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EFFECTS OF FLOW VELOCITY ON RBI ANALYSIS OF COOLING WATER HEAT EXCHANGERS

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ABSTRACT

Failure of heat exchanger tubes is a common problem in the oil and gas as well as petrochemical industry across the world. Cooling water corrosion and fouling are closely related and should be analyzed together. Fluid temperature, type of water, type of cooling system, oxygen content and fluid velocities are the critical factors contributing to these damage mechanisms. In this study, the effects of flow velocity in the cooling water service to the corrosion rate were analyzed and the risk assessment was conducted using the risk-based inspection (RBI) principal. A condenser type heat exchanger used to cool water at the bundle/tubes side was chosen as a case study. The results showed that the flow velocity in the cooling water system gave a great effect on the corrosion rate, and ultimately affecting the risk category. Higher corrosion rate was seen at the minimum flow velocity.

Keywords: RBI analysis, cooling water heat exchanger.

INTRODUCTION

Failure of heat exchanger tubes is one of the common problems in the oil and gas as well as petrochemical industry. Heat exchangers usually provide a long service life with little maintenance, other than a routine inspection and cleaning. The main causes of degraded performance or failure of heat exchangers are typically due to fouling and corrosion. A very expensive failure occurs when a leak develops, allowing the cooling water to mix with the process fluid, contaminating both the process system and the cooling water system.

This study focuses on cooling water corrosion, which is one of the damage mechanisms occur in the cooling water tubes. Cooling water corrosion and fouling are closely related and should be considered together. Fluid temperature, type of water and the type of cooling system, oxygen content and fluid velocity are the critical factors of cooling water corrosion.

This study will focus on the fluid velocity, one of the main variables that influence the cooling water corrosion. At very low velocity, bio-fouling or deposit build up can occur, promoting under deposit type of attack or microbiologically-induced corrosion (MIC). Even if fouling deposits do not occur, low velocity encourages higher metal temperatures that results in an increase in the corrosion rate. For carbon steel, there is a range of flow where temperature does not influence the corrosion rate. If the flow velocities are outside these limits, the velocity factor may be determined.

In this study, the effect of flow velocity in the cooling water service of a heat exchanger to the corrosion rate was analyzed, followed by conducting the risk assessment using the principal of Risk Based Inspection (RBI) standard, API 581: Risk Based Inspection Methodology. The case study was on a cooling water service of shell and tubes heat exchanger of a new facility in Malaysia.

LITERATURE REVIEW

Cooling water corrosion

Water is the most commonly used cooling fluid to remove unwanted heat from the heat transfer surfaces. At the present time, the demands for better utilization of limited water supplies are due to population growth and increasing development. Due to this, open recirculating cooling water systems that reuse cooling water are frequently used at utility stations at chemical, petrochemical, and petroleum refining plants.

Cooling water corrosion is a damage of carbon steels and other metals caused by dissolved salts, gases, organic compounds or microbiological activity. Cooling water corrosion and fouling are closely related and should be considered together. Several critical factors for this damage are fluid temperature, type of water (fresh, brackish, salt water) and the type of cooling system (once-through, open circulating, closed circulating), oxygen content and fluid velocities. Cooling water corrosion can result in many different forms of damage including general corrosion, pitting corrosion, MIC, stress corrosion cracking and fouling [1].

Fouling may occur from mineral deposits (hardness), silt, suspended organic materials, corrosion products, mill scale, marine and microbiological growth. Velocities should be high enough to minimize fouling and drop out of deposits but not so high to avoid erosion. Velocities below about 1 m/s are likely to result in fouling, sedimentation and increased corrosion in fresh and brackish water systems. Accelerated corrosion can also result from dead spots or stagnant areas if cooling water is used on the shell side of condensers/coolers rather than the preferred tube side. Velocity limits depend on the tube material and water quality [1].

Corrosion of various parts of a cooling system may result if treatment is absent or inadequate and may lead to expensive replacement. Product contamination may also occur due to leakage of cooling water into the process stream. Corrosion may be controlled in a cooling

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system by adopting one or more of the following techniques [1]:

a) **Materials of construction:** Resistant metals such as stainless steel and cupro-nickel are normally too expensive to incorporate into an entire water cooling system, but may be used for components including heat exchangers. Protective coatings are now available for mild steel and if properly applied can be very successful. Plastics too are now used extensively, particularly for tower packing. The use of plastic piping may also be considered.
b) **Corrosion inhibitors:** Inhibitors have the function of modifying reactions at the metal surfaces. Corrosion inhibitors can be justified only in terms of cost effectiveness, but toxicity and pollution aspects must be considered.
c) **Biological control:** The conditions inside a re-circulating cooling system are very often conducive to build up of micro-organisms, which in turn can lead to problems of heat exchanger fouling and deterioration in tower performance. It is advisable to take steps to control the level of micro-organisms in the system.

Risk based inspection

Risk-Based Inspection (RBI) is a process that identifies and assesses risks due to corrosion and stress cracking, which compromise equipment integrity in both pressurized equipment and structural elements. RBI addresses risks that can be controlled through proper inspections and analysis. During the RBI process, engineers design inspection that most efficiently match the predicted degradation mechanisms based on the corrosion studies conducted.

The objective of RBI is to determine what incident could occur (i.e. consequence) in the event of an equipment failure, and how likely (i.e. probability) is it that the incident could happen. Combining the probability of one or more of the events with its consequences will determine the risk to the operation. Some failures may occur relatively frequently without significant adverse safety, environmental or economic impacts. Similarly, some failures have potentially serious consequences, but if the probability of the incident is low, then the risk may not warrant immediate action. However, if the probability and consequence combination (i.e. risk) is high enough to be unacceptable, then a mitigation action to predict or prevent the event is recommended.

The primary outputs of the RBI assessment approach are strategies that address ways to manage risks of equipment. These equipment strategies highlight risks from a safety/health/environment perspective and/or from an economic standpoint. Cost-effective actions for risk mitigation are also recommended along with the resulting level of risk mitigation expected.

Risk plotting is an effective method of representing risk graphically. In the risk matrix, the probability of failure (PoF) and consequence of failure (Cof) categories are arranged so that the highest risk components are towards the upper right-hand corner. The risk categories are differentiated by different colors, depending on which tool or approach used.

METHODOLOGY

The assessment of corrosion rate and risk analysis was based on API 581[8] with the utilization of the RBI software as conduct the risk analysis.

Determination of corrosion rate

The corrosion rate, CR is determined using Equation. (1) where the base corrosion rate, CR_B, is adjusted for temperature and flow velocity to calculate the corrosion rate.

$$CR = CR_B \times F_T \times F_V \quad (1)$$

where, CR= final corrosion rate (mm/year), CR_B= base corrosion rate (mm/year), F_T= is the corrosion rate temperature correction and F_V= is the corrosion rate velocity correction.

The base corrosion rate,CR_B, is an estimation of corrosion rate that is determined from the water scale tendency, chloride concentration and a threshold for flow velocity. In the existing plant with sufficient of inspection data conducted to obtain the actual corrosion rate, it can be the representative estimated corrosion rate to be used in the analysis. The corrosion rate of carbon steel has shown to increase almost linearly with temperature from 27 ºC to 29 ºC This correlation has been used to adjust the calculated corrosion rates. Therefore, to calculate the temperature adjustment, the ΔT is calculated by subtracting 24 °C from the actual metal temperature T_{op} o

$$\Delta T = T_{op} - T_{adjust} \quad (2)$$

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Table-1. Temperature adjustment factor, F_T.

Operating temperature, °C	F_T – Closed system	F_T – Open system	Operating temperature, °C	F_T – Closed system	F_T – Open system
27.00	0.30	0.30	63.00	2.40	2.40
29.00	0.40	0.40	66.00	2.50	2.50
32.00	0.60	0.60	68.00	2.70	2.70
35.00	0.80	0.80	71.00	2.90	2.90
38.00	0.90	0.90	74.00	3.00	3.00
41.00	1.10	1.10	77.00	3.20	3.20
43.00	1.20	1.20	79.00	3.40	3.30
46.00	1.40	1.40	82.00	3.50	3.30
49.00	1.60	1.60	85.00	3.70	3.30
52.00	1.70	1.70	88.00	3.80	3.30
54.00	1.90	1.90	91.00	4.00	3.10
57.00	2.10	2.10	93.00	4.20	2.90
60.00	2.20	2.20	99.00	4.50	1.70

Velocity is one of the variables influencing cooling water corrosion. At very low velocity, bio-fouling or deposit build up can occur promoting under deposit type of attack or microbiologically-induced corrosion (MIC). Even if fouling deposits do not occur, low velocity encourages higher metal temperatures that results in an increase in the corrosion rate. Velocity may be determined using Equation. (3) where V_a is the actual velocity in m/s.

$$F_v = \begin{cases} 1 + 1.64(0.914 - V_a) & for V_a < 0.914 \\ 1 & for 0.914 < V_a < 2.44 \\ 1 + 0.82(V_a - 2.44) & for V_a > 2.44 \end{cases}$$
(3)

Risk assessment

In this study, the risk assessment was done using the in-house RBI analysis software. The purpose of RBI analysis is to develop focus risk analysis that is associated with an active damage mechanism and its consequences. RBI analysis categorized the equipment into individual risk - High, Medium, Low and Very Low.

The primary failure case is loss of containment, which is the basis for this study. A thorough knowledge of potential failure mechanism is required to develop an effective inspection program in an oil & gas production facility. After assessing all the related information, the software is used to generate a calculated risk ranking. The risk associated with operating equipment is defined by the expression:

Risk = Probability of Failure (PoF) × Consequence of Failure (CoF)

The consequence and the probability are then combined to give a risk rating for each equipment. A high-risk component is due to either a high Probability of Failure and a low Consequence of Failure, or conversely a high consequence of failure and a low probability of failure. An inspection program can influence the category of the probability of failure, however not affecting the consequence. Where a high-risk component is driven by the consequence value, other actions such as a more precise analysis (Quantitative Risk Assessment) and upgrading of mitigation system may be considered. The results of the RBI analyses can be conveniently presented in a six by five risk matrix with the probability category of A to E and the consequence category of 0 to 5. The lowest risk category will be 0-A, and the highest risk category will be 5-E.

Probability of failure

The PoF of equipment is a direct function of the nature and rate of the degradation mechanisms to which it is subjected to. The essential steps taken to analyze PoF are identify the damage mechanism(s), predict the rate of degradation, assess the inspection confidence and identify the service age.

PoF analysis usually considers three types of damage mechanisms for both internal and external which include thinning, environmental cracking and other expected damage mechanisms. For this study, it focuses on the cooling water corrosion where the morphology of the degradation is thinning. Below are steps of wall loss analysis to obtain PoF:

Step 1: Calculate component age in service, a.
$a =$ date of analysis - date of service
Step 2: Calculate wall loss, WL.
$WL = a \times r$ where r = corrosion rate
Step 3: Calculate fractional wall loss
Fractional wall loss $= \frac{a \times r}{t}$ where t = initial wall thickness

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Step 4: Determine number of inspection and inspection confidence level.
Step 5: Determine the corrosion factor.
Step 6: Determine the internal corrosion probability category.

Consequence of failure

The CoF is calculated by considering five categories; Flammability, Toxicity, Production Loss, Environment and Reputation. The production loss consequence is determined by considering the cost associated with component failure which also includes labor cost, replacement cost and miscellaneous cost. The criteria are provided in Ref [8].Consequence analysis for Environment and Reputation Category are performed in qualitative manner following a set of criteria. In considering the environment consequence, it has been assumed that any leak of the process liquid will be contained within the facility compound and will not be discharged to the surrounding thus limiting the impact.

RESULTS AND DISCUSSIONS

In this study, a newly installed condenser type heat exchanger was used in the analysis, where the shell and tube heat exchanger type AES is utilizing cooling water at bundle/tubes side as a cooling medium to condense vapor of naphtha at the outlet of overhead atmospheric column in the crude distillation unit.

Determination of corrosion rate

Since the heat exchanger is a new facility where no velocity data available, a set of velocity range flow was used for the corrosion rate calculation. CR_B used in this study was based on the actual average corrosion rate calculated from an existing facility of the same service. The corrosion rate was agreed by the subject matter experts and operation personnel of the plant, where $CR_B = 0.1$ mm/year will be used in this study. The operating temperature, T_{op} = 34°C and the adjustment factor of temperature, F_T= 0.8 were used to calculated CR for different flow velocity, as shown in Table-2. Minimum flow velocity of 0.15 m/s was being calculated up to maximum velocity of 6.10 m/s. It was assumed that the cooling water systems in the refining industry will not experience water flow velocity to exceed 6.10 m/s.

Table-2. Summary of the calculated CR with respect to different F_V.

Flow velocity (m/s)	F_V	**CR**(mm/yr)	**Flow velocity** (m/s)	F_V	**CR** (mm/yr)
0.15	2.25	0.18	3.35	1.75	0.14
0.30	2.00	0.16	3.66	2.00	0.16
0.61	1.50	0.12	3.96	2.25	0.18
0.91	1.00	0.08	4.27	2.50	0.20
1.22	1.00	0.08	4.57	2.75	0.22
1.52	1.00	0.08	4.88	3.00	0.24
1.83	1.00	0.08	5.18	3.25	0.26
2.13	1.00	0.08	5.49	3.50	0.28
2.44	1.00	0.08	5.79	3.75	0.30
2.74	1.25	0.10	6.10	4.00	0.32
3.05	1.50	0.12			

Higher CR is expected at the minimum flow velocity, where CR keeps decreasing as the flow velocity increasing up to 0.9 m/s. The CRapparently constant from 0.9 m/s, and starts do increase when the velocity reaches 2.4 m/s.

Higher $CR$is expected at low flow velocity, where bio-fouling or deposit build up can occur promoting under deposit type of attack or microbiologically-induced corrosion (MIC). Even if fouling deposits do not occur, low velocity encourages higher metal temperatures that results in an increase in the corrosion rate. As the velocity hiked up above 2.4 m/s, CR increases where the attack changes to erosion-corrosion.

Low velocity is expected when the heat exchanger is located at elevated area while high velocity is expected when the heat exchanger is located after pump. It is recommended to focus on monitoring at those areas where the corrosion rate is accelerated.

Risk assessment

Risk assessment was conducted by identifying the PoF and CoF of the exchanger tubes. The assumptions used were:

- The heat exchanger is 5 years in service.
- The fractional wall loss was calculated based on age and wall loss.
- The initial thickness of tubes in the exchanger,t, was 2.77 mm.

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- One baseline inspection has been conducted on tubes and inspection effectiveness is set to be "Highly Effective."

Based on this data, the resulting corrosion factor was 80 (i.e. refer to API 581) and was categorized under probability category of "C". The consequence category of the exchanger tubes has been analyzed during previous study. Cooling water is a non-toxic and non-flammable fluid which does not gives any impact on people, health and safety consequence. It also has no impact on Environment and Reputation consequence. On economics basis, any shut down of cooling water system will affect the production of the refinery main products (i.e. kerosene, diesel, wild naphtha, and atmospheric residue), which will cause a total plant production loss per day of USD11,112,104.16, leading to catastrophic "Asset" consequence, i.e. CoF 5. Table-3 summarizes the resulting risk analyzed based on different value of flow velocity.

Table-3. Risk categorization on velocity effect.

Flow velocity (m/s)	*CR* (mm/yr)	ar/t	Corrosion factor	PoF	Risk	Flow velocity (m/s)	*CR* (mm/yr)	ar/t	Corrosion factor	PoF	Risk
0.15	0.18	0.32	80	C	High	3.35	0.14	0.25	20	C	High
0.30	0.16	0.29	30	C	High	3.66	0.16	0.29	30	C	High
0.61	0.12	0.22	20	C	High	3.96	0.18	0.32	80	C	High
0.91	0.08	0.14	1	B	Medium	4.27	0.20	0.36	130	D	High
1.22	0.08	0.14	1	B	Medium	4.57	0.22	0.40	130	D	High
1.52	0.08	0.14	1	B	Medium	4.88	0.24	0.43	200	D	High
1.83	0.08	0.14	1	B	Medium	5.18	0.26	0.47	270	D	High
2.13	0.08	0.14	1	B	Medium	5.49	0.28	0.51	350	D	High
2.44	0.08	0.14	1	B	Medium	5.79	0.30	0.54	350	D	High
2.74	0.10	0.18	7	B	Medium	6.10	0.32	0.58	500	D	High
3.05	0.12	0.22	20	C	High						

From Table-3, it can be seen that the effect of flow velocity to the resulting risk, whereby, flow velocity of below 0.9 m/s and above 2.7 m/s resulting in HIGH risk. However, flow velocity between 0.9 m/s to 2.7 m/s resulting in MEDIUM risk. The risk distribution is presented in Risk Matrix as shown in Figure-1.

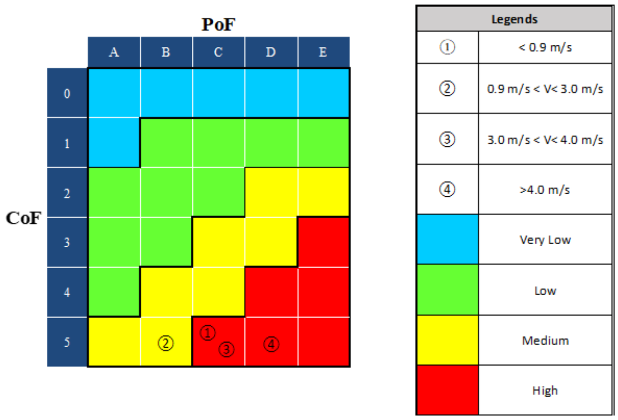

Figure-1. Risk matrix distribution based on velocity range.

Comparison against actual existing data

A set of actual data was obtained to perform a comparison study between the calculated corrosion rate as per API 581 and the actual inspection data (Table-4). Figure-2 shows that the corrosion rate of the existing 8 exchangers was plotted against the calculated corrosion rate. It can be seen that the corrosion rate of the actual exchangers was closed to the calculated corrosion rate, where at flow velocity of 2.374 m/s, corrosion rate starts to increase, thus conform the analysis conducted on the calculated corrosion rate.

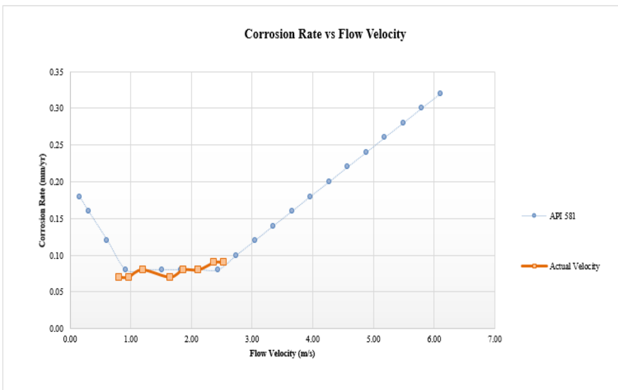

Figure-2. Comparison of actual velocity and API 581.

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Table-4. List of existing heat exchangers.

HEX	Flow velocity	CR (mm/yr)	HEX	Flow velocity	CR (mm/yr)
A	0.813	0.07	E	1.865	0.08
B	0.965	0.07	F	2.118	0.08
C	1.196	0.08	G	2.374	0.09
D	1.644	0.07	H	2.528	0.09

From the analysis, flow velocity in cooling water system gives a great effect on the corrosion rate, and ultimately affecting RISK category. Table-5 summarizes the effect on velocity to RISK

Table-5. Risk categorization on velocity.

Flow velocity	**CR** (mm/yr)	Risk	Flow velocity	**CR** (mm/yr)	Risk
0.15	0.18	High	3.05	0.12	High
0.30	0.16	High	3.35	0.14	High
0.61	0.12	High	3.66	0.16	High
0.91	0.08	Medium	3.96	0.18	High
1.22	0.08	Medium	4.27	0.20	High
1.52	0.08	Medium	4.57	0.22	High
1.83	0.08	Medium	4.88	0.24	High
2.13	0.08	Medium	5.18	0.26	High
2.44	0.08	Medium	5.49	0.28	High
2.74	0.10	Medium	5.79	0.30	High
			6.10	0.32	High

CONCLUSIONS

RBI has been developed on the cooling water exchanger with the main damage mechanism of cooling water corrosion being assessed, whereby study on the effects of velocity to the corrosion rate and risk analysis has been conducted using in-house RBI tool. The results showed that higher corrosion rate is expected at the minimum flow velocity, where the corrosion rate keeps decreasing as the flow velocity increasing up to 0.9 m/s. The corrosion rate apparently constant from 0.9 m/s, and starts to increase when the velocity reaches 2.4 m/s. Flow velocity of below 0.9 m/s and above 2.7 m/s resulting in HIGH risk and the flow velocity between 0.9 m/s to 2.7 m/s resulting in MEDIUM risk.

Higher CR is expected at low flow velocity, where bio-fouling or deposit build up can occur promoting under deposit type of attack or MIC. Even if fouling deposits do not occur, low velocity encourages higher metal temperatures that results in an increase in the corrosion rate. As the velocity hiked up above 2.4 m/s, the corrosion rate increases where the attack changes to erosion-corrosion. This result was validated by comparison study conducted on 8 existing heat exchangers with different flow velocity.

It is recommended that close monitoring shall be conducted at the suspected low flow velocity and high flow velocity area. Focus should be given to the equipment located at high elevation and equipment located after pump. Suggested monitoring such as corrosion coupon or corrosion probe to be installed at the outlet piping of the tube side. In addition, cooling water quality should be monitored for variables that affect corrosion and fouling including, pH, oxygen content, cycles of concentration, biocide residual, biological activity, cooling water outlet temperatures, hydrocarbon contamination and process leaks.

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