Towards Smart City Platform Intelligence: PI Decoupling Math Model for Temperature and Humidity Control

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Providing a comfortable indoor climate for people, using heating, ventilation and air conditioning (HVAC) systems, in commercial or residential buildings is an extremely important problem. This is directly related to the design of the multi-channel controllers for temperature, humidity, and air quality. First, the analysis and building of an interactive nonlinear mathematical model of the required comfort temperature, humidity, and air quality are presented in this paper. Then, the article refers to methods of design of traditional PID controllers, PID controllers combined with decoupled controllers, and PID controllers with self-tuning parameters based on fuzzy logic principles, combined with decoupled controllers for heating and humidifying processes. Finally, we present the simulation results of a proposed fuzzy-PID controller in Matlab, and analyze experimental results for a 6-month period by applying the proposed system.

Keywords – HVAC; PID; Smart Energy; Smart City;

I. INTRODUCTION

The air environment in buildings, regulated by many parameters of exposure to exogenous and endogenous factors, determines the working and living conditions, health, and comfort of a person. Providing a "healthy" and comfortable air environment is very expensive, because expensive technically complex, and multi-functional engineering systems are used. In order to remove only 1kW of excess heat in buildings or premises (to maintain air temperature), could cost in the region of 300–600 USD. Previously, engineers generally related the provision of comfort to an estimate of only three parameters of the microclimate and their deviations: air temperature (± 1 °C) and surrounding surfaces, relative humidity (RH) (± 7%).

For the abovementioned reasons, today indoor environment quality and comfort have become a topic of relevance, and for this reason heating, ventilation, and air conditioning (HVAC) systems have become popular in many buildings. Reducing the power consumption of these systems, while maintaining a suitable comfort level, is of great interest, and has not yet been completely resolved. According to the International Energy Agency, about 40% of total energy use in residential and commercial buildings is from HVAC-system equipment.

II. PROBLEM STATEMENT

The aim of this control strategy is to design strategies by combining conventional and intelligent control technologies for indoor environment quality control, including indoor air temperature, indoor humidity control, by computational modeling and experimental investigation, and to show the potential direction for improving occupants' comfort in a built environment. Two controllers will be designed to analyze the potential of newly proposed controllers for indoor environment quality control, and the idea of using complex control strategies combined by different control techniques. The work is broken down into several parts as shown Figure 1.

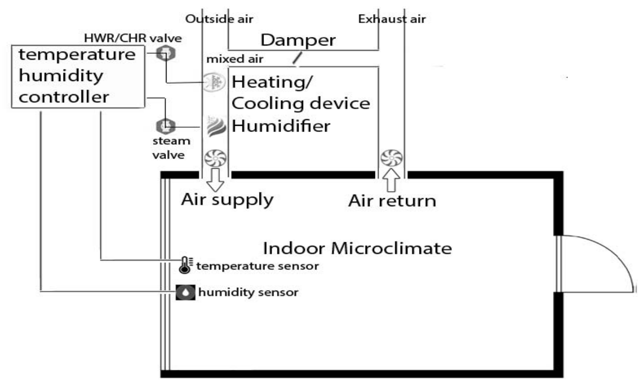

Figure 1. Flowchart of fuzzy block

III. MATHEMATICAL MODEL

A. Mathematical Model of the Indoor Air Temperature

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 Figure 2. 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 *Fp* through the HWR/CHR control valve. The steam humidifier also gives the indoor air a thermal-humid energy *Q* by varying the steam flowrate *Fq* through the control steam valve. This system uses the temperature & humidity controller to adjusting the position of hot/cold water, steam valves, and then can change flowrate *Fp, Fq* following formulas:

$$P = a_p F_p; \quad Q = a_q F_q \tag{1}$$

Indoor temperature is affected by the initial indoor microclimate air temperature, outdoor temperature, volume of the premises, heater, and heat loss from the wall as illustrated in Figure 2. Therefore, the indoor air temperature can be expressed as follows, based on energy conservation principles:

$$\rho_a V_{indoor} C_p \frac{dT_{indoor}(\tau)}{d\tau} = a_p F_p(t) - U_w S_w \left[T_{indoor}(\tau) - T_{outdoor}(\tau)\right] \quad (5)$$

The overall heat transfer coefficient for the wall, U_w, is calculated as [3]:

$$U_w = \frac{1}{\left(\frac{1}{h_A} + \frac{d_w}{K_b} + \frac{1}{h_B}\right)} \quad (6)$$

In this case, we can considerthe individual convection heat transfer coefficients for fluid on either side of the wall as equal to h_{air} (convection heat transfer coefficients of air), $h_A = h_B = h_{air}$. Then, U_w can be calculated as:

$$U_w = \frac{1}{\left(\frac{2}{h_{air}} + \frac{d_w}{K_b}\right)} \quad (7)$$

By using Laplace transforms in equation (3), we obtain by simplification:

$$\left[\frac{\rho_a V_{indoor} C_p}{U_W S_W} s + 1\right] \cdot T_{indoor}(s) = \frac{a_P}{U_W S_W} F_P(s) + T_{outdoor}(s) \quad (8)$$

Assume that $T_{outdoor} = 0$, and taking into consideration the effect of the time delay of the heat transfer process in an indoor environment, then (6) can be simplified as follows:

$$G_{11} = \frac{T_p(s)}{F_p(s)} = \frac{k_{tp} e^{-q_{tp}s}}{t_{tp}s + 1} \quad (9)$$

There, $t_{tp} = \frac{\rho_{air} C_p V_{indoor}}{U_W A_W}$ and $k_{tp} = \frac{a_p}{U_W A_W}$

Temperature and humidity changes are related. Therefore, the indoor air temperature is also affected by the humidifier. Considering the temperature (T_q) affected by the humidifier, we get:

$$G_{12} = \frac{T_q(s)}{F_q(s)} = \frac{k_{tq} e^{-q_{tq}s}}{t_{tq}s + 1} \quad (10)$$

where, $t_{tq} = \frac{V_{indoor}}{f_a}$, $k_{tq} = \frac{a_q a_t}{f_a r_a E_p}$

B. Mathematical Model of the Indoor Air Humidity

In our study, the indoor air humidity is affected by the initial indoor air humidity, air humidity of supplied air, the humidifier, and the volume of the indoor environment as shown in Figure 2. Considering all these parameters, based on the energy conservation principle, indoor air humidity is described as follows:

$$r_a V_{indoor} E_p \frac{dH_q(\tau)}{d\tau} = a_q F_q(t) - r_a f_a E_p \left[H_q - H_{outdoor}\right] \quad (11)$$

Using Laplace transforms, and assuming $H_{outdoor} = 0$ in order to simplify the equation (10) we get:

$$G_{22} = \frac{h_q(s)}{F_q(s)} = \frac{k_{hq} e^{-q_{hq}s}}{t_{hq}s + 1} \quad (12)$$

where, $t_{hq} = \frac{V_{indoor}}{f_a}$, and $k_{hq} = \frac{a_q}{f_a r_a E_p}$.

Indoor air humidity levelsare also affected by heaters. Thus, humidity can be presented as the follows:

$$G_{21} = \frac{H_p(s)}{F_p(s)} = \frac{k_{hp} e^{-q_{hp}s}}{t_{hp}s + 1} \quad (13)$$

where, $t_{hp} = \frac{r_a C_p V_{indoor}}{U_W A_W}$, and $k_{hq} = \frac{a_p a_h}{U_W A_W}$.

C. Decoupling Strategyy

The temperature and humidity control process in the indoor environment is complicated because temperature and humidity changes are interrelated. Therefore, in order to remove the relationship between these two parameters, it is necessary to add decoupling controllers.

In our study, PID controllers with self-tuning parameters based on fuzzy logic calculations, are proposed for the feedback control loop of the temperature and humidity control processes. The structure of the fuzzy-PID controllers decoupling-controller for temperature and humidity control in a HVAC system, is proposed in Figure 2, where, R_T, and R_H are Fuzzy-PID controllers; k_{P0}, k_{I0}, and k_{D0} are initial parameters of the PID controller; k_p, k_i,,are k_d are self-tuning parameters based on fuzzy logic calculations. R_{TH} and R_{HT} are the decoupling controllers, designed based on the decoupling control principle. Most control valves are designed so that the flow rate through the valve is a near-linear function of the signal to the valve.

D. Dynamic Model of Control Valve

Most control valves are designed so that the flow rate through the valve is a near-linear function of the signal to the valve actuator. Therefore, a first-order transfer function is an adequate model [94-96] for the dynamic characteristics of the electric-pneumatic valve in this study:

$$\begin{cases} G_{vt} = \dfrac{F_p(s)}{I_t(s)} = \dfrac{k_{vt}e^{-q_{vt}s}}{t_{vt}s+1} \\ G_{vh} = \dfrac{F_q(s)}{I_h(s)} = \dfrac{k_{vh}e^{-q_{vh}s}}{t_{vh}s+1} \end{cases} \tag{14}$$

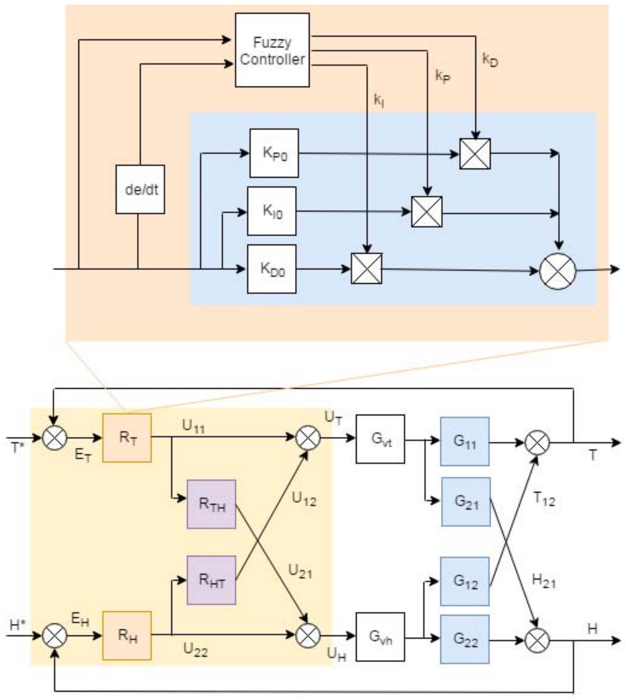

Figure 2. Structure of fuzzy-PID decoupling controller for HVAC system

E. Math model of The Control Object in an Indoor Air Temperature and Humidity Control System

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

$$\begin{bmatrix} T \\ H \end{bmatrix} = \begin{bmatrix} G_{vt}G_{11} & G_{vh}G_{12} \\ G_{vt}G_{21} & G_{vh}G_{22} \end{bmatrix} \begin{bmatrix} Q_{heater} \\ Q_{humid} \end{bmatrix} \tag{15}$$

In this research, our test laboratory is at the Smart City and Artificial Intelligence Laboratory at Gachon University. The length of the room is 6 m, width is 3m, height is 3m; the thickness of the brick wall is 0.3 m; and the target indoor temperature is 22°C.

Therefore, $V_i = 24m^3$, $A_w = 36m^2$, $d_w = 0.3m$, $f_a = 0.015m^3/s$. From [91, 97] we receive values as follows: $E_p = 2538kJ/kg$, $C_p = 1005J/kg^oC$, $K_b = 0.6W/m^oC$, $\rho_a = 1.2kg/m^3$, $h_a = 10W/m^oC$.

And then we can calculate: Uw=1.43, ktp=0.019, τ_{tp} =562.24, ktq=1600, We assume: α_t =0.4, α_h =0.3, θ_{tp} =5.6, θ_{tq} =6.4, $\theta_{hp} = 1.7$, $\theta_{hq} = 16$, $k_{vt} = 22$, $\tau_{vt} = 1.5$, $\theta_{vt} = 0.6$, $k_{vh} = 23.75$, $\tau_{vh} = 2.5$, $\theta_{vh} = 1.2$

By using all these parameters and applying them in equations (9), (10), (12) - (14) we calculate transfer functions and get

$$\begin{cases} G_{11} = \dfrac{0.013e^{-5.6S}}{843.36s+1} & G_{12} = \dfrac{0.009e^{-6.4S}}{3600s+1} \\ G_{21} = \dfrac{0.004e^{-1.7S}}{843.36s+1} & G_{22} = \dfrac{0.022e^{-16S}}{3600s+1} \\ G_{vt} = \dfrac{22e^{-0.6S}}{1.5s+1} & G_{vh} = \dfrac{23.75e^{-1.2S}}{2.5s+1} \end{cases} \tag{16}$$

Arcoding to the decoupling control principle, the decoupler R_{TH} is designed to cancel H_{21} arising from process interaction between UT and H, and the decoupler R_{HT} is designed to cancel T_{12} arising from process interaction between UH and T. In order to cancelling the influence between temperature and humidity chanels, output U_{21} & U_{12} need to satisfy conditions:

$$\begin{cases} G_{vt}G_{21}U_{11} + G_{vh}G_{22}U_{21} = 0 \\ G_{vh}G_{12}U_{22} + G_{vt}G_{11}U_{12} = 0 \end{cases} \tag{17}$$

Hence we obtain the transfer function of the decouplers:

$$\begin{cases} R_{TH}(s) = -\dfrac{G_{vt}(s)G_{21}(s)}{G_{vh}(s)G_{22}(s)} \\ R_{HT}(s) = -\dfrac{G_{vh}(s)G_{12}(s)}{G_{vt}(s)G_{11}(s)} \end{cases} \tag{18}$$

And, by applying G_{vt}, G_{vh}, G_{11}, G_{12}, G_{21}, G_{22}, we take:

$$\begin{cases} R_{TH}(s) = -\dfrac{G_{vt}(s)G_{21}(s)}{G_{vh}(s)G_{22}(s)} = \\ -\dfrac{22e^{-0.6s}\cdot 0.004e^{-1.75s}}{(1.5s+1)(843.36s+1)}\cdot\dfrac{(2.5s+1)(3600s+1)}{23.75e^{-1.2s}0.022e^{-16s}} = \\ = \dfrac{0.17(3600s+1)(2.5s+1)e^{-2.3s}}{(843.36s+1)(1.5s+1)e^{-17.2s}} \\ R_{HT}(s) = -\dfrac{G_{vh}(s)G_{12}(s)}{G_{vt}(s)G_{11}(s)} = \\ -\dfrac{23.75e^{-1.2s}\cdot 0.009e^{-6.4s}}{(2.5s+1)(3600s+1)}\cdot\dfrac{(1.5s+1)(843.36s+1)}{22e^{-0.6s}0.013e^{-5.6s}} = \\ = -\dfrac{0.75(843.36s+1)(1.5s+1)e^{-7.6s}}{(3600s+1)(2.5s+1)e^{-6.2s}} \end{cases} \tag{19}$$

By applying Skogestad's approximation [33] to equation (19) we get:

$$
\begin{cases}
R_{TH}(s) = -\dfrac{0.17(3601.25s+1)(18.45s+1)}{(844.11s+1)(3.05s+1)} \\
R_{HT}(s) = -\dfrac{0.75(844.11s+1)(6.95s+1)}{(3601.25s+1)(8.85s+1)}
\end{cases} \tag{20}
$$

And, coefficients G_{vt}, G_{vh}, G_{11}, G_{12}, G_{21}, G_{22},, $R_{TH}(s)$, and $R_{HT}(s)$ will determine k_p, k_i and k_d parameters.

5. Results

Results of the created mathematical model were used to create Fuzzy-PID controller for temperature and RBFNN-PID controller for humidity control. Figure 3 illustrates the simulation results with proposed controllers by applying the proposed math model.

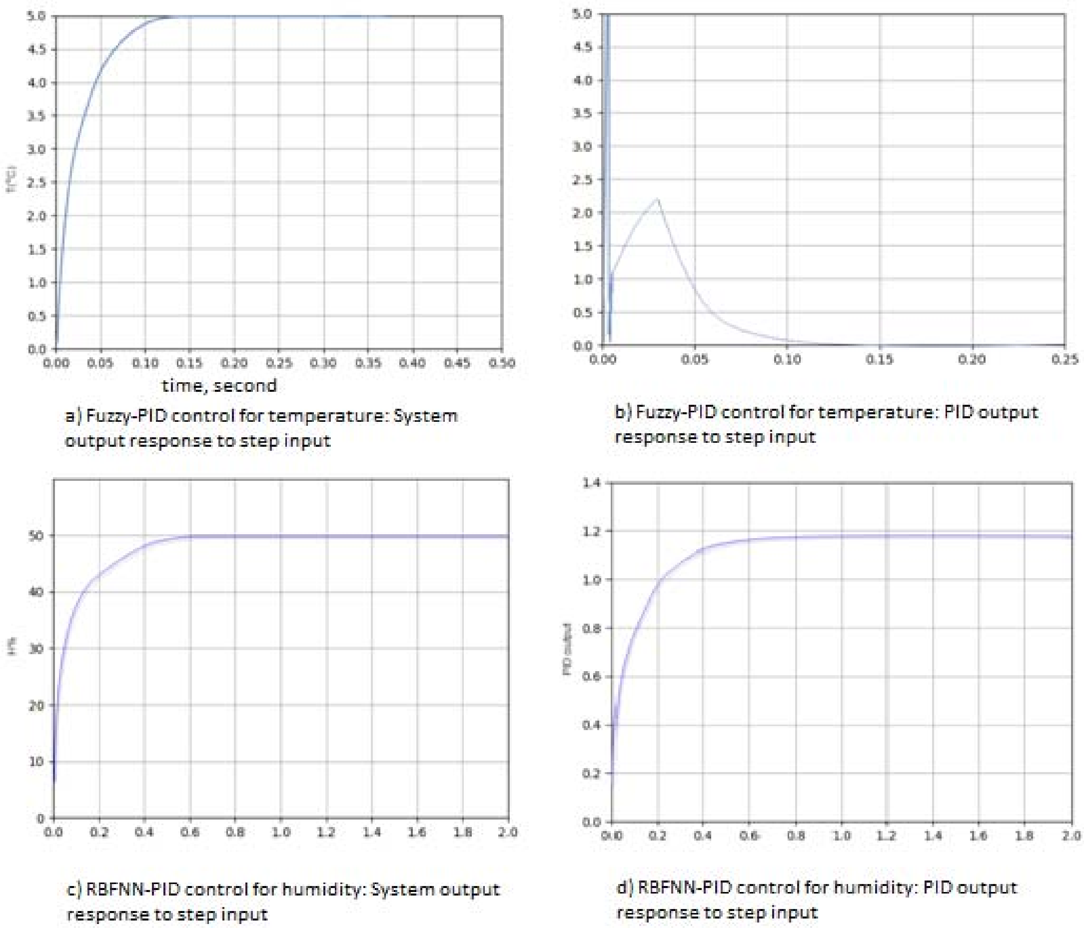

Figure 3. Simulation results with Fuzzy-PID and RBFNN-PID controllers for temperature and humidity control

Conclusion

Ensure a comfortable climate in a building, considering energy-efficient operation, attracts a great deal of attention worldwide. In this paper, we proposed a fuzzy-PID controller to ensure a comfortable indoor environment. To obtain high accuracy in controlling the comfort parameters, mathematical models of the parameters are investigated, after which decoupling strategies for comfort parameters are considered. To obtain a quick response and high accuracy, NN algorithms were applied.

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