Smart Systems and Green Energy (2022)
Clausius Scientific Press, Canada

DOI: 10.23977/ssge.2022.040105
ISSN 2523-904X Vol. 4 Num. 1

Analysis and Research on Coupling Characteristics of Temperature and Humidity Control System Based on Industrial Process

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Keywords: Temperature and Humidity; Control Strategy; Coupling Characteristics; Gain Matrix; Coupling Index.

Abstract: The artificial light source type plant factory has a special environmental structure, and there is a coupling relationship of mutual influence and mutual restriction between temperature and humidity, which is not conducive to the control and application of environmental parameters. Therefore, based on the analysis of the complete nonlinear dynamic model of the temperature and humidity control system, the transfer function of the temperature and humidity system of the artificial light source type plant factory is determined, and the PID control strategy is used to solve the coupling problem of the multi-input multi-variable (MIMO) system. Combined with the characteristics of the system process transfer function, based on the relative regularization gain matrix and coupling index, using the steady-state operating point environmental parameters, according to the temperature and humidity system control structure selection algorithm and decoupling, determine the supply air temperature and cold water flow pairing, internal The temperature and supply air flow are paired, the internal moisture content is paired with the supply air moisture content, the control strategy after the decoupling of the temperature and humidity system is established, and the system control structure in the artificial light source type plant factory is determined to control the temperature and humidity environment equipment. The implementation lays a theoretical basis for it.

1. Introduction

As the core of artificial light source plant factory production technology, environmental control technology is a comprehensive application of contemporary agricultural biology, environmental science, computer control and management science, a technology for comprehensive adjustment and control of environmental factors, and a solution to artificial light source plants. One of the effective ways to solve the bottleneck problems such as high initial construction cost of the factory, high energy consumption of light sources and air conditioners, and low economic benefits.

The temperature and humidity environment system of the artificial light source type plant factory is a typical multiple-input multiple-output (MIMO) system. The main factors affecting the temperature and humidity are supply air temperature, supply air volume flow, supply air moisture content, etc., and there are differences between temperature and humidity. Due to strong cross-coupling and time delay, it is difficult to control environmental parameters alone. Therefore, the most common and widely used PID control algorithm in industrial control is used to realize the timely tracking of the output value and the anti-interference of the system in the temperature and humidity environment control. When using the PID control strategy to solve the coupling problem in the multiple-input multiple-output (MIMO) system, combined with the characteristics of the system process transfer function[1-2], based on the relative regularization gain matrix[3] and the coupling index[4], Determine the system control structure for MIMO. Based on the dynamic nonlinear model of the temperature and humidity control system, this paper decouples the temperature and humidity dynamic system through the relative regularization gain matrix and the coupling index, and establishes a decoupled control strategy for the temperature and humidity system.

2. Determination of Ambient Temperature and Humidity Control Structure

2.1. Determination of Temperature and Humidity Coupled Dynamic System

A complete nonlinear dynamic model of the temperature and humidity control system is constructed[5], see equation (1), and the dynamic characteristics of the temperature and humidity control system in the plant factory are analyzed and obtained.

From the analysis of formula (1), the following conclusions can be drawn:

The factors affecting the temperature environment are mainly the volume flow of the supply air-q_s, the supply air temperature-t_s, the power of the artificial light source-p, the running time of the artificial light source-t_W, and the internal relative humidity-RH_{in}; The factors affecting the humidity environment are mainly the volume flow of the supply air, the supply air content. Humidity-q_s, Supply air moisture content-W_s, power of artificial light source-p, running time of artificial light source-t_W, internal temperature-t_a; environmental factors that affect the temperature and air supply volume are mainly internal temperature-t_a, cold water flow in the fan coil-q_w, and cold water temperature difference.

In this paper, the research is carried out from the perspective of the control-oriented artificial light source type plant factory. From the above analysis, it can be seen that the regulation of internal temperature and humidity is mainly controlled and influenced by the three variables of supply air volume, supply air temperature and cold water flow. There are also mutual influences between various variables, that is, there is mutual coupling and time-delay relationship between temperature and humidity.

$$
\begin{cases}
\dfrac{dt_a}{dt}+\left(\dfrac{k_s\cdot q_s}{V\cdot c_{ap}}-\dfrac{A_p}{r_a\cdot V}\right)t_a=\dfrac{k_s\cdot q_s\cdot t_s}{V\cdot c_{ap}}+\dfrac{\tau\sum_{i=1}^{n}p_i t_W}{\rho_a\cdot V\cdot c_{ap}}+\dfrac{A_p}{r_a\cdot V}t_p \\
\qquad -\dfrac{A_p\cdot R_n\cdot\left(1-e^{-kLAI}\right)}{\rho_a\cdot V\cdot c_{ap}+\dfrac{\rho_a\cdot V\cdot c_{ap}\cdot\gamma\left(t_p-t_a\right)}{e_0 RH_{in}\left(e^{\frac{17.4t_p}{239+t_p}}-e^{\frac{17.4t_a}{239+t_a}}\right)}} \\
\dfrac{dW_a}{dt}=\dfrac{\left(1-e^{-KLAI}\right)\cdot R_n}{\rho_a\cdot V\cdot\lambda(1+\beta)}+\dfrac{q_s\cdot(W_S-W_a)}{V} \\
\dfrac{m_w C_f}{q_s C_a}\dfrac{dt_s}{dt}+t_s=\dfrac{q_x t_x+q_h t_a}{q_s}-\dfrac{q_w C_f}{q_s C_a}\left(t_{w2}-t_{w1}\right)
\end{cases}
\qquad (1)
$$

In order to facilitate theoretical research and field implementation, on the premise of clarifying the mechanism model of the temperature and humidity control system of the artificial light source type plant factory, the mature and general PID control strategy in the industrial system is used to solve the temperature and humidity control problem[6-10], so that the control Strategies are more general and practical, as shown in Figure 1.

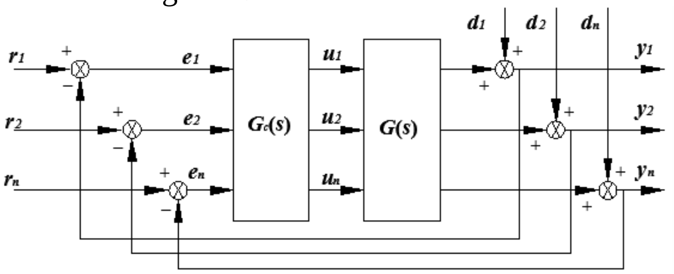

Figure 1: Control System (Undecoupled State)

For a typical $n\times n$ multivariable process $G(s)=\left[g_{ij}(s)\right]$ $(i,j=1,2,\ldots n)$, $G_c(s)$ is the *PID* controller; r_i、e_i、u_i、d_i、y_i in its closed-loop control structure, it is the reference input, output deviation, control input, disturbance input, and system output.

Therefore, the supply air moisture content is introduced as the input of the temperature and humidity control system, the multivariable control system is constructed from a non-square structure into a square structure, and a three-input and three-output temperature-humidity coupled dynamic system (MIMO) is established. , cold water flow, supply air humidity as input, indoor temperature, supply air temperature, indoor humidity as output, control and adjust the temperature and humidity inside the plant factory.

2.2. Transfer Function Modeling

Set $G(s)$ as the transfer function matrix, and establish the transfer function between the input quantity (t_s, t_a, W_a) and the output quantity (q_w, q_s, W_s) according to the dynamic model formula (1) of the temperature and humidity environment.

$$
G(s)=\left[G_{ij}(s)\right]\quad (i,j\in(1,3)) \qquad (2)
$$

$$M_1 = \frac{k_s \cdot q_s}{V \cdot c_{ap}} - \frac{A_p}{r_a \cdot V}$$

$$M_2 = \frac{A_p}{r_a \cdot V} t_p - \frac{A_p \cdot R_n \cdot \left(1 - e^{-kLAI}\right)}{\rho_{\mathrm{a}} \cdot V \cdot c_{ap} + \dfrac{\rho_{\mathrm{a}} \cdot V \cdot c_{ap} \cdot \gamma \left(t_p - t_a\right)}{e_0 RH_{in} \left(e^{\frac{17.4 t_p}{239 + t_p}} - e^{\frac{17.4 t_a}{239 + t_a}} \right)}}$$

Among them, M_2 is the interference item, including leaf area index, artificial light source radiation intensity, leaf temperature, internal humidity and other related parameters in the plant factory, and its value can be obtained by measurement. Get:

$$\frac{dt_a}{dt} + M_1 t_a = \frac{k_s \cdot q_s \cdot t_s}{V \cdot c_{ap}} + \frac{\tau \sum_{i=1}^{n} p_i t_W}{\rho_{\mathrm{a}} \cdot V \cdot c_{ap}} + M_2 \tag{3}$$

$$M_3 = \frac{q_s}{V},$$

$$M_4 = \frac{\left(1 - e^{-KLAI}\right) R_n}{\rho_a \lambda (1 + \beta)}$$

Among them, M_4 is the interference item, including the relevant parameters in the plant factory such as leaf area index, leaf temperature, artificial light source radiation intensity, internal humidity, etc., and its value can be obtained by measurement. Get:

$$\frac{dW_a}{dt} + M_3 W_a = \frac{q_s W_s}{V} + M_4 \tag{4}$$

$$M_5 = \frac{q_s C_a}{m_w C_f}$$

$$M_6 = -\frac{C_a}{m_w C_f} q_h \left(t_x - t_a\right)$$

Among them, M_6 is the interference item, including the relevant parameters in the plant factory such as return air flow, fresh air temperature, internal temperature, etc., and their values can be obtained by measurement. Get:

$$\frac{dt_s}{dt} + M_5 t_s = \frac{C_a}{m_w C_f} t_x q_s - \frac{\left(t_{w2} - t_{w1}\right)}{m_w} q_w + M_6 \tag{5}$$

(1) Transfer function of supply air temperature dynamic model

① The transfer function of t_s and q_w is $G_{11}(s)=\frac{K_{11}}{T_{11}S+1}$, and the Laplace transform on both sides of equation (5) is performed to obtain $T_{11}=\frac{1}{M_5}$; $K_{11}=-\frac{C_f}{q_s C_a}(t_{w2}-t_{w1})$; T_{31} is the time constant (s).

② The transfer function of t_s and q_s is $G_{12}(s)=\frac{K_{12}}{T_{12}S+1}$. It can be seen from (5) that there is a nonlinear relationship between t_s and q_s, so after the Taylor series is expanded, $T_{12}=\frac{1}{M_5}$; $K_{12}=\frac{1}{q_s^2}\left[-q_s t_x+q_x t_x+\frac{q_w C_w}{C_a}(t_{w2}-t_{w1})\right]$; T_{12} is the time constant (s).

③The transfer function between t_s and W_s is $G_{13}(s)=\frac{K_{13}}{T_{13}S+1}=0$.

(2) Ambient temperature dynamic model transfer function

①The transfer functions of t_a and q_w are $G_{21}(s)$, $G_{11}(s)=\frac{K_{11}}{T_{11}s+1}$. From equation (3), we can see that the transfer functions of t_a and t_s are $G_s(s)=\frac{K_s}{T_s s+1}$, $K_s=\frac{k_s\cdot q_s\cdot t_s}{V\cdot c_{ap}\cdot M_1}$, and $T_s=\frac{1}{M_1}$; because the transfer functions of t_s and q_w are $G_{11}(s)=\frac{K_{11}}{T_{11}s+1}$, so $G_{21}(s)=\frac{t_a}{t_s}\cdot\frac{t_s}{q_w}=G_s G_{11}=\frac{K_s K_{11}}{(T_s s+1)(T_1 s+1)}$.

② The transfer function of t_a and q_s is $G_{22}(s)$, and it can be seen from (3) that $G_{22}(s)=G_{22\text{-}1}(s)G_{22\text{-}2}(s)$, so t_s and q_s have a nonlinear relationship, so after the Taylor series is expanded, $G_{22\text{-}1}(s)=\frac{K_{22\text{-}1}}{T_{22\text{-}1}s+1}$ obtains $T_{22\text{-}1}=T_s$; $K_{22\text{-}1}=M_1^2 q_s\left(\frac{\tau\sum_{i=1}^{n}p_i t_w}{\rho_a V c_{ap}}+M_2\right)$; in addition, $G_{22\text{-}2}(s)=\frac{t_a}{t_s}\cdot\frac{t_s}{q_w}=G_s G_{12}=\frac{K_s K_{12}}{(T_s s+1)(T_{12}s+1)}$; $G_{22}(s)=\frac{K_{22\text{-}1}T_{12}+(K_{22\text{-}1}+K_{12}K_s)}{(T_{12}s+1)(T_s s+1)}$.

③ The transfer function of t_a and W_s is $G_{23}(s)=\frac{K_{23}}{T_{23}s+1}=0$.

(3) Environmental Moisture Content Dynamic Model Transfer Function

①The transfer function of W_a and q_w is $G_{31}(s)=0$.

②The transfer function of W_a and q_s is $G_{32}(s)=\frac{K_{32}}{T_{32}s+1}$. From (4), it can be seen that W_a and q_s have a nonlinear relationship, so after Taylor series is expanded, $T_{32}=\frac{1}{M_3}$; $K_{32}=-\frac{M_4}{q_s^2}$; T_{12} are time constants (s).

③ The transfer function of W_a and W_s is $G_{33}(s)=\frac{K_{33}}{T_{33}s+1}=\frac{1}{T_{32}s+1}$.

In summary, the transfer function matrix of the system is

$$G(s)=\begin{bmatrix} \frac{K_{11}}{T_{11}s+1} & \frac{K_{12}}{T_{12}s+1} & 0 \\ \frac{K_{11}K_s}{(T_{11}s+1)(T_s s+1)} & \frac{K_{22}T_{12}+(K_{22}+K_{12}K_s)}{(T_{12}s+1)(T_s s+1)} & 0 \\ 0 & \frac{K_{32}}{T_{32}s+1} & \frac{K_{32}}{T_{33}s+1} \end{bmatrix} \tag{6}$$

Obtained, the transfer function model of the temperature and humidity control system of the artificial light source type plant factory is:

$$\begin{bmatrix} t_s \\ t_a \\ W_a \end{bmatrix}=\begin{bmatrix} \frac{K_{11}}{T_{11}s+1} & \frac{K_{12}}{T_{12}s+1} & 0 \\ \frac{K_{11}K_s}{(T_{11}s+1)(T_s s+1)} & \frac{K_{22}T_{12}+(K_{22}+K_{12}K_s)}{(T_{12}s+1)(T_s s+1)} & 0 \\ 0 & \frac{K_{32}}{T_{32}s+1} & \frac{K_{32}}{T_{33}s+1} \end{bmatrix}\begin{bmatrix} q_w \\ q_s \\ W_s \end{bmatrix} \tag{7}$$

3. Coupling Characteristics of Temperature and Humidity Control System

There is a coupling relationship of mutual influence and mutual restriction between temperature and humidity. When the temperature in the working area increases, if the moisture content in the area remains unchanged, the saturated partial pressure of water vapor in the air will change, and the relative humidity of the air-conditioning area will change. (increase in temperature, decrease in relative humidity; decrease in temperature, increase in relative humidity). In the adjustment process, the adjustment of a certain parameter often causes some other parameters to change. For example, the change of the cold water flow in the fan coil will cause the change of the supply air temperature, and the change of the supply air temperature will cause the change of the temperature of the working area. Therefore, the decoupling of temperature and humidity facilitates the adjustment and control of temperature and humidity.

3.1. Coupling Characteristic Index

Due to the special environmental structure in the artificial light source type plant factory, the temperature and humidity environment control model, after mechanism modeling and parameter identification and verification, determined a more accurate transfer function. In order to facilitate the control and application of environmental parameters, therefore, the analysis of the coupling characteristics of multivariable (MIMO) systems based on industrial processes[11-13], selected by Bristol, through the transfer function, the result operation is performed to determine the input and output quantities. Pairwise relationship between, and combined with index (NI), to filter out unstable pairing choices[14].

(1) RGA and $Niederlinski$ the index

For $n\times n$ multivariate process $G(s)=\left[g_{ij}(s)\right]$ $(i,j=1,2,\ldots n)$, let K be $G(s)$ steady-state gain matrix, then RGA is defined as:

$$\Lambda=[\lambda_{ij}, i, j=1,2,...,n]=K\otimes K^{-T} \tag{8}$$

In formula (8), $\otimes$ - K is multiplied by the corresponding element in K^T.

RGA[15]:

Coupling properties in RGA[15]:

1) $\lambda_{ij}=1$,The closed-loop gain between B and C is equal to the open-loop gain, and B and C are selected for pairing.

2) $\lambda_{ij}=0$,The open loop gain between y_i and u_j is 0, and the pairing of y_i and u_j is not selected

3) $0<\lambda_{ij}<1$,The closed-loop gain between y_i and u_j is greater than the open-loop gain. The degree of coupling is determined by the relationship between λ_{ij} and 0.5. When $0<\lambda_{ij}\le 0.5$, the pairing of y_i and u_j is not selected; when $0.5<\lambda_{ij}<1$, the pairing of y_i and u_j is selected.

4) $\lambda_{ij}>1$,The closed-loop gain between y_i and u_j is less than the open-loop gain. If the value of λ_{ij} is very large, do not choose y_i and u_j pairing.

5) $\lambda_{ij}<0$,The open-loop gain between y_i and u_j is opposite in sign to the closed-loop gain, and the y_i and u_j pairing is not selected.

In addition, when the values of K and K^T in RGA are large, the condition number is required for judgment.

The condition number $\gamma(G)$ is the ratio of the largest singular value $\overline{\sigma}(G)$ to the smallest singular value $\underline{\sigma}(G)$, as a measure of y_i and u_j.

$$\gamma(G)=\overline{\sigma}(G)/\underline{\sigma}(G) \tag{9}$$

When decoupling pair selection, unstable structures may appear, requiring the use of an RGA-$Niederlinski$ index approach.

When $\mathrm{n}\times\mathrm{n}$ MIMO's $G(s)$,its y_i and u_j pairing mode is $y_1\leftrightarrow u_1/y_2\leftrightarrow u_2/\cdots/y_n\leftrightarrow u_n$,

$$y(s)=G(s)u(s) \tag{10}$$

When the system loops are closed, if $Niederlinski<0$, the system is unstable.

$$NI=\frac{G(0)}{\prod_{i=1}^{n} g_{ij}(0)}=\frac{dekK}{\prod_{i=1}^{n} k_{ij}}<0 \tag{11}$$

Condition:①When the system dimension is $n=2$, $Niederlinski<0$ is judged as a sufficient and necessary condition; ②When the system dimension is $n>2$, $Niederlinski<0$ is judged as a sufficient and non-essential condition, and whether the system is stable is controlled by the controller parameters.

(2) Relative regularization gain matrix

$G(s)=\overline{G}(s)\otimes K$, $\otimes$ means element-wise multiplication, K is the system gain matrix

$$K=\lfloor k_{ij}\rfloor_{n\times n}=G(0),\ \overline{G}(s)=[\overline{g}_{ij}(s)]_{n\times n} \tag{12}$$

Among $\overline{g}_{ij}(0)=1$, hypothetically, $\forall ij$, $\overline{g}_{ij}(s)$ are open and stable, and $\overline{y}_i=\overline{g}_{ij}(s)u$, $u_0=0$. Let u_i be the unit step input, ART (average dwell time):

$$\tau_{arij} = \left| \int_0^{\infty} \bar{y}_i(\infty) - \bar{y}_i(t) \mathrm{d}t \right| \qquad (13)$$

When $\mathrm{g_{ij}(s) = k_{ij} \frac{1}{\tau_{ij} s + 1}}$, then $\tau_{arij} = \tau_{ij} + \theta_{ij}$

There is a linear relationship between ART and τ_{ij} and θ_{ij}. See Table 1 for ART of the general procedure.

Let $RATA$ (average dwell time matrix):

$$T_{ar} = \left[\tau_{arij}\right]_{n\times n} \qquad (14)$$

NGA (regularized gain matrix) is:

$$K_N = K \odot T_{ar} \qquad (15)$$

$\odot$ is element-wise division, $RNGA$ (relative regularization gain matrix):

$$\Lambda_N = \left[\lambda_{ij}, i, j = 1,2,\cdots n\right] = K_N \otimes K_N^{-T} \qquad (16)$$

$-T$ is the matrix inverse transpose.

Relative average dwell time:

$$\gamma_{ij} \overset{\Delta}{=} \frac{\bar{\tau}_{arij}}{\tau_{arij}} = \frac{\lambda_{Nij}}{\lambda_{ij}} \qquad (17)$$

Table 1: ART of a typical multivariate process

$g_{ij}(s)$	k_{ij}	$k_{ij}e^{-\theta_{ij}s}$	$\frac{k_{ij}e^{-\theta_{ij}s}}{\tau_{ij}s+1}$
τ_{arij}	$\varepsilon(\varepsilon \to +0)$	θ_{ij}	$\theta_{ij} + \tau_{ij}$

$RARTA$ (Relative Average Dwell Time Matrix):

$$\Gamma = \left[\gamma_{ij},\ \mathrm{i},\ \mathrm{j} = 1, 2, \cdots,\ \mathrm{n}\right] = \Lambda_N \odot \Lambda \qquad (18)$$

Therefore, the pairing process of $RGA - NI - RNGA$ is shown in Figure 2.

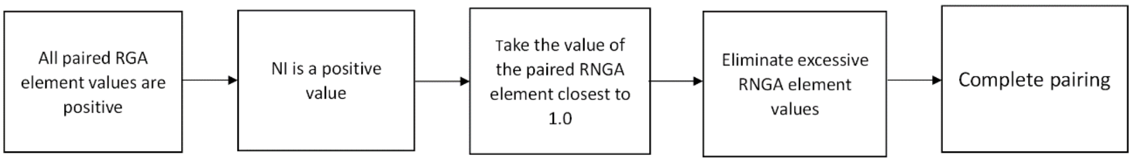

Figure 2: Matching process of $RGA - NI - RNGA$

(3) Coupling index

After using $RGA - NI - RNGA$ pairing procedure, recalculate $RNGA$, the coupling index[15]:

$$\beta_{ij} = \left| \frac{\lambda_{N,ij}}{\lambda_{N,ii}} \right| = \left| \frac{\lambda_{ij}\gamma_{ij}}{\lambda_{ii}\gamma_{ii}} \right| \qquad (19)$$

IIA (coupling index matrix) with all 1s on the diagonal:

$$B = \lfloor \beta_{ij} \rfloor_{n\times n} \tag{20}$$

① $\beta_{ij}(i \neq j)$ is very small, which is equivalent to very small $\lambda_{ij}/\lambda_{ii}$ or γ_{ij}/γ_{ii}, then u_j has little influence on y_i; the main loop can effectively filter out the high-frequency disturbance of the fast feedback loop.

② $\beta_{ij}(i \neq j)$ is very large, which means that $\lambda_{ij}/\lambda_{ii}$ or γ_{ij}/γ_{ii} is very large, then u_j has a great influence on y_i; the main loop can effectively filter out the constant value disturbance of the feedback slow loop.

Control the threshold ρ selected during design, if the value of the $(k,1)$th element satisfies: $\beta_{lk} > \rho, k, l = 1, 2, \ldots n, k \neq l$, Then there is a strong coupling effect between the k-th loop and the l-th loop, so $\beta_{ij}(i \neq j)$ is used as the coupling measure between the loops.

When $0.15 \leq \beta_{ij} \leq 8$, the coupling between the loop and the main loop is strong, so $0.15 \leq \beta_{ij} \leq 8, \bar{\rho} = 8$.

3.2. Decoupling of Temperature and Humidity Control System

(1) Select the decoupling algorithm to determine

Since the transfer function of the temperature and humidity system of the artificial light source type plant factory is determined, the PID control strategy is used to solve the coupling problem in the multi-input multi-variable (MIMO) system. Combined with the characteristics of the system process transfer function, the gain matrix and coupling index are relatively regularized. Based on this, the system control structure of MIMO is determined.

(2) Decoupling of temperature and humidity system control system

Under the premise that the artificial light source type plant factory works stably, the environmental physical parameters and environmental test parameters of the dynamic system at the steady-state operating point are shown in Table 2, and $\tau/T \approx 0.1$[16] is selected. Then the transfer function model of the temperature and humidity control system of the artificial light source type plant factory is:

$$\begin{bmatrix} t_s \\ t_a \\ W_a \end{bmatrix} = \begin{bmatrix} \dfrac{K_{11}}{T_{11}s+1}e^{-1.86s} & \dfrac{K_{12}}{T_{12}s+1}e^{-1.86s} & 0 \\ \dfrac{K_{11}K_s}{(T_{11}s+1)(T_s s+1)}e^{-1.84s} & \dfrac{K_{22}T_{12}+(K_{22}+K_{12}K_s)}{(T_{12}s+1)(T_s s+1)}e^{-1.84s} & 0 \\ 0 & \dfrac{K_{32}}{T_{32}s+1}e^{-40s} & \dfrac{K_{32}}{T_{33}s+1}e^{-40s} \end{bmatrix} \begin{bmatrix} q_w \\ q_s \\ W_s \end{bmatrix}$$

Among them, t_s, t_a, and W_a are the supply air temperature (°C), the internal temperature (°C), and the internal moisture content (g/kg), respectively;

q_w, q_s, and W_s are the cold water flow (kg/s), the supply air flow (m^3/h), and the moisture content of the supply air (g/kg).

$$\begin{bmatrix} t_s \\ t_a \\ W_a \end{bmatrix} = \begin{bmatrix} \frac{19.35}{23.22s+1}e^{-1.92s} & \frac{0.06}{23.22s+1}e^{-1.92s} & 0 \\ \frac{18.28}{(23.22s+1)(421s+1)}e^{-1.86s} & \frac{0.17s+7.3}{(23.22s+1)(421s+1)}e^{-1.86s} & 0 \\ 0 & \frac{4.16}{420s+1}e^{-42s} & \frac{1}{420s+1}e^{-42s} \end{bmatrix} \begin{bmatrix} q_w \\ q_s \\ W_s \end{bmatrix}$$

Table 2: Parameter values of temperature and humidity environment system of plant factory artificial light source (A)

	Parameter name	Parameter symbol	Environment status and parameter values					
Environment initial setup	Time point		August 21st 9:00	August 23st 9:00	August 25st 9:00	August 21st 21:00	August 23st 21:00	August 25st 21:00
	Growth state		One leaf stage	Two-leaf stage	Trefoil	One leaf stage	Two-leaf stage	Trefoil
Stable operating point measurement	Thermometer constant	γ	$\gamma = 0.0646 \mathrm{kPa/^\circ C}$					
	Air supply capacity coefficient	k_s	$k_s = 1.21\left(\mathrm{kJ}/\left(\mathrm{m^3 \cdot {}^\circ C}\right)\right)$					
	Air density	ρ_a	$\rho_a = 1.199\left(\mathrm{kg/m^3}\right)$					
	Constant air pressure specific heat	c_{ap}	$c_{ap} = 1.009\left(\mathrm{kJ}/\left(\mathrm{kg \cdot {}^\circ C}\right)\right)$					
	Cold water specific heat	C_w	4.18 $\mathrm{kJ/(kg \cdot {}^\circ C)}$					
	Cold water density	ρ_w	1000 $\mathrm{kg/m^3}$					
	Fresh air ratio	$\frac{q_x}{q_s}$	30%					
	Specific heat of air	C_a	1.0 $\mathrm{kJ/(kg \cdot {}^\circ C)}$					
	Fan coil unit specific heat	C_f	0.39 $\mathrm{kJ/(kg \cdot {}^\circ C)}$					
	The temperature difference between the inlet and outlet water of the fan coil	Δt	-3℃					
	amount of cold water	q_w	0.51 $\mathrm{m^3/h}$					
	Work area volume	V	20.16 $\mathrm{m^3}$					
	Leaf area index	LAI	4.35e-6	3.23e-5	7.07e-5	4.35e-6	3.23e-5	7.07e-5
	Leaf temperature	$\sum t_p$	26.2	27.1	27.9	19.4	18.2	15.2
	Fan coil inlet air	t_{s1}	22	20	20	13	13	13
	Fresh air temperature	t_x	14	13	14	10	10	11

	Regional air humidity	W_a	11.89	11.35	12.09	12.42	11.71	11.65
	Air volume	q_s	5.22	5.18	5.22	5.62	5.58	4.94
	Supply air temperature	t_s	26	26	26	16	16	16
	Supply air moisture content	W_s	11.53	11.38	11.53	12.91	12.75	10.62
Calculate the value	Internal temperature	t_a	23.77	23.79	23.79	15.86	16.2	12.89
	Internal humidity	RH_{in}	61.87	59.82	62.95	57.72	55.12	65.83
Validate the value	Internal temperature	t_a	25.4	26.0	27.2	20.1	18.5	14.6
	Internal humidity	RH_{in}	63.6	62.1	64.7	60.2	58.4	69.2
Temperature	Absolute error	$\lvert t_a \rvert$	1.63	2.21	3.41	4.24	2.3	1.71
	Relative error	%	6.86	9.29	14.33	26.73	14.20	13.27
Humidity	Absolute error	$\lvert RH_{in} \rvert$	1.73	2.28	1.75	2.48	3.28	3.37
	Relative error	%	2.80	3.81	2.78	4.30	5.95	5.12

Because each element in the transfer function approximates the form of $FOPDT$, according to the temperature and humidity system control structure selection algorithm, calculate K, Λ, T_{ar}, K_N, Λ_N, and then calculate $NI = 0.4144 > 0$. Based on the results, rearrange the transfer function matrix.

$$K = \begin{bmatrix} 19.35 & 0.06 & 0 \\ 18.28 & 0.17 & 0 \\ 0 & 4.16 & 1 \end{bmatrix}, \quad \Lambda = \begin{bmatrix} -0.5781 & -0.2622 & 0 \\ 2.1384 & -1.2860 & 0 \\ 0 & 2.5482 & -0.9880 \end{bmatrix}$$

$$T_{ar} = \begin{bmatrix} 340 & 243 & 360 \\ 8 & 11 & 243 \\ 20 & 30 & 472 \end{bmatrix}, \quad K_N = \begin{bmatrix} 0.0023 & -0.0004 & -0.0029 \\ -0.2000 & -0.0491 & -0.0005 \\ 0.0090 & 0.0085 & 0.0006 \end{bmatrix}$$

$$\Lambda_N = \begin{bmatrix} -0.0174 & -0.0144 & 1.0318 \\ 1.3773 & -0.3806 & 0.0032 \\ -0.3559 & 1.3950 & -0.0351 \end{bmatrix}$$

According to the pairing structure, the transfer function of the temperature and humidity control system is rearranged as:

$$\begin{bmatrix} t_s \\ t_a \\ W_a \end{bmatrix} = \begin{bmatrix} 0 & \frac{0.06}{23.22s+1}e^{-1.92s} & \frac{19.35}{23.22s+1}e^{-1.92s} \\ 0 & \frac{17.22}{(23.22s+1)(421s+1)}e^{-1.86s} & \frac{0.15s+6.7}{(23.22s+1)(421s+1)}e^{-1.86s} \\ \frac{1}{421s+1}e^{-42s} & 0 & \frac{4.16}{420s+1}e^{-42s} \end{bmatrix} \begin{bmatrix} q_w \\ q_s \\ W_s \end{bmatrix} \tag{21}$$

Then Λ_N in $RNGA$ and B in IIA:

$$\Lambda_N = \begin{bmatrix} \underline{1.038} & -0.0174 & -0.0144 \\ 0.0032 & \underline{0.3773} & -0.3806 \\ -0.0351 & -0.3599 & \underline{1.3950} \end{bmatrix}, \quad B = \begin{bmatrix} 1.0000 & 0.0169 & 0.0139 \\ 0.0024 & 1.0000 & 0.2763 \\ 0.0251 & 0.2580 & 1.0000 \end{bmatrix}$$

Therefore, the suitable pairing method is $t_s \leftrightarrow q_w / t_a \leftrightarrow q_s / W_a \leftrightarrow W_s$, that is, the supply air temperature is paired with the cold water flow rate, the internal temperature is paired with the supply air flow rate, and the internal moisture content is paired with the supply air moisture content.

3.3. Decoupling Control Structure of Temperature and Humidity System

According to the decoupling pairing results, the temperature and humidity control system ($MIMO$) is decoupled[16]. As shown in Figure 3, the temperature and humidity decoupling control loop is established as the supply air temperature control loop, the internal temperature control loop, and the internal moisture content control loop.

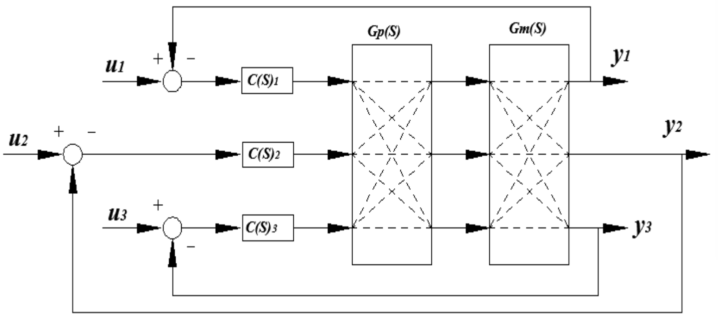

Figure 3: JDecoupling control block diagram of temperature and humidity system

4. Conclusion

Through the analysis of the nonlinear dynamic model of the temperature and humidity control system, the environmental factors that affect the temperature and air volume of the supply air are initially established, mainly the internal temperature, the flow of cold water in the fan coil, and the temperature difference of the cold water. The mature and general PID control strategy in industrial systems is used to solve the temperature and humidity control problem. Combined with the characteristics of the system process transfer function, based on the relative regularization gain matrix and coupling index, a three-input and three-output temperature and humidity coupled dynamic system (MIMO) is established.), that is, the supply air flow, cold water flow, and supply air moisture content are used as input quantities, and indoor temperature, supply air temperature, and indoor moisture content are output quantities to control and adjust the temperature and humidity inside the plant factory. Through the decoupling of temperature and humidity, it is convenient to adjust and control the temperature and humidity. Using the steady-state operating point environmental parameters, according to the temperature and humidity system control structure selection algorithm and decoupling method, the decoupling control strategy of the temperature and humidity system is established, which provides a theoretical basis for the implementation of temperature and humidity control equipment on site.

Acknowledgements

Heilongjiang Institute of Technology's 2020 Provincial Undergraduate Universities Basic Scientific Research Business Expenses Special Fund Project: Environmental Mechanism Analysis and Control Technology Research of Crop Breeding in Plant Factories (2020-KYYWF-0519).

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