Fitness for service evaluation of bulging in delayed Coke drums

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Abstract—Delayed Coking is the most commonly used carbon rejection process that upgrades heavy residual feed stocks to a wide range of lighter hydrocarbon gases through thermal cracking. Delayed coke drums are operated under severe conditions of cyclic heating and forced cooling during this process that apply repetitive type of thermal stresses to the drum walls which causes bulging and distortions of drums. Coke drums are designed as per ASME Sec VIII, Div 1 as cylindrical pressure vessels which considers internal pressure as primary stress and neglects low cycle fatigue which is main cause of failure in case of coke drums. The reliability and longevity of delayed coke drums is critical for efficient and economic operation of refineries. A Fitness for Service (FFS) evaluation is required to determine the acceptability of a coke drum containing bulges and cracks for continued service. This paper discusses several methods like finite element analysis, laser profiling of bulge maps, bulge severity analysis to detect and minimize this phenomenon from occurring.

Key words-- bulge intensity factor, coke drum, finite element analysis, fitness for service

I. INTRODUCTION

The Delayed coking is the most commonly used carbon rejection process that upgrades residues to a wide range of lighter hydrocarbon gases and distillates through thermal cracking. The feed stream, which mainly consists of vacuum reduced crude (VRC), is heated in a fired heater to about 485-505°C so that it attains thermal cracking temperatures. The residence time in the furnace is very short and coking is delayed until the feed reaches the large coking drums downstream of the heater as shown in Figure 1.

This is a batch-continuous process where the flow of feed stream is continuous [1], [2]. The feed stream is switched between two drums. One drum is on-line filling with coke while the other drum is being cooled, decoked and warmed up. Delayed coking is a cyclic operation with batch duration (cycles) from as low as 10 hours to as long as 48 hours.

In practice, coke drums undergo cyclic processing stages such as steam testing, vapor heating, oil filling, steam and water quenching, and unheading with temperature fluctuating from ambient to about 482°C (900°F) [2],[3]. The severe thermal cycling causes excessive thermal and mechanical stresses in the drum shell and attachment structures. It has been recognized that the common failure mechanisms for coke drums are related to the low cycle fatigue, bulging and cracking caused by these cyclic thermal stresses.

II. DESIGN CRITERIA FOR COKE DRUM

Coke drums are designed and built according to the ASME Sec. VIII, Division 1 as cylindrical pressure vessels, which is towards the burst failure of the vessels with respect to the ultimate strength of the material [1] ,[4]. A Division 1 vessel is conservatively designed for burst which is a function of the Ultimate Strength. In contrast, Low Cycle Fatigue is related to the elastic Yield Strength and particularly stress exceeding twice Yield. The ASME code assumes that internal pressure is the primary (largest) stress to which a pressure vessel is subjected. The internal operating pressure, typically ranging from 276 kPa to 414 kPa (40–60 psi), and hydrostatic pressure due to coke charge and water quenching are considered in the selection of the materials and shell thickness of the coke drum. This traditionally results in horizontally-arranged courses varying in thickness from the bottom of the drum to the thinnest plates at the top as in Figure 2. Life of coke drum is based on a number of cycles of operation at specific stress ranges, and not as a function of time to failure [1].
III. INSPECTION AND MONITORING METHODS

Structural integrity assessment of Coke Drum is determined by Fitness for Service evaluations. Fitness-for-service evaluations are conducted periodically to determine whether the component with existing damages is suitable for continued service [3]. The life of a coke drum ends when there are unacceptable amounts of circumferential through-wall cracking due to low cycle fatigue. The individual inspection techniques that are now being used include Acoustic emission testing to globally inspect the drums for ID and OD connected cracks, Strain gauging to measure drum wall stresses during the heating/quench cycle, Finite element analysis to locate high stress spots, Laser surface profiling to measure drum distortion and bulging, and improved drum construction techniques for repairing or replacing sections of coke drums.

1) Acoustic Emission Testing

Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material. When a structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy, in the form of stress waves, which propagate to the surface and are recorded by acoustic sensors [6].

The application of the AET on in-service drums is often accompanied with skin weldable thermocouples. The TC’s produce the temperature trends experienced by the drum’s outer surface, both during heat-up and quench. Although very fast, these quench rates last for only a few minutes but their impact on the thermal stresses imposed on the drum’s surface, and across their wall thickness, is significant.

Acoustic emission testing provides the coke drum operator with inspection tool to verify the structural integrity of pressure vessels with no disturbance to operations.

2) Strain Gages and Coke Drums

Strain Gages are uniaxial resistive element sensors attached to the outer wall of a coke drum [4]. As they are stretched or shortened their resistance changes, and the Wheatstone bridge circuitry converts this to an output voltage which can be scaled as micro strain. A data logger records these signals, as well as associated temperature. A practical strain gage for the application is constructed of a Platinum Tungsten wire filament capable of 593.33°C (1100°F) which is highly temperature sensitive.

The manufacturer provides data for each sensor to calculate apparent strain error as a function of temperature which must be measured at each location. This is performed during the processing of the recorded measurements.

Locations for strain gage placement on a coke drum must be carefully selected using a laser map to guide the location, particularly on older, bulged and corrugated drum shells. A location on a minimum bulge diameter will behave differently than a location on the maximum of a bulge diameter due to the interaction of average membrane stress and bending stress on the outer surface. Advance knowledge of the often-corrugated shape gives a range of considerations regarding the location and orientation of each gage. Furthermore, the results from the individual gages can be better interpreted by knowing the general shapes of the surrounding area.

3) Finite Element Analysis

A simple and effective method of evaluating the influence of bulging in a corrugated vessel is to solve a finite element model with internal pressure loading. Figure 4 displays such a model using 3-D shell elements capable of providing membrane and bending stress. An internal pressure load will create local stress gradients due to ring bending and an extension of the bulge.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element type</td>
<td>Shell model</td>
</tr>
<tr>
<td>Geometery</td>
<td>Hollow cylinder</td>
</tr>
<tr>
<td>Internal pressure</td>
<td>1.24 MPa (180 psi)</td>
</tr>
<tr>
<td>Analysis type</td>
<td>Static analysis</td>
</tr>
<tr>
<td>Software used</td>
<td>ANSYS 12.0</td>
</tr>
</tbody>
</table>

Stress contour results indicate locations with highest stress and these will be the most likely candidates for crack
propagation. Other loadings can be applied to the model such as local and global thermal gradients, and coke crushing due to radial interference.

**Figure 4: Finite Element Model**

FE analysis has indicated three sources of high stresses measured on coke drums: Localized hot spot, Coke/shell differential shrinkage stress, Skirt/shell attachment.

Finite element analyses can be performed using a hypothetical loading cycle and the actual drum surface profile as derived from the measured laser survey (Figure 5). The figure shows the result obtained using Drum view software which is developed by CIA Inspection Inc. Laser distance measurements (ranges) to accuracy of 1.411 mm are collected on a 25.4 X 25.4mm grid over the entire vertical surface of the drum (between the tangent lines of the top and bottom drum sections). This range data is further processed by custom software to:

a. "Roll out" the drum cylinder to obtain flat surface representation.

b. Create colour visualization (contour map) of the drum, with bulge depths indicated.

The results of such an analysis can identify the location of the highest stress risers and can quantify the magnitude of the stress riser relative to the average stress in unbulged areas of the drum. When an “actual” loading profile is used in a finite element calculation, the real stress values are calculated which can lead to a direct determination of the remaining fatigue life.

**Source: Drum View software by CIA inspections**

**Figure 5: Profile scans used in finite element model.**

Early manual inspection methods for locating and characterizing drum wall distortion, performed after scaffolding the inside of the vessel, have largely been replaced by remotely controlled laser profiling. A laser surface profiling system can internally profile coke drums during the short time period between coke cutting and refilling, eliminating the need to wait for a turnaround to perform internal measurement. It employs a remotely-controlled sensor package attached to the coke drum’s drill stem as in Figure 6.

Regular laser profiling of coke drums over several-year periods allows operators to compare the degree of deformity among their different drums, thereby identifying which drums are likely to require more inspection effort and compare the change in drum deformities over time and predict when bulges will reach unacceptable levels.

**Figure 6: Coke Drum inspection system with laser profiler**

In addition, finite element modeling tools can be applied to the measured surface profile of the drum to model the effects of a typical quench cycle to determine the relative levels of stresses that appear across welds.

**IV. BULGING PHENOMENON**

Shell corrugations, called bulges, are distortions of the diameter that extend fully or partially around the circumference at various elevations on the vessel. Coke drums tend to suffer from a "bulging" phenomenon due to the cyclic nature of their service [6]. The bulges typically are located near the circumferential weld seams joining the cylindrical shell courses. As the number of thermal cycles increase, the bulges grow larger and cause cracking in the vessel shell. The cracking also increases in length, depth and number of cracks as cycle frequency increases. At some point in operation, the cracking must be repaired, the shell sections replaced or the entire vessel replaced for continued safe operation.

Industry studies of operating coking units, which included thermal and mechanical stress analysis, have determined that the circumferential weld seams act as a stiffener during the water quench cycle, causing the shell to distort a short distance above and/or below the weld seam. Several methods to minimize this phenomenon from occurring have been proposed by those in the coking industry with only incremental success.

**1) Effect of Quenching on Drum Bulging**

**4) Laser Profiling of Coke drum**
The rate of cooling water injection is critical. Increasing the flow of water too rapidly can "case harden" the main channels up through the Coker without cooling all of the coke radially across the coke bed. The coke has low porosity which then allows the water to flow away from the main channels in the coke drum.

If the rate of water is too high, the high pressure causes the water to flow up the outside of the coke bed cooling the wall of the coke drum. Coke has a higher coefficient of thermal expansion than steel (154 for coke versus 120 for steel, cm/cm/°C x 10\(^{-7}\)).

2) Unit Quench Factor

The bulging is most severe in the lower cylindrical portion of the vessel, typically the first 40 to 50 feet above the cone section. This section of the vessel experiences the highest quench rates during the quench cycle [6]. High quenching rates produced thermal gradients in excess of 10°F per inch; lower quenching rates produced smaller gradients thus less bulging.

\[ \text{UQF} = \frac{\text{Water quenching time (minutes)}}{\text{Coke Capacity (tons)}} \]

Unit Quench Factor (UQF) that is the ratio of water-quenching time in minutes to the coke yield per drum in tons. When UQF is greater than 0.50 the bulging is minimal. When it is greater than 0.80 the bulging is non-existent. The UQF is directly proportional to the rate of water injection during the quench cycle, the slower more controlled the quench the greater the UQF and consequently less bulging. Currently the trend is for even shorter cycles which mean lower UQF that will ultimately reduce the overall life span of the vessel.

Though thermal shock is the main mechanism for the initiation of the cracks, high relative strength of the circumferential weld metal as compared to the lower strength of the adjacent base metal is also one cause of the bulging.

V. BULGE SEVERITY ANALYSIS

Surface correction or bulging factors are used to quantify the local increase in the state of stress at the location of a crack in a shell which occurs because of local bulging. Variables such as vessel construction, cycle times, operating practices such as pre-heat and quench rates and feed stock characteristics have a greater impact on how the vessel ages [16], [17].

In situations where bulges have occurred near welds, the bulge profiles tend to be “sharper”, since a significant radial distortion is present along a relatively short vertical wall distance. The steepness of the bulge gradient in these situations can result in stress concentrations in the wall material, with obvious implications on the possibility for failure in these areas. The apex of the bulge “grows” faster over time than the bulge tails. The girth seams, due to the higher yield strength of the weld metal, tends to augment the bulging causing a “constrained balloon shape” as illustrated in Figure 7 [2].

![Figure 7: Successive stages in bulging deformation in coke drums](image)

It is common industry knowledge through thermal and stress analyses of operating units that the higher strength of the weld metal in the circumferential seams tends to have a stiffening effect which increases stress leading to distortion and cracking [9]. The longitudinal weld seams required to make the shell courses are reported to be unaffected by the thermal cycling except where these seams intersect the circumferential seams. In the bulge areas near the circumferential seams, the longitudinal weld seams are also affected by the thinning effect and will crack, given enough thermal cycles.

1) Bulge Intensity factor (BIF)

The Bulging Intensity Factor (BIF) is a geometry based technique for assessing the severity of coke drum bulges. The method is designed to help in:

a. Planning maintenance outages, repairs, and replacement
b. Determining the frequency of laser scans
c. Quantifying the risk of failure
d. Prioritizing inspections and optimizing resource allocations.

For the case of unstiffened shell structures, the bulging factor can be calculated as the ratio of stress-intensity (SIF) of a curved shell to the stress-intensity factor of a flat panel.

\[ \text{Bulging factor} = \frac{\text{SIF (curved)}}{\text{SIF (flat)}} \]

BIF is a new tool for analyzing laser scans as it provides excellent correlation between 3D geometric patterns and...
cracking histories. It is economically attractive compared to comprehensive finite element models. It identifies and ranks areas most susceptible to cracking and helps inspectors optimize their resources.

BIF Output can be obtained in various forms like Two-dimensional color contour plots, Three-dimensional surface maps, Ranking of most severe locations, multiple scans, Statistical analysis, Growth rate analysis, Future cracking projections [17].

![Figure 9: 2D and 3D BIF plots showing Bulges](image)

BIF results are used to evaluate bulge severity of the drum surface. Results are intended as a guide to rank bulges for inspection priority as a function of their likelihood to encourage cracking. BIF factor correlates the geometric bulging patterns of past cracking histories, developed from examine other coke drums, to the bulges on the coke drum.

<table>
<thead>
<tr>
<th>BIF</th>
<th>Internal Cracking Likelihood</th>
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<tbody>
<tr>
<td>&gt;+2</td>
<td>Severe</td>
</tr>
<tr>
<td>+1.5 to +2</td>
<td>Very High</td>
</tr>
<tr>
<td>+1 to +1.5</td>
<td>High</td>
</tr>
<tr>
<td>+0.75 to +1</td>
<td>Medium</td>
</tr>
<tr>
<td>0 to +0.75</td>
<td>Low</td>
</tr>
</tbody>
</table>

2) Innovations and design trends to minimize Bulge Severity

There has been a significant amount of study by industries concerning the mechanical issues surrounding coke drum life. Recent developments to minimize bulge severity shows following results:

a. Use a quench schedule that is checked to meet requirements for minimum stress.

b. New drum material selection has been towards increasing Chrome Moly alloy content. Steels with higher Cr and Mo contents are considered to have better thermal cycling resistance and also they are cladded with either 405 or 410S Stainless steel to prevent the corrosion.

c. Vertical Plate Coke Drum technology is used which gives longer coke-drum life and is more tolerant to operating upsets. Orienting the shell plates with their long direction vertical provides an increased (up to more than 40 feet) shell length without a girth seam. Since the low cycle fatigue stresses due to the quench cycle are axial, fatigue cracking invariably initiates in circumferential welds which could be eliminated by using vertical plate technology.

d. T-Rex skirt shell attachment can be used for reduction of stresses in the shell to avoid shell cracks [18]. The skirt includes one circumferential horizontal plate attached to coke drum and it is sandwiched between a lower supporting plate that supports the weight of drum and upper retaining plate that prevents the coke drum from tipping. The upper and lower plates are anchored to a concrete support base. The sliding connection of the plates allows the drum to thermally expand and contract while reducing stresses and metal fatigue.

VI CONCLUSION

The bulging and eventual cracking of the circumferential weld seams located in the critical quench area of a coke drum is a problem that has plagued the coking industry almost from its inception. There is general agreement that the root cause is low cycle thermal fatigue from the quenching operation, the quench rate being the significant parameter. All have recognized the stiffening effect of the circumferential weld seams primarily caused by the weld metal to base metal yield strength mismatch. Accordingly, the quench rate and the use of circumferential weld joints are major factors in determining the useful life of coke drums.

Together, the combination of a variety of techniques, all of which provide insight to the present condition of the coke drum, offer owners a powerful analytical tool which can improve the overall economics of operating a modern day coking plant. Current strict state and federal safety and environmental regulations impose on plant owners/operators a much higher degree of awareness on the structural integrity of pressure vessels and piping systems.

Repair strategies can be developed from the information obtained by Laser scan, Finite element analysis and strain gauges. As the drums reach their end of life, these tools can aid the operators in determining just how far they can push the Delayed Coker unit before ultimate replacement is necessary. This advance information and predictability is essential in effective planning for vessel replacement. Management through knowledge is the best approach in any process unit and is particularly appropriate in a delayed Coker.

VII. REFERENCES


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