© January 2025 | IJIRT | Volume 11 Issue 8 | ISSN: 2349-6002

Review on Life Estimation of Coke Drum Operating Under Fatigue Condition

Nitesh Kumar[1], Vaishnavi Battul[2], Siddharth Shete[3], KVL Bhuvaneshwary[4]
[1,2,3,4]*Member, DYPIEMR, Akurdi, Pune.*

***Abstract*— Coke drums are thin-walled pressure vessels that endure some of a refinery's highest levels of heat cycling. Consequences of high thermal stresses can cause premature drum failure in the form of through-wall low cycle fatigue cracking and failure of the weld-joint between the skirt and drum when they are applied repeatedly. Therefore, it is essential to calculate the probabilistic life of the coke drum so that the operator can choose the level of risk to be assumed in the future with regard to coke drum maintenance. Different techniques are used in the industry to estimate the life of coke drums; some of these techniques are covered in this study. An analytical solution to estimate the probable life of a coke drum is provided based on the results of the fatigue test.**

***Index Terms*— Coke Drum, Futigue Life**

I. INTRODUCTION

[Figure 1 depicts a coke drum, which is a thin-walled pressure vessel used in the coking, cooling, and removal phases of the manufacturing cycle. They also go by the name thermal cracking reactor because of the numerous thermal cyclic loadings they endure. These loading circumstances are quite complex, with the maximum temperature being around 495°C and the lowest being around 85°C.

At roughly 450°C, feed enters the drum, and the residue solidifies to make coke. Temperature of the rum wall during this time ranging from 370°C to 425°C. The drum is quickly cooled from 425°C to steam temperature after solidification is complete, with steaming followed by water quenching from the bottom. As a result, the coke drum's base metal and weld joints can survive the effects of thermo-mechanical fatigue, fatigue creep, and high temperature low cycle fatigue. The drum's shape transforms from a cylinder to an inverted vessel as a result, and its diameter below the steam level lowers. Currently, according to an industry assessment by the American Petroleum Institute (API), 87% of coke drum destruction incidents happened when the drum body and skirt were connected during welding.

The cooling process typically depends on the length of the process cycle, the coke bed's porosity, and the rate at which quench water is fed. If coke is porous, quenching will take place evenly all the way around the drum, causing the ring to compress and the hot coke drum above it to vary in diameter. This change from a cold to a hot shell raises steam up to the drum wall, which causes thermal forces to be exerted on the drum and eventually causes cracks to form. This crack generally starts at the weldments along the circumference of the stack.

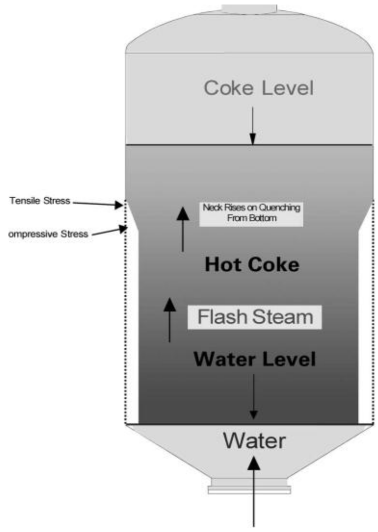


Fig. 1 Schematic of coke drum and vasing process [1]

1.1 PROBLEMS WITH COKE DRUM

From the standpoint of the damage mechanism, high temperature low cycle fatigue failure of the welding connection between the drum body and the skirt is one of the primary factors that affects the safe life of a coke drum and the following areas are where crack starts to form.

1. Shell circumferential seam repairs close to significant deformities.

2. Cracking at skirt junctions.

3. Nozzle malfunction.

Damage mechanisms are caused by regional hotspots. These hot spots are a result of the coke bed's uneven cooling because, during quench, the hot area is compressed by the cooler zones around it, causing a hot spot to form permanently. If a weld is placed in this region, the shell will flex severely, increased by raisers such undercuts or existing fissures.

The common problem region is the skirt to shell weld. Because the skirt is not sufficiently expanded by the preheating drum to match the vessel's size, the junction will be overloaded, and the peak stress will cause cracking at the weld and in the keyhole slots. Older drums frequently exhibit the effects of low cycle fatigue due to their slotted skirts. They might be crooked and cracked and bring down the building.

Another issue with coke barrels is their tendency to bulge. This is nothing more than the base plate metal's and the circumferential weld seam's relative strength. As a result, a tension ratchet forms between these zones. Additionally, when a weld has a higher yield, the plate distorts more and is resisted by a stronger weld, causing drum distortion. The seam distorts more than the plate if the balance is in the opposite way. Because of the shorter bulging that develops, the peak is sharper at the maximum.

II. LIFE ESTIMATION OF COKE DRUM

The spot where the drum body and skirt are joined by welding (as seen in figure 2) is the most problematic cross section of the coke drum and is where fatigue failure occurs in industry, as we have seen from the coke drum's structure in figure. Therefore, a coke drum's service life in the environment must be estimated.

Various techniques or procedures are used to estimate the life of a coke drum, including the ones listed below.

1. A phased method to assessment.

2. Methodology for general life assessments.

3. Program for evaluating Coke drums.

4. Simulation using numbers.

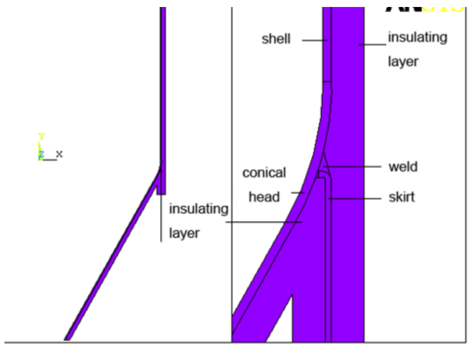


Fig. 2 Detailed structure of skirt to shell junction [2]

2.1 PHASED ASSESSMENT APPROCH [1]

The following steps make up the current ERA's coke drum life evaluation method, which is based on a phased methodology.

Monitoring and recording of the past

Critical locations on the drum are located using records of inspection and maintenance, experience of the operator, and these locations are then fitted with high temperature strain gauges and thermocouples.

gathering and analysing data After the strain gauges are installed, their output is used to determine the drum's cyclic response across a number of operational cycles. Data that are interpreted as strain amplitudes are submitted to algorithm for evaluation of life. These observations offer a thorough insight of the drum's operational cycle when combined with the response of local temperature and an operational data overlay. This can serve as the foundation for initial suggestions about cycle optimization with reference to the cooling procedure for reduction of thermal stresses and increase operational lifetime.

Re-analysis of the data and a life assessment study

Based on the measured stresses and temperature response, a probabilistic life evaluation was conducted. The requirements for extending the life of the coke drum are directly at odds with the requirements for maximising the life of the coke drum, which calls for a quick cooling process at the conclusion of each operational cycle. Due to modifications in operational procedures, process optimization and drum life extension are both achievable.

2.2 COMMON LIFE ASSESSMENT PROCEDURE [1]

A different technique of evaluating a person's quality of life is based on the concepts of low cycle fatigue crack initiation and growth. This method uses linear elastic fracture mechanics to describe growth while predicting crack initiation based on local fatigue endurance. The material's tensile and fracture toughness parameters are used to determine failure.

The benefit of this method is that input data like material properties and cyclic strain can be changed. This approach offers a distribution of potential outcomes with probability of occurrence and does not require deterministic calculation. Figure 4 illustrates how these can be used to generate cumulative probability curves for crack start and failure as a function of operating cycles. When deciding on a future maintenance and inspection approach, the operator might determine on this basis how much risk he is willing to take.

Figure 3 shows a flow chart outlining the present course of analysis.

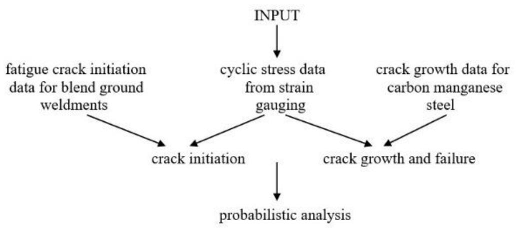


Fig. 3 The probabilistic methodology flow chart [1]

2.3 COKE DRUM EVALUATION PROGRAM [3]

With an unders of drum condition, the remaining life of other drums may not be as terrible. Reasonable preparation can be started to extend the usable life. The plan to assess these vessels is as follows.

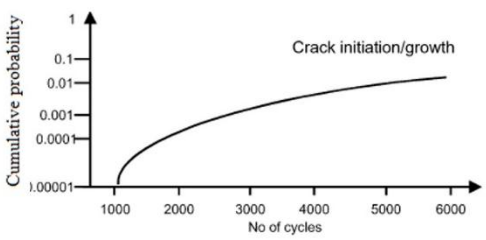


Fig. 4 Graph indicating crack initiation and growth [1]

Initial Phase

Using cutting-edge laser measurement techniques, the first distortion profiles are acquired in this step and used as the foundation for an examination of the vessel's current state. With the online service, a thorough internal examination is completed in between batch cycles in about four hours. The drill stem is immediately mounted with instruments that are rated for explosive conditions. With the aid of these methods, the vessel can be virtually and dimensionally described without the need to blind it or set up scaffolding.

Second Phase

For various longitudinal and circumferential sections, a thorough thickness survey and inspection should be carried out in the second stage.

Third Phase

Strain gauges are put at key points during this phase. Typically, a hoop/axial pair is positioned at the "peak" and "vally" sites, where the coke drum diameter is greatest and smallest, respectively, close to the centre of the coke bed. Additionally, thermocouples are positioned close to the gauges; this arrangement provides a better representation of the membrane stress. A sufficient number of cycles should be documented in order to produce a reliable statistical mean stress during quench. Thermocouples can be positioned from top to bottom at each horizontal seam and recorded simultaneously if a further structural investigation of the drum is required.

Fourth Phase

In the fourth stage, metallurgical analysis is completed, and samples of the drum should be used to determine the material qualities. Additionally, if a fracture is found in the sample, its failure limits are determined, and the plate's and the weld's suitability is noted. In the absence of this, assumptions are made.

Fifth Phase

At this stage, the operation history is examined, and key crack sizes are established with the aid of a fracture mechanics analysis, which aids in making repair decisions.

Sixth Phase

To limit the vessel's capacity, the repaired vessel will be handled as a pressure vessel in the final stage, which creates membrane stress and axial bending stress. Diameter profile scan results are quickly entered into a three-dimensional "Finite Element Model." The membrane and surface stress generated are used to describe the severity of bulges.

2.4 NUMERICAL SIMULATION [2]

For a numerical simulation to accurately predict the safe life of the coke drum, the strain amplitude that is induced in the production environment must be acquired. Using ANSYS finite element software, the strain amplitude of the connecting weld area between the drum body and skirt is modelled. According to the ANSYS finite element numerical simulation, the greatest equivalent strain is 344.32 MPa, the highest equivalent strain is 0.0033128, and the highest equivalent strain amplitude is 0.0032619.

III. FATGUE TESTING RESULTS AND ANALYSIS [2]

3.1 PROCEDURE

The dynamic material testing machine was used to conduct the tensile and fatigue tests. The specimen is heated in the furnace to 500°C for 30 minutes before to the fatigue test, and the strain rate is kept at 0.4%/s. The specimen was tested using two different types of loads, as seen in figure 5. In light of real-world operational circumstances, strain ratio is zero throughout the test.

The tensile and fatigue tests were performed using the dynamic material testing apparatus. Before the fatigue test, the specimen is heated in the furnace to 500°C for 30 minutes, with the strain rate held at 0.4%/s. Figure 5 shows the specimen being examined with two distinct types of loads. In comparison to operational conditions in real-world settings, strain ratio is zero throughout the test.

Practically speaking, industry places a high value on the evaluation of equipment's safe life. Coffin modified the Manson-Coffin expression as follows to account for the load frequency, v, impact on HTF life, Nf

$$(N_f \cdot v^{k-1})^{\beta} \cdot \Delta_{\dot{\varepsilon}p} = C_2 \qquad (1)$$

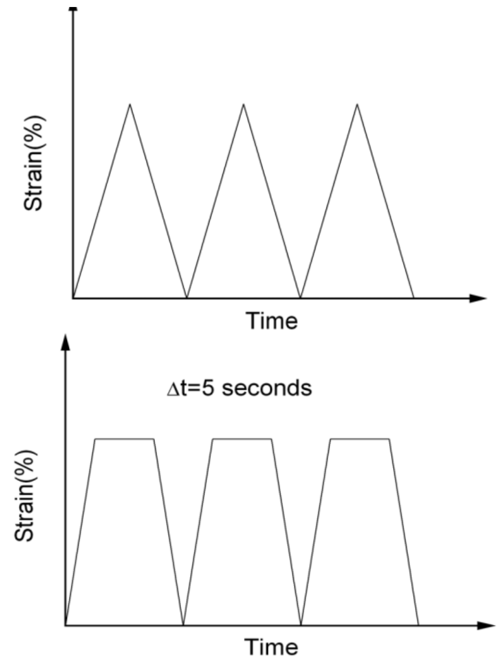


Fig. 5 Schematic illustration of load spectrum A and spectrum B respectively [2]

TABLE I
Fatigue test results of 14Cr1MoR steel plate butt-welds at load A at High-temp [2]

$\Delta_{\dot{\varepsilon}}$/%	1	0.8	0.6	0.5	0.49	0.46	0.44
N_i	538	950	2062	2133	4222	5170	8815
N_f	622	1301	2542	2438	4961	5625	16950

TABLE III
Fatigue test results of 14Cr1MoR steel plate butt-welds at load B at High-temp [2]

$\Delta_{\dot{\varepsilon}}$/%	0.9	0.8	0.48	0.46	0.44
N_i	755	1074	3403	3786	5968
N_f	912	1219	3760	4001	10537

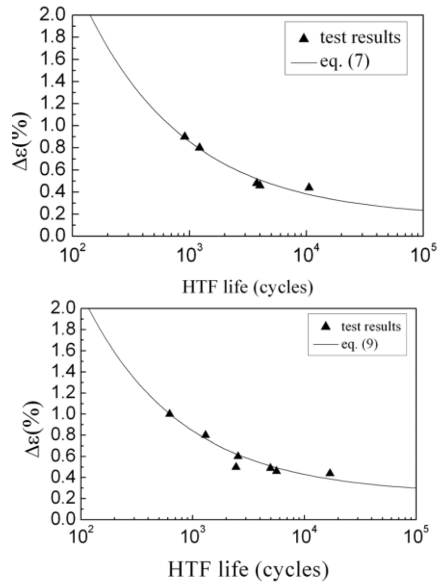
$\beta = 0.5$. In unidirectional tensile condition, $N_f = 1/4$, $k = 1$, when $\Delta_{\dot{\varepsilon}p}/2 = \dot{\varepsilon}_f$ the braking of specimen will occur, so $C_2 = \dot{\varepsilon}_f$. $\dot{\varepsilon}_f$ is metals' ductility during fracture. At k=1, cyclic strain governs how materials deform and fracture, whereas when k=0, creep governs how materials deform and fracture. The interaction between tiredness and creep happens at $0<k<1$.

According to research on the mechanisms of fatigue, the primary factor in creating fatigue damage is the local plastic cyclic strain that is created in the material. According to reference [5], a critical cyclic strain range ($\Delta\dot{\varepsilon}_C$) is always present in metals, below which metals have no cyclic local plastic strain and, as a result, minimal fatigue damage. The limit of theoretical strain fatigue of metals is what this crucial cyclic strain range represents.

The principal cause of fatigue damage in metals is this damage strain range. As a result, the relationship between the metals' fatigue life (Nf) and damage range ($\Delta\dot{\varepsilon}_D$) is as follows.

$$\Delta\dot{\varepsilon}_D = \Delta\dot{\varepsilon} - \Delta\dot{\varepsilon}_C \quad (2)$$

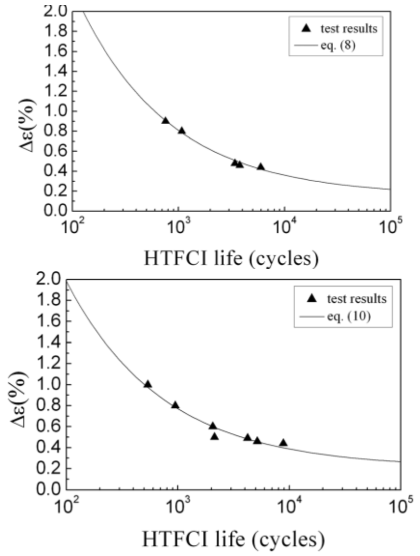
$$\log N_f = \log A' - 2\log(\Delta\dot{\varepsilon} - \Delta\dot{\varepsilon}_C) \quad (3)$$



$$N_f = 0.0476\,(\Delta\dot{\varepsilon} - 1.662\text{x } 10^{-3})^{-2} \quad (4)$$

$$N_f = 0.0362\,(\Delta\dot{\varepsilon} - 2.40 \text{ x } 10^{-3})^{-2} \quad (5)$$

Fig. 6 HTF test results and regression analysis under load A [2]



$$N_i = 0.0429\,(\Delta\dot{\varepsilon} - 1.535\text{x } 10^{-3})^{-2} \quad (6)$$

$$N_i = 0.0314\,(\Delta\dot{\varepsilon} - 2.102 \text{ x } 10^{-3})^{-2} \quad (7)$$

Fig. 7 HTFCI test results and regression analysis under load B [2]

IV. SUMMARY

It has been observed from literature survey that, how to go about estimating the life of a coke barrel practically and it is shown that high-temperature, low cycle conditions are the most likely to cause the welding junction between the drum body and skirt to fail.

The majority of operators use a risk-based inspection technique that incorporates technology that makes it possible to monitor the temperature and stresses of the coke drums online while they are operating cyclically. The same process may be applied to these temperature and strain numbers to obtain cumulative failure probability at various stages of the coke drum in the present and the future. Based on this, the operator can choose their future course of action and accept the risk associated with maintaining the coke drum. Additionally, it has been observed that strain gauge measurements are a crucial instrument for defining the real loading stress ranges that an operational delayed coking drum experiences.

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