Analysis of tube bending deformation in petrochemical heater furnace tubes

Yufeng Ye¹,², *, Xingyang Chen¹,², Haoping Xie¹,², Huibin Liu¹

¹Zhejiang Academy of Special Equipment Science, Hangzhou, China
²Key Laboratory of Special Equipment Safety Testing Technology of Zhejiang Province, Hangzhou, China

*Corresponding author e-mail: 328710426@qq.com

Abstract. Serious bending deformation of the tubes was found in the tubular furnace at a petrochemical company. In order to find out its specific reason, Thickness measurement and metallographic analysis were conducted on the problematic part of the furnace tube. Stress analysis by using CAESAR was carried out, in which the working conditions were considered. The results show that the microstructure of the furnace tubes was not abnormal, and there is no overheating, creeping and deterioration damage was existed during operation. Stress analysis show that the primary and secondary stress values of each node were less than the allowable stress for furnace tubes under current condition. However, the secondary stress will exceed the allowable stress when the furnace tube is bended up to 400 mm. Therefore, in order to avoid the replacement of furnace tube and the unnecessary economic loss, the tubes could be used safely under closely monitored after structural rectification.

1. Introduction

As a basic energy industry, petrochemical industry plays an important role in the development of the economic society. The cracking or reaction of feedstock oil is completed under certain temperature and pressure. Reheating furnace, a heating equipment providing energy for reaction, is almost participated in the whole process of refinery and chemical industry in petrochemical enterprises. However, failure accident of furnace tube such as coking or pitting is easy to occur during operation due to the harsh condition (high temperature and pressure) and the corrosive, flammable, explosive, easy coking medium in the tube. Thus, failure accident of furnace tube will significantly affect the production planning and personal security. Therefore, the safety of the reheating furnace is an important guarantee for the safe operation of the plant in the enterprise [1-9].

In this paper, a debutanizer-based reboiler in a continuous reforming unit was studied, in which a furnace tube was undergone serious bending deformation in reheating furnace. In order to find out the reason of bending, macroscopic inspection, wall thickness measure, outer diameter measure and metallographic analysis were carried out for the furnace tube in reheating furnace. In addition, stress analysis combined with operating conditions was conducted by using business software CAESAR to evaluate the stress level of the bended furnace tube.
2. Inspection strategies
The furnace was put into use in November 2006 and its average thermal efficiency is more than 90% at present. The furnace is a two-program vertical tube cylinder reheating furnace with a single side fired and its design heat load is 5100kW. The medium first enters into the radiation section from the upper part of the convection section, and then finally comes out to the bottom of the radiation section. The furnace tube is made of 20 # steel and its design temperature is 207 °C at the entrance and 230 °C at the exit section.

2.1. Furnace tube macroscopic inspection
The results of macroscopic inspection of the furnace show that the radiation section 1, 2# tube is severely bent. Fig.1 shows that the illustrations of furnace tube that undergo bending deformation. The maximum bending deformation offset is 107 mm for 1 # furnace tube and 96 mm for 2 # furnace tube. Fig.1 also shows the picture of 1#, 2 # furnace tube and its corresponding location of bend. Fig. 2 shows the illustrations of 1#, 2# furnace tube and its corresponding actual offset distance. 1# tube is one of the exit pipelines of the radiant section of the reheating furnace, which connected to an elbow (90°) at the top and to an elbow (180°) at the bottom. The elbow at the bottom is a guide tube which can restrict the furnace tube stretching up and down. After field investigation, it was found that the bottom guide tubes connect with tubes 1 and 2 is stuck and cannot be retracted up and down freely. Meanwhile, the top elbow of the upper part of the 1# tube is contact with the furnace wall. The furnace tube cannot expand freely when the furnace tube being heated. Therefore, the straight pipe, which is lateral bended, may suffered a great thermal stress. 2# furnace tube also had lateral bending due to the stuck of the guide tube at the bottom. The constraint stress is smaller than that of the 1# tube because the upper elbow doesn’t contact with the furnace wall.

In addition, a pit about 30 mm in diameter and 2 mm in depth was found between the elbow and the supporter in the furnace pipe, also as shown in Fig. 2. The collision between the elbow and the supporter is caused by the offset of the tube during the process of operation. Vibration caused by uneven flow of internal medium can lead to the impact between the tube and hook. Thus, a pit may be formed when the vibration amplitude is large.

The furnace tube deviates from the original position during the process of operation, in which the bottom guide tube for furnace tube is too long to extend. Thus, the furnace tube will be expanded.
downward when the tube heated. Once the furnace tube is stuck by the furnace bottom structure, the furnace tube could not continue to extend down. As a result, the damage such as pit could be occurred in the furnace tube.

2.2. Furnace Tube Wall Thickness Measure

The wall thickness of the furnace directly affects the safe operation of the furnace. The aim of the wall thickness inspection is mainly to check the corrosion problem. The furnace tube can be eroded by the inner medium or oxidized under high temperature. Wall thickness reduction can reflect the feature of dew point corrosion by flue gas. High corrosive furnace tube needs the dense thickness measuring point to obtain the accurate wall thickness thinning value. Compared with the historical wall thickness data, the corrosion rate of the furnace tube and the thickness reduction data for the next operation cycle can be calculated.

Furnace tube 1#, 2# which suffered bending deformation were selected to measure the wall thickness. The bend deformation of furnace tube starts at 1m in height and end at 7 m in height. The minimum radial thickness of furnace tube is shown in Table 1. From the result of wall thickness of furnace tube, there is no abnormal data for the wall thickness of the bended furnace tube. No obvious thinning phenomenon was found in the measured thickness data of the bended furnace tube at the different dislocation compared with the other furnace tubes.

| Location (height) | Furnace tube number and thickness |
|-------------------|----------------------------------|
| 1m                | 7.6  7.1  7.7  7.6  8.0  7.7  7.9  7.8  7.6 |
| 4m                | 7.2  6.8  7.6  7.4  8.1  7.6  7.6  7.4  7.5 |
| 7m                | 7.8  7.0  7.8  7.7  7.4  7.8  7.9  8.2  7.6 |

2.3. Furnace tube Outer Diameter Measure

As the tube creep expansion to a certain extent, there will be a large number of cracks on the inner surface and finally result in fracture. Outer diameter measure is an effective method to calculate and analyze the creep feature of furnace tube. The precision of external diameter measurement is 0.01mm and the slight creep can be detected. The outer diameter measurement was conducted from two directions through the cross section. The outer diameter (the average value) of the cross section was calculated by measuring the values of the two directions.

The field measure adopts the maximum value of the measured values as the external diameter of the section. The result of field diameter inspection shows that the cross section of the furnace tube is elliptical. During the inspection process, considering the difference of outer diameter (the maximum allowable deviation of diameter is +1%D0) caused by the original manufacture, the outer diameter at the weld joint should be firstly tested to determine the deviation during the original manufacture and then correct the measurement data.

| Creep level | Furnace tube | Acceptance situations |
|-------------|--------------|-----------------------|
| No creep    | ≤2.0%        | Acceptable            |
| Slight creep| 2.0%~3.5%    | Expand detection ratio|
| Creep       | ≥3.5%        | Expand detection ratio, safety evaluation or exchange |
Table 3. The outside diameter measured date of furnace tube at 4m high.

| Creep level     | Furnace tube | Acceptance situations |
|-----------------|--------------|-----------------------|
| No creep        | ≤2.0%        | Acceptable            |
| Slight creep    | 2.0%~3.5%    | Expand detection ratio|
| Creep           | ≥3.5%        | Expand detection ratio, safety evaluation or exchange |

The creep limit can be judged by calculating the creep data of boiler tube with worse working conditions. According to the requirements of TSGG7002-2015 on the diameter of furnace tube, the diameter of carbon steel tube is cannot exceed 3.5% of the original diameter. The bulging coarsening of the alloy steel pipe is not more than 2.5% of the original diameter, and the local bulging height is not more than 3 mm. Table 2 shows the creep level grading of the tube and its corresponding acceptance situations based on expansion.

The outer diameter of the tube (4m layer height) with maximum bending deformation is selected for the measurement. The corresponding values are listed as in Table 3. The outer diameter measurement of furnace tube is a whole judgment to the creep of furnace tube. Usually, the creep of the tube is featured with the abnormal local diameter of furnace tube and occurs at the place under circumferential stress. The maximum diameter of furnace tube is 153.4 mm and the expansion degree is 0.92 mm, which is larger than that of other extraction tubes tested at the same height. No obvious expansion has been found. According to the requirements of the inspection rules for the diameter of the furnace tube, these furnace tubes are acceptable.

2.4. Metallographic analysis

The mechanical properties of the furnace tube after long service depend on the change of the chemical composition, structure, temperature and stress of the material. The microstructure of the furnace tube is observed and analyzed by metallographic analysis, the damage of furnace tube can be observed by studying the microstructure of furnace tube under high temperature. Fig. 3 shows the metallographic of the furnace tube 1# and 2#.

Table 4. Metallographic analysis.

| Metallographic site | 1# 2 m height | 1# 4m height | 2# 2 m height | 2# 4m height |
|---------------------|---------------|--------------|---------------|--------------|
| The parent metal    | 20            |              |               |              |
| Metallographic structure | Pearlite+ferrite+ a few dot-like carbides |

Table 4 shows the metallographic analysis of the heating surface of the bended tube flame. By on-site analysis, these materials are homogenized and no large-area carburization occurred. By on-site metallographic analysis, there is no material deterioration for the whole tube.

3. Stress Analysis of the Furnace Tube

In order to ensure the sufficient flexibility for furnace tubes, appropriate constraints would be set combining with the working conditions during operation in the design stage. During the operation of the furnace, the stress value of the furnace tubes often exceeded the allowable stress value, which was
caused by the thermal expansion and the constraint conditions. In order to analyze the reason for bending deformation, business pipeline analysis software CAESAR was used to calculate the stress distribution of furnace tubes. The constraint conditions and its corresponding node were shown in Table 5.

| Node No. | 10 | 120 | 240 | 280 | 310 | 340 | 370 | 400 |
|----------|----|-----|-----|-----|-----|-----|-----|-----|
| Constraints direction | Y & Z, 250mm | Y & Z | +Y | Z | +Y | Z | +Y | Z |

Table 5. Constraints for node.

![Figure 4. Tubes Model.](image1)

![Figure 5. Primary stress, second stress distribution of furnace tubes.](image2)

In this paper, a three-dimensional finite element model was built by using CAESAR II pipeline analysis software to simulate the stress of pipeline. The primary stress, secondary stress and joint displacement involved in the pipeline was calculated. The load includes inner pressure, self-weight of the pipeline and thermal expansion were considered during calculation. A model was adopted to simulate the furnace tubes and a number of nodes were set to get the stress value or displacement at certain location, as shown in Fig. 4. The finite element simulation parameters were set as follows, the density, elastic modulus and poisson's ratio were referred to 7800kg/m3, 2.03x10^5MPa and 0.286, separately.

As shown in Fig. 5, the primary stress, the secondary stress and the node displacement of the furnace tubes under the constraint conditions were calculated and the stress distribution curves were drawn. In order to meet the requirements of safety use of the furnace tubes, the stress was checked according to the ASME B31.3 [10], which is required that the primary and secondary stress value of each node should be less than the allowable stress. As can be seen in Fig. 5, the primary stress, the secondary can satisfy the following relationship under specific constraints. The primary stress curve was with little range, and the stress of the most severe part of the furnace tubes and the restraint part should be mainly concerned. It could be found that the primary stress and the secondary stress at the maximum bending position were lower than the up and down ends. The reason for this phenomenon was that the stress at the maximum deformation portion released, and the stress at the top and bottom end elbow portions was increased due to constraints. Among them, the maximum value of secondary stress at node 20# was 172.2 MPa, in which the node suffers stress concentration.

It is assumed that the furnace tubes are in the original constraints condition, and the maximum lateral bending offset value of the 1# furnace tube reaches 400 mm, the maximum value of primary stress and secondary stress at the node can be calculated, as shown also in Fig. 5.
It can also be seen from Fig. 5, the primary stress is at the range of allowable stress and less variation. The reason for this phenomenon was that the primary stress, was calculated according to the load includes inner pressure, self-weight of the pipeline. The maximum value of secondary stress is at the node 20#, the corresponding stress for 20# node (located at the top of the furnace tube elbow) is 242.47MPa, which is exceed the allowable stress value of the material (239.61MPa). Stress corrosion cracking is easy to occur due to the stress concentration at node 20#. The actual security offset of the tube is less than the theoretical value. The reason is that the bending rate of the gradual change, the deformation of the material due to temperature changes, and the influence of corrosion on the furnace tube are not considered in the calculation.

4. Conclusion
According to the regulations, the furnace tube should be replaced as the guide tube or the guide groove lose its guiding effect due to the severely bent of furnace tube. The examination results of wall thickness test, outer diameter detection and metallographic test for furnace tube 1#, 2# show that no material deterioration was found for furnace tube 1#, 2#. Stress analysis show that the primary and secondary stress values of each node were less than the allowable stress for furnace tubes under current condition. The primary and secondary stress value of each node is less than the allowable stress. The furnace tubes meet the requirements of safety use. Only when the bend offset of furnace tube 1# reaches to 400 mm, the secondary stress will exceeds the allowable stress and cannot meet the requirement Therefore, it is only necessary to ameliorate the guide tube and pay close attention to the bending condition of the furnace tube except replacing the furnace tube.

Acknowledgments
This work was financially supported by National Quality Infrastructure plan project of Zhejiang Bureau of Quality and Technical Supervision (No.20190112).

References
[1] Babakr,A.B.M., Al-Ahmrai,A., (2009), Failure Investigation of a Furnace Tube Support, Journal of Failure Analysis and Prevention, Vol. 1, pp. 16-22.
[2] Concari,S., Fairman,A., (2011), HIDA databank-its development and future, The International Journal of Pressure Vessels and Piping, Vol. 78, pp. 1031-1042.
[3] Khodamorad,S.H., Haghshenas Fatmehsari, D., (2012), Analysis of ethylene cracking furnace tubes, Engineering Failure Analysis, Vol. 21, pp. 1-8.
[4] Swaminathan, J., Singh, R., Gunjan, M.K., & Mahato,B., (2011), Sensitization induced stress corrosion failure of aisi 347 stainless steel fractionator furnace tubes, Engineering Failure Analysis,Vol.18, No. 8, pp. 2211-2221.
[5] Yan Xiqing., (2013), Corrosion analysis of extract furnace tubes for furfural refining plant and countermeasures, Corrosion & Protection in petrochemical industry, Vol. 30, No. 2, pp. 34-37.
[6] Al-Meshari,A., (2013), Failure Analysis of Furnace Tube, Journal of Failure Analysis and Prevention, Vol. 13, pp. 282-291.
[7] Wenhe Wang, Kaifu Liang, (2014), Comparative analysis of failure probability for ethylene cracking furnace tube using Monte Carlo and API RBI technology, Engineering Failure Analysis, Vol.45, pp. 278-282.
[8] Zhang Jianjun, (2015), Finite Element Analysis for Bending Deformation of Coking Furnace Tube, Process Equipment & Piping, Vol. 52 No. 5, pp. 36-39.
[9] Wang Jianhua, (2016), Analysis on the reliability of carbon steel furnace tubes of tube furnace after long-term service, Value Engineering, pp. 105-106.
[10] ASME B31.3-2014, process piping.