Temperature Intelligent Control System of Large-Scale Standing Quench Furnace *

HE Jian-jun, YU Shou-yi
(College of Information Science and Engineering, Central South University Changsha 410083 China)

Abstract Considering some characteristics of large-scale standing quench furnace, such as great heat inertia, evident time lag, strong coupling influence, hard to establish exact mathematical models of plant and etc, an artificial intelligent fuzzy control algorithm is put forward in this paper. Through adjusting the on-off ratio of electric heating elements, the temperature in furnace is controlled accurately. This paper describes structure and qualities of the large-scale standing quench furnace briefly, introduces constitution of control system, and expounds principle and implementation of intelligent control algorithm. The applied results prove that the intelligent control system can completely satisfy the technological requirements. Namely, it can realize fast increasing temperature with a little overshoot, exact holding temperature, and well-distributed temperature in quench furnace. It has raised the output and quality of aluminum material, and brought the outstanding economic and social benefits.

Key words quench furnace; temperature control system; artificial intelligent fuzzy control; on-off ratio

A large-scale standing QF is the important device for producing high intensive aluminum alloy materials. The height is 31.64 m and the outer diameter is 2.8 m, the section view of the furnace is shown as Fig.1. The furnace is composed of heating room and working room. It’s filled with silicate cotton between heating room and furnace wall. The working room is made of stainless steel. Furnace temperature is adjusted by changing the power of electric heating elements, which are firmly adhered to the inner wall of heating room. The furnace is fallen into 11 heating areas from top to bottom. Each area’s temperature is measured by a thermocouple. Workpieces are hung up in the center of the working room. The roof, middle, bottom temperatures of working room are measured respectively by seven thermocouples. In order to let the temperature even, two powerful ventilators are placed at the bottom of furnace to force air circulating between heating room and working room and to increase heat exchanging speed in furnace. According to production technology, the heating process may be regarded as two stages, i.e., temperature- increasing stage and temperature-holding stage. During the former stage, the admitted maximum overshoot is 10 °C. During the temperature-holding stage, the required control precision of temperature is ±3 °C.

Because the main working mode is heat convection, there are many problems, such as great heat inertia, evident time lag and strong temperature coupling among heating areas, furthermore, it’s difficult to establish the mathematical model of temperature field in furnace. In order to make temperature even in furnace and realize exact control of temperature, a control algorithm that can synthetically consider above various factors is to be studied.

Fuzzy control technology has been rapidly developed and widely used in recent more than ten years. It is a non-linear control algorithm based on fuzzy theory of sets, fuzzy language variable and fuzzy logic deduction \[1,2\]. Owing to introduction of expect logic thoughts, the fuzzy controller has good self-adaptive control ability. It is especially suited for a class of plants that are hard to be described by accurate

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mathematical models, and has strong robustness and stability\(^3\). Utilizing these merits of fuzzy controller in combination with expert experiences and artificial operating skills, an artificial intelligent fuzzy control algorithm based on fuzzy control theory is proposed and applied in temperature control system of QF\(^4\).

1 Constitution of Control System

The temperature control system is made up of two levels of computers as shown in Fig.2. The upper level, including IPC 610 industrial computer and programmable terminal (PT), performs parameter setting, product processing list inputting, industrial condition monitoring, data storing, data process, data inquiring, report printing, and etc. Siemens S7-314 programmable logic controller (PLC), which is acted as field control level, connects directly with operating table, thermoelectric power-adjusting cupboard (PAC), ventilator control cupboard (VCC) and thermocouples, and fulfills mainly the functions such as temperature sampling, operation order sending and receiving, control algorithm realizing, power adjusting and ventilator interlocking and start. IPC610, PT and PLC are linked with a three-way plug, adopting MPI protocols to realize data communication. When the IPC610 works normally, PT is just used for display screen, which synchronously monitors working conditions of QF with IPC610. Once IPC610 is wrong, PT is used to carry out processing list inputting (setting temperature and temperature-holding time), data real-time printing and temperature monitoring on line, and to maintain normal running of the whole system.

2 Intelligent Control Algorithm and Its Realization

2.1 Temperature Regulating in Stage

According to technological control requirement, we divide the quench process into three stages: the fast temperature-increasing stage, the slow temperature-increasing stage and the temperature-holding stage. During the temperature-holding stage, the main technological requirement is the preserving temperature and the preserving-temperature time. The given temperature, which is initialized by IPC610 or PT and transmitted to PLC, is compared with the practical temperature. PLC judges through fuzzy decision and gets the on-off ratio \( k \) of electrical heating elements, where, \( k = \tau / t \), \( \tau \) is the conduction time in one period, in this system \( t = 45s \). The temperature in furnace is regulated through solid-state relay controlling the conducting and cutting-off current of electric heating elements. Temperature regulating in stage is shown in Fig.3. 1) The fast temperature-increasing stage: during this stage the practical temperature is widely discrepant with the given temperature. The on-off ratio \( k = 1 \), that is to say, the electric heating elements are conducted in full power and the temperature is rapidly raised. In this stage, it is important to choose appropriate threshold value \( T_1 \). Because much higher \( T_1 \) would cause excessive overshoot, whereas much lower \( T_1 \) would cause too long temperature-increasing time. 2) The slow temperature-increasing stage: during this stage the practical temperature is lesser discrepant with the given temperature. In order to avoid the excessive overshoot, the on-off ratio regulating mode is adopted. According to temperature error and its variation, the on-off ratio \( k \) is adjusted. The temperature in QF is slowly closed to the given temperature. The overshoot is decreased. 3) The temperature-holding stage: during this stage the average temperature in QF has reached the given temperature. Electric heating elements work in the minimum on-off ratio \( k \) to maintain the temperature stable until the temperature-holding process is over.
2.2 Control Algorithm Realization

The heating room is split into 11 heating areas. The electric heating elements have different power in these areas. The 2 areas near the ventilator have the most power, the 7 middle areas take second place and the 2 top areas have the least power. From the top to the bottom, the working room is separated into 7 non-equal-distance temperature control areas. Every temperature control area is influenced mainly by its adjacent heating area and also by other heating areas in reality because of the hot air circulation in QF. As a result, every area is controlled separately by using artificial intelligent fuzzy control algorithm. The algorithm principle is described as Fig.4.

In Fig.4, the temperature error (TE) and the temperature error variation (TEV) is firstly fuzzified, then fuzzy inference through databases of membership grade vector values and expert rules are carried out, next the fuzzy inquiring tables of the on-off ratio \( k \) are obtained defuzzifying by means of weighting average method, finally, these tables is used to control the conducting and cutting-off time of the electric heating elements. Because the mainly heating mode is air circulating indirect heating, the structural characteristics of QF result in that the temperature distribution is not even. So in temperature-increasing stage, the top temperature is the highest, and overshoot is severe. So in the slow temperature-increasing stage, the on-off ratio \( k \) is decided by the fuzzy inquiring tables, to let the temperatures reach the given temperatures in lower speed.

When 1 °C > \( E > -1 \) °C in all the temperature control areas, the heating process is in temperature-holding stage, the on-off ratio \( k \) is the minimum, the heat quantity of come from electrical heating element can just compensate the heat loss.

To the different temperature control areas, the temperature threshold value \( T_1 \) are different selected and the on-off ratios are different, so the different fuzzy tables are established. Considering temperature overshoot, the temperature error region in the top control area is divided into 14 grades: \(-4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, 7, 8, \) and 9. In the 5 middle control area, the region is divided into 12 grades: \(-4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6, \) and 7. In the bottom control area, the region is divided into 9 grades: \(-4, -3, -2, -1, 0, 1, 2, 3, 4, \) and 4, the value of fuzzy language variable is \( E = \{NB, NM, NS, ZO, PS, PM, PB\}, EC = \{NB, NM, NS, ZO, PS, PM, PB\} \).

Because the fuzzy table establishment and division of these 7 control areas are approximately the same, we take the bottom control area as an example. Through fuzzy treating, the fuzzy variable evaluation table and fuzzy inquiring table are shown in Tab.1 and Tab.2.

![Fig.4 Chart of fuzzy control principle](image)

When \( E > 8 \) °C in the top temperature control area, \( E > 6 \) °C in the 5 middle temperature control areas, and \( E > 3 \) °C in the bottom temperature control area, the heating process is in fast temperature-increasing stage, the on-off ratio \( k = 1 \), the electric heating element in responding area is conducted in full power and temperature is rapidly raised to close the given temperature.

| Tab.1 Fuzzy variable \( E \) evaluating table of the bottom control area |
|-------------------|---|---|---|---|---|---|---|
| \( E \) | PB | PM | PS | ZO | NS | NM | NB |
| *G* | 4 | 0  | 0  | 0  | 0  | 0  | 0  | \( e > 3 \) |
|      | 3 | 0.3 | 0.5 | 0.2 | 0  | 0  | 0  | 2 \( e \leq 3 \) |
|      | 2 | 0  | 0  | 1  | 0  | 0  | 0  | 1 \( e \leq 2 \) |
|      | 1 | 0  | 0  | 0.5 | 0.5 | 0 | 0  | 0 \( e \leq 1 \) |
|      | 0 | 0  | 0  | 0  | 1  | 0  | 0  | 0 \( e = 0 \) |
|      | -1 | 0 | 0  | 0  | 0.5 | 0.5 | 0 | 0  | \( e < 0 \) |
|      | -2 | 0  | 0  | 0  | 0  | 0  | 1  | 0  | \( e < -2 \) |
|      | -3 | 0  | 0  | 0  | 0  | 0.3 | 0.5 | 0.2  | \( e < -3 \) |
|      | -4 | 0  | 0  | 0  | 0  | 0  | 0  | 1  | \( e < -3 \) |

*G: Grade*
These tables indicate that, when the temperature error is big and the error variation is positive, then the on-off ratio $k = 1$, when temperature error in the range of $(-3, +3)$, the on-off ratio $k$ changes with the temperature error and its variation.

### 2.3 Temperature Control Result

The QF temperature control system has been put into use. Fig. 5 shows the temperature measuring result when the system is running in full load. The curve ①, ③ and ⑦, respectively, represent the temperatures of the top, middle and bottom control areas. When the given temperature is $475 \, ^\circ\text{C}$, the maximum overshoot is $7 \, ^\circ\text{C}$. It is in the admitted range of $10 \, ^\circ\text{C}$. When the system produces continuously, it comes into the temperature-holding stage within less than 20 min. The control precision during temperature-holding stage is ±$1 \, ^\circ\text{C}$. The temperature distribution in QF is very even. All these indexes satisfy completely the quench technological requirements.

### 3 Conclusions

The control system satisfies completely the quench technological requirements. Therefore, the intelligent control strategy is of great reference value for the temperature control of other furnaces. Especially, for a class of large-scale furnaces with great heat inertia, evident time lag, strong coupling influence and no exact mathematical model, the ideal control effect can be obtained by the strategy.

### References


### Brief Introduction to Author(s)

HE Jian-jun (贺建军) received the B.E. degree in automatic control engineering from North University of China, in 1989 and the M.S. degree in industrial automation from Central South University (CSU) in 1992 and the Ph.D. degree in electromechanical engineering from CSU in 2004. From 1992 he has worked in CSU as a lecturer and a vice-professor. His research interests include electromechanical coupling, fuzzy control, adaptive control, optimal control and intelligent control. Tel:0731-8879628, E-mail:csuhjj@163.com.

YU Shou-yi (喻寿益) received the B.E. degree in automatic control engineering from Central South University of Technology (CSUT) in 1965. He is currently a professor with CSUT. His research fields include control theory, control engineering and process control of computer.