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The Study of Mechanical Failure in Helical Steam Generator of High Temperature Gas-Cooled Reactor (HTGR)

Muhammad Subhan[1,2], Topan Setiadipura[1], Mohammad Dhandhang Purwadi[1], Muksin Aji Setiawan[1], Tresna Priyana Soemardi[*,2], Ario Sunar Baskoro[2], Cecep Slamet Abadi [3], Evi Latifah[3], Nafisah Amalia[4], Yusi Amalia Renaningtyas[4].

[1]*Research Center for Nuclear Reactor Technology, National Research and Innovation Agency of Indonesia (BRIN), PUSPIPTEK Serpong, 15314, Indonesia*
[2]*Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Kampus UI Depok 16424, Indonesia*
[3]*Department of Mechanical Engineering, State Polytechnic of Jakarta, Kampus UI Depok 16425, Indonesia*
[4]*Department of Mechanical Engineering, State Polytechnic of Semarang, Tembalang Semarang 50275, Indonesia*

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A B S T R A C T

This research examines mechanical damage in helical steam generators, focusing on the causes, contributing factors, and impact of damage on the performance of the steam generator (SG). The research methodology involves analyzing various data sources, including scientific literature and previous nuclear industry experiences. The analysis results indicate that thermal stress, pressure fluctuations, material wear, and design errors can cause mechanical damage in helical SGs. Volumetric defects and leaks at pipe joints or welds are also potential issues. This study provides insights into failure mechanisms and highlights the importance of routine maintenance and inspection to prevent more serious failures. By better understanding these issues, innovative solutions can be developed to improve the performance and safety of helical steam generators in nuclear reactors.

1. INTRODUCTION

The International Energy Agency (IEA) focuses on the reliance on fossil fuels in most countries worldwide [1]. Clean energy has become a focal point of discussion at international forums to accelerate the energy transition [2]. The most advantageous alternatives are the diversification of energy sources and the enhanced technology that is more efficient and safer. One of the efficient, safe, and clean energy sources is nuclear energy. The use of nuclear energy for electricity production remains an attractive alternative for the current and future global energy matrix [3].

Improved nuclear reactor designs are being developed internationally, focusing on economic, security, and safety aspects [4]. The development of Generation IV nuclear reactors has also begun in several countries. For instance, China has developed the HTR-10 [5] and HTR-PM [6]. Both reactors are High-Temperature Gas-cooled Reactors (HTGRs) that use helium as a coolant and graphite as a moderator [7]. In these reactors, the steam generator (SG) used is the one-through-helical steam generator (OTHSG), which transfers heat from the primary to the secondary system [8]. When the nuclear reactor operates under normal conditions, critical components such as the steam generator play an

*Corresponding: Tresna Priyana Soemardi
Email:subhanbatan@gmail.com
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essential role in producing electricity [6]. However, the successful utilization of this technology is not without potential risks of mechanical failure. An in-depth understanding of the mechanical failure mechanisms in helical steam generators from nuclear reactors is crucial. These failures can be caused by various factors, including thermal stress, material wear, or even design errors [7]. Therefore, careful study of the causes and mechanisms of failure is essential.

An in-depth analysis of potential mechanical failures in helical steam generators can provide valuable insights into enhancing the reliability and safety of nuclear reactor operations. By understanding the factors that can lead to failure, appropriate preventive measures can be taken to minimize the risk of accidents and losses.

This research investigates the mechanical failures leading to leakage in helix-type steam generators. This study seeks to understand the causes of damage, identify contributing factors, and evaluate the impact of damage on SG performance. This study will explore various aspects related to mechanical failures in helical steam generators, including analyses of failures occurring during nuclear reactor operation, design errors, and other failures caused by different parameters. The research aims not only to understand mechanical failure phenomena but also to make a positive contribution to nuclear technology development. By better understanding of failure mechanisms, helical steam generator technology can be continuously improved to achieve higher safety standards.

2. THEORY

The first nuclear power plant to use a helical steam generator was the Bruce B Unit 1 nuclear power plant in Scotland, which began operating in 1974. This plant employed the Helical Coil Once-Through Steam Generator (HCOTSG) designed by Babcock & Wilcox. The HCOTSG is a type of steam generator with helical coils that twist once. This structure differs from conventional steam generators, which have straight pipes. In conventional steam generators, the fluid flow inside the pipes is laminar, meaning it is smooth and orderly. Laminar flow has lower heat transfer efficiency compared to turbulent flow. In HCOTSG steam generators, the fluid flow inside the pipes is turbulent, meaning it is irregular and swirling. Turbulent flow has higher heat transfer efficiency compared to laminar flow [9].

The HCOTSG steam generator exhibits higher heat transfer efficiency compared to conventional steam generators. This increased heat transfer efficiency can enhance the overall efficiency of electricity generation.

2.1 The Advantages of the Helical Coil Steam Generator Model

The Helical Coil Steam Generator is a tube that exhibits superior and more effective heat transfer performance compared to straight tubes due to its compactness and increased heat transfer coefficient. The improvement in heat transfer coefficient is a consequence of the coil curvature, which induces centrifugal forces to act on the moving fluid, leading to the development of secondary flow [10].

One of its primary advantages is the compactness of the helical-coil design. By winding the tubes into spirals, steam generators can be designed in a smaller space compared to conventional steam generators with straight tubes. Apart from space-saving benefits, this allows for more flexible placement within the reactor, maximizing space utilization and enabling better integration with other systems.

The helical-coil design also enhances structural and operational reliability. Because the tubes form tightly wound spirals, they possess greater structural strength and fewer potential weak points compared to straight tubes in conventional steam generators. This spiral design can reduce the risk of leaks or structural failures, thereby enhancing overall reactor reliability and safety [10].

2.2 The Weakness of the Helical Coil Steam Generator Model

One of the drawbacks to consider in the helical coil design model is that, although this design offers compactness and significant heat transfer enhancement, the tubes forming the helical coils are susceptible to fouling and plugging. Deposits accumulating on the tube surfaces can reduce the efficiency of the steam generator and necessitate intensive cleaning processes, potentially leading to operational disruptions. The helix model design entails an increased pressure drop due to the fluid flow having to adapt to the helical structure. Additionally, the complexity of helix equipment makes maintenance more difficult [11].

Furthermore, helical-coil steam generators are susceptible to common steam generator issues such as corrosion and tube leakage. The presence of helium as the primary coolant in HTGRs can also increase the risk of corrosion on steam generator components, especially if there is a mixing between primary and secondary fluids [12]. Tube leaks are a common failure in helical-type steam generators. These leaks occur when there is a breach in the tubes carrying hot fluid within the steam generator. These leaks can result in the mixing of fluids inside the tube with the shell fluid. Drastic temperature changes in the tubes can cause differential expansion between the tube and the support material. These temperature changes can lead to significant thermal stress on the tube and ultimately result in leaks [13].

3. METHODOLOGY

The Steam generator in this study will be based on relevant criteria such as the materials used and operational history. Samples will be carefully chosen to encompass sufficient variation in relevant characteristics. Data will be collected from various sources, including scientific publications, books, standard codes, and the Internet. The data will be analyzed to identify the types and levels of damage occurring in the structure and materials of the SG. The results of the analysis will be interpreted to draw research findings. These findings will be compared with relevant literature and previous experiences in the nuclear industry. The study will conclude by summarizing of the analysis results and key findings. These conclusions will provide insights into the issues of damage to the structure and materials of SG shells and tubes in nuclear reactors.

4. RESULTS AND DISCUSSION

The loads on the steam generator tubes include several factors that need to be considered in the design and analysis, as shown in Fig. 1. First, the weight of the tube structure and related components becomes the dead load that must be supported. The structural load is generally divided into two parts: the weight of the SG vessel structure and the internal structure, which consists of the helical and helium circulator components [14].

Secondly, there are the forces generated by the fluid flow through the tubes. In HTGR-type reactors that use helium as the working fluid, the helium flow will circulate through the inner part of the SG and cause vibration of the helical tubes. Then, within the helical section, the feed water will experience three phases: economizer, evaporation, and superheater. Due to the presence of these two fluids, the helium on the outer side of the helical section and the water on the inner side, a significant pressure difference will be induced [15].

The third component is the force from earthquakes, which will cause harmonic vibrations on the inner and outer parts of the SG. According to the IAEA-TECDOC-1668 guidelines on the Safety Classification of Structures, Systems, and Components in Nuclear Power Plants [16], the components in a nuclear reactor must be able to withstand an earthquake. This is highly important to ensure the safety of the workers and the proper maintenance of the plant.

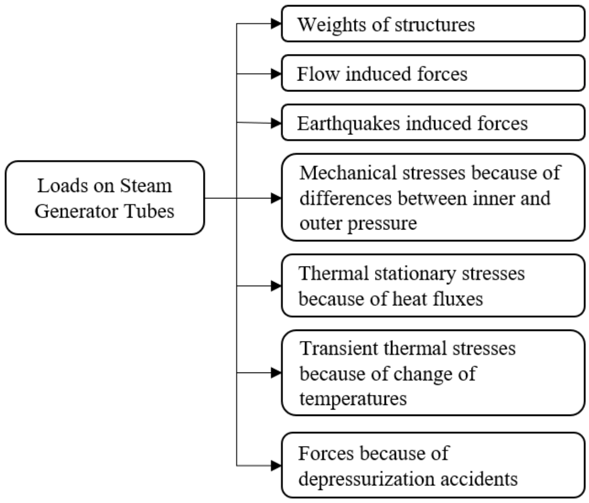

Fig.1. Difference Load Steam Generator [12]

The fourth aspect is the mechanical stress caused by the difference between internal and external pressures, which must be carefully considered. The design temperature and pressure of the primary helium loop are 800 ℃ and 8 MPa, while those of the secondary loop are 600 ℃ and 18 MPa [17]. This pressure difference will result in significant stress if the helical construction design is not well-engineered.

Furthermore, the steady-state thermal stresses due to heat flow and the transient thermal stresses due to temperature changes must be carefully considered. Finally, a depressurization accident can cause additional forces that need to be addressed. All these factors must be accounted for to ensure the safe and reliable operation of the steam generator tubes [18].

Mechanical failure in the helical steam generator can occur in the pipes, joints, or heating elements. Such failures can affect the efficiency reduction of the steam generator and the safety of the nuclear power reactor. Various factors, including thermal stress, pressure fluctuations, and material fatigue, can cause these failures. Repeated heating and cooling cycles can cause significant thermal stresses on the piping system, which can lead

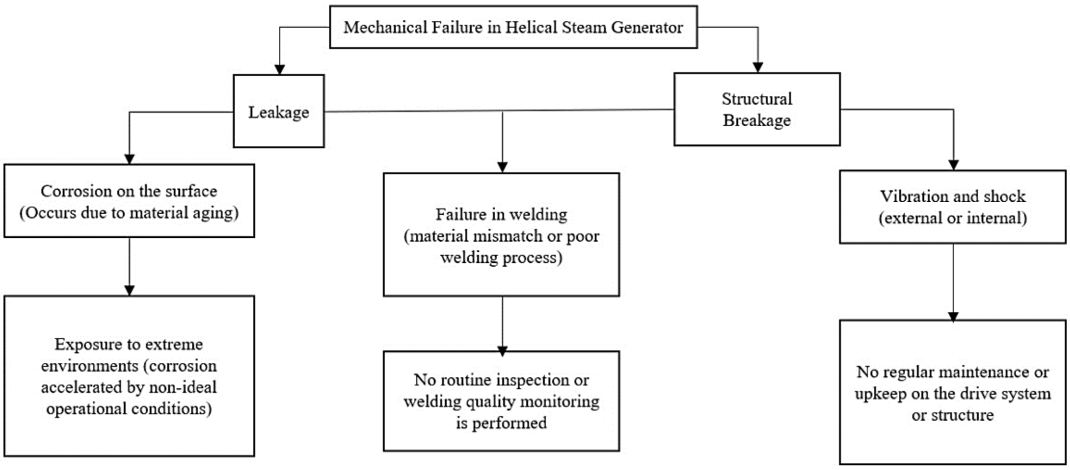

Fig. 2. FTA Mechanical Failure Helical SG

cracking or deformation over time [19]. Pressure fluctuations within the steam generator can cause mechanical vibrations that potentially loosen the joints or even cause pipe rupture. In addition to pressure fluctuations, the influence of the flow passing through the helical structure can result in vibration and deformation. The potential mechanical failure mechanisms associated with Flow-Induced Vibrations (FIV) in critical components such as the helical steam generator in nuclear reactors include collision between the vibrating tubes, wear due to friction between the tubes and their support structures, and structural fatigue due to repeated vibrations. These three mechanisms can cause serious damage to the helical steam generator, which in turn can threaten the operational safety of the nuclear reactor and affect the performance of the overall system [20].

In the helical geometry, volumetric defects such as elliptical wear, square wear, and conical wear can also cause mechanical failure in the helical steam generator during nuclear reactor operations. These defects can occur due to friction between the steam generator tubes and supporting structures, as shown in Fig. 3. The depth of the defect, the length of the defect, and the angle of the defect are key parameters that affect the load-bearing capacity of the tube. The depth of the defect is the most influential parameter on the tube's failure pressure. Additionally, the length of the defect and the angle of the defect also affect the tube's load-bearing capacity.

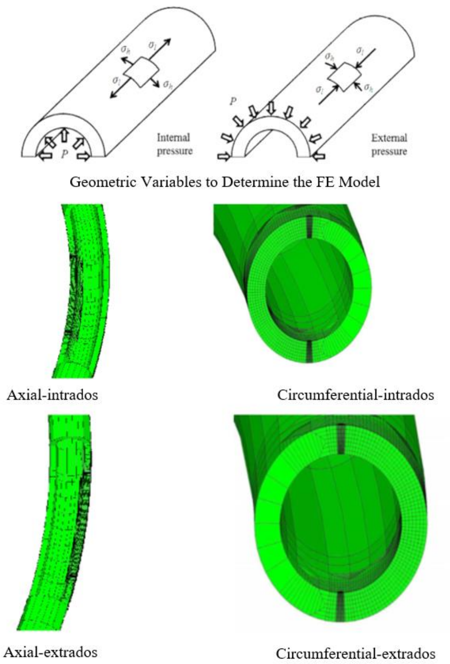

Fig.3. FE Model of Through-Wall Cracked Tubes for Various Locations [13]

Leaks can also occur at pipe joints, welding joints, or within the pipe layers themselves. Leakage in the helical steam generator can result in steam loss and its mingling with other fluids inside the shell. Mechanical failures in the helical steam generator can have serious consequences. Material fatigue is also a critical factor, as continuous exposure to high-temperature steam and corrosive environments can compromise the structural integrity of the materials used in steam generator construction. Selecting the SG materials capable of withstanding such harsh conditions is crucial to prevent mechanical failures. Regular maintenance and inspections are vital for identifying signs of wear early on, enabling timely repairs or replacements before more severe failures occur.

Mechanical failures in helical-coil steam generators, as illustrated in Fig. 3, can lead to various undesirable events, thereby disrupting performance and operational safety. The two main categories of failures recorded are tube failures and generator structure failures. Examples of tube failures include leaks, which are often caused by surface corrosion due to material aging. This corrosion process can weaken the integrity of the tubes, eventually leading to potentially serious leaks. On the other hand, structural failures, such as fractures in the structure, usually arise from different causes. For instance, weld failures can occur due to material incompatibility or poor welding processes, which can compromise the structural integrity of the steam generator.

Additionally, vibrations and shocks, whether from external or internal sources, pose further risks that can lead to structural damage. Non-ideal operational environmental conditions, such as exposure to extreme environments, can accelerate the corrosion process and exacerbate the risk of failure. Lack of regular inspections or monitoring of weld quality and conditions can also increase the risk of tube or structural failures in the generator. Neglecting routine maintenance on the drive system or structure can further heighten the vulnerability of the steam generator to overall mechanical failure. Therefore, a deep understanding of these factors and the implementation of appropriate preventive measures are crucial to maintaining the reliability and operational safety of helical-coil steam generators in nuclear reactors.

5. CONCLUSION

This study emphasizes a deep understanding of the mechanisms of mechanical failure in helical-coil steam generators within the context of nuclear reactor operations. By focusing on risks such as corrosion, tube leaks, and structural failures, this research highlights the importance of identifying the causal factors and the impact of damage on system performance. Loads on the steam generator (SG), including structural loads, stress due to internal and external pressure differences, the effects of significant heat transfer loads, earthquakes, and potential nuclear reactor accidents, are crucial considerations as they contribute to mechanical failure. By better understanding the weaknesses and strengths of helical-coil designs and implementing appropriate preventive measures, efforts can be made to enhance the safety, reliability, and operational efficiency of steam generators in nuclear reactors.

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AUTHOR CONTRIBUTION

All authors contributed as the main contributors to this paper. All authors read and approved the final version of the paper.

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