Failure analysis of pipeline elbow connecting high pressure heater to deaerator in a steam power plant

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Abstract. The coal-based steam power plant accounts for the largest electricity generation in Indonesia. Disruption in operation mostly caused by a failure of a component of the system and considered a serious problem and must be prevented. Failure can be originated from operations as well as the design. In the present work, a root cause study was performed on failure elbow in the steam line from the high-pressure heater (HPH) to the deaerator. The failure occurred only after 5 years of operation. The analysis was started with a visual examination, material verification, microstructural investigation, thickness measurement, and computational modelling. The analysis and simulation study showed that the failure of the elbow caused by two-phase flow where steam quality was compromised. The recommendation was to examine the HPH and to find possible leaks of the waterside to the steam side in the HPH system.

Keywords: failure analysis, elbow, pipe line, deaerator, CFD, multiphase flow, erosion

1. Introduction
This increased demand for electricity is in line with the increasing rate of economic growth, and the rapid development of the industrial sector. The power plant has several important components in generating electricity. Starting from boilers, turbines, condensers, pumps, feedwater heaters, and deaerators [2]. In operation, it is often that failures occur on the components. This failure can be defined as the inability of a material/component to function properly for any reason.

Failures occur in the power plant that operates at high temperatures, high pressures, and abrasive environments allow for variations in the failure mechanisms, i.e., overheating [3], pitting corrosion [4], creep [5], erosion [6], corrosion erosion [7], thermal fatigue [8], corrosion fatigue [9] and stress corrosion cracking [10]. One common example of a power plant failure that is commonly observed is an elbow of tube and pipe. The failure can be in the form of holes that cause leakage or just thinning.

Fluid velocity effect to the rate of corrosion-erosion. Corrosion is dominant if the fluid velocity is very slow, whereas if the fluid velocity is very high then erosion will be more dominant. This is due to the time of fluid contact with the material. While low fluid velocity, the contact time between fluid and material will be longer, so the time needed for the corrosion process will be longer [11].
In the present study, the pipe elbow under experienced a failure in the form of a hole is presented. Figure 1 shows the failed elbow taken from a boiler for producing 100 MW peak power. This elbow showed a leak in the extrados and some erosion and corrosion from the inside. The elbow is connecting a pipeline of drain steam from the high-pressure heater (HPH) to the deaerator. Table 1 is operation design, and basic materials information is given in the drawing and manual of the power plant.

2. Methods and materials

2.1 Laboratory analysis
The laboratory analysis started with sample preparation and specimen preparation. The thickness of the samples measured and map with the ultrasonic grid by grid. The sample was cut to prepare OES sample and microstructural study. The sample was ground and polished before the etching process for revealing the microstructure. Olympus optical microscope were used to examine the
microstructure close and far from the leaks. Two samples were prepared, i.e., close to the leak hole and far from it.

2.2 Computational fluid dynamics

CFD simulation of transient multiphase elbow pipe (HPH to Deaerator) using a 100000 mesh hexahedral map as shown in Figure 2. Then proceed with the simulation in Fluent 16.2. In Fluent 16.2, we use multiphase model VOF (Volume of Fluid), standard k-epsilon, transient, and gravity 9.81 m s\(^{-2}\). In multiphase itself, the primary phase is steam and the secondary phase is liquid water. The input boundary conditions are inlet velocity 34 m s\(^{-1}\), gauge pressure 1340000 Pa (1.34 MPa).

![Figure 2. Pipe mesh model for simulation CFD multiphase](image)

The solution method using simple, pressure spatial discretization presto, and volume fraction is geo reconstruct. Then the residual scales are inputted to determine convergence are momentum, k, epsilon, and velocity x, y, z 10\(^{-4}\). After completing the setup, the initialization process uses hybrid initialization and run calculations with time step size 0.01 s, number of time steps 100, Max iteration/Time step 50.

3. Result and discussion

3.1 Elbow materials

Testing the chemical composition contained in the elbow pipe material is carried out by the spectrometry testing method. This test is done by cutting a portion of the material to be used as a test sample. The sample is then tested using a spectrometer and compared with the chemical composition according to the ASTM A216 grade WCB standard (Wrought Carbon grade B) as shown in Table 2.

After comparing with the standard chemical composition, namely ASTM A216, both specimens 1 and 2 have a chemical composition according to ASTM A216. From spectrometry testing, it was found that several chemical compositions make up the material, one of which is the carbon (C) content of 0.23 in specimen 1 and 0.223 in specimen 2. This shows that the elbow pipe is a type of low carbon steel (cast) material. The spectrometer results showed a slight difference in chemical composition, but overall, it was still considered in accordance with ASTM A216 [11]. These results indicate the effect of corrosion elements, which make the elbow pipe fail very little.
3.2 Visual observation
Visual observations were made on the outer and inner surface of the elbow pipe as shown in Figure 3. From visual observation, the reduction in thickness that occurs in the elbow pipe can be caused by erosion that occurs on the inner surface of the elbow pipe due to the two-phase flow of the steam drain which still contains water. Erosion that occurs continuously causes the elbow pipe to leak.

![Figure 3. Hole on the elbow, b) Discoloration, c) there are holes in the inner surface of the elbow pipe, and d) The area around the hole on the inner surface of the pipe elbow](image)

This is evidenced by the existence of a hole in the area around the outer corner of the pipe. Color changes on the inner surface of the elbow pipe indicate an indication of a corrosion process associated with the element oxygen (O₂) from water as a corrosive medium or electrolyte and cause the elbow pipe to fail. The brick red color on the inner surface of the elbow pipe is a corrosion product of Fe₂O₃ or hematite. At the same time, the brownish-black color is formed due to Fe in the working environment contacting the inner surface of the elbow pipe, which is a corrosion product of Fe₃O₄ or magnetite. Hematite and magnetite are formed due to Fe in the work environment in direct contact with water continuously. The brighter the color that appears on the inner surface of the elbow pipe, the greater the thickness reduction that occurs. This can be
seen from the indentation on the inner surface of the pipe. Where when there is a change in color, the basin begins to appear and will enlarge when it is at the brightest color (yellowish white).

In theory, the location of the orifice, which is not in the center of the outer corner of the pipe makes this failure a rare type of failure. This can be caused by a two-phase flow (steam and water) with the droplet volume of water divided into two at each edge (many droplets to the edges). The erosion and color changes that occur indicate an erosion process accompanied by corrosion due to two-phase flow (steam and water) [7]. So that the erosion process that occurs is included in the material failure category due to liquid droplet impingement (LDI) [7]. The occurrence of erosion to make the elbow pipe leak indicates that the elbow pipe is no longer safe to use because it will result in losses in terms of decreased efficiency and make the work process ineffective.

3.3 Wall thickness test
After the visual observation was made, the wall thickness test was then carried out to determine the thickness profile of the specimen, especially on the part that experienced a color change. The measurement was done by an Ultrasonic Test (UT) thickness. This test is done by making a line on the test plane every 2 cm in a vertical and horizontal direction. So that there is an intersection point from the meeting of the two lines. At each point, a wall thickness test was carried out. There are 13 vertical lines and 21 horizontal lines, so the number of points tested is 273 points. The grid system is shown in Figure 4 for clarity. The highest result is at point -10M with a thickness value of 4.94 mm. The smallest results are at points 12J and 13J with a thickness value of 0.00 mm (right on the hole). In addition, the test results obtained an extreme difference in thickness. One example is the difference in thickness from point 14B to point 14C with a thickness value from 4.31 mm to 1.41 mm (a difference of 2.9 mm). These all numerical value is plotted in the heat map style presented in Figure 4.

Figure 4. Plot of wall thickness from grid system (distance between the points is 2 cm). Colour show the level of the wall thickness in which red indicates thin wall, and yellow and green means a thick wall

From Figure 4 it can be seen the difference in color at each point. The difference in color explains the amount of thickness. Where the yellow color shows the greatest thickness, the green color shows the thickness is medium, the red color shows the smallest thickness, the degradation
between yellow-green indicates the thickness between large to medium, and green-red color degradation shows the thickness between medium to small.

![Image of cross-section view indicating level of thinning](image)

**Figure 5.** Cross-section view indicate level of thinning: a) Piece A - A, b) Piece B - B, c) Piece C - C, d) Piece D - D, e) Cut E - E

Depletion of different thicknesses and the location of the smallest thickness (red color) not in the middle indicates that the shape of the flow that hits the wall is a two-phase flow (steam and water) with the droplet volume of water divided into two at each edge (many droplets to the edges). And the difference in thickness that is classified as extreme (difference in height) indicates that failure is more predominantly caused by erosion [11]. Macroscopic thickness measurements using calipers are carried out at the top (steam drain in), middle and bottom (steam drain out) diameters, as shown in Figure 5.

From the thickness measurement results, the comparison between the initial dimensions and the dimensions after failure is obtained. Where the extreme dimensional differences occur in the diameter of the center (Section B - B, Cut C - C, and Section D - D). One example is in pieces B - B, at points 5B and 6B to be precise. Where from the measurement results, it can produce quite extreme differences in thickness, namely from a thickness of 4.45 mm to 0.93 mm.

This difference in thickness shows that the shape of the flow hitting the wall is a two-phase flow (steam and water) where droplets from water hit the inner surface of the pipe so that deformation occurs by droplets from the water to the surface in the pipe. The compressive force from the droplets to the inner surface of the pipe continuously causes the surface to be eroded until holes are formed [7,11]. And the difference in thickness that is classified as extreme (difference in height) indicates that failure is more dominant due to erosion [11].

### 3.4 Metallographic testing

Microstructure analysis was carried out to determine changes in the microstructure of a test specimen taken from the section on the ASTM A216 elbow pipe with Grade WCA due to its working environment. ASTM A216 with WCA Grade is a low carbon steel (cast) group with a maximum carbon composition of 0.3%. The inner surface of the elbow pipe is in direct contact with the vapor from the HPH in the temperature range 194.4 - 197.9 °C, and the outer surface of the elbow pipe is insulated. The samples used in microstructure testing are specimens shown in Figure 6.
With the chemical composition of the specimens that are ASTM A216 standard, the elbow pipe specimens consisted of ferrite and pearlite and are classified as low carbon steel (cast). It can be seen from Figure 7 that there is no significant differences appear in both microstructures for close or far from the leak. The absence of phase differences in specimens indicates that the specimens did not undergo any treatment such as tensile or compression, which resulted in a macroscopic change of shape so that the microstructure also changed. This is consistent with the theory that the failure is due to erosion-corrosion with no change in the microstructure [7].

3.5 CFD multiphase
The velocity contour of the mixture between steam and liquid water in Figure 8 shows the separation point which makes the velocity contour in the downstream elbow narrow and backflow occurs. Then in the elbow area itself there is a collision on the elbow wall which makes the velocity in the elbow wall area lower [12]. The pressure contour of mixture between steam and water liquid when it hit the elbow is large in the elbow wall area which can cause cracks in that area. Then before and after entering the elbow area, it can be seen that the pressure contour is from yellow to green which means the elbow makes the pressure decrease which can result in energy losses [12]. The results of this volume fraction describe the state of each phase in each area in the multiphase CFD simulation. It can be seen that the contour of the volume fraction between steam and water with high velocity input makes the steam and liquid water separate and spread in various areas after passing through the elbow. Steam seems to be more spread in various areas, while liquid water is more dominant in that flow [12].
3.6 Discussion on causes and mechanisms of failure

Having conducting sample analysis, we summarize that the cause of the failure that occurred in the elbow pipe from high-pressure heater (HPH) to the deaerator was erosion-corrosion of the type of liquid droplet impingement (LDI) by two-phase flow (steam and water) [7]. This is evidenced by visual observations with the results of significant changes in thickness due to the effect of erosion by two-phase flow (steam and water). From the wall thickness test and measurement of the thickness, the results are the smallest thickness on edge caused by the volume of the droplet, which is larger on edge. From spectrometry and metallography testing, the results showed no changes in chemical composition and microstructure. This is consistent with the existing theory that failure due to erosion corrosion does not cause changes in the chemical composition and microstructure [7].

The erosion involving collision of liquid droplets that create impulsive and destructive pressure. The process starts from the incubation stage, where at this stage, the surface of the material does not change because the material only undergoes elastic deformation. At the acceleration stage, erosion begins to occur on the surface due to the stress concentration exceeding the material fatigue limit, and the depletion rate in the material walls increases rapidly. Then, the level of thinning in the material walls reaches a maximum value (maximum level of erosion). When the surface of the material becomes rough by plastic deformation, the level of thinning in the material walls decreases due to the bearing effect by the presence of a liquid coating over the rough surface (deceleration stage). After that, the level of wall depletion approaches the final stage, where the erosion rate becomes constant with time [11]. This happened continuously with a flow rate of 33.42 m s\(^{-1}\), 35.38 m s\(^{-1}\) so that a hole occurred only 5 years from the time the pipe was used.

Figure 8. a) Contour velocity, b) Contour pressure, and c) Contour volume fraction on the elbow
4. Conclusion
Failure analysis of pipeline elbow experience early failure has been conducted. The results of the wall thickness test show a significant reduction in thickness at the extrados of the pipe elbow close to the leak. The chemical composition of the steel elbow was following ASTM A216. Metallographic testing showed that microstructure is typical ferrite and pearlite with no degradation. It was combining the laboratory analysis and CFD modelling to explain that the erosion process is a liquid droplet impingement (LDI). The failure mechanism starts from a two-phase flow, namely steam, and water, in the form of droplets flowing and hitting the inner surface of the elbow pipe and causing erosion. This process happened continuously with a flow rate of 33.42 m s⁻¹-35.38 m s⁻¹ so that a hole occurred only 5 years from the time the pipe was used.

5. References
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