

Design and Implementation of a Fan Coil Unit Controller Based on the Duty Ratio Fuzzy Method

Liang Zhao, Jili Zhang, Kai Li

Abstract—A microcontroller-based fan coil unit (FCU) fuzzy controller is designed and implemented in this paper. The controller employs the concept of duty ratio on the electric valve control, which could make full use of the cooling and dehumidifying capacity of the FCU when the valve is off. The traditional control method and its limitations are analyzed. The hardware and software design processes are introduced in detail. The experimental results show that the proposed method is more energy efficient compared to the traditional controlling strategy. Furthermore, a more comfortable room condition could be achieved by the proposed method. The proposed low-cost FCU fuzzy controller deserves to be widely used in engineering applications.

Keywords—Fan coil unit, duty ratio, fuzzy controller, experiment.

I. INTRODUCTION

THE FCU is a major component of terminal equipment for a central air conditioning system, which can maintain a constant room temperature by circulating cooled or heated water through a coil. The advantages of the FCU include small size, easy installation and flexible layout, making it suitable to be widely used in residential, commercial, and industrial buildings [1]. Controlling the FCU can not only improve the overall thermal comfort, but it also an important method for developing an energy saving central air-conditioning system, which has attracted numerous research studies in recent years [2]-[4]. Numerous innovative technologies have been developed in this regard, and many studies are still being undertaken.

Chen [3] presented a unique controlling method based on skin-load to solve the issues of the FCU systems, by using the application of a radiant temperature sensor. In 2002, Ke [4] compared the operational performance of constant air volume type FCUs to variable air volume (VAV) type FCUs experimentally. The results showed that the VAV-type FCU had greater energy saving potential. Based on this, in 2007, Ke et al. [5] proposed an innovative, differential FCU control method, which integrated the consideration of both the energy saving aspect and indoor air quality. In 2012, Edwards et al. [6] simulated the performance of different combinations of FCU and pump speeds over a range of capacities by using an empirical fan coil and pump model. But, the model is too

simple [7], [8]. Moreover, the performance under the experimental condition is unknown. However, it is difficult to get the precise mathematical model of a FCU using traditional control methods due to its nonlinear, large delay, and time-varying characteristics. Besides that, traditional methods cannot adjust the working status of the controller according to the change in room temperature in a timely manner, which negates the energy saving effect. In this context, some researchers considered introducing intelligent control theory for the FCU energy-efficiency control, such as the fuzzy control method.

In 1995, Jiang et al. [9] proposed a controller, which could adjust the speed of the fan and the three-way valve bypass ratio of the FCU system by using fuzzy theory. In 2001, Ghiaus [10] developed a T-S type fuzzy model-based control method to describe the operational performance of the FCU. The experimental results showed that the performance of the fuzzy control method was better than the traditional PID control method, especially in terms of its energy saving potential and indoor thermal comfort. In literature [11]-[13], the researchers designed a combination of fuzzy and PID control by introducing optimization and feedback into the process of logical reasoning, which could automatically reason through different parameters. Furthermore, Guo et al. [14] introduced a genetic algorithm into the fuzzy control system, which could find the optimal value automatically by collaborating the input variable membership functions and the control rules. The only shortcoming was that the developed model was too complex and required a large amount of data which might not be available in most cases.

Our research team has also been concerned about this direction and to promote the operating efficiency of the HVAC system. In 2010, Chi et al. [15] proposed a duty ratio fuzzy control method in the electric valve control of the fan coil by simulation. After that, Zhao et al. [16] verified the correctness of it through an experimental study. The results showed that this strategy could achieve a good control effect and was more energy efficient than the traditional control methods. In addition, a preferable control effect for the temperature in room could be achieved as well.

Based on the research results, this paper develops a low-cost FCU controller, which has the possibility of replacing other expensive controllers in engineering applications. The rest of this paper is organized as follows: Section II describes the traditional method for FCU and the corresponding problems. The design of the proposed fuzzy controller for the FCU, which includes hardware and software design, is introduced in Section III. Section IV discusses the experimental results. Finally,

Liang Zhao is with the Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology, Dalian 116024, China (e-mail: zliang@dut.edu.cn).

Jili Zhang is with the Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, China.

Kai Li is with the Northeast Architectural Design & Research Institute Co., Ltd., Shenyang, 11000, China.

Section V concludes the paper.

II. THE TRADITIONAL CONTROL STRATEGY FOR FCU

A. Control Strategy

Generally speaking, there are two main control strategies for a fan coil; the first one is the water volume control, which is achieved by adjusting the two-way or three-way solenoid valve, and the other one is the air volume control, which is

implemented by controlling three fan levels (high, medium and low). The structure of the FCU selected in this paper is the most widely used. The control points are illustrated in Fig. 1. The input parameters of the controller include the room temperature, set point of the room temperature, and the operating mode of the fan coil. The output parameters include the three-speed signal and the make-and-break signal of the electric water valve.

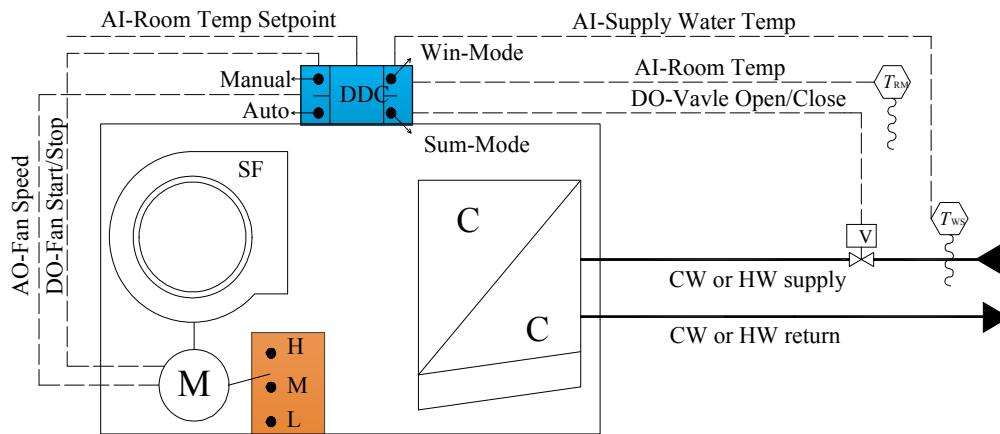


Fig. 1 Control points of the FCU

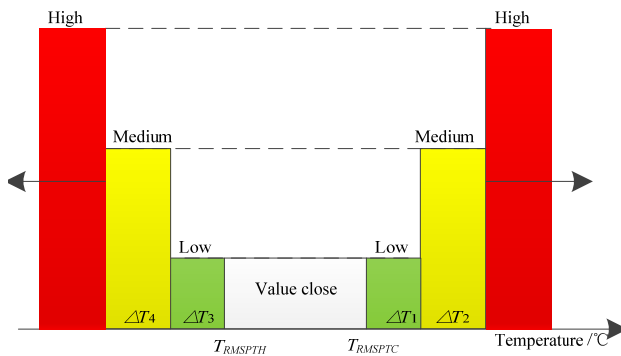


Fig. 2 Traditional control method of FCU

A diagram of a traditional control strategy for a FCU is described in Fig. 2, $TRMSPTH$ and $TRMSPTC$ are room temperature setting values in winter and summer mode, respectively. The control strategy is as follows:

1. Winter Mode

- (1) Valve will be closed when $TRMSPTH$ is higher than the room temperature, otherwise it is open;
- (2) Fan running at a low speed when the room temperature is between $TRMSPTH - \Delta T_3$ and $TRMSPTH$;
- (3) Fan running at a medium speed when the room temperature is between $TRMSPTH - \Delta T_4$ and $TRMSPTH - \Delta T_3$;
- (4) Fan running at a high speed when the room temperature is lower than $TRMSPTH - \Delta T_4$.

2. In Summer Mode

- (1) Valve will be closed when $TRMSPTC$ is lower than room temperature, otherwise opened;
- (2) Fan running at a low speed, when the room temperature is between $TRMSPTC$ and $TRMSPTC + \Delta T_1$;
- (3) Fan running at a medium speed, when the room temperature is between $TRMSPTC + \Delta T_1$ and $TRMSPTC + \Delta T_2$;
- (4) Fan running at a high speed, when the room temperature is higher than $TRMSPTC + \Delta T_2$.

B. Problem Description

Traditional fan coil control strategy has a certain control effect; however, there are still a few areas that could be improved for greater energy saving. The detailed comments are as follows:

- (1) The status of the valve is on most of the time using the traditional control strategy, which means that power is being used to maintain the open state. The opening time could be reduced if some appropriate methods are adopted, such as taking advantage of the cooling and dehumidifying capabilities of the unit during the short period after the water valve has just closed. In addition, chilled water flow and chilled pump power consumption could be reduced with this method.
- (2) The traditional control strategy for the valve is on-off mode, which is not suitable for intelligent control theory. We can modify it to an analog signal mode based on the duty ratio, and introduce fuzzy methodology to optimize the FCU control.

(3) Room temperature deviation is the only consideration for the traditional control strategy method in auto mode, as shown in Fig. 2. In this case, the FCU speed control signal will be changed persistently and cause temperature fluctuations, affecting the control function.

In order to solve the above problems, this paper develops a FCU controller, which employs the concept of a duty ratio on an electric valve in order to fully utilize the cooling capacity of the FCU. The duty ratio of the electric valve and the fan speed signal are decided according to temperature deviation and deviation change of the indoor temperature.

III. DESIGN OF THE FAN COIL FUZZY CONTROLLER

A. Overall Design

The overall interfaces of the controller are shown in Fig. 3. The fuzzy controller consists of two thermistor inputs. The three-wire connecting mode is used to eliminate the measuring errors due to large wire resistance generated by the long communication cable from the temperature sensors to the controller (the sensors and the controller will be installed in different places in most cases). Besides that, seven channel controllable silicon switches are designed in order to control the three fan speeds (three channels) and the water valve (2x2, four channels). Furthermore, two digital and analog interfaces are reserved for the future expansion. Finally, an RS485 communication interface is designed for communicating with the computer.

B. Hardware Design

The forward channel of the system is consisted of four sensor modules, which can measure room temperatures via the NTC thermistors, measure the temperature of the water in the fan coil via the PT1000, and capture the temperature setting point and the fan operating status by using a smart meter. The forward

channel of the controller mainly consists of the electric bridge circuit, amplifying circuit and a low-pass filtering circuit, which is described in detail as follows:

1. Electric Bridge Circuit

The principle behind measuring the resistance with the bridge method is shown in Fig. 4 (a), where R_t denotes the thermistor, R_w denotes the wire resistance, R_1 , R_2 , R_3 denote the bridge arm resistances, respectively. Temperature changes will result in variations of the thermistor resistance, and the voltage difference between the two sides of the bridge will then change accordingly.

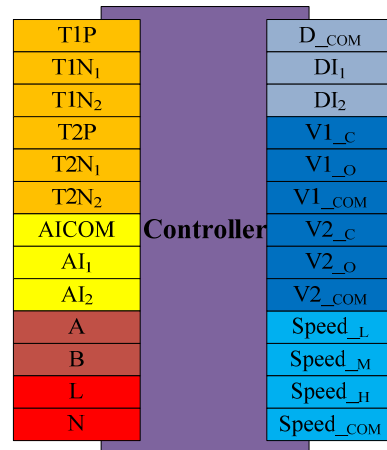
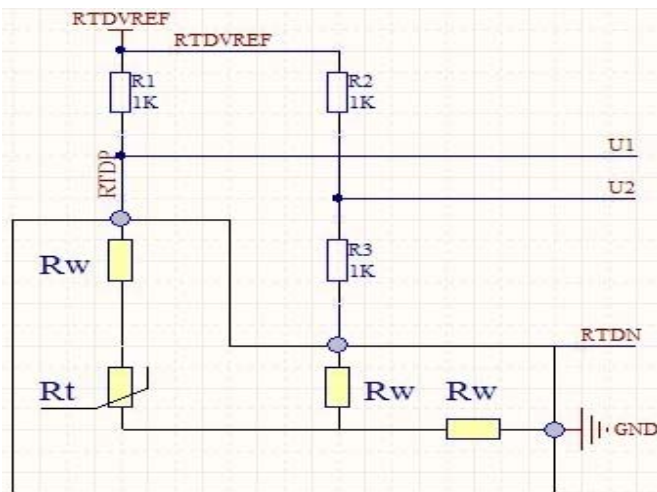
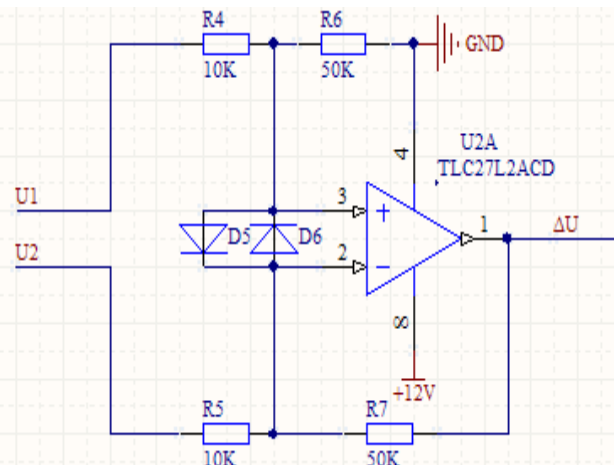


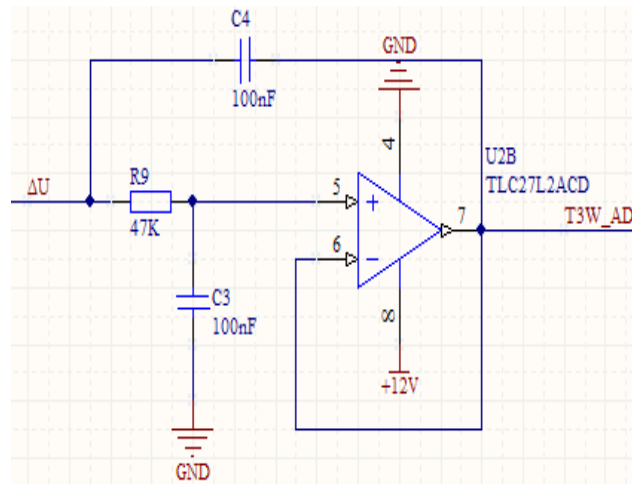
Fig. 3 Interfaces of FCU controller



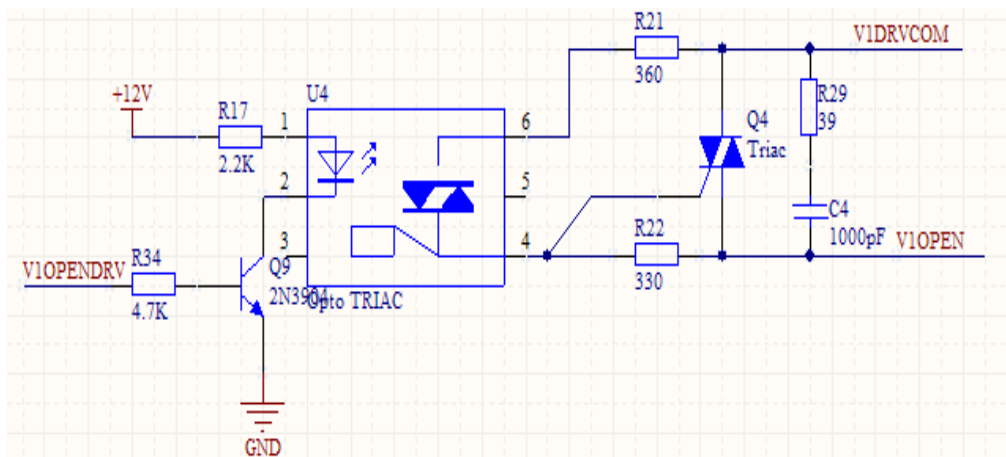
(a) Bridge circuit



(b) Amplifying circuit



(c) Filter circuit



(d) Water valve control circuit

Fig. 4 Schematic diagrams of hardware circuit

2. Amplifying Circuit

The voltages signal generated by the bridge circuit are usually very small, especially in normal temperatures and temperature ranges fluctuating several degrees around normal temperatures, resulting in the low accuracy of temperature measurements. Therefore, it is necessary to amplify the bridge circuit with the operational amplifying circuit to improve accuracy, as shown in Fig. 4 (b). The amplifying principle behind the circuit is to make the voltage difference of the bridge mostly fall within the AD reference voltage range within the entire temperature range.

3. Low-passing Filter Circuit

The low-passing filter circuit is incorporated to avoid the effects of high-frequency fluctuations. The filtered voltage signals are input to the AD converters of the micro-controller. The circuit is shown in Fig. 4 (c), where the cutoff frequency is $1/2\pi RC = 33.86$ Hz, meaning that the signal with a frequency higher than this value will be filtered out automatically.

4. Controller Driven Electric Water Valve

The forward channel of the fuzzy controller is designed to control the make-and-break of the electric water valve and the three speeds (high, medium and low) of the fan. The four interface pins of the micro-controller can exercise control over the make-and-break of at most two electric water valves. The circuits are shown in Fig. 4 (d), where Opto TRIAC is an optical isolation component. If the output pin V1OPENDRV delivers the digital value of one, then the triode 2N3904 is on, and the second pin of the Opto TRIAC generates a low voltage to turn on the controllable silicon switch. Then, the right circuit will be connected to drive the electrical water valve. If the output pin V1OPENDRV provides the digital value of zero, the controllable silicon switch will be turned off and the electrical water valve takes no actions.

C. The Software Design

1. Duty-Cycle Fuzzy Controlling Strategy

A novel strategy, known as duty cycle fuzzy control, is proposed to optimize the control over the FCU. We begin with describing the concept of the duty cycle R_{ON} . In controlling

period τ_{cyc} , if the electrical water valve is opened at τ_{on} , then R_{ON} is calculated as:

$$R_{on} = \frac{\tau_{on}}{\tau_{cyc}} \quad (1)$$

Consider that the difference between the current room temperature and the room temperature set point is e_T , the change of the room temperature difference is ec_T (the difference between the current room temperature deviation and the room temperature deviation at the previous time step). In the proposed strategy, R_{ON} and the fan speed are regulated simultaneously according to e_T and ec_T , as shown in Fig. 5, where FS denotes the speed status of the fan.

Using the summer automatic mode of the fan as an example, if the room temperature is lower than the set point, then R_{ON} is 0 (i.e. the water valve is turned off in the current controlling period), and the fan is at the low speed or turned off. If the room temperature is in the range $T_{RMSPT} - T_{RMSPT} + \Delta T$ (the shaded area in Fig. 5), then the output values of the fan speed signal and R_{ON} are determined via fuzzy logic reasoning together with e_T and ec_T . If the room temperature is above $T_{RMSPT} + \Delta T$, then R_{ON} is set to 1, the water valve is opened, and the fan is set to the high speed.

In the manual mode, the duty cycle of the water is computed via fuzzy logic reasoning to determine when the valve is to be opened, without taking into account the control over the fan speed. The strategies for the winter mode are similar.

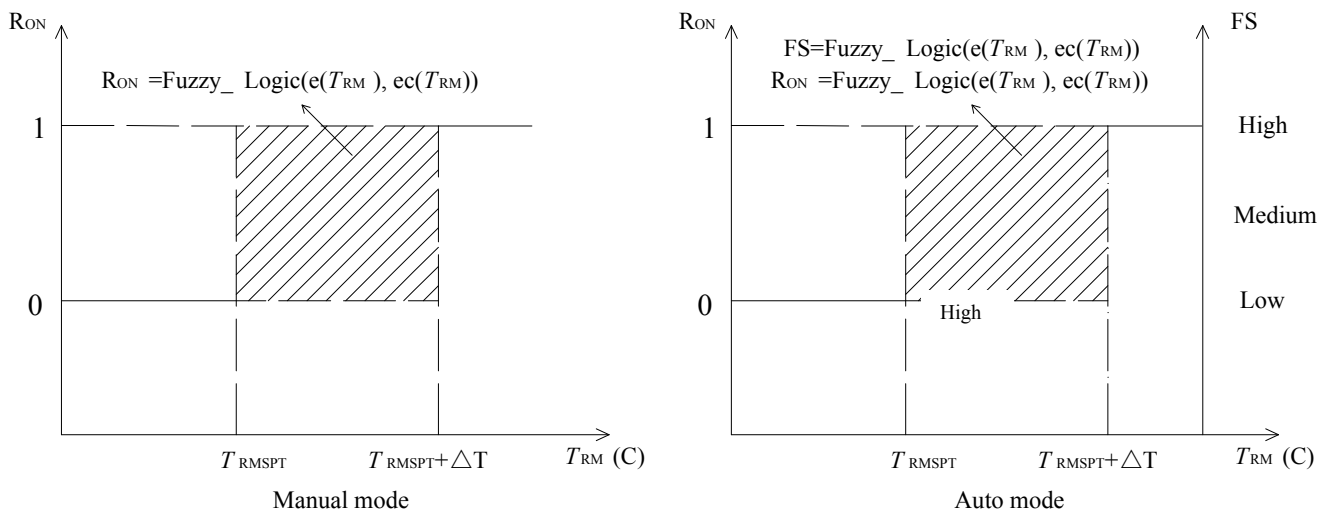


Fig. 5 The strategy of fuzzy controlling

The core of the algorithm is the shadow area in Fig. 5. The input parameters of the algorithm include the room temperature measurements, room temperature set points, and the fan's operating mode. The aim of the algorithm is to exercise control over the electrical water valve and the three-speed fan. The outputs of the algorithm are the valve's duty cycle and the fan's speed signal.

2. Duty-Cycle Fuzzy Controlling Algorithm

The procedures of the duty cycle fuzzy controlling algorithm are shown in Figs. 6 (a) and (b).

As for the control over the fan speed, if the fuzzy controller detects the manual mode, then the program will skip; if the automatic mode is detected, the controller will compute the speed of the fan via fuzzy reasoning along with the room temperature measurements, especially when the temperature is too high or too low.

As for the control over the electrical water valve, the fuzzy controller will first determine the operating status with the

temperature measurements of the water supply, and then compute the duty cycle of the valve via fuzzy reasoning in order to determine when the valve is to be opened, especially when the temperature is too high or too low.

In addition to the controlling strategies in Figs. 6 (a) and (b), the room temperature changes need to be monitored in real-time due to the adverse effects of the sudden rise of room loads on the room temperature control. If T_{RM} is higher than $T_{RMSPT} + \Delta T$ continuously for a period of time (30 s in the design, dependent on actual applications) or higher than $T_{RMSPT} + \Delta T_1$ (30 s in the design, dependent on actual applications), T_{RMS} denotes the sampling value of the room temperature at the previous moment), then the fan is set automatically to the high speed and the duty cycle of the valve is set to one. The detailed description of the related parameters for the control algorithm is shown in Table I.

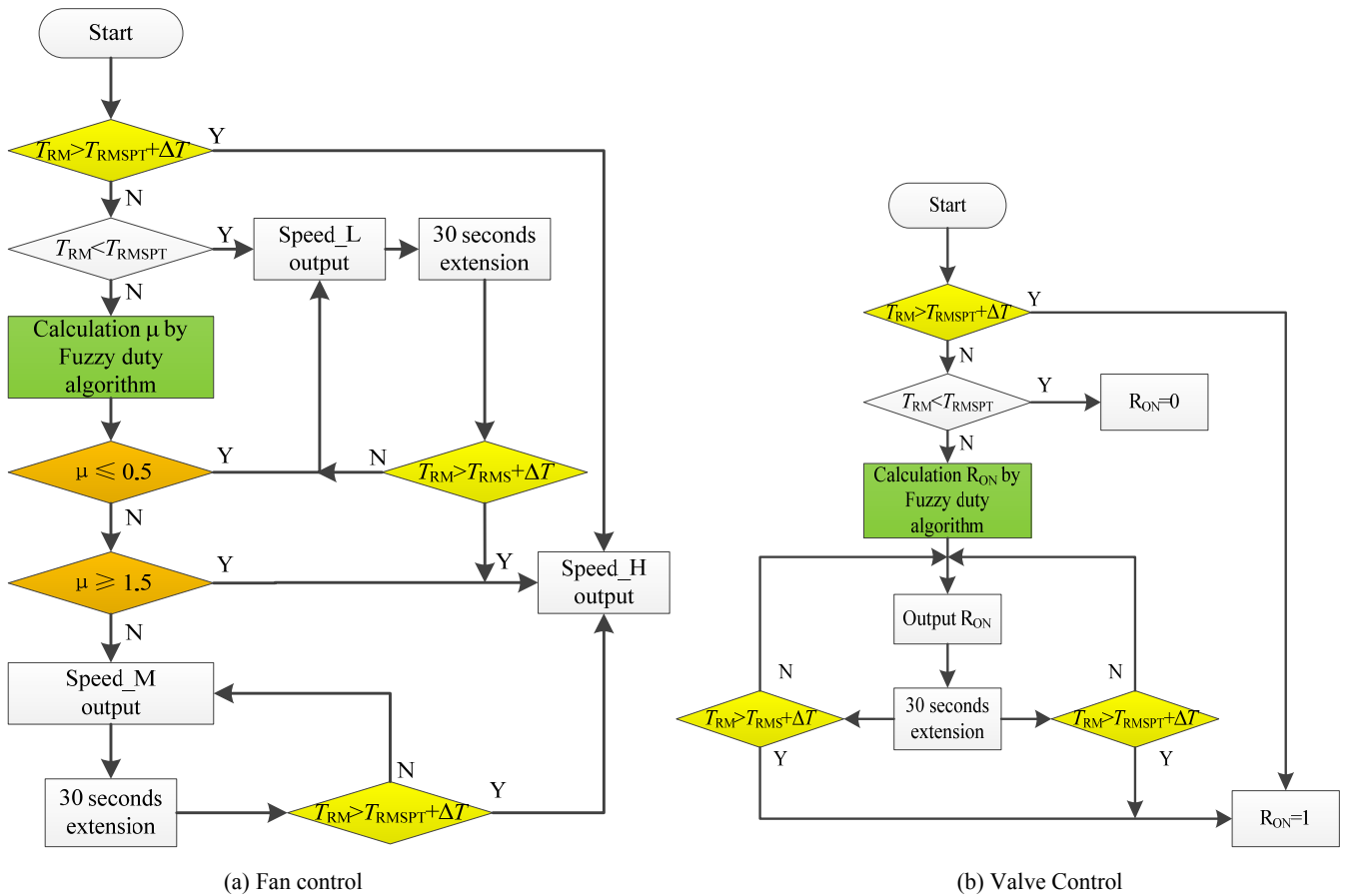


Fig. 6 Flow-charts of fuzzy duty algorithm

TABLE I
 PARAMETERS OF DUTY RATIO FUZZY CONTROL METHOD FOR FCU

Type	Name	Sign	Unit	Comments
Monitoring parameters	Room temperature	T_{RM}	°C	From the smart meter
	Room setting point temperature	T_{RMSPT}	°C	From the smart meter
	Season mode	Sum/Win		From the smart meter
	Control mode	Manual/Auto		From the smart meter
Control parameters	Fan speed	FS		High, medium, low levels
	Valve status	VS		On/Off
Algorithm parameters	Fuzzy domain of e_T	$[-F_{eT}, F_{eT}]$		Set according to algorithm
	Fuzzy domain of ec_T	$[-F_{ecT}, F_{ecT}]$		Set according to algorithm
	Fuzzy domain of u	$[-F_u, F_u]$		Set according to algorithm
	Duty ratio	R_{ON}		Analog output, [0,1]
Adjust parameters	Control cycle	τ_{cyc}	s	Set according to algorithm
	High limit of e_T	ΔT	°C	Set according to algorithm and room temperature
	High limit of ec_T	ΔT_1	°C	Set according to algorithm and room temperature

IV. EXPERIMENTS ON FAN COIL FUZZY CONTROLLER

A. Introduction of Experimental Platform

Fig. 7 shows some pictures of the experiment environment. Fig. 7 (a) is the test room (10 m²), with two heat furnaces and an electric heater, which could be used to implement the function of the load in the room. Fig. 7 (b) is FCU module, and Figs. 7 (c) and (d) are humidity and temperature sensors, respectively. Fig. 7 (e) is the Keithley data acquisition system, which could store the experimental data in the form of Excel, convenient for

further processes. Fig. 7 (f) is the anemometer for measuring the wind volume, with an accuracy of 3%. In this case, the data could be read from the screen directly.

The experiments are performed to compare the performance of the proposed method with that of the traditional controlling strategy. The measuring points of the fan coil are shown in Fig. 8. The details of the measuring points are listed in Table II.



(a) Test room



(f) Hot-wire anemometer

Fig. 7 Experimental conditions



(b) Fan coil unit

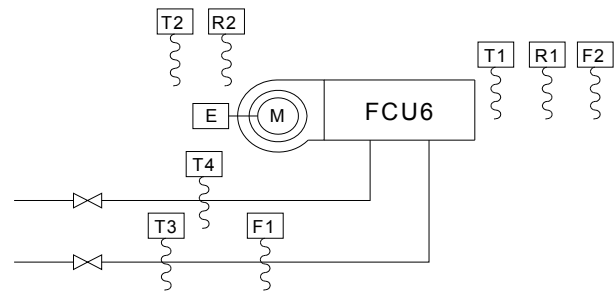
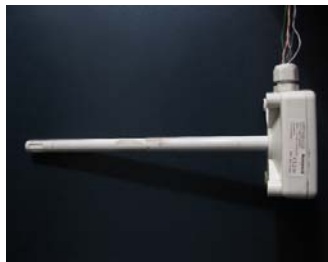


Fig. 8 FCU testing points distribution diagram



(c) Humidity sensor



(d) Temperature sensor



(e) Keithley data acquisition system

TABLE II
DESCRIPTION OF THE TESTING POINTS

Sign	Name	Unit	Meter	Comments
T1	Supply air temperature	°C	PT1000	Accuracy grade 0.2
T2	Return air temperature	°C	PT1000	Accuracy grade 0.2
T3	Supply water temperature	°C	PT1000	Accuracy grade 0.2
T4	Return water temperature	°C	PT1000	Accuracy grade 0.2
R1	Supply humidity temperature	%	Humidity sensor	0~10v output
R2	Return humidity temperature	%	Humidity sensor	0~10v output
F1	Supply water volume	L/h	Rotor flow meter	range 1000 L/h
F2	Supply air volume	m ³ /h	Anemobiagraph	
E	FCU power	kW	Electric meter	

B. Experimental Results

The experimental cycle is 6 h. A 600 W heat source is added to the experimental room at the beginning of each hour and stays on for 10 minutes. The setting algorithm parameters of the two methods are listed in Tables III and IV, respectively.

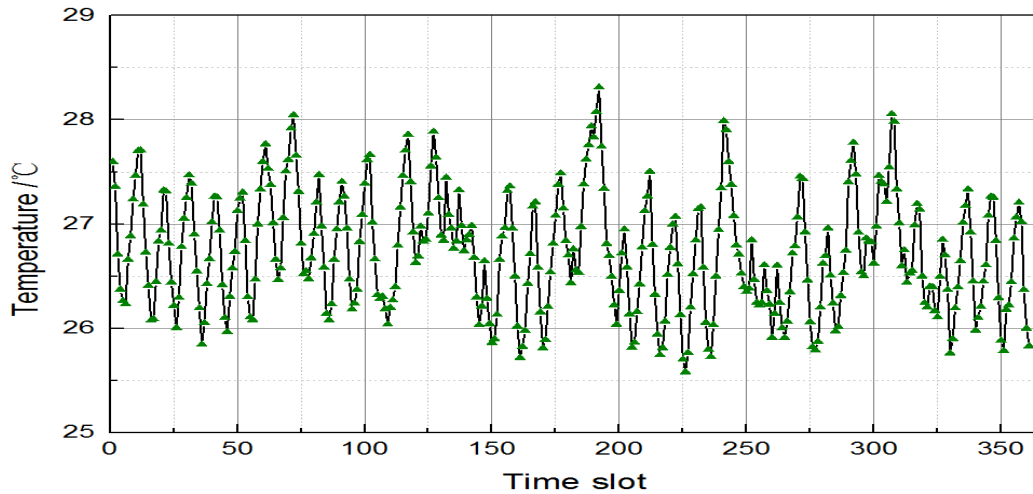
TABLE III
PARAMETERS OF THE FUZZY DUTY CONTROL ALGORITHM

Type	No.	Name	Valve
Working condition parameters	1	Running mode	Summer/Auto
	2	Supply water temperature	14~15 °C
	3	Supply water volume	380L/h
Algorithm parameters	1	Control period	5 minutes
	2	Sampling period	1 minute
	3	e_T, ec_T and u fuzzy domain	[-6,6]°C
	4	e_T actual domain	[0,2]°C
	5	ec_T actual domain	[-0.5,0.5]°C
	6	R_{on} actual domain	[0,1]

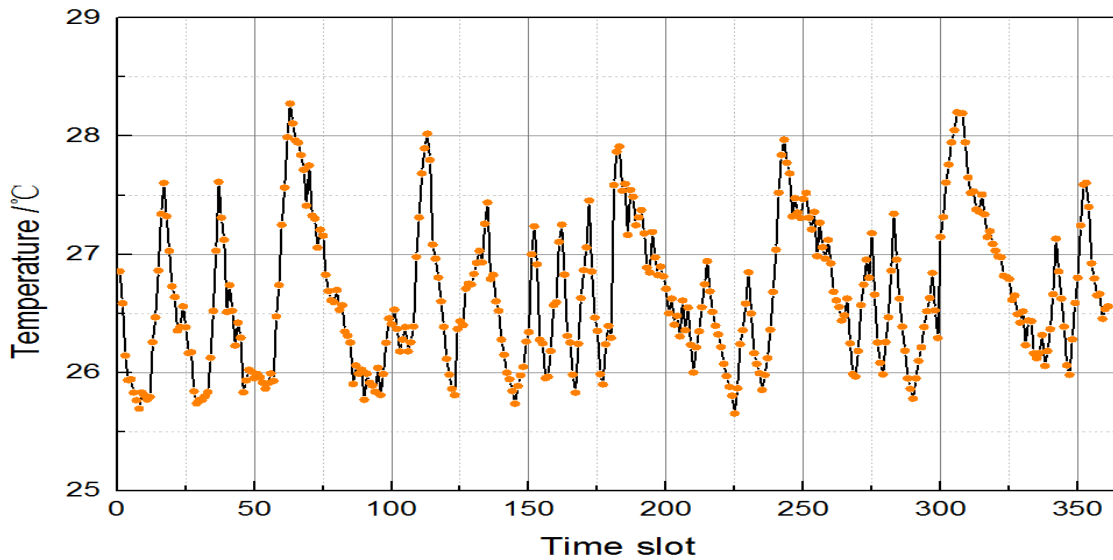
TABLE IV
 PARAMETERS OF TRADITIONAL CONTROL ALGORITHM

Type	No.	Name	Value
Working condition parameters	1	Running mode	Summer/Auto
	2	Supply water temperature	14~15°C
	3	Supply water volume	380L/h
Algorithm parameters	1	ΔT_1 (In Fig. 1 (b))	0.5°C
	2	ΔT_2 (In Fig. 1 (b))	1°C
	3	Dead Band	2°C

The changes of the room temperatures are shown in Figs. 9 (a) and (b), respectively. From Fig. 9 (a), it can be seen that the room temperature is mostly in the range 26~28 °C under the duty cycle fuzzy controlling scheme and fluctuates at 0.3 °C/min. The reason for the extreme temperature fluctuation is the considerable cooling power of the fan due to its immense air blowing ability. From Fig. 9 (b), it can be seen that the amplitude fluctuation is more intense. But overall, both methods have attained a controlling effect.



(a) Fuzzy control method



(b) Traditional control method

Fig. 9 Room temperature change curves

For comparison, two control methods will be arranged in ascending order, from small to large. The comparisons of the controlling effects and the cooling capacities of both methods are shown in Figs. 10 and 11. The duty cycle signal of the duty cycle controlling algorithm is shown in Fig. 12. Table V shows the fan speed controlling signal, water valve controlling signal, full cooling capacity, and comparisons of the controlling effects.

From the room temperature controlling effects, it can be seen that the averages of the room temperature absolute deviations for both methods are close to each other. But, the response curve indicates that the traditional method fluctuates more violently than the proposed method, because the former strategy does not account for the effects of room temperature deviation. The average cooling capacity of the proposed method is 2.21 kW, higher than 1.52 kW of the traditional

method. But, Table V demonstrates that the water supplying time of the proposed scheme is much shorter than that of the traditional method. That is to say, the proposed method fully exploits the cooling capacity of the water valve when it is closed. The fan power consumption also illustrates this point, which means that the proposed method is more energy efficient.

TABLE V
 CONTRAST BETWEEN THE TWO KINDS OF CONTROL METHODS

Method	Fan control /h			Valve control /h	Average temperature deviation/°C	Fan power consumption /kWh
	High speed	Medium speed	Low speed	Run time		
T-M	1	1.5	3.5	4.9	0.66	0.635
F-M	0.75	1	4.25	2.4	0.74	0.412

* T-M traditional method; F-M Fuzzy duty control method

V. CONCLUSIONS

This paper developed a microcontroller-based FCU fuzzy controller, which introduced the concept of duty ratio into the electric control valve and changed the double-digit amount of the traditional methods of control to the duty cycle conversion of analog control. The controller takes full advantage of the cooling capacity of the fan coil when its water supply is cut off, thereby saving some delivery of chilled water consumption. Experimental results show that the proposed method can reduce fan power consumption, cooling water consumption and cooling capacity compared with the traditional controlling strategy, as well as make the room temperature more comfortable.

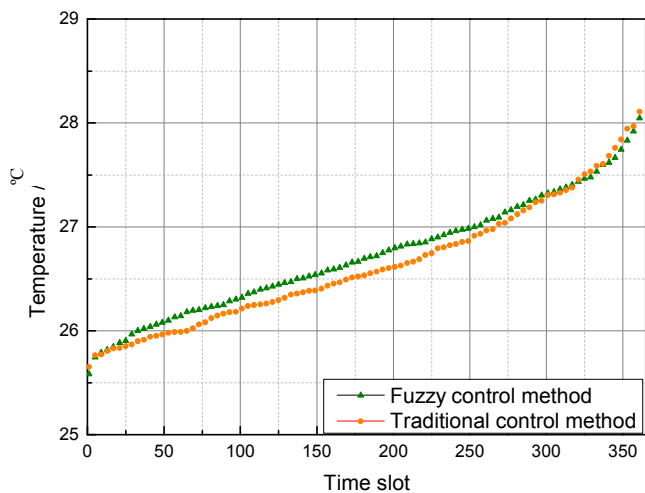


Fig. 10 Contrast of room temperature between the two methods

Although some achievements are made in the development and experiments on the proposed fuzzy controller, this work still requires some improvements. After success in experiments on the single fan coil, the direction of the next phase work will focus on how to control the coordination and operation of the entire fan coil system.

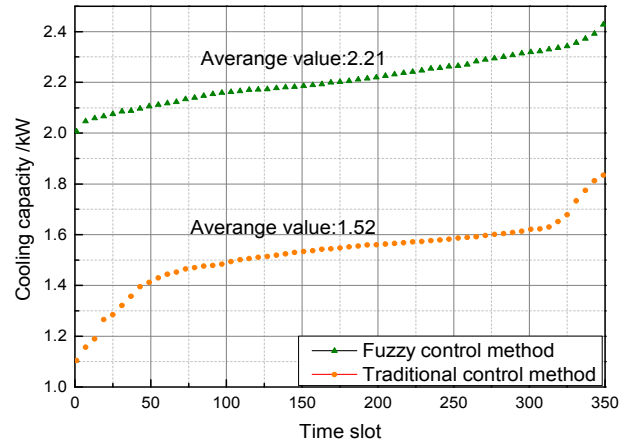


Fig. 11 Curve of cooling capacity for two control methods

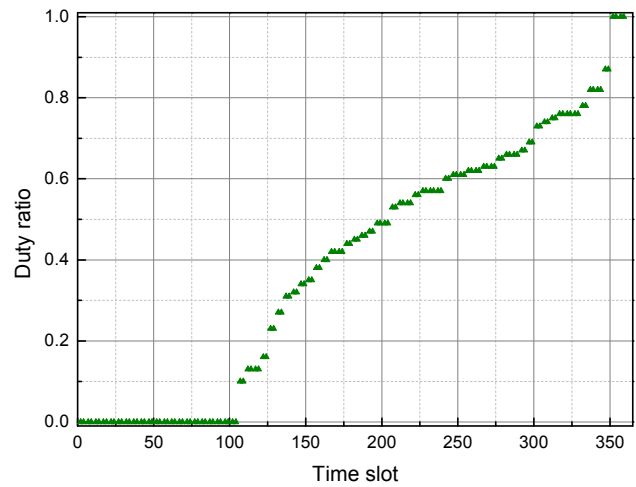


Fig. 12 Curve of duty ratio signal

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