Design of Fuzzy-PI Decoupling Controller for the Temperature and Humidity Process in HVAC System

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Abstract: Ensuring the comfortable air quality for people, using the heating, ventilation and air conditioning (HVAC) system, in the commercial center buildings or underground infrastructures is extremely important. This is directly related to the design of the controllers for two channels of the air conditioning: temperature and humidity of the indoor air. Firstly, the analysis and building an interactive nonlinear mathematical model of the indoor air is presented in this paper. Then, the article refers to methods of design the traditional PI controller, PI controller combined with decoupled controller and PI controller with self-tuning parameter based on fuzzy logic principle combined with decoupled controller for the heating and humidifying processes of the indoor air. Finally, the proposed controllers for temperature and humidity process is simulated and tested on MatLab.

Keywords: Temperature And Humidity; Fuzzy Logic Control; Decoupling Control; PID; Self-Tunning Fuzzy PID; HVAC.

I. INTRODUCTION

The strong growth in the civil industrial construction and transport infrastructure leading to the introduction of more high buildings, commercial centers, many tunnels, undergrounds ... where are required to be equipped with the HVAC system [1]. HVAC systems ensure to supply and maintain the comfortable indoor air for occupants with the desired air temperature, humidity and quality. The comfortable air inside these buildings depends on the accurate temperature and relative humidity process control in HVAC system [2-4]. The comfortable temperature and humidity range are changing following on seasons and different countries [3]. Moreover, conventional HVAC systems consume approximate half of the total electric energy that is largely depend upon fossil fuel in modern cities [5]. This causes polluted atmosphere and increasing in greenhouse gases emissions from HVAC applications. Therefore, the demand for the comfortable indoor air is in conflict with the call for reduction of energy consumption and environmental protection. Besides the problem of energy consumption, sometimes the incorrect operation of the HVAC systems may not help to improve indoor air [6-7]. Hence, it is a necessity to design control temperature and humidity strategies in order to improve the performance of HVAC systems. The control systems for indoor building air can be mainly classified into two categories according to the approaches employed: the conventional controllers and computational intelligence techniques. The proportional integrative derivative (PID) controller is employed the popular in conventional HVAC systems, because of the simpleness, easy installation and use [8-9]. However, PID is not solved completely nonlinear plant, resisting noise weakly, and not satisfying demand about the indoor air quality. Intelligent controller, fuzzy logic or neural networks have
recently become practical as a fast, accurate and flexible tool to HVAC control strategy modeling, simulation and design [10-14]. With the designed controller, the performance of a HVAC system can be significantly improved [4,15]. Moreover, there are several disadvantages that limit the performance of current control technologies, such as the on/off control causes the system switching working state too frequently; and neural networks are hard to put into application; controller is so complex. The results of applying the self-tuning intelligent PID, fuzzy adaptive PID, adaptive predictive decoupling control, fuzzy control combined with neural network for the HVAC system, in papers [16-21], are to improve performance of the HVAC system. But the nonlinear model and the interaction between temperature and humidity process were not regarded completely. Hence, it is worth developing temperature and humidity process controllers of HVAC system for the purpose of improving the indoor air quality and energy efficiency.

In this paper, by combining advantages of the self-tuning parameters fuzzy PI control and decoupling control method, new temperature and humidity controller are developed and their performances as well as their potentials in HVAC control systems are discussed. The proposed control system is finally tested and evaluated by the simulation on Matlab.

II. MATHEMATICAL MODEL OF THE INDOOR AIR TEMPERATURE & HUMIDITY CONTROL SYSTEM

We study a room, equipped with the base HVAC system which has the heater by hot/cold water and the humidifier by steam, such as Fig.1. Depend on the mixed air temperature after the filter, the outside air is heating or cooling by the heating/cooling coil. Then, the outside air can be humidified by the steam humidifier, and then it is supplied into the room by the supply fan. The exhaust air is conducted out the room by the return fan. The heating/cooling coil gives the indoor air a thermal-humid energy \( P \) by changing the hot/cold water flowrate \( F_R \) through the HWCR/CHR control valve. The steam humidifier also gives the indoor air a thermal-humid energy \( Q \) by varying the steam flowrate \( F_Q \) through the control steam valve. This system uses the temperature & humidity controller to adjust the position of hot/cold water, steam valves, and then can change flowrate \( F_R, F_Q \) following equation:

\[
P = \alpha_p F_R; \quad Q = \alpha_q F_Q
\]

2.1. Mathematical model of the indoor air temperature

The indoor air temperature is affected by the outside air temperature, initial indoor air temperature, volume of the room, heat loss from the wall, hot/cold water flowrate and steam flowrate as presented in Fig. 1. Thus, the indoor air temperature can be expressed as follow:

\[
T(t) = T_{in}(t) + T_R(t)
\]

The main temperature \( T_R \) is supplied by the hot/cold water flowrate through the heating/cooling coil. Hence, it can be expressed as follows based on energy conservation principle:

\[
r_a C_p V_s \frac{dT}{dt} = a_q F_Q(t) - U_a A_w [T_R(t) - T_{in}(t)]
\]

Assume \( T_{in} = 0 \) and consider the time delay of the heat transfer process in the wall \( U_w \) when the individual convection heat transfer coefficients for fluid on each side of the wall is equal, can be calculated as [3,6-7]:

\[
U_w = \frac{2}{h_w} + \frac{d}{K_a}
\]

By using Laplace transform, after changing equation (2) can be described as follows:

\[
\left[ \frac{r_a C_p V_s}{U_w A_w} + 1 \right] \frac{T_R(s)}{T_{in}(s)} = \frac{a_q}{U_w A_w} F_Q(s) + T_{in}(s)
\]

Assume \( T_{in} = 0 \), then (5) can be simply transferred as follows:

\[
G_{11} = \frac{T_R(s)}{F_Q(s)} = \frac{k_p e^{-\frac{s}{\tau_p}}}{\tau_p s + 1} \cdot \frac{r_a C_p V_s}{U_w A_w} \cdot \frac{a_q}{U_w A_w}
\]

The indoor air temperature is also affected by the steam humidifier. Calculating the same as the main temperature, the temperature \( T_q \) causes by the steam humidifier, is expressed as

\[
G_{12} = \frac{T_q(s)}{F_Q(s)} = \frac{k_q e^{-\frac{s}{\tau_q}}}{\tau_q s + 1} \cdot \frac{r_a C_p V_s}{U_w A_w} \cdot \frac{a_q}{f_a E_p}
\]

2.2. Mathematical model of the indoor air humidity

The indoor air humidity is directly affected by the steam humidifier, initial indoor air humidity, heating/cooling coil as in Fig.1. The indoor air humidity can be expressed as follows:

\[
H(t) = H_{in}(t) + H_R(t)
\]

The main indoor air humidity \( H_R \) is produced by adjusting the position of the steam valve. So that it can be described as follows based on the energy conservation principle:

\[
r_a V_s \frac{dH_R}{dt} = a_q F_Q(t) - r_a f_a E_p (H_q - H_{in})
\]

Assume \( H_{in} = 0 \), then (9) can be simply transferred in Laplace - domain, as follows:

\[
G_{22} = \frac{H_q(s)}{F_Q(s)} = \frac{k_q e^{-\frac{s}{\tau_q}}}{\tau_q s + 1} \cdot \frac{V_s}{f_a} \cdot \frac{a_q}{f_a E_p}
\]

The indoor air humidity is also affected by the heating/cooling coil. So that humidity \( H_R \) can be presented as:

\[
G_{21} = \frac{H_R(s)}{F_Q(s)} = \frac{k_p e^{-\frac{s}{\tau_p}}}{\tau_p s + 1} \cdot \frac{r_a C_p V_s}{U_w A_w} \cdot \frac{a_q}{U_w A_w}
\]
2.3. Dynamic model of control valve

Most of the control valves are usually designed so that the flow rate through the valve is a nearly linear function of the signal to the valve actuator. Therefore, a first-order transfer function is an adequate model [8,14] for the dynamic characteristic of the electric-pneumatic valve in this project:

\[ G_{tv} = \frac{F_p}{I_t} = k_{tv} e^{0.1t} \quad \text{and} \quad G_{ih} = \frac{F_i}{I_h} = k_{ih} e^{0.1t} \quad (12) \]

2.4. The Mathematical model of the control object in the indoor air temperature and humidity control system

When considering interaction between temperature and humidity, the indoor air temperature and humidity processes is a two-input two-output model. The matrix transfer of control object in the indoor air temperature and humidity control system, when adding the model of the control valve, is given as follows:

\[
egin{bmatrix}
T \\
H
\end{bmatrix} = \begin{bmatrix}
G_{tv}G_{t1} & G_{tv}G_{t2} & F_p \\
G_{ih}G_{i1} & G_{ih}G_{i2} & F_i
\end{bmatrix} \begin{bmatrix}
T \\
H
\end{bmatrix}
\]

(13)

In this paper, we assume that the length of the testing room is 4m, width is 2m, height is 3m; the thickness of the brick wall is 0.3m; and the desired indoor temperature is 20°C. Based on fuzzy logic calculations, the parameters are determined as follows:

\[
T = \begin{bmatrix}
G_{t1} & G_{t2} \\
G_{i1} & G_{i2}
\end{bmatrix}\]

3.1. The PI controllers design

The purpose of the PI controllers design is determined the initial parameters for Fuzzy-PI controllers \((k_{P0}, k_{I0})\) for two temperature & humidity feedback control loop. If neglecting interaction between temperature and humidity, the transfer function of the temperature control loop object as:

\[ G_t = G_{t0}G_{t1} = \frac{0.42e^{0.6s}}{(562.24s + 1)(1.5s + 1)} \quad (14) \]

The transfer function of the humidity control loop object:

\[ G_h = G_{h0}G_{h2} = \frac{0.52e^{17.2s}}{(1600s + 1)(2.5s + 1)} \quad (15) \]

Applied Skogestad’s approximation method, we have:

\[ G_t = \frac{0.42e^{6.95s}}{(562.99s + 1)(6.95s + 1)} \quad (16) \]

\[ G_h = \frac{0.52e^{18.45s}}{(1601.25s + 1)(18.45s + 1)} \quad (17) \]

According to the optimal module principle [22], the parameters \(k_{P0}, k_{I0}\) can be determined as follows:

\[ R_{P0}^o(s) = k_P^o + \frac{k_T^o}{s} \quad \text{and} \quad R_{I0}^o(s) = k_I^o + \frac{k_R^0}{s} \quad (18) \]

\[ k_{P0}^o = \frac{562.99}{2x0.42x6.95} = 96.44, \quad k_{I0}^o = \frac{1}{2x0.42x6.95} = 0.17 \]

\[ k_{P0}^h = \frac{1601.25}{2x0.52x18.45} = 83.45, \quad k_{I0}^h = \frac{1}{2x0.52x18.45} = 0.05 \]

3.2. The decoupling controllers design

Arcoding to the decoupling control principle, the decoupler \(R_{HI}\) is designed to cancel \(H_2\) arising from process interaction between \(U_2\) and \(H\), and the decoupler \(R_{HT}\) is designed to cancel \(T_1\) arising from process interaction between \(U_1\) and \(T\). In order to cancelling the influence between temperature and humidity channels, output \(U_{12}\) & \(U_{12}\) need to satisfy conditions:

\[ G_{t0}G_{22}U_{11} + G_{h0}G_{22}U_{12} = 0, \quad G_{h0}G_{12}U_{21} + G_{t0}G_{12}U_{22} = 0 \quad (19) \]

Hence we obtain the transfer function of the decouplers:

\[ R_{HI}(s) = - \frac{G_{h0}(s)G_{22}(s)}{G_{a0}(s)G_{22}(s)} \quad \text{and} \quad R_{HT}(s) = - \frac{G_{t0}(s)G_{12}(s)}{G_{h0}(s)G_{12}(s)} \quad (20) \]
Using Skogestad’s approximation [22], the decoupling controllers have the following form:

\[
R_{TH}(s) = -\frac{0.25(1601.25s + 1)(18.45s + 1)}{(562.99s + 1)(3.05s + 1)}
\]  
(21)

\[
R_{TT}(s) = -\frac{0.51(562.99s + 1)(6.95s + 1)}{(1601.25s + 1)(8.85s + 1)}
\]  
(22)

3.3. The fuzzy logic calculation blocks design

Fuzzy logic calculations blocks (FC) have: two inputs - temperature/humidity error (ET or EH), derivative of temperature error (DET or DEH); two output is PT (or PH), IT (or IH) corresponding to the output value \( k_{PT}, k_{IT} (or k_{PH}, k_{IH}) \).

Using membership functions are shaped triangular for all variables, fuzzied for all input variables by 5 fuzzy sets \{ NL (Negative Large), NS (Negative Small), ZE (Zero), PS (Positive Small), PL (Positive Large) \}, fuzzied for all output variables by 5 fuzzy sets \{ SM (Small), ME (Medium), LA (Large), QL (Quite Large), VL (Very Large) \}. The physical domain of the input & output variables are determined as: ET \([-50,50]\), DET \([-5,5]\), PT \([-100,100]\), IT \([-0,0.5]\), PH \([-95,95]\), IH \([-5,5]\), EH \([-95,95]\), DEH \([-10,10]\).

Depending on the characteristics of the indoor air temperature (or humidity) control process and the PID control principle in order to improve quality control for system (see Tab.1), we define the 25 base fuzzy rules as Tab.2.

Tab.1. The effect of \( k_p, k_i \) tuning

<table>
<thead>
<tr>
<th>Closed-loop response</th>
<th>Rise time</th>
<th>Settling time</th>
<th>Overshoot</th>
<th>Steady state error</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing ( k_p )</td>
<td>Decrease</td>
<td>Increase</td>
<td>Small increase</td>
<td>Decrease</td>
<td>Degrade</td>
</tr>
<tr>
<td>Increasing ( k_i )</td>
<td>Small decrease</td>
<td>Increase</td>
<td>Increase</td>
<td>Large decrease</td>
<td>Degrade</td>
</tr>
</tbody>
</table>

Tab.2. The base fuzzy rule of \( k_{PT}, k_{IT} (or k_{PH}, k_{IH}) \)

<table>
<thead>
<tr>
<th>PT (or PH)</th>
<th>IT (or IH)</th>
<th>ET (or EH)</th>
<th>NL</th>
<th>NZ</th>
<th>ZE</th>
<th>PS</th>
<th>PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DET (or DEH)</td>
<td>NS</td>
<td>SM</td>
<td>SM</td>
<td>SM</td>
<td>SM</td>
<td>SM</td>
<td>SM</td>
</tr>
<tr>
<td>ZE</td>
<td>SM</td>
<td>SM</td>
<td>LA</td>
<td>LA</td>
<td>QL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>SM</td>
<td>SM</td>
<td>LA</td>
<td>QL</td>
<td>VL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>SM</td>
<td>SM</td>
<td>QL</td>
<td>VL</td>
<td>VL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using the Max-Min composition rule and the cetroid defuzzification method, we can obtain the clear output value of FCs: \( k_{PT}, k_{IT} \) for temperature loop and \( k_{PH}, k_{IH} \) for humidity loop. Then, the self-tuning parameters of PI controllers can be calculated by equations:

\[
k_{PT}^{*} = k_{p_{PT}}k_{T}^{*}, k_{IT}^{*} = k_{I_{PT}}k_{I}^{*}
\]  
(23)

\[
k_{PH}^{*} = k_{p_{PH}}k_{P}^{*}, k_{IH}^{*} = k_{I_{PH}}k_{I}^{*}
\]  
(24)

IV. SIMULATION AND RESULT

The simulation is carried out to analyse the performance of three controllers for the humidity and temperature control loops in HVAC system: (1) - PI controller (PI), (2) - PI decoupling controller (PI\(_{IDcP}\)); (3) - fuzzy-PID decoupling controller (FPI\(_{IDcP}\)). The PI controller was designed in 3.1. The PI decoupling controller is composed of the decoupler in 3.2 and the PI controller in 3.1. The fuzzy-PID decoupling controller consists of the decoupler in 3.2 and the PI controller with self-tunning parameters (the fuzzy logic calculation block was designed in 3.3, the PI initial parameters in 3.1). The simulations have been taken on the platform of Matlab as describled in Fig.3. The simulating results are used to indicate the controllers’ performance including several indexes: overshoot, steady time, steady error, coupling effect.

The simulation was tested with initial indoor air situations: 15\(^{\circ}\)C, 10\% and assume required humidity & temperature
The simulation results have proved the proposed fuzzy-PI decoupling controller has excellent performance on efficient auto tuning of the PI parameters only when needed: fast response speed; small overshoot; small steady error; and stability and adaptability response to uncertain factors. In other words the fuzzy-PI decoupling controller suits for controlling simultaneously the indoor air temperature and humidity processes in HVAC system. The fuzzy-PI decoupling controller can improve the indoor air quality; increase the process efficiency and bring economic benefits to the user.

**V. CONCLUSION**

The indoor air temperature and humidity control process was studied and presented in this paper. Based on the nonlinear model of the indoor air temperature and humidity, considering the influence of the coupling channels, three controllers (PI controller, PI decoupling controller, fuzzy-PI decoupling controller) were designed, simulated on Matlab.

### Tab.3. The proposed controllers’ performance

<table>
<thead>
<tr>
<th>Control process</th>
<th>Controller</th>
<th>Over-shoot (%)</th>
<th>Steady time (s)</th>
<th>Steady error (%)</th>
<th>Coupling effect (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tempeature</td>
<td>PI</td>
<td>55.9</td>
<td>84.5</td>
<td>0.02</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>PIdcp</td>
<td>15.3</td>
<td>39.5</td>
<td>0.01</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>FPIdcp</td>
<td>~ 0</td>
<td>31.4</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>Humidity</td>
<td>PI</td>
<td>2.1</td>
<td>80.2</td>
<td>0.08</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>PIdcp</td>
<td>5.6</td>
<td>104.3</td>
<td>0.21</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>FPIdcp</td>
<td>~ 0</td>
<td>80.1</td>
<td>0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The simulating results of the proposed temperature and humidity controllers show that the FPIdcp has the best control system output; the decoupling controllers eliminate the nonlinear model of the indoor air temperature and humidity, was studied and presented in this paper. Based on the interaction between temperature & humidity processes. better PI control parameters selection can ensure the desired considering the influence of the coupling channels, three channels disturances when it was compared to other controllers: PI, PIdcp.

Therefore, with the proposed FPIdcp controller, the indoor air quality can be well control since: PI controller is suitable for various control object including indoor climate factors control; the fuzzy logic calculation block for optimal PI parameters tuning to ensure adaptability to different situations; better PI control parameters selection can ensure the desired system output; the decoupling controllers eliminate the interaction between temperature & humidity processes.

### REFERENCE


[13] T.Y. Chen (2002); Application of adaptive predictive control to a floor heating system with a large thermal lag; Energy Build. 34.


**Fig. 4.** Response curves of temperature & humidity control with 3 controllers: 4-T*, 4-H*, 1-PI, 2-Pidcp, 3-FPIdcp, 6-varying H* affect the temperature response, 7-varying T* effect the humidity response.
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