Hybrid Modeling Method for Predicting the Cooling Water Outlet Temperature in Plate Heat Exchanger

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Abstract: The circulating cooling water system which ensures the production process running safely plays a very important role in the iron and steel enterprise and its energy-saving operation is based on the accurate prediction of the cooling water outlet temperature in the plate heat exchanger. A hybrid modeling method is proposed in this paper to predict the cooling water outlet temperature in the plate heat exchanger. By analyzing the operational mechanism of the heat transfer process in the plate heat exchanger, the mechanistic model is established according to the thermal transfer equation and the thermal balance equation and then the radial basis function neural network (RBFNN) is applied to develop the hybrid model with the mechanistic model, in which the RBFNN corrects the error made by the mechanistic model due to the theoretical assumption and the inaccurate value of parameter. Finally the simulation is made to verify the modeling method and the results show that the hybrid model has the better prediction performance than the mechanistic model, which lays the foundation for the operation optimization of the circulating cooling water system.

Key Words: Plate Heat Exchanger, Cooling Water Temperature, Hybrid Model, Radial Basis Function Neural Network

1 INTRODUCTION

The plate heat exchanger as the key equipment in circulating cooling water system has the particular advantage of convenience to maintain and less occupied area due to its compact structure and high heat transfer coefficient compared with other types of heat exchangers [1], therefore, it is extensively used in the field of chemical, electric power, iron and steel in recent years. However, with the long-running of plate heat exchanger, its performance is changing gradually under the influence of the cooling water quality, changes of the operating conditions and equipment aging, so establishing an accurate model of the plate heat exchangers to predict the cooling water outlet temperature is necessary.

Much attention has been paid to the issues on predicting the fouling resistance based on the experiments [2-3], simplification of the heat transfer coefficient [4] and optimization of device parameters by the numerical simulation of heat and mass transfer inside plate heat exchanger by computational fluid dynamics [5-7]. The mechanistic model of plate heat exchanger is used in many researches [8-10] which predicts the cooling water outlet temperature according to the thermal transfer equation and the thermal balance equation by the analysis of heat transfer process in the plate heat exchanger between the cooling water and the thermal fluid. Although this type of model can be applied to predict the cooling water outlet temperature in different operating conditions, the accuracy is not satisfactory due to the complexity of heat transfer process and the inaccuracy value of the parameters.

This paper presents a model which describes the relationship between the cooling water outlet temperature and the cooling water flow rate, the cooling water inlet temperature, the thermal fluid flow rate and inlet temperature in the plate heat exchanger. Due to the theoretical assumption and the inaccurate value of parameter, the deviation between the output of mechanistic model and the actual operation data exists. To decrease the deviation, the RBFNN is used to compensate it so as to improve the prediction accuracy and generalization performance.

2 OPERATING PRINCIPLE

The operating principle of plate heat exchanger is shown in Fig. 1.

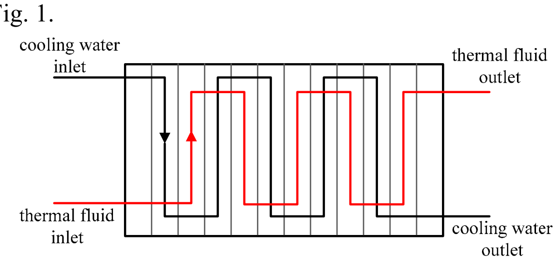

Fig. 1 Schematic diagram of the plate heat exchanger

The plate heat exchanger consists of the frame and the heat exchange plate compressed by the external force, in which the fluid flows. The fluid becomes drastic turbulent flow with the action of corrugation on the heat exchange plate which enlarges the heat exchange area. The cooling water

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and the thermal fluid flow on either side of the plate separately while the quantity of heat transfers from the thermal fluid to the cooling water through the plate, then the thermal fluid temperature declines with the quantity of heat transferring, which makes the fluid can be recycled. In the meantime, the cooling water temperature rises because of absorbing heat and it is recycled after cooled by the cooling towers and other facilities.

3 MECHANISTIC MODEL

Establishing the mechanistic model of the plate heat exchanger is to describe the relationship between the cooling water outlet temperature and the cooling water flow rate, the cooling water inlet temperature, the thermal fluid flow rate and the thermal fluid inlet temperature according to the thermal transfer equation and the thermal balance equation. The calculation of heat transfer here employs several assumptions:

- The value of mass flow rate and specific heat for the cooling water and the thermal fluid remain unchanged on the whole heat transfer surface.
- The heat transfer coefficient on the whole heat transfer surface is constant value.
- The plate heat exchanger has no heat loss.
- The phase change and the single phase heat convection can't exist simultaneously in the process of flowing from the inlet to the outlet for any type of fluid.

The mechanistic model of the plate heat exchanger is based on the two equations as follows:

1) Thermal balance equation

$$Q = q_1 c_1 \Delta t_1 = q_2 c_2 \Delta t_2 \tag{1}$$

Where Q is the thermal load, W. q_1, q_2 are the mass flow rate of the thermal fluid and the cooling water separately, kg/s. c_1, c_2 are the specific heat of the thermal fluid and the cooling water separately, J/kg•℃. $\Delta t_1, \Delta t_2$ are the temperature difference of the thermal fluid and the cooling water separately between inlet and outlet, ℃.

2) Thermal transfer equation:

$$Q = KF\Delta t_m \tag{2}$$

Where K is the average heat transfer coefficient, W/(m^2·℃). F is the heat transfer area, m^2. Δt_m is the average temperature difference between the thermal fluid and the cooling water, ℃ .

The value of Δt_m in the equation (2) can be obtained by the means of correcting the value of Δt_{1m} which is the logarithmic mean temperature difference in the countercurrent condition:

$$\Delta t_m = \psi \cdot \Delta t_{1m} \tag{3}$$

The expression of logarithmic mean temperature difference Δt_{1m} is as follows:

$$\Delta t_{1m} = \frac{\Delta t_{\max} - \Delta t_{\min}}{\ln \frac{\Delta t_{\max}}{\Delta t_{\min}}} \tag{4}$$

Where $\Delta t_{\max}$ and $\Delta t_{\min}$ are the maximum and the minimum of the terminal temperature difference in the countercurrent condition. ψ is the correction coefficient.

The computational formula of K in the equation (1) is:

$$K = (\frac{1}{\alpha_1} + R_{s1} + \frac{\delta}{\lambda} + R_{s2} + \frac{1}{\alpha_2})^{-1} \tag{5}$$

Where R_s is the fouling resistance. δ is the thickness of plate，m. λ is the heat conductivity coefficient. α is the heat transfer coefficient.

Due to the fluid flows in turbulence way in the plate heat exchanger, the heat transfer coefficient can be obtained by the heat transfer criterion equation (6).

$$Nu = C\,\mathrm{Re}^n\,\mathrm{Pr}^m \tag{6}$$

Where C , m and n are the coefficient of criterion equation decided by experiment, the value of which changes with the type the plate varying. The value range of C is 0.1-0.4. The value range of n is 0.60-0.85. The value range of m is 0.30-0.45. Pr is the Prandtl number.

Nu in the equation (3) is the Nuselt number, which can be calculated by the equation (7):

$$Nu = \frac{\alpha d_e}{\varepsilon} \tag{7}$$

Where d_e is the equivalent diameter, m. ε is the thermal conductivity of fluid, $W/(m \cdot K)$.

Re in the equation (3) is the Reynolds number, which can be calculated by the equation (8):

$$\mathrm{Re} = \frac{\omega d_e}{\nu} \tag{8}$$

Where ω is the flow rate of fluid, m/s . ν is the kinematic viscosity, m^2/s .

The expression of heat transfer coefficient α is as follows which is obtained by the above equations:

$$\alpha = C\frac{\varepsilon}{d_e}\mathrm{Re}^n P_r^m \tag{9}$$

The cooling water outlet temperature of plate heat exchanger can be obtained by iteration method according to the above mechanistic model. However, the accuracy of this model is not satisfactory because of the complexity of heat transfer process, the theoretical assumption and the inaccuracy value of the parameters in the model, therefore, a hybrid model of plate heat exchanger which compensates the deviation between the mechanistic model and the real data will be developed in the following sections.

4 HYBRID MODEL

4.1 Schematic of Hybrid Model

The structure of the hybrid model is shown in Fig. 2. The main part of hybrid model is the mechanistic model which is applied to predict the cooling water outlet temperature in the heat exchanger. Duo to the theoretical assumption and the inaccurate value of parameter, there is certain deviation between the output of the mechanistic model and the actual data, therefore, the RBFNN is applied to correct the output of mechanistic model because of its advantage of fast convergence speed and good capacity of global approximation.

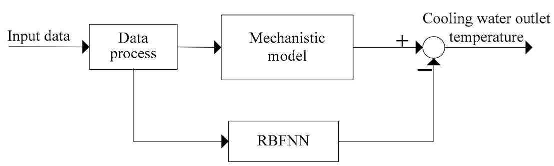

Fig. 2 Schematic diagram of the hybrid model

The input variables of the hybrid model are: the cooling water flow rate, the cooling water inlet temperature, the thermal fluid flow rate and the thermal fluid inlet temperature. The output variable of the hybrid model is: the cooling water outlet temperature.

4.2 Design of RBFNN

The RBFNN is applied to correct the error of the mechanistic model and the input variables of the RBFNN are the thermal fluid flow rate q_1, the thermal fluid inlet temperature t_1', the cooling water flow rate q_2, the cooling water inlet temperature t_2'. The output variable of the RBFNN is the error correction value of cooling water outlet temperature Δt_{out}. If the number of node in hidden layer is n, the structure of the RBFNN is shown in Fig. 3.

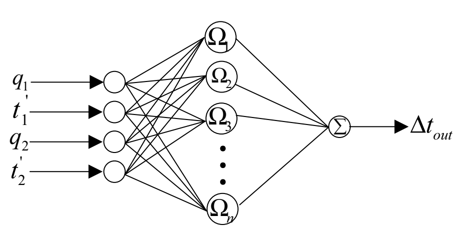

Fig. 3 Structure of the RBFNN

The output of the RBFNN can be described as follows:

$$\Delta t_{out} = \omega_0 + \sum_{j=1}^{n} \omega_j \Omega_j (\| Z - C_j \|) \tag{10}$$

$$Z = [q_1 \ t_1' \ q_2 \ t_2']^T \tag{11}$$

Where $\|\bullet\|$ is the expression of the distance, ω_j is the value of the connection weight between the output layer and the hidden layer, $\Omega(\cdot)$ is the radial basis function which is the Gaussian function in this paper, C_j is the centre of hidden layer which has the width coefficient $\zeta_j (j = 1, 2, \ldots)$.

The values of connection weight and node centre in the hidden layer can be obtained by means of PLS [11] and the procedures are described as follows:

Step 1 normalizing the training data.

Step 2 making the node centre in the hidden layer in the one-to-one correspondence with the training data.

Step 3 calculating the distance between the node centre in the hidden layer and the training data.

Step 4 choosing the width coefficient by experience and calculating the activation matrix.

Step 5 establishing the regression model and solving it by the PLSR [12] so as to obtain the connection weight value of the RBFNN.

5 MODEL APPLICATION

To verify the prediction performance of the hybrid model, 157 samples are obtained from the plate heat exchanger running in the circulating cooling water system in certain iron and steel enterprise. 127 samples are applied to train the RBFNN to establish the model and the other 30 samples are used to verify the prediction performance of the model. The parameters in the mechanistic model are obtained by experience and the value of C, m and n in the criteria equation are 0.35, 0.64 and 0.36 separately. The value of temperature correction coefficient is 0.94 and the value of the fouling resistance on the cooling side or the thermal side of the plate is 0.00034. The outputs of mechanistic model is also showed in the figure to compare with the outputs of hybrid model and the real data.

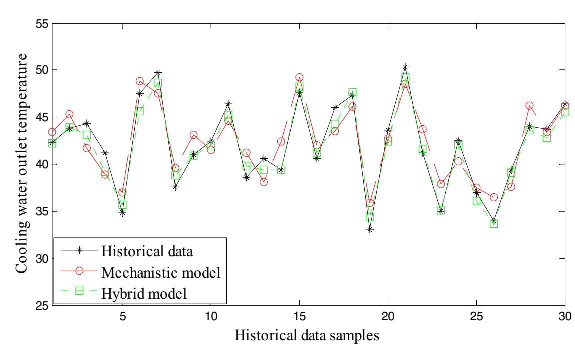

Fig. 4 Prediction curve of cooling water outlet temperature

The trained hybrid model is verified with test samples set and the results are shown in Fig. 4. To illustrate the prediction performance of the hybrid model, the outputs of mechanistic model are applied to compare with the outputs of hybrid model. The root-mean-square error of the hybrid model is 0.9914 and the maximum error is 1.6985, which are better than the corresponding value 1.9939 and 2.9358 of mechanistic model.

6 CONCLUSIONS

A hybrid model of the plate heat exchanger has been developed which can be used to predict the cooling water outlet temperature. The hybrid model consists of mechanistic model describing the heat transfer process in the heat exchanger and RBFNN which is applied to correct the error of mechanistic model with a parallel configuration. The parallel configuration not only reflect the principle of the heat transfer but also reduce the errors of mechanistic model caused by the theoretical assumption and the inaccurate value of parameter, which improves the prediction performance so as to lay the foundation for the operation optimization of the circulating cooling water system.

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