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Failure Analysis of Heat Exchanger Tubes at Different Operational Conditions

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Abstract— Heat exchanger tubes generally deteriorate or corrode as a result of their susceptibility to a wide range of tube and shell mediums under varying working conditions. The current study aimed to conduct a failure analysis of heat exchangers in the Petrochemical Industries under various operating conditions. According to kinetic and thermal analysis, heat exchanger tubes corroded primarily as a result of the carbon dioxide (CO2) solute in crude oil passing through the tubes, causing electrochemical corrosion. Polarized tests were carried out to analyze the outer surface cavities produced on the tubes. Tests revealed that CO2 had no substantial association with cavities on the surface of the tube. Additionally, microstructural analysis of corroded heat exchanger's tubes demonstrated that solid suspended particles of high hardness present in crude oil or methanol detached from previous phase catalysis causing electrochemical as well as the erosion-corrosion mechanism inside and outside heat exchanger tubes. Appropriate methods for prevention or mitigation of tubes corrosion were proposed based on the corrosion cause.

Keywords— Heat Exchangers, Errosion, Corrosion, XRF Petrochemical Industries.

I. INTRODUCTION

Corrosion is regarded as the common issue contributing to annually billion dollars losses [1]. Most industries' apparatus and amenities maintenance and repairs losses are instigated by corrosion. Heat exchangers are susceptible to consequent failure and corrosion [2]. The applications of heat exchangers vary from condensers, boilers to gas industries and petrochemical [3]. Heat exchangers are used in a variety of applications, including condensers, boilers, gas industries, and petrochemicals [3]. In general, heat exchanger is mainly utilized for cooling or heating of the process fluids, and the proper maneuver of this equipment is critical to the operation of a processing unit [4]. Many heat exchangers are designed for such applications where slot embedment, sedimentation, dissimilar metals connection, high fluid speed, stagnant fluid presence, and thermal ascents at the surface of metal and fluid are unavoidable [5]. In heat exchanger, the corrosive fluid accelerates corrosion, causes equipment failure, accelerates destruction, and ultimately phases out the production cycle. In chemical plants, reboilers are critical equipment used for the distillation of effective substances by heating the medium. Heat exchanger tubes is the reboiler critical components. Still, because they operate under complex conditions like two-phase flow [6], the high-temperature difference [7], and high pressure [8], and reboiler's heat exchanger tubes are susceptible to failures [9]. As a result, the failure of reboiler's heat exchanger tubes should be closely monitored to make sure that reboilers operate safely.

One of the most common causes of system shutdown in petrochemical refineries is the corrosion of heat exchangers [10]. In petrochemical plant, Heat exchanger tube corrosion can have severe consequences such as tubes perforation causes the leakage of coolant fluid into the process fluid. Significant product damage and loss caused by pollution of the processing fluid. There have been numerous expositions of heat exchanger failure caused by various corrosion contrivances, including stress cracking, even pitting, erosion, selective, intergranular, crevice, galvanic, and microbiologically induced corrosion [11-15]. The heat exchanger failure due to crude methanol contact constitute solute CO2 gas, water, and other side products is investigated in this paper. As per the refinery reports, corrosion is occurring in the tube. All of the doling out entities were investigated, and potential causes of heat exchanger corrosion and failures, such as ineffective inspection, inapt processing conditions, and repairs activities', or inadequate material assortment, were investigated. Besides sampling and tubes analysis, corrosion causes and mechanisms were examined through laboratory tests designed for desired heat exchanger. Lastly, appropriate solutions for corrosion prevention and mitigation are proposed within the research context..

II. METHODOLOGY

The Heat exchanger tubes made of carbon-steel sample was tested in a Pakistan-based oil refinery. The carbon-steel composition and transported medium crude methanol inlet and outlet temperature of 39.2 ◦C and 68.6◦C respectively are shown in Table-1. Figure 1 illustrate the failed or corroded heat exchanger tubes and Figure 2 shows immersion tests for corrosion. Two different sites i.e. Site I and II corroded heat exchanger tubes were collected along with corrosion product deposited on tubes. Microstructural analysis and surface morphology of site I and II samples taken were investigated with Scanning electron microscopy (SEM). X-rays Fluorescence (XRF) was performed to characterize elements, verify the composition of sample, and ionic chromatography was utilized for better examination. The heat exchanger tubes samples were immersed in simulated crude methanol of 300 mL inside electrochemical experiments. Similar to tubes, the cell was composed of steel samples and worked as an electrode. Silver and Silver chloride (Ag/AgCl) electrode was used as a reference electrode whereas the counter electrode was made of platinum plates. The forward scan voltage of the polarized sample was -0.2V to +1V against reversed scan open circuit potential -0.2V.

III. RESULTS

A. *Microstructural Analysis:*

Define Scanning electron microscopy images demonstrate the sample tube corrosion in Figures 2a, 2b, and 2c. The tube out surface looks like a regular pattern gear wheel and reduced thickness can be clearly seen in specified regions. The curved cavities formation on tube surface (2b) attributed to erosion-corrosion phenomenon. Additionally, accelerated under-deposited corrosion is caused by corrosion of the tube's outer surface. The spherical morphology of shell deposited corrosion is clear. It might be either caused by solid pollutant particles in crude methanol or products of detached corrosion. Also, sharp edges elimination on SEM image demonstrated the erosion phenomenon. X-rays fluorescence spectroscopy (XRF) and Energy dispersive spectroscopy (EDS) were performed for composition and deposited elements determination respectively. The deposited layer on the heat exchanger tubes was Fe, C, and O as shown in Figure 3. The composition of heat exchanger tubes before and after corrosion are shown in Table 2. The carbon contents increased from the original sample 0.06 wt% to 6 wt% on the corroded sample whereas oxygen was absenting the original sample but appeared in the corroded sample. The percentage loss of C, O, and Fe is actually the carbon steel sample corrosion. In short, iron oxide sand carbonate are the possible combinations that cause heat exchanger tube corrosion. Moreover, the iron carbonate was present in higher quantity compared to iron oxide which may conclude that iron oxide at the beginning was converted into carbonate due to crude methanol passage with CO2 through tubes.

IV. DISCUSSION

The perforation appearance on the inner wall expanded to the outer wall indicates that corrosion progress from inside to the outer side of the tube. Microstructural analysis of corroded heat exchanger tube deposited layer revealed that elements like iron, oxygen, and carbon weightage increased from original content. The percentage loss of iron is actually the carbon steel corrosion. The possible causes of heat exchanger tubes are iron oxide and carbonate which initiate the corrosion with iron oxide and transforms into iron carbonate by close contact with CO2 present in crude methanol. The presence of elements like Zn, Al, Si, Cu, and K on the shell deposited layer confirms that crude methanol had abrasive and hard particles as reported in Energy dispersive spectroscopy. Additionally, high content of Fe, C, and O was present which implies that FeCO3 might be the reason for accelerated corrosion in heat exchanger tubes.

The heat exchanger tubes deposited layer was analyzed using EDS-XRD where spectrum of various compound such as SiO2, ZnCO3, CuO, Fe2O, Cu2O, and Al2O3 were seen on the corroded sample. Abrasive particles include silica, alumina, and carbonate. These particles, depending on fluid motion types and flow intensity, can cause a significant surge in mechanical degradation influencing erosion-corrosion [16]. Moreover, with spontaneous reaction electrochemical corrosion rate enhanced with crude methanol substituted cupper particles [17, 18].

When the sediment of medium accumulated on the tube's surface, formic acid spot corrosion occurred easily beneath the sediment. S30408 was susceptible to stress concentration in pits [19, 20]. According to the results of the energy spectrum analysis, the corrosion position of the leakage fracture contained a high concentration of chloride ions. When chloride ion is present in the medium and the tubes are in the dry-wet, water-vapor alternated environment, the chloride is locally concentrated, and the sensitivity of stress corrosion cracking is significantly increased, according to GB/T 30579-2014 "Damage modes identification for pressure equipment." [21] The stress corrosion cracking of the tubes is indicated by the microstructure pattern of the river and a small amount of fan in the leakage fracture [22].

Overall, evidence from the macroscopic and microscopic examination of tube surface inveterate that the cavities are caused by solid particles such as ZnCO3, Al2O3, FeO, SiO2, and others corrosive particles. The relative hardness of particles silica, alumina, and carbonate are 2200 HV, 2600 HV, and 420 HV which is substantially higher than tube carbon steel 129 H. These particles can create corrosion cavities on the substrate. Additionally, according to the literature [23, 24], the iron carbonate layer had low adhesion substrate at temperature<70 C, confirmed by EDS results. Given that the heat exchanger's working temperature is around 53 C, the carbonate layer easily eroded and cannot protect corrosion [25]. These findings validated that erosion-corrosion is the primary cause of exchanger failure. Other corrosion possibilities are pitting, under-deposit corrosion, galvanic, and cavitation. For pitting corrosion, cyclic polarization testing revealed that without solid particles, pitting is unlikely [26].

SEM outcomes revealed that the cavities formed depth are almost equal or about to the mouth size, ruling out the pitting corrosion possibility [27]. Cavitation due to CO2 low vapor pressure at crude methanol average temperature of, i.e. 53 C, might be another possibilities. Producing holes seen on the tube is incapable [28]. The third possibility is Fe and Cu galvanic coupling. As per XRD analysis, Cu exists in the form of oxide and carbonate, not as a metal form capable of electrical contact. Furthermore, the Cu formation in corrosion deposits caused by galvanic coupling.

Furthermore, galvanic coupling reduces the thickness and increases the brightness of the active metal, in this case steel tube. Visual inspection, on the other hand, revealed a coarse and nonglossy surface. Moreover, the cathode to anode area ratio, which is an important factor in galvanic coupling, is substantially lower [29]. The galvanic coupling possibilities rule out in the system. Lastly, pits are deeper than the mouth under-deposit corrosion results. Furthermore, crude methanol high speed (66.5 Kg/s) protected the deposits beneath, implying that it might not be the corrosion primary mechanism [30].

A. *Figures and Tables*

TABLE I. CARBON STEEL COMPOSITION AS PER ASTM A179

Element	Composition (%wt)
C	0.06-0.08
Si	–
Mn	0.27-0.63
P	<0.035
S	<0.035
Compound	**Molar Percentage**
CH_3OH	80.61
H_2O	18.49
CO_2	0.73
CH_4	0.05
H_2	0.02
CO	0.01
N_2	0.01

TABLE II. COMPARISON OF BEFORE AND AFTER COMPOSITION OF CORRODED SAMPLE

Element	Composition Before (%wt)	Composition after Corrosion wt%
C	0.06-0.08	6.00
Si	-	-
Mn	0.27-0.63	0.27-0.63
P	<0.035	<0.035
S	<0.035	<0.035
O	Not present	Present
FeO	Not present	Present
$FeCO_3$	NP	Present

TABLE III. XRF ANALYSIS OF TUBE MATERIAL COMPOSITION

Element	Composition Before (%wt)
Cu	43.092
Zn	9.82
Al_2O_3	15.92
SiO_2	15.32
Na_2O	4.32
Fe_2O_3	3.25
K_2O	0.841
MgO	1.004

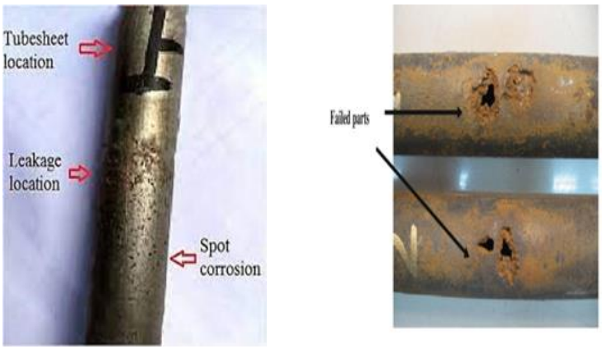

Figure 1. Heat Exchanger corroded tubes

Figure 2. Immersion test for corroded tubes sample with methanol

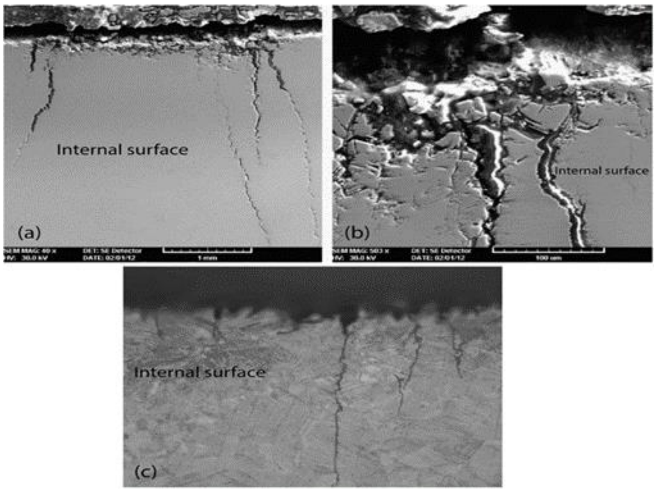

Figure 3. Scanning Electron Microscopy of Corroded heat exchanger tubes a) internal surface cracks, b) internal stress cracks, and c) erosion-corrosion

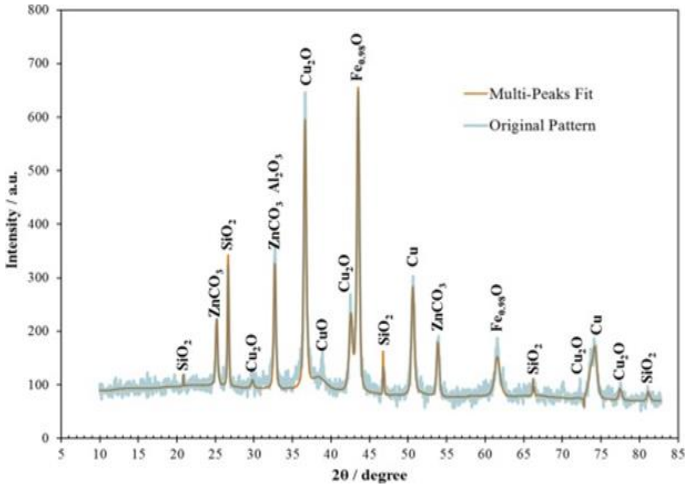

Figure 4. EDS-XRD of Corroded sample

CONFLICT OF INTEREST

The Author claims no conflict of interest.

CONCUSLION

Our study found that heat exchanger tubes corroded and failed due to the manifestation of solid abrasive particles in crude methanol. These abrasive particles lead to the erosion-corrosion phenomenon. Additionally, it was found that the formation of iron oxides and iron carbonate causes heat exchanger tubes failure due to corrosion in petrochemical industries. As a result, appropriate corrosion preclusion approaches were suggested, such as: using alloy steels A213; heat exchanger tubes to be made of higher carbon content carbon steel, tube surface hardening like carburizing; and filtration of crude methanol with suspended abrasive particles prior to entering heat exchanger.

REFERENCES

[1] G. Eason, T.Y. Rizk, K.M. Al-Nabulsi, M.H. Cho, Microbially induced rupture of a heat exchanger shell, Eng. Fail. Anal. 76 (2017) 1–9.

[2] T.K. Nguyen, M. Sheikholeslami, M. Jafaryar, A. Shafee, Z. Li, K.V.V. Chandra Mouli, I. Tlili, Design of heat exchanger with combined turbulator, J. Therm. Anal. Calorim. 139 (1) (2020) 649–659.

[3] W. Faes, S. Lecompte, Z. Yunus Ahmed, J. Van Bael, R. Salenbien, K. Verbeken, M. De Paepe, Corrosion and corrosion prevention in heat exchangers, Corrosion Rev. 37 (2) (2019) 131–155.

[4] J. Xie, K. Yazdanfar, G. Anning, T. Rockwell, A. Ahmed, Corrosion of a vertical shell and tube heat exchanger, NACE Int. (2015).

[5] Z. Qiankun, S. Yafei, R. Sixian, L. Huifeng, Z. Xingjiang, Corrosion failure analysis on heat exchanger pipes, J. Failure Anal. Prevention 17 (2) (2017) 349–353.

[6] Y. Gong, Z.G. Yang, J.Z. Yuan, Failure analysis of leakage on titanium tubes within heat exchangers in a nuclear power plant. Part II: Mechanical degradation, Mater. Corrosion 63 (1) (2012) 18–28.

[7] C.R. Corleto, G.R. Argade, Failure analysis of dissimilar weld in heat exchanger, Case Stud. Eng. Fail. Anal. 9 (2017) 27–34.

[8] U. Klein, A. Zunkel, A. Eberle, Breakdown of heat exchangers due to erosion corrosion and fretting caused by inappropriate operating conditions, Eng. Fail. Anal. 43 (2014) 271–280.

[9] D. Ifezue, F.H. Tobins, Corrosion failure of aluminum heat exchanger tubes, J. Fail. Anal. Preven. 15 (4) (2015) 541–547.

[10] K. Thulukkanam. Heat exchanger design handbook, CRC press, 2013. [14] Y.D. Li, N. Xu, X.F. Wu, W.M. Guo, J.B. Shi, Q.S. Zang, Failure analysis of the condenser brass tube in 150 MW thermal power units, Eng. Failure Anal. 33 (2013) 75–82.

[11] A. Prithiraj, I.O. Otunniyi, P. Osifo, J. van der Merwe, Corrosion behaviour of stainless and carbon steels exposed to sulphate – reducing bacteria from industrial heat exchangers, Eng. Failure Anal. 104 (2019) 977–986.

[12] K.M. Deen, M.A. Virk, C.I. Haque, R. Ahmad, I.H. Khan, Failure investigation of heat exchanger plates due to pitting corrosion, Eng. Fail. Anal. 17 (4) (2010) 886–893.

[13] R. Sharma, H. Poelman, G.B. Marin, V.V. Galvita, Approaches for selective oxidation of methane to methanol, Catalysts 10 (2) (2020) 194.

[14] R. Julian, K. Lichti, E. Mroczek, B. Mountain, Heavy metal scaling and corrosion in a geothermal heat exchanger, Proceedings World Geothermal Congress (2015).

[15] F.M. Song, D.W. Kirk, J.W. Graydon, D.E. Cormack, Predicting carbon dioxide corrosion of bare steel under an aqueous boundary layer, Corrosion 60 (8) (2004) 736–748. [20] T. Tanupabrungsun, B. Brown, S. Nesic, Effect of pH on CO2 corrosion of mild steel at elevated temperatures, Proc. Corros. (2013) 2348.

[16] F.J. Chen, C. Yao, Z.G. Yang, Failure analysis on abnormal wall thinning of heat-transfer titanium tubes of condensers in nuclear power plant Part I: corrosion and wear, Eng. Fail. Anal. 37 (2014) 29–41.

[17] F.J. Chen, C. Yao, Z.G. Yang, Failure analysis on abnormal wall thinning of heat-transfer titanium tubes of condensers in nuclear power plant Part II: Erosion and cavitation corrosion, Eng. Fail. Anal. 37 (2014) 42–52.

[18] Z.G. Yang, Y. Gong, J.Z. Yuan, Failure analysis of leakage on titanium tubes within heat exchangers in a nuclear power plant. Part I: Electrochemical corrosion, Mater. Corros. 63 (1) (2012) 7–17.

[19] Y. Gong, Z.G. Yang, J.Z. Yuan, Failure analysis of leakage on titanium tubes within heat exchangers in a nuclear power plant. Part II: Mechanical degradation, Mater. Corros. 63 (1) (2012) 18–28.

[20] Y. Gong, Z.G. Yang, X.H. Meng, Failure analysis of one peculiar 'Yin-Yang'corrosion morphology on heat exchanger tubes in purified terephthalic acid (PTA) dryer, Eng. Fail. Anal. 31 (2013) 203–210.

[21] S. Xu, C. Wang, W. Wang, Failure analysis of stress corrosion cracking in heat exchanger tubes during start-up operation, Eng. Fail. Anal. 51 (2015) 1–8.

[22] J.S. Corte, J.M.A. Rebello, M.C.L. Areiza, et al., Failure analysis of AISI 321 tubes of heat exchanger, Eng. Fail. Anal. 56 (2015) 170–176.

[23] D.S. Weaver, J.A. Fitzpatrick, A review of cross-flow induced vibrations in heat exchanger tube arrays, J. Fluids Struct. 2 (1) (1988) 73–93. [15]

H.G.D. Goyder, Flow-induced vibration in heat exchangers, Chem. Eng. Res. Des. 80 (3) (2002) 226–232.

[24] A. Korchef, M. Touaibi, Effect of pH and temperature on calcium carbonate precipitation by CO2 removal from iron-rich water, Water Environ. J. (2019) 1–11.

[25] F. Pessu, R. Barker, A. Neville, CO2-corrosion of carbon steel: the synergy of chloride ion concentration and temperature on metal penetration, Corrosion (2020).

[26] T. Magne, R. Paridaens, F. Ravelet, S. Khelladi, F. Bakir, P. Tomov, L. Pora, Effect of gas content on the cavitating and non-cavitating performance of an axial three-bladed inducer, Multiphase Sci. Technol. 32 (1) (2020).

[27] J.X. Jia, G. Song, A. Atrens, Influence of geometry on galvanic corrosion of AZ91D coupled to steel, Corros. Sci. 48 (8) (2006) 2133–2153.

[28] Y. Hou, C. Aldrich, K. Lepkova, B. Kinsella, Detection of under deposit corrosion in a CO2 environment by using electrochemical noise and recurrence quantification analysis, Electrochim. Acta 274 (2018) 160–169.

[29] E.H. Williamson, M. Gee, D. Robertson, J.F. Watts, M.J. Whiting, J.A. Yeomans, Wear performance and characterisation of coatings for nuclear applications: WC-(W, Cr)2C-Ni and hard chromium plate, Wear 430–431 (2019) 169–182.

[30] P.P. Adsul, L. Dineshkumar, On code verification of 2D transient heat conduction in composite wall, IOP Conf. Ser. Mater. Sci. Eng. (2018), 012128.

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