Sensors & Transducers, Vol. 155, Issue 8, August 2013, pp. 205-213

Sensors & Transducers

http://www.sensorsportal.com

Analysis on Temperature Control of Tubular Furnace Based on Fuzzy Control

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Received: 16 May 2013 /Accepted: 12 August 2013 /Published: 20 August 2013

Abstract: By analyzing of the tube-type heating furnace features and process, the temperature heating of the furnace was unidirectional, large inertia, heavy lag and changeable, it is hard to build an exact mathematical model confirmed parameters. Applying traditional control theory and method is difficult to achieve perfect control effect. We studied the application of the fuzzy control in tubular furnace temperature control. Then according to the dynamic response process of the second order system, fuzzy control rule table is established. The input and output relationship of fuzzy control rule table is introduced applying of synthesis reasoning rules, so as to calculate the fuzzy output vector corresponding to the deviation and the deviation change rate, and then fuzzy judged by using the center of gravity method, finally the adjustment amount of time interval for push rod is obtained. The feeding time of push-off arm was adjusted to control the heat-up time of each blank in the tubular heater dynamically, and ensures it reach the set temperature when coming out of the tubular furnace. This paper, finally, analyzes the factors that influence the system error and processes them adopting error analysis method, so as to improve the control precision of system. *Copyright © 2013 IFSA.*

Keywords: Fuzzy control, Feeding time, Heat-up time, Error analysis, Control precision.

1. Introductions

A great many metal work pieces was finished by investment casting, machining and post processing, yet investment casting had many shortcomings: blank ingredients and organization structure were not uniform, cutting workability was bad, utilization rate of raw materials was low and so on, now the workability and quality of the products were improved by adopting the bar heating and then precision forging. A key factor influencing the forging bar's quality is the temperature control when heating the bar. At present the heating way we adopted is intermediate frequency induction heating way. Induction heating output electricity power via the tubular furnace made by induction circle and heat up metal bar by electromagnetism induction. Because the temperature heating of the furnace was unidirectional, large inertia, heavy lag and changeable, it is hard to build an exact mathematical model confirmed parameters. Applying traditional control theory and method is difficult to achieve perfect control effect.

This text analyses tubular finance's working character and adopts the fuzzy control algorithm to solve the heating temperature control problem, enhancing system's controllability and reliability.

2. The Analysis of Tubular Intermediate Frequency Induction Furnace

Furnace mainly consists of material pushing system, intermediate frequency heating power supply, induction circle, stove and temperature control system.

Medium frequency is 1500 Hz, the length of work piece base material determined by the standard of each group product. The number of the work pieces in the stove cannot beyond 10, the diameter of the material among 80~90 mm. When out of stove, the surface temperature of material must among the deviation limits set point allowed, it means that system ask for the base material controlled by constant temperature. This system have two different control way. The first is pushing material pushing use constant beat, on the basis of temperature when work pieces out stove to adjust the heat source power. The second is heat source power setting a fixed power output, according work pieces temperature to adjust pushing beat to change work pieces' heating time. In most cases, furnace source power is heavy, adopting the first method source power would adjust frequently, when power is weak, because the conduction angles of the silicon controlled in rectifier bridge is small, harmonic wave is big and easy to affect the steady of electrified wire netting[1-3]. Thus this text chooses the second control way.

The structure of tubular furnace is show in Fig. 1.

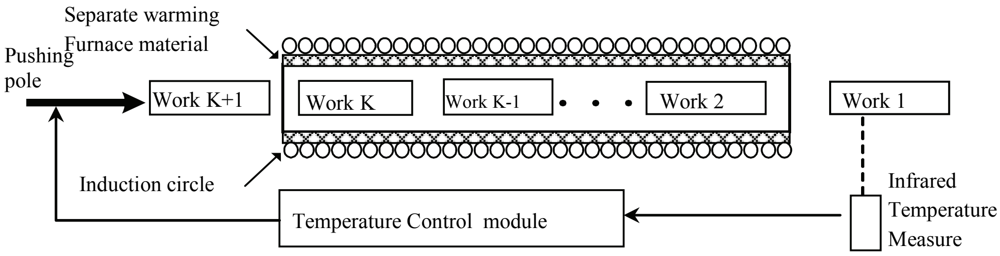


Fig. 1. Tubular furnace structure.

The part of main power source consists of three-phase power source, three-phase controlled rectifier, DC filter, and intermediate frequency inverter and induction furnace and so on. The part of control consists of automatic send\out system, intermediate frequency power source control system and temperature control system. Intermediate frequency power source control system manages the part of rectification and contra variant, and ensures the induction furnace output power keep constant in heating process. Intermediate frequency control system protects the whole induction power source overheating, overflow and phase lack at the same time. Temperature control system adopt infrared measuring temperature sensor to measure each material's outing temperature, then rely on the setting temperature to adjust pushing beat.

Through the above analysis, we get systemic electrical frame diagram as show in Fig. 2.

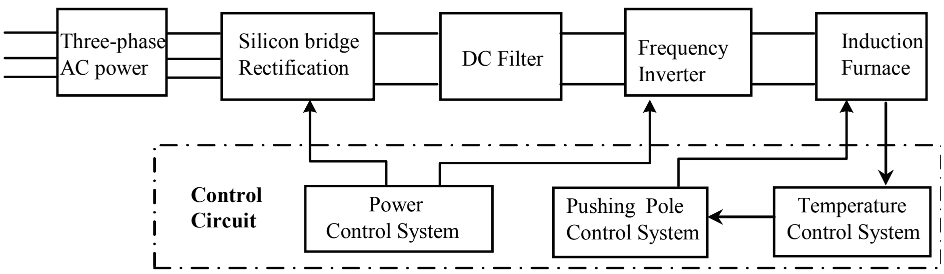


Fig. 2. System hardware frame.

3. The Study Work Pieces Temperature Control Algorithm

3.1. The Analysis of System Fuzzy Control

In consideration of rapid control and easy achievement, this text builds a two dimension fuzzy controller to control the temperature. In fuzzy control, input temperature deviation et and temperature alteration etc, adopt incremental control by changing Δt to adjust pushing beat time jp_t, system's setting temperature and sampling actual temperature are x, y, k means the K^{th} calculated data [4-5].

There be:

$$et(k) = x(k) - y(k) \tag{1}$$

$$etc(k) = et(k) - et(k-1) \tag{2}$$

Based on the fuzzy subset setting rule, set the fuzzy language variable of *et, etc, Δt* respectively be

ET, ETC, ΔT. Theirs change limits respectively define 14, 13, and 13 grade fuzzy domain:

$$X_{et}=\{-6, -5, -4, -3, -2, -1, -0, +0, 1, 2, 3, 4, 5, 6\};$$
$$Y_{etc}=\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\};$$
$$Z_{\Delta T}=\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$$

The language described fuzzy subset of *ET, ETC* and *ΔT* respectively be:

$$ET=\{NB, NM ,NS, NO, PO, PS, PM, PB\};$$
$$ETC=\{NB, NM, NS ,ZO, PS, PM, PB\};$$
$$\Delta T=\{NB, NM, NS, ZO, PS, PM, PB\}$$

This tubular furnace temperature control error demand is ±5, so temperature deviation basic domain setting is [-5, +5], quantize in fuzzy domain [-6, 6], temperature deviation quantification factor Ket=6/5=1.2. Because warming speed is not fast, setting temperature deviation change rate basic domain is [-2, +2], difference in temperature change rate fuzzy domain is [-6, 6], deviation change quantification factor K_{etc}=6/2=3. The adjustment basic domain output quantity beat time based on systemic fixed power and material's volume, thus here on setting [0, 100].

According to above setting, the transformation of fuzzy control physical quantity as show in Fig. 3.

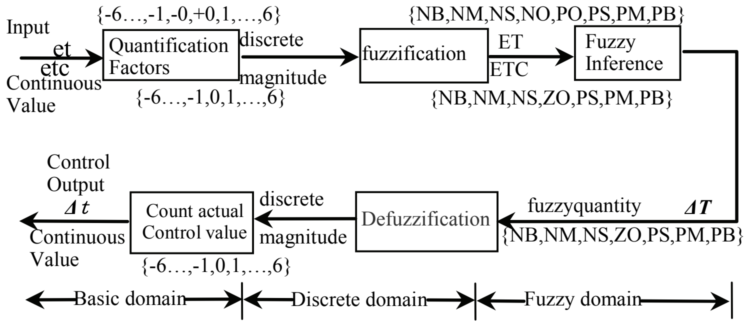


Fig. 3. Transformation figure of vague control physical quantity.

Because fuzzy control character is not sensitive about fuzzy language membership function form, mainly depend on the number of membership function and the fuzzy domain of each function [20]. According to the confirmed principle of membership function of fuzzy function: membership function must meet the demand of convex fuzzy set; in large deviation area we adopt low resolution fuzzy set, in small deviation area we adopt high resolution fuzzy set; the two spacing fuzzy membership set should not try to intersect, making sure one point not be covered more than two in domain, avoiding fuzzy membership set concept contradictory [6]. Thus fuzzy variable *ET, ETC, ΔT* adopt triangular MF, fuzzy variable membership curves as show in Fig. 4.

According to MF curve we can get the membership degree of each fuzzy variable, on the basis of fuzzy set's Zadeh express method, there be:

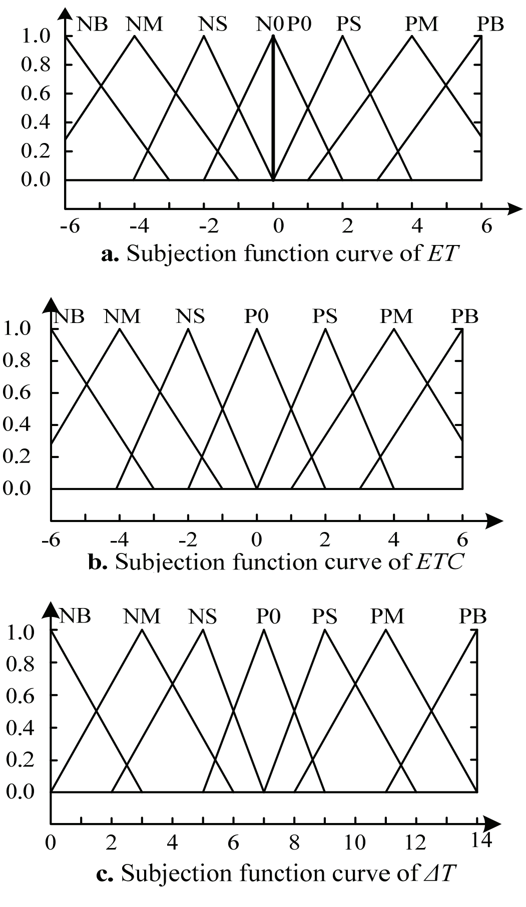
$$NB_{ET} = \frac{1.0}{-6} + \frac{0.7}{-5} + \frac{0.3}{-4}$$

$$NM_{ET} = \frac{0.3}{-6} + \frac{0.7}{-5} + \frac{1.0}{-4} + \frac{0.7}{-3} + \frac{0.3}{-2}$$

$$NS_{ET} = \frac{0.5}{-3} + \frac{1.0}{-2} + \frac{0.5}{-1}$$

$$N0_{ET} = \frac{0.5}{-1} + \frac{1.0}{0}$$

…



a. Subjection function curve of *ET*

b. Subjection function curve of *ETC*

c. Subjection function curve of *ΔT*

Fig. 4. Subjection function curve.

On the basis of temperature deviation fuzzy set expression we can clear up and get MF assignment table as show in Table 1. Successively write the expression of fuzzy set *ET, ETC, ΔT,* the same management we can get their MF assignment table.

For example second order system's step leap response curve, systemic trends character curve as show in Fig. 5, mainly consists of 4 cases.

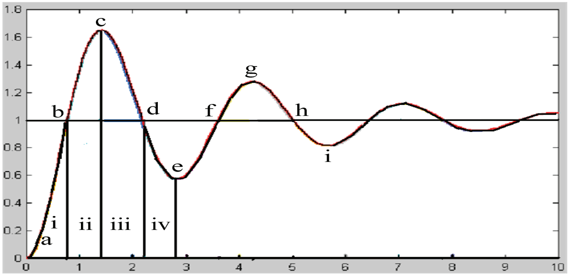


Fig. 5. Second order systems step response curve.

A. *et > 0 etc < 0 (i)*;
B. *et < 0 etc < 0 (ii)*;
C. *et < 0 etc > 0 (iii)*;
D. *et > 0 etc > 0 (iv)*;
The crossing, highest and lowest
Crossing:1.*e>0→e<0,Δe<o(b, f)*
2.*e<0→e>0,Δe>0(d, h)*
Highest: *Δe=0,e<0(c, g)*
lowest: *Δe=0,e>0(e, i)*

According to the direction and size of *ET, ETC,* determine the control rule as follows:

in i area when et is large, to shorten rise time *Δt<0*;when e is small, to prevent overshoot *Δt=0*;

in ii area to reduce overshoot, *Δt<0*;

in iii area when et is large, to shorten fall time *Δt<0*; when et is small reaching set point *Δt=0*;

in iv area to reduce lowest deviation *Δt>0*;

For crossing, highest and lowest, if et and etc both be 0 Δt=0;

Crossing: 1.*et >0→et<0, etc<0 (b, f), Δt <0*
2. *et <0→et>0, etc<0(d, h), Δt>0*;
Highest: *Δe=0,e<0(c, g), Δt<0*
Lowest: *Δe=0, e>0(e, i), Δt>0*

According above rules we can design fuzzy control principle table as show in Table 1.

Table 1. Vague control principle list.

ETC \ ET	NB	NM	NS	ZO	PS	PM	PB
NB	PB (R1)	PB	PB	PB	PM	ZO	ZO (49)
NM	PB (R2)	PB	PB	PM	PM	ZO	ZO
NS	PM	PM	PM	PS	ZO	NS	NS
NO	PB	PM	PS	ZO	NS	NM	NB
PO	PB	PM	PS	ZO	NS	NM	NB
PS	PS	PS	ZO	NS	NM	NM	NM
PM	ZO	ZO	NM	NM	NB	NB	NB
PB	ZO	ZO	NM	NB	NB	NB	NB (R56)

According to the sampling get et and figure out etc, then quantize them corresponding get an element *ET* and *ETC* in vague domain [7-10]. Through the Table 1, it can be found that the condition part of fuzzy relation R was comprised by the two conditions connected by using the "AND" operator. The satisfaction of general conditions can be calculated with the minimum of the subcondition membership function. For example, the subordinate degree of the two conditions for R_m (m=1,2…56) can be calculated by the following formula.

$$\mu_{ETm \cap ETCm}(X_{et}, Y_{etc}) = min\{\mu_{ETm}(X_{et}), \mu_{ETCm}(Y_{etc})\} \tag{3}$$

The general conditions of R_m can be expressed as two-dimensional matrices:

$$\begin{aligned} &\mu_m(X_{et}, Y_{etc}) = min\{\mu_{ETm}(X_{et}), \mu_{ETCm}(Y_{etc})\} \\ &= min\{[\mu_{ETm}(X_{et1}), \cdots \mu_{ETm}(X_{et14})]^T \times [\mu_{ETCm}(Y_{etc1}), \cdots \mu_{ETm}(Y_{etc13})]\} \\ &= \begin{bmatrix} min\{\mu_{ETm}(X_{et1}), \mu_{ETC1}(Y_{etc1})\}, \cdots min\{\mu_{ETm}(X_{et1}), \mu_{ETC1}(Y_{etc13})\} \\ min\{\mu_{ETm}(X_{et2}), \mu_{ETC1}(Y_{etc1})\}, \cdots min\{\mu_{ETm}(X_{et2}), \mu_{ETC1}(Y_{etc13})\} \\ \vdots \\ min\{\mu_{ETm}(X_{et14}), \mu_{ETC1}(Y_{etc1})\}, \cdots min\{\mu_{ETm}(X_{et8}), \mu_{ETC1}(Y_{etc13})\} \end{bmatrix} \end{aligned} \tag{4}$$

It will be receiving "(7×8)×1" matrices (formula 5) that write the row element of the "7×8" two-dimensional matrices from the first row in turn in rank.

$$\mu_m(X_{et}, Y_{etc}) = \begin{bmatrix} min\{\mu_{ETm}(X_{et1}), \mu_{ETC1}(Y_{etc1})\} \\ \vdots \\ min\{\mu_{ETm}(X_{et1}), \mu_{ETC1}(Y_{etc13})\} \\ \\ min\{\mu_{ETm}(X_{et2}), \mu_{ETC1}(Y_{etc1})\} \\ \vdots \\ min\{\mu_{ETm}(X_{et2}), \mu_{ETC1}(Y_{etc13})\} \\ \vdots \\ min\{\mu_{ETm}(X_{et14}), \mu_{ETC1}(Y_{etc13})\} \\ \vdots \\ min\{\mu_{ETm}(X_{et14}), \mu_{ETC1}(Y_{etc13})\} \end{bmatrix} \tag{5}$$

The "if-then" relation may be represented by the cross product of conditions and conclusion in fuzzy logic, the membership function of cross product is the minimum of the membership function of conditions and conclusion. So, the fuzzy relations "R_m" can be expressed as follow.

$$\begin{cases} R_m = (ET_m^T \times ETC_m)^T \times \Delta T_m \\ \mu_{Rm}(X_{et}, Y_{etc}, Z_{\Delta T}) = min\{min\{\mu_{ETm}(X_{et}), \\ \qquad \mu_{ETCm}(Y_{etc})\}, \mu_{\Delta Tm}(Z_{\Delta T})\} \end{cases} \tag{6}$$

The formula 6 can be written as the matrix format as the formula 7. According to the formula 7, every rule can be computed.

$$\mu_{Rm}(X_{et},Y_{etc},Z_{\Delta T})=\begin{bmatrix} min\{min\{\mu_{ETm}(X_{et1}),\mu_{ETCm}(Y_{etc1})\},\mu_{\Delta Tm}(Z_{\Delta T1})\},...,min\{min\{\mu_{ETm}(X_{et1}),\mu_{ETCm}(Y_{etc1})\},\mu_{\Delta Tm}(Z_{\Delta T15})\} \\ ... \\ min\{min\{\mu_{ETm}(X_{et1}),\mu_{ETCm}(Y_{etc2})\},\mu_{\Delta Tm}(Z_{\Delta T1})\},...,min\{min\{\mu_{ETm}(X_{et1}),\mu_{ETCm}(Y_{etc2})\},\mu_{\Delta Tm}(Z_{\Delta T15})\} \\ ... \\ min\{min\{\mu_{ETm}(X_{et2}),\mu_{ETCm}(Y_{etc2})\},\mu_{\Delta Tm}(Z_{\Delta T1})\},...,min\{min\{\mu_{ETm}(X_{et2}),\mu_{ETCm}(Y_{etc2})\},\mu_{\Delta Tm}(Z_{\Delta T15}) \\ ... \\ min\{min\{\mu_{ETm}(X_{et14}),\mu_{ETCm}(Y_{etc13})\},\mu_{\Delta Tm}(Z_{\Delta T1})\},...,min\{min\{\mu_{ETm}(X_{et14}),\mu_{ETCm}(Y_{etc13})\},\mu_{\Delta Tm}(Z_{\Delta T15}) \end{bmatrix} \quad (7)$$

Fuzzy relation matrix of System is the result of all control rules connected by the "OR" operator.

$$\begin{cases} R = R_1 \vee R_2 \vee ... \vee R_{56} \\ \mu_R(X_{et},Y_{etc},Z_{\Delta T}) = max\{\mu_{R1}(X_{et},Y_{etc},Z_{\Delta T}),\mu_{R2}(X_{et},Y_{etc},Z_{\Delta T}), \\ \qquad ...,\mu_{R56}(X_{et},Y_{etc},Z_{\Delta T})\} \end{cases} \quad (8)$$

For a given input (X_{et}, Y_{etc}), the fuzzy output for the R_m is as follow.

$$\Delta T_m = (X_{et} \times Y_{etc}) \circ R_m \quad (9)$$

The output of controller can be written as the formula (10).

$$\begin{cases} \Delta T = \bigcup_{m=1}^{56} [(X_{et} \times Y_{etc}) \circ R_m] \\ \mu_{\Delta T}(\Delta T) = max\{min\{min\{\mu_{ETi}(X_{et}),\mu_{ETCi}(Y_{etc})\}, \\ \qquad \mu_R(X_{et},Y_{etc},Z_{\Delta T})\}\} \end{cases} \quad (10)$$

If the output of controller for the given (X_{et}, Y_{etc}) input is

$$\Delta T = \{r_0, r_1, r_2, \cdots r_{14}\} \quad r_n \in (0,1)(n = 0,1\cdots 14),$$

the fuzzy vector can be written as the

$$\Delta T = \frac{r0}{-6} + \frac{r1}{-5} + \frac{r2}{-4} \cdots + \frac{r14}{6} \quad (11)$$

Output from the defuzzification process of controller output by using the weighted average method can be calculated as the follow.

$$\Delta T = \frac{\sum_{n=1}^{14} r_n \bullet Z_{\Delta T n}}{\sum_{n=1}^{14} r_n} \quad (12)$$

Then last result of controller is the follow formula.

$$\Delta t = \Delta T K_{\Delta t} \quad (13)$$

Then put the MCU control data into a table form and write on SCM's program storage, realizing locating method in SCM [4].

3.2. The Self-tuning Algorithm of Control Rule

i) Property test.

Owing to the fact that initial control rules are rough, it can not achieve satisfactory performance requirements, and to achieve better control effect, you must modify the control rules, which is necessary to test the performance of the controller [11]. Typically, the control effect and performance requirements deviation of error *et(nT)* and error rate of change of *ce (nT)* to test, set up et and *etc(nT)* belongs to fuzzy set *ET (nT)* and *ETC (nT)*. Through the test of the deviation *ET (nT)* and *ETC (nT)*, on the controller output is corrected, the correction of the amount of *P (nT)* is expected to improve the control effect of the system, i.e.

$$ET(nT) \to ETC(nT) \to P(nT)$$

$$(ET(nT) = NB) \to (ETC(nT) = NS) \to (P(nT) = PB)$$

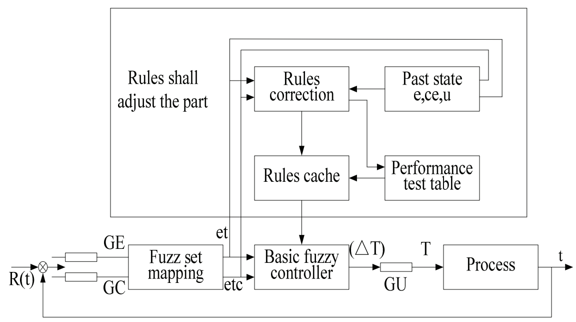


Fig. 6. Control Rules Fuzzy Logic Controller.

ii) Correction of control input.

According to each of the performance measurement of output *P (nT)*, we can calculate for the process control of the amount of correction of the input *r (nT)*, which the purpose is that the output characteristic can be changed later. We can discuss in following situations:

a) SISO system.

$$r(nT) = k_p(nT)$$

If input and output which frequently change in the process can be normalized to the maximum, then $k = 1$.

b) MIMO system.

For a MIMO system, we have the input-output relationship

$$X = F(X^T, U^T), \quad (14)$$

where X is the output vector of the system, and U is the input vector, then through a sampling period, the incremental relationship is:

$$\Delta X \approx TJ\Delta U = M\Delta U \quad (15)$$

J represents the Jacobian matrix in the formula. The formula which determines the incremental model ranging from the input change ΔU and the output change ΔX ,which can be called the process of incremental model. Thus (Process) correction of the amount of input *r (nT)* can be obtained by the above incremental model

$$r(nT) = M^{-1}P(nT) \quad (16)$$

In actual operation, because they do not know the exact model of the system, and therefore do not know the coupling coefficient between the input and output. Thus typically we can be based on experience for the understanding of the system, assuming a coupling coefficient, and then through a self-learning process to overcome the inaccuracy of the assumed [12].

c) Delay system.

As to the system which is larger delay, we need to determine control action of which moment should be responsible for the poor performance, which is defined by time delay period mT of the offline measurement-delay.

iii) Amendments to the rules of control.

We use the example of SISO system as an introduction to the amendment process of the control rules. The delay is assumed that the system of m sampling period, the control input of the sampling time *(nT-mT)* have a greatest impact on the performance of process output at time nT. If the initial rule of the control rule table as follows:

$$ET(nT-mT) \to ETC(nT-mT) \to \Delta T(nT-mT)$$

Through nT time characteristics test should be amended as:

$$ET(nT-mT) \to ETC(nT-mT) \to V(nT-mT)$$

and

$$ET(nT-mT) = F\{et(nT-mT)\}$$
$$ETC(nT-mT) = F\{etc(nT-mT)\}$$
$$\Delta T(nT-mT) = F\{\Delta t(nT-mT)\}$$
$$V(nT-mT) = F\{\Delta T(nT-mT) + r(nT)\}$$

Write the sentence form, is shown as:

$$IF \quad e = ET(nT-mT) \quad and \quad etc = ETC(nT-mT) \quad THEN$$
$$\Delta t = \Delta T(nT-mT) \quad (17)$$

The revised results as:

$$IF \quad e = ET(nT-mT) \quad and \quad etc = ETC(nT-mT) \quad THEN$$
$$\Delta t = V(nT-mT) \quad (18)$$

Using the relation matrix can be expressed as:

$$R'(nT) = ET(nT-mT) \times ETC(nT-mT) \times U(nT-mT) \quad (19)$$

and

$$R''(nT) = ET(nT-mT) \times ETC(nT-mT) \times V(nT-mT) \quad (20)$$

Let *R(nT)* is the current moment controller relation matrix, *R(nT+T)* is a modified matrix, realizing the conversion equations can be expressed the following statement:

$$R(nT+T) = \{R(nT) \ \text{is not} \ R'(nT)\} \ \text{else} \ R''(nT)$$

Also available for set representation:

$$R(nT+T) = \{R(nT) \wedge \overline{R'(nT)}\} \vee R''(nT)$$

General method for correcting controller type is proposed by E. H. Mamdan, this time the new relationship matrix is obtained, then according to the synthesis of *et (nT)*, *etc (nT)* and *R (nT+T)*, obtained fuzzy grade control quantity, After decisions to draw firm control, added it to the system, to complete a control action.

As nearly above, this method is time-consuming and accounted for a large amount of storage space. Here are both intuitive and simple and practical algorithms.

iv) A new control rule modification algorithm.

Here need to supplement equation (16) is the actual process input control signal, and if it is converted to fuzzy control. The output of the system, *r (nT)* should be divided by *GU*, as

$$r'(nT) = \frac{1}{GU} M^{-1}P(nT) = (GU \bullet M)^{-1}P(nT) = M_1^{-1}P(nT), \quad (21)$$

where $M1 = GU \cdot M$.

We want to revisit the relationship between the original rules and the new rules.

$$r(nT) = r'(nT)$$

The original rules:

$$T'\{et(nT-mT), etc(nT-mT)\} = \Delta T(nT-mT)$$

The new rules:

$$T'\{et(nT-mT), etc(nT-mT)\} = V(nT-mT)$$

But we found that, If we simply modified according to the above formula ,there will be such a problem, If two consecutive side was even in the delay period (*mT*), the two times are the same, namely *et(nT-mT)*, *etc(nT-mT+T)* and *ET (nT-mT+T)*, *ETC (nT-mT+T)* are equal, then because of the (*nT*) time will change

$$T'\{et(nT-mT),etc(nT-mT)\}=\Delta T(nT-mT)$$

into

$$T'\{et(nT-mT),etc(nT-mT)\}=V(nT-mT)$$

As in (*nT*+*T*), the original rules no longer exists, in accordance with the revised rules, the new rules

$$T'\{et(nT-mT+T),etc(nT-mT+T)\}$$
$$=T'\{et(nT-mT),etc(nT-mT)\}=V(nT-mT)$$

and then amended as follows:

$$T'\{et(nT-mT+T),etc(nT-mT+T)\}$$
$$=T'\{et(nT-mT),etc(nT-mT)\}=V'(nT-mT)$$

The equation

$$V'(nT-mT)=F\{\Delta t(nT-mT+T)+r(nT+T)\}$$
$$=F\{\Delta t(nT-mT+T)+r(nT)+r(nT+T)\} \tag{22}$$

Taking into account the above, we change the rule modification method.

The original rules:

$$T'\{et(nT-mT),etc(nT-mT)\}=U(nT-mT)$$

The new rules:

If in the past *(nT-mT)* of mT delay period, there is a *et (nT-mT-iT)*, *etc (nT-mT-iT)* and *et(nT-mT)* and *etc(nT-mT-iT)* are the same, then in the second amendment, the rules are:

$$T'\{et(nT-mT),etc(nT-mT)\}$$
$$=\{\alpha T'\{\{et(nT-mT),etc(nT-mT)\}+(1-\alpha)V(nT-mT)\}$$

Otherwise:

$$T'\{et(nT-mT+T),etc(nT-mT)\}=V(nT-mT)$$

Among them, $0<\alpha<1$, $i=1,\cdots,m-1$.

Now our new algorithm can be summarized as follows

Step 0: To establish buffer rushed 3 * 2m units of data storage.

$$\begin{cases} et(nT),et(nT-T),\cdots,et(nT-2mT+T) \\ etc(nT),etc(nT-T),\cdots,etc(nT-2mT+T) \\ \Delta T(nT),\Delta T(nT-T),\cdots,\Delta T(nT-2mT+T) \end{cases} \tag{23}$$

Step 1: Calculating *et(nT)*, *etc(nT)*;

Step 2: Look-up table $T'(et,etc)$, to get Δt *(nt-mT)*,

Look-up table $T''(et,etc)$, to get *p(nt-mT)*,

Calculating $V(nT-mT)=\Delta t\,(nT-mT)+r(nT)$;

Step 3: Modifying the control decision tableT′(e,c):

For i=1 to i=m-1

{Compare *et(nT-mT)*,*etc(nT-mT)* and *et(nT-mT-iT)*,*etc(nT-mT-iT)*;if the same, then Flag=1;else Flag=0};

If flag=1, then

$$T'_{nT+T}\{et(nT-mT),etc(nT-mT)\}$$
$$=\alpha T'\{et(nT-mT),etc(nT-mT)\}+(1+\alpha)V(nT-mT)$$

Otherwise,

$$T'_{nT+T}\{et(nT-mT),etc(nT-mT)\}=V(nT-mT)$$

Step 4: To determine the control amount of *U*(nT+T)* at the time of *(nT+T)*

$$\Delta T(nT+T)=\Delta T(nT+T)\times G\Delta T=T'_{(nT+T)}\{et(nT),etc(nT)\}\times G\Delta T$$

There $T'(et,etc)$ is the control decision table, $T''(et,etc)$ is the performance test correction table, These stored in the computer in advance.

4. The Design of Fuzzy Controller

This system use MCU to design a temperature controller which mainly consist of micro control device, infrared temperature survey and signal disposal circuit, beat drive module, keyboard and display module and power supply module [13-14]. System temperature set and initial beat time input by keyboard, the temperature of furnace exit work pieces are measured by infrared temperature measure instrument and go through signal disposal circuit transformed voltage span SCM AD needed. According to measured temperature went through fuzzy control to get the beat time to ensure heat work pieces reaching set temperature. Software uses modules structure programming, mainly consists of keyboard input /output, show, temperature measure and filtration, fuzzy control arithmetic subroutine. To decrease the SCM's program difficulty, control quantity output was calculated off-line of fuzzy control's 56 rules and put them into a table [15]. The controller output in MCU is a hexadecimal data, so the Control variable should be converted into hexadecimal. The MCU domain is [00H, 01H, …, FFH], so the Conversion relationship is formula 24.

$$\begin{aligned} &D_{MCU\_Table}=(D_{control\_var}+6)\times 256/12 \\ &D_{MCU\_Table}: Data\ of\ MCU\ table \\ &D_{control\_var}: Data\ of\ \Delta t\ table's\ control\ variable \end{aligned} \tag{24}$$

5. Analysis of the Temperature Error of Workpiece Experimental Test Result

5.1. Analysis and Treatment of Temperature Error of the Workpiece

According to control theory the precision of the system depends on the accuracy of given and feedback, so the heating furnace's control temperature precision is mainly decided by the given value and measured value of the temperature. In order to reduce the factors that may influence system error, the set point of temperature is given by keyboard to eliminate the given error. So the factors that mainly influence system error are in the link of temperature measurement [16-17].

Thermometry link consists of temperature transmitting (temperature signal is converted to 4 ~ 20 mA) and AD collecting process, so the errors of temperature measurement are mainly stochastic nonlinear error, gross error and the nonlinearity of data transformation [18]. The response time of thermometer is 50 ms, and each time when the work pieces being push out from heating furnace, the passing time in thermometer is 1 ~ 2.5 seconds (the length of each work piece is different), so each work piece's temperature measurement time is 20 ~ 50 times. In order to gain effective measurement data, the measure standard is based on the shortest work piece measured 15 times. According to the characteristics of random error, the random error of temperature measurement generally obey normal distribution, when the confidence interval is [-3σ, 3σ], the confidence probability is 99.7 % as shown in Fig. 7.

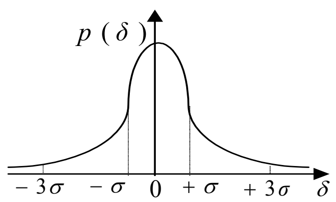


Fig. 7. Probability density curve of random error.

The measured temperature of each work pieces are $y1,y2,\ldots yi$ $(i=1,2\ldots15)$, the average value of each work piece's temperature is follow.

$$\overline{y} = \frac{1}{15}\sum_{i=1}^{15} y_i$$

The measured temperature root-mean-square error is got using Palin jess formula

$$\sigma = \sqrt{\frac{\pi}{2}}\frac{\sum_{i=1}^{n}|y_i - \overline{y}|}{\sqrt{n(n-1)}} \approx \frac{5}{4}\frac{\sum_{i=1}^{n}|y_i - \overline{y}|}{n-\frac{1}{2}} \qquad (25)$$

When $|y_i - \overline{y}| > 3\sigma$, then y_i is out of confidence interval, it will be deleted from measured data. Then recount $\overline{y}$ *and* σ until all left measuring point dropping in confidence interval. At present temperature measurement result is $\overline{y} \pm \sigma$.

During temperature measurement gross error adopts Wright's standards, firstly calculating Bessel data of measured value,

Among measured data, if y_i fits $|y_i - \overline{y}| > 3\sigma$ condition, this measured value will be deleted. Rest data will be processed by random error.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{15}(y_i - \overline{y})^2}{15-1}} \qquad (26)$$

Measuring temperature data's nonlinearity dispose adopts segmented correction method [19]. According to the accuracy requirement, $Y_i=f(y)$ is divided into n segment. And the dots in $Y_i=f(y)$ *1, 2, 3, ….n* are calculated correspondingly getting dots 1', 2', 3', …..n' in $Y_{2i} = K_{2i}y$. When n is large enough, each segment on $f(y)$ can be seen as a straight line, with slope K_{1i}. as shows in the Fig. 8.

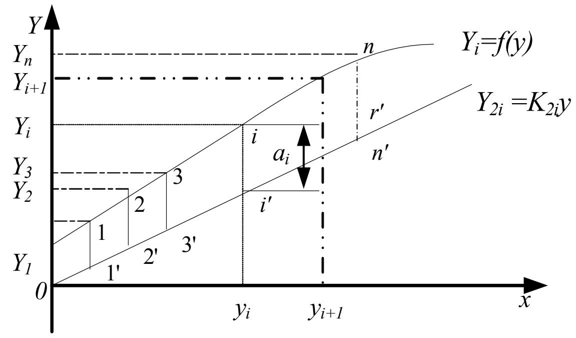


Fig. 8. Temperature acquisition nonlinear correction method.

Y_i—the ith segment linear equation is got as follows:

$$Y_i = Y_{i0} + K_{1i}(y - y_i)$$

Y_{i0} is the initial value for this segment. K_{1i} is straight line slope for ith segment. Corresponding to y_{2i} the straight line equation of the ith segment is as follows:

$$Y_{2i} = (Y_i - a_i) + K_{2i}(y - y_i),$$

where a_i is the difference between i and i' segment, K_i is the difference of slope the between i^{th} and i^{th} segment, i.e.

$$K_i = K_{1i} - K_{2i}$$

By the three formulas above:

$$
\begin{aligned}
Y_{2i} &= (Y_i - a_i) + (K_{1i} - K_{2i})(y - y_i) \\
&= [Y_i + K_{1i}(y - y_i)] - [a_i + K_i(y - y_i)] \\
&= Y_{1i} - [a_i + K_i(y - y_i)]
\end{aligned}
$$

5.2. The Analysis of Experimental Test Result

Using this controller in tubular furnace, setting work piece warming time 1100 s and initial beat 45 seconds, containing three work pieces in this furnace, gathering 20 work pieces' temperature during warming process, we get experimental graph show in Fig. 9.

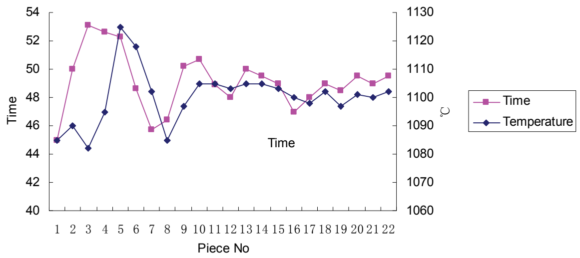


Fig. 9 The curve of push-time and temperature of workpieces.

6. Conclusions

This paper presents a tubular furnace temperature control system based on fuzzy control theory. On the basis of the features of tubular furnace, a fuzzy controller was designed applying two dimensions fuzzy control theory. The control rules were modified by the self-tuning algorithm of control rule during the controller running. Experiment indicated that induction furnace based on fuzzy control has the characters of high control accuracy, strong anti-interference ability and so on.

Acknowledgements

Xi'an Technological University president fund support. Xi'an Science and Technology Bureau Innovation fund support (CXY1130).

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