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Effect of Drum Pressure on Flow Accelerated Corrosion in Gas-Fired Combined Cycle Power Plant: A Case Study in the light of Literature Review

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ABSTRACT

The dissolution of ferrous ions from the protective oxide layer and/or base metal by corrosion with the assistance of turbulent flow is called flow accelerated corrosion (FAC). Flow accelerated corrosion is the most common and continuous corrosion reaction in combined cycle power plants (CCPP). Heat recovery steam generator (HRSG) drum pressure fluctuation and/or turbulent drum water greatly influences the FAC of drum and economizer. This kind of FAC was investigated in the low-pressure drum (LPD) and low-pressure economizer (LPE) of a 210 MW gas-fired combined cycle power plant (Four-unit HRSG & GT) with an air-cooled condenser (ACC). Severe FAC was observed due to the fluctuation of pressure in the LPD with respect to time. As a result, huge amounts of soluble iron (Fe^{2+}) and insoluble (Fe^{3+}) was found in all running HRSG's LPD water. Due to pressure fluctuations in the LPD, a protective oxide layer (mostly magnetite), as well as the base metal, were corroded from the LPD and LPE even after carefully maintaining recently developed water cycle chemistry in this CCPP. Severe leakage was found in the LPE due to corrosion. The actual reason for the problem was found to be a malfunctioning steam-control valve in the turbine unit's LP system. This valve was malfunctioning by suddenly opening to 100% and then closing to around 10% continuously. This malfunction creates enormous pressure drops in both the LPD and LPE units. It is understood that water turbulence is the main cause of FAC affecting the LDP and LPE. This assessment is based on chemical laboratory analysis and physical inspection. There was no non-destructive testing (NDT) performed in this study. The severe FAC happened in four days and for this reason, HRSG

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and steam turbines were shut down. Maintenance work on the control valve and flushing of the LPD and LPE successfully resolved the FAC problem. One week later, LPE leakage was found on the unit-3 HRSG and as reported in this study this was also found to be the result of FAC. From this case study, it is concluded that not only water quality but also water turbulence can create severe FAC problem.

Abbreviations

CCPP	Combined Cycle Power Plant
EPRI	Electric Power Research Institute
FAC	Flow Accelerated Corrosion
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
LP	Low Pressure
LPD	Low Pressure Drum
LPE	Low Pressure Economiser
MTC	Mass Transfer Coefficient
ORP	Oxidizing-Reducing Potential
SECM	Scanning Electrochemical Microscope
ST	Steam Turbine

1. Introduction

After the Surry Nuclear Power Station accident on December 9, 1986, due to flow accelerated corrosion (FAC) many types of research have been reported on this issue. FAC is a well-studied topic since 1986. FAC has widely been studied all over the world particularly in western countries rather than Bangladesh. Bangladesh is a developing country and it has an enormous energy crisis in every division of respective sectors. To mitigate this energy crisis in Bangladesh, large numbers of power plants are being installed in Bangladesh which operated by coal, gas, fossil fuels, and nuclear power. It has also been reported that, due to mitigating big energy demand, the country has only the production capacity of 15,000 MW. This energy demand will be 30,000 MW in Bangladesh by 2030 (*Power System Master Plan 2016 Summary*, 2016).

In this research, a practical case study of a power station in Mymensingh has been illustrated in this paper. Recently a severe single-phase FAC incident happened in a 210 MW gas-fired combined cycle power plant in Bangladesh. This power plant configured with a four-unit gas turbine (GT) and the four-unit heat recovery steam generator (HRSG) with one steam turbine (ST). LPE and LPD associated FAC incidents happened in all running HRSG units. The FAC incident was a single phase and it was significantly investigated for HRSG units to avoid associated consequences. Dooley (2008) and the Electric Power Research Institute (EPRI) reported that FAC will be controlled if the recent developed cycle chemistry is maintained properly in a thermal power plant (R. Barry Dooley & Tilley, 2005). However, in this case, study, the

cycle chemistry was maintained but the FAC incident happened.

Figure 1: Typical view of single-phase FAC failure in the pipeline. (R. Barry Dooley, 2008)

2. Understanding Flow Accelerated Corrosion (FAC)

Flow-accelerated corrosion (FAC) dissolves the protective oxide layers from the inner surface of carbon steel pipe during the faster water or steam flows in it. Due to protective oxide layer damage by FAC, the underlying base metal is corroded, and this is how the pipe's thickness is reduced slowly. Corrosion reaction basically forms the protective oxide layers on the pipe again, and thus the metal loss is continued. Normally FAC is observed in carbon steel piping but not extremely found in stainless-steel piping (R. Barry Dooley, 2008). A typical view FAC is shown in Figure 1 with red marks (A, B and C).

In Figure 1, the arrows (A) indicate the sharp edges which are basically happened after a significant reduction of pipe thickness due to FAC. On the other hand, the rough surface is shown by the red circle (C), this is also due to FAC. The red rectangle (B) indicates the thick edge to realize the original thickness of the carbon steel pipe. The variation of edge thickness reflects a lot of clues about FAC that occurred in CCPP. The illustration of FAC with its various consequences are mainly shown in this section for better understanding.

Dooley reported that, in combined cycle power plants, 35-40% heat recovery steam generator (HRSG) tube failures are caused by FAC (R. Barry Dooley, 2008). In a combined cycle power plant, the overall tubing and piping of high and intermediate economizers are the most sensible areas for flow accelerated corrosion. FAC is also harmful to the tubing and piping of the evaporator. On the other hand, high-pressure economizer and evaporator are free from FAC because at high pressure it is difficult to dissolve the protective oxide into water. A typical view of economizer, evaporator and superheater units of combined cycle power plant operated at pressurized condition is shown in the following Figure 2.

During plant operation LP main steam control valve was found faster closing and opening due to malfunctioning, and for this reason, pressure fluctuation observed in LPD. As a result, the inlet control valves of LPD were found open and closed with the water level fluctuation in the LPD. The overall pressure and water fluctuations in the LPD ultimately create LPE turbulence. This continuous effect of turbulence highly accelerates FAC in the respective industrial transport systems.

Figure 2: Schematic diagram of economizer, evaporator, and superheater of the combined cycle power plant.

2.1 Mechanism and influential factors of FAC

According to the Electric Power Research Institute (EPRI), the guidelines for controlling FAC in fossil and combined cycle plants are briefly discussed in this section. Dooley & Tilley (2005) and Ahmed (2012) reported that the protective oxide layers on the carbon steels in the economizer are formed from oxygen-free water and reducing agent. This kind of protective layer exclusively forms magnetite as a result of FAC which shown in the following reaction (Eq. 1).

Dooley & Tilley (2005) also reported that the above reaction can be explained by two reaction mechanisms. The first mechanism is the integration of general anodic and cathodic reactions of iron and oxygen-free water. This reaction can also be occurred when water contains a reducing agent. The reactions are shown by Eq. 2 and Eq. 3.

In reducing alkalized water, the cathodic reaction:

Combining the anodic and cathodic reactions:

The ferrous oxide transferred to magnetite by the Schikorr reaction which shown in Eq. 2. This is the second reaction mechanism as shown in Eq. 5 and Eq. 6. The schematic diagram of magnetite reaction mechanisms is shown in Figure 3.

Overall reaction:

From the above mechanism of FAC as shown in Figure 3, it can be proposed that, during the operation of HRSG with reducing water, a magnetite (Fe_3O_4) protective oxide layer is formed in the carbon steel tubing of economizer or evaporator [reaction schemes 1-3]. Oxide protective layers mostly formed in the epistatic region. According to Dooley & Tilley (2005), Ahmed (2012) and Amimer, Noel, & Stevens (2008), it can also be said that FAC is occurred

in reducing water through several steps of electrochemical reactions. The first reaction step is the oxidation of iron in the base metal-protective oxide layer in the presence of water in the topotactic region. The second step is the diffusion of ferrous ion to the oxide-water interface through the porous oxide layer from the metal surface at the boundary layer. The dissolution of the magnetic protective oxide layer and mass transfer of ferrous ion into the main flowing water basically happens from the boundary layer.

Scheme 1:

Scheme 2:

Scheme 3:

The ferrous iron dissolution from the magnetite protective oxide layer and base metal (carbon steel) initiated by the action of reducing the environment and fast-flowing water and/or turbulence flow water. The dissolution of ferrous ion is happening from magnetite because magnetite is a composition of FeO (Fe^{+2}) and Fe_2O_3 (Fe^{+3}) (Bueker, 2012). The overall mechanism for the formation of Ferrous and Ferric ions is shown in Figure 4.

Normally flow accelerated corrosion (FAC) can't be stooped fully in a combined cycle power plant due to its several factors. FAC depends on plant parameters such as water chemistry, materials, structural geometry of material, flow turbulence and mass transfer. The above factors are briefly discussed in the following sections.

2.1.1 Water Chemistry

Water chemistry is the most important factor in FAC. Water chemistry includes redox (oxidation and reduction) conditions of water, temperature, and pH of water which discussed in the following representation with the graphical diagram.

2.1.1.1 Redox conditions of water

Many researchers for example Dooley (R. Barry Dooley, 2008; R. Barry Dooley & Tilley, 2005) and Bouvier, Bouchacourt, & Fruzzetti (2002) and Fujiwara, Yoneda, & Inada (2017) reported the effect of reduction and oxidation conditions of FAC. They found FAC rate increases when water is in reducing condition and it decreases when reducing agents eliminate or water is in oxidizing condition. The presence of a small amount of oxygen will increase the oxidizing-reducing potential (ORP) and reduces the FAC rate (Bouvier et al., 2002; R. Barry Dooley, 2008; R. Barry Dooley & Tilley, 2005; Fujiwara et al., 2017). The following Figure 5 shows the effect of the redox condition of the FAC rate (R.B. Dooley et al., 2003).

Figure 4: Schematic diagram of the FAC mechanism. (Parmar, 2017)

2.1.1.2 Temperature and pH

Temperature and pH have a potential impact on the FAC rate, and this message is well established in the literature from forty years back. R. Barry Dooley & Tilley (2005), Fujiwara et al. (2017), Kain (2014) and Schefski, Pietralik, Dyke, & Lewis (1995) reported the effect of water, pH and temperature on FAC rate. The variation of FAC with pH and temperature is shown in Figures 6 and Figure 7.

In Figure 6 the variation of iron concentration (ppb) is sharply decreasing with increasing pH. This behaviour is probably due to the presence of a high alkaline substrate in the fluid medium. However, this can be minimized by maintaining the desired pH values.

In Figure 7 FAC is maximum at 180°C and at pH 7. On the other hand, at high pH (9.2) FAC is lower than low pH.

Figure 5: Effect of redox conditions on FAC in the economizer. (R.B. Dooley et al., 2003)

2.1.2 Materials and structural geometry:

FAC is also depended on the type of piping materials and their geometry. It is proven that carbon steel is most susceptible to FAC but stainless steel is almost free from FAC (R. Barry Dooley, 2008; Jonas, 2004). Many researchers e.g. (R. Barry Dooley, 2008), (Jonas, 2004), (Poulson, 2014), (Bouchacourt, 1990) reported that the addition of small amount chromium with stainless steel during fabrication can significantly reduce the FAC. It has also been reported that the addition of copper and molybdenum in the fabrication of stain less steel can be beneficial for FAC reduction in

some cases. Alaba, Adedigba, Olupinla, Agboola, & Sanni (2019) reported that the incorporation of chromium in carbon steel helps to reduce the corrosion (Figure 8). The following Figures (8 and 9) show the effect of incorporated material on FAC.

Structural geometry is one of the most influential factors of FAC. If we analyse the FAC failures in past reported studies, it can be said that, in most cases, FAC occurred at the bending position of the pipeline. On the other hand, it is also reported that straight pipelines are generally free from FAC if there is no flow turbulence.

Figure 6: Effect of pH and water on the FAC rate. (R. Barry Dooley & Tilley, 2005)

2.1.3 Flow turbulence and mass transfer

Mass transfer of ferrous ion occurred in the physical mechanism of FAC (Ahmed, 2012). It has been investigated that FAC is influenced by flow turbulence and mass transfer (Ahmed, 2012; Amimer et al., 2008; Betova, Bojinov, & Saario, 2010; R. Barry Dooley, 2008; R. Barry Dooley & Tilley, 2005; Lister, Liu, & Feicht, 2008). The mass transfer [expressed by Sherwood number (Sh)] is directly related to the flow turbulence [Expressed by Reynolds number (Re)] as follows (Ahmed, 2012):

$$Sh = a Re^b Sc^c \quad (7)$$

Where, Sc = Schmidt (Sc) numbers and a , b and c are related to mass transfer which occurs under a given flow condition and can only be obtained experimentally.

Ahmed (2012) and Lister et al. (2008) reported a model (Eq. 8) that can be used for FAC rate calculation.

2.2 Control Systems in the Control Trainer Graphical User Interface

$$FAC \text{ rate} = \text{Mass transfer coefficient} \times \Delta C \quad (8)$$

Where, ΔC is the undersaturation concentration in iron (Lister et al., 2008) and it is the difference between the concentration of ferrous ions at the oxide/water interface (C_w) and the concentration of ferrous in the bulk of water (C_b) (Ahmed, 2012).

Ahmed (2012) showed another relation between the mass transfer coefficient (MTC) and Sherwood number (Sh) which as follows (Eq. 9):

$$Sh = MTC \cdot d_H / D \quad (9)$$

Where d_H = hydraulic diameter and D = diffusion coefficient of iron in the water.

From equations 7, 8 and 9, it can be said that mass transfer increases with flow turbulence and as a result, the FAC rate will be increased. And also, mass transfer decreases with laminar flow (low Reynolds number, Re or low turbulence) and the FAC rate will be decreased.

Figure 7: Effect of temperature and pH on the FAC rate. (Fujiwara et al., 2017)

Figure 8: Elemental analysis of corrosion products on the scratched areas investigated by scanning electrochemical microscope (SECM) experiment. (Alaba et al., 2019)

Figure 9: Effect of chromium addition on FAC rate. (Bouchacourt, 1990)

2.2 Control mechanism of FAC

In the open literature, many research articles (Bouvier et al., 2002; Bueker, 2012; R. Barry Dooley, 2008; R. Barry Dooley & Tilley, 2005; Fujiwara et al., 2017; Lister et al., 2008) have reported that the presence of a small amount of oxygen can suppress markedly FAC rate. Fujiwara et al. (2017) showed that, if 4 ppb dissolved oxygen present in alkaline water at 180 °C then the FAC rate will be suppressed. R. Barry Dooley (2008) reported that, in the presence of dissolved oxygen, the protective cover layer pores become plugged with ferric

oxide hydrate (FeO-OH) or ferric oxide (Fe_2O_3) (Figure 10). As a result, the ferrous ion can't diffuse from the base carbon steel through the protective oxide layer and in this way FAC can be inhibited. R. Barry Dooley & Tilley (2005) shows the following oxidation reactions.

Figure 10: Control mechanism of FAC in the presence of dissolved oxygen. (R.B. Dooley et al., 2003)

From the above discussion it can be assumed that, during the inhibition of FAC, oxygen penetrates through the pores of the magnetite from the fluid boundary layer to the metal-oxide interface and react with the Fe^{2+} . This is how the continuous formation of Fe^{2+} helps to build more protective oxide maghemite ($\gamma\text{-FeOOH}$) or haematite ($\alpha\text{-Fe}_2\text{O}_3$) (Lister et al., 2008). The red colour maghemite ($\gamma\text{-FeOOH}$) has a spinel structure which would also help to form large crystals of protective oxide layers (Betova et al., 2010) (Figure 11).

3. Materials and Methods

Effect of drum pressure on FAC in gas-fired combined cycle power plant has been discussed in this section in the light of Physico-chemical parameters (section: 3.1 & 3.2). This case study was performed for three months in 2014 (August-September).

3.1 Chemical parameters analysis

The chemical analysis was performed in the chemical laboratory of the plant. Total iron (soluble and

insoluble iron) was measured for FAC investigation. The water sample was collected from the LPD for analysis.

3.2 Physical parameters monitoring

FAC was investigated in LPD and LPE outlet water from 30th August 2014 to 3rd September 2014. FAC has already been explained in Figure 2 for LP Drum of combined cycle power plant (CCPP). Although all recently developed cycle chemistry was maintained in the plant site but FAC found to be un-prevented due to LP

drum pressure fluctuation in all HRSG units (Unit-1, 3 and 4). It is reported that HRSG unit-2 was found normal at standby condition. The pressure at the LP drum was fluctuated because of malfunction which occurred at the superheated main steam control valve. Basically, the superheated main steam control valve was found rapid opened and closed due to malfunction. The cycle chemistry status of CCPP at the time of FAC is shown in Table 1.

Table 1: Details information on power plant cycle chemistry.

A 210 MW CCPP with 4 Gas Turbine (GT), 4HRSG, one Steam Turbine (ST) and Air Cooled Condenser (ACC) cooling system				
Plant Details →	Gas turbine (4×35 MW): General Electric (GE) Frame 6	HRSG (4×unit): Standard Fasel Lentjes, Siemens Nederland N.V.	Steam turbine: SIEMENS Germany	Water treatment system: CHRIST Netherlands
Cycle Chemistry details	HRSG unit-1	HRSG unit-2	HRSG unit-3	HRSG unit-4
LP drum pre.	4.3 bar	4.3 bar	4.3 bar	4.3 bar
LP economizer water downstream Temp.	125-130 °C	125-130 °C	125-130 °C	125-130 °C
Flow velocity (LP Eco)	10-15 t/h	10-15 t/h	10-15 t/h	10-15 t/h
BFW pH	>9.2	>9.2	>9.2	>9.2
LP drum water pH	>9.5	>9.5	>9.5	>9.5
O ₂ in LP drum water (After deaerator)	5-15 µg/L	5-15 µg/L	5-15 µg/L	5-15 µg/L
AVT(R)/ AVT(O)/OT	AVT(O)	AVT(O)	AVT(O)	AVT(O)
Materials (Economizer & LP drum)	Carbon steel	Carbon steel	Carbon steel	Carbon steel
FAC incident Date	30 th Aug to 3 rd Sep. 2014	30 th Aug to 3 rd Sep. 2014	30 th Aug to 3 rd Sep. 2014	30 th Aug to 3 rd Sep. 2014
Locations	LP economizer & LP drum	LP economizer & LP drum	LP economizer & LP drum	LP economizer & LP drum

During evening shift CCPP (on 30th of August 2014), malfunctioning was observed at LP superheated main steam control valve. Due to this malfunction abnormal iron (Fe²⁺) was found in the LPD water and HRSG-streams. To reduce abnormal iron, continuous and intermittent air blow was applied through the downward of respective units but abnormal Fe²⁺ found the same. The variation of abnormal iron concentration is shown in Figure 12.

3.3 Determination of iron concentration

Total iron (Fe) analysis was done with calibrated HACH DR/2500 spectrometer (FerroVer® powder pillows method: 10249) (GmbH, 2014). FerroVer® Iron Reagent converts all soluble and insoluble Fe to soluble ferrous iron (Fe²⁺). The ferrous iron reacts with the phenanthroline indicator and forms an orange colour in proportion to the iron concentration. The measurement wavelength was used 510 nm for spectrophotometers and/or 520 nm for colorimeters.

4. Results and Discussions

The variation of abnormal iron concentration and pressure fluctuation due to FAC are shown in Figures 12 and Figure 13 respectively. The variation of Fe

concentration is mainly shown in Figure 12 for HRSG units (1, 3, & 4). On the other hand, pressure fluctuation is shown in Figure 13 for HRSG unit 1.

In Figure 12, the plotted values were collected in 2014 from 28th August to 9th September. In the graph, FAC remediation time is 4th September to 9th September 2014. The FAC incident time is 30th August to 4th September 2014; where the iron concentration is high compared to other time spans. The maximum iron concentration was observed on 31st August 2014 for all HRSG units during the FAC incident.

FAC started when the turbulence created in LPD. At the same time, due to drum pressure fluctuation, the LPD level also fluctuated and as a result of the LPD water inlet control valve also opened and closed very fast with time. LPE sample collection was not possible due to its faster opening and closing of control valves. Therefore, no significant result of LPE was provided here.

LPE sample was not possible to collect for analysis but FAC was confirmed from the leakage at HRSG unit-3 economizer. It means that FAC happened in both LPD and LPE due to pressure fluctuation otherwise how and from where the leakage occurred at LPE. The leakages at LPE are shown in Figure 14 by red marks.

Figure 11: The red areas are protected by FeOOH in the single-phase areas. (R. Barry Dooley & Tilley, 2005)

Figure 12: Variation of abnormal iron (Fe) concentrations during the FAC incident.

In Figure 13, LPD pressure stated from normal operation to FAC remediation through FAC incident time. Hourly data was taken from the drum pressure trend. On 2nd September, the plant was shut down for control valve maintenance work. For this reason, the pressure was dropped.

During FAC, the concentration of Fe in all running HRS units was found high. At the final stage of FAC when iron concentration is abnormally high (Figure 12: 31st August to 1st September); red-coloured water was coming from the LPD. This is basically due to insoluble magnetite.

Firstly, the plant operators tried to solve this problem without shutdown the running plant, but they didn't succeed. Plant instrument and control (I&C) team and the mechanical team jointly tried to reset the control

valve through online control modules but that was not successful as well. Finally, the plant management team took a decision on 2nd September 2014 to shut down the steam turbines and all HRS units for control valve maintenance work. Steam turbine and HRS shutdowns were executed accordingly at 9:00 am.

I & C team fixed LP superheated main steam control valve and overall operation. On the other hand, the mechanical team fixed the LPD and LPD flushing. The control valve maintenance work was fixed with completing LPD and LPE flushing modules. Then the operation team started HRS and steam turbine by converting single cycle mode to combined cycle mode. After fixing all occurred faults in the plant, the iron concentration was found normal (3rd-9th September).

2014; Figure 12). This is also noted that the pressure turbulence no more appeared from 3rd-9th September 2014 (Figure 13). At normal conditions when there was

no pressure turbulence, the total iron (Fe) in LPD water is 0.05~0.3 mg/L at the start-up period but this value finally increased up to 1.0 mg/L.

Figure 13: Variation of pressure at HRSG unit-1.

Figure 14: LPE up comer leakage of HRSG unit-3.

5. Conclusions and Recommendations

Normally FAC can't be stopped fully but it can be reduced to the lowest level if all influential factors maintain carefully. FAC incident can happen if one of the influential factors malfunctioned even; if the recently developed cycle chemistry is being maintained. In this case, cycle chemistry such as pH and dissolved oxygen was maintained according to respective guidelines but the FAC incident was not prevented due to economizer and drum water turbulence. During the FAC incident, erosion-corrosion also happened because insoluble iron (Fe) found in the LP drum water. So, by considering all influential factors of FAC; water turbulence is more

sensible than other influential factors because if water turbulence happens then FAC and erosion-corrosion will be started simultaneously. However, further research is recommended on erosion in FAC of the gas-fired combined cycle power plant.

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