Feed Water Heaters Performance Indicators and Characteristics on the 405MW Coal-Thermal Power Plant

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Abstract

The coal-fired thermal power plant with a capacity of 3x135 MW gross or a total of 405 MW is composed of two high-pressure, one deaerator-heater and four low-pressure feed water heaters arranged in cascading stages on each of the three units. The objectives of the study are to determine the performance of these feed water heaters, both HP and LP, using the American Society of Mechanical Engineers Performance Test Code (ASME PTC) 12.1 and Heat Exchange Institute (HEI) Inc. procedures with engineering report and comparative discussions. Performance indicators such as terminal temperature difference (TTD), drain cooler approach (DCA) and temperature rise (TR) across heater were used to determine each unit's feed water heater system performance. The results showed that the high-pressure feed water heaters (HPH) were significantly more efficient compared to the low-pressure feed water heaters (LPH). An alarming off-design condition was encountered by the last stage heater, LPH7, in unit one where it showed a lower TR of around 2.95°C and the highest TTD of 49.86ºC. Thus, the results of the test showed that unit one and two has some problem on its last stage heater while unit three was performing better than the other two units. Based on the evaluation of the results, the last stage heaters were recommended to be evaluated for further analysis to prevent failure of equipment and these need necessary improvements. Generally, heaters are part of power station for the increase of cycle efficiency.

***Keywords**:* terminal temperature difference, drain cooler approach, temperature rise

1. Introduction

The determination of the performance on feed water heaters is an essential milestone of the thermal power plant. These heaters performance are used for evaluation of the unit's overall efficiency as a reheat-regenerative Rankine cycle system. The regenerative Rankine system is accomplished by heating the compressed liquid at a number of finite heaters by steam, which is bled from the turbine at selected stages (Kiameh, 2002). Since the temperature of feed water with pre-heating stages is higher than feed water without heaters, the efficiency is higher with regeneration (Nag, 1981). Thermal power plants were involved in these complex systems in order to improve the overall efficiency with an increased power output for the least input. By adding the feed water heater in the power plant cycle, the overall efficiency of the power plant is increased by around 2.4% (Devandiran *et al.*, 2016). The ASME assembled the PTC 12.1 closed feed water heaters to provide procedures, directions, and guidance for determining the performance of a closed feed water heater (ASME PTC 12.1, 1978). Some of the indicators used to determine the performance were TTD and DCA. The TR across heater can also be used as performance indicators as employed in the studies of Kumar (2014), Kushawaha (2015), and Bode (2016) to elaborate discussions and evaluations. These indicators are important tools for evaluation to monitor the condition of the heater before serious breakdown and failure occur. Several researchers previously mentioned have used this method in order to determine the status of a heater which was quite effective.

This study focused on performance monitoring and determination on the 3x135MW CFPP feed water heater system using ASME PTC 12.1 codes. The performance indications such as TTD and DCA were calculated based on the results of the tests. The TR will was included for further analysis and interpretation of the results. Data needed such as inlet and outlet feed water temperatures, extraction steam pressure, and heater drain temperature can be recorded from the data acquisition in the control room station. The extraction steam saturation temperature was plotted on the software computer-aided thermodynamic in Table 3. Since the three generating units were built identically, there were no modifications and alterations on the design related to the feed water heater system during the test.

The feed water temperature entering the boiler, on a basic Rankine cycle, is relatively low. Thus, it will increase the boiler heat addition and lower the cycle efficiency. One possibility to prevent this shortcoming is to increase the feed water inlet temperature to the boiler. A practical regeneration process design is to bleed steam from the turbine (extraction steam) at various points to pre-heat the feed water through a heater before admitting it to the boiler at a series of stages (Cengel and Boles, 2008). It does not only increase the cycle efficiency but it also de-aerates the non-condensable gasses out of the system. Aside from the classification of either high-pressure or low-pressure, there are two main types of feed water heater: closed-type and open-type. The increasing number of heater stages will also increase the efficiency, but it is not economical to have a large number of heaters just to increase its efficiency. Thus, based on a techno-economic study, the numbers of heaters generally used on a large capacity is around six to seven heaters (C. Kumar and D. Kumar, 2014).

The most commonly used feed water heater in a thermal power plant is the closed-type. It is a simple shell-and-tube type heat exchanger arranged either horizontally or vertically. The feed water passes through the tubes of the heat exchanger while the bled steam transfers energy on the shell side. Closed-type heaters are very similar to the condensers except that they operate at higher pressures (Kiameh, 2002). Considering the heat balance design on the heater, the closed-type heater performance can be monitored using the TTD and DCA methods, as well as TR, to evaluate its condition. No real law says that the output feed water must be saturated water, but generally, it is, and this is specified in the heater heat balance as "TTD = 0" on ideal assumptions (Black and Veatch, 1996). Accordingly, a too low TTD is too good to be true while a too high TTD reduced cycle efficiency.

The open-type feed water heater can also be called contact-type heater where both bled steam and the incoming feed water are mixed in the heater. This type of heater uses the heat exchanger device known as deaerator. The presence of dissolved and non-condensable gases (e.g., oxygen, carbon dioxide and etc.) in the water makes it corrosive, as they react with the metal to form iron oxide (Nag, 1981) and must be necessarily removed through mechanical scavenging at the deaerator or chemical scavenging through chemical injections. This type of heater is not applicable to the ASME PTC 12.1 guidelines and thus, can only be evaluated by the TR across the heater method.

The two last stage feed water heaters (LPH6 and LPH7) have been observed operating on an abnormal manner by the operations and maintenance group. The problem showed an unusual opening of the last stage heater emergency drain valve which damped water to the condenser. This condition might be an indication of off-design behavior and it could have bad effects on the unit in the future. Off-design condition only exists when the unit power output is minimum, low or equipment deration where these conditions have not met the required design values (Kushawaha and Koshti, 2015). This paper is an evaluation on the performance of the feed water heaters on a 3x135 MW coal-fired power plant (CFPP). The study aimed to determine the performance of the feed water heater system using the codes recommended by the ASME PTC 12.1 and HEI Inc. standards for heat exchangers, using performance indicators as tools. Comparative analysis is also discussed on the later part of the results of the test since all units were identical.

The study is an important tool for engineers and frontline personnel to study the condition of the feed water heaters. The results of the study could provide knowledge and information for the key personnel of the plant and will allow them to interpret the condition of the feed water heaters before breakdown. The primary purpose of the study is to detect abnormal and costly performance trends due to tube leakage, tube fouling, air blanketing and among others. The effects of these anticipated operating variations effectively mask the performance-robbing phenomena (e.g., tube sheet leakage) sought in such tests (Klink, 1989). Klink (1989) described a method for normalizing out the effect of known operating variations. This study will help operators, maintenance groups, and concerned people to evaluate the condition which the unit experiences during off-design behavior.

2. Methodology

2.1 System Setup Description

The experiment involved the determination and monitoring of the performance of the feed water heater system at each of the three units of a coal-fired thermal power plant built in 2016 at Villanueva, Misamis Oriental, Philippines. The gross capacity of each of the three-units is around 135 MW and identical in design with common auxiliary systems. Performance indicators were based from the ASME PTC 12.1 and HEI Inc. standards with TR as an additional indicator for further analysis of the heater condition. Comparative analysis discussions were also elaborated to investigate the problem involving at the last stage heater.

The set-up shown in Figure 1 is a schematic and process flow with details of instruments and location points. The feed water heater system is composed of two high-pressure heater closed-type, one deaerator heater open-type, and four low-pressure heater closed-type. They are arranged in a series of stages to

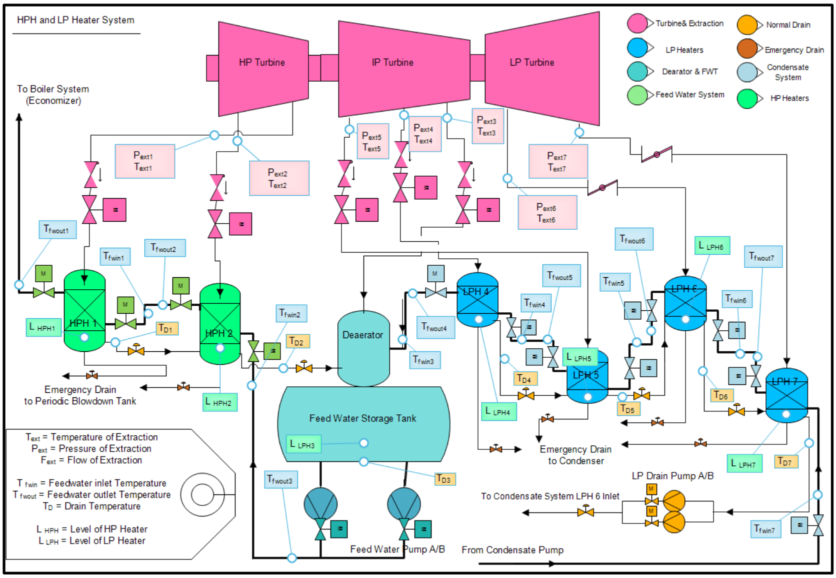

Figure 1. System setup schematic and process flow diagram

pre-heat the feed water flowing from condenser to the boiler inlet. The extraction or bled steam has a total number of seven tapping points of which two from HP turbine, three from IP turbine and two from LP turbine. A cascading flow set-up is also used of which the two high-pressure heaters (HPH) cascades back to the deaerator-storage tank and pumped as incoming feed water to the boiler through the HPH, while the four low-pressure heaters (LPH) are cascaded until to the last stage heater-LPH7 where it is also pumped back to the condensate line at LPH6 inlet.

The test included gathering of necessary data such as inlet and outlet feed water temperature, extraction steam pressure and heater drain temperature. These data were recorded by the data historian and are available from the control room station. Other data such as extraction steam saturation temperature can be plotted using steam tables or software. A total of five tests were conducted during the experiment per unit at the maximum power generated. The results were tabulated in a graphical presentation at an average value of the five tests. These results can be used as for heater condition and monitoring. A comparative analysis was discussed for the three units to elaborate further on their existing condition.

2.2 Assumption of the Current Study

The system was assumed to be carried out in a steady flow condition applying the Steady-State Steady-Flow (SSSF) thermodynamic equations on each process neglecting kinetic and potential energy (Bode and Gore, 2016). There is negligible heat transfer between the heater and its pipeline to the surroundings since both are assumed to be well insulated. There are no alterations on the design relating to the feed water heater system during the test and assumed to be identical for the three units. No air-in leakage in the deaerator device which could affect temperature distribution since it operates above atmospheric conditions. The various operating conditions affect factors of the equation for the rate of condensation were overall heat transfer coefficient, tube surface area, and mean temperature difference across heater. If any of these parameters changes, the rate of heat transfer from the steam changes (Kumar, 2017).

2.3 Performance Indicators and Analysis of Data

2.3.1 Performance Indicators

The performance indicators used in determining the condition of the close-type feed water heater was based from the guidelines on ASME PTC 12.1. These indicators were used for evaluation and report on the current status of each of the feed water heaters, as well as a comparison of the units. There are several studies that used these procedures to predict condition and problem occurring at the heater. Kumar and Kumar (2014) concluded in their study on performance analysis of the regenerative feed heating in a steam power plant that the efficiency of the heater could relatively affect the cycle efficiency. Other studies included the causes of poor performance of a heater and off-design behavior causes (Bode and Gore, 2016; Kushwaha and Koshti, 2015).

The first performance indicator mentioned by the code was the TTD. It is used to provide feedback on the heater's performance relative to heat transfer. It is described by the code as the difference in saturation temperature of steam to the outlet temperature of the feed water heater (ASME PTC 12.1). An increasing TTD indicates the reduction in heat transfer while a decreasing TTD denotes improvement (Kushwaha & Koshti, 2015).

$$TTD = T_{sat} - T_{fwout} \tag{1}$$

The next performance indicator was the DCA. It is used to determine heater water level based on the temperature difference. It is described as the difference between a heater drain outlet temperature to the inlet feed water heater temperature (ASME PTC 12.1). The increase in DCA of a heater could mean a flashing or heating at the drain cooler zone of the heater which is designed to be liquid only. This could significantly damage the area in the drain zone of a heater.

$$DCA = T_d - T_{fwin} \tag{2}$$

The other performance indicator which can be useful for analysis is the TR on across heater. It is described as the difference between outlet and inlet feed water heater temperature (EPRI, 2015). The value for the TR must be more than zero since it indicates a transfer of heat from steam to the feed water by the heater.

$$TR = T_{fwout} - T_{fwin} \tag{3}$$

where:

T_{sat} = Steam saturation temperature
T_{fwout} = Feed water outlet temperature
T_{fwin} = Feed water inlet temperature
$T(d)$ = Heater drain temperature

The performance indicators mentioned, TTD, DCA, and DCA, were used for the engineering report and discussions of the performance of each heater per unit. The peculiar behavior on the last stage heater observed could now determine the possible causes and prediction of a problem that could occur.

2.3.2 Designed Performance

The ideal performance indicator can be determined based on the designed heat balance of the system. Table 1 below shows the designed performance values for TTD, DCA, and TR of the heaters according to the theoretically designed heat balance. These can be used as a basis for comparing the three unit's feed water heater performance.

Table 1. Design Heater Performance

Heater	TTD (°C)	DCA (°C)	TR (°C)
HPH1	0.2	5	22.2
HPH2	0	8.2	41.7
DEA			38.6
LPH4	2.8	5	29
LPH5	2.8	5	34.3
LPH6	2.8	5	22.4
LPH7	2.2		23.2

The actual TTD is generally around 2.78°C (for Metric units) or 5°F (for English units), but can be as high as 10°F, for English units (Black & Veatch, 1996). These general TTD values mentioned were the acceptable normal range based from the zero value design at the above table. A too low TTD, lower than 2.78°C to zero, is too good to be true. While a too high TTD, above 2.8°C, can reduce the overall efficiency.

The DCA for the last stage heater-LPH7 cannot be determined but is predicted to be higher than normal since it is the last stage heater and can be serve as a sacrificing equipment. The DCA is generally around 10°F but may be as high as 20°F (Black & Veatch, 1996). It is important to note that both TTD and DCA were results of difference in temperatures making its conversion fixed on both units.

The design TR of each heater is expected to be at least more than 20°C and the HPH2 has the highest temperature rise of around 41.7°C. A properly performing heater should meet the manufacturer's design specifications. This indicator can also be a useful tool for determining the condition and performance of the feed water heater although it may not have been included in the PTC 12.1 procedures. The rise in temperature in the feed water can increase the cycle efficiency of the system, thereby reducing the fuel consumption and saving expenses on raw material fuel. An increase in feed water temperature of 5°C can decrease fuel consumption by approximately 1 %.

3. Results and Discussion

3.1 Performance Indicator Results on Heaters

The performance test results shown on each figure are the average values of the five tests during the experiment. The generation outputs of units one, two and three have average values of 135.219MW, 135.082MW & 135.087MW, respectively, during the tests. On each of the figures below, every heater was arranged as unit 1, 2 and 3 with a variety of near-color representation. The results showed that some values were near its designed values while some have unusual results.

The average of the five test results in unit one was summarized and tabulated in Table 2. It shows that high-pressure heaters TTD with ranges of 4 °C to 6°C were comparatively lower than the low-pressure heaters TTD of averaging around 10°C to 30°C. Figure 2 which shows a graphical presentation of TTD results, indicated that the TTD value increased in low-pressure heaters as it cascaded to the last stage heater.

Table 2. Terminal temperature difference results of each heater

Heater	Terminal Temperature Difference (TTD) (°C)			
	Design	Unit 1	Unit 2	Unit 3
HPH1	0.2	6.23	4.35	4.81
HPH2	0	3.42	3.39	3.88
LPH4	2.8	5.94	6.11	6.03
LPH5	2.8	9.47	9.27	8.79
LPH6	2.8	22.01	24.24	13.77
LPH7	2.2	49.86	38.53	33.43

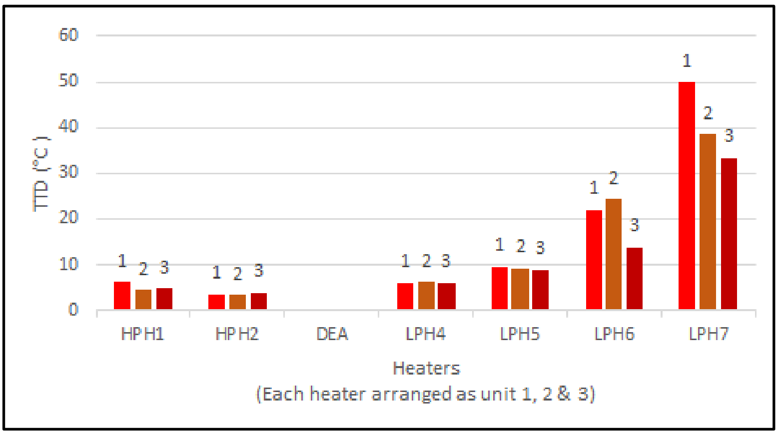

Figure 2. Graphical presentation on TTD results of each heater

The last stage heaters had alarming results in TTD value, especially in unit one, where the value was surprisingly higher at around 49.86°C. Although unit one had the highest result, the other two units also significantly higher TTD than normal. The same results also experienced by Bode and Gore (2016) on their feed water heater study. A very high TTD could indicate a poor heat transfer of steam to the feed water in a heater. There are many possible causes of this phenomena according to EPRI (2015) and the most common causes are increased heat transfer load, leakage at partition plate inside the heater, operating level too high, vents closed/degraded, flashing in drain cooler and among others. In the case of units and two, it could mean that most of the bled (extracted) steam has an improper transfer of heat due to the peculiar condition of a frequent opening of its LPH6 emergency drain to the condenser instead back to LPH7 making it off-design. The heat energy content in that steam was dumped back and absorbed by the condenser. As a result, the TTD was increased. This is not a normal and efficient operation of a feed water heater and it may deteriorate the internal parts of the heater that could cause a breakdown of the equipment.

The second performance indicator to check is the DCA for the closed-type feed water heaters. The results in Table 3 show that the HPH1on all units has a negative value of DCA. This may indicate that this heater has sub-cooled the drain water temperature below than its inlet feed water temperature. This is not ideal since the drain water temperature is assumed to be close to the inlet-feed-water temperature. However, this can be considered acceptable since the values are close to the design temperature at only a few degrees. The rest of the closed-type heaters (HPH2 to LPH7) had DCA results higher than that of the normal design. While LPH6 in units one and two had the highest DCA of around 29.55°C and 28.4°C, respectively. These results were plotted in Figure 3 for an elaborated graphical manner.

Table 3. Drain cooler approach (DCA) results for each year

Heater	Drain Cooler Approach (DCA) (°C)			
	Design	Unit 1	Unit 2	Unit 3
HPH1	5	-0.37	-2.27	-2.5
HPH2	8.2	2.08	14.68	9.53
LPH4	5	12.03	13.29	11.42
LPH5	5	26.69	25.38	22.23
LPH6	5	29.55	28.4	19.86
LPH7		15.53	15.98	20.51

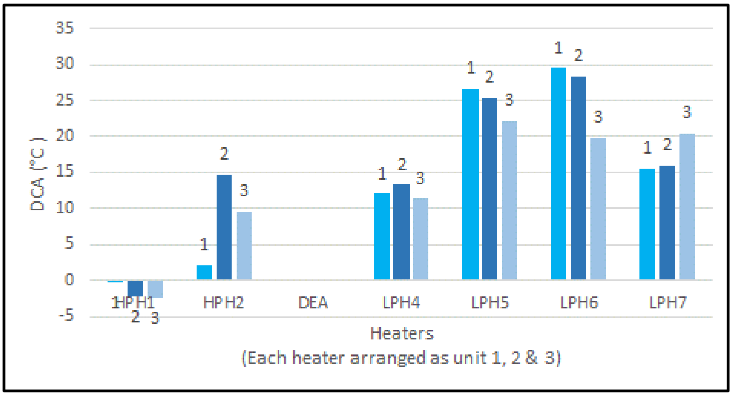

Figure 3. Graphical presentation on DCA results of each heater

An improper level of DCA may indicate an abno rmal operating condition in the drain cooler zoned of a heater according to the importance of proper level control of feed water heaters (Yokell *et al.*, 2014). The high results of DCA in a heater mean a potential for flashing in the drain zone (sub-cooling zone) in a heater. As mentioned previously, DCA is related to the heater water level. The high results of DCA may indicate that the heater drain has high temperature and may cause a steaming or flashing formation on this area provided that the level may not be properly adjusted to its correct range. It is important to remember that this zone is specifically designed for a water-to-water closed exchanger, thus, any admission of flashed steam in this zone can result to potential damage. According to study, flashing phenomenon is typically more problematic in low-pressure heaters than high-pressure heaters, although both are susceptible (Yokell *et al.*, 2014). Correct water level also influences the DCA and flashing on the heater. A heater manufacturer's recommendation must be followed throughout the operation. In case the heater is exposed to too high water level, emergency drains allow the passage of water damping it to the condenser to prevent water ingress to the turbine.

Going back to the TTD results in last stage heaters of units one and two, the DCA for the LPH6 shows high results and may indicate that the frequent opening of emergency drain valves is a result of too high water level because of flashing.

The last performance indicators to monitor in a feed water heater is the TR across the heater. Table 4 shows the average summarized results of the five tests during the experiment and a graphical presentation from Figure 4 below.

It showed a normal rise on the last stage heater of unit three but a poor TR on the other two units. If we recall the TTD results previously, unit one had the highest TTD and as expected to have the lowest TR of only an increase of 2.95°C only. It clearly shows that the first unit last stage heater-LPH7, as well as to the second unit, has problems on the operation of its heaters and experiencing an off-design condition even a maximum load output of 135MW where it was designed to have low TTD and high TR according to heat balance. The rest of the heaters (HPH1 to LPH6) had TR result values near its design. Too much TR could also stress out internal parts and may lead to damage the components. The highest TR results were found in unit two (HPH2) where it reached 46.94°C. This number exceeds its design value. In this condition, an exceeding TR value can be considerably normal provided that the heater feed water temperature on its outlet is just below its maximum allowable temperature by the manufacturer. In the HPH2 case, it has a

Table 4. Temperature Rise (TR) results of each heater

Heater	Temperature Rise (TR) (°C)			
	Design	Unit 1	Unit 2	Unit 3
HPH1	22.2	20.46	21.97	22.49
HPH2	41.7	36.54	46.94	39.86
DEA	38.6	38.99	38.72	38.23
LPH4	29	28.95	28.09	27.74
LPH5	34.3	39.45	37.43	33.26
LPH6	22.4	34.89	34.59	24.1
LPH7	23.2	2.95	6.66	22.78

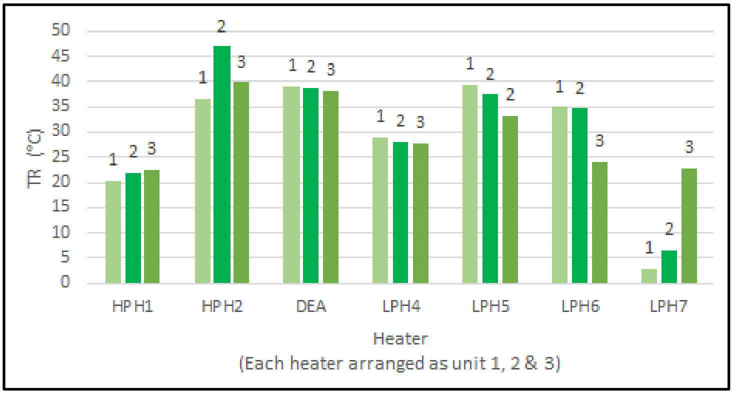

Figure 4. Graphical presentation on TR results of each heater

maximum allowed design of 365°C on shell side and 265°C on the tube side based from specifications. Deaerator-type feed water heater TR results showed normal rise in all units. A proper allowable TR based from specifications should be followed as prescribed by the heater's manufacturer.

3.2 Comparative Analysis

The results of the tests on each unit's performance indicators clearly showed that the most performance of the heater is not within the design value while some are worse in terms of their TTD and DCA. The TR results were almost near the design value except that on last stage heaters. If we gather the results, all the unit's high-pressure heaters, both HPH1 & HPH2, performed efficiently while low-pressure heaters were less efficient with problems observed on last stage heater-LPH7 in the two units. The first and second units clearly showed off-design behaviors in their last stage heaters which may severely affect their overall cycle efficiency and could result in deterioration of the particular heater. The combination of high TTD and DCA while low TR on a heater can be a problem (EPRI, 2015). Bode and Gore (2016) stated that this problem is mainly caused by (1) tube fouling which results to reduction in heat transfer coefficient; (2) excessive tube plugging resulting in reduced heat transfer; (3) air binding at shell side that leads to the reduction of heat transfer area; (4) turbine extraction steam flow failure; and (5) internal or external leakage.

In the case of the 3x135MW, the LPH6 and LPH7 might already have some damages because of the performance results, and this may be due to any of the aforementioned possible causes. Units one and two showed the leading TTD in most heaters while Unit 3 had most of the lowest TTD. As mentioned from the previous discussions, low TTD heaters are performing better due to less heat loss.

The correct water level on the heater can also influence the performance of the heater. A discussion on the significance of heater drain water level was elaborated by Buckshumiyanm and Sabarish (2017), in which they explained that if a feed water heater water level is too high, it might cause (1) water induction to the turbine through the extraction steam piping; (2) reduction in overall thermal efficiency; (3) decreased turbine efficiency; and (4) damping of hot water drains to the condenser. If a feed water heater water level is too low, it might cause (1) equipment damage due to the leaking of steam to the drain zone; (2) baffles, tube, partition damage due to impingement and high flow induced vibration; and (3) overall thermal efficiency decreased due to steam blowing through drains or leaks points.

The DCA results showed that unit one had the most number of the heaters with high DCA while unit three had the least. However, it is also important to note that the low-pressure heaters have high TTD in all units. This is a possible flashing occurrence on the drain zone part of a heater in the low-pressure side. This could severely affect the heater drain zone parts if continuously run at a very long period.

The last performance indicator, TR, in units one and two, had shown that the last stage heater might be experiencing poor heat transfer due to a very low rise in temperature of the feed water. This could be due to the frequent opening of the LPH6 emergency drain valve back to the condenser without utilizing the heat that was supposed to be used by the LPH7.

The results of the test showed that the unit three 135MW had the most efficient feed water heater system and its performance indications were within tolerable limits. This also confirms that this unit had the high overall cycle efficiency due to the feed water heater regenerative system performance. However, the overall cycle efficiency of a unit cannot still be confirmed until performance test of each sub-systems performance is measured. Nonetheless, the performance results on the feed water heaters are significant factors in the overall cycle efficiency.

4. Conclusion and Recommendation

The test results showed that the high-pressure heaters (HPH) had remarkable results than the low-pressure heaters (LPH). The heaters' performances in TTD, DCA, and TR in all units were near its design limits. There were also no off-design behaviors observed during the experimental test of their performances.

The LPH6 and LPH7, last stage heater, mostly encountered the problem on off-design especially that of units one and two. The last stage heaters in the said units had a poor performance and could indicate that the heater might have already been damaged. The LPH6 had a problem of an increased rise in water level that results in the frequent opening of its emergency drain valve. There is an increased chance of a possibility of flashing in the drain cooler zone for these heaters.

Unit three at 135MW had the better performance of the heaters and could contribute a big factor to a high overall cycle efficiency. While its last stage heater had high TTD and DCA, the rest of its heaters were operating normally.

The following can be recommended for the further study of the paper. First, conduct periodic maintenance to be recorded in the engine log sheet as indicated in the manual process of operations or commissioning, in particular, in the last stage heaters as observed. Proper water heater maintenance will extend life expectancy of any system. Second, proper preventive maintenance or (PMS) is very important, especially if there is worst tube leak in shell and tube heater which makes low performance of heater. Third, a feed water heater control maybe introduced for performance improvement and improved plant heat rate. Fourth, inadequate liquid level control can lead to tube failure or heater drain degradation. Fifth, take note of the importance of proper level control of feed water heaters. Sixth, proper inspection and investigation on the LPH6 and last stage heater should be made during the outage period to check if there are problems found at the internals of the heater. Seventh, conduct more routine performance test quarterly or annually to monitor the degradation of the heater performance or improvement. Lastly, calculation of the heater's efficiency and overall cycle efficiency of a unit should be included.

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