in the set points of indoor air dry-bulb and wet-bulb temperatures. As seen, indoor air temperature settings were at 23 ℃ for dry-bulb temperature and 16 ℃ for wet-bulb temperature before the changes were introduced. At t=300 s, the above settings were changed to 25 ℃ and 18 ℃, respectively, and the PD-law-combining fuzzy logic controller reacted immediately by simultaneously varying the compressor and supply fan speeds, as shown in Figure 7. The indoor air dry-bulb and wet-bulb temperatures reached their respective new set points after about 1500s. With a little overshoot and oscillation, the indoor air temperatures maintained stably at their new set points with satisfactory accuracy for the rest of the test, as shown in Figure 6. Therefore, the PD-law-combining fuzzy logic controller developed is able to track the changes in the indoor air dry-bulb and wet-bulb temperature settings.

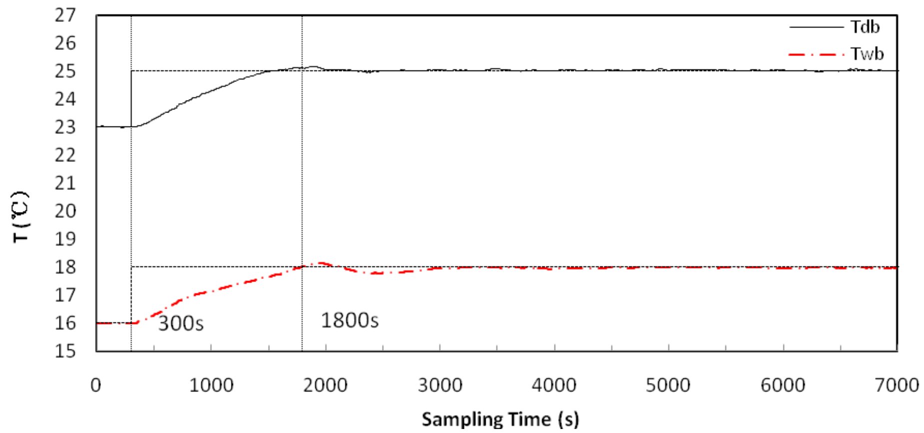


Figure 6: Variation of temperatures in command following test

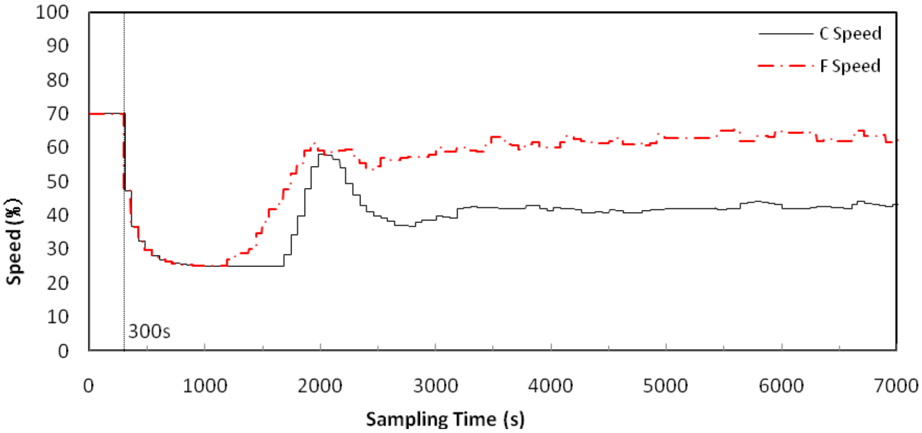


Figure 7: Variation of compressor and supply fan speeds in command following test

4.2 Disturbance rejection test

During the disturbance rejection test, the indoor air temperature settings were 23 ℃ for air dry-bulb temperature and 16 ℃ for air wet-bulb temperature, respectively. The PD-law-combining fuzzy logic controller was expected to maintain these settings after the disturbances in both sensible and latent cooling loads were introduced. The PD-law-combining fuzzy logic controller was enabled when the deviation caused by disturbances in cooling loads for both the measured indoor air dry-bulb and wet-bulb temperatures were greater than ±0.5 ℃.

Figure 8 and 9 presents the results of disturbance rejection test for the PD-law-combining fuzzy logic controller. As seen, prior to the introduction of disturbance at t=300s, indoor air temperatures were stably maintained at their respective set points. At t=300s, space sensible cooling load was reduced from 5.26 kW to 3.97 kW and latent cooling load from 1.42 kW to 1.15 kW, respectively. In response to the decreased space cooling load, both indoor air dry-bulb and wet-bulb temperatures gradually decreased. At about 990 s, when indoor air wet-bulb temperature dropped to 15.5 ℃, the PD-law-combining fuzzy logic controller was enabled. The indoor air dry-bulb and wet-bulb temperatures were dragged back to their respective set points after about 1000s and were maintained stably for the rest of the test, as shown in Figure 8. Figure 9 presents the variation profile of compressor speed and supply fan speed. As seen, the controller began to regulate the compressor and supply fan speeds immediately since enabled. At the final stage of the test, the compressor and supply fan speeds were maintained stably at a new combination, suggesting that the output cooling capacities from the VS DX A/C system at this speed combination matched the decreased indoor sensible and latent cooling loads, therefore realizing simultaneous control of the indoor air temperature and humidity.

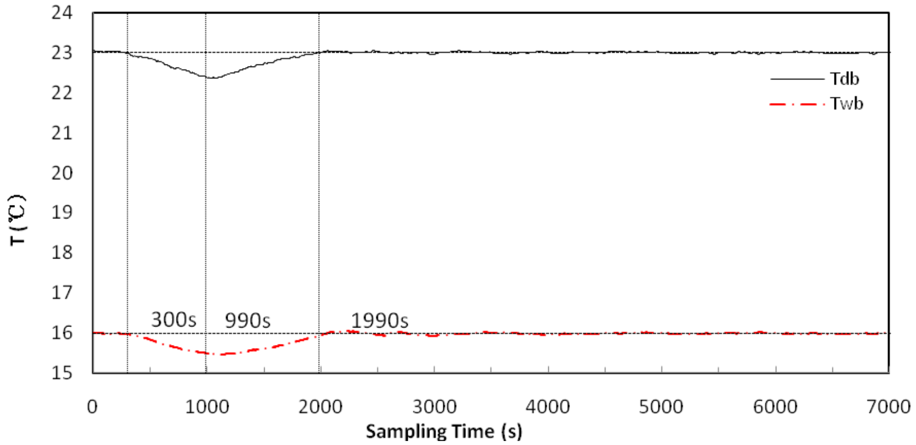


Figure 8: Variation of temperatures in disturbance rejection test

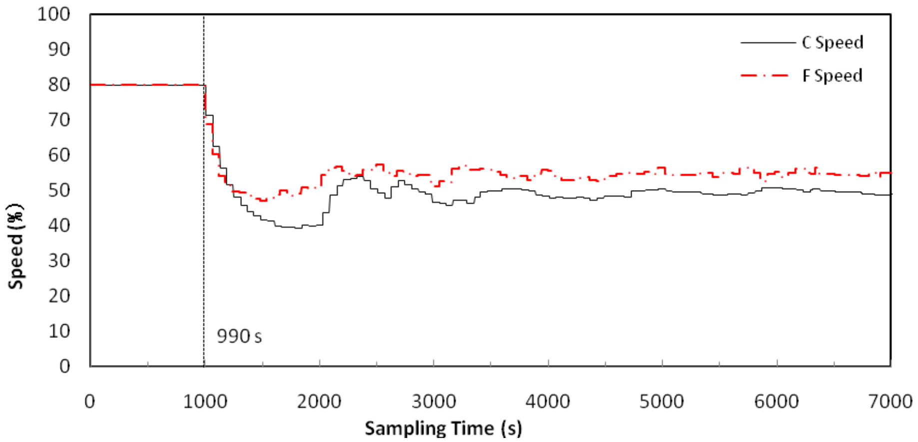


Figure 9: Variation of compressor and supply fan speeds in disturbance rejection test

The disturbance rejection test validated that the PD-law-combining fuzzy logic controller was able to bring back the indoor air dry-bulb and wet-bulb temperatures to their respective set points after indoor cooling loads were varied, with satisfactory control performance in terms of control sensitivity and accuracy. As seen, when the indoor temperatures were maintained, deviation or oscillation can hardly be found in the tests.

5. CONCLUSIONS

In this paper, a PD-law-combining fuzzy logic control algorithm for a VS DX A/C system has been proposed that varying compressor speeds according to the indoor wet-bulb temperature and supply fan speed to the air dry-bulb temperature. The controller was developed and experimentally validated through controllability tests, including command following test and disturbance rejection test, carried out using an experimental VS DX A/C system. One same set of weights (see Table 1) for developing the PD-law-combining fuzzy logic controllers was used in both sets of experiments. In command following test, the indoor air dry-bulb temperature and wet-bulb temperature could be maintained at their respective new set points. In the disturbance rejection test, the results proved that the PD-law-combining fuzzy logic controller could effectively maintain the indoor air dry-bulb and wet-bulb temperatures at their respective set points when disturbances to the indoor sensible and latent cooling load were experienced. Therefore, the experimental results showed that this PD-law-combining fuzzy logic controller developed can realize simultaneous control of indoor temperature and humidity by varying compressor and supply fan speeds of the VS DX A/C system with an adequate control accuracy and sensitivity while simpler development than other sophisticate controllers which are physical or empirical models based.

NOMENCLATURE

C	percentage of the maximum compressor speed	(%)
F	percentage of the maximum supply air fan speed	(%)
T	indoor air temperature	(℃)
t	sampling time step	(–)
W	indoor air absolute humidity	(g/kg)
W	weight assigned to each linguistic variable	(–)

Subscript

db	dry-bulb
wb	wet-bulb

Abbreviations

A/C	air conditioning
DX	direct expansion
PFC	PD law based fuzzy logic sub controller

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