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Predictive Model of Corrosion Rates in Refinery Boiler Compartments (Suction Air Duct, Bank Tubes and Desuperheater Coils)

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Abstract: This study presents the development of a model that predicts the general corrosion rates of the boiler compartments. The model uses the principle of material balance in the boiler system to predict the internal corrosion rates of the boiler compartments tubes which has been recorded by Ultrasonic Thickness Scanning technique (UTS) for a period of 4 years. A comparison of the results from the predictive model equation is made with that from the ultrasonic thickness scanning technique for suction air duct, bank tubes and desuperheater coils. The metal loss in suction air duct was; 0.54-1.8 mm from UTS reading while that from the model was 0.06-1.98 mm, metal loss in bank tubes was 0.025-0.30 mm from UTS reading while that from the model was; 0.026-0.28 mm and metal loss from desuperheater coil was 0.25-3.30 mm, from UTS reading while that from the model is between 0.32-3.79 mm. The percentage deviation of the model from the UTS reading was calculated to show agreement between the two results. The capability of the model has been demonstrated by using it to predict the internal corrosion rates of the three boiler compartments of the refinery boiler.

Key words: Boiler compartments, model equation, internal corrosion, boiler tubes, bank tubes, suction air duct, desuperheater coils

INTRODUCTION

Corrosion is a major problem in petroleum refineries and chemical process plants. Key equipment, such as piping, valves, vessels, condensers, boilers and heat exchangers can be degraded by corrosion attack. Such attack can reduce equipment performance and reliability and in extreme cases lead to unexpected failures and shut down. Corrosion attack is the most serious aging mechanism for such equipment (Jaske *et al*., 1995).

Corrosion attack of process equipment may be external or internal. Therefore in a general corrosion assessment, the possibility of both external and internal attack must be considered. Thus, the effects of corrosion must be incorporated into component remaining life assessment and aging management programs (Koch and Jaske, 1991; Shah and Macdonald, 1993).

Process units, such as the boiler affected by these severe corrosion attacks which are as a result of the heating steam and condensate water which passes through the system unit in large volumes daily. Boiler tube failures continue to be the single largest source of forced outages in industries type steam generators. These boilers are extremely important to the overall operation of the processing facilities, therefore the need to maintain trouble free boilers is mandatory (Jaffer *et al*., 2003). If the main operating problems with the boilers (corrosion) could be predicted, a contingency plan could be arranged to overcome the shutdown problems.

In order to operate the refinery under safe and reliable conditions, it is important to know the rate of corrosion of the internal part of the boiler and the environment in which it is operating. Determination of the boiler tube failure and its corrosion rate is important for the prevention of future problems and for effective maintenance of the boiler compartment tubes. According to Farrell *et al*. (2002), corrosion, fouling and sometimes failure of the heat exchanger tubing that make up the boiler walls is a major obstacle to minimize boiler downtown.

The proper identification of corrosion rates and correct modeling of the corrosion rates of the internal boiler compartments will improve performance in corrosion monitoring and enhance diagnostics to support effective maintenance in boiler operation and management throughout the boiler life.

This mathematical predictive model based on material balance equation of the boiler is being used to make

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possible the correct identification of boiler tube corrosion rates and hence measure the effectiveness of the chemical program of the refinery boiler. This study developed a predictive model for the corrosion rates in refinery boiler data measured from Ultrasonic Thickness Scanning technique (UTS). The refinery boiler compartments that is used in this study are suction air duct, bank tubes and desuperheater coil.

MATERIALS AND METHODS

Mathematical model formulation: The mathematical model formulated to predict the corrosion rates of the three boiler compartments was based on ordinary differential equation. The boiler is a recycle system, hence there is no accumulation. Therefore, the material balance equation is given as:

Corrosion rate = Rate of inflow of material in to the system + Rate of generation of chemical reaction within the system – Rate of consumption of corroison inhibitors – Rate of outflow of materials from the system (1)

Mathematically expressed as:

$$\frac{dC_R}{dt} = F_{SO} + G_S - C_S - F_S \tag{2}$$

Where:

C_R = Corrosion rate of the system (mm year^{-1})
F_{SO} = Rate of inflow into the system (m^3 sec^{-3})
G_S = Rate of generation of chemical reaction within the system (m^3 sec^{-1})
C_S = Rate of consumption of corrosion inhibitors (mol/dm^3 sec^{-3})
dt = Change in time (years)

$$F_{SO} = F_S \tag{3}$$

$$F_{SO} = F_S = O \tag{4}$$

Substituting Eq. 4 into 2 gives:

$$\frac{dC_R}{dt} = G_S - C_S \tag{5}$$

But:

$$G_S = K_C C_R \tag{6}$$

$$C_S = G_R - C_{RO} \tag{7}$$

Using Eq. 6 and 7 into Eq. 5 gives:

$$\frac{dC_R}{dt} = C_R - C_{RO} + K_C C_R \tag{8}$$

Assuming no consumption of corrosion inhibitors:

$$C_R - C_{RO} = O \tag{9}$$

$$C_R = C_{RO} \tag{10}$$

Using Eq. 9 into Eq. 8 yields:

$$\frac{dC_R}{C_R} = K_C C_R \tag{11}$$

Separating the variables of Eq. 11 gives:

$$\frac{dC_R}{dt} = K_C dt \tag{12}$$

Integrating both sides of Eq. 12 gives:

$$\int_{C_{RO}}^{C_R} \frac{dC_R}{C_R} = K_C \int dt, \ln C_R - \ln C_{RO} = K_C (t - o),$$
$$\ln - C_R \ln C_{RO} = K_C t, \ln \frac{C_R}{C_{RO}} = K_C t \tag{13}$$

Taking exponential on both sides of Eq. 13 gives:

$$e^{\ln\left(\frac{C_R}{C_{RO}}\right)} = e^{K_C t}, \frac{C_R}{C_{RO}} = e^{K_C t}, C_R = C_{RO} e^{K_C t} \tag{14}$$

This equation predicts the corrosion rates in the refinery boiler compartments at any given time. To develop an equation that takes care of the effect of corrosion inhibitors: K_C in Eq. 14 is takes care of by the corrosion inhibitor adsorption equation:

$$1 - \theta = \frac{1}{1 + K_{inh} C_{inh}} \tag{15}$$

Which is a modification of langmuir type adsorption isotherm, where:

K_{inh} = Adsorption constant for the combined effect of the corrosion inhibitors
C_{inh} = Concentration of the corrosion inhibitors
θ = Degree of inhibitor coverage/protection

From Eq. 15:

$$(1-\theta)(1+K_{inh}C_{inh})=1 \quad (16)$$

$$K_{inh}=\frac{K_{inh}\theta}{1-\theta} \quad (17)$$

Putting Eq. 17 into 14 gives:

$$C_R=C_{RO}e\left[\frac{C_{inh}\theta}{1-\theta}t\right] \quad (18)$$

This Eq. 18 is used in predicting corrosion rates of the boiler compartments in the presence of inhibitors.

Determination of corrosion rate constant (K_C): The ultrasonic thickness scanning measured corrosion rates for 4 years. The initial corrosion rate (i.e., the loss of metal in the 1st year) is designated as C_{RO}. A graph of corrosion rates is drawn for each of the boiler compartments and a slope [change in corrosion rate divided by change in time (years)] was gotten from the graph. Mathematically, $C_{R2\text{-}CR2}/t_2\text{-}t_1$, give the slope of the curve which is a constant. The corrosion rate is then calculated to see if it agrees with the one measured by UTS. The K_C values for the different compartments are; suction air duct was 0.40, bank tubes was 0.025 for lower level and 0.075 for higher level and for desuperheater coil was 0.25 lower level and 0.575 higher level.

RESULTS

The results shown were obtained from Ultrasonic Thickness Scanning (UTS) of the boiler compartments and the predictive model Eq. 14 and the inhibitor model Eq. 18. Percentage deviation was calculated between the UTS result and that of the predictive model equation to see if they correlate. The percentage deviation is calculated from the equation:

$$\text{Percentage deviation}=\frac{\text{Model data}-\text{UTS data}}{\text{UTS data}}\times 100$$

The UTS reading in the suction air duct showed that 1.8 mm metal loss was observed over the period of 4 years. Initial metal loss was 0.54 mm in the 1st year, in the 2nd year it grew to 0.80 mm, in the 3rd year it was 1.20 mm. The predictive model equation results showed that over the 4 year period that 1.98 mm metal loss was observed. Initial or 1st year metal loss was 0.60 mm, in the 2nd year it was 0.89 mm metal loss and in the 3rd year 1.32 mm metal loss was recorded. The percentage deviation in the 1st year was 3.24%, 2nd year was 11.25% while it was 10%, respectively from the 3rd and 4th year. The inhibitor model equation gave 0.7 mm metal loss in 4 years. Initial metal loss was 0.27 mm, in the 2nd year metal loss increased to 0.47 mm and in the 3rd year it was recorded as 0.6 mm metal loss, as can be seen in Table 1.

In the bank tubes, UTS reading recorded between 0.1-0.3 mm metal loss in 4 years. In the 1st year metal loss recorded was between 0.025-0.075 mm, in the 2nd year, it rose to between 0.05-0.15 mm metal loss and in the 3rd year, it was between 0.075-0.225 mm metal loss. The predictive model equation gave metal loss of 0.028-0.28 mm in 4 years, 1st year metal loss was between 0.026-0.081 mm, 2nd year gave between 0.027-0.194 mm. Percentage deviation in the 1st year was 8%, 2nd year was 13.3%, 3rd year was -13.8 and -6.67% in the 4th year. The inhibitor model equation gave between 0.0427-0.131 mm metal loss in 4 years. Initial metal loss was between 0.017-0.052 mm, the 2nd year metal loss increased to between 0.029-0.087 mm and in the 3rd year it was recorded as between 0.0371-0.111 mm metal loss as can be seen in Table 2.

In the desuperheater coil, UTS reading recorded between 0.25-0.57 mm metal loss in 4 years. In the 1st year, metal loss recorded was between 0.25-0.575 mm, in the 2nd year was between 0.60-1.65 mm metal loss and in the 3rd year it was between 0.75-2.035 mm metal loss. The predictive model equation gave metal loss of 0.88-3.79 mm in 4 years. 1st year metal loss was between 0.32-1.02 mm, 2nd year gave between 0.71-1.82 mm metal loss and 3rd year metal loss recorded was 0.83-2.23 mm. Percentage deviation in the 1st year 16.57%, 2nd year was 10.30%, 3rd year was 9.85 and 14.85% in the 4th year. The inhibitor model equation gave between 0.429-0.98 mm metal loss in 4 years. Initial year metal loss was between 0.172-0.395 mm, the 2nd year metal loss was recorded as between 0.292-0.666 mm and in the 3rd year it was recorded as between 0.373-0.853 mm metal loss as seen in Table 3.

Table 1: Corrosion rate (metal loss) for F.D. suction air duct

No. of years	Rate from UTS ($mm\ year^{-1}$)	Rate from model ($mm\ year^{-1}$)	Deviation (%)	Rate from model inhibitor ($mm\ year^{-1}$)
1	0.54	0.60	3.24	0.27
2	0.80	0.89	11.25	0.47
3	1.20	1.32	10.00	0.60
4	1.80	1.98	10.00	0.70

Table 2: Corrosion rate (metal loss) for bank rubes

No. of years	Rate from UTS ($mm\ year^{-1}$)	Rate from model ($mm\ year^{-1}$)	Deviation (%)	Rate from model inhibitor ($mm\ year^{-1}$)
1	0.025-0.075	0.026-0.081	8.00	0.017-0.052
2	0.050-0.150	0.026-0.130	-13.30	0.029-0.087
3	0.075-0.225	0.027-0.194	-13.80	0.0371-0.11
4	0.100-0.300	0.028-0.280	-6.67	0.0427-0.13

Table 3: Corrosion rate (metal loss) for desuperheater coil

No. of years	Rate from UTS (mm year^{-1})	Rate from model (mm year^{-1})	Deviation (%)	Rate from model inhibitor (mm year^{-1})
1	0.25-0.575	0.32-1.02	16.57	0.172-0.395
2	0.60-1.650	0.71-1.82	10.30	0.292-0.666
3	0.75-2.035	0.83-2.23	9.85	0.373-0.853
4	1.00-3.300	0.88-3.79	14.85	0.429-0.983

DISCUSSION

The predictive corrosion rates of the boiler compartments are discussed in comparison to the corrosion rates measured by the Ultrasonic Thickness Scanning techniques (UTS). The predictive model equation is based on Eq. 13. However, the corrosion noted occured for a period of 4 years and the resulting information is, therefore of limited value. In terms of evaluating the impact of specific operating conditions or even fuel properties and the resulting model allows for a direct comparison between corrosion rate calculated from the model and the actual amount of metal loss to corrosion from the ultrasonic thickness scanning technique.

Under conventional combustion conditions, corrosion rates in a boiler typically should be <0.25 mm year^{-1} (Linjewile *et al*., 2003) which is according to the predictive model equation which will allow plant personnel to track tube damage rates during schedule outages. With the information from the data results, it will enhance corrosion monitoring to indicate when process parameters are outside the target range (Jaske *et al*., 1995).

In order to investigate the effect of corrosion inhibitors in the different compartments in the refinery boiler, Eq. 18 is developed. The equation assumed that corrosion inhibitors cover a portion of steel surface thereby preventing electrochemical reactions from taking place and is accounted for by surface coverage (θ) in Eq. 18. The model assumes that in a scale of 1 (one) that 0.75 part of it is covered by the corrosion inhibitors which absorbs unto the steel surface and prevents the electrochemical reactions from occurring on the underlying surface by the inhibitor growth. It can be seen that corrosion rates decreased greatly in the course of the 4 years prediction as against the predictive model equation. The model clearly showed that corrosion inhibitor films formed greatly reduced the corrosion rates toan appreciable extent in all the boiler compartments.

The physics and chemistry controlling corrosion processes in the boiler can be highly non-linear. Therefore, brief periods of exposure to unusual conditions can dominate overall material loss. The ability to understand, monitor and manage boiler wall loss could be improved through the application of predictive modeling technique like this one. A comparison of the corrosion data measured by the UTS technique and the model equation developed in this study is able to provide a reliable qualitative information on the corrosion rates (metal loss) in the boiler compartments.

CONCLUSION

The results of the model agreed with that measured by ultrasonic thickness scanning technique.

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