

AN EXPERT CONTROLLER FOR THE LAMINAR COOLING PROCESS OF HOT ROLLED SLAB

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Abstract: A fuzzy logic-based, multi-input/multi-output expert controller has been designed for laminar water curtain controlled cooling system at the Anshan Steel Corporation. This controller can automatically find the specified working points under boundary conditions instead of obtaining them from a lot of experiments. On the basis of these working points, the linearized models can be used to determine the control variables. The simulation results show that the expert controller has an excellent performance and can be used in a practical environment.

Keywords: Working Point, Laminar Cooling, Water Curtain, Fuzzy Logic, Expert Controller, Cooling Rate.

1. INTRODUCTION

In order to improve the metallurgical properties of the hot rolled slab, manufacturer usually use the accelerated cooling system on the runout table to cool the slab from the austenitic finishing temperatures in the range between 820 and 900 °C to the straightening temperatures between 500 and 700°C based upon the slab thickness and steel grade.

The accelerated cooling process is very complex because it is affected by many elements such as the temperature, gauge, shape, an material of the slab, the water's and environment's temperature; these elements are also changed with the different process. Moreover, when the slab is cooled on the runout table, the transformation from austenite($\gamma-Fe$) to ferrite($\alpha-Fe$) takes place, the heat generated during the transformation is clearly visible, but having no method to measure these changes, so accurately controlling this cooling process is impossible. It is also impossible to set up an accurate mathematical model(e.g. a transfer function) to this process[1-5]. The conventional control theory(e.g. predictive control, optimal control) can not be used to control this cooling process.

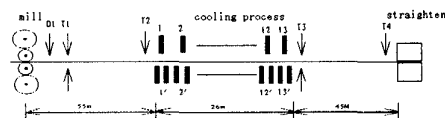
In order to simplify industrial complex processes, the distributed-computer control systems(DCS) are usually used in the industry. Hence the multivariable complex process is divided into several single-variable control loops, which include open-loops and closed-loops. These single-variable control-loops can obtain satisfactory properties by means of the conventional control methods(e.g. PID control, Fuzzy control). Therefore, the main problem existed in the DCS is how to give the setpoint value of each control-loop to optimize the whole process and to satisfy the technological requirements. Usually a process controller is required, but it is very difficult to set up the controlling model due to the properties of the process such as multivariable, non-linear, stronger couples and distributed-parameters. In practice, there are two methods people usually used, one is the

technological model, that is a simple model derived from physical partial difference equations, and the other is looking for a group of optimal solutions from the process complex models under some constraints. The former need to determine the model's parameters, so it needs a lot of experiments resulting to cost a lot of time and money, and it is not sure to get a correct model in many manufacturing situation. The latter requires an accurate process model, it is also impossible for many complex processes. Moreover, both these two methods are not suitable when they are used to control the complex industrial processes at the situation of the boundary conditions changing sharply.

In this paper, a new strategy is adopted to realize the closed-loop control of the whole cooling process, that is, defining typical manufacturing states based upon the slab's material, gauge, final cooling temperature and cooling pattern, then obtaining a working point of each manufacturing state(note: working point means a group of setpoint values derived from some specified boundary conditions acts on the cooling process through DCS, and the cooling results happen to satisfy the technical requirements, then these variables of the boundary conditions, setpoint values and technical indexes compose a working point.). Next the linear control models, which are then adapted by self-adaptation algorithms, are set up by linearizing the non-linear models at the working points. In substance, the above strategy is a piecewise linearized method which is used to deal with non-linear functions. The expert controller being introduced next is only used to find the working points, the other parts of the control models will not be concerned.

2. LAMINAR WATER CURTAIN COOLING SYSTEM

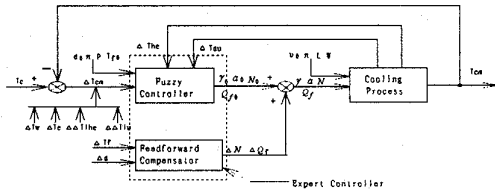
The laminar flow cooling equipment installed on the runout table may be divided into two different types. One is the conventional (or traditional) strip mill cooling system which has a large number of headers and circular nozzles which are prone to blockage and therefore require a large maintenance effort. The other is a recently developed water curtain cooling system, which consists of along header transverse to slab direction and a slit nozzle with a very large aspect ratio. To the steel slabs which have the thickness range from 10mm to 40mm, they require a large cooling capacity, so the later cooling equipment--called water curtain cooling system--has been exploited (see Figure 1.).



T1-T4--four pyrometers D1--x-ray gauge
Figure 1. Cooling equipment

The runout table is 126m long from the last finishing stand to the straightener, the water cooling zone is 26m long. There are four temperature pyrometers along the runout table located at the exit of mill, the entry and exit of cooling zone, and the entry of the straightener. One x-ray gauge is located at the exit of mill. The cooling zone consists of thirteen sections, one includes a water curtain on top and two spray headers on bottom.

3. EXPERT CONTROLLER



Note: Appendix gives the meaning of the symbols
Figure 2. Expert controller

Fig.2 shows the expert control system used to find the working points, which consists of two parts: one is the fuzzy controller and the other is the feedforward compensator. The fuzzy controller is used to modify the control variables γ , α , N and Q_f based upon the error ΔT_{cm} , ΔT_{du} and ΔT_{he} , until these errors remain within a tolerance range. During this process, the water's temperature and environment's temperature vary slightly. The temperature difference ΔT_{du} and ΔT_{he} also change slightly because of the relatively long time (about 20 seconds) of the slab's moving across the long runout table between the rolling mill and the cooling system, and the reversible rolled process in the rolling mill. Moreover, the expert fuzzy controller has the property of strong robustness, so these four factors can be ignored. As to the error ΔT_f and Δd , they are significant and have a large effect on the cooling process. So they are regarded as measurable disturbances and are compensated by the feedforward compensator. With the help of the compensator, the entry conditions of the fuzzy controller can be treated as invariable and the "increment control" (increment control means regulating the incremental value of the control variables based on the errors) can be realized. From the physical analysis, the models of the compensator are obtained as following:

$$\Delta N = \alpha_c \frac{c \times d \times T_1 \times (T_1 - T_2) \times v}{Q_{f0}} - N_0 \quad (1)$$

$$\Delta Q_f = \left(\frac{N_0 + \Delta N}{INT(N_0 + \Delta N + 0.5)} - 1 \right) \times Q_{f0} \quad (2)$$

The incorrect working points ($\gamma_0, \alpha_0, N_0, Q_{f0}$) are modified by a set of fuzzy rules of the form "if...then...". These rules

sometimes include some logic judgments which can be regarded as having a singleton membership functions.

The fuzzy variables are selected as d , ΔT_{du} , γ , ΔT_{he} , α , ΔT_{cm} , N and Q_f . The fuzzy sets, membership functions(MF) and control rule tables are chosen as following.

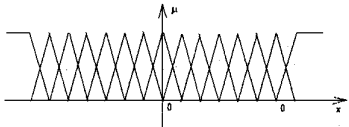


Figure 3. Membership functions for d , ΔT_{du} , ΔT_{he} and ΔT_{cm}

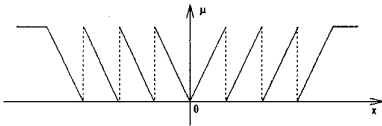


Figure 4. Membership functions for γ , α , N and Q_f

TABLE 1 Fuzzy Tuning Rules For γ

d $\Delta \gamma$ ΔT_{dt}	HZ	MS	HMS	HM	HMB	HB	HL
NL	NL	NL	NL	NL	NL	NL	NL
NB	NL	NL	NL	NB	NB	NB	NB
NM	NL	NL	NB	NB	NMB	NMB	NMB
NS	NMB	NMB	NMB	NMB	NM	NMS	NMS
NZ	NMS	NMS	NMS	NS	NS	NZ	NZ
PZ	PS	PS	PS	PS	PZ	PZ	PZ
PS	PM	PM	PMS	PMS	PS	PS	PS
PMS	PMB	PMB	PMS	PMS	PS	PS	PS
PMB	PB	PB	PM	PM	PM	PMS	PMS
PB	PL	PL	PMB	PMB	PMB	PM	PM
PL	PL	PL	PB	PB	PMB	PMB	PMB

TABLE 2 Fuzzy Tuning Rules For α

d $\Delta \alpha$ ΔT_{he}	HZ	MS	HMS	HM	HMB	HB	HL
NL	NL	NL	NL	NL	NL	NB	NB
NB	NL	NL	NL	NL	NB	NMB	NMB
NMB	NL	NL	NB	NB	NMB	NM	NM
NMS	NL	NL	NB	NMB	NM	NMS	NMS
NS	NMB	NMB	NMB	NM	NMS	NS	NS
NZ	NS	NS	NS	NS	NZ	NZ	NZ
PZ	PS	PS	PS	PS	PZ	PZ	PZ
PS	PMB	PMB	PMB	PM	PMS	PS	PS
PMS	PL	PL	PB	PMB	PM	PMS	PMS
PMB	PL	PL	PL	PB	PMB	PM	PMS
PB	PL	PL	PL	PL	PB	PMB	PM
PL	PL	PL	PL	PL	PL	PB	PMB

TABLE 3 Fuzzy Tuning Rules For N

d ΔN ΔT_{cm}	Z	MS	HMS	HM	HMB	HB	HL
NL	PL	PL	PL	PL	PL	PL	PL
NB	PB	PB	PB	PB	PL	PL	PL
NM	PM	PM	PM	PM	PB	PB	PB
NS	PZ	PZ	PZ	PZ	PS	PS	PS
PS	NZ	NZ	NZ	NZ	NS	NS	NS
PM	NS	NS	NS	NS	NM	NM	NM
PB	NM	NM	NM	NM	NL	NL	NL
PL	NL	NL	NL	NL	NL	NL	NL

TABLE 4 Fuzzy Tuning Rules For Q_f

ΔQ_i	PL	PB	PM	PS	PZ	NZ	NS	NM	NB	NL
ΔT_{ci}	NL	NB	NM	NS	NZ	PZ	PS	PM	PB	PL

The truth value of the rule μ_i (the grade of the membership functions) is obtained by the product of the MF values in the antecedent part of the rule:

$$\mu_i = \mu_{A_i}[x_1(k)] \times \mu_{B_i}[x_2(k)] \times \dots \quad (3)$$

where $x(k)$ is the one of the fuzzy variables, A_i and B_i are the fuzzy sets of the corresponding fuzzy variables. Based on μ_i , the values of Δa , $\Delta \gamma$, ΔN and ΔQ_f are determined from their corresponding membership functions.

By using the membership functions in Figure 5, getting the following conditions[6]:

$$\sum_{i=1}^m \mu_i = 1 \quad (4)$$

where m is the total number of the excited rules. Then the defuzzification yields the following:

$$\Delta \gamma = \sum_{i=1}^m \mu_i \times \Delta \gamma_i \quad (5a)$$

$$\Delta a = \sum_{i=1}^m \mu_i \times \Delta a_i \quad (5b)$$

$$\Delta N = \sum_{i=1}^m \mu_i \times \Delta N_i \quad (5c)$$

$$\Delta Q_f = \sum_{i=1}^m \mu_i \times \Delta Q_{fi} \quad (5d)$$

where $\Delta \gamma_i$ is the value of $\Delta \gamma$ corresponding to the grade μ_i for the i th rule, Δa , ΔN and ΔQ_f are obtained in the same way.

The control variables γ , a , N and Q_f couples each other in the cooling process. Considering each variable's function, it is known that γ and a have remarkable effects to the N and Q_f , but N and Q_f have a little action to γ and a , so it is enough to consider the couples of γ and a to N and Q_f . From the above analysis, the following strategies are defined for the expert fuzzy controller's regulating:

- 1) Rough Regulating : if $\Delta \gamma$ or Δa is relatively large (PL,PB,PMB,PM,NM,NMB, NB,NL), or ΔT_{cm} is big(PL,PB,NB,NL), then regulating N to eliminate error ΔT_{cm} ,
- 2) Fine Regulating : if $\Delta \gamma$ and Δa is OK or nearly OK(PMS,PS,PZ,NZ,NS,NMS) and ΔN is zero, then regulating Q_f to clear up ΔT_{cm} .

Note: OK means $\Delta T_{du}(\Delta T_{he}, \Delta T_{cm})$ within a tolerance range, for example, $0 < \Delta T_{du} < 20^\circ \text{C}$, $|\Delta T_{he}| < 15^\circ \text{C}$, $|\Delta T_{cm}| < 15^\circ \text{C}$.

Strictly speaking, the above fuzzy increment regulating rules only apply to one steel grade(e.g. low-carbon steel 0.23%C) or the ones with parameters that are nearly the same as low-carbon steel. If the steel's physical property(k and c) changes largely, the above fuzzy rules' regulating results may be bad or even invalid. From the heat transfer theory, it is known the thermal diffusivity k can reflect the capacity of steel's heat conduction, therefore, defining the modifying factor η to revise the fuzzy inference results, that is:

$$\eta = k_0 / k \quad (6)$$

Where k is the thermal diffusivity of any steel grade, k_0 is the thermal diffusivity of the steel the fuzzy rules based upon.

Then the final fuzzy inference results are as follows:

$$\Delta \gamma^* = \eta \times \sum_{i=1}^m \mu_i \times \Delta \gamma_i \quad (7a)$$

$$\Delta a^* = \eta \times \sum_{i=1}^m \mu_i \times \Delta a_i \quad (7b)$$

$$\Delta N^* = \eta \times \sum_{i=1}^m \mu_i \times \Delta N_i \quad (7c)$$

$$\Delta Q_f^* = \eta \times \sum_{i=1}^m \mu_i \times \Delta Q_{fi} \quad (7d)$$

4. SIMULATION RESULTS

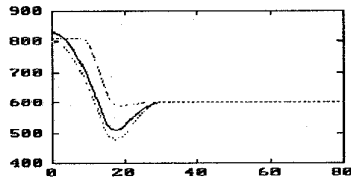


Fig.5 The curves of cooling process
top temperature
bottom temperature
center temperature

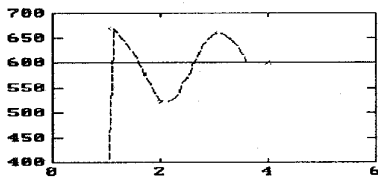


Fig.6 Looking for the working point under conditions:
 $800\text{ }^{\circ}\text{C} < T_1 < 859\text{ }^{\circ}\text{C}$, $d=20\pm 5\text{ mm}$
 $\Delta T_{du}=20\pm 3\text{ }^{\circ}\text{C}$, $\Delta T_{he}=0$, $T_w=30\pm 5\text{ }^{\circ}\text{C}$
 $T_e=30\pm 5\text{ }^{\circ}\text{C}$, FCT is $600\pm 5\text{ }^{\circ}\text{C}$
the steel is 0.23%C(Low-Carbon)

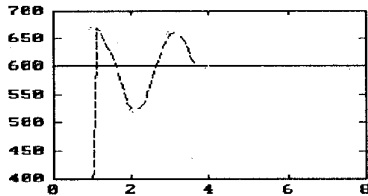


Fig.7 Looking for the working point under conditions:
 $\alpha_2=90\%\alpha$, the other conditions are the same as Fig.6

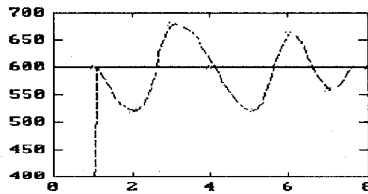


Fig.8 Looking for the working point under conditions:
 $\alpha_3=110\%\alpha$, the other conditions are the same as Fig.6

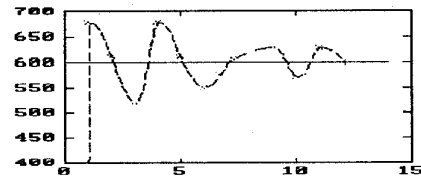


Fig.9 Looking for the working point under conditions:
steel is 1.5%Mn(Manganese),
 η is not added, the other conditions are the same as Fig.6

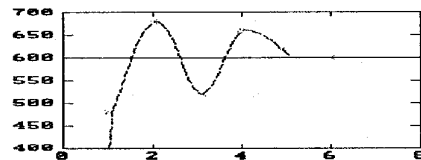


Fig.10 Looking for the working point under conditions:
the same with Fig.9, η is added.

The expert controller has been tested on a variety of situations. Fig.5 ~ Fig.10 show the representative simulation results.

Fig.5 shows the cooling process of any cross section (top, bottom and center temperatures). Fig.6 illustrates the expert fuzzy controller being able to find the working point through the number of 4 slabs (ΔT_{em} , ΔT_{du} and ΔT_{he} satisfy our requirements). Fig.7 and Fig.8 show that the controller can also find the working points even though the heat transfer coefficient α changed. Fig.9 and Fig.10 show the importance of the modifying factor η when the steel grade is changed.

The above simulations show that the expert controller is valid in finding the working points under some boundary conditions, and has a good performance(robustness) to resist various disturbances. In practical using, after several typical experiments, the fuzzified scale factor of the fuzzy rules based upon are regulated a little, then the satisfactory results are obtained almost the same as the above simulations.

5. CONCLUSIONS

The proposed expert controller utilizes fuzzy rules and physical model to determine the working points of each product's group in the cooling process. This work is only a part of the real-time expert system of the controlled cooling process of hot rolled slab for Anshan Steel Corporation. This method largely reduces the burden of manually determining the working points and

simplifies the task of setting up controlling models. Moreover, the method used to model the cooling process can extend to the other metallurgical processes such as reheating furnace, rolling mill, and realize the closed-loop control of these processes.

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APPENDIX List of Symbols

FCT -- Final Cooling Temperature
 CR -- Cooling Rate
 d -- slab thickness(mm)
 T_c -- desired FCT($^{\circ}\text{C}$)
 T_{cm} -- real FCT ($^{\circ}\text{C}$)
 T_1 -- temperature of slab at beginning($^{\circ}\text{C}$)
 T_2 -- temperature of slab at end($^{\circ}\text{C}$)
 T_{iu} -- top temperature of slab at the entry of cooling zone($^{\circ}\text{C}$)

T_{id} -- bottom temperature of slab at the entry of cooling zone($^{\circ}\text{C}$)
 T_w -- water temperature($^{\circ}\text{C}$)
 T_e -- environment temperature($^{\circ}\text{C}$)
 T_{ih} -- the i th sample of slab at the entry of cooling zone($^{\circ}\text{C}$)
 T_{ie} -- the $i+1$ th sample of slab at the entry of cooling zone($^{\circ}\text{C}$)
 $\Delta T_{ihe} = T_{ih} - T_{ie}$ $\Delta T_{idu} = T_{id} - T_{ie}$
 ΔT_{du} -- temperature error between bottom and top at the exit of cooling zone
 ΔT_{he} -- temperature error along the longitudinal($^{\circ}\text{C}$)
 $\Delta T_{cm} = T_{cm} - T_c$
 $T_{iu0}, \Delta T_{idu0}, \Delta T_{ihe0}, T_{w0}, T_{e0}, d_0$ --physical parameters at the working point
 $T_{f0} = T_{iu0}, T_u$ -- cooling rate ($^{\circ}\text{C/s}$)
 $\Delta d = d - d_0, \Delta \Delta T_{idu} = \Delta T_{idu} - \Delta T_{idu0},$
 $\Delta \Delta T_{ihe} = \Delta T_{ihe} - \Delta T_{ihe0}$
 $\Delta T_w = T_w - T_{w0}, \Delta T_e = T_e - T_{e0}, \Delta T_f = T_{iu} - T_{iu0}$
 P -- steel grade
 α -- heat transfer coefficient($\text{W/m}^2 \cdot ^{\circ}\text{C}$)
 k -- thermal diffusivity (m^2/s)
 c -- heat capacity of steel(J/kg.K)
 l -- thermal conductivity (W/m.K)
 Q_f -- flow of one top curtain(m^3/h)
 N -- number of cooling sections
 γ -- flow radio
 U -- speed of runout table (m/s)
 a -- acceleration of runout table(mm/s^2)
 π -- cooling pattern
 W -- covering width of slab's edge(mm)
 L -- runout table joined scope
 $Q_{f0}, N_0, \gamma_0, U_0, a_0$ -- control variables at the working point
 $\Delta Q_f = Q_f - Q_{f0}, \Delta N = N - N_0, \Delta \gamma = \gamma - \gamma_0,$
 $\Delta a = a - a_0$