Identifying Risk Management Locations for Synthetic Natural Gas Plant Using Pipe Stress Analysis and Finite Element Analysis

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Abstract - While they are becoming more viable, synthetic natural gas (SNG) plants, with their high temperatures and pressures, are still heavily dependent on advancements in the state-of-the-art technologies. However, most of the current work in the literature is focused on optimizing chemical processes and process variables, with little work being done on relevant mechanical damage and maintenance engineering. In this study, a combination of pipe system stress analysis and detailed local stress analysis was implemented to prioritize the inspection locations for main pipes of SNG plant in accordance to ASME B31.3. A pipe system stress analysis was conducted for pre-selecting critical locations by considering design condition and actual operating conditions such as heat-up and cool-down. Identified critical locations were further analyzed using a finite element method to locate specific high-stress points. Resultant stress values met...
ASME B31.3 code standards for the gasification reactor and lower transition piece (bend Y in Fig.1); however, it is recommended that the vertical displacement of bend Y be restricted more. The results presented here provide valuable information for future risk based maintenance inspection and further safe operation considerations.

**Key words**: SNG, Synthetic Natural Gas, Finite Element Analysis, Pipe Stress Analysis, Maintenance

### 1. Introduction

The number of synthetic natural gas (SNG) plants has been increasing across the world since the 1980s in parallel with new technological developments and is driven by the increasing demand for alternative energy sources. Those countries actively implementing the SNG technology such as USA and China, have numerous SNG plants and are planning to build many more in the near future (Yang & Jackson 2012). SNG plants are supported as a solution to the natural gas demand of the urban population and are helping shift air pollution to the outskirts of the cities (H. Li et al. 2014). However, coal based SNG plants does not offer a sustainable solution to the CO2 reduction yet (Ding et al. 2013) as this technology is still immature and depends heavily on research and development (Huo et al. 2013). Most of the literature investigates the characteristics of the chemical reactions occurring in these plants and focuses on system optimization (Koytsoumpa et al. 2015; He et al. 2013; Swain et al. 2011; S. Li et al. 2014) there is little research conducted on the mechanical damage and maintenance engineering for SNG plants.

This paper presents the two step pipe stress analysis (Yoon et al. 2015) of an SNG plant under operation for inspection location selection similar to risk based inspection (RBI) (Dou et al. 2017; Chang et al. 2005) in the most basic sense however it only focuses on stress analysis. Plant components selected for consideration are those that would have the most serious effect on the plant in case of a malfunctioning or wrong operation (Keiser et al. 1994; Hirano 2006). First, a pipe system stress analysis was conducted for identifying critical locations at which relatively high stress were generated during operation. For this, AutoPIPE V8i was used in accordance with the ASME B31.3 process piping design code. Subsequently, a finite element analysis (FEA) was conducted for these critical locations using ANSYS 16.0 Workbench to get a better understanding of cause of the high stress and the distribution of the high stress points for future inspections and maintenance.

### 2. System specifications

For practical reasons, each component of the SNG plant, starting from the gasification reactor and until to the boiler, has given a short name since the original names were quite long. Main pipes were named as pipe A, B and C, and similarly bends were called bend X, Y and Z. A 3D model of the plant layout including the actual component names is shown in Fig 1.

The gasification reactor is the structure where the highest temperature values are observed, reaching over 1400°C. The bottom part of the reactor is not attached to any stationary component and is used for slag removal. The reactor has an inner refractory lining to protect the outer shell from high temperatures. Thus, the shell is not exposed to temperatures over 200°C as long as the lining is intact. Skin temperature during operation was about 140~170°C depending on the operating mode. Owing to the gasification of the coal, pressure values as high as 5 MPa are expected inside the gasification reactor. These high temperatures subside to around 1000°C and 870°C as the produced gases travel through the pipe B and C respectively, which also have pro-
During overhaul period for maintenance, shell skin of the SNG plant need to be inspected by non-destructive method or by field-replication method for ensuring structural integrity of the shell pipes. The current analysis was conducted to identify the most important inspection points where stress driven damage can possibly occur (Yoon et al., 2016).

3. Modeling

3–1 Pipe system stress analysis

The shell and lining were modeled as attached to each other even though small separations might have occurred during installation. Anchors were used where supports restricted any kind of movement. At the Pipe C, a combination of a guide and spring support system with 4 spring hangers was used. For spring supports, cold loads and spring rates were the main design considerations. Empty shell weight was used for the analysis. A total of 163 m pipe length was modeled including 3 bends, 1 tee and 4 reducers.

Design temperature and pressure values (343°C and 5.6 MPa, respectively) were the main analysis parameters; however, operating, start-up, and cool-down temperatures were also used during the analysis to check if there were any stress differences large enough to cause fatigue failure at any location. All input parameters are summarized in Table 1.
Table 1. Summary of input parameters

| Parameter                  | Description                                      |
|----------------------------|--------------------------------------------------|
| Design code                | ASME B31.3                                       |
| Pipe material              | SA516-70N (Normalized)                           |
| Corrosion thickness        | 3.2 mm                                           |
| Shell temperature          | 343 °C Design temperature                        |
|                           | 154/161 °C gasification reactor/bend Y Operating skin temperature |
|                           | 146/149 °C gasification reactor/bend Y Heat-up skin temperature |
|                           | 112/132 °C gasification reactor/bend Y Cool-down skin temperature |
| Gas pressure               | 5.6 MPa Design pressure, 4.96 MPa Operating pressure |

3–2 Finite element analysis

For finite element analysis, parts selected from the pipe system stress analysis were used.

3–2–1 Gasification reactor model, meshing, and boundary conditions

The gasification reactor was modeled excluding the inner lining, as can be seen in Fig 2. The side panels of the T-section were excluded as the design pressure can be applied to the inner material surface whether the structure is enclosed or not. The reactor was modeled starting from the end of the anchor support, which was taken as a fixed support. Standard gravity was taken as 9.806 m/s², acting downward from the fixed support to the slug exit hole. The bottom was not restricted in any direction. The operational weight of the reactor was distributed into two sections: the slender slug grinder pipe for 101.3
tons and the remaining parts including the left and right sleeves and the nozzle connected to the fixed support for 544.3 tons. The design pressure value was set as the internal gas pressure. All available temperature values were applied separately to observe the resulting stress variance. For meshing, a patch-conforming algorithm (ANSYS, 2015) was used with all quad elements and with element mid-side nodes. For critical sharp points where two pipes merge, the face size of the inner pipe was increased.

3-2-2 Bend Y model, meshing, and boundary conditions

The bend Y was modeled similar to the gasification reactor. As can be seen in Fig 3, modelling of the inner lining was also excluded here as refractory linings are not direct load-bearing components. As the bend Y is not directly connected to any support, the moment and force values acting on both of its ends were calculated and integrated into the model according to the initial pipe system stress analysis results at run points (AutoPIPE, 2011). Designing this component to include some parts of the pipe B was favorable as that enabled the use of these run points. Thus, the nozzle and the pipe connecting it to the bend Y was included in the design. For the top of the nozzle, the displacement values, which were also obtained from the initial stress analysis, were applied. However, the other end of the bend Y, which is connected to the pipe C, was unrestricted in any type of movement to benefit from the initial analysis results. Meshing was done using a hex-dominant method with an all quad, free face mesh type. Less definition was employed for the pipe B nozzle and more emphasis was put on the bend Y and pipe B connection point. Design pressure was used as the gas pressure value. Design temperature and operational temperatures were applied separately to check the stress variance for fatigue failure.

3-2-3 Mechanical properties

From the ASME Boiler and Pressure Vessel Code, Section II, Part D (American Society of Mechanical Engineers, 2010), the time dependent properties of SA516-70 were obtained, as they were necessary for the analysis. This data can be seen in the plot in Fig. 4.

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Fig. 3. Bend Y boundary conditions and meshing.
Fig. 4. Yield strength, elastic modulus, and tensile strength of SA516-70N as a function of temperature.

4. Results and discussion

As the entire spectrum of components was not included in this analysis, a design verification at three critical points was done. This is summarized in Table 2, where the displacement values from the design data and from the findings of this analysis are compared. This verification was done to see if there is any excessive elongation at the bend Y due to the unrestricted bend Z, which in reality is connected to the boiler. This comparison shows that the largest difference is 18% (16 mm), which is within the acceptable range considering the omission of the boiler connected to the bend Z. In addition, the alignment of the displacement directions between the model and the verification indicates a proper design orientation.

Pipe system stress analysis has shown high stress concentrations at the gasification reactor and high elongation values for the bend Y, which is under tensile stress. In Table 3 and Fig. 5, the five highest stress values and their locations are presented for design and operating conditions (Fig. 5a and Fig. 5b, respectively). The bend Y is one of the two locations dominated by tensile stress as the bend Z is connected to a boiler system and its corresponding support. As bend Y is relatively a small component, the significance of the system moment acting on it is small and so its displacement is almost exclusively in the vertical direction. Due to the its support type, pipe B is relatively stiff and this increases the effect of pipe C on bend Y as it has more free space to move on as it can be seen in Fig. 6. All components were within the acceptable stress range; however, three out of the five highest stress values in the entire system were found on the gasification reactor at design conditions. For the gasification reactor, hoop stress values were dominant. Stress values governing the bend Y were also acceptable during the initial analysis; however; owing to the domi-
Table 2. Bend Y design verification with respect to designed and calculated displacements

| Node/Coordinate | Designed displacement (mm) | Calculated displacement (mm) | Difference (mm) |
|-----------------|-----------------------------|-------------------------------|-----------------|
| D16 X           | 0.018                       | 0.110                         | 0.092           |
|                 | Y -49.750                   | -47.030                       | 2.720           |
|                 | Z -1.557                    | -0.500                        | 1.057           |
|                 | X 0.026                     | 0.160                         | 0.134           |
| D18 Y           | -70.614                     | -69.590                       | 1.024           |
|                 | Z -3.673                    | -1.140                        | 2.533           |
|                 | X 0.024                     | 0.160                         | 0.136           |
| D22 Y           | -87.357                     | -70.940                       | 16.417          |
|                 | Z 17.740                    | 18.890                        | 1.150           |

Fig. 5. Pipe system stress analysis results for (a) design conditions and (b) operating conditions with five highest stress locations.
Table 3. Pipe system stress analysis results (ranked with respect to the von-Mises stress values).

| Model            | Order | Von Mises stress (MPa) | Sustain stress (MPa) | Hoop stress (MPa) | Expansion stress (MPa) |
|------------------|-------|------------------------|----------------------|-------------------|------------------------|
| Operating        |       |                        |                      |                   |                        |
| Conditions       | 1     | 116.9                  | 58.1                | 134.0             | -                      |
|                  | 2     | 116.6                  | 55.8                | 134.0             | -                      |
|                  | 3     | 116.6                  | 55.8                | 134.0             | -                      |
|                  | 4     | 116.6                  | 55.5                | 134.0             | -                      |
|                  | 5     | 116.6                  | 55.5                | 134.0             | -                      |
| Design           |       |                        |                      |                   |                        |
| Conditions       | 1     | 134.8                  | 58.0                | 146.6             | 25.3                   |
|                  | 2     | 131.9                  | 65.2                | 151.3             | -                      |
|                  | 3     | 131.7                  | 65.2                | 151.3             | -                      |
|                  | 4     | 131.7                  | 65.2                | 151.3             | -                      |
|                  | 5     | 131.7                  | 58.1                | 148.0             | 12.2                   |

Fig. 6. System deformation under operating conditions and bend Y from the plant.
nance of tensile stress and high elongation, the bend Y was considered a critical location. Stress variation with different temperatures can be seen in Fig. 7. along the pipe system starting from the bottom of

Fig. 7. Pipe system stress analysis results for different system conditions.

Fig. 8. Finite element stress analysis results for (a) the gasification reactor and (b) the bend Y.
the gasification reactor (Tee sleeves are excluded). These two parts were analyzed in more detail during the FEA.

FEA showed that the stress values inside the gasification reactor were highest at the inner corners, as can be seen in Fig. 8a. The highest stress values were acceptable according to the ASME Code (American Society of Mechanical Engineers, 2001) as the primary general membrane ($P_m$), the primary local membrane ($P_L$), the primary local membrane plus bending ($P_L+P_b$), and the primary plus secondary ($P_L+P_b+Q$) were well within the specified range. The hoop stress is the main reason of the stresses in the gasification reactor. The bend Y has lower stress values at the connecting point of two pipes, which were also acceptable according to the ASME code, as can be seen in Fig. 8b; these values exceeded the yield strength of the material. The critical points were due to excessive displacement on the surface where two pipes face each other. There were also high stress locations inside the bend, at the sides, however stress on those locations were less than the stress at the connection point of the bend and the pipe. There was no difference in the system stress with varying temperatures.

5. Conclusions

A two-step analysis with pipe system stress analysis and finite element analysis was conducted for the most critical parts of an SNG plant to aid the selection of future inspection locations with high risk of failure. For the crude pipe system stress analysis, AutoPIPE V8i was used at design temperature and pressure values as well as for start-up, cool-down, and operational skin temperatures. Parts that were critical according to the ASME B31.3 process piping design code and which are in a mechanical disadvantage, were reevaluated using the commercial FEA program ANSYS 16.0. Design temperature and pressure values as well as start-up, cool-down, and operational skin temperatures were applied.

For the gasification reactor, high failure risk locations were at the inner corners with a maximum Von-Mises stress value of 383 MPa for design condition. This value is higher than the yield strength of the material but is acceptable according to the ASME B31.1 code. As the highest stress location is inside the reactor it is not possible to inspect it directly and frequently. So instead the top and bottom connection points of the reactor sleeves and the main pipe should be checked visually as in similar fashion the highest stresses are concentrated in those locations around 200 MPa. These points should also be checked with thermal sensors for any heat leakage in case of a lining failure regularly. The highest stress location on bend Y is just next to the point where it is connected to pipe B. As this location is on the surface it can be inspected visually with high frequency.

There was no significant stress variance for start-up, cool-down, and operational skin temperature values; this reduces the likelihood of fatigue failure becoming a possible cause for future system failure. To decrease the amount of stress acting on the bend Y, implementing auxiliary support systems is recommended as it due to system design whereas stresses at the gasification reactor is due to operating conditions. The results obtained provide valuable information for prioritizing future inspection points. For the remaining parts of the system, further analysis is necessary to determine their criticality in terms of the entire system.

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