Research on Method of Improving Thermal Efficiency of Oilfield Horizontal Water Jacket Heating Furnace Based on Smith Algorithms

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Abstract. In view of the low thermal efficiency of oil field horizontal water jacket heating furnace, the single neuron SVM-Smith predictive control method was proposed to improve the heating efficiency according to the structure of the reformed heating furnace. The Support Vector Machine (SVM) was used to predict the flow rate of heated medium and improved the accuracy of Smith prediction and compensation. The single neuron PID control and Smith predictive compensation were combined to tune the parameters of the control system. The experiments showed that the thermal efficiency had been significantly improved, and the control algorithm had achieved good control effect.

1. Introduction

Now the heating furnace widely used in oil and gas field industry is called oil field heating furnace, which is one of the most widely used oil field special equipment in oil and gas gathering and transportation system [1-3]. Oil field heating furnaces are special heating equipment for heating medium such as crude oil, natural gas, water and mixtures thereof by flame. At present, there are more than 5000 heating furnaces in Changqing Oilfield, and more than 80% of them are horizontal jacket heating furnaces. And the flue gas temperature of horizontal jacket heater in oil field is still relatively high. The average thermal efficiency of oil field horizontal jacket heating furnace is about 83%, and the thermal efficiency is low.

When optimizing the structure of the furnace body, the heat pipes are used to enhance heat transfer, and the waste heat of flue gas is recovered and utilized. Therefore, according to the structure of oil field heating furnace and water temperature process requirements, as well as the flow rate and flow rate of heated medium, the improved Smith algorithm is proposed to control water temperature to reduce fuel consumption and improve efficiency.

2. The Improved Smith Predictive Water Temperature Control Algorithms for Heating Furnace

According to the structure of heating furnace, in order to improve thermal efficiency, it is necessary to strictly control water temperature and reduce fuel consumption. The water temperature control of heating furnace has the characteristics of large inertia and pure delay. Moreover, due to the characteristics of heat pipe and the uncertainty of the flow rate of heated medium, the conventional PID control algorithm may lead to large overshoot and poor control efficiency. In this paper, the support vector machine (SVM) is used to predict the flow rate of heated medium and Smith algorithm is used to predict and compensate the flow rate. The Smith predictive compensation and the single
neuron PID algorithm are used to improve the system, reduce overshoot, accurately control water temperature and improve thermal efficiency.

2.1 Support Vector Machine

Support Vector Machine (SVM) is a practical machine learning algorithm. The model is simple to build and easy to operate. Many scholars use support vector machine to solve some engineering problems in petroleum engineering. For example, Liu Wei [4] used support vector machine to recognize and classify dynamometers. Yu Deliang [5] et al. used support vector machine (SVM) to optimize the submergence degree of pumps. In this paper, the support vector machine is used to predict the medium flow through the oil field heating furnace by on-line regression.

2.1.1 Construction of Support Vector Regression Machine Model

Assuming given sample data \((x_1, y_1), (x_2, y_2), \cdots, (x_l, y_l) \in \mathbb{R}^n \times \mathbb{R}\), the estimation function of support vector machine is \(f(x) = w \cdot \phi(x) + b\), then it is transformed into the following optimization problems:

\[
\begin{align*}
\min \quad & \phi(w, \xi, \xi^*) = \frac{1}{2} w^T w + C \sum_{i=1}^{l} (\xi_i + \xi_i^*) \\
\text{s.t.} \quad & y_i - w^T \phi(x_i) \leq \varepsilon + \xi_i \\
& w^T \phi(x_i) - y_i \leq \varepsilon + \xi_i^* \\
& \xi_i \geq 0 \\
& \xi_i^* \geq 0, \quad i = 1, 2, \ldots, l
\end{align*}
\]

(1)

Where \(x_i\) is input sample, \(y_i\) is expected output, \(l\) is sample size, \(\phi()\) is nonlinear mapping, \(C\) is regularization parameters, \(\xi\) and \(\xi^*\) are relaxation variable.

Introduce the Lagrange multiplier \(\alpha, \alpha^*, \eta, \eta^*\)

\[
\begin{align*}
L_\alpha &= \frac{1}{2} w^T w + C \sum_{i=1}^{l} (\xi_i + \xi_i^*) + \sum_{i=1}^{l} (\eta_i \xi_i + \eta_i^* \xi_i^*) \\
&\quad - \sum_{i=1}^{l} \alpha_i (y_i - \varepsilon - \xi_i + w^T \phi(x_i) + b) \\
&\quad - \sum_{i=1}^{l} \alpha_i^* (y_i + \varepsilon^* + \xi_i - w^T \phi(x_i) - b)
\end{align*}
\]

(2)

The problem is transformed into a quadratic optimization problem as follows:

\[
\begin{align*}
\min D = \frac{1}{2} \sum_{i=1}^{l} \sum_{j=1}^{l} k(x_i, x_j) (\alpha_i - \alpha_i^*) (\alpha_j - \alpha_j^*) + \varepsilon \sum_{i=1}^{l} (\alpha_i + \alpha_i^*) - \sum_{i=1}^{l} y_i (\alpha_i - \alpha_i^*)
\end{align*}
\]

(3)

\[
\begin{align*}
0 \leq \alpha_i, \alpha_i^* \leq C, i = 1, 2, \ldots, l \\
\sum_{i=1}^{l} (\alpha_i - \alpha_i^*) = 0
\end{align*}
\]

The regression model is

\[
\phi(x) = \sum_{i=1}^{l} (a_i - a_i^*) k(x_i, x) + b
\]

(4)
2.1.2 Kernel Function Selection and Parameter Optimization

The generalization ability of support vector regression model shown in formula (4) depends on the selected kernel function and the corresponding parameters. In the process of building support vector regression model, the optimization of kernel function and corresponding parameters is an important part. Because the radial basis function can be estimated smoothly, the radial basis function is chosen in the regression model of support vector machine. The parameters that have important influence on the model are penalty parameter $C$ and kernel function parameter $g$. For different values of the $\varepsilon$, the prediction error has a similar trend with parameters $C$ and $g$. Therefore, we can determine $C$ and $g$ first, and then turn the three-parameter optimization into two-parameter optimization.

The model is built by choosing the radial basis function. There are two very important characteristic parameters, $C$ and $g$, respectively. Among them, $C$ represents the tolerance range of experimental errors, $g$ is the parameter of selecting the radial basis function, which determines the general trend of sample data mapping to another space [6]. The cross validation method is used to optimize factor $C$ and $g$. The data of the flow sensor is selected as the sample data for timing recording. The sample data are normalized to $[-1, 1]$. Based on the normalized time series of medium flow data flowing through heating furnace, the training sample of support vector machine is constructed to predict the variation of medium flow.

2.2 Single Neuron SVM-Smith Predictive Water Temperature Control

According to the structure of oil field water jacket heating furnace, it can be seen that besides the temperature control is a lagging system, the change of the flow rate of the heated medium and the use of heat pipe will have a certain impact on the temperature control. In order to improve the thermal efficiency of heating furnace, it is necessary to control water temperature more accurately.

Generally, for large time-delay systems, the conventional PID control algorithm is not ideal, and the additional compensation is needed. Smith predictive compensation can effectively reduce overshoot and accelerate response, but it needs precise matching with control model. It is difficult to do so in oil field heating furnace. When Smith prediction method mismatches the model, the control effect will be unsatisfactory. Therefore, the Smith model is improved to combine adaptive control with Smith predictor. The structure of single neuron SVM-Smith predictive control system is shown in Fig. 1. And the single neuron PID control algorithm with adjustable gain is shown in Fig. 2. The improved Smith predictive compensation is used to reduce the overshoot of the PID control, and the single neuron is used to tune the parameters of the PID to match the Smith predictive compensation with the control model. In order to improve the accuracy of predictive compensation, the support vector machine (SVM) algorithm is used to predict the flow rate of heated medium.

![Fig. 1 The schematic diagram of single neuron SVM-Smith predictive control system](image-url)
Fig. 2 The single neuron PID control algorithm with adjustable gain

In Figure 2, \( y^r \) and \( y_0 \) are the set and output values of the system.

\[
\begin{align*}
x_1(k) &= e(k) \\
x_2(k) &= \Delta e(k) \\
x_3(k) &= e(k) - 2e(k-1) + e(k-2) \\
e(k) &= y^r(k) - y_0(k)
\end{align*}
\] (5)

Then the output of the neuron controller can be written as:

\[
\Delta u(k) = K(k)(w_1x_1 + w_2x_2 + w_3x_3) = K(k)\sum_{i=1}^{3}w_i(k)x_i(k)
\] (6)

Using Hebb learning rules, after standardization

\[
\begin{align*}
\Delta w_i(k) &= K(k)\sum_{i=1}^{3}w_i(k)x_i(k) \\
\overline{w}_i(k) &= \frac{w_i(k)}{\sum_{i=1}^{3}|w_i(k)|} \\
w_i(k+1) &= w_i(k) + \eta_Iu(k)e(k)x_i(k) \\
w_2(k+1) &= w_2(k) + \eta_Pu(k)e(k)x_2(k) \\
w_3(k+1) &= w_3(k) + \eta_Du(k)e(k)x_3(k)
\end{align*}
\] (7)

Where \( \eta_I, \eta_P, \eta_D \) are the learning rates of integration, proportion and differentiation, respectively.

For the adjustment of gain \( K \), the PSD algorithm is combined with the single neuron PID control to form a gain adjustable controller. The adjustment algorithm is as follows:

\[
\begin{align*}
K(k) &= K(k-1) + c\frac{K(k-1)}{T_s(k-1)} \cdot \text{sgn}[e(k)] = \text{sgn}[e(k-1)] \\
K(k) &= 0.75K(k-1) \\
\text{sgn}[e(k)] \neq \text{sgn}[e(k-1)] \\
T_s(k) &= T_s(k-1) + L'\text{sgn}[\Delta^2e(k)] - T_s(k-1)|\Delta^2e(k)|
\end{align*}
\] (8)

In the formula, \( 0.025 \leq c \leq 0.05 \), \( 0.05 \leq L' \leq 0.1 \).

3. Test application
The 600 kW horizontal water jacket heating furnace is selected for test because of its large consumption. Ten heating furnaces have been installed, and the structure of the heating furnaces used in the test is identical. Heat pipes and two coils are installed in the heating furnace. According to the structure size of the furnace body, the carbon steel-water heat pipes with length of 600 mm and length of 32 x 3.5 are selected, and the number of them is 52. The parameters of gas consumption, furnace
body temperature, inlet and outlet temperature and pressure of coil and exhaust gas temperature are recorded. Mean values of 10 reheating furnaces are recorded at the same time, and the test results shown in Table 1 are obtained.

### Table 1 Test Record Table

| Experiment item                      | Application of improved Smith Algorithms |
|--------------------------------------|------------------------------------------|
|                                      | no | yes |
| Gas consumption (m³•h⁻¹)             | 58 | 50  |
| Furnace body temperature °C          | 85 | 85  |
| Coil 1 inlet temperature (in) °C     | 6  | 6   |
| Coil 1 outlet temperature (in) °C    | 32 | 33  |
| Coil 2 inlet temperature (out) °C    | 30 | 31  |
| Coil 2 inlet temperature (out) °C    | 50 | 51  |
| Coil 1 outlet Pressure (in) MPa      | 2.5| 2.5 |
| Coil 2 outlet pressure (out) MPa     | 3.8| 3.8 |
| Exhaust temperature °C              | 178| 100 |
| Thermal efficiency %                | 83.2| 93 |

The experimental results show that the average gas consumption is reduced from 58 m³•h⁻¹ to 50 m³•h⁻¹, the exhaust temperature is reduced from 178°C to 100 °C, and the thermal efficiency is increased from 83.2% to 93%.

### 4. Conclusion

Horizontal water jacket heater is the main energy consumption equipment in oil field. The temperature control of water jacket is conducive to the improvement of thermal efficiency. Because of the change of heating medium, the optimization of furnace structure and the influence of environment, it is difficult to control the water temperature of water jacket. Therefore, on the basis of conventional PID control, single neuron is used to tune the parameters of PID. Smith Prediction is compensated to the hysteresis of water temperature control. Support vector machine is used to predict the flow rate of heating medium and improve the accuracy of Smith compensation. The improved Smith control algorithm is composed of the above algorithms.

According to the test results, it can be seen that the temperature of flue gas in reheating furnace decreased obviously, the average thermal efficiency increase by about 10%, and the thermal efficiency improves obviously after using the modified temperature control algorithm. It can be seen that the smoke exhaust temperature of reheating furnace decreases obviously after using the modified temperature control algorithm from those test results. And the average increase of thermal efficiency is about 10%.

Through the application research of the improved Smith algorithm of oil field water jacket heating furnace, the following conclusions can be drawn:

1) The single neuron SVM-Smith predictive control for water temperature control of reheating furnace is effective and reliable. The single neuron PID control, Smith predictive compensation and SVM algorithm are combined to tune the parameters of the control system. The experiment proves that the control effect is good.

2) Through the application research of heat pipe waste heat recovery in oil field horizontal water jacket heating furnace, it is feasible to install carbon steel-water heat pipe directly in the flue gas return chamber of heating furnace to recover flue gas waste heat and improve the thermal efficiency.

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