Cooling Efficiency Study of Hydrogen Batch Annealing Process

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Due to the low efficiency of the indirect cooling water system at the old-type coil base of hydrogen batch annealing process, the cooling time has been extended 2 hrs for hydrogen cooling from 430°C to 70°C, and consequently the 6,400 tons of cold coil production have been lost annually. This study was to find a suitable strategy to improve the cooling efficiency through selecting a de-scaling agent and scale inhibitor, and adjusting the flow rate of the cooling water for the system. By measuring the heat resistance coefficient of the heat exchanger, an optimum dose, type of chemicals, calcium hardness and flow rate of cooling water were determined. The experimental results showed that 10ppm of scale inhibitor (ASC-2) and 36-40m^3/hr cooling water were suitable for the indirect cooling water, which resulted in the resistance coefficient of heat exchanger decreasing from 3.7 to 2.5x10^{-4} m^2-°C/W at <800ppm of calcium hardness, and therefore the cooling time of the cold coil was reduced from 14 to 12 hrs. The operation conditions found in this study should be recommended as the best strategy to increase the production rate of cold coil.

1. INTRODUCTION

China Steel Corporation (CSC) is an integrated steel company, which involves processes operated at high temperatures. A large quantity of cooling water is needed during the steel manufacturing. Due to the increase in production, the manufacturing machinery is often stressed by the high temperatures and overloading. Therefore, a scale problem, especially on the coil base of the hydrogen batch process, occurs in the cooling water system, and is one of the major concerns as it results in equipment fouling or even process shutdown. Because the heat exchanger has a serious fouling problem the cooling time is extended by 2 hours from 12 to 14 hours as the cooling temperature of hydrogen is from 430°C to 70°C. Therefore, due to the production yield interruption and profit loss of cold coil base resulting from the excess fouling in cooling water system, the fouling problem needs to be solved.

In 2005, Ryznar[1,2] proposed using a Ryznar Stability Index (RSI) to forecast the scaling and/or corrosion tendency in the cooling water system, and also suggested that the RSI value should be controlled near 6 by adjusting the cooling water quality. Herro[3] also reported that the $CaCO_3$ crystal particles easily settled down on the pipe when the flow velocity is below 0.5 m/sec. In 2005, Zo[4] confirmed that the morphology of $CaCO_3$ scale was calcite and that the main function of an anti-scale inhibitor was to distort the morphology of $CaCO_3$. [5,6]. From KURITA Handbook of Water Treatment [7], the scale inhibition ratios of poly phosphate, poly acrylate and phosphate type are 31, 50, and 100%, respectively. The acceptable scale rate is under 10 mg/cm^2 per month, as recommended by the American USX, British Corus, Japanese JFE and Korean Pohang steel companies. In 2005, Y.I. Cho[8] developed a laboratory fouling simulation device and used the heat transfer theory to determine the fouling factor of the heat exchanger. Zhan (2003) [9,10] described a linear relationship between the fouling resistance and the thickness of the $CaCO_3$ scale.

The production interruption and profit loss have apparently resulted from the excess fouling of the heat exchanger on the coil base of the hydrogen batch process in CSC's alkaline cooling water system. Therefore, the purpose of this study is to select a suitable anti-scaling agent(s) for the coil base of the hydrogen batch process, to determine the agent dose, and to optimize the operating conditions such as flow rate and calcium carbonate concentration.

2. EXPERIMENTAL METHODS

For the No.115 base of the heat exchanger, it is necessary to use ionic chromatography (I.C.) and traditional methods to analyze the cooling water quality to build the background data of the cooling water quality. According to the results of a previous study[10], the RSI (Ryznar Stability Index) is defined as RSI = p(Ca^{+2}) + p(M- Alkalinity) + 8.1 by calculation of cooling water. The value of calcium ion-concentration is one of the main factors to affect the fouling rate of cooling water. Therefore, it is necessary to improve the cooling water quality by increasing the blow down the cooling water system in order to lower the Ca^{2+} concentration from the preset value of 1,000 ppm to 800ppm, and to keep the RSI value near 6.

The heat exchanger performance is very important to the cooling efficiency of steel coils. Thermal analysis of a heat exchanger is governed by the conservation of energy in that the heat released by the hot fluid equals the heat gained by the cold fluid. The overall heat transfer coefficient under fouled conditions for the heat exchanger can be obtained by inserting the fouling resistances. We can write the overall heat transfer coefficient U as follows:

$$\frac{1}{U} = R_s + R_m + R_f + R_w$$

$$= \frac{1}{\alpha_s} + \frac{(d+2\delta)}{2\lambda} ln(\frac{d+2\delta}{d}) + R_f + \frac{d+2\delta}{d\alpha_w} \quad .... (1)$$

where R_s, R_m, R_f and R_w are the thermal resistance on the outside of the tube, the wall resistance, the thermal resistance of the scale, and the thermal resistance on the inside of the tube, respectively. U is the overall heat transfer coefficient (W/m^2°C), and $1/U$ is the total thermal resistance. d and δ are the tube inside diameter and the thickness of the tube (m), respectively. α_s and α_w represent the heat transfer coefficients on the outside and the inside of the tube, respectively. λ is the tube material thermal conductivity.

3. RESULTS AND DISCUSSION

3.1 Selecting the Best Anti-scaling Agent

In order to compare the change of $CaCO_3$ particle size and shape caused by the effect of the difference types of anti-scale inhibitor, such as ASC-1, ASC-2 and ASC-3, the morphology of the $CaCO_3$ scales in the cooling water of 800ppm calcium hardness is shown in Fig. 1. Figure 1 shows that the $CaCO_3$ particle shape, by adding 10ppm ASC-3, is similar to a plate form and that the particles have accumulated to form larger particles. When adding ASC-2, the $CaCO_3$ morphologic shape belongs to a spherical shape similar to ASC-1, though particle size is about 1-5μm which is larger than ASC-1. Therefore ASC-1 is probably the best anti-scale inhibitor, ASC-2 is next, and ASC-3 is the worst anti-scale inhibitor.

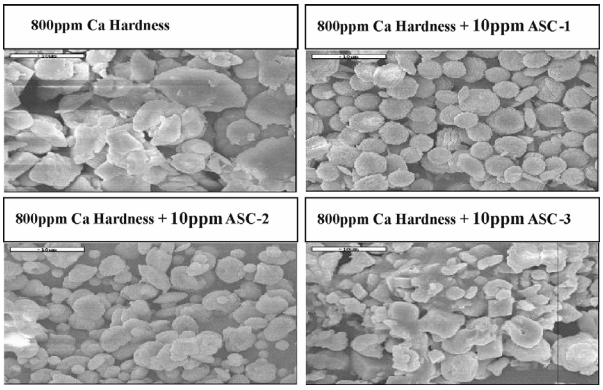


Fig. 1. The change of particles size and shape by adding 10ppm different scale inhibitors under 800 ppm Ca hardness condition.

Table 1 Water quality of indirect cooling water system

Items / Date	pH	Cond. (ms/cm)	Calcium-H (ppm)	Alkalinity (ppm)	RSI
2007.06.25	7.6	2.8	860	48	5.2
2007.07.17	7.7	3.1	925	46	5.0
2007.07.26	7.5	3.0	907	40	5.4
2007.09.17	7.5	2.9	825	50	5.3
2007.10.22	7.8	2.5	763	44	5.1
2007.10.25	7.5	2.5	760	32	5.7
2007.11.05	7.6	2.6	745	32	5.6
2007.11.14	7.4	2.7	780	36	5.7
2007.11.26	7.6	2.7	755	45	5.3
Control value	7.8~8.5	＜6.0	＜800	---	6.0
Notes	RSI＜6.0 -- scale tendency; RSI = 6.0 -- no scale/corrosion tendency; RSI＞ 6.0 -- corrosion tendency				

3.2 Water Quality of Open Indirect Cooling Water System

The status of the water quality in the field test of an open cooling water system for heat exchanger is shown in Table 1. The results of Table 1 show that the average values of pH, conductivity, calcium hardness, alkalinity and RSI are 7.6, 2.4 ms/cm, 813 ppm, 41 ppm, and 5.4, respectively. After October, 2007, the calcium hardness was maintained below 800 ppm, which meant that the Utility Section had improved the cooling water quality and met the field requirement for the cooling water system of the heat exchanger.

3.3 Field Performance Test of Anti-Scale Inhibitor

(1) By Addition of ASC-1

According to the pilot plant test, both ASC-1 and ASC-2 are excellent anti-scale chemicals. This study first chose ASC-1 to applying to the field test in May 2007 and the result is shown in Table 2. Table 2 shows that the cooling time of the hydrogen gas in the cold coil process increased from the original 14 hours to 17 hours after adding 40 ppm ASC-1 for 2 months and that it could not meet the field requirement.

In order to figure out this problem from adding ASC-1, it was necessary to open the heat exchanger. A lot of ASC-1 fouling materials were found to adsorb on the surface and inner tube at the end of heat exchanger and pipe, as shown in Fig. 2. After serious lab testing, it was established that the severe fouling problem was caused by the low solubility of ASC-1.

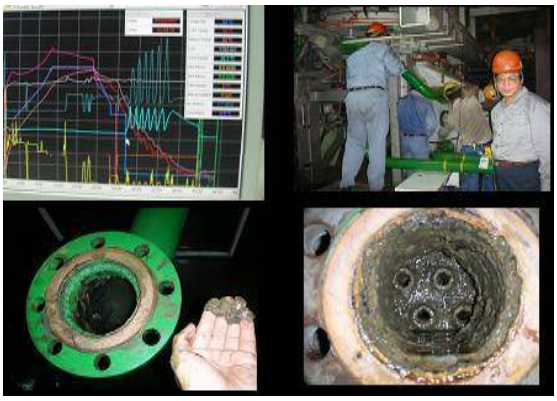


Fig. 2. Fouling material after addition of ASC-1 to heat exchanger.

(2) By Adding ASC-2 anti-scale inhibitor

After removing the fouling materials from the ASC-1 test run by using a lot of water to wash and clean the tube and pipe, the cooling time of hydrogen gas was shortened from originally 17 hours to 12-13 hours. It was therefore found that ASC-1 has the scale remover characteristic.

In order to avoid the drawbacks of adding ASC-1, it was decided to use ASC-2 instead of ASC-1. It was necessary to confirm the solubility of ASC-2 in distillated water through the dilution method on laboratory test. The result showed that ASC-2 has excellent water solubility characteristics.

With the ASC-2 concentration controlled at 10 ppm, an on-site the field test of the cooling water system was performed and the results are shown as Table 3.

(3) After testing for one month from July 2007, the cooling time of the cold coil has maintained at 12 hours under the conditions of calcium hardness, water temperature, flow quantity and flow velocity for cooling water system being at 800 ppm, 27°C, 25 m^3/hr and 1.0 m/sec, respectively. The result met the field requirement. These results emphasized the importance of the solubility and the performance of the anti-scaling chemicals in the cooling water treatment.

3.4 Relationship of Heat Transfer Coefficient of Heat Exchanger and Cooling Time of Cold Coil

The relationship between the heat transfer coefficient of the heat exchanger and the cooling time of the cold coil can be understood by field test, and the results are shown as Table 4. Table 4 shows that :

(1) the heat transfer coefficient of the heat exchanger by adding ASC-1 is from 3.7×10^{-4} to 1.4×10^{-3} m^2, °C/W, and cooling time is from 14 to 17 relatively; from the previous study and data of fouling measurement and heat transfer coefficient, the extrapolation method can be used to predict that fouling rate is about 50 to 100 mg/cm^2 per month.

(2) after washing the heat exchanger and adding 10ppm ASC-2, the heat transfer coefficient of heat exchanger is from $1.4\times10^{-3}$to 2.3×10^{-4} m^2, °C /W, and the fouling rate is from 100 to 25mg/cm^2 per month. Under these conditions, the cooling time could be maintained at 12 hours. These results emphasized the performance of ASC-2 in cooling water treatment.

Table 2 Difference of cooling time on heat exchanger by adding ASC-1

No. 115 Heat exchanger	No added ASC-1	With added ASC-1
Cooling time	14 hours	17hours

Table 3 Effect of cooling time on heat exchanger by adding ASC-2

No. 115 Heat exchanger	Adding ASC-2
Cooling time	12hours

Table 4 Relationship of heat transfer coefficient of heat exchanger and cooling time of cold coil

Items	Heat resistance coefficient (m^2, °C/W)	Fouling rate (mg/cm^2-month)	Cooling time (hr)
Before adding ASC-1	3.7×10^{-4}	50	14
After adding ASC-1	1.4×10^{-3}	＞100	17
After cleaning the heat exchanger	---	---	12~13
After adding ASC-2	2.3×10^{-4}	25	12

Under the test conditions of the hydrogen temperature, the inlet/outlet temperature and flow quantity of cooling water being 110.25°C, 32.22/41.50°C and 20.72 m^3/hr, respectively,the cooling time was 14 hours, and the heat resistance coefficient of heat exchanger was about 3.7×10^{-4} m^2, °C/W. The calculation is as follows:

(1) Total heat transfer rate

$Q = \rho D_w C_p (T_{w2} - T_{w1})$

= 993.43Kg/m^3 × 4178*J*/*kg*°C × (20.07m^3/hr ÷ 3600) m^3/s×(41.50-32.22) °C

=221,579.62 W

(2) Overall heat transfer coefficient *U*:

$$U = \frac{Q}{AF\ (T_{w2} - T_{w1})} \ln\left(\frac{T_s - T_{w1}}{T_s - T_{w2}}\right)$$

= 221,579.62 W/ 15.1958 m^2×1×(41.50-32.22) °C ×ln（110.25-32.22 / 110.25-41.50）

= 199.01 W/ m^2, °C

(3) Total thermal resistance 1/U = 1/199.01 = 5.025×10^{-3} m^2, °C/W

$$\frac{1}{U} = R_s + R_m + R_f + R_w$$

$$= \frac{1}{\alpha_s} + \frac{(d+2\delta)}{2\lambda} ln\left(\frac{d+2\delta}{d}\right) + R_f + \frac{d+2\delta}{d\alpha_w}$$

1/U=5.025×10^{-3} m^2, °C/W

=4.36×10^{-3}+2.45×10^{-5}+R_f +2.68×10^{-4}

=>The fouling resistance of the heat exchanger R_f = 3.7×10^{-4} m^2, °C/W

Under the test conditions of the hydrogen temperature, the inlet/outlet temperature and flow quantity of cooling water being 127.76°C, 27.74/39.42°C and 21.76 m^3/hr, respectively, during the winter season, the cooling time was 12 hours, and the heat resistance coefficient of heat exchanger decreased from 3.7×10^{-4} m^2, °C/W to 2.3×10^{-4} m^2, °C/W. The calculation is as follows:

(1) Total heat transfer rate $Q = \rho D_w C_p (T_{w2} - T_{w1})$

=994.55 Kg/m^3×4178.5 *J*/*kg*°C×(21.76 m^3/hr÷3600) m^3 / *s* ×(39.42-27.74) °C

=293292 W

(2) Overall heat transfer coefficient *U*:

$$U = \frac{Q}{AF\ (T_{w2} - T_{w1})} \ln\left(\frac{T_s - T_{w1}}{T_s - T_{w2}}\right)$$

= 293292 W / 15.1958 m^2 ×1×(39.42-27.74)°C×ln（127.76-27.74 / 110.25-39.42）

= 205.19 W/ m^2, °C

(3) Total thermal resistance 1/U= 1/ 205.19 = 4.874×10^{-3} m^2, °C/W

$$\frac{1}{U} = R_s + R_m + R_f + R_w$$

$$= \frac{1}{\alpha_s} + \frac{(d+2\delta)}{2\lambda} ln\left(\frac{d+2\delta}{d}\right) + R_f + \frac{d+2\delta}{d\alpha_w}$$

1/U=4.874×10^{-3} m^2, °C/W

=4.36×10^{-3}+2.45×10^{-5}+R_f +2.68×10^{-4}

=>The fouling resistance R_f = 2.3×10^{-4} m^2, °C/W

3.5 Effect of Piping Designed Type to Flow Quanitity and Flow Velocity

In order to increase the heat transfer in the heat exchanger and to reduce the cooling time of cold coil, the piping designed systems were rearranged in order to increase the flow quantity and flow rate of the cooling water. The results of the field test are shown as Table 5. Table 5 shows that the flow quantity and flow rate of cooling water rose from 25 m^3/hr and 0.7m/sec under

Table 5 Effect of piping designed to flow quantity and flow velocity

No.115 Heat exchanger	Hydrogen batch annealing process	
	Original piping designed systems	New piping designed systems
Flow quantity	25 m^3/hr	36 m^3/hr
Flow velocity	0.7 m/sec	1.2 m/sec
Cooling time	14 hours	12 hours

the old type piping system to 36m^3/hr and 1.2 m/sec using the new type piping system, and the cooling time was reduced from 14 hours to 12 hours under the same calcium hardness of the cooling water below 800ppm. From the result, it is clear that rearranging the piping designed systems to increase flow quantity and flow rate and lower the calcium hardness of the cooling water is effective at reducing the cooling time of the cold coil.

4. CONCLUSIONS

(1) The Utility Section has improved the indirect water quality by decreasing the calcium hardness from 1,000 to 800 ppm to mitigate the fouling rate, and ASC-2 is a more suitable anti-scaling chemical than ASC-1 and ASC-3 for the indirect cooling water system, and the proper dosage is about 10 ppm.

(2) 10 ppm ASC-2 and 36-40m^3/hr cooling water were suitable for the indirect cooling water, which resulted in the resistance coefficient of heat exchanger decreasing from 3.7 to 2.3×10^{-4} m^2-°C/W at <800ppm of calcium hardness, and therefore the cooling time of the cold coil was reduced from 14 to 12 hrs.

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