Simulation Study on the Performances of Different FCU Control Logics

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ABSTRACT

The paper studies the performances of three different Fan Coil Unit (FCU) control logics using simulation. One of them is to open/close water valve to meet temperature set point, which is the conventional control logic. Another control logic is to open/close water valve according to a duty ratio decided by a fuzzy logic. The third one is a new control logic proposed by this paper, which controls fan speed level and water valve duty ratio to meet both temperature and humidity set points. The simulation results show that the proposed control logic can achieve better control performance than the previous two control logics.

KEYWORDS

FCU, on/off control, Fuzzy control, duty ratio control

INTRODUCTION

Fan-coil unit (FCU) is a widely used air-conditioning device especially for central air-conditioned office or hotel rooms, which have relatively small floor area, because FCU systems are easy to install and maintain with low-cost. Although one single FCU consumes small amount of electricity, but due to the large quantity and the long running hours, the total electric power consumption of FCUs is the main part of the electric power consumption of HVAC systems. For this reason, optimizing the control logics of FCU can not only improve thermal comfort level, but also potentially contribute a large amount of energy savings.

The conventional FCU control logic is open/close water valve by comparing sensed room temperature with the set point and control band. It’s simple and good in performance of temperature control. But this control logic does not consider the room humidity control, which might cause the humidity to go out of comfort range. For these reasons, a lot of researchers are trying to develop better control logics. Chu et al. (2005) proposes a least enthalpy estimator to provide timely suitable settings. According to the temperature and relative humidity settings, a fuzzy controller makes decisions and adjusts the output of the FCU system. Chung et al. (2006) developed a networking fan coil controller for mulit-FCUs that serve a spaces of medium to large size. Zhao (2011) developed a fuzzy control logic for FCU systems, which uses mamdani-type fuzzy rules and functioning-fuzzy-subset inference methods to decide the duty ratio of valve and fan speed signals according to the deviation and deviation changes of the room temperature.

However, most current researches on FCU control do not consider humidity control. Even some researches give both temperature and humidity set points, but do not discuss how to operate the FCU to meet both set points. Therefore this paper proposes a new FCU control logic, which controls both the temperature and the humidity using two Proportional-Integral-Derivative (PID) controllers. In order to study the

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advantages and disadvantages of this control logic, the performances of proposed the double PID control logic are simulated and compared with the conventional control methods and fuzzy control method.

SIMULATION MODEL

The simulation models of the room and control logics are set up in the Matlab simulink environment. As shown in Figure 1.

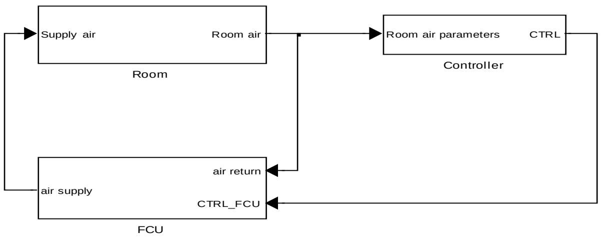

Figure 1. *Simulation model built in the Matlab Simulink environment.*

The simulation model consists of three parts: room model, FCU model and control logic model.

Room Model

The room model is to emulate an ordinary office room with floor area of 30 m^2 and 90 m^3 in volume. The periodical change in every 4 hours of room natural temperature and humidity is set to simulate the influences of weather fluctuation.
Room air temperatures are simulated using State Space Method (Hong and Jiang 1997), as shown in Equation 1.

$$T(\tau)=\Psi^{-1}(\tau)\cdot U(\tau) \qquad (1)$$

Where U represents the heat disturbance added to the room and Ψ represents the contribution of the heat disturbance to room temperature.
Room humidity is simulation using the humidity ratio derivative equation, as shown in Equation 2.

$$V\rho_a \frac{\partial d}{\partial \tau} = G_a \rho_a (d_{as} - d_{ar}) + W + I \qquad (2)$$

Where,
d: Air humidity ratio, g/kgDA
V: Room air volume, m^3
G_a: FCU air flow rate, m^3/s
ρ_a: Air density, kg/m^3
d_{as}: FCU supply air humidity ratio, g/kgDA
d_{ar}: Room air humidity ratio, g/kgDA
W: Indoor moisture emission rate, g/s
I: Moisture gain from infiltration air , g/s

The other simulation conditions are set as follows: 1) Occupant density is 10 m^2 per person and 0.016 g/s moister gain per person; 2) Room humidity ratio changes along a sine wave with an average of 0.3 g, amplitude of 0.04 g, and period of 4 hours. The simulation results of room natural temperature and humidity without control are as shown in Figure 2.

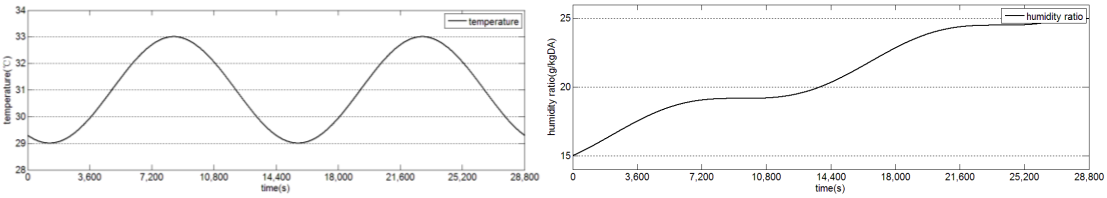

Figure 2. *Simulation results of room temperature and humidity without control*

FCU Model

The inlet chilled water temperature is set at 7℃. The on/off water valve is changed according to a certain control logic. The fan can work at three speed-levels: low, medium and high, which supplies air volume flow rate of 400, 500 and 700 m^3/h respectively. The coil model is a three-row coil model, and the former row coil outlet air parameters are input to the latter row coil. The heat transfer equations of the coil are shown as follows.

The heat transfer equation of air side is:

$$G_a C_{pa}(t_{ain} - t_a) = K_{ra} A_f (t_a - t_r) \quad (3)$$

The differential equation of coil metal parts temperature is:

$$C_r \frac{\partial t_r}{\partial \tau} = K_{rw} A_w (t_w - t_r) + K_{ra} A_f (t_a - t_r) \quad (4)$$

The heat transfer equation of the chilled water side is:

$$G_w C_{pw}(t_{win} - t_w) = K_{rw} A_w (t_w - t_r) \quad (5)$$

When the chilled water temperature is lower than air dew-point temperature, water will be condensed at the surface of coil. The air humidity ratio is calculated using Equation 6.

$$V_a \rho_a \frac{\partial d_a}{\partial \tau} = G_a (d_{in} - d_a) + G_a \sigma (d_s - d_a) \quad (6)$$

Where,

A_f : the coil and fin surface area (m^2);

A_w : the coil tube inside surface area (m^2);

C_{pa} : air specific heat (J/(kgK));

C_{pw} : water specific heat (J/(kgK));

d_{in} : inlet air humidity ratio (g/kgDA);

d_a : outlet air humidity ratio (g/kgDA);

d_s : humidity ratio of saturated air at the temperature of chilled water (g/kgDA);

G_a : the air flaw rate (kg/s);

G_w : the water flaw rate (kg/s);
K_{ra} : the coefficient of heat transfer between fin and air(W/(m^{2}k));
K_{rw} : the coefficient of heat transfer between pipe wall and water(W/(m^{2}k));
t_{ain} : the coils inlet air temperature;
t_a : the outlet air temperature;
t_r : the coil metal parts temperature (Temperature distribution at the fin surface is ignored);
t_w : the outlet chilled water temperature;
t_{win} : the coils inlet water temperature;
V_a : air volume at every row of coil (m^3);
ρ_a : air density (kg/m^3);
σ : coefficient of moisture transfer (-);
τ : time (s).

Control Logics

Proposed Control Logic. This paper proposes a novel control logic that can adjust both room humidity and temperature to meet set points through automatically control fan speed and water valve.

Two PID controllers are used to produce the action command of fan speed and water valve on/off action. The intent is to control room air temperature by tuning fan supply air flow rate through change fan speed level and control room air humidity by tuning supply air humidity trough turning on/off chilled water valve. Considering that supply air flow rate and supply air conditions influence both room air temperature and humidity, the inputs to the two PID controller should not be the room temperature and humidity separately and should be the coupling of them. Therefore the weighted average of room air temperature and humidity deviation is used as the inputs to the PID controllers, as shown in Equation 7 and 8.

$$PID_{in} = \alpha(t_{ar} - t_{set}) + \beta(d_{ar} - d_{set}) \quad (7)$$

$$\alpha + \beta = 1 \quad (8)$$

Where,
t_{ar}: room air temperature, (°C);
t_{set}: room air temperature set point, (°C);
d_{ar}: room air humidity ratio, (g/kgDA);
dt_{set}: room air humidity ratio set point, (g/kgDA);

The α and β in Equation 7 show the influencing weights of room air temperature and humidity deviation to the fan speed and water valve duty ratio respectively. The larger α means more influence of temperature deviation to the PID controller output and larger β means more influence of humidity deviation. In this simulation, for the inputs to fan speed PID controller α equals 0.8 and β equals 0.2, which intends to mainly use fan speed to control room temperature. And for the inputs to water valve duty ratio PID controller, α equals 0.2 and β equals 0.8, intending to mainly use water valve to control room humidity. The flow chart of proposed control logic is shown in Figure 3.

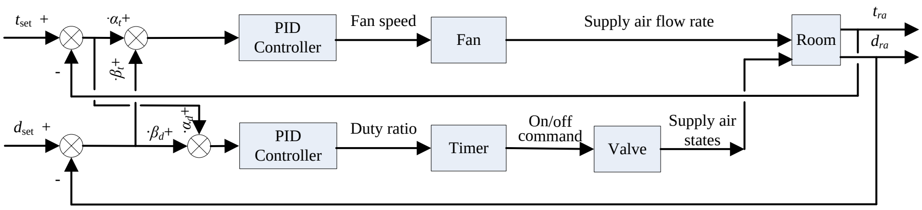

Figure 3. *Flow chart of the newly proposed control logic*

For the purpose of evaluate the performance the proposed control logic, the performances of two more control logics, conventional valve on/off control and fuzzy valve duty ratio control are simulated as well.

Conventional Control Logic. The most often used FCU control logic is to open/close water valve according to the deviation of room air temperature from the set point and the fan speed is set by room occupants according to their preferences, as shown in Figure 4. The merit of this control logic is that it is simple and the frequency of the water valve on-off action is the least at a certain control band. However, the weakness of this control logic is that it can only control temperature in the setting range without consideration of humidity. During simulation, the fan speed is set randomly to simulate the behavior of room occupants' manual setting fan speed. The duty ratio period is set at 300 s.

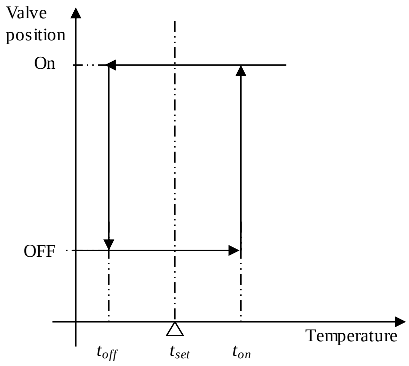

Figure 4. *Conventional valve on/off control logic*

Fuzzy control. Fuzzy control is widely used in many systems in recent years. For the application in FCU control, fuzzy logic is often used to determine the water valve on-off states according to the difference between room temperature and the setting temperature. To use fuzzy control logic, firstly it needs to develop a fuzzy control table in which duty ratios are defined at different conditions of room temperature and humidity. Moreover, a proper duty period should be selected to ensure the control accuracy.

Table 1 shows a fuzzy control table used by this simulation. Where, *dt* is the difference between room air temperature and setting temperature, and *dd* is the difference between room air humidity ratio and its set point. This fuzzy logic intends to control both room temperature and humidity. The values of duty ratio in this fuzzy control table are determined empirically according to the thermal performance of the room and FCU system. Same as the conventional control logic, the fan speed is set randomly to simulate the behavior of room occupants' manual setting fan speed and the duty ratio period is set at 300 s.

Table 1. Fuzzy control parameters of valve duty ratio

<table>
<tr><th>dt \ dd</th><th>(-∞,-1.6)</th><th>(-1.6,-1)</th><th>(-1,-0.3)</th><th>(-0.3,0.3)</th><th>(0.3,1)</th><th>(1,1.6)</th><th>(1.6,+∞)</th></tr>
<tr><td>(-∞,-0.8)</td><td colspan="7">1</td></tr>
<tr><td>(-0.8,-0.3)</td><td rowspan="5">0.6</td><td>0.93</td><td>0.86</td><td>0.79</td><td>0.71</td><td>0.64</td><td rowspan="5">0</td></tr>
<tr><td>(-0.3,-0.1)</td><td>0.71</td><td>0.64</td><td>0.57</td><td>0.5</td><td>0.43</td></tr>
<tr><td>(-0.1,0.1)</td><td>0.57</td><td>0.5</td><td>0.43</td><td>0.36</td><td>0.29</td></tr>
<tr><td>(0.1,0.3)</td><td>0.5</td><td>0.43</td><td>0.36</td><td>0.29</td><td>0.21</td></tr>
<tr><td>(0.3,0.8)</td><td>0.43</td><td>0.36</td><td>0.29</td><td>0.21</td><td>0.14</td></tr>
<tr><td>(0.8,+∞)</td><td>0.2</td><td colspan="5">0</td><td>0</td></tr>
</table>

Simulation Results

A period of 12 hours simulation was conducted. The control accuracy objectives are temperature band 25±0.5oC and relative humidity band 50%±5%. Because the simulation conditions include four-hour periodical heat and moisture disturbances, as an example the simulation results at the four-hour period of simulation time from 40000 s to 54400 s are picked out for comparison. The simulated control accuracies of room air temperature and humidity and the action frequency of water valve on/off are compared to evaluate the control performances of former mentioned three control logics. The simulated room air temperature and humidity are shown in Figure 5, 6 and 7. The summaries of control accuracy and action frequency of water valve on/off are shown in Table 2.

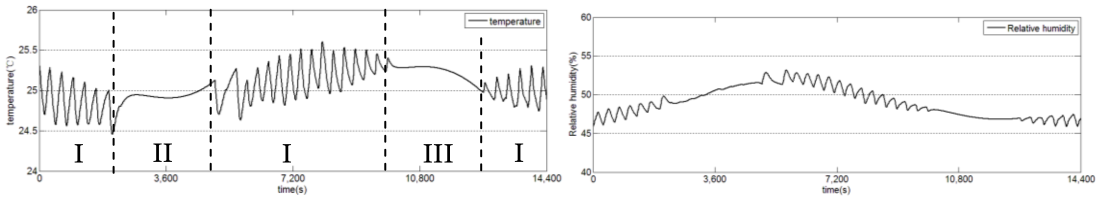

Figure 5. *Temperature and humidity simulation results of proposed control logic*

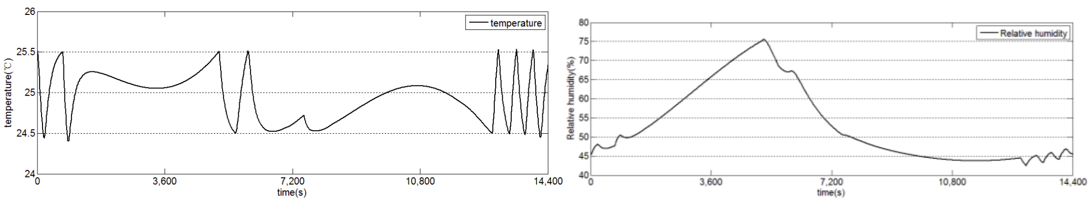

Figure 6. *Temperature and humidity simulation results of conventional valve on/off control logic.*

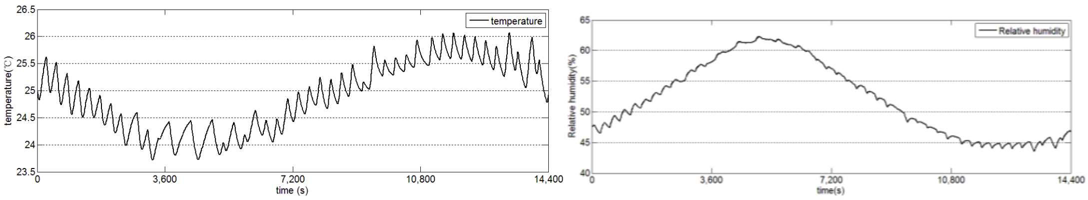

Figure 7. *Temperature and humidity simulation results of valve duty ratio fuzzy control logic*

Table 2. *Comparison of simulated temperature, humidity and action frequency of valve on/off*

Control Logic	Temperature accuracy (^oC)	Humidity accuracy	Action frequency of valve on/off (time/h)
Proposed double-PID control logic	25±0.5	50%±3%	15
Conventional valve on/off control logic	25±0.5	43%~75%	3.5
Valve duty ratio fuzzy control logic	23.7~26.1	43%~62%	22

From Figure 5， it can be seen that the temperature and humidity curves show three different performances: I) the temperature and humidity fluctuate according to valve on/off action; II) the temperature and humidity smoothly increase because during this period the cooling load is small and valve is totally closed; III) the temperature and humidity smoothly decrease because during this period the cooling load is large and valve is totally opened. In the four-hour period, the total valve on/off action times is 60 and the action frequency is 15 times/h.

DISCUSSIONS

With respect to the temperature control, both conventional control logic and proposed control logic can meet the accuracy requirement of 25±0.5 ^oC. The fuzzy control logic controls room air temperature in range of 23.7~26.1 ^oC, with a maximum overshoot of 0.8 ^oC.

Regarding humidity control, only proposed control logic can meet the accuracy requirement of 50%±5%. The conventional control logic results in a large range of humidity of 43%~75%, with a maximum overshoot of 20%. The fuzzy control logic controls humidity better than conventional logic with a result of 43%~62% and maximum overshoot of 7%.

As for the valve action frequency, the conventional control logic shows the least action frequency of 3.5 times/h. The proposed control logic and fuzzy control logic shows larger action frequency of 15 and 22 times/h respectively. Lower action frequency mean longer valve life.

For the purpose of extending the valve life span, a simulation is conducted to check the control performances if the valve duty ratio period is extended from 300 s to 600 s. The simulation results are shown in Figure 8.

From Figure 8, it can be seen that the temperature control accuracy is 25±1 ^oC, and humidity control accuracy is 50±7%. The total valve on/off action times is 32 and the action frequency is 8 times/h. The temperature control accuracy decreased, but the valve on/off action frequency decreased as well, which helps to extend valve life. During actual operation, it needs to decide a proper control accuracy and duty ratio period according to the requirements of temperature and humidity accuracy and valve life.

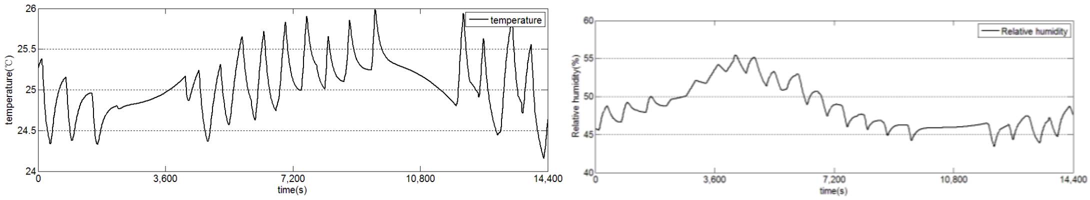

Figure 8. *Temperature and humidity simulation results of proposed control logic with the duty ratio period of 600 s*

CONCLUSIONS

FCUs are able to control both room air temperature and humidity. But the conventional control logic control room temperature only so that the room humidity sometime exceeds comfort zone. This paper proposes new control logic to control both room air temperature and humidity using two PID controllers to control fan speed and valve duty ratio respectively. The inputs to the PID controllers are the weighted average of room temperature and humidity deviations from their set points. The performances of proposed control logic are compared using simulation with the conventional valve on/off control logic and valve duty ratio fuzzy control logic.

The simulation results show that the proposed control logic shows the best control performance with the temperature accuracy of ±0.5 ^{o}C and humidity accuracy of ±3%. But the valve on/off action frequency if 4 times larger than the conventional on/off control logic when the duty ratio period is 300 s. Simulation results show as well that if extend the duty ratio period from 300 s to 600 s, the valve life can be doubled with the cost of sacrificing the control accuracy of temperature from ±0.5 ^{o}C to ±1 ^{o}C and humidity accuracy from ±3% to ±7%. For actual operation, it needs to decide proper control accuracy objectives and duty ratio period according to the actual requirements of temperature and humidity control accuracy and valve life.

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