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International Journal of Mechanical and Sustainability Engineering Technology

Journal homepage:
https://uniexpertsacademy.com/index.php/IJMSET/index
ISSN: 3083-8363

Failure Mechanisms of SA213-TP304L Stainless Steel Tubes in Steam Generator Applications: A Review

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ARTICLE INFO

Article history:
Received 08 April 2026
Received in revised form 30 June 2026
Accepted 30 June 2026
Available online 30 June 2026

Keywords:

Steam generator; SA213-TP304L stainless steel; Heat exchanger tube failure; Stress corrosion cracking; Boiler feed water corrosion

ABSTRACT

SA213-TP304L stainless steel is widely used for heat exchanger and steam generator tubes because of its good corrosion resistance, weldability and suitability for high-temperature service. However, premature cracking may still occur when the material is exposed to aggressive operating environments, particularly in steam generator systems involving boiler feed water, elevated temperature and thermal-mechanical loading. This review discusses the possible failure mechanisms of SA213-TP304L stainless steel tubes in steam generator applications, with emphasis on stress corrosion cracking, boiler feed water-related corrosion and thermal stress. Previous studies involving scanning electron microscopy and energy dispersive X-ray spectroscopy are reviewed to identify common microstructural and elemental evidence associated with tube failure, including branched cracking, trans granular or intergranular crack propagation, corrosion deposits, pitting and the presence of aggressive species such as chloride, sulphur and oxygen. In addition, computational approaches such as computational fluid dynamics and finite element analysis are examined for their ability to predict temperature distribution, flow behaviour, thermal deformation and stress concentration in heat exchanger tubes. The reviewed literature indicates that premature tube failure is rarely caused by a single factor. Instead, failure commonly results from the combined effects of poor boiler feed water control, localised corrosion, deposit formation, tensile or residual stress and repeated thermal loading. Therefore, effective failure prevention requires proper material selection, controlled water chemistry, improved fabrication quality, regular inspection and the application of simulation tools to identify critical stress and temperature regions. This review provides a clearer understanding of the degradation mechanisms affecting SA213-TP304L stainless steel tubes and supports more reliable operation of steam generator systems in refinery and process industries.

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1. Introduction

Heat exchangers are important components in many industrial processes because they transfer thermal energy between fluids at different temperatures. They are widely used in power plants, petroleum refineries, chemical processing industries and steam generation systems for heating, cooling, evaporation, condensation and heat recovery. In these applications, heat exchangers often operate under high temperature and pressure while being exposed to fluids that may contain corrosive species. Therefore, the selection of tube material is an important factor that affects heat exchanger performance, durability, reliability and failure risk.

In refinery steam generator applications, stainless steel tubes are commonly used because of their good corrosion resistance and mechanical durability. However, unexpected failure may still occur when the operating environment becomes aggressive or when the tube is subjected to combined chemical, thermal and mechanical effects. In a real case encountered at a refinery complex, cracking was discovered on the outer surface of SA213-TP304L stainless steel tubes that were in contact with boiler feed water (BFW) and operated within a kettle-type steam generator. This failure caused operational downtime and high initial repair cost. The failure mode was considered unexpected because common degradation mechanisms in similar heat exchanger systems are usually associated with thinning and pitting rather than cracking [1]. Moreover, the failure occurred before the expected service life, where stainless steel tubes are generally expected to have a minimum lifespan of 20 years depending on operating conditions and maintenance practice [2]. Therefore, understanding the possible failure mechanisms affecting SA213-TP304L stainless steel tubes is essential for improving steam generator reliability and preventing premature failure.

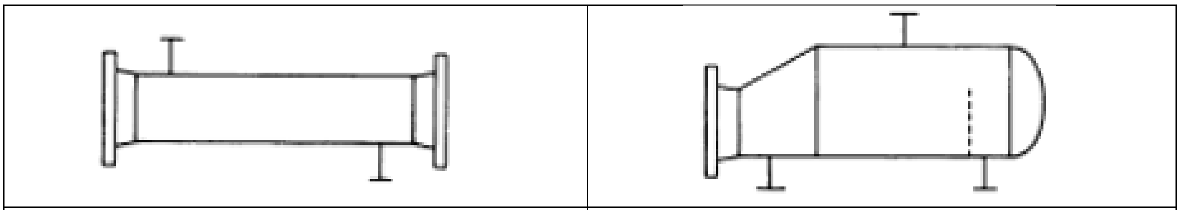
1.1 Heat Exchangers

A heat exchanger is a device that enables heat transfer between two or more fluids at different temperatures. The selection of a suitable heat exchanger depends on factors such as fluid characteristics, operating temperature, operating pressure, heat duty and maintenance requirements [3]. Heat exchangers can be classified based on the type of heat transfer process, flow arrangement and construction. Based on the heat transfer process, heat exchangers may be divided into direct-contact and indirect-contact types. In direct-contact heat exchangers, the fluids mix and exchange heat directly, while in indirect-contact heat exchangers, the fluids are separated by a solid wall, and heat transfer occurs through the wall by conduction and convection [4]. Based on flow arrangement, heat exchangers may be classified as parallel-flow, counter-flow and crossflow systems. In terms of construction, common types include tubular heat exchangers, plate heat exchangers and extended-surface heat exchangers [4].

1.1.1 Shell and Tube Heat Exchangers

Shell-and-tube heat exchangers are among the most widely used heat exchangers in industrial applications. This type of heat exchanger consists of a cylindrical shell containing a bundle of tubes, where one fluid flows through the tubes and another fluid flows through the shell side [5]. Baffles are commonly installed inside the shell to guide the shell-side fluid across the tube bundle, increase turbulence and improve heat transfer performance [6]. The Tubular Exchanger Manufacturers Association (TEMA) classifies shell-and-tube heat exchangers according to their application and service requirements into Class R for refinery service, Class B for chemical service and Class C for general commercial service [3]. TEMA also uses a three-letter designation system to describe the front head type, shell type and rear head type of shell-and-tube heat exchangers [6].

One of the common shell configurations is the one-pass shell, also known as Type E. In this design, the shell-side fluid flows through the shell in a single pass. This configuration is commonly used because of its simple design and relatively low cost [4]. Another relevant configuration is the kettle-type reboiler, also known as Type K, which is commonly applied in systems requiring partial vaporisation of liquid. In this design, a weir is installed at the outlet side of the shell to maintain the liquid level above the tube bundle [8]. Kettle-type reboilers are suitable for large vapor loads, although their application at high pressure may require thicker shell walls and higher construction cost [9]. The common one-pass shell and kettle-type reboiler configurations are shown in Fig. 1.



(a) (b)

Fig. 1 Common shell types: (a) one-pass shell (Type E); (b) kettle-type reboiler (Type K)

1.2 Common Materials Used in Heat Exchangers

Stainless steel (SS) and carbon steel (CS) are among the commonly used materials for heat exchanger tubes because each material offers different advantages depending on the operating environment. Stainless steel is widely used in chemical and refinery applications because of its corrosion resistance, high-temperature resistance and resistance to fouling [10]. Carbon steel is also widely used because it is economical, mechanically strong and has good thermal conductivity. However, carbon steel is more susceptible to corrosion and is normally suitable for applications where the corrosiveness of the working fluid is properly controlled [11]. Therefore, the selection between stainless steel and carbon steel depends on corrosion resistance requirements, cost considerations, operating temperature, pressure and the properties of the working fluid.

1.2.1 Stainless Steel

Stainless steels are corrosion-resistant alloys that are primarily composed of iron, chromium and other alloying elements such as nickel, molybdenum and manganese. They contain at least 10.5% chromium, which promotes the formation of a passive oxide film on the metal surface and improves corrosion resistance [12]. Austenitic stainless steels are the largest and most widely used group of stainless steels because of their good formability, weldability and toughness [13]. They have a face-centred cubic (FCC) crystal structure that remains stable over a wide temperature range. Austenitic stainless steels are not strengthened by heat treatment but can be strengthened by cold working [14].

Table 1 Chemical composition of SS 304, 304L, 316 and 316L [15]

Grade	%C	%Mn	%Si	%S	%P	%Cr	%Ni	%Mo
304	0.08	2.00	1.00	0.030	0.045	18.0-20.0	8.0-11.0	-
304L	0.03	2.00	1.00	0.030	0.045	18.0-20.0	8.0-12.0	-
316	0.08	2.00	1.00	0.030	0.045	16.0-18.0	10.0-14.0	2.00-3.00
316L	0.03	2.00	1.00	0.030	0.045	16.0-18.0	10.0-14.0	2.00-3.00

Austenitic stainless steels are commonly divided into the 300 series and 200 series. The 300 series mainly use nickel to stabilise the austenitic structure, while the 200 series use manganese and nitrogen as partial substitutes for nickel [13]. Grade 304 stainless steel is the most used austenitic stainless steel and generally contains approximately 18% chromium and 8-10% nickel [13]. Grade 304L is the low-carbon version of 304 stainless steel and is preferred for welded applications because its lower carbon content reduces the risk of sensitisation [13]. Grade 316 stainless steel provides better corrosion resistance than Grade 304, especially in chloride-containing environments, due to the addition of molybdenum. Grade 316L is the low-carbon version of Grade 316 and is also suitable for welded applications [13]. The chemical compositions of stainless-steel grades 304, 304L, 316 and 316L are shown in Table 1 [15].

1.2.2 Carbon Steel

Carbon steel is an alloy primarily composed of iron and carbon, with small amounts of other elements such as phosphorus, Sulphur and manganese. It is widely used in engineering because of its mechanical strength, ductility, availability and cost effectiveness. The carbon content strongly affects its hardness, strength and ductility [16]. In general, carbon steels are classified into low carbon steel, medium carbon steel, high carbon steel and ultra-high carbon steel based on their carbon content [16].

Low carbon steel contains up to approximately 0.25%-0.30% carbon and usually consists of ferrite and pearlite microstructures. It is relatively soft, ductile, machinable and weldable, making it suitable for sheet, strip and general fabrication applications [16]. Medium carbon steel contains approximately 0.30%-0.55% carbon and 0.60%-1.65% manganese. It has higher strength and hardness than low carbon steel but lower ductility, and it is commonly used for machinery, railway and automotive components after suitable heat treatment [16]. High carbon steel contains approximately 0.55%-1.00% carbon and 0.30%-0.90% manganese. It provides high hardness and strength but has limited ductility and weldability, making it suitable for cutting tools, springs and wear-resistant applications [16]. Ultra-high carbon steel contains approximately 1.0%-2.1% carbon and offers very high hardness and strength, making it suitable for highly wear-resistant applications such as hand tools, drill bits and knives [16].

Although carbon steel is important in many heat exchanger applications, this review focuses mainly on SA213-TP304L stainless steel tubes because the reported premature cracking occurred in stainless steel tubes used in a steam generator unit. The following section therefore discusses the main failure mechanisms that may contribute to the degradation and cracking of heat exchanger tubes, particularly under corrosive boiler feed water, tensile stress and thermal loading conditions.

2. Review Methodology

This review was conducted using a structured narrative approach to examine the possible failure mechanisms of SA213-TP304L stainless steel tubes in steam generator and heat exchanger applications. The review focused on literature related to stainless steel tube degradation, heat exchanger failure, stress corrosion cracking, boiler feed water corrosion, thermal stress, and numerical simulation of thermal-mechanical behaviour. The selected literature was mainly used to identify the relationship between operating environment, tube material, corrosion products, crack morphology, water chemistry, thermal loading and stress distribution.

The literature search was guided by several keywords and keyword combinations, including SA213-TP304L stainless steel, 304L stainless steel tube failure, steam generator tube failure, heat exchanger tube failure, stress corrosion cracking, chloride-induced stress corrosion cracking, boiler feed water corrosion, thermal stress, thermal fatigue, scanning electron microscopy, energy dispersive X-ray spectroscopy, computational fluid dynamics and finite element analysis. These keywords were selected because they represent the main technical areas associated with premature cracking of stainless-steel tubes in steam generator environments.

The selected studies were screened based on their relevance to the scope of this review. Studies were included when they discussed failure mechanisms in stainless steel or heat exchanger tubes, presented microstructural or elemental evidence of degradation, analysed the effect of corrosive species or boiler feed water chemistry, or applied simulation methods to evaluate temperature distribution, deformation and stress concentration. General references on heat exchanger design, stainless steel classification and material composition were used to support the background discussion, while studies with limited relevance to heat exchanger or steam generator tube failure were not emphasised.

The reviewed literature was classified into four main themes. The first theme focused on stress corrosion cracking, particularly studies that reported branched cracks, trans granular or intergranular crack propagation, pitting and the presence of aggressive ions such as chloride and sulphur. The second theme examined boiler feed water-related corrosion, including the role of dissolved gases, scaling ions, poor demineralisation, deposits and electrochemical attack. The third theme covered thermal stress and thermal fatigue, especially failures associated with temperature gradients, cyclic heating, tube-to-tube sheet joints, fabrication conditions and differential thermal expansion. The fourth theme reviewed simulation-based studies, particularly computational fluid dynamics and finite element analysis, for predicting flow behaviour, heat transfer, thermal deformation and stress concentration in heat exchanger tubes.

For each selected study, the important information was extracted and compared, including the material investigated, operating environment, failure location, observed damage morphology, detected corrosive elements, proposed failure mechanism and relevance to SA213-TP304L stainless steel tube failure. The extracted findings were then synthesised to identify recurring degradation patterns and to explain how boiler feed water quality, localised corrosion, tensile or residual stress and thermal loading may interact to cause premature cracking. This approach provides a focused basis for discussing the failure mechanisms and preventive measures for SA213-TP304L stainless steel tubes used in steam generator applications.

3. Failure Mechanisms of Heat Exchanger Tubes

Heat exchanger tubes operate under complex service conditions involving temperature variation, pressure loading, fluid flow, chemical impurities and mechanical constraints. These conditions may lead to gradual material degradation and, in severe cases, premature tube failure. The failure of heat exchanger tubes may occur through several mechanisms, including fouling, corrosion, erosion, fatigue and vibration-induced damage [17]. Among these mechanisms, fouling and erosion mainly reduce heat transfer performance, while corrosion, fatigue and vibration-induced damage can directly affect tube integrity and lead to leakage or rupture [17]. In steam generator applications, tube degradation is often more complex because thermal loading, boiler feed water chemistry and residual or operating stresses may interact with one another. Therefore, identifying the dominant failure mechanism is important for determining the root cause of failure and proposing suitable preventive measures.

For SA213-TP304L stainless steel tubes, premature cracking is of particular concern because the material is generally selected for its corrosion resistance, weldability and suitability for heat exchanger service. However, under aggressive operating conditions, stainless steel may become susceptible to localised corrosion and cracking. Based on the reviewed studies, the most relevant mechanisms associated with premature tube failure are stress corrosion cracking, boiler feed water corrosion and thermal stress. These mechanisms may occur independently, but in actual steam generator operation, they often act together. For example, poor boiler feed water quality may initiate pitting or deposit formation on the tube surface, while tensile stress, residual stress or thermal stress may promote crack initiation and propagation. The following subsections discuss these mechanisms in detail.

3.1 Stress Corrosion Cracking

Stress corrosion cracking (SCC) is a localised failure mechanism that occurs due to the combined effect of tensile stress, susceptible material and a specific corrosive environment. It is considered a dangerous form of failure because cracking may occur with little visible deformation and may remain undetected until leakage or rupture occurs. SCC is commonly characterised by fine cracks, crack branching and brittle-like fracture behavior [18]. In stainless steel heat exchanger tubes, SCC is especially critical because cracks can initiate from small surface defects, corrosion pits or deposits and then propagate through the tube wall under sustained or residual tensile stress.

Austenitic stainless steels are vulnerable to SCC when exposed to aggressive environments containing chloride, sulphide or other corrosive species. Chloride-related SCC is commonly associated with austenitic 300 series stainless steels in the presence of chloride ions, oxygen and elevated temperature conditions [20]. Sulphide-related SCC may occur in environments containing hydrogen sulphide, which is commonly encountered in oil, gas and petrochemical processing systems [18]. The reviewed studies show that SCC is usually confirmed through microstructural and elemental evidence, particularly using scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX). SEM is useful for identifying crack morphology, while EDX helps detect corrosive elements at crack surfaces or corrosion deposits. Table 2 summarises selected studies that investigated SCC in stainless steel heat exchanger tubes.

Table 2 Findings of SCC

No.	Researchers	Topic	Summary
1.	Ravindranath and Alazemi [20]	Failure of stainless steel 304L air cooler tubes due to stress corrosion cracking caused by organic chlorides	This study investigated stainless steel 304L air cooler tube failure caused by stress corrosion cracking associated with organic chlorides. The failure was initiated by hydrochloric acid from organic chloride decomposition. SEM of the internal tube surface revealed pits, cracks and branching morphology. The cracks showed trans granular propagation, a typical SCC feature. EDX at crack locations showed strong chloride peaks compared with chromium and nickel. SEM observations, EDX results and fluid analysis confirmed chloride-induced SCC as the main failure mechanism

Table 2 Findings of SCC (Cont.)

No.	Researchers	Topic	Summary
2.	Zhai et al. [19]	Failure analysis on 304 stainless steel tube of semi water gas preheater in coal chemical plant	This study examined the failure of 304 stainless steel tubes used in a semi water gas preheater at a coal chemical plant. SEM images showed slender and branched cracks with numerous secondary cracks at the crack tips. The cracks propagated in a trans granular manner through the metal grains, indicating the presence of SCC. EDX analysis detected high concentrations of iron, sulphur and oxygen in the corroded regions. These findings indicated that corrosion occurred in a wet hydrogen sulphide environment. Therefore, sulphide-related SCC was identified as the primary cause of failure.
3.	Jin and Li [21]	Failure analysis and preventative measures on cracking of tube-to-tube sheet joints of the large-scale heat exchanger	This study conducted SEM and EDX analyses on S31603 stainless steel tubes from a large-scale EO/EG heat exchanger to investigate cracking at the tube-to-tube sheet joints. SEM observations revealed a combination of trans granular and intergranular cracking. The cracks initiated from corrosion pits on the outer surface of the tube, and secondary cracks were observed near crack path changes. The cracks were covered with corrosion products, which was consistent with SCC behaviour. EDX results showed the presence of oxygen, calcium, copper, chlorine and sulphur in the fracture areas. These corrosive elements were associated with boiler water and EO reaction feedstock. The results showed that electrochemical reactions, boiler water impurities and elevated temperature contributed to the cracking mechanism.

The reviewed studies indicate that SCC is a significant failure mechanism for stainless steel heat exchanger tubes, particularly when aggressive ions are present under tensile stress and elevated temperature conditions. The common evidence of SCC includes surface pits, branched cracks, trans granular or intergranular crack propagation and corrosion deposits. EDX analysis commonly detects aggressive elements such as chlorine, sulphur and oxygen, which support the role of corrosive environments in crack initiation and propagation. In the context of SA213-TP304L stainless steel tubes in steam generator service, SCC may occur when boiler feeding water impurities or local deposits create aggressive conditions on the tube surface. Therefore, strict control of water chemistry, reduction of chloride contamination, minimization of residual stress and regular inspection are important to reduce the risk of SCC.

3.2 Boiler Feed Water Corrosion

Boiler feed water (BFW) quality plays an important role in the reliability and service life of boilers, steam generators and heat exchanger tubes. BFW normally consists of treated make-up water and returned condensate. It must be properly treated because impurities in the water can lead to corrosion, scale formation, deposit accumulation and overheating of tubes. Common harmful impurities include dissolved oxygen, carbon dioxide, chloride ions, iron oxides, calcium and magnesium compounds. Carbon dioxide may react with water to form carbonic acid, which can corrode steam and condensate lines. Dissolved oxygen can promote electrochemical corrosion, while calcium and magnesium compounds may form scale deposits that reduce heat transfer efficiency and cause local overheating. Therefore, effective BFW treatment is essential for minimizing corrosion-related failure and maintaining reliable steam generator operation [22].

Table 3 Findings of BFW corrosion

No.	Researchers	Topic	Summary
1.	Liu et al. [23]	Corrosion failure analysis of the heat exchanger in a hot water heating boiler	This study investigated corrosion failure in heat exchanger tubes made of 20G carbon steel used in a hot water boiler. The failure was attributed to BFW with excessive concentrations of calcium, magnesium and oxygen due to poor maintenance of the demineralised water unit. Chloride ions promoted pitting corrosion and contributed to the formation of a porous oxide layer. The porous oxide layer allowed further ion penetration, which accelerated the degradation process. Although the material was carbon steel, the study demonstrates the importance of water chemistry control in preventing tube corrosion.
2.	Skoczko and Szatylowicz [24]	Treatment method assessment of the impact on the corrosivity and aggressiveness for the boiler feed water	This study assessed the corrosivity of BFW before and after the improvement of a water treatment system. The findings showed that untreated groundwater was highly corrosive due to carbon dioxide and mineral imbalance. After the application of pre-aeration, filtration, ion exchange and degassing, the corrosivity of the water was significantly reduced. This study highlights that poor water quality is a major contributor to corrosion and that an effective treatment system is important for reducing corrosion-related damage in boiler and heat exchanger systems.

In heat exchanger tubes, BFW-related corrosion can be initiated as pitting, under-deposit corrosion, oxide layer breakdown or localised electrochemical attack. For stainless steel tubes, corrosion may begin when the passive oxide film is locally damaged by aggressive ions or concentrated deposits. Once pits are formed, they can act as stress concentration sites and may become initiation points for SCC under tensile or thermal stress. Therefore, BFW corrosion should not be treated only as a general corrosion issue, but also as a possible precursor to cracking. Table 3 summarises studies related to BFW corrosion and its effect on heat exchanger tube degradation.

The studies reviewed in Table 3 show that BFW corrosion is strongly related to water chemistry and the effectiveness of the treatment system. Poor control of dissolved gases, chloride ions and scaling compounds can promote pitting, oxide film breakdown, deposit formation and local overheating. In steam generator tubes, these conditions may become more severe because boiling and evaporation can concentrate impurities at local regions on the tube surface. For SA213-TP304L stainless steel tubes, the presence of chloride ions and oxygen is particularly important because these species can damage the passive film and promote localised corrosion. Once pits or deposits form, they may provide favorable sites for SCC initiation. Therefore, continuous monitoring of BFW quality, proper demineralization, filtration, degassing and control of chloride and oxygen levels are necessary to reduce corrosion risk.

3.3 Thermal Stress

Thermal stress occurs when a material experiences non-uniform expansion or contraction due to temperature differences. In heat exchanger tubes, thermal stress may arise when hot and cold fluids create temperature gradients across the tube wall, tube length or tube-to-tube sheet region. If the expansion or contraction of the tube is restricted, internal stresses develop within the material [25]. Repeated heating and cooling during start-up, shutdown or unstable operation can also produce cyclic thermal loading. Over time, these repeated stresses may lead to thermal fatigue, crack initiation and crack propagation [26].

In steam generator and shell-and-tube heat exchanger systems, thermal stress is influenced by operating temperature, heat flux, flow distribution, support condition and the mechanical constraint between the tube and tube sheet. Locations such as tube-to-tube sheet joints, bends, expanded regions and areas exposed to strong temperature gradients are more susceptible to thermal stress concentration. Thermal stress can also interact with corrosion mechanisms. For example, deposits or scale on the tube surface may reduce heat transfer and create local hotspots. These hotspots may increase thermal gradients and promote cracking. Similarly, fabrication-related residual stress or insufficient tube expansion may increase local tensile stress and accelerate SCC under corrosive conditions. Table 4 summarises studies related to thermal stress in heat exchanger and steam generator tubes.

Table 4 Findings of thermal stress

No.	Researchers	Topic	Summary
1.	He et al. [27]	Failure analysis on unexpected fracture of tube-to-tubesheet joints of a circulating oil steam generator	This study investigated the unexpected fracture of S32168 tube-to-tubesheet joints in a circulating oil steam generator. The failure originated from the tube outer wall exposed to boiler water and steam. The absence of clear expansion marks on the inner wall indicated improper tube expansion during fabrication. This created a gap between the tube and tubesheet, allowing sodium and chloride ions to accumulate and cause caustic SCC. The fracture occurred at the expanded section, where tensile stress was high due to differential thermal expansion

Table 4 Findings of thermal stress (cont.)

No.	Researchers	Topic	Summary
2.	Ali et al. [28]	Failure analysis of heat exchanger tubes	This study reviewed failure cases involving ASTM A213 Grade T-11 boiler tubes used in an ammonia plant. The tubes were exposed to process gas at 960°C on the shell side and water at 306°C and 1500 psig on the tube side. The study showed that temperature oscillations caused by poor water circulation generated thermal stresses. Circumferential cracks formed across the tube axis, while overheating due to water leakage caused longitudinal cracks and tube bulging. The findings highlight the importance of proper process control, adequate water circulation and regular inspection to prevent thermal stress-related failures in heat exchanger systems.

The reviewed studies show that thermal stress is an important contributor to heat exchanger tube failure, particularly in regions where thermal expansion is restricted, or temperature gradients are severe. Failures frequently occur at tube-to-tube sheet joints, expanded sections or areas affected by poor water circulation because these regions experience higher stress concentration. Thermal stress may also support the development of SCC when corrosive species are present. In the case of SA213-TP304L stainless steel steam generator tubes, repeated thermal cycling, local overheating, poor water circulation and differential expansion between tube and tube sheet components may contribute to crack initiation and propagation. Therefore, thermal stress management should include proper fabrication control, adequate tube expansion, stable operating conditions, good water circulation, monitoring of start-up and shutdown procedures and regular inspection of critical tube regions.

Overall, the failure mechanisms discussed in this section show that premature cracking of heat exchanger tubes is rarely caused by a single factor. SCC, BFW corrosion and thermal stress may interact through a combined degradation pathway. Poor BFW quality can initiate pitting and deposits, while thermal gradients and tensile stresses can accelerate crack initiation and propagation. For SA213-TP304L stainless steel tubes, this interaction is particularly important because the material depends on a stable passive film for corrosion protection. Once this passive film is locally damaged, the tube may become vulnerable to localised corrosion and SCC. Therefore, a complete failure assessment should consider material condition, water chemistry, corrosion products, crack morphology, thermal loading and stress distribution together.

4. Simulation Studies

Simulation studies are important tools for understanding the thermal and mechanical behavior of heat exchanger tubes under complex operating conditions. In steam generator and heat exchanger applications, tube failure is often influenced by fluid flow distribution, heat transfer behavior, temperature gradients, thermal deformation and stress concentration. These parameters are difficult to evaluate fully through visual inspection or experimental analysis alone. Therefore, numerical simulation can provide useful support in identifying critical regions where local overheating, excessive deformation or high stress may occur.

Computational Fluid Dynamics (CFD) is commonly used to analyse fluid flow and heat transfer behavior in heat exchanger systems. CFD divides the fluid domain into small computational cells and solves the governing equations numerically to predict velocity distribution, pressure drop, temperature distribution and heat transfer performance [30]. In the context of heat exchanger tube failure, CFD can help identify areas with poor flow distribution, stagnant flow, high temperature gradients and possible deposit-prone regions. These conditions are important because they may contribute to localised corrosion, under-deposit corrosion, thermal hotspots and reduced heat transfer efficiency.

Finite Element Analysis (FEA) is another important numerical method used to evaluate mechanical and thermal responses in heat exchanger tubes. FEA can be applied to analyse stress, strain, deformation and temperature distribution in tube structures [31]. In failure assessment, FEA is useful for identifying high-stress regions such as tube-to-tubesheet joints, expanded sections, bends and regions affected by differential thermal expansion. When thermal and structural analyses are coupled, FEA can also predict how temperature gradients produce thermal stress and deformation. This is particularly relevant to steam generator tubes because thermal stress may interact with corrosion and tensile stress to accelerate crack initiation and propagation.

ANSYS is widely used in both CFD and FEA applications because it provides capabilities for fluid flow, heat transfer, thermal analysis and structural stress analysis [29]. The integration of CFD and FEA allows a more complete understanding of heat exchanger tube performance. CFD can be used to determine flow and temperature fields, while FEA can use this thermal information to evaluate deformation and stress concentration. This combined approach is useful for assessing whether thermal gradients, poor flow distribution or mechanical constraints may contribute to premature tube failure. Table 5 summarises selected CFD and FEA studies related to heat exchanger performance and failure assessment.

Table 5 Findings of CFD and FEA simulation studies

No.	Researchers	Topic	Summary
1.	Tusar et al. [32]	CFD study of heat transfer enhancement and fluid flow characteristics of laminar flow through tube with helical screw tape insert	This study used ANSYS Fluent to analyse the effect of helical screw tape inserts on heat transfer and fluid flow in a tube. The results showed that the enhanced tube produced a lower outlet temperature and more uniform wall temperature distribution, indicating improved heat transfer. Parametric analysis was also conducted by varying Reynolds number from 400 to 2000. The heat transfer coefficient and Nusselt number increased with Reynolds number and were slightly higher for the tube with helical screw tape inserts.

Table 5 Findings of CFD and FEA simulation studies (Cont.)

No.	Researchers	Topic	Summary
2.	Laiti and Zainulabidin [33]	The Evaluation of Shell-and-Tube Heat Exchanger using Computer Simulation for Oil and Gas Industry	This study evaluated the thermal performance of a shell-and-tube heat exchanger for oil and gas applications using CFD simulation in ANSYS Fluent. The simulation was used to model the heat exchanger and assess the effect of Malaysia's ambient temperature conditions on heat transfer performance. The results showed that the heat exchanger was able to maintain thermal performance despite environmental heat exposure. The findings were also consistent with previous literature, supporting the reliability of the CFD approach.
3.	Zhai et al. [19]	Failure analysis on 304 stainless steel tube of semi water gas preheater in coal chemical plant	This study applied FEA to investigate stress-related failure in a 304 stainless steel tube used in a semi water gas preheater. The simulation was conducted to determine whether sulphide stress corrosion cracking was supported by tensile stress along the tube. Thermal analysis was first performed to obtain the temperature distribution, followed by coupled thermal-structural analysis to evaluate thermal deformation. The results showed a maximum displacement of 0.75 mm, while static structural analysis indicated a tensile stress of 40.5 MPa along the tube.
4.	Li et al. [29]	Thermal analysis and stress analysis of the heat-exchange pipe based on ANSYS	This study used SOLID90 elements for steady-state thermal and stress analyses of a heat-exchange pipe. The highest temperature occurred on the pipe surface exposed to shell-side steam, highlighting the need for materials with good thermal conductivity and heat resistance. Structural analysis showed maximum thermal stress at the junction between the pipe and pipe plates, indicating that this region requires careful design attention

5.Preventive Measures and Engineering Implications

The reviewed failure mechanisms show that premature cracking of SA213-TP304L stainless steel tubes in steam generator applications may result from the combined effects of corrosive boiler feed water, localised corrosion, tensile or residual stress and thermal loading. Therefore, effective prevention should not depend on material selection alone. Instead, a combined approach involving water chemistry control, proper fabrication practice, operating condition monitoring, regular inspection and simulation-assisted assessment is required to reduce the risk of tube failure.

Boiler feed water quality should be strictly controlled because poor water treatment can promote corrosion, pitting, deposit formation and local overheating. Important water quality parameters such as pH, conductivity, dissolved oxygen, chloride concentration, hardness and scaling ions should be monitored regularly to ensure that the water remains within acceptable operating limits. Proper operation of demineralization, filtration, degassing and chemical treatment systems is also necessary to reduce the accumulation of aggressive ions and deposits on the tube surface. Since localised corrosion and pits may become initiation points for stress corrosion cracking, maintaining stable and clean boiler feed water is one of the most important preventive measures [22–24].

Stress corrosion cracking can be reduced by minimizing the combined presence of aggressive ions and tensile stress. In SA213-TP304L stainless steel tubes, chloride contamination should be carefully controlled because chloride ions can damage the passive oxide film and promote crack initiation under elevated temperature conditions. Fabrication quality is also important because residual stress, improper tube expansion and defects at tube-to-tubesheet joints may increase local stress concentration. Therefore, tube installation, expansion and welding procedures should be properly controlled to reduce residual stress and prevent gaps that may trap corrosive species [19–21,27].

Thermal stress should also be considered in steam generator operation because repeated heating and cooling may cause differential expansion, thermal fatigue and crack propagation. Stable operating conditions should be maintained during start-up, shutdown and load changes to reduce sudden temperature gradients across the tube wall and tube-to-tubesheet region. Good water circulation is also necessary to prevent local overheating and temperature oscillation. Critical regions such as tube bends, expanded sections and tube-to-tubesheet joints should receive more attention during inspection because these locations are more likely to experience stress concentration and thermal mismatch [25–28].

Regular inspection and failure monitoring are necessary to detect early signs of degradation before leakage or rupture occurs. Visual inspection, non-destructive testing and tube condition monitoring can help identify surface defects, wall thinning, deposits and crack indications. When failed samples are available, SEM and EDX analyses should be used to examine crack morphology and identify corrosion-related elements. SEM can reveal branched cracks, pits and trans granular or intergranular crack propagation, while EDX can detect aggressive elements such as chlorine, sulphur and oxygen. These analyses are useful for confirming whether the failure is related to stress corrosion cracking, boiler feed water corrosion or other degradation mechanisms [19–21].

Simulation tools can further support preventive maintenance and failure assessment. CFD can be used to predict flow distribution, temperature variation and possible stagnant or hotspot regions in the steam generator, while FEA can identify areas of high thermal stress, deformation and stress concentration. The integration of CFD and FEA is useful for identifying critical tube regions before failure occurs and for improving future design or operating strategies. Therefore, simulation methods should be used together with inspection data and material analysis to support root cause analysis and reliability improvement of SA213-TP304L stainless steel tubes [29–33].

Overall, the prevention of premature tube failure requires an integrated engineering approach. Good boiler feed water control can reduce corrosion and deposit formation, proper fabrication can minimize residual stress and crevice formation, stable operation can reduce thermal fatigue, and regular inspection can detect early damage. When combined with SEM, EDX, CFD and FEA, these measures provide a more reliable basis for preventing recurrent failure and improving the long-term performance of steam generator tubes.

6. Conclusion

This review examined the possible failure mechanisms of SA213-TP304L stainless steel tubes used in steam generator and heat exchanger applications. Although SA213-TP304L stainless steel is widely selected because of its corrosion resistance, weldability and suitability for elevated-temperature service, the reviewed studies show that the material may still experience premature failure when exposed to aggressive operating conditions. The main mechanisms associated with tube degradation are stress corrosion cracking, boiler feed water-related corrosion and thermal stress.

Stress corrosion cracking was identified as one of the most critical mechanisms because it can occur with limited visible deformation and may remain undetected until leakage or rupture occurs. The reviewed SEM and EDX findings showed that SCC is commonly associated with branched cracks, trans granular or intergranular crack propagation, surface pits, corrosion deposits and aggressive species such as chloride, sulphur and oxygen. Boiler feed water corrosion was also shown to play an important role because poor water treatment can introduce dissolved gases, chloride ions, hardness compounds and other impurities that promote pitting, oxide film breakdown, deposit formation and local overheating. These defects may later act as initiation sites for cracking.

Thermal stress is another important contributor to tube failure, particularly in regions subjected to temperature gradients, cyclic heating, poor water circulation and differential thermal expansion. Critical locations such as tube-to-tubesheet joints, expanded sections and bends are more susceptible to stress concentration and crack initiation. The reviewed literature indicates that premature failure is rarely caused by a single factor. Instead, it commonly results from the interaction between corrosive boiler feed water, localised corrosion, residual or tensile stress and repeated thermal loading.

Simulation studies using computational fluid dynamics and finite element analysis provide useful support for understanding heat exchanger tube failure. CFD can identify flow maldistribution, temperature variation, stagnant regions and possible hotspots, while FEA can predict deformation, thermal stress and stress concentration. When combined with SEM and EDX analysis, these tools provide a more complete approach for identifying the root cause of failure and improving the reliability of steam generator tubes.

Overall, preventing premature failure of SA213-TP304L stainless steel tubes requires an integrated engineering approach. Strict boiler feed water control, proper demineralization and degassing, minimization of chloride and oxygen contamination, good fabrication practice, proper tube expansion, stable operating conditions and regular inspection are necessary to reduce the risk of corrosion and cracking. The findings of this review provide useful guidance for improving failure prevention, maintenance planning and design assessment of stainless-steel tubes in steam generator and refinery heat exchanger systems.

Acknowledgement

The authors would like to express their sincere appreciation to Universiti Tun Hussein Onn Malaysia (UTHM) for supporting this research activity. The authors also acknowledge the Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, for providing the necessary facilities, technical support and academic environment that contributed to the completion of this work.

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