

## 배관응력해석 및 유한요소해석에 의한 SNG플랜트의 리스크 관리 위치 선정

데니즈 타이군 엘텐 · 유종민 · 윤기봉\*<sup>†</sup> · 김지윤\*\*

중앙대학교 대학원 기계공학과, \*중앙대학교 기계공학부, \*\*㈜에너지기술융합센터  
(2017년 5월 26일 접수, 2017년 6월 21일 수정, 2017년 6월 22일 채택)

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

Deniz Taygun Erten, Jong Min Yu, Kee Bong Yoon\*<sup>†</sup>, Ji Yoon Kim\*\*

Department of Mechanical Engineering, Graduate School, Chung Ang University

\*Department of Mechanical Engineering, Chung Ang University

\*\*ETCC(Energy Technology Convergence Center Inc.)

(Received 26 May 2017, Revised 21 June 2017, Accepted 22 June 2017)

#### 요 약

최근 합성천연가스(synthetic natural gas, SNG)의 사용과 합성천연가스를 생산하는 플랜트의 실증 운영이 증가하고 있다. SNG 플랜트는 다양하게 개발된 여러 합성 공정 기술이 적용되고 있으며, 이러한 공정의 특성상 고온, 고압의 운전 조건을 가진다. 기존 여러 연구들은 주로 합성천연가스 생산을 위한 화학적 합성 공정의 변수와 공정 최적화에 대한 연구에 집중되어 왔다. 이에 비해, 기존 산업 플랜트와는 다소 차별되는, 공정 특성으로 인한 SNG 플랜트의 기계적 손상과 유지보수 기법에 대한 연구는 많지 않다. 본 연구에서는 SNG 플랜트의 주요 배관계통에 대해 ASME B31.3에 의거한 배관 시스템 응력 해석을 수행하였다. 또한 특이 부위에 대해 상세 국부 응력 해석을 수행하였다. 해석 결과로부터 배관 주요부위 중 파손 리스크가 높은 취약부의 위치를 선정하였다. 이 위치들은 배관 위험도 관리 대상으로 활용할 수 있다. 배관 시스템 응력 해석은 설계 운전조건과 실제 운전조건을 고려하여 수행되었다. 배관 시스템 응력 해석을 통해 도출된 주요 부위에 대해서는 국부적 상세 응력 해석을 위해 유한 요소 해석이 수행되었다. 발생하는 상세 응력 값은 가스화 반응기 및 하부 곡관부 대한 ASME B31.3 코드 표준을 만족하였다. 하부 곡관부의 경우 수직 변위를 제한하는 것이 구조적으로 안전 향상에 좋을 것으로 파악되었다. 수행된 해석결과는 향후 위험도 기반 유지 보수 검사 및 안전 운영에 대해 기반 정보로 사용될 수 있을 것으로 판단된다.

**주요어 :** SNG, 합성 천연 가스, 유한 요소 해석, 배관 응력 해석, 유지 보수

**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

<sup>†</sup>To whom corresponding should be addressed.  
Tel : 02-821-1547, E-mail : kbyoon@cau.ac.kr

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 CO<sub>2</sub> 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 con-

ducted 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-

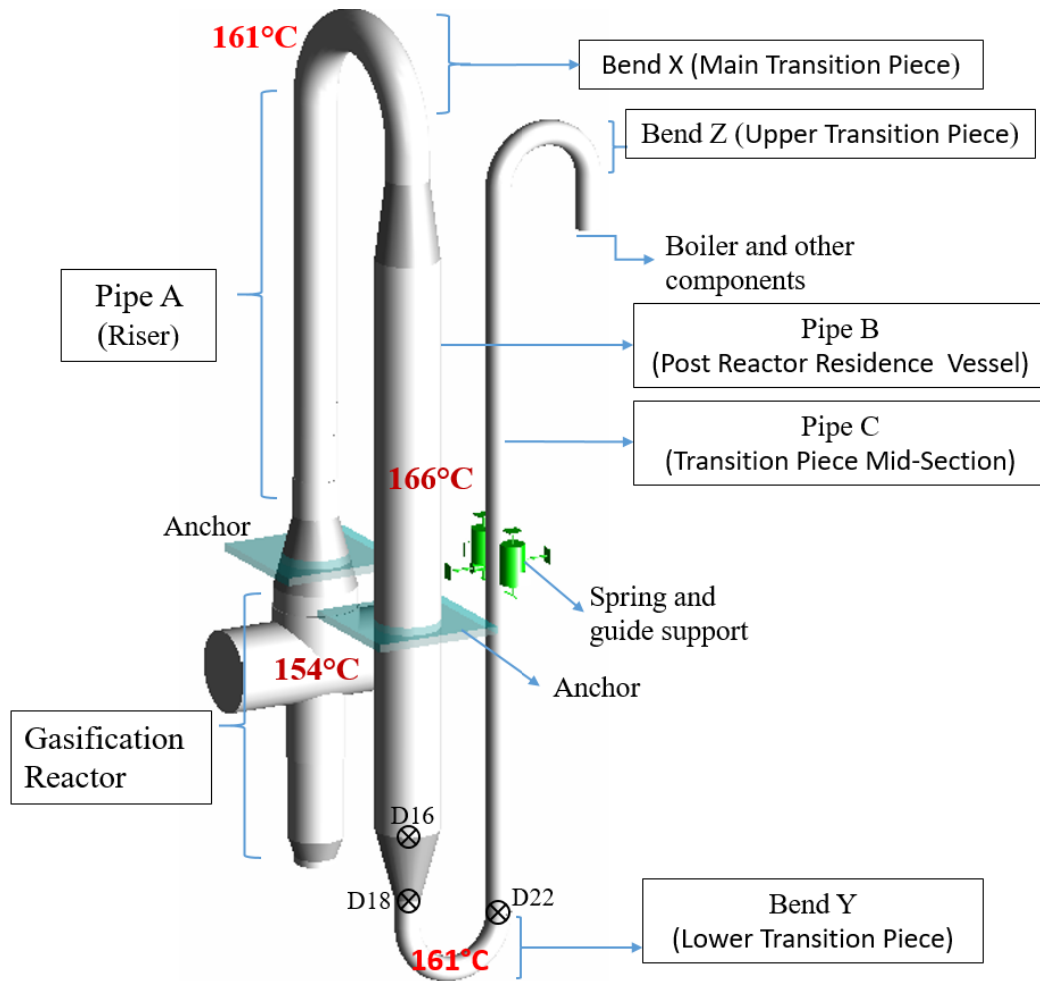


Fig. 1. 3D Model of the SNG plant components, operating skin temperatures, and bend Y nodes.

protective inner linings owing to the high temperatures in these regions.

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

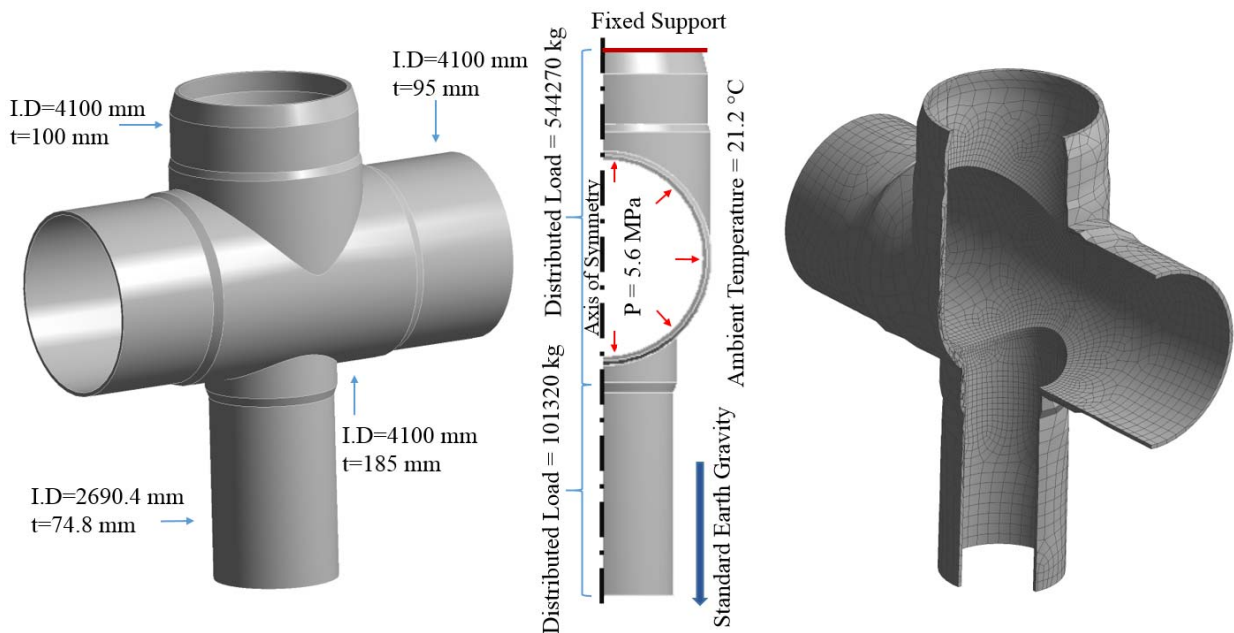
The shell and lining were modeled as attached to each other even though small separations might have occurred during installation. Anchors were used

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

**Fig. 2.** Gasification reactor model, boundary conditions, and meshing.

### 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  $9.806 \text{ m/s}^2$ , 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.

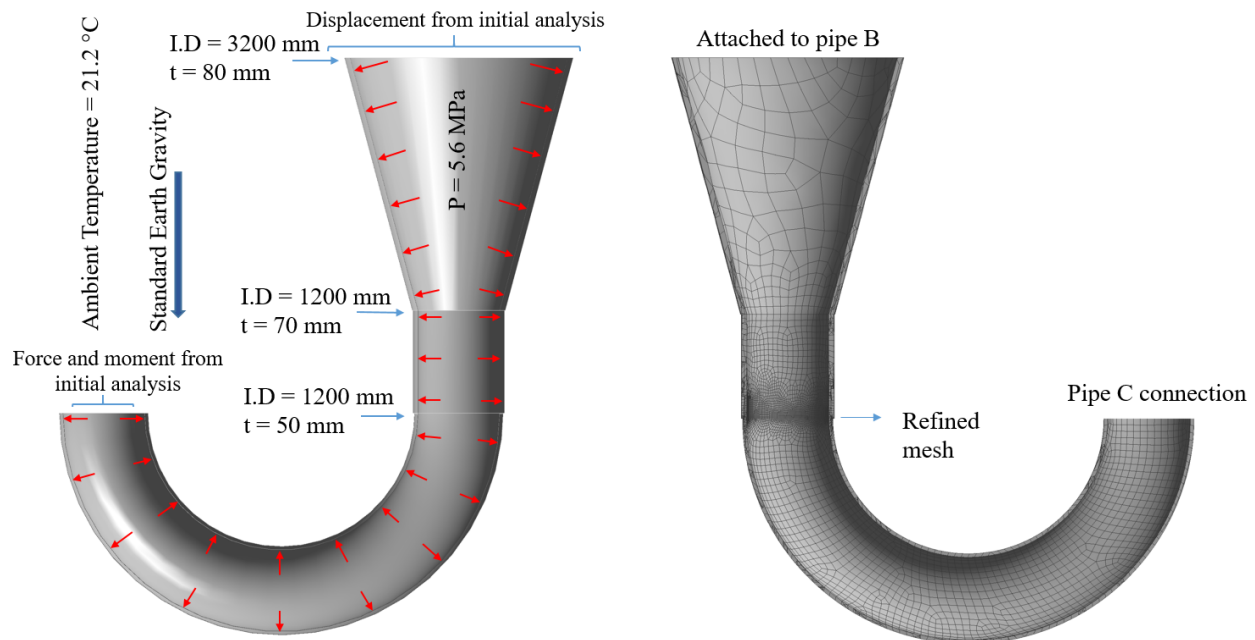
**3-2-2 Bend Y model, meshing, and boundary conditions**

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.



**Fig. 3.** Bend Y boundary conditions and meshing.

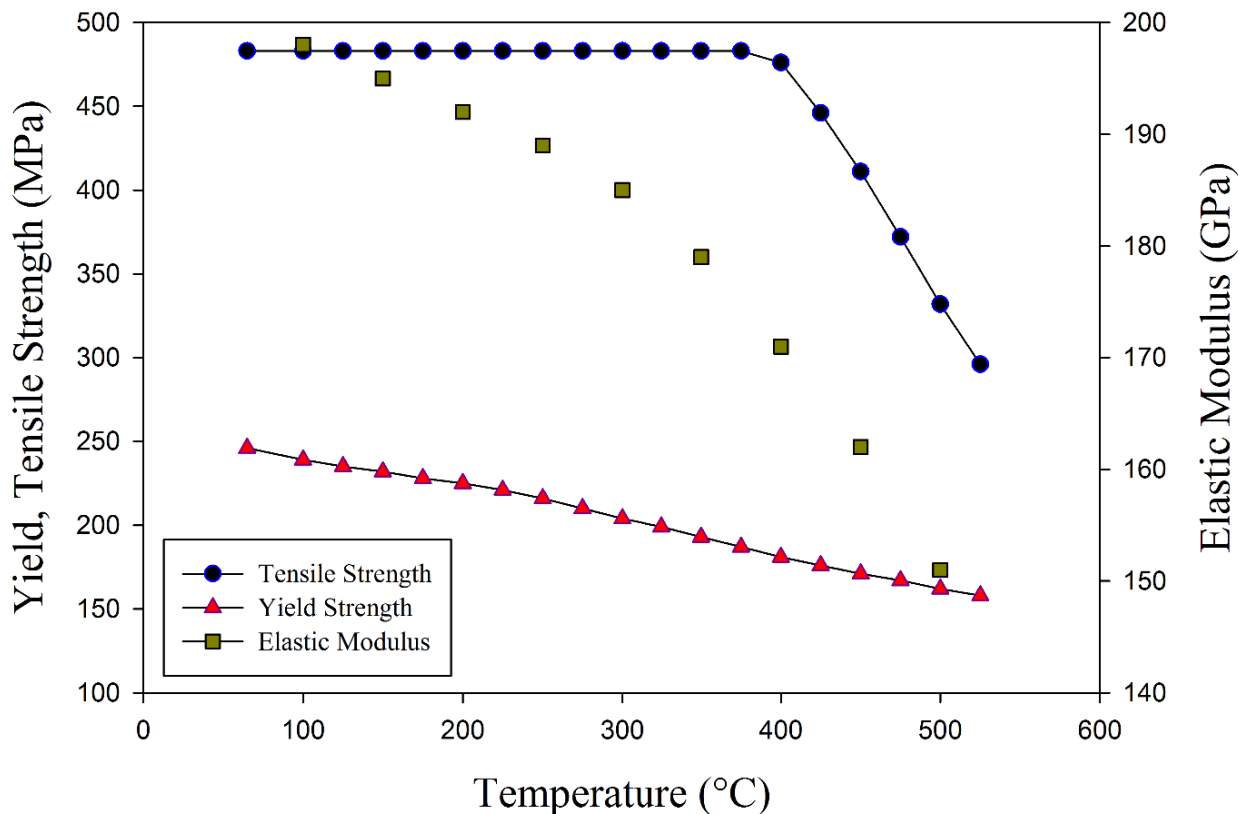


Fig. 4. Yield strength, elastic modulus, and tensile strength of SA516-70N as a function of temperature.

#### 4. Results and discussion

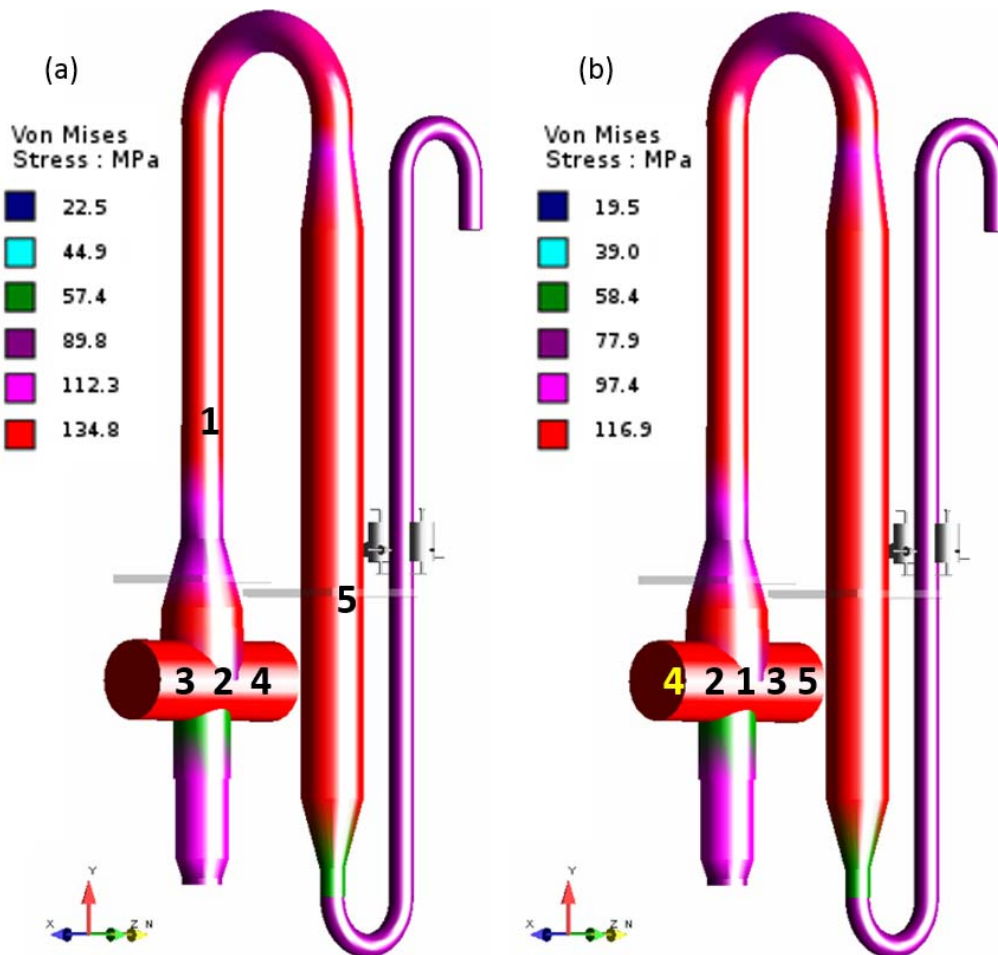
As the entire spectrum of components was not included in this analysis, a design verification at three critical points was done. This is summarized in Table 2, where the displacement values from the design data and from the findings of this analysis are compared. This verification was done to see if 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 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
	Y	-49.750	-47.030
	Z	-1.557	-0.500
D18	X	0.026	0.160
	Y	-70.614	-69.590
	Z	-3.673	-1.140
D22	X	0.024	0.160
	Y	-87.357	-70.940
	Z	17.740	18.890

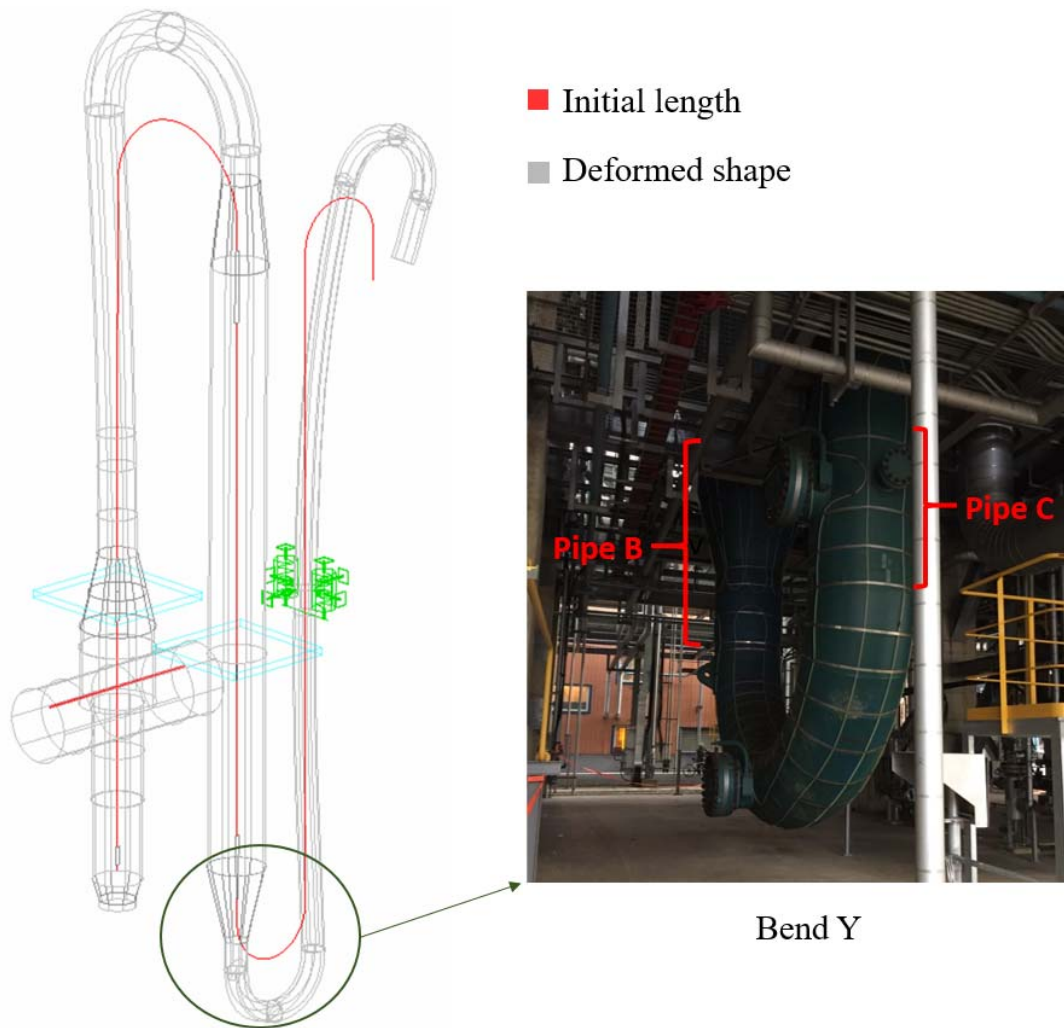


**Fig. 5.** Pipe system stress analysis results for (a) design conditions and (b) operating conditions with five highest stress locations.



**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.



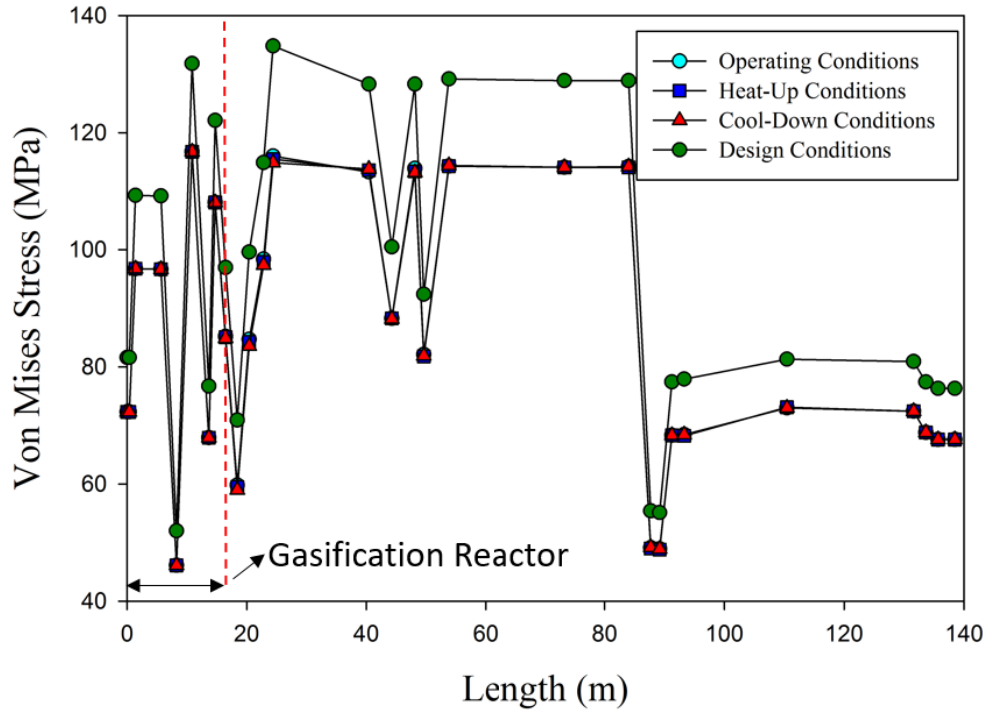


Fig. 7. Pipe system stress analysis results for different system conditions.

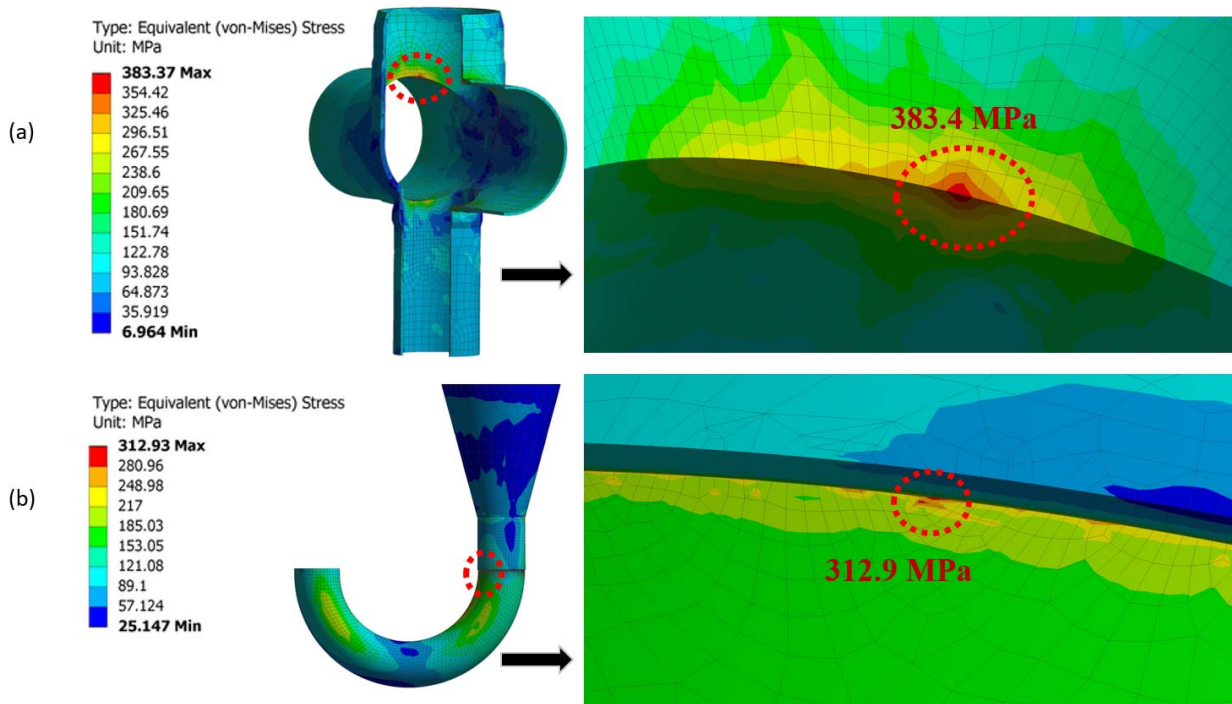


Fig. 8. Finite element stress analysis results for (a) the gasification reactor and (b) the bend Y.

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

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 loca-

tions 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.

## Acknowledgment

This work was supported by the Power Generation and Electricity Delivery Core Program of KETEP funded by the MOTIE (No. 20141010101850). This research was also supported by the KIAT grant funded by the Korea Government MOTIE (No. N0001075).

## References

1. ANSYS® Academic Research, Release 16.0, 2015
2. ASME Boiler and Pressure Vessel Code II Part

- D: Properties. ASME, NY, USA; 2010.
3. ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Part 5, ASME, 2001.
  4. AutoPIPE Version 8i SELECTseries3 release 9.4. User's manual. Bentley 2011
  5. Chang, M.K. et al., 2005. Application of risk based inspection in refinery and processing piping. *Journal of Loss Prevention in the Process Industries*, 18(4-6), pp.397-402
  6. Ding, Y. et al., 2013. Coal-based synthetic natural gas (SNG): A solution to China's energy security and CO<sub>2</sub> reduction? *Energy Policy*, 55, pp.445-453
  7. Dou, Z. et al., 2017. Applications of RBI on leakage risk assessment of direct coal liquefaction process. *Journal of Loss Prevention in the Process Industries*, 45, pp.194-202
  8. He, C., Feng, X. & Chu, K.H., 2013. Process modeling and thermodynamic analysis of Lurgi fixed-bed coal gasifier in an SNG plant. *Applied Energy*, 111, pp.742-757
  9. Hirano, T., 2006. Gas explosions caused by gasification of condensed phase combustibles. *Journal of Loss Prevention in the Process Industries*, 19 (2-3), pp.245-249
  10. Huo, J. et al., 2013. Feasibility analysis and policy recommendations for the development of the coal based SNG industry in Xinjiang. *Energy Policy*, 61, pp.3-11
  11. Keiser, J.R., Dias, O.C. & Mayotte, J.R.D.A.-S., 1994. Analysis of Pipe Failure at the Great-Plains Coal-Gasification Plant. *Materials Characterization*, 33, p.147-153
  12. Koysoumpa, E.I. et al., 2015. Modelling and assessment of acid gas removal processes in coal-derived SNG production. *Applied Thermal Engineering*, 74, pp.128-135
  13. Li, H. et al., 2014. Analysis of rationality of coal-based synthetic natural gas (SNG) production in China. *Energy Policy*, 71, pp.180-188
  14. Li, S. et al., 2014. Coal to SNG: Technical progress, modeling and system optimization through exergy analysis. *Applied Energy*, 136, pp.98-109
  15. Swain, P.K., Das, L.M. & Naik, S.N., 2011. Biomass to liquid: A prospective challenge to research and development in 21st century. *Renewable and Sustainable Energy Reviews*, 15(9), pp.4917-4933
  16. Yang, C.J. & Jackson, R.B., 2012. China's growing methanol economy and its implications for energy and the environment. *Energy Policy*, 41, pp.878-884
  17. Yoon, K.B., Yu, J.M. & Nguyen, T.S., 2015. Stress relaxation cracking in 304H stainless steel weld of a chemical reactor serviced at 560 °C. *Engineering Failure Analysis*, 56, pp.288-299
  18. Yoon, K.B. et al., 2016. Creep cracking and damage assessment in P91 and P92 piping system. EPRI 2nd Asia-Pacific Workshop: Service experience of creep strength enhanced ferritic steels, Eastern & Oriental Hotel, Penang Malaysia March 9-11