RESWARA: Journal of Engineering Research
2026, Vol. 4, No. 3, pp. 613-632
E-ISSN: 3025-9444

CFD-DPM Numerical Investigation of Erosion-Corrosion in Elbow 180° Evaporator Tube HRSG: Effect of Weld Defect and Feedwater TDS on Flow-Accelerated Corrosion

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Abstract: *Heat Recovery Steam Generator (HRSG) evaporator tubes are susceptible to premature failure due to the combined effects of flow-accelerated corrosion (FAC) and erosion under high-temperature two-phase flow conditions. Understanding the interaction between hydrodynamic behavior, weld defects, and feedwater quality is essential for improving HRSG reliability. This study aims to investigate the effect of weld defects and feedwater total dissolved solids (TDS) on erosion-corrosion behavior in a 180° evaporator tube elbow of an HRSG system. A numerical case study was conducted using Computational Fluid Dynamics coupled with the Discrete Phase Model (CFD-DPM) implemented in ANSYS Fluent. Two tube configurations, namely a weld-defective tube and a defect-free tube, were simulated under actual operating conditions, while TDS concentration was represented by discrete solid particles. The results indicate that the 180° elbow geometry generates high turbulence and particle impingement, leading to localized erosion at the downstream outer curvature of the elbow. Under actual operating conditions with an average feedwater TDS of 1,873 ppm, the predicted erosion rate reached 1.83 mm/year in the weld-defective condition, compared with 0.55 mm/year in the defect-free condition, indicating more than a threefold increase in material degradation. Higher TDS levels further accelerated the erosion process. The predicted erosion hotspot corresponded closely with the actual leakage location observed in the field. These findings demonstrate that the synergistic interaction of FAC, particle-induced erosion, elevated TDS, and weld defects is the primary cause of repeated evaporator tube failures in the investigated HRSG system.*

Article history:
Received: 17 June 2026
Revised: 22 July 2026
Accepted: 24 July 2026
Published: 26 July 2026

Keywords:
flow-accelerated corrosion, erosion-corrosion, computational fluid dynamics, heat recovery steam generator, weld defect

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How to cite: Rahmadani, R., & Guntur, H. L. (2026). CFD-DPM Numerical Investigation of Erosion-Corrosion in Elbow 180° Evaporator Tube HRSG: Effect of Weld Defect and Feedwater TDS on Flow-Accelerated Corrosion. *RESWARA: Journal of Engineering Research*, *4*(3), 613–632. https://doi.org/10.70716/reswara.v4i3.619

INTRODUCTION

Heat Recovery Steam Generator (HRSG) is a key component in a combined cycle power generation system that utilizes gas turbine exhaust heat to generate steam and improve the energy efficiency of the plant (Eriksen, 2017). The reliability of HRSG is a very important aspect because failures in these components not only reduce operational efficiency, but can also lead to production stoppages, increased maintenance costs, and significant loss of production opportunities (Dooley & Anderson, 2019). In heavy oil production facilities, HRSG also acts as a steam supplier for the Enhanced Oil Recovery (EOR) process, so that disruptions to the HRSG system can have a direct impact on the sustainability of oil production. Recent industrial failure analyses also confirm that degradation of steam generator systems remains a persistent operational risk in thermal facilities (Al Fazari & Aulaqi, 2024; Ma et al., 2025; Manzoor & Saleem, 2024).

Although HRSG technology has developed rapidly, failures in piping systems are still one of the main problems affecting the reliability of its operations. Various studies show that damage to boiler pipes and HRSG is generally caused by corrosion, erosion, fatigue, and creep mechanisms. Among these mechanisms, degradation triggered by the interaction between fluid flow, water chemical conditions, and material characteristics is one of the dominant causes of piping component failure

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(Dooley & Anderson, 2019; A. O. Ibrahim et al., 2025). In fact, uncontrolled chemical quality of water is reported to be a contributing factor to most HRSG failures through corrosion mechanisms, including Flow Accelerated Corrosion (FAC) which is widely found in high-pressure piping systems (Sánchez-Sánchez et al., 2024). Recent predictive frameworks further emphasize that FAC behavior is strongly influenced by coupled hydrodynamics and water chemistry, requiring mechanistic and CFD-based modeling approaches for accurate prediction (Fujiwara & Yoneda, 2025; Li et al., 2025; Sampath et al., 2025).

FAC is a material degradation phenomenon that occurs due to the interaction between electrochemical reactions and flow hydrodynamic conditions that cause the protective oxide layer on the metal surface to continue to dissolve and erode. This phenomenon generally occurs in locations that experience high turbulence, changes in flow direction, as well as geometric disturbances that increase mass displacement near the surface of the pipe wall (Khunphakdee & Chalermsinsuwan, 2023; Song et al., 2025). Recent advances in CFD-DEM and coupled numerical approaches demonstrate that erosion and flow-induced degradation can now be resolved with higher fidelity, including particle-fluid interaction and turbulent flow structures (Mu et al., 2025; Rahimi-Larki et al., 2024; Xu et al., 2025). Microstructural research conducted by (Hu et al., 2023) showed that an increase in flow rate significantly accelerates the rate of FAC in carbon steel through increased release of protective oxide layers. In addition, poor feedwater quality, dissolved solids content, inadequate pH control, and the presence of certain contaminants can further accelerate the material degradation process in the HRSG system (Boyd, 2020; A. O. Ibrahim et al., 2025).

In addition to FAC, changes in flow direction in components such as elbows are also known to increase the risk of erosion due to the formation of local turbulence and the concentration of kinetic energy particles in certain areas. Numerical studies conducted (Rahman et al., 2022) It shows that the maximum erosion rate at elbow 180° occurs in areas near the outlet or downstream side, and increases significantly as the flow speed increases. Similar results were also reported by (Dai et al., 2023; Mahmoudi & Shiri, 2025a; Zhang et al., 2020; Zhao et al., 2023), which indicates that flow characteristics, particle size, impact intensity, and elbow geometry are the main factors determining the degree of erosion in the piping system. On the other hand, the condition of the weld joint can also affect the flow distribution due to the presence of weld beads or geometric imperfections that have the potential to trigger voltage concentrations or local turbulence (Hussin & Che Lah, 2020). This factor becomes even more critical when combined with high temperature and pressure operating conditions that can accelerate the degradation of the mechanical properties of welding materials and heat affected zones (Rezaeian et al., 2020).

At the generating facility in support of the EOR Facility, repeated leakage problems were found in the 180° elbow weld connection of the HRSG evaporator. During the 2021-2025 period, six leak incidents were recorded at the same location, namely on the downstream side of the elbow evaporator. These conditions cause unplanned shutdowns, increased repair costs, loss of steam production, and potentially cause environmental impacts due to the release of suspended solids from the feedwater system. Field findings also show the accumulation of solid crystals in the area around the leak which indicates the possible involvement of water quality factors and corrosion-erosion phenomena in the damage mechanism that occurred. Therefore, this phenomenon of repeated leaks is an important technical issue to be investigated in depth.

Various previous studies have examined the phenomenon of FAC, erosion on the elbow, the influence of water quality, and flow characteristics using experimental approaches and numerical simulations (Khunphakdee & Chalermsinsuwan, 2023; Rahman et al., 2022; Song et al., 2025; Zhao et al., 2023). However, most of these studies have focused on modeling the mechanism of damage or evaluating individual parameters under both laboratory and simulation conditions. Research that integrates field failure evidence, actual operation data, flow characteristics, welding conditions, and potential FAC mechanisms in the case of repeated leakage of the HRSG evaporator elbow is still

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relatively limited. These limitations lead to a lack of a comprehensive understanding of the dominant factors that trigger repeated failures of these components under real operating conditions.

Based on the research gap, this study was conducted to answer the question of the main factors that cause repeated leaks in the 180° elbow weld joints of the HRSG evaporator as well as alternative mitigation measures that can be applied to prevent similar failures in the future. Specifically, the study aims to identify the dominant fault mechanisms that cause leaks and formulate technical recommendations to improve the reliability of HRSG operations. The contribution of this research lies in providing empirical evidence based on industrial cases regarding the relationship between actual operating conditions, flow characteristics, feedwater quality, and material degradation in HRSG elbow evaporators, so as to enrich the understanding of failure mechanisms in power generation systems and become a reference for the development of more effective inspection and maintenance strategies.

RESEARCH METHODS

This study uses a case study-based quantitative approach with numerical simulation support to evaluate the failure mechanism in the Heat Recovery Steam Generator (HRSG) tube evaporator. The main focus of the study is to identify the influence of operating conditions, feedwater quality, and fluid flow characteristics on material degradation that leads to pipe leaks. This approach was chosen because it is able to integrate actual field data with numerical modeling-based analysis so as to provide a comprehensive picture of the failure phenomenon that occurs.

The object of the research is a horizontal tube–horizontal gas flow type HRSG evaporator system with a configuration of four evaporator modules arranged vertically. Each module has one inlet and one outlet and receives a flow of feedwater from the economizer before being distributed into the evaporator tube. The analysis was focused on the area of the evaporator tube, especially on the 180° elbow and weld joint, which based on field findings indicated thinning and leakage.

The research data was obtained from two main sources, namely the operational data of the HRSG system and the data from material testing and feed water quality. Operational data includes pressure, temperature, flow rate, phase fraction, as well as two-phase flow conditions in the system. Meanwhile, feedwater quality data includes chemical parameters such as pH, total dissolved solids (TDS), conductivity, ion content (Cl^-, Na^+, Ca^{2+}), and dissolved iron content. In addition, pipe thickness data from inspections in 2021 and 2023 were used to evaluate the actual rate of material degradation in the field.

Data collection is carried out through documentation of operation reports, results of water analysis laboratories, as well as material thickness inspection reports and radiographs from related parties. All of the data is then used as input for the analysis of operating conditions and as a basis for validation of the results of the numerical simulation carried out.

The analysis stages in this study are carried out in stages and integrated with each other. In the initial stage, an evaluation of the operating conditions and feedwater characteristics is carried out to identify the system boundary conditions which include thermohydraulic and chemical parameters of the working fluid. This analysis aims to determine whether operating conditions are within safe limits or have the potential to cause material degradation.

Furthermore, a material degradation analysis was carried out based on pipe thickness inspection data and field observation results. At this stage, the rate of depletion of the pipe wall is calculated based on a comparison of thickness data of two different time periods, then correlated with the location of the damage to identify the most critical areas. The results of the radiographic inspection are also used to confirm the presence of internal defects such as local thinning or internal concavity in the weld joint.

The next stage is numerical analysis using Computational Fluid Dynamics (CFD) to understand the fluid flow behavior within the geometry of the evaporator tube. The modeling was carried out by considering the two-phase flow conditions (water-steam) as well as the influence of dissolved solid

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particles modeled using the discrete phase model (DPM). The simulation included two main scenarios, namely weld-defected and weld-defect-free pipe conditions, to evaluate the influence of geometric imperfections on flow characteristics, pressure distribution, velocity, turbulent kinetic energy, and erosion patterns.

The simulation geometry is constructed based on the actual condition of the evaporator pipe by considering the straight pipe and 180° elbow segments as critical locations of flow direction changes. Once the geometry is formed, a meshing process is carried out using tetrahedral elements with adaptive settings to ensure a balance between yield accuracy and computational efficiency. The flow model was then solved using a pressure-based solver with the k-omega SST turbulence model and a multiphase mixture approach to represent the interaction between the liquid and steam phases.

In the final stage, the simulation results are analyzed qualitatively and quantitatively to see the distribution of flow parameters as well as erosion patterns on the pipe walls. The simulation results were then compared with field data, specifically material depletion patterns, to validate the failure mechanism that occurred in the HRSG evaporator system. With this approach, the research not only describes the actual state of the system, but also explains the underlying physical mechanisms for failure more comprehensively.

RESULTS AND DISCUSSION

Analysis of Results and Discussion of *Feed Water Properties*

The quality of feed water is the most critical parameter that determines the reliability of HRSG and the service life of its components. The chemical composition of feed water directly affects the corrosion rate, the mechanism of deposit formation, and the integrity of the tubes and pipes commonly used in economiczers and evaporators. In contrast to boilers operating at high pressures where chemical controls are usually stricter, HRSG systems that operate with suboptimal feed water often undergo accelerated degradation due to a combination of various corrosion factors.

TDS, Chloride and Sodium Ions

Total dissolved solids (TDS), chloride (Cl^-), and sodium (Na^+) are the main factors that accelerate corrosion in the HRSG feed water system. Sodium ions, which are often carried along with chlorides, undergo a hydrolysis cycle that produces sodium hydroxide (NaOH), which attacks the iron oxide protective layer and triggers or accelerates the corrosion process (M. F. B. Ibrahim, 2013). High TDS concentrations signal poor water treatment efficiency and increased conductivity, which is directly correlated with aggressive water chemistry that accelerates common and local corrosion mechanisms. The measured feed water TDS concentration of 1,874-2,200 mg/L far exceeded the maximum recommended limit of about 100 mg/L in accordance with API 534 and EPRI guidelines, which is a deviation from the standard.

Ph level and effect of dissolved oxygen on FAC

FAC is recognized as the main failure mechanism in HRSG feed water system, mainly affecting carbon steel tubes in economicizers and evaporators. The pathogenesis of FAC depends primarily on pH and dissolved oxygen concentrations, not just on flow velocity as historically assumed. The protective layer of magnetite (Fe_3O_4) on the surface of carbon steel exhibits stability and protective characteristics only within a certain window of pH and oxygen (Daniels, 2012):

- Under reductive (oxygen-free) conditions with low pH (below ~8.8-9.0), magnetite dissolves, so that bare steel is exposed to corrosion attack.

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- At pH 9.1-9.8 for ferrous systems with adequate oxygen levels (5-20 ppb in ferrous systems, 30-150 ppb in oxygenated systems), a tightly protective oxide layer is formed, which suppresses flow-accelerated corrosion (FAC).

The measured pH range of 8.51-8.95 is slightly below the optimal protective range of 8.8-9.2, especially considering the high ion content and potential for oxygen entry in the economical area. The high concentration of TDS indicates that the water treatment is not yet effective, thus increasing the conductivity of the water. This higher conductivity is directly correlated with aggressive water chemistry, which accelerates corrosion reactions on steel surfaces by increasing the transport rate of corrosive ions such as Cl^- and Na^+. This condition causes the protective magnetite layer to become less stable and boosts the occurrence of adverse corrosion in the HRSG system, especially in economical areas that are susceptible to oxygen entry (Buecker, 2011).

Iron Corrosion Products and FAC Indicators

High iron concentrations in feed water (measured 0.02-2.22 mg/L) directly indicate active corrosion and ongoing iron corrosion (FAC). Iron corrosion products, especially in the form of particles, stick to the surface of the tube and trigger corrosion under the deposit, which further accelerates material loss. Iron monitoring serves as a real-time diagnostic indicator for the severity of FAC and the effectiveness of chemical control programs.

Hardness and Crust Formation

Calcium and magnesium salts collectively measured as hardness (measured 9.59-45.81 mg/L as $CaCO_3$) precipitate and form hard crust deposits on the surface of high-pressure tubes. These deposits reduce heat transfer, accelerate thermal oxidation and cracking, and create local corrosion points through the effects of gap and differential aeration. Measured hardness values exceed the recommended limit of <1 mg/L up to one to two orders of magnitude (Kraetsch, 2024).

Hydrodynamic and Erosion Analysis on HRSG Tube Evaporator

Fluid Pressure Distribution

The simulation results show that the pressure distribution in the evaporator tube with or without weld defects has a relatively similar pattern as shown in Figure 1. The maximum pressure is localized on the outer side of the elbow curvature with a value of approximately 5.62×10^6 Pa, while the minimum pressure is on the inner side of the curvature. The pressure difference indicates the formation of a pressure gradient due to centrifugal force when a two-phase fluid experiences a change in flow direction of 180°. The fluid is pushed towards the outer side of the bend thus increasing the local pressure, while the inner side experiences a decrease in pressure.

After passing the elbow, the pressure distribution returns to more uniform although there is still a pressure drop due to wall friction and secondary turbulence. These findings suggest that elbow geometry is the dominant factor controlling the pressure distribution in the system. In contrast, the effect of weld defects on macroscopic pressure distribution is relatively small because the dimensions are much smaller than the diameter of the tube, so the flow disturbances formed are local (Hussin & Che Lah, 2020; Pechenkina et al., 2022).

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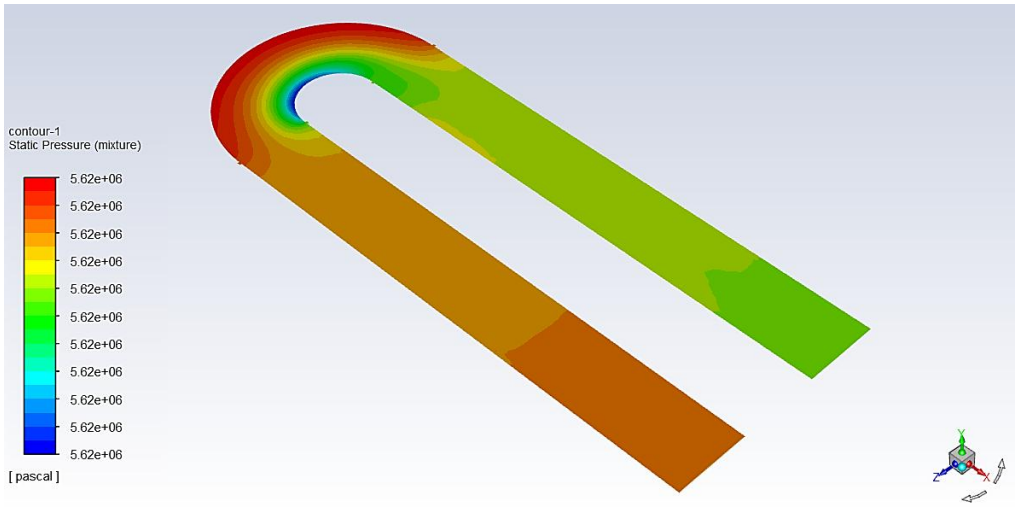

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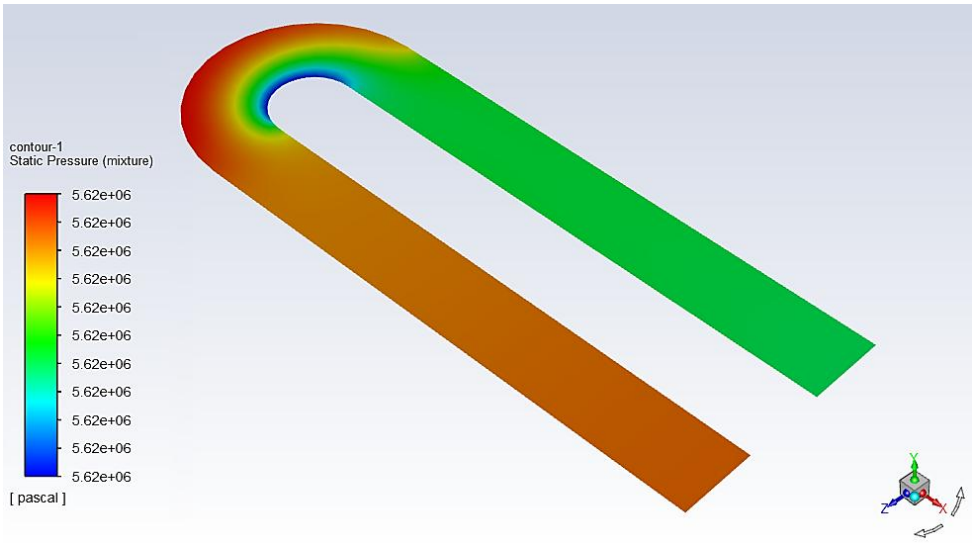

(b)

Figure 1. The distribution of fluid pressure that occurs in the evaporator tube model: (a) with weld defects; (b) without welding defects

Velocity Distribution

The flow velocity profile on the tube evaporator is shown in Figure 2. The simulation results showed that the maximum speed occurred in the elbow area and reached about 4.83 m/s. This increase in speed occurs due to a change in flow direction that results in the redistribution of fluid momentum during a bend. After passing the elbow, the velocity distribution becomes uneven and shifts towards the outer side of the curvature due to the influence of centrifugal force.

This phenomenon is important because the increase in flow speed contributes directly to the increase in the kinetic energy of the fluid-carried particles. The higher the particle velocity, the greater the impact energy the tube surface receives, so the erosion potential increases. These findings are in

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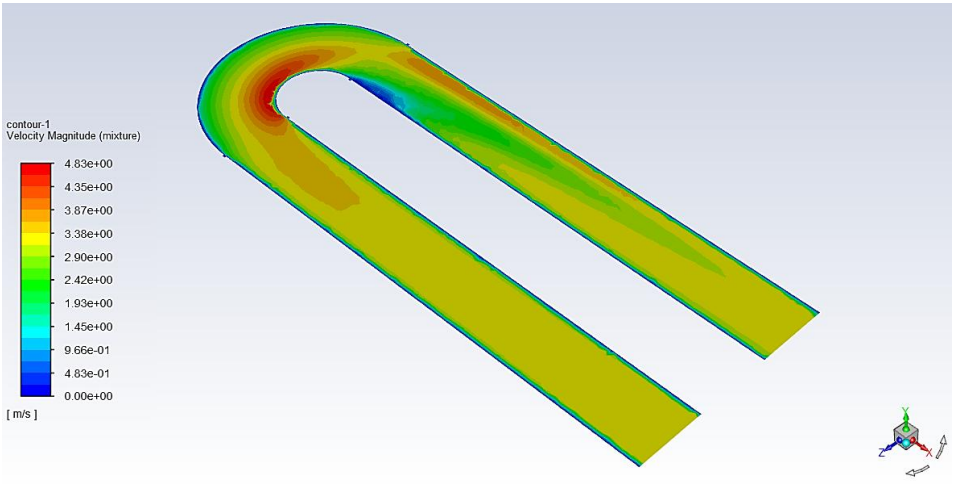
line with (Dai et al., 2023) which reports that the rate of erosion increases significantly as the flow rate in the piping system turns increases.



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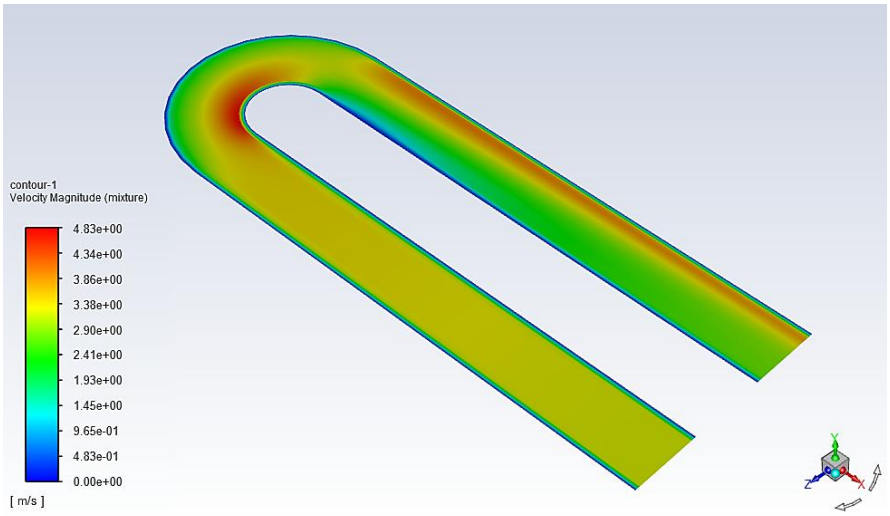

(b)

Figure 4.2. The velocity profile that occurs in the tube evaporator model: (a) with weld defects; (b) without welding defects

Turbulent Kinetic Energy Distribution

Although it does not cause significant pressure changes, the presence of weld defects has been shown to affect local flow characteristics. The distribution of turbulent kinetic energy in Figure 3. indicates that the weld defect area produces higher turbulence than the defectless condition. Geometric irregularities in weld joints cause vortex formation and flow separation that increases the intensity of turbulence around the area.

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Increased turbulence causes solid particles to change trajectories more often and are pushed towards the surface of the tube. In addition to increasing the frequency of impact, turbulence also increases the particle's momentum so that the impact energy becomes greater. Therefore, weld defects play a role as a trigger for local turbulence concentrations that magnify the potential for material degradation at certain locations.

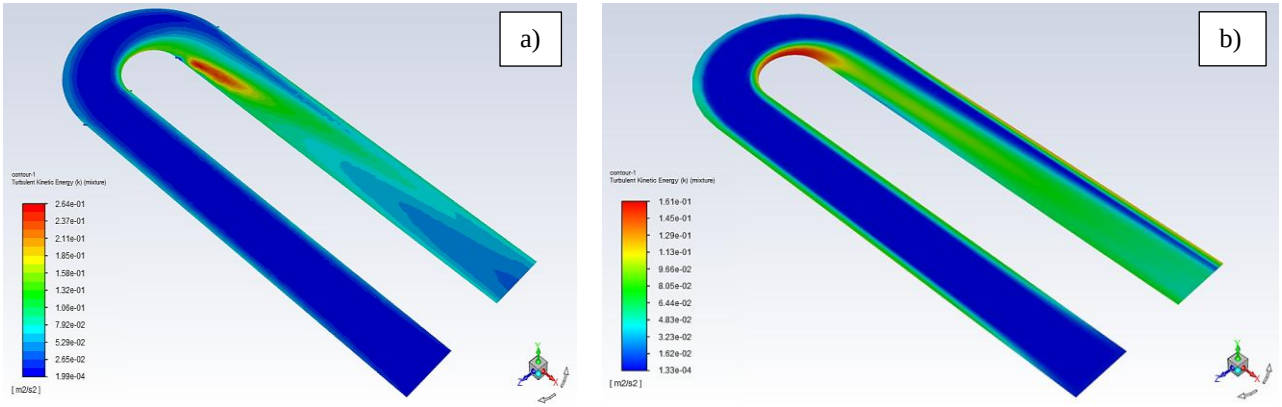
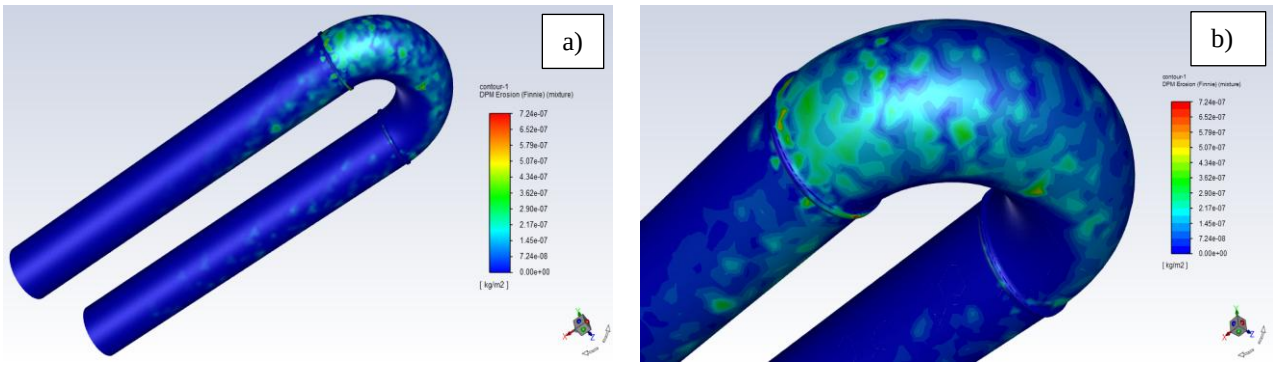


Figure 3. Turbulent kinetic energy distribution in HRSG tube evaporators: (a) with weld defects; (b) without welding defects

Erosion Rate Distribution

The distribution of the erosion surface of the simulation is shown in Figure 4. The highest erosion rate was identified in the downstream portion of the 180° outer elbow curvature. This location is an area of particle concentration due to the combination of centrifugal force and gravity that pushes the particles towards the outside of the bend. As it passes through the elbow, the particles undergo a gradual acceleration and change of direction. In the upstream part of the outer curve, most of the particles are still in the redistribution phase so the impact energy is relatively low. On the other hand, in the downstream part of the outer curvature, the particles have reached a more stable trajectory and have a higher momentum so that the impact against the wall becomes more intense. This condition causes the maximum erosion rate to occur before the elbow outlet. This pattern is consistent with the results of the research of Zhang et al. (2020), Zhao et al. (2023), Mahmoudi and Shiri (2025), and Rahman et al. (2022) which show that the maximum erosion zone on the elbow is generally located in the outer curvature near the elbow outlet due to particle concentration and increased impact energy.



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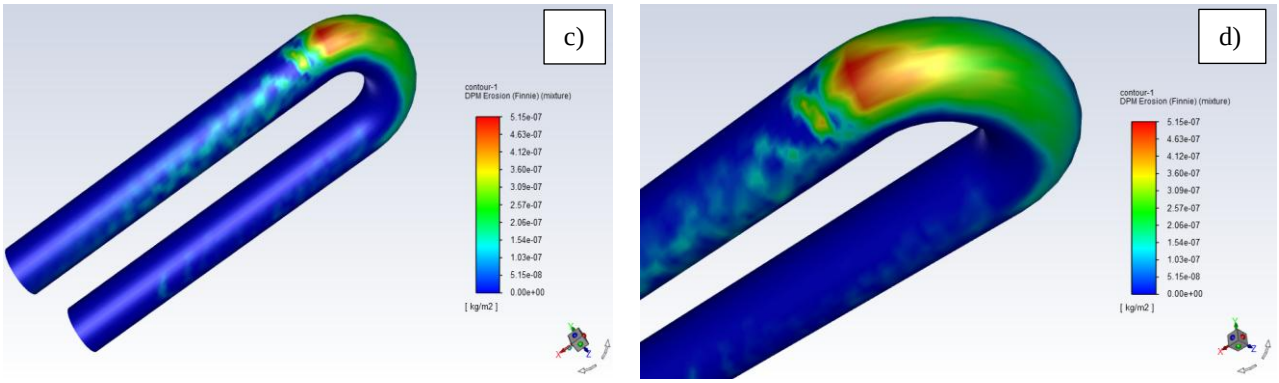

Figure 4. Surface distribution of erosion that occurs in the HRSG tube evaporator model: (a) and (b) with weld defects; (c) and (d) without welding defects

In addition to hydrodynamic factors, the vulnerability of the weld area to erosion is also influenced by the characteristics of the material. The welding process causes changes in the microstructure of the heat affected zone area which can reduce the resistance of materials to degradation at high operating temperatures (Qi et al., 2024; Rezaeian et al., 2020). Thus, the weld area not only experiences increased hydrodynamic loads, but also has lower material resistance to erosion.

Effect of TDS and Weld Defects on Erosion Rate

Follow-up simulations were conducted to evaluate the effect of total dissolved solids (TDS) content on erosion rates. The simulation results showed that an increase in TDS from 200 to 1000 ppm caused an almost linear increase in erosion rate both in conditions with and without weld defects. In the actual operating conditions of HRSG with an average TDS of 1,873 ppm, the erosion rate is predicted to reach around 1.83 mm/year in weld defect areas and around 0.55 mm/year in flawless conditions. Thus, the presence of weld defects increases the erosion rate by more than three times compared to normal conditions.

The increase in erosion rate at high TDS is related to the increased number of solid particles carried by the stream so that the frequency of impact against the tube wall increases (Boyd, 2020). At the same time, the high flow speed in the elbow area increases the impact energy of the particles, thus accelerating the material erosion process (Boyd, 2020; Liu et al., 2020). These results show that elbow geometry, flow turbulence, high TDS content, and the presence of weld defects work simultaneously in increasing the rate of material degradation. Overall, the results of the CFD simulation show that the downstream area of the 180° outer elbow curvature is the location with the highest combination of speed, turbulence, and erosion rate. The location corresponds to the actual leak area found on the HRSG evaporator, indicating that hydrodynamic factors have an important role in the failure process.

Based on the analysis using the CFD-DPM method, the erosion rate in the HRSG tube evaporator is influenced by factors including the flow speed of the fluid, the mass rate of solid particles flowing along with the fluid, and The size of the solid particles flowing along with the fluid. In this modeling, the flow speed of the working fluid is 3.29 m/s (2-phase speed inside a straight pipe evaporator). The mass rate of solid particles is adjusted to the TDS content in the feed water to be analyzed. While the size of solid particles is assumed to be uniform by 10 µm. The independent variable used in this analysis is the TDS condition in feedwater, while the bound variable is the erosion rate. Figure 5 below shows the rate of mass erosion per unit area of the HRSG tube evaporator at TDS

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conditions of 200 ppm, 400 ppm, 600 ppm, 800 ppm, and 1000 ppm. Based on the graph, it can be seen that the higher the TDS content in the feed water, the greater the erosion mass per unit area. In addition, the eroded mass has a linear relationship with the time of exposure to erosion. The longer the time of exposure to erosion, the greater the erosion mass that occurs in the material (Mahmoudi & Shiri, 2025b).

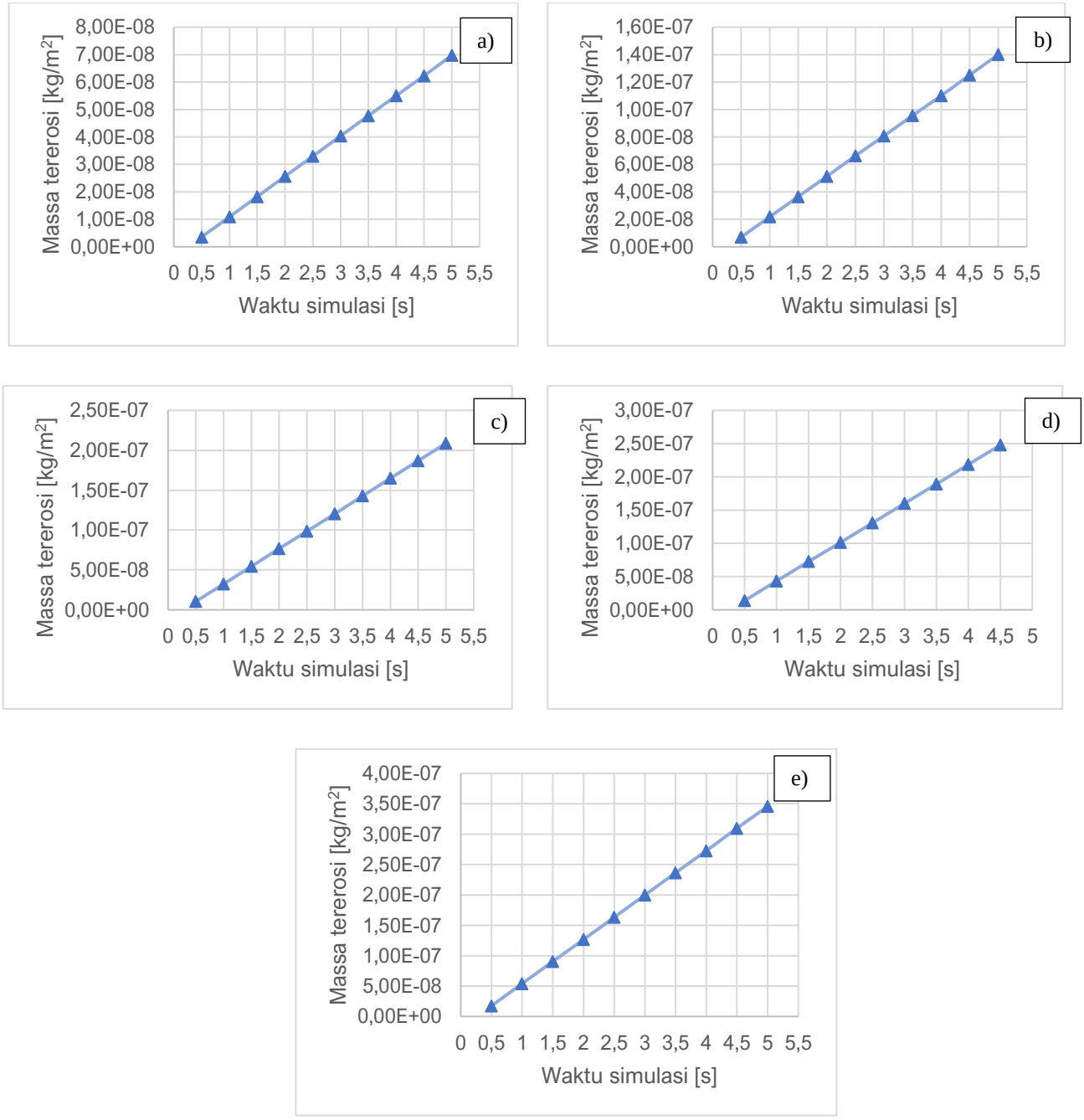

Figure 5. The rate of mass erosion per unit area of the HRSG tube evaporator under the conditions: (a) TDS 200 ppm; (b) TDS 400 ppm; (c) TDS 600 ppm; (d) 800 ppm; (e) 1000 ppm

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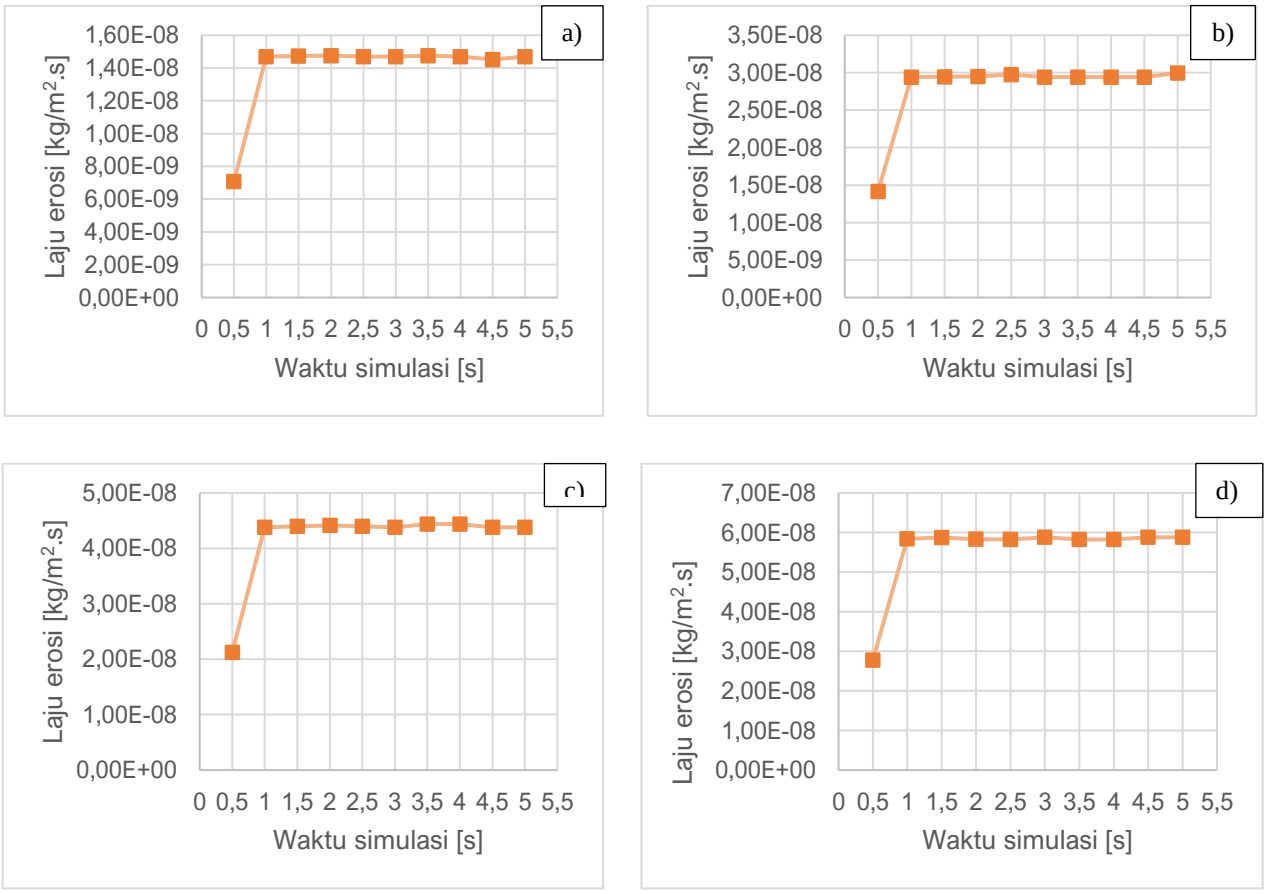
The representation of the erosion rate that occurs in the HRSG tube evaporator is shown in Figure Based on the graph, it can be seen that the greater the TDS content in the feedwater, the higher the erosion rate. Water with a high TDS content, as reported in the results of the water analysis, contains significant concentrations of ions and dissolved minerals, such as calcium, magnesium, chloride, and sulfate, which has the potential to increase the risk of corrosion and sedimentation in the system (Buecker, 2011). When water is evaporated in the HRSG, these solutes will be more concentrated, thus accelerating the formation of deposits (scale) or scale on the surface of the tube. These deposits cause hot spots that increase the risk of erosion due to thermal imbalances. Some ions in TDS (such as chlorides and sulfates) are corrosive. If these ions are concentrated, it can speed up the corrosion process on the surface of the tube. This corrosion will weaken the metal structure, making it more susceptible to erosion due to the flow of high-speed fluids or vapors The combination of high TDS with the rapid flow of fluid or steam within the HRSG can lead to the phenomenon of erosion-corrosion. Scale deposits or early corrosion create an uneven surface, and the rapid flow of fluid will accelerate the erosion of the material from the tube surface. Water with a high TDS content is more prone to produce small steam bubbles due to pressure differences. These bubbles can burst near the surface of the tube, causing cavitation which also contributes to erosion. By controlling TDS in feedwater, the risk of erosion and descaling in HRSG can be minimized. This can be done by pretreating feedwater such as demineralization, reverse osmosis (RO), or softening to lower TDS. In addition, blowdowns should be done regularly to control the concentration of TDS within the HRSG.



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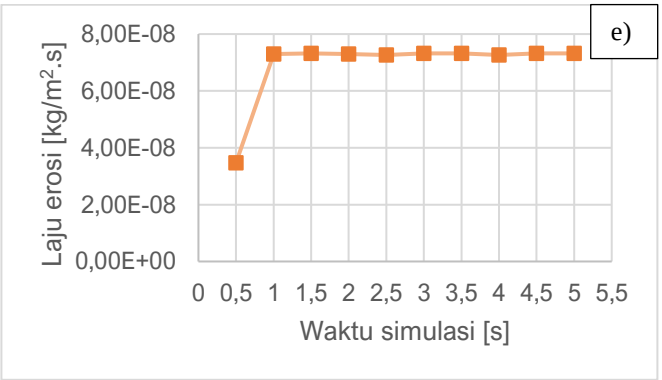

Figure 6. The evaporator tube erosion rate under conditions: (a) TDS 200 ppm; (b) TDS 400 ppm; (c) TDS 600 ppm; (d) 800 ppm; (e) 1000 ppm

The graph in Figure 6 shows the representation of the erosion rate per unit area and the erosion rate per unit time consecutively in the HRSG tube evaporator with no weld defects. The simulation was then continued to compare the erosion rate per unit area and per unit time by adding weld defect variables at various TDS conditions. The simulation results are shown by the graphs in Figure 7 and Figure 8 respectively.

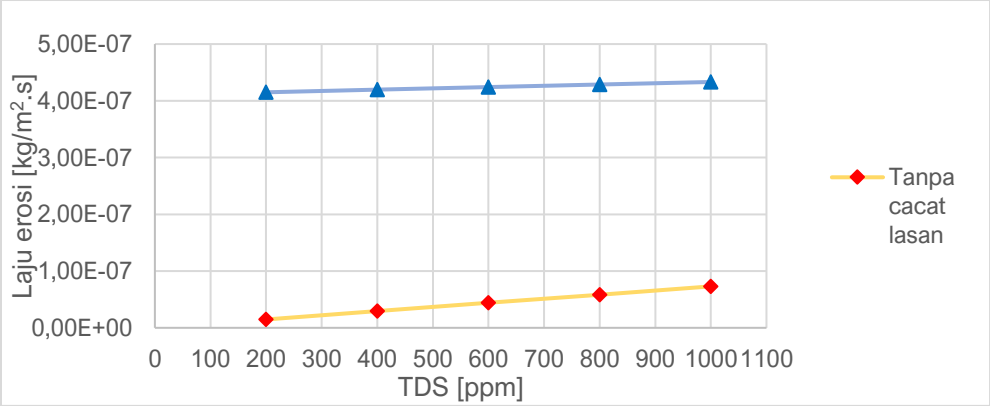

Figure 7. Effect of weld defects on the rate of mass erosion per unit area of the HRSG tube evaporator under various TDS conditions

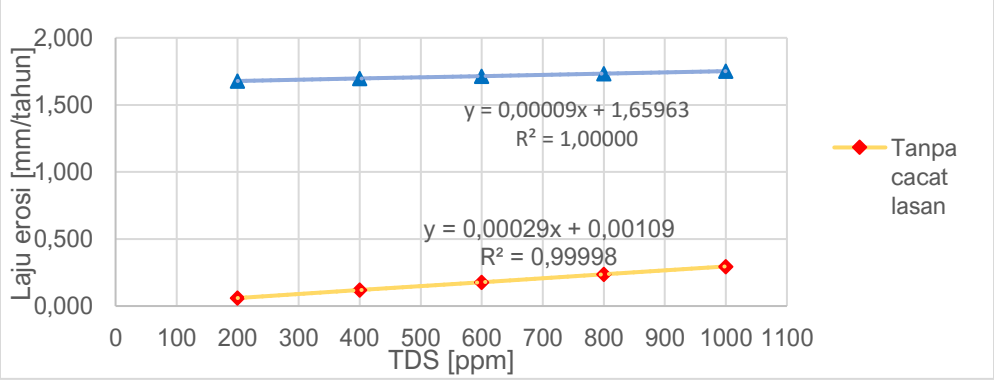

Figure 8. Effect of weld defects on the erosion rate of the HRSG tube evaporator under various TDS conditions

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Based on the graphs in Figure 7 and Figure 8, it can be seen that the condition of the tube evaporator with weld defects significantly increases the erosion rate, both in low and high TDS conditions (in this simulation the TDS content is reviewed between 200 – 1000 ppm). The relationship between TDS content (ppm) and erosion rate (mm/year) under the weld-free condition is written as a linear relationship, as shown in Equation (1) below:

$$Laju\ erosi\ \left(\frac{mm}{tahun}\right) = 0.00029x + 0.00109$$

Equation (1) has a coefficient of determination of R^2 = 0.9998, indicating that the linear model explains almost all of the variance in erosion rate across the simulated TDS range and confirms a near-perfect linear relationship between TDS content and erosion rate under the weld-free condition.

For the condition with weld defects, the relationship is expressed in Equation (2) below:

$$Laju\ erosi\ \left(\frac{mm}{tahun}\right) = 0.00009x + 1.65963$$

Equation (2) has a coefficient of determination of R^2 = 1.000, confirming an almost perfectly linear relationship between TDS content and erosion rate under the weld-defect condition.

Where x is the TDS content in feedwater. Using the above formula, it can be obtained that the erosion rate in the evaporator tube with weld defects at the current TDS condition (average 1873 ppm) is 1.83 mm/year. This value is much higher than the erosion rate with no weld defects, which is 0.553 mm/year. Therefore, it can be concluded that weld defects have a great effect on the erosion rate in the evaporator tube.

Furthermore, the leakage condition was identified at the welded 180° elbow downstream of the evaporator unit of the HRSG system. In elbow pipes with a certain angle (e.g. 90° or 180°), the erosion rate is predicted to be much worse. This prediction is based on the accumulation of corrosion and sediment particles focused on the defect areas and curvature of the pipe. In addition, as was done in the velocity simulation in chapter 4, after passing the elbow, the velocity of the fluid becomes uneven with the maximum velocity moving from the center to the side of the outer curvature of the elbow due to centrifugation forces. In the case of an evaporator elbow pipe, the simulation shows that the maximum speed value can reach 4.83 m/s on a pipe with or without defects. It has been widely accepted and presented in a publication that increasing the velocity of the fluid will also increase the rate of erosion (Dai et al., 2023).

Figure 9. Effect of solid particle size in TDS on the erosion rate of the HRSG tube evaporator at TDS 1000 ppm

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In addition to TDS concentration, the size of solid particles also affects the erosion rate in the HRSG tube evaporator. Simulations using particle size variations of 0.01–100 μm show that the larger the particle size, the greater the impact energy received by the tube wall, resulting in increased erosion potential. These findings suggest that feedwater quality control as well as the prevention of weld defects, especially with 100% met radiography inspection at 180° elbow joints, are important steps to reduce the rate of material degradation. In addition, routine preventive maintenance efforts are needed to check the condition of leaks that occur in the section tube so that the integrity of the HRSG tube structure is well maintained.

Effects of Flow Speed and Turbulence on Erosion

The two-phase flow in the HRSG evaporator produces high turbulence, especially in the 180° elbow area. The interaction between the steam bubbles and the liquid phase can cause local pressure fluctuations, while the phenomenon of collapsing bubbles has the potential to produce microjets that accelerate the degradation of the tube surface. This effect becomes more significant in areas with sharp changes in flow direction, such as 180° elbows, where turbulence and flow disturbances tend to increase (Krisnanda et al., 2019).

In addition, the TDS content of feedwater which reaches 1,873 ppm causes solid particles to be carried along with the two-phase flow and contribute to the erosion process. Continuous collisions of particles can erode the protective oxide layer so that the metal surface becomes more susceptible to further corrosion. The results of the study by Rahman et al. (2022) show that in a two-phase flow in the 180° elbow, the maximum erosion location is generally in the outer curvature near the elbow outlet due to particle concentration and increased impact energy.

These findings are consistent with the results of the CFD simulation in this study which showed the erosion concentration in the downstream of the outer elbow curvature and was reinforced by the radiographic results that identified the presence of internal concavity in the leak area (Figure 10). The consistency between the simulation results and the field inspection evidence indicates that flow turbulence and solid particle impact are important factors that accelerate the depletion of tube walls in HRSG evaporators.

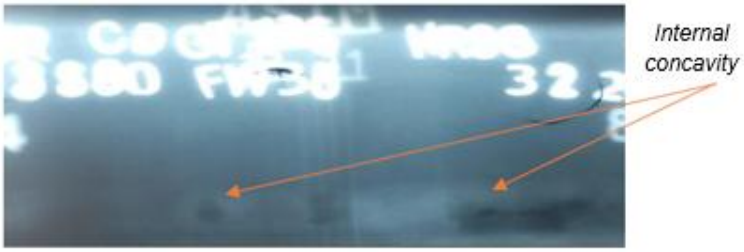

Figure 10. Radiographic inspection results showing internal concavity in the HRSG tube evaporator

Failure Mechanism and Mitigation Implications

To identify the main cause of repeated leaks in the HRSG-4 evaporator, the results of the CFD simulation were integrated with inspection data, feed water quality data, and unit operating characteristics. The fishbone and fault tree analysis shown in Figure 11 and Figure 12 showed that the failure was not caused by a single factor, but by the interaction between the chemical conditions of

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the feed water, the characteristics of the two-phase flow, the geometry of the 180° elbow, and the presence of weld defects in the tube joints.

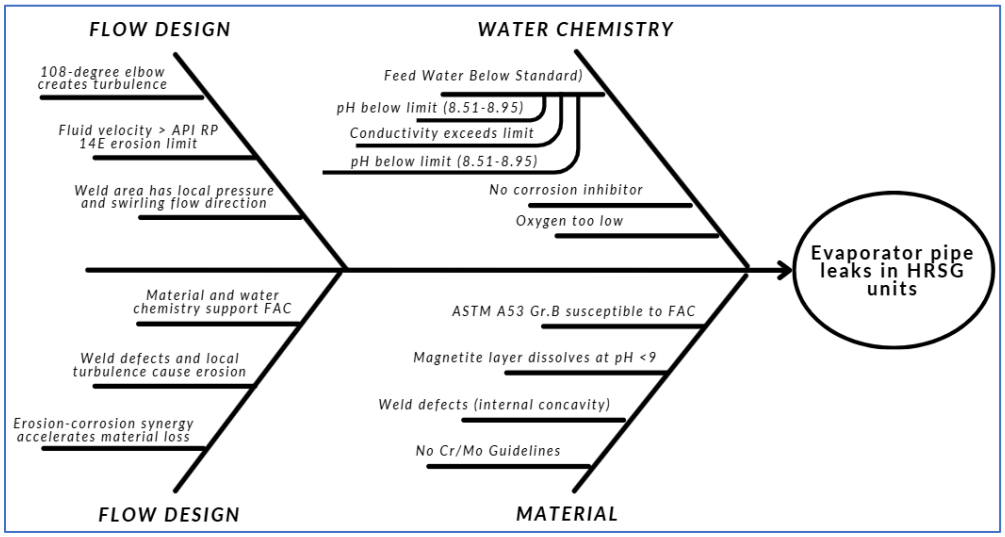

Figure 11. Fishbone diagram of the failure mechanism of the HRSG tube evaporator

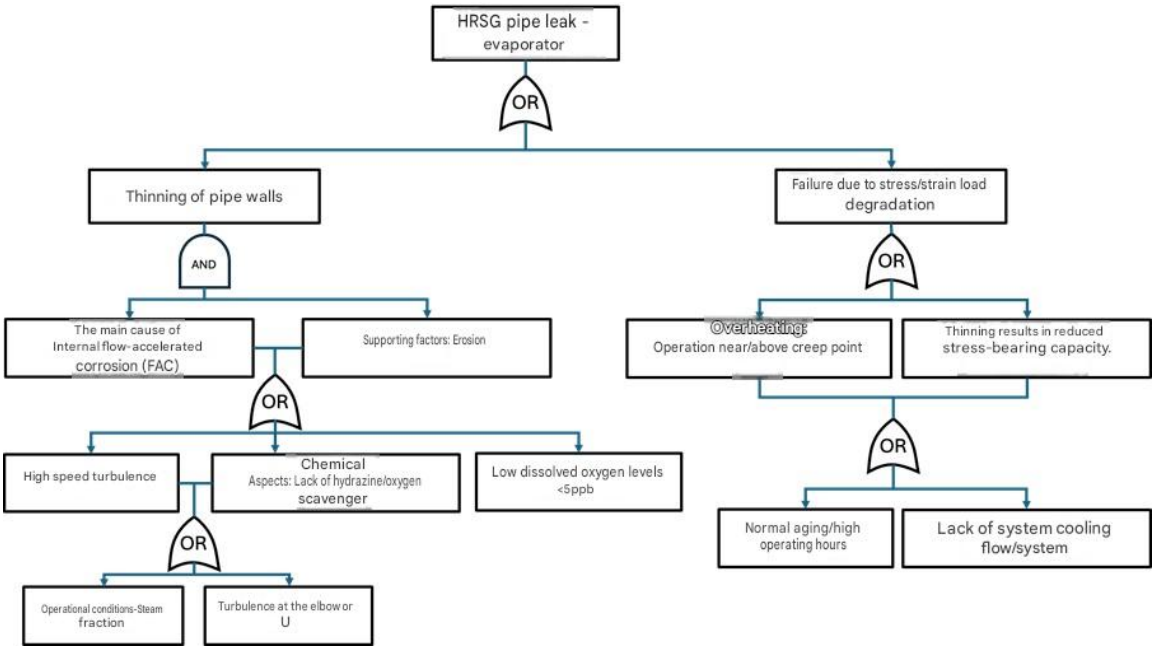

Figure 12. Fault tree diagram of the failure mechanism of the HRSG tube evaporator

The results of the analysis showed that the primary degradation mechanism that was most likely to occur was flow-accelerated corrosion (FAC). Indications of FAC are indicated by a high rate of thinning in the elbow area, the presence of local corrosion in the high-speed zone, the dissolved iron content in the feed water of 0.02–2.22 mg/L, and the operating pH condition of 8.51–8.95 which is below the optimal range of the formation of a protective layer of magnetite (Fe_3O_4). Under these conditions, the oxide layer becomes less stable and more easily dissolvable so that the metal surface is continuously exposed to corrosive environments. This phenomenon is in accordance with the FAC

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mechanism that has been reported by the (Hu et al., 2023; A. O. Ibrahim et al., 2025; Khunphakdee & Chalermsinsuwan, 2023; Song et al., 2025).

In addition to being influenced by the chemical conditions of water, the development of FAC is also accelerated by the hydrodynamic characteristics of the system. The results of the CFD simulation showed that the flow speed increased in the elbow area, accelerating the transport of corrosion products and inhibiting the reformation of the protective oxide layer. This condition causes the rate of material thinning in the elbow area to be higher than the straight pipe section. These findings are in line with the results of a study by Dooley and Anderson (2019) which showed that elbow is one of the most vulnerable locations to FAC in the HRSG system due to a combination of flow acceleration and local turbulence. Although FAC is the main degradation mechanism, it does not fully explain the occurrence of highly localized leaks in 180° elbow weld joints. The results of the CFD simulation show that the actual leak location corresponds to the area with the highest erosion rate. Therefore, the most representative failure mechanism to explain the phenomenon that occurs is the synergy between FAC and erosion-corrosion synergy.

In the initial stage, FAC causes thinning of the tube walls and increases the surface roughness of the material. The increasingly rough surface then increases the impact effectiveness of solid particles derived from high TDS content and flow-borne corrosion products. The impact of the particles removes the protective oxide layer and opens up new metal surfaces to further corrosion. This cycle takes place repeatedly, accelerating the rate of material degradation significantly. The mechanism is in accordance with the concept of erosion-corrosion synergy described by (Sun et al., 2025), where the interaction between mechanical erosion and electrochemical corrosion results in a greater rate of damage than the contribution of each mechanism separately.

The role of weld defects is an important factor in determining the location of failure. The results of the CFD show that the geometric irregularities in the weld area result in local turbulence, vortex formation, and an increase in turbulent kinetic energy that causes solid particles to pound the surface of the tube more frequently. In addition, changes in the microstructure in the weld area and heat affected zone cause the material's resistance to corrosion and erosion tends to be lower than that of the parent material (Qi et al., 2024; Rezaeian et al., 2020). As a result, the weld area serves as a location that accelerates FAC interaction and erosion-corrosion so that it becomes the starting point for local damage to form.

These findings are supported by simulation results that show that in actual operating conditions with an average TDS of 1,873 ppm, the erosion rate in the weld defect area is predicted to reach around 1.83 mm/year, while in the defectless condition it is only about 0.55 mm/year. Thus, the presence of weld defects increases the degradation rate by more than three times and acts as an accelerating factor in the failure process.

To verify the mechanism, the simulation results were compared with radiographic inspection data showing the presence of internal concavity in the evaporator elbow area as seen in Figure 10. This form of damage indicates the occurrence of internal erosion that develops progressively due to a combination of corrosion and particle erosion during operation. The correspondence between the actual damage location and the maximum erosion zone of the CFD results reinforces the conjecture that material degradation is controlled by the interaction between FAC, erosion-corrosion, and weld defects.

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Based on all the results of the analysis, the failure process is estimated to take place through four main stages as summarized in Figure 13. The first stage was initiated by FAC due to suboptimal feed water chemical conditions, causing the dissolution of the protective magnetite layer and the initial depletion of the material. The second stage is characterized by the accumulation of corrosion products and deposits that increase the roughness of the tube surface. The third stage is in the form of acceleration of erosion-corrosion due to the impact of solid particles in areas that have been depleted. At this stage, the presence of weld defects strengthens local turbulence and increases the concentration of particle impact. The last stage occurs when the wall thickness reaches a critical condition so that a perforation is formed that causes a leak in the 180° elbow weld joint of the HRSG evaporator.

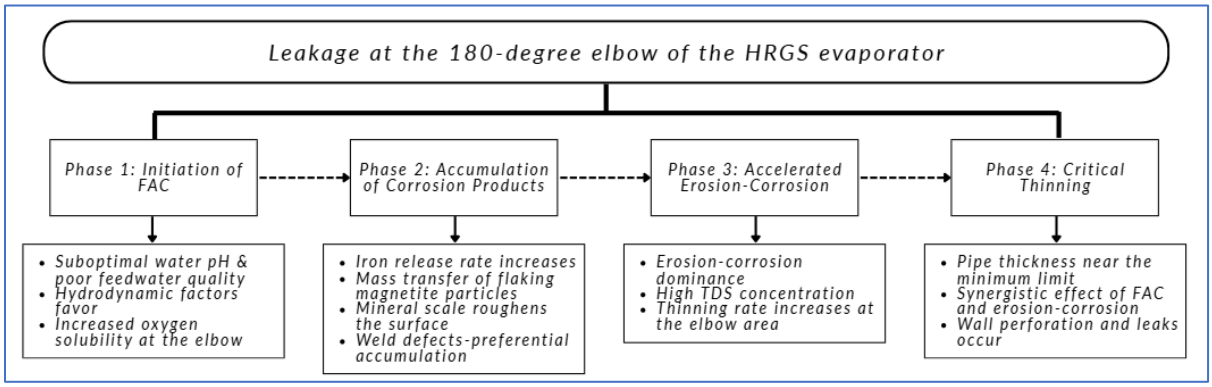

Figure 13. Timeline of HRSG tube evaporator failure due to FAC synergy and erosion-corrosion

The findings of this study show that the main cause of repeated leaks in the 180° elbow weld joints of the HRSG-4 evaporator is not only triggered by FAC or erosion individually, but by the synergy of the two mechanisms which are concentrated in areas with critical hydrodynamic characteristics. The main contribution of this study is to show that weld defects act as a local reinforcing factor that accelerates the process of material degradation in areas that have been vulnerable to FAC and particle erosion.

From a practical perspective, the results of the study indicate that mitigation strategies must be carried out in an integrated manner. Feed water quality control needs to be focused on reducing TDS, chloride, and dissolved iron content and maintaining the operating pH at a range that supports the stability of the protective magnetite layer. In addition, the quality of weld joints needs to be improved through 100% radiographic inspection of critical areas, especially 180° elbows, both during construction and repair stages. Regular monitoring of tube thickness using non-destructive testing methods is also recommended to detect wall thinning before it reaches critical conditions. The implementation of these measures is expected to reduce the rate of material degradation and improve the reliability of HRSG operations in the long term.

CONCLUSION

The results showed that the main degradation mechanism that occurred was low-Accelerated Corrosion (FAC), which was triggered by suboptimal feed water chemistry conditions, characterized by an operating pH that was below the optimal range of protective magnetite layer formation and high dissolved iron content as an indicator of active corrosion. This condition causes progressive thinning

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of the tube wall, especially in the elbow area which experiences accelerated flow and high turbulence. In addition to FAC, this study shows that leakage is not caused by a single mechanism, but by the synergy between FAC and erosion-corrosion synergy. The initial thinning due to FAC results in an increasingly rough surface that is susceptible to collision of solid particles derived from the content of total dissolved solids (TDS) and flow-borne corrosion products. The interaction of the two mechanisms forms a degradation cycle that accelerates each other, significantly increasing the rate of material loss. The results of the CFD simulation confirm that the downstream area of the 180° outer elbow curvature is the location with the highest combination of flow speed, turbulence, and erosion rate. This location corresponds to the actual leak point found on the HRSG evaporator. The simulation also showed that the presence of weld defects increased local turbulence and increased the erosion rate by more than three times compared to defectless conditions. These findings suggest that weld defects are not the main cause of failure, but act as a reinforcing factor that accelerates degradation in areas that are already vulnerable to FAC and erosion-corrosion. Based on all the results of the analysis, the failure mechanism is estimated to take place through four main stages, namely the initiation of FAC due to suboptimal water chemical conditions, the formation of corrosion products and the increase in surface roughness, the acceleration of erosion-corrosion due to particle impact in the area that has been depleted, and the perforation of the tube wall when the thickness of the material reaches critical conditions. Thus, the main cause of repeated leakage in the 180° elbow weld joint of the HRSG evaporator is the result of the interaction between the hydrodynamic characteristics of the flow, the quality of the feed water, the geometry of the elbow, and the presence of weld defects.

This research has several limitations. CFD simulations are conducted based on operating conditions and material parameters that are assumed to be constant so that they do not fully represent the variation in actual operating conditions in the long run. In addition, the erosion model used is still based on a numerical approach and has not been validated through experimental testing or direct measurement of the depletion rate during operation. Therefore, further research is recommended to integrate periodic tube thickness monitoring, laboratory testing of FAC and erosion-corrosion behavior, and the development of a transient CFD model that considers operating load fluctuations and two-phase flow characteristics in more detail. From the practical side, the results of the study show that mitigation efforts need to be carried out in an integrated manner through improving feed water quality by controlling pH, TDS, and chloride content, improving the quality of weld joint inspection through radiography in critical areas, and periodic monitoring of tube thickness at 180° elbow. In addition, design modifications such as the use of long-radius elbows and the selection of materials with better corrosion and erosion resistance have the potential to improve the reliability of HRSG operations and reduce the risk of repeated leaks in the future.

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