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High-accuracy Fuzzy Controllers for Vacuum Cooling of Phosphoric Slurry Using Variable Universes of Discourse

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Abstract

Maintaining phosphoric slurry within the optimal temperature range is of great significance in improving the quality of the phosphoric acid product. Due to the lack of integral parts and the limited number of expert rules, general fuzzy controllers are commonly incapable of achieving accurate output. This paper proposed a novel fuzzy controller based on variable universes of discourse (VUD) to improve the accuracy of the temperature of phosphoric slurry. By tuning the motorized motor in the vacuum pump, the controller can obtain an appropriate vacuum degree in flash evaporators. With the online operation of contraction-expansion factors, fuzzy rules can be reproduced online, which is equivalent to the densification of fuzzy sets on universes of discourse. Thus, the output accuracy of VUD fuzzy controllers can be enhanced significantly. The experimental results show that VUD fuzzy controllers can tune the temperature of phosphoric slurry to within the optimal range and have a much better effect than general fuzzy controllers.

***Keywords**: Fuzzy Systems, Expert Rules, Fuzzy Control, Variable Universes of Discourse, Flash Evaporator, Phosphoric Slurry*

1. Introduction

Flash evaporators are widely used in the "wet" process of phosphoric acid production. Industrial phosphoric acid is usually extracted from phosphate ore by using vitriolic acid, following the creation of a by-product of calcium sulfate dihydrate. When the concentration of the phosphoric acid product ranges from 26% to 28%, calcium sulfate dihydrate is easier to filter through separators, compared to calcium sulfate hemihydrate in the dihydrate "wet" process in [1, 2]. However, the process imposes a rigid requirement on the temperature control of phosphoric slurry. Several tests have shown that the chemical reactions in the process generate so much heat that the temperature of phosphoric slurry can rise to 130℃ if no cooling operation is done. Some studies have further suggested that the feasible temperature is in the range of 75~ 80℃ and that the optimum temperature is 78±0.3℃, which is difficult to achieve for most field engineers and operators in [3, 4]. To optimize the conditions of phosphoric acid extraction, it is necessary to use a fine controller to maintain the temperature at 78℃. The present method entails using flash evaporators to remove part of the water in phosphoric slurry for cooling purposes. This can significantly improve efficiency in cooling and reducing the discharge of pollutants, compared with the method based on air blowers. In theory, a given vacuum pressure in the flash evaporator can lead to an accurate temperature of the phosphoric slurry. However, the actual effect may suffer from some disturbances, such as

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variation in the percentages of P_2O_5, carbonate, and impurities. The percentage of P_2O_5 determines the concentration of phosphoric acid. The concentration of phosphoric acid determines the viscosity of phosphoric slurry. Then, the viscosity of phosphoric slurry partly determines the rate of water evaporation. Moreover, carbonate or impurities can greatly influence the volume of foam in phosphoric slurry in [5]. This also partly determines the rate of water evaporation. The occurrence of such disturbances causes the temperature to fluctuate. Thus, a field adjustment for vacuum pressure is needed.

The vacuum pressure in flash evaporators is usually set by having fully experienced operators tune the valve opening of the vacuum pump in [6]. It is necessary to closely monitor whether or not all indicators are in normal state during the whole process of adjustment (2~6 hours). When one or more indicators go into an abnormal state, an immediate adjustment must be done. A slight carelessness may lead to unfavorable fluctuations of the technology indicators and a decline in the quality of phosphoric acid. Therefore, it is necessary to develop a controller for online tuning of the valve opening of the vacuum pump to achieve the optimal temperature of phosphoric slurry.

The extraction tank is a complicated object with big inertia; thus, it is hard to establish a mathematical model for control purposes in [7]. To avoid this difficulty, fuzzy controllers are commonly applied to such control problems, as the fuzzy if-then rules provide the foundation for an expert knowledge base and inference engine in [8-12]. Due to the lack of integral parts and the finite number of rules, however, general fuzzy controllers present difficulties in achieving the desired control accuracy. Fortunately, a new fuzzy control method by means of introducing a VUD method has been proposed in Refs. [13,14]. By using a set of nonlinear contraction-expansion factors, VUD fuzzy controllers can not only effectively improve the control accuracy but also significantly reduce the number of rules needed. In 2002, an experiment with VUD fuzzy controllers was successfully done on a quadruple inverted pendulum in [15, 16]. This achievement was widely received because controlling a quadruple inverted pendulum was a great challenge at that time. As a result, many researchers developed a keen interest in the theoretical analysis and practical design of VUD fuzzy controllers. For example, some VUD methods for chaotic systems and auto-gauge control systems were discussed in [17-19]; an analog circuit that made use of VUD fuzzy systems was developed in [20]; and some approximation properties and design methods for fuzzy systems were investigated in [21-27]. These works showed that VUD fuzzy controllers were capable of achieving good performance in control accuracy. However, the construction of VUD fuzzy controllers continues to be challenging in the aspects of optimizing contraction-expansion factors and obtaining concise fuzzy rules. This paper focuses on a method based on a look-up table to construct a VUD fuzzy controller for the temperature adjustment of an extraction tank.

The rest of the paper is organized as follows. After the Introduction, a schematic diagram of the vacuum cooling system and the basic structure of the control system are presented in Section II. Section III discusses the construction of VUD fuzzy controllers, and Section Ⅳ presents some experimental results. Finally, Section V presents the conclusions drawn from this study.

2. The Structure of a VUD Fuzzy Vacuum Cooling System

A flash evaporator can remove a large amount of heat in phosphoric slurry by maintaining the appropriate rate of water evaporation. The lower the vacuum pressure in a flash evaporator goes down, the quicker the water evaporation in phosphoric slurry becomes. A flowchart of the vacuum cooling system is presented in Figure 1, in which five major devices are marked. These are an extraction tank, a flash evaporator, a slurry pump, a condenser, and a vacuum pump. Their working mechanism is as follows: The slurry pump sucks phosphoric slurry into the

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flash evaporator, where water evaporates quickly to remove heat from the phosphoric slurry at a given vacuum pressure. The vacuum pump provides appropriate vacuum pressure to the flash evaporator. At the same time, room-temperature water sprays into the condenser. Thus, the hot steam piped from the flash evaporator condenses into water, which is then discharged into a receiver and pumped into a phosphoric slurry filter as washing water. Waste gas is processed to meet the environment protection standard before finally being exhausted out the chimney. Engineering experiences have shown that the actual effect of the cooling system relies heavily on an accurate vacuum pressure. Therefore, a controller with high-accuracy output is needed for the adjustment of the vacuum pressure through a motorized valve.

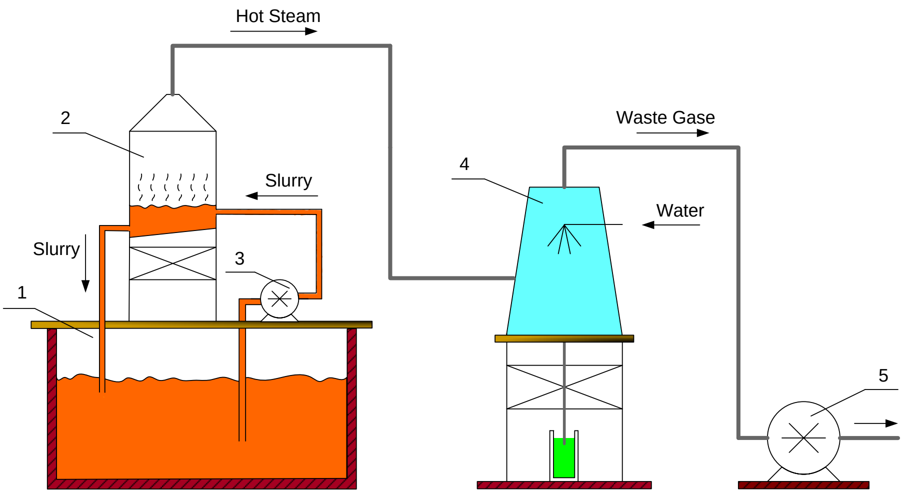

Figure 1. The Flowchart of Phosphoric Slurry Vacuum Cooling System

As mentioned in the previous section, VUD fuzzy controllers can achieve high-accuracy output; thus, it is applied to tuning the opening degree of the motorized valve in the vacuum cooling system. Figure 2 shows that the system consists of eight units: Temperature to Pressure, Pressure Correction, VUD Fuzzy Controller, Motorized Valve, Flash Evaporator, Extraction Tank, Temperature Sensor, and Pressure Sensor. Temperature to Pressure is used to convert the temperature error E_t into the vacuum pressure P_t. Pressure Correction is used to compensate P_t for the interference from the variation in P_2O_5, CaO, and organic substance (OS) in the phosphoric slurry. VUD Fuzzy Controller is the core of the vacuum cooling system and outputs a direct current signal (4~20mA) toward Motorized Valve. The temperature of phosphoric slurry in Extraction Tank is determined by the rate of water evaporation, which is controlled by the vacuum pressure, which in turn is controlled by the opening degree of Motorized Valve. Pressure Sensor and Temperature Sensor are responsible for collecting vacuum pressure data in Flash Evaporator and temperature data in Extraction Tank, respectively.

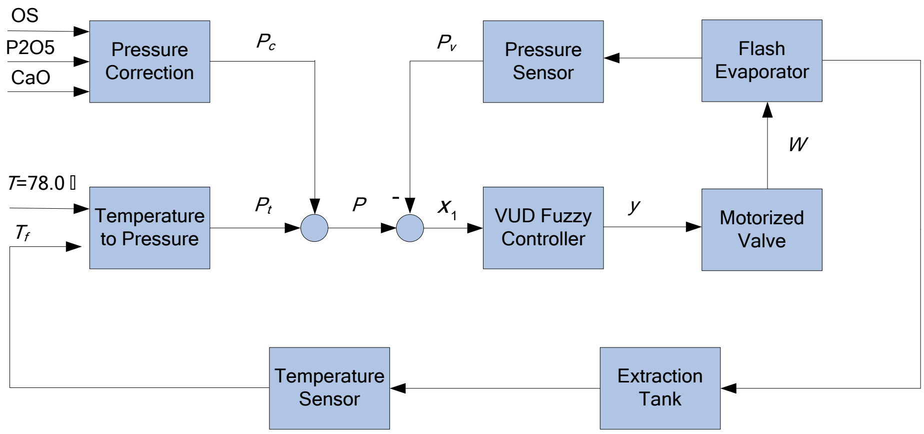

Figure 2. The Structure of a Vacuum Cooling System

The value of the input temperature T is set to 78℃, and the value of T_f is collected by temperature sensors in the extraction tank. Under the condition $T = 78$℃, T_f is converted to P_t by the function, which is defined as:

$$P_t = F_P(T_f) = \begin{cases} 101.3, & T_f \leq 70℃, \\ 45 - 1.25(T_f - 70), & 70℃ < T_f \leq 86℃, \\ 25, & T_f > 86℃, \end{cases} \quad (1)$$

P_t is given in kPa(A), which is a unit of absolute pressure in SI units. P_t is known to be an intermediate input variable of the VUD fuzzy controller. The final vacuum pressure needs to be adjusted because some interferences may occur as the percentages of P_2O_5, OS, and CaO cannot always be guaranteed to be constant. The final vacuum pressure is defined by the formula $P = P_t + P_c$, where P_c is a correction value. To obtain a reasonable value of P_c, three linguistic expressions—Low, Medium, and High—are used to depict the variations in P_2O_5, OS, and CaO, as shown in Table 1. At the same time, a base of expert rules is presented to look up the correction value, as shown in Table 2. Next, the value collected by pressure sensors is denoted as P_v, an error value defined by $x_1 = P - P_v$ inputs to the VUD fuzzy controller, the output value of which is denoted by y.

3. Design of VUD Fuzzy Controllers

The VUD fuzzy controller shown in Figure 2 functions as the core of the vacuum cooling system of the phosphoric slurry, and it plays a key role in the cooling effect of the system. Next, our work focuses on the construction of a VUD fuzzy controller.

Table 1. The Linguistic Expressions of Correction Variables

Variables	Linguistic expressions		
	Low	Medium	High
OS	<0.21%		>=2.1%
P_2O_5	<25%	25~30%	30%
CaO	<26.5%	26.5~33.8%	33.8%

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Table 2. The Expert Rules for the Pressure Correction in Vacuum Condenser

SN	Condition	P_c / kPa
1	OS is Low and P_2O_5 is Low and CaO is Low	+1.50
2	OS is Low and P_2O_5 is Low and CaO is Medium	+0.95
3	OS is Low and P_2O_5 is Low and CaO is High	+0.65
4	OS is Low and P_2O_5 is Medium and CaO is Low	+1.25
5	OS is Low and P_2O_5 is Medium and CaO is Medium	+0.35
6	OS is Low and P_2O_5 is Medium and CaO is High	+0.25
7	OS is Low and P_2O_5 is High and CaO is Low	+0.20
8	OS is Low and P_2O_5 is High and CaO is Medium	0
9	OS is Low and P_2O_5 is High and CaO is High	−0.15
10	OS is High and P_2O_5 is Low and CaO is Low	0.25
11	OS is High and P_2O_5 is Low and CaO is Medium	−0.15
12	OS is High and P_2O_5 is Low and CaO is High	−0.50
13	OS is High and P_2O_5 is Medium and CaO is Low	−0.75
14	OS is High and P_2O_5 is Medium and CaO is Medium	−0.95
15	OS is High and P_2O_5 is Medium and CaO is High	−1.25
16	OS is High and P_2O_5 is High and CaO is Low	−1.15
17	OS is High and P_2O_5 is High and CaO is Medium	−1.35
18	OS is High and P_2O_5 is High and CaO is High	−1.45

3.1 Contraction-expansion Factors and Membership Functions

A VUD fuzzy controller consists of five parts: $\Delta x_1/\Delta k$, $F(e_1^k, e_2^k, u^k)$, and three contraction-expansion factors, as shown in Figure 3. $\Delta x_1/\Delta k$ Represents a differential, and $F(e_1^k, e_2^k, u^k)$ denotes a function that acts as a general fuzzy controller.

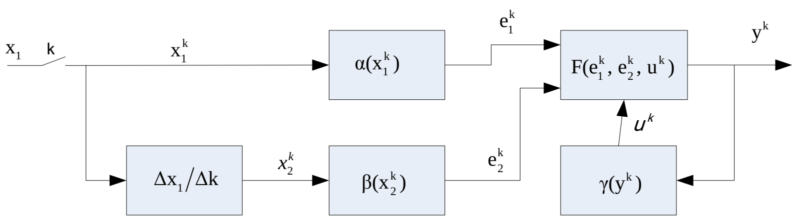

Figure 3. The Schematic of A VUD Fuzzy Controller

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The contraction-expansion factors are defined as

$$\alpha(x_1^k)=\begin{cases}1, & k=0,\\ \left(\left|\dfrac{x_1^k}{2.5}\right|\right)^{\tau}+\delta, & k=1,2,3,\cdots,\end{cases} \tag{2}$$

$$\beta(x_2^k)=\begin{cases}1, & k=0,\\ \left(\left|x_2^k\right|\right)^{\tau}+\delta, & k=1,2,3,\cdots,\end{cases} \tag{3}$$

$$\gamma(y^k)=\begin{cases}1, & k=0,\\ \left(\dfrac{\left|y^k-12\right|}{8}\right)^{\tau}+\delta, & k=1,2,3,\cdots,\end{cases} \tag{4}$$

where $\tau=0.85$ and $\delta=10^{-6}$. To construct a VUD fuzzy controller, the first step is to set initial universes of discourse and their membership functions. The sample step is denoted as $k=0,1,2,\cdots$. For the three variables x_1^k, x_2^k, and y^k, the initial universes of discourse are denoted as $U_1^0=[-2.5,\ 2.5]\mathrm{kPa}$, $U_2^0=[-1.0,\ 1.0]\mathrm{Pa/s}$, and $V^k=[4,\ 20]$ mA, respectively. Suppose that the same number of fuzzy sets are partitioned on U_1^0, U_2^0, and V^0, where the central points of the fuzzy sets are equally distributed. To obtain the total number of fuzzy sets needed in a universe of discourse, the approximation accuracy is pre-set to $\varepsilon=0.1$. That is to say, the error between the output of the VUD fuzzy controller and that of the optimal controller is less than 0.1. The optimal controller is denoted as $y=g(x_1^k,\ x_2^k)$. According to the experts' experiences, it is reasonable to set

$$\left\|\frac{\partial^2 g}{(\partial x_1^k)^2}\right\|_\infty=0.47\ , \tag{5}$$

$$\left\|\frac{\partial^2 g}{(\partial x_2^k)^2}\right\|_\infty=0.049\ . \tag{6}$$

Using the results in [21], and the total number of fuzzy sets can be calculated by

$$M=\mathrm{INT}\left(5\sqrt{\frac{1}{8\varepsilon}\left(\left\|\frac{\partial^2 g}{(\partial x_1^k)^2}\right\|_\infty+\left\|\frac{\partial^2 g}{(\partial x_2^k)^2}\right\|_\infty\right)}\right)+1\ , \tag{7}$$

where INT is a function that rounds off its independent variable to the nearest integer value toward minus infinity. For the initial step of $k=0$, M should be set to 5 by using (7). That is to say, any one of the three initial universes of discourse—U_1^0, U_2^0, and V^0—should be partitioned as five fuzzy sets. For simplicity, triangle membership functions are applied, as shown in Figures 4 and 5.

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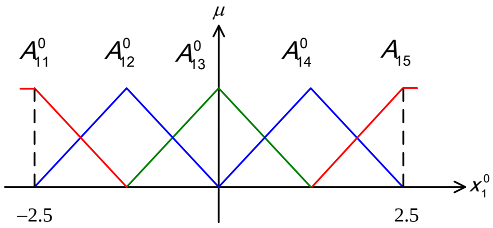

Figure 4. Membership Functions On U_1^0

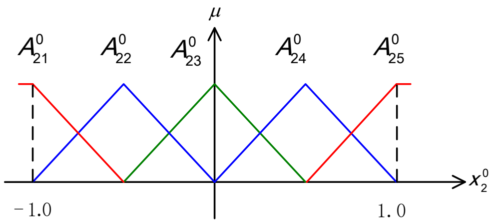

Figure 5. Membership Functions On U_2^0

Figure 4 shows that the central points of $A_{11}^0, A_{12}^0, \cdots, A_{15}^0$ are equally distributed on U_1^0. These can then be calculated as -2.5, -1.25, 0, 1.25, and 2.5, respectively. Their five membership functions are defined as:

$$\mu_{A_{11}^0}(x_1^0) = \begin{cases} 1, & x_1^0 < -2.5 \\ \left(x_1^0 + 1.25\right) / \left(-2.5 + 1.25\right), & -2.5 \le x_1^0 < -1.25, \\ 0, & \text{otherwise}, \end{cases} \tag{8}$$

$$\mu_{A_{12}^0}(x_1^0) = \begin{cases} \left(x_1^0 + 2.5\right) / \left(-1.25 + 2.5\right), & -2.5 \le x_1^0 < -1.25, \\ \left(x_1^0 - 0\right) / \left(-1.25 - 0\right), & -1.25 \le x_1^0 < 0, \\ 0, & \text{otherwise}, \end{cases} \tag{9}$$

…

$$\mu_{A_{15}^0}(x^k) = \begin{cases} 0, & x_1^0 < 1.25 \\ \left(x_1^0 - 1.25\right) / \left(2.5 - 1.25\right), & 1.25 \le x_1^0 < 2.5, \\ 1, & \text{otherwise}. \end{cases} \tag{10}$$

Similarly, the central points of $A_{21}^0, A_{22}^0, \cdots, A_{25}^0$ in Figure 5 can be calculated as -1.0, -0.5, 0, 0.5, and 1.0, respectively. Their membership functions are defined as:

$$\mu_{A_{21}^0}(x_2^0) = \begin{cases} 1, & x_2^0 < -1.0 \\ \left(x_2^0 + 0.5\right) / \left(-1.0 + 0.5\right), & -1.0 \le x_2^0 < -0.5, \\ 0, & \text{otherwise}, \end{cases} \tag{11}$$

$$\mu_{A_{22}^0}(x^k) = \begin{cases} \left(x_2^0 + 1.0\right) / \left(-0.5 + 1.0\right), & -1.0 \le x_2^0 < -0.5, \\ \left(x_2^0 - 0\right) / \left(-0.5 - 0\right), & -0.5 \le x_2^0 < 0, \\ 0, \text{ otherwise}, \end{cases} \tag{12}$$

$$\cdots$$

$$\mu_{A_{25}^0}(x^k) = \begin{cases} 0, & x_2^0 < 0.5 \\ \left(x_2^0 - 0.5\right) / \left(1.0 - 0.5\right), & 0.5 \le x_2^0 < 1.0, \\ 1, & \text{otherwise}. \end{cases} \tag{13}$$

The five fuzzy sets on V^0 are denoted as $B_1^0, B_2^0, \cdots, B_5^0$, and their respective central points are set to 4.0, 8.0, 12.0, 16.0, and 20. For the sample steps of $k = 0,\ 1,\ 2,\ \cdots$, the central points of A_{1j}^k, A_{2j}^k, and B_j^k are denoted as $\bar{x}_{1j}^k$, $\bar{x}_{2j}^k$, and $\bar{y}_j^k$, respectively. Based on these membership functions, a fuzzy rules table is obtained, as shown in Table 3.

Table 3. A Fuzzy Rules Table

x_1^k	x_2^k				
	A_{21}^0	A_{22}^0	A_{23}^0	A_{24}^0	A_{25}^0
A_{1j}^0	B_1^0	B_1^0	B_1^0	B_1^0	B_1^0
A_{12}^0	B_1^0	B_2^0	B_2^0	B_2^0	B_3^0
A_{13}^0	B_3^0	B_3^0	B_3^0	B_3^0	B_3^0
A_{14}^0	B_4^0	B_4^0	B_4^0	B_4^0	B_5^0
A_{14}^0	B_5^0	B_5^0	B_5^0	B_5^0	B_5^0

3.2 VUD Control Algorithm

Denote the fuzzy sets of U_1^0, U_2^0, and V^0 as $\{A_{1j_1}^0 \mid j_1 = 1, 2, \cdots, 5\}$, $\{A_{1j_2}^0 \mid j_2 = 1, 2, \cdots, 5\}$, and $\{B_{j_3}^0 \mid j_3 = 1, 2, \cdots, 5\}$, respectively. At the same time, a base of fuzzy rules is listed as follows:

$$R_j \text{ : IF } x_1^0 \text{ is } A_{1j}^0 \text{ and } x_2^0 \text{ is } A_{2j}^0, \text{THEN } y^0 \text{ is } B_j^0,\ j = 1,\ 2,\ \cdots,\ 25, \tag{14}$$

where $A_{1j}^k \in \{A_{1j_1}^0 \mid j_1 = 1, 2, \cdots, 5\}$, $A_{2j}^k \in \{A_{1j_2}^0 \mid j_2 = 1, 2, \cdots, 5\}$, and $B_j^0 \in \{B_{j_3}^0 \mid j_3 = 1, 2, \cdots, 5\}$. The mapping $[(j_1, j_2) \to j]$ between (j_1, j_2) and j is expressed as $[(1,1) \to 1]$, $[(1,2) \to 2]$, $\cdots$, $[(2,1) \to 6]$, $[(2,2) \to 7]$, $\cdots$, $[(5,5) \to 25]$.

Step 1: For $k = 0$, with a singleton fuzzifier, product inference, and a central average defuzzifier in [13,28], a VUD fuzzy controller can be written as

$$y^1 = f(x_1^0, x_2^0) = \frac{\sum_{j=1}^{25} \bar{y}_j^0 \mu_{A_{1j}^0}\left(x_1^0\right) \mu_{A_{2j}^0}\left(x_2^0\right)}{\sum_{j=1}^{m} \mu_{A_{1j}^0}\left(x_1^0\right) \mu_{A_{2j}^0}\left(x_2^0\right)}, \tag{15}$$

where $\bar{y}_j^0$ is the central point of B_j^0.

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Step 2: For $k=1$, the three online universes of discourse can be denoted as $U_1^1=[-2.5\alpha(x_1^1), 2.5\alpha(x_1^1)]\mathrm{kPa}$, $U_2^1=[-1.0\beta(x_2^1), 1.0\beta(x_2^1)]\mathrm{Pa}/$, and $V^1=[4\gamma(y^1), 20\gamma(y^1)]$ mA, respectively. Thus, the VUD fuzzy controller can be rewritten as

$$, \tag{16}$$

Step *k*: For any $k\geq 2$, the three online universes of discourse can be denoted as $U_1^k=[-2.5\alpha(x_1^k), \ 2.5\alpha(x_1^k)]\mathrm{kPa}$, $U_2^k=[-1.0\beta(x_2^k), 1.0\beta(x_2^k)]\mathrm{Pa}/$, and $V^k=[4\gamma(y^k), 20\gamma(y^k)]$ mA, respectively. Thus, the VUD fuzzy controller can be rewritten as

$$y^{k+1}=f(x_1^k, x_2^k)=\frac{\sum_{j=1}^{25}\bar{y}_j^k\mu_{A_{1j}^k}\left(x_1^k\right)\mu_{A_{2j}^k}\left(x_2^k\right)}{\sum_{j=1}^{m}\mu_{A_{1j}^k}\left(x_1^k\right)\mu_{A_{2j}^k}\left(x_2^k\right)}. \tag{17}$$

For x_1^k and x_2^k, the online central points can be calculated by $\bar{x}_{1j}^k=\alpha(x_1^k)\bar{x}_{1j}^0$, $\bar{x}_{2j}^k=\beta(x_2^k)\bar{x}_{2j}^0$, and $\bar{y}_j^k=\gamma(y^k)\bar{y}_j^0+12$. According to the results in [21], one can easily get

$$.. \tag{18}$$

which follows

$$\begin{cases}\mu_{A_{1j}^k}(x_1^k)=\mu_{A_{1j}^0}\left[\left(x_1^k/\alpha(x_1^k)\right)\right],\\ \mu_{A_{2j}^k}(x_2^k)=\mu_{A_{2j}^0}\left[\left(x_2^k/\beta(x_2^k)\right)\right].\end{cases} \tag{19}$$

Thus, the expression of the VUD fuzzy controller is degenerated into

$$y^{k+1}=f(x_1^k, x_2^k)=\frac{\sum_{j=1}^{25}\left[\gamma(y^k)\bar{y}_j^0+12\right]\mu_{A_{1j}^0}\left(\dfrac{x_1^k}{\alpha(x_1^k)}\right)\mu_{A_{2j}^0}\left(\dfrac{x_2^k}{\beta(x_2^k)}\right)}{\sum_{j=1}^{m}\mu_{A_{1j}^0}\left(\dfrac{x_1^k}{\alpha(x_1^k)}\right)\mu_{A_{2j}^0}\left(\dfrac{x_2^k}{\beta(x_2^k)}\right)}. \tag{20}$$

The VUD fuzzy controller in the form of (20) can effectively enhance the control accuracy. By means of the contraction-expansion factors, U_1^k will definitely shrink as x_1^k approaches the central point of A_{13}^0 shown in Figure 4. On the other hand, the total number of fuzzy sets on $U_1^k(k=1, \ 2, 3, \cdots)$ continues to be invariable. Thus, the shape of the fuzzy sets will become narrow. When the same number of fuzzy rules acts on a smaller U_1^k (compared with U_1^0), the densification of fuzzy partitions means that rules are reproduced. The closer x_1^k is to the central point of A_{13}^0, the more significant the reproduction effect. The same effect can be obtained on U_2^k. Therefore, it is feasible to use the VUD fuzzy controller to obtain a fine output.

3.3 An Example of Numerical Calculation

To detail the calculation process of the VUD fuzzy controller, a representative set of input-output data at k is considered, which consists of: T_f of 79.5 ℃ collected by temperature sensors , P_v of 30.2 kPa collected by pressure sensors, OS percentage of 0.25%, P_2O_5 percentage of 25.2%, CaO percentage of 34.6%, and y^k of 16.41mA. Fig. 2 shows that the input temperature T is set as 78℃. By using (1), $P_t=33.125$ kPa can easily be obtained. Based on Table 1, the data on OS, P_2O_5, and CaO fire the

15th expert rule in Table 2. Then, the correction value P_c is set as -1.25 kPa. Thus, one gets:

$$P = P_t + P_c = 33.125 - 1.25 = 31.875 \text{ kPa} \tag{21}$$

$$x_1^k = P - P_v = 31.875 - 30.2 = 1.675 \text{ kPa} \tag{22}$$

By measuring the output of the differential part of x_1^k, one gets $x_2^k = -0.382$ Pa/s. Using the definition of contraction-expansion factor in (2), (3), and (4), one obtains: $\alpha(x_1^k) = 0.712$, $\beta(x_2^k) = 0.441$, $\gamma(y^k) = 0.603$. Equations (8), (9), and (10) lead to: $\mu_{A_{11}^0}[x_1^k / \alpha(x_1^k)] = 0$, $\mu_{A_{12}^0}[x_1^k / \alpha(x_1^k)] = 0$, $\mu_{A_{13}^0}[x_1^k / \alpha(x_1^k)] = 0$, $\mu_{A_{14}^0}[x_1^k / \alpha(x_1^k)] = 0.114$, and $\mu_{A_{15}^0}[x_1^k / \alpha(x_1^k)] = 0.886$. Using the same method, one gets: $\mu_{A_{21}^0}[x_2^k / \beta(x_2^k)] = 0.732$, $\mu_{A_{22}^0}[x_2^k / \beta(x_2^k)] = 0.268$, $\mu_{A_{23}^0}[x_2^k / \beta(x_2^k)] = 0$, $\mu_{A_{24}^0}[x_2^k / \beta(x_2^k)] = 0$, and $\mu_{A_{25}^0}[x_2^k / \beta(x_2^k)] = 0$. Table 3 indicates that the four fuzzy rules $(j = 16, 17, 21, 22)$ are activated in (14). From (20), the output of the VUD fuzzy controller can be calculated by:

$$y^{k+1} = f(x_1^k, x_2^k) = \frac{\sum\limits_{j=16,17,21,22} \left[\gamma(y^k)\overline{y}_j^0 + 12\right] \mu_{A_{1j}^0}\left(\dfrac{x_1^k}{\alpha(x_1^k)}\right) \mu_{A_{2j}^0}\left(\dfrac{x_2^k}{\beta(x_2^k)}\right)}{\sum\limits_{j=1}^{m} \mu_{A_{1j}^0}\left(\dfrac{x_1^k}{\alpha(x_1^k)}\right) \mu_{A_{2j}^0}\left(\dfrac{x_2^k}{\beta(x_2^k)}\right)}. \tag{23}$$

Thus, one gets $y^{k+1} = 16.547$ mA. That is say, in the sample step of $k+1$, a direct current with a voltage of 16.547mA is outputted into the motorized valve for the adjustment of vacuum pressure.

4. Experimental Results

To contrast the actual effect, a general fuzzy controller and a VUD fuzzy controller are applied to the vacuum cooling system of a phosphoric acid plant in Tengfei Chemical Ltd., China. The general fuzzy controller can be obtained by defining $\alpha(x_1^k) = \beta(x_2^k) = \gamma(y^k) \equiv 1$ by using (20). At the same time, two representative types of phosphorus ore, Baokang and Yicheng, are used in this study. Table 3 provides a list of the percentage of contents. To ensure that they have the same experimental conditions before the control system is started, the Baokang and Yicheng phosphoric slurries are heated to the same initial temperature of 22.6℃, which is a little higher than the ambient temperature.

Table 4. The Percentage of Contents of Phosphoric Ore

Ore Type	Contents(%)							
	P_2O_5	Cao	OS	SiO_2	F	MgO	Al_2O_3	Fe_2O_3
Baokang	35.23	29.43	0.18	22.67	1.07	1.06	0.72	1.52
Yicheng	26.77	31.98	0.25	27.35	1.38	0.87	1.41	1.23

In the case of the Baokang ore, a general fuzzy controller and a VUD fuzzy controller are applied to tune the opening degree of the motorized valve. The sample size is set to 1.0 minute. Two sets of temperature data collected by temperature sensors, T_{B1} and T_{B2}, are plotted in Figure 6. T_{B1} represents the effect of the VUD

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fuzzy controller, and T_{B2} denotes the effect of the general fuzzy controller. To provide a closer look at the error between the actual temperature and the expected temperature in the range of $200 \le t \le 800$, two notations are defined: $e_{B1} = T_{B1} - 78$ and $e_{B2} = T_{B2} - 78$. Figure 7 shows the data related to e_{B1} and e_{B2}. Similarly, in the case of the Yicheng ore, two sets of temperature data, T_{Y1} and T_{Y2}, are plotted in Figure 8. Two notations are defined: $e_{Y1} = T_{Y1} - 78$ and $e_{Y2} = T_{Y2} - 78$. Figure 9 presents the data related to e_{Y1} and e_{Y2}.

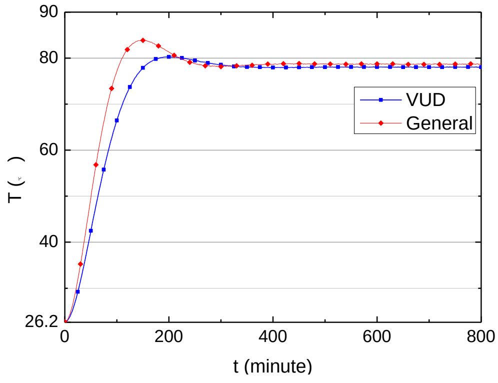

Figure 6. Comparison of Baokang

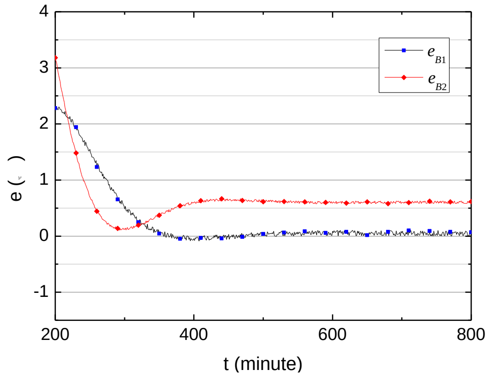

Figure 7. Error Comparison of Baokang

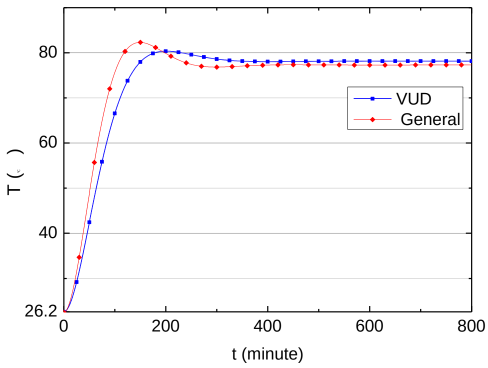

Figure 8. Comparison of Yicheng

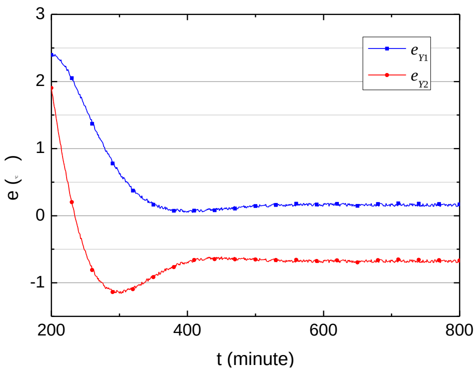

Figure 9. Error Comparison of Yicheng

Both Figure 6 and Figure 8 show that the general fuzzy controller responds a little faster than the VUD fuzzy controller. However, the two figures also show that the overshoot of the latter is much less than that of the former. With respect to the control accuracy, the latter is better. In the case of the Baokang slurry, when k is larger than 400, as shown in Figure 7, the VUD fuzzy controller outperforms the general fuzzy controller because e_{B1} is limited to the range of $[0, 0.2]$ ℃, and e_{B2} is limited to the range of $[0, 0.6]$ ℃. A similar result can be found in the Yicheng slurry, as shown in Figure 9, in which the curve of e_{Y1} is within the scope of $[0, 0.2]$ ℃, and the curve of e_{Y2} is within the scope of $[-0.7, 0]$ ℃. This result indicates that the performance of the VUD fuzzy controller is significantly improved in both the overshoot and the control accuracy; the response speed is slightly reduced but still acceptable in terms of technological requirements in the “wet” dihydrate process.

5. Conclusions

To rapidly cool phosphoric slurry, flash evaporators are widely applied in the “wet” process of dihydrate phosphoric acid production. However, it is difficult to manually control the vacuum degree of flash evaporators to maintain the temperature of phosphoric slurry in the optimal range because the temperature stability is subject not only to the vacuum degree but also to some disturbances, such as variations in the percentages of P_2O_5, CaO, and organic substance. Because they do not require a mathematical model, fuzzy controllers are usually considered to automatically tune the temperature.

This paper proposed a novel VUD fuzzy controller to adjust the opening degree of the motorized valve so as to achieve temperature stability. With the online operation of contraction-expansion factors, universes of discourse can be modified online. When the input variables are small, the VUD fuzzy controller can significantly improve the control accuracy. To simplify the design of the controller, triangle membership functions are used, and the central points of fuzzy sets are placed equidistantly on their corresponding universe of discourse. More importantly, to gain an appropriate fuzzy partitioning, an important formula is introduced to calculate the total number of fuzzy sets. Finally, to examine the actual effect of the controller, two representative sets of phosphoric ore are used in our tests. The experimental results show that the VUD fuzzy controller can limit the temperature of phosphoric slurry to within the optimal range and that it considerably outperforms the general fuzzy controller.

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