Flange Leak Investigation on Kettle Heat Exchanger Operating at Low-Temperature Condition

Andi D. Prasetyo* and Fauzan Fitra

Technical Department, PT. Badak NGL, Bontang, Indonesia
Email: adprasetyo@badaklng.com (A.D.P.), fauzanfitra@badaklng.com (F.F.)
*Corresponding author

***Abstract*—A kettle-type evaporator heat exchanger (TEMA BKU) is utilized to cool natural gas on the tube side from −34 °C to −55 °C, using Multi-component Refrigerant (MCR) as the cooling medium on the shell side. During operation, the heat exchanger encountered recurrent leakage issues at the channel-tubesheet bolted flange joint, particularly during the cooling down process. The primary objective of this research is to identify the causes of leakage and to propose viable solutions for minimizing the risk of leakage. To achieve this, Finite Element Method (FEM) was employed as an investigative tool to analyze the mechanical factors contributing to leakage. Results from the FEM investigation indicate that the leakage in the bolted joint of the heat exchanger is attributed to reduce of gasket seating stress as an effect of bolts self-loosening, influenced by several factors such as bolts plastic deformation, flange stiffness characteristics, and uneven temperature distribution. The study also reveals that gasket seating stress decreases after each shutdown compared to the previous start-up due to plastic deformation on bolts and flange gasket surfaces after shutdown. The findings of this study provide critical insights into the mechanical behavior of bolted flange joints in heat exchangers and offer guidance for their improved design and maintenance, enhancing operational reliability.**

***Keywords*—flange, bolt, leakage, gasket, low temperature, kettle heat exchanger**

I. Introduction

The kettle boiler type heat exchanger (TEMA type K) is often used as a reboiler in distillation columns and is also frequently employed as an evaporator [1]. In Liquified Natural Gas (LNG) plants, conventional kettle heat exchangers are commonly utilized in low temperature condition, for cooling process fluids using refrigerants with lower boiling points than the process fluid temperatures. Kettle heat exchangers offer advantages in that they are relatively insensitive to hydraulic systems and can operate efficiently with a small temperature driving force. On the downside, their low circulation makes them susceptible to fouling, and their larger size makes them relatively expensive [2].

Most pressure vessels are vulnerable at their bolted flange sections where several leaks and ruptures have occurred at flanges in pressure vessels and pipes [3]. Bolted flange sections, in general, are the most susceptible when it comes to strength and sealing capability [4]. The design of bolted flanges is governed by common official standards and codes like ASME BPVC Section VIII Div.1 and EN 13345-3. However, even if the HE is designed in accordance with these standards, it is not a guarantee that the HE will not experience leaks during operation. The rules in the Code are based on simplifications and assumptions, which cannot predict the behavior of flanged joints [5, 6]. The standards typically consider only static loading and steady state conditions for the designing of flange system [5].

Various studies have proposed methods to improve the existing flange design methodologies in standards. Jinescu *et al.* [5] proposed a method for calculating flange joints under special conditions like temperature differences between flanges and bolts, thermal loading, and cyclic loading conditions. Koves [6] proposed a design methodology considering external loads, consistent with the ASME BFJ approach.

Studies have analyzed flange design performance considering factors like external bending moments [7–10], temperature [11, 12], material elasticity of bolts, flanges, and gaskets [13, 14], gasket seating stress, internal pressure [15], and other factors as well. Wu *et al.* [10] found that low bolt pre-load values can lead to more variable bolt tensions, significantly affecting flange and flanges' interface contact pressure distribution. Li *et al.* [13] researched preload relaxation models due to elastic interaction among tightened bolts with different tightening sequences. Zhu *et al.* [16] developed an analytical model to optimize initial bolt tightening for achieving uniform final preload. Grzejda [17] created a model of a multi-bolted system to predict the effect of tightening sequence on preload value and contact pressure.

An analytical method proposed by Cheng *et al.* [18] aimed to estimate the gasket leak rate using deformation models of the entire flange. Analysis results from

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Girkar *et al.* [19] highlighted the vulnerability of flange channels in HE, particularly in partitioned areas.

The selection of the type and material of the gasket also has an important influence on the sealing performance of a flange system. Jaszak [14] modeled expanded graphite material in SWG gaskets, an important gasket material especially at low temperatures. Krishna *et al.* [20] simulated the sealing performance of bolted joints with spiral wound gaskets using various types of fillers.

This paper addresses the issue of a real case of repetitive leakage from the channel-tubesheet-shell flange joint of a kettle-type Heat Exchanger (HE) operating at low temperatures. Kettle-type heat exchangers are commonly used for evaporating or condensing fluids within the shell, resulting in relatively stable temperatures due to operating within the range of their saturated temperatures. However, in the case of the kettle HE discussed in this paper, the fluid entering the shell is a Multi-component Refrigerant (MCR), consisting of several components such as Nitrogen, Methane, Ethane, etc., each with its own boiling point. This composition leads to a significant temperature difference between the inlet and outlet shell fluids. Such variations present unique challenges in maintaining the integrity, especially in terms of thermal stresses and potential impacts on the sealing performance of the flange joint between channel, tubesheet, and shell.

The Finite Element Method (FEM) analysis was conducted to investigate the causes of leakage in the bolted flange joint. The criteria for leakage were determined using a methodology similar to that employed by Girkar *et al.* [19], involving a comparison between the gasket seating stress (contact pressure) and the “mp” value, which is the product of the gasket’s “m” factor and the “p” vessel’s design pressure.

II. Problem Description

As an effort towards production optimization, a kettle evaporator type Heat Exchanger (TEMA type BKU) was installed in an LNG plant to lower the temperature of natural gas (feed gas) from −33.9 ºC to −55 ºC, using a Multi-Component Refrigerant (MCR) for the process. The designed MCR inlet temperature to the heat exchanger’s shell is −81.1 ºC while the outlet temperature of the MCR is −57 ºC (see Fig. 1). Data regarding the HE and process fluids is presented in Table I.

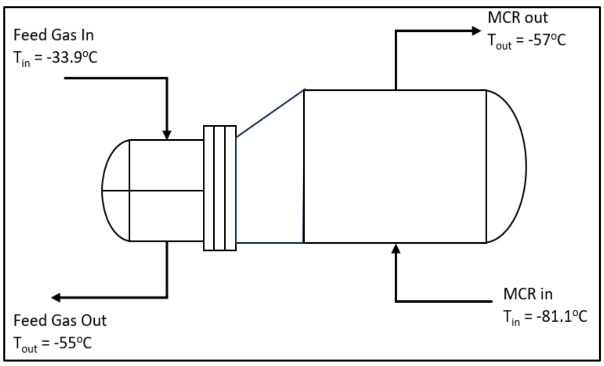

Fig. 1. Schematic process diagram of kettle HE.

TABLE I. Process and Design Data Summary

	Parameter	Shell Side	Tube Side
Performance Data	Fluid Name	MCR	Feed Gas
	Fluid Qty, Total (1000kg/hr)	96.78	380.88
	Temp. (In/Out) (ºC)	−81.10 −57.00	−33.90 −55.00
	Inlet Pressure (kgf/cm^{2}A)	3.782	37.523
	Heat Exchanged (kW)	9040	
Construction Data	Design Pressure (kgf/cm^{2}G)	10.50	49.20
	Design Temp (ºC)	66.00	66.00
	TEMA Type	BKU	
	Number of Tubes	2043U	
Material Data	Tube	SA-213M TP304L	
	Tubesheet	SA-965M F304	
	Shell	SA-204M 304	
	Shell Girth Flange	SA-182M F304	
	Channel	SA-240M 304	
	Channel Girth Flange	SA-182 F304	
	Bolt	SA-320 B8	
	Gasket	Graphite-filled kamm profile	

During operation, HE experienced recurrent leaks at the channel-tubesheet flange joint, especially during process start-up or during HE cooldown. Extensive efforts had been made, including precise bolt tightening using tensioning tools, girth flange gasket type replacement from double-jacketed metal gaskets to kammprofile gaskets, and performing machining repair on flanges’ gasket faces to enhance the flatness of the gasket face surfaces.

The result of the machining of the flange gasket face surface (channel side) can be seen in Fig. 2. According to ASME PCC-1 Appendix D [21], T1 is the maximum difference between the highest and lowest measurement for the gasket face’s circumferential measurement. The acceptable value for T1 according to the standard is T1 < 0.006”. It can be seen in Fig. 2 that after machining, T1 is 0.005”, which is within the tolerance of the ASME PCC-1 standard. However, the HE still experienced leakage at the flange during subsequent operation.

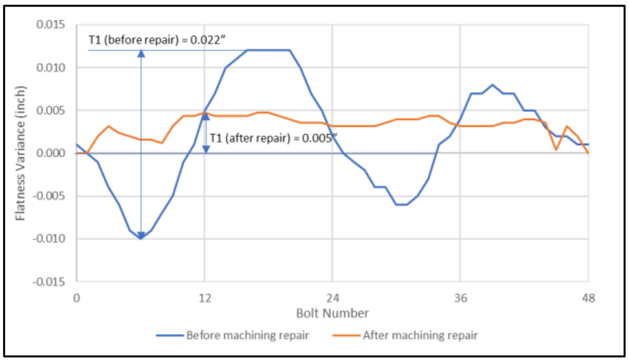

Fig. 2. Flatness variance of flange gasket face (channel side).

The equipment owner and manufacturer conducted an investigation to determine the cause of the leakage from a design perspective. The evaluation results indicated that the heat exchanger’s design fully met the technical requirements standardized in the ASME Code and TEMA Standard. Therefore, further efforts were necessary to conduct a Finite Element Analysis (FEA) to identify the root cause of the issue.

III. Finite Element Modeling

A. Finite Element Model & Material Properties

Due to the similarity in the mechanical properties of the heat exchanger materials, the main material of the HE was assumed to be the same as SA-182M F304, except for the gasket material, which was assumed to be graphite. The non-linear behavior of materials was determined by using Ramberg-Osberg relation [22]. Table II shows mechanical properties of the materials.

TABLE II. Mechanical Properties of Materials

Properties	SA-182M F304	Graphite
Density (ton/mm^3)	7.8E−09	1.8E−09
Poisson's ratio	0.29	0.17
Coefficient of thermal expansion (mm/mm°C)	1.7E−05	2E−06
Thermal conductivity (W/m°C)	0.015	0.025
Young's Modulus (MPa) @ Temp		
−100 °C	209000	41000
−81 °C	207495	41000
−55 °C	205437	41000
−33 °C	203695	41000
−30 °C	203458	41000
−29 °C	203379	41000
20 °C	199500	41000

The FEM analysis was performed using ABAQUS software, where the model was constructed based on the dimensions from the drawing, as shown in Fig. 3. The tubes were not explicitly modeled but were assumed to behave as springs with a given stiffness value "K" that was assigned to the tubesheet.

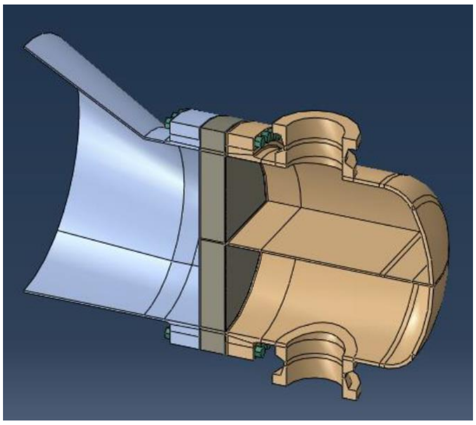

Fig. 3. Mechanical model of HE.

B. Thermal Load

Thermal analysis was conducted to represent the temperature load during the occurrence of the leakage incident. Based on the results of the simulation process, temperature distribution within the HE was obtained, both during startup conditions and during operational conditions, as illustrated in Fig. 4.

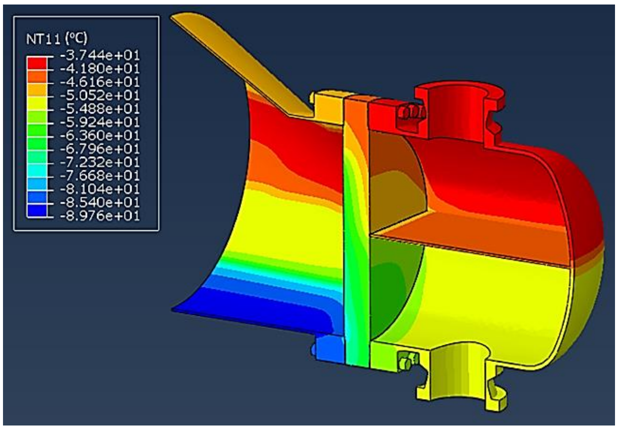

Fig. 4. Temperature distribution during operating condition.

C. Load Condition

The load conditions to simulate the general operational circumstances of the heat exchanger include:

- Hydrostatic condition: to simulate the effect of internal pressure load to the change of bolt tension and gasket seating stress on flange. It was initiated by applying pre-tension to bolt models, followed by internal pressure to the channel side. Metal temperatures were set to ambient temperature (30 °C)
- Start-up condition: initiated by applying pre-tension to bolt models, followed by internal pressure to the channel and applying the temperature distribution during the start-up phase, i.e. channel temperature was set to −33.9 °C while shell temperature was set to ambient temperature.
- Operating condition: continued by applying pressure to the shell and managing the temperature distribution as shown in Fig. 4.
- Shutdown condition: pressure and thermal loads are removed from the HE (back to ambient condition).

IV. Result and Discussion

A. Flange Deformation and Gasket Pressure Distribution

When bolts are tightened to a specified tension, it results in the deformation of the flange, with the degree of deformation depends on the stiffness of the channel, tubesheet, and shell under specific loading conditions. Fig. 5 depicts the typical deformation of the HE flanges after pre-tensioning, where there is bending stress applied on both the flange and bolts. The bending deformation of the flange becomes non-uniform with the presence of partitions and nozzles in the chamber. Basically, the stiffness on areas with partitions and nozzles is higher, making the flange to be less deformed compared to areas with lower stiffness.

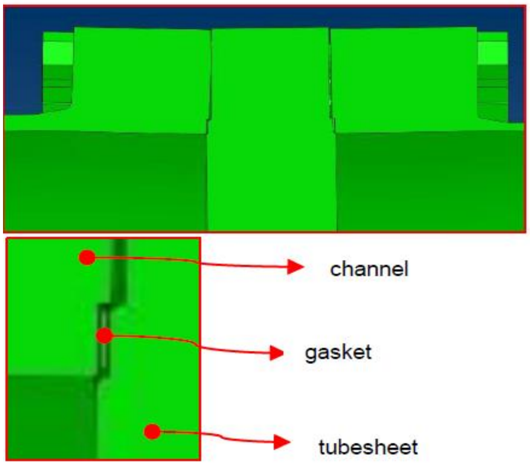

Fig. 5. Typical deformation on flanges due to bolt tightening.

The consequence of bending deformation on the flange is non uniform pressure acting on the gasket face, which the outer radius gasket pressure is higher than inner radius as shown in Fig. 6.

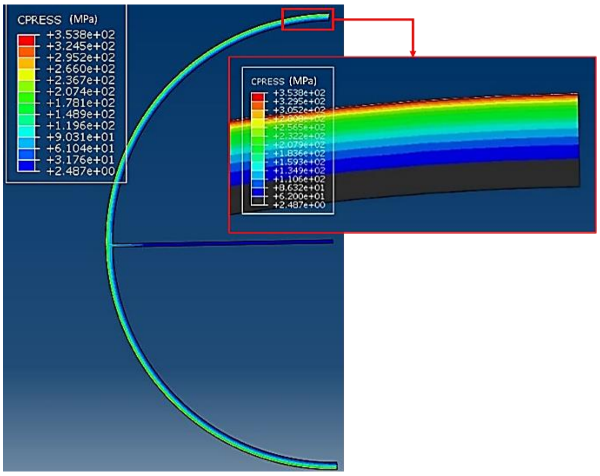

Fig. 6. Stress distribution on gasket

B. *Effects of Internal Pressure on Flange Leak*

The effect of internal pressure on bolt tension of the heat exchanger model can be observed in Fig. 7. For reference, the design bolt tension according to ASME BPVC Section VIII Div.1 [23] for this heat exchanger is 425 kN, which is shown by the dashed red line in Fig. 7.

For simulation purpose, the bolts are pretensioned to 450 kN (green line). After internal pressure (hydrotest pressure) is set to channel side, the resulting bolt tension is indicated by "Hydrotest 1" line (orange line). After that, pre-tension load is increased to 510 kN (represented by "Pre-tension 2", purple line). The resulting bolt tension under hydrotest pressure is shown by "Hydrotest 2" (yellow line).

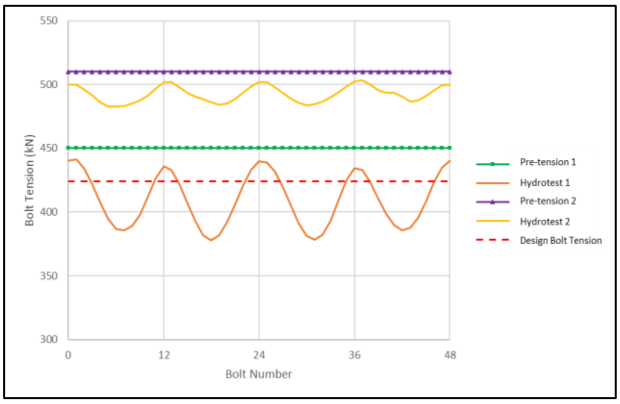

Fig. 7. Effect of internal pressure on bold tension.

The effect of internal pressure load on gasket contact stress from each of the above steps can be seen in Figs. 8 and 9. According to the specifications, the kammprofile gasket has an "m" value of 3.75, while pressure design "p" is 4.9 MPa, resulting in an "mp" value of 18.4 MPa. Leakage potential will arise if the gasket seating stress falls below the "mp" value.

In Figs. 8 and 9, it is demonstrated that even if bolts are tightened in accordance with the ASME's bolt tension design, leaks during hydrotesting may still occur due to a decrease in bolt tension when the flange deforms due to internal pressure load, especially in the 90° and 270° areas (partition area). This simulation result is in line with the research by Wu *et al.* [10], where a lower bolt tension value will result in a greater decrease in bolt tension due to the bending moment at the joint, which of course causes a more significant effect on the flange-to-flange interface contact stress distribution. Additionally, this condition confirms findings similar to the research by Girkar *et al.* [19], where the pass partition is a vulnerable area because the flange has greater stiffness in that area. High stiffness results in the gasket not receiving much compression in the partitioned area.

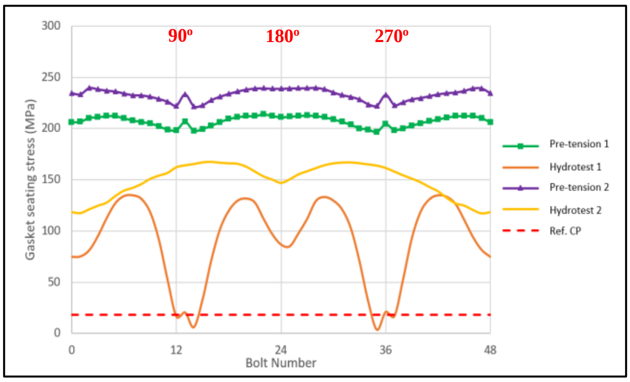

Fig. 8. Effect of internal pressure on gasket seating stress.

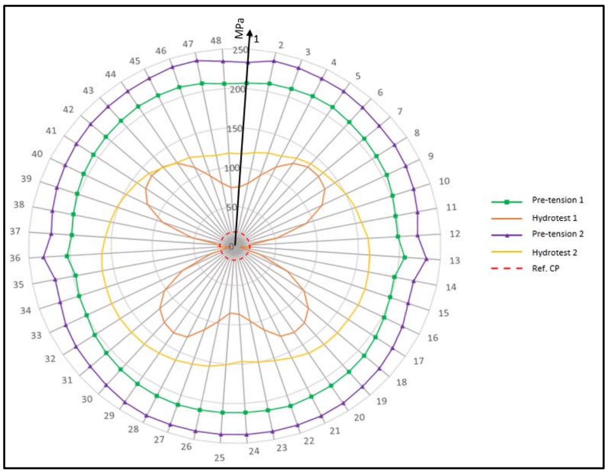

Fig. 9. Radar chart of gasket seating stress distribution under internal pressure load.

C. *Effects of Operating Loads (Combination between Internal Load and Thermal Load) on Bolts and Gasket*

During operating condition, the heat exchanger is subjected to combination of internal pressure and thermal loads. The variations in bolt tension during start-up, operation, and shutdown conditions can be observed in Fig. 10. Meanwhile, the distribution of gasket seating stress can be seen in Fig. 11.

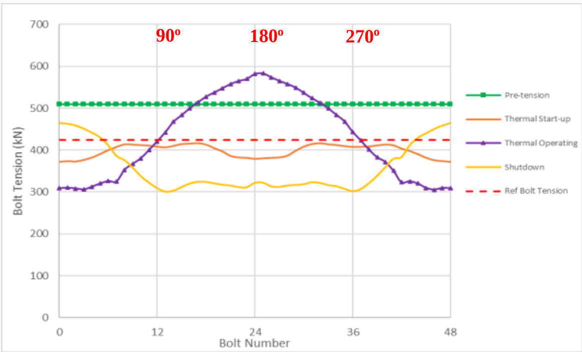

Fig. 10. Effect of internal pressure and thermal load on bolt tension.

In Fig. 10, it is shown that bolt tension undergoes considerable variation during the operating condition of the HE. As a note, the pre-tension of the bolts is uniformly set at 510 kN (green line). In the start-up condition (orange line), the bolt tension undergoes a significant change, primarily influenced by the internal pressure load, while the effect of the temperature load is not very significant. A substantial change in tension occurs when the HE enters the operating condition (purple line), where in this condition, the effect of the thermal load becomes more significant with the presence of a temperature gradient on the flange. In the shutdown condition, the distribution of bolt tension is indicated by the yellow line.

Figs. 11 and 12 show reductions in gasket seating stress during the start-up, operating, and shutdown conditions. The weakest seating stress during operation is observed at the 135° and 225° positions, indicating potential leak spots in the flange connection.

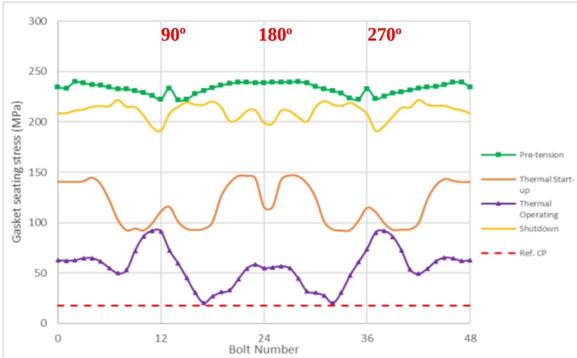

Fig. 11. Effect of internal pressure and thermal load on gasket seating stress.

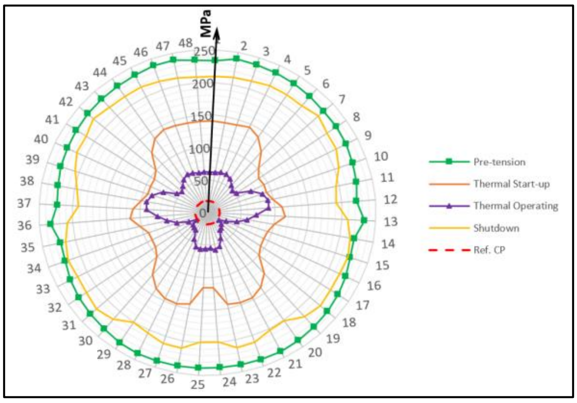

Fig. 12. Radar chart of gasket seating stress distribution.

Observing the cross-sectional view of the tubesheet as depicted in Fig. 13, the 135° and 225° directions correspond to the location where the bottom row of the tube bundle resides. Given that the MCR fluid enters from the bottom of the shell, heat transfers between the fluid inside the tubes and the MCR begins in this area. It can be inferred that the flange is at risk of leaking in these areas due to the initiation of considerable temperature gradients across the metal surfaces in these zones. This simulation result is consistent with the research conducted by Lošák *et al.* [11], where an uneven temperature distribution leads to a decrease in the gasket contact stress.

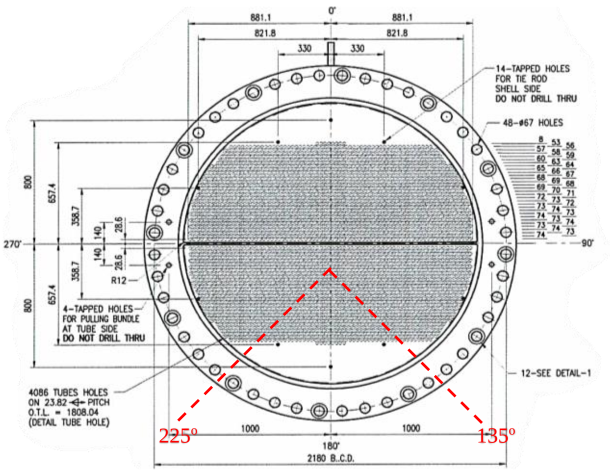

Fig. 13. Tubesheet section view.

In Figs. 10 and 11, the yellow line represents the condition of bolt tension and gasket seating stress after being in the shutdown condition. Both bolt tension and gasket seating stress do not revert to their original pre-operational values but instead show a decline. This indicates the occurrence of non-linear deformation in both the bolt and the flange of the heat exchanger.

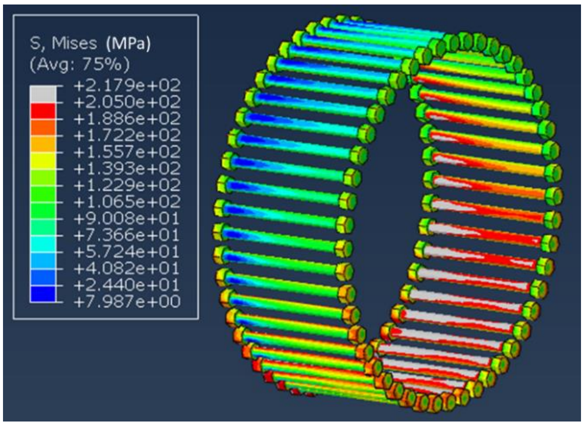

Fig. 14. Stress distribution on bolts (grey color indicates overstressed area).

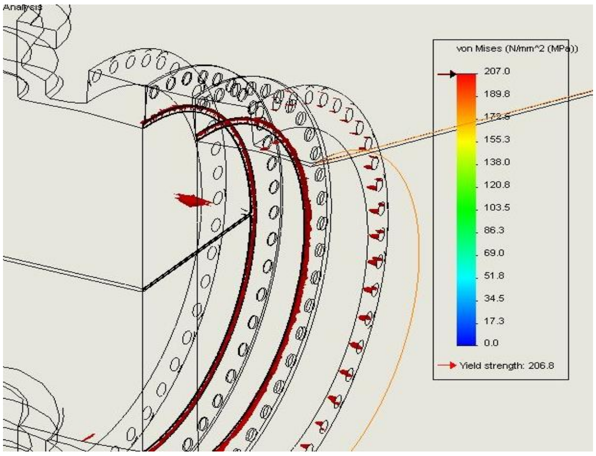

Fig. 15. Overstressed area on flange gasket faces (indicated by red colored area).

Figs. 14 and 15 show the stress distribution during the shutdown condition, where these figures indicate the presence of local overstress on the bolt and gasket face. The presence of overstress, which causes plastic deformation of the bolts and the flange surface, results in the gasket compression and bolt stress not returning to their initial values prior to the operation of the HE.

D. Discussion and Mitigations

Based on the above evaluation, the leakage condition in the kettle HE is actually an inherent issue, a combination due to the inappropriate selection of HE and bolt materials, and the unusual operating design of the HE compared to other typical kettle type HE. The bolts and the HE are made of SS 304 material, which has a lower yield strength compared to general carbon steel. However, in this case of the HE, SS 304 was chosen for the purpose of cold temperature design (lower than −46°C, which is the limit of low temperature carbon steel materials). Basically, if there is a leak at flanges, it can typically be resolved by tightening the flange bolts uniformly. However, in this particular HE case, such tightening needs to be approached with caution due to the overstressed conditions on the bolts and flanges. The overstress condition on the bolts can be addressed by replacing bolts from SA-320 Grade B8 to SA-320 Grade L7. For reference, a comparison between the material specifications of SA-320 Grade B8 and Grade L7 is shown in Table III.

TABLE III. BOLT MATERIAL PROPERTIES

Material Spec	Grade	Yield Strength (MPa)	Tensile Strength (MPa)	Hardness max (HBW)	Note
SA-320	B8 (Cl.1)	205	515	223	Old bolts
SA-320	L7	725	860	321	New bolts

However, to address the overstress that causes deformation on the flanges, replacing the material is certainly not a viable option for this HE. Mitigation can only be done by re-machining the flange to correct deformations on the gasket face surface, in order to comply with the flange surface flatness standards in ASME PCC-1 Appendix D, as an effort to reduce the risk of leakage during operation.

The equipment owner has scheduled the replacement of bolt material from SA 320 Grade B8 to SA 320 Grade L7 at the next HE's shutdown opportunity. The results of the above analysis are also used as a reference by the equipment owner in handling recent leakage cases. Since the tightening of the bolts on this HE flanges is done using a bolt tensioner tool, the trend of bolt tension can be monitored and checked each time a leak occurs. If the bolt tension exceeds a certain limit (540 kN according to the procedure), the equipment owner will schedule flange machining repair to improve the flatness of the gasket face surface of the flanges.

V. CONCLUSION

The investigation into the leakage of the HE was conducted using a Finite Element Method (FEM) approach. The study focused on the variation in bolt tension as well as gasket seating stress throughout different operational stages of the HE, including start-up, steady-state operation, and the shutdown process.

The analysis revealed that the gasket underwent a decrease in seating stress under internal pressure load condition and during the HE's operational phase. When under internal pressure load only (such as hydrostatic test), the flange weak points were located at partition sides (90° and 270°). While during operating, the most susceptible points being in the regions at 135° and 225°. These areas represent the initial contact points between the shell fluid and the tubes, located at the lowest part of the tube bundle.

Plastic deformation was observed on the bolts and the gasket face of the flange, leading to a reduction in both bolt tension and gasket seating stress compared to their pre-operational levels. Besides operational conditions, this issue is also attributed to a poor decision in material selection, reflecting a lack of engineering judgement during the initial design of the HE.

This case study reaffirms that designing a flange based on standards does not guarantee the sealing performance of the flange. Therefore, during the engineering and design stage, it would be prudent to conduct a more in-depth evaluation of the potential effects of internal pressure or significant temperature gradients on the flange surface.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Andi D. Prasetyo collected data, performed analysis, and drafted the manuscript; Fauzan Fitra supervised the manuscript writing and reviewed the manuscript; all authors had approved the final version.

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