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THE SIGNIFICANCE OF COKE RESISTANCE IN COKE DRUM FAILURES

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ABSTRACT

Shell bulging and cracking in coke drums have been documented for decades. Most of the literature on the subject attributes these failures to severe spatial and temporal thermal gradients that develop during the quench part of the operating cycle. While transient thermal gradients can be severe and can cause excessive stresses, they alone cannot explain all types of observed shell damage in drums. In this paper, the authors present and discuss observations that suggest that when a cooling shell contracts during quenching, the interaction of the cooling shell with the in-situ coke in the drum can induce substantial hoop and axial stresses in its wall. The manner and degree to which this resistance plays a role in causing damage appears to depend on the type of coke produced and the way drums are operated.

INTRODUCTION

Coke drums are pressure vessels that process heavy oils to produce lighter hydrocarbons and petroleum coke. The process exposes these vessels to severe thermal and mechanical cyclic loads that, over years of operation, result in various types of mechanical and structural damage mechanisms.

The most common types of damage in coke drums are cracking and bulging of the cylindrical shell. Cracking can develop at or away from bulging. Either one can cause loss of containment, unplanned outages, costly repairs, and even premature replacement.

Bulging which is a non-uniform radial growth of the wall was considered a common failure mode in 1958 by Weil and Rapasky [1]. At that time, most drums were made out of carbon steel and were operated at relatively long cycle times. According to the 1996 API Survey [2], 57% reported shell bulging and of the drums that bulged, 87% cracked. The maximum-size bulge reported by industry had an average radial size of 2.1 inches (53 mm), an average vertical length of 65 inches (1,651 mm), and an average circumferential length of 547 inches (13,894 mm). Clearly, the size, severity, and frequency of bulges and consequent cracking in coke drums are truly unique in industry.

Despite numerous efforts to instrument, monitor, and analyze coke drums, engineers are still unable to accurately define the thermomechanical loads that produce common bulging and cracking in these vessels. As a result, one cannot reliably make predictions regarding the locations, severity, and timing of these failures.

Most of the literature on the subject attributes these common failures to severe spatial and temporal thermal gradients that develop during the quench part of the operating cycle. The general consensus is that quench water which is injected inside the in-situ coke flows

through randomly formed channels to the wall in a highly non-uniform manner causing these damaging gradients. While severe temperature gradients are well documented and are indeed capable of producing the large plastic distortions in coke drums, they cannot alone explain all observed damage.

Over the last 30 years, it has been occasionally hypothesized that, during quenching, the shrinking of the cooler shell on hot solid coke can result in stresses that may contribute to coke drum bulging. Terms like "coke crushing" and "shrink-fit stresses" have been used to describe this loading mechanism. The first official mention of this hypothesis was in the 2013 API survey which was published in 2016 as a part of 934-G Technical Report. It stated that "an evaluation of responses related to the type of coke (shot, sponge and needle) and coke hardness showed no relation to the tendency of cracking and/or bulging", [8]. Descriptions of the different types of petroleum coke are provided in the following section. The report, however, did not provide the raw data which is needed to understand the basis of this conclusion such as the number of responses per coke type, the measure of coke hardness, and how the tendency of cracking and/or bulging was quantified. Until this information becomes available, it is difficult to analyze this conclusion and reconcile it with the evidence presented in this paper.

To the authors' knowledge, there has been no published in-depth treatment of this subject in the literature. In this paper, the hypothesis that coke resistance plays a significant role in coke drum failures is presented and examined using available evidence. First, some background information on the process and properties of petroleum coke is discussed. Then, evidence of coke resistance is presented using strain gage measurements and observed bulging patterns.

COKE PROPERTIES

The Delayed Coking process thermally "cracks" heavy, low value hydrocarbon liquids into lighter, more valuable liquid and gas products for use as feedstocks to other refinery process units. The process rejects much of the carbon and contaminants inherent in the heavy hydrocarbons into the solid petroleum coke product, which forms and accumulates in the coke drum. Hot feed is introduced at the bottom of the coke drum as a two-phase fluid, which passes up through the bed of accumulating coke by creating "channels" to the top of the developing coke bed. Operating practices and procedures are employed to ensure that these channels are sustained and remain clear.

Over time, the coke drum becomes full of coke; it is then taken off line by switching the feed into a sister coke drum, and the full coke drum is cooled (quenched) to a low temperature to allow safely removing the coke from the drum. The quenching process is performed by pumping cold water into the bottom of the coke drum at a managed rate to induce the water to flow preferentially through the coke bed channels that were created while the coke bed was formed, and to permeate the coke structure as much as possible. If the quenching water flow is unable to pass through all of the channels, or partially bypasses the coke bed and flows preferentially between the coke drum wall and the coke bed, inadequate quenching can occur. This can lead to zones of very hot coke in the bed, which may result in a safety issue during the coke cutting step, known as a blowout, in which hot coke, water and steam are explosively expelled from the top or bottom of the coke drum. Additional severe stresses are also placed on the coke drum walls due to the amplification of the thermal gradient between hot coke and cold water in direct contact with the wall.

As mentioned previously, petroleum coke is generally categorized into three types, depending on its physical structure. The type of coke that is produced in any coker is strongly dependent on the feed properties, and somewhat dependent on coke drum operating conditions. Sponge coke is so called because it exhibits many pores of varying size distributed throughout a continuous matrix, resembling a sponge. Shot coke by contrast consists of small spheres with a smooth and shiny outer surface, exhibiting significantly fewer and smaller pores than seen in sponge coke. The spheres may be loose and discrete, sometimes agglomerating into easily fractured balls, or embedded in a matrix of more sponge like coke. Premium coke, also called needle coke, exhibits a very uniform, homogeneous structure of thin crystals resembling needles, with many small pores distributed throughout the structure. It is sometimes considered as a subset type of sponge coke

Sponge cokers typically process a vacuum resid feed from light crudes with low levels of sulfur and contaminants, while shot cokers are generally using vacuum resid from heavy crudes with higher levels of sulfur and contaminants. The operating pressure and recycle ratio used to make sponge coke are generally higher than for shot cokers; operating temperature may also be higher for sponge cokers than for shot coke depending on the particular sponge coke properties desired. Premium cokers process a variety of other types of heavy oils with very low levels of sulfur and contaminants; the feed may be a proprietary combination of oils that are specifically selected to obtain a particular set of coke properties. Operating pressure, temperature, and recycle ratio in premium cokers are typically higher than in sponge or shot cokers.

The continuous matrix nature of sponge coke generates a stable and fairly homogeneous coke bed, which in conjunction with the significant porosity provided by the large number of pores, makes it relatively easy to properly quench the entire coke bed. The loose nature of shot coke results in a discontinuous, unstable coke bed that is easily fractured and disrupted, making the channels through the coke bed more prone to collapse. Along with the inherently low porosity, this

makes properly quenching a shot coke bed much more difficult than for a sponge coke bed. Finally, the higher porosity and continuous and highly homogeneous nature of premium coke makes it easy to quench the entire bed well, similar to sponge coke beds.

The physical properties that are primarily considered when evaluating coke are porosity, volatile matter (VM), thermal coefficient of expansion (CTE) and hardness expressed as Hardgrove Grindability Index (HGI). Ellis et al [9] reported their analyses demonstrated that sponge cokes have about twice the porosity of shot coke, which contributes to the greater difficulty in quenching shot coke beds. They also reported that CTE of shot coke is significantly higher than sponge and needle cokes, by 25% to roughly 300%. VM is a measure of the amount of incompletely converted heavy hydrocarbon remaining on the coke expressed as weight percent, and is largely dependent on operating temperature. Average VM ranges from 8% to 15% are commonly observed in commercial cokers. HGI is an indication of the hardness and difficulty of crushing, and is affected by the type of coke and operating temperature. Low HGI values indicate harder coke; shot coke HGI will typically range from 30 to 50, while some sponge cokes can range from 40 to 60 or more. HGI values for premium coke are seldom published, however it is expected that it will have a lower HGI than typical sponge coke.

These physical properties, and other analyses such as Vibrated Bulk Density (VBD), can only be performed on the coke after it has been cut from the drum, and in some cases after extensive sample preparation and modification. They can only provide an indirect measurement of the characteristics and field strength of the coke bed while in-situ (in the coke drum), instead of a direct indication. Further, in-situ coke properties are not uniform in the drum: due to the bottom feed configuration, the coke at the bottom of the drum has been exposed to high temperature for a longer period of time than the coke at the top of the drum. This causes the VM and HGI to be lower at the bottom, and higher at the top, so in-situ field strength of the coke bed is not uniform. The coke bed also has a significant void fraction – largely caused by the flow channels described previously, as well as some contribution from the overall porosity. Therefore it is very difficult to evaluate the field strength of coke in the drum by looking at the granular bulk solid coke as cut from the drum.

STRAIN MEASUREMENTS

For decades, industry has utilized thermocouple measurements and thermal gradients as the key component in understanding coke drum stresses. In the authors' experience, thermal gradients and transients appear to be more important for some grades of coke rather than others. For example, shot coke is prone to have more local 'hot spots' than anode sponge coke morphology. While thermal gradients and transients are a very important component of understanding coke drum stress, strain gage data have informed engineers about phenomena that they did not know about until the 1990s.

Strain gage measurements have provided a better understanding of actual stresses that the shell has to accommodate in service. Since strain data is very random, to make good conclusions, one has to look at a statistically significant number of observations. Usually, in a large set of data, it is common to find few cycles that are outliers to a 'tame' histogram. Sometimes, one can look back at operational variables and see a reason for the outlier, sometimes not. It is an imperfect tool, but the best that engineers have to understand drum response to operations.

Critical to all observations derived from strain gages is the understanding that: (1) these measurements help to quantify the response (or output) of the vessel not the load (or input) to it, and (2) a strain gage can only describe the state of strain on the outside surface of the wall at one specific point on the vessel. Due to randomness of channeling and water flow, the strain state can be significantly different on the inside surface or on the outside surface just a couple of inches / centimeters away from a measurement point. Therefore, while it can demonstrate the existence, severity, and nature of high stresses, a measured strain cannot be used to define loading or characterize damage in an entire drum.

Given the above limitations, extremely valuable strain measurements have been obtained in the last three decades. Very high plastic-regime strains that usually last for relatively short periods of time during water quenching have been consistently reported in the literature [3, 4]. Linear stresses calculated from these high measured strains can be an order of magnitude larger than typical Code allowable design stresses. Typically, measured strains significantly vary from cycle to cycle and from one location on the drum to another.

One of the key observations from strain data is that there appears to be no consistent correlation between strain amplitude and temperature gradients. This observation tells us that there is more to the puzzle than just thermal gradients.

Of course, if the cause of high measured strains was only a pressure type load, basic Barlow pressure vessel equations would have us believe that hoop stress would always be twice the longitudinal stress. But often measured axial stresses are much higher than hoop stresses. Therefore, a pressure-type load does not explain the bi-axial stress ratio.

A commonly-cited hypothesis is that, since highest stresses on the drum wall typically occur during the time when water quench level passes the observed point, high measured axial stresses are caused by what is referred to as the "vasing effect". In other words, since the shell just below the water level is cooler than it is above the water level, a vertical temperature gradient forces the drum to distort in the shape of a vase causing high bending stresses that show up as axial stresses on the outside surface of the shell. There are two problems with this

hypothesis: (1) high measured strain amplitudes can be positive or negative from one cycle to another, and (2) finite element models have repeatedly suggested that maximum measured axial thermal gradients can only result in a small fraction of maximum measured strains. A recent comprehensive model that examined temporal and spatial gradients including through-wall components confirmed prior art and showed that the most severe thermocouple temperature profile that was obtained from an operating coke drum on 12 hour cycles would induce no plasticity in the wall, [5].

Because of random channeling, hot and cool spots routinely form during quenching of coke drums. Severe spots can cause plastic strains and do explain the initiation of local bulges. However, since these spots are random in location, size, and severity, they cannot be treated as recurring load for deterministic calculation of fatigue life or simulation of progressive growth of bulges. More importantly, thermal spots cannot explain all types of bulges, as discussed later in this paper.

The above observations suggest that the nature of large-magnitude strain measurements cannot be totally explained by thermal gradients and that there is probable cause to suspect other loading mechanisms.

As discussed below, a close examination of a large database of strain measurements suggests that the resistance of solid coke to shrinking shell can be a major load on coke drums.

Figure 1 shows strain and temperature measurements obtained from a premium coke drum shell over three operating cycles. Axial and hoop strains during the third cycle quench (circled in black) are similar to strain measurements obtained from lower stiffness coke drums where strains spike for few minutes during the drop in shell temperature caused by quenching. The second cycle in Figure 1 shows a different pattern. Measured strains (circled in red) are representative of what the authors have repeatedly observed on premium coke drums. Unlike typical measurements where strains drop rapidly during cooling, stresses in these measurements rise to a maximum for the cycle as water level passes, but do not drop back down for hours – sometimes staying high until the coke was cut from the drums eight hours later. Figure 2 is another example that shows stresses calculated from strain measurements in a premium coke drum during quenching. Both axial and hoop stresses stay high for hours almost until cutting the drum. Figure 2 also serves as an example of compressive axial stresses that cannot be explained using the "vasing effect" described above. Since high thermal gradients during quench transients can only last for a short period of time, the above measurements offer clear and irrefutable evidence of the effect of in-situ coke on drum shell.

Generally, stable sponge type cokes seem to be the 'easiest' operations in terms of drum stress response, with the coke being more permeable for water percolation – the shell is in general more uniformly cooled with much fewer hot spots. Also sponge coke is often softer or less hard than shot coke bb's or lump premium coke – so the effect of the drum shrinking on coke would likely be of less magnitude. Explains why some drums seem to run for many more cycles than drums in other services.

Shot coke seems to be not so predictable – for reasons, shot coke can be more difficult to 'coke well' throughout the coke bed. If areas are not so well coked, they seem be 'oilier' and to be more resistant to permeation of the quench water – leaving hot spots and high local thermal stresses. So thermal stresses may be more dominant for shot cokes, if you 'shake up' a shot coke bed and it slumps – it would seem apparent that a 'bag of sand' would also have a contributing effect on wall stresses.

Another telling observation is that strains measured at the peak of bulges are often larger in magnitude than those at non-bulged locations. Since pressure-induced stresses at the peak of most bulges are lower than nominal stresses due to the dome-like response [6], higher strain measurements at bulge peaks could well lead us to think that coke resistance is amplified by the interaction with the locally deformed shell which is not only shrinking diametrically but also longitudinally as it gets cooler during quench.

Typically, discriminating between the various causes of drum stress in a strain measurement is not possible. The use of strain gages only allows us to examine the overall additive effect of these causes and to help us understand underlying phenomena.

BULGING PATTERNS

Since coking is a time-temperature dependent thermal cracking process, coke in the bottom of the drum sees longer time at higher temperature. This is why in-situ coke is typically significantly harder at the bottom of the drum than it is in the top. A first indication to an observer that coke field strength in the drum has a real effect on the drum shell comes from the observation that coke drum bulging and diameter increase are typically more dominant in the lower third of drum shells. This observation seems to be more pronounced if the coke made in the observed drum is hard.

A recently published paper demonstrated that there are several distinctly different bulging patterns in coke drums that are caused by more than one loading mechanism [7]. These patterns are grouped under two broad categories - uniform and local bulging. Uniform bulging is mostly constant around the circumference of coke drums. Local bulging is only confined to small areas of the shell. While some of these patterns can be explained using thermal gradients in the shell, others cannot.

Figures in this section use a height-profile view of entire coke drums in which the abscissa is height above bottom Tangent Line, the ordinate is radius, and the out-of-plane direction is azimuth. These figures were

obtained from operating drums using internal laser scanning.

One type of uniform bulging is Tapered Growth, three examples of which are shown in Figure 3. In all three drums, the average radius tapers almost linearly from a maximum at the bottom of the drum to the original radius at the top over the length of the drum. Since hot spots are non-uniform and nominal thermal gradients do not generate yielding, this type of bulging may be a demonstration of a direct correlation (almost linear) between the magnitude of average bulging and coke stiffness along the height of the drum. This relationship might have been amplified by creep damage in these carbon steel drums. In drums that are made out of other materials that are not susceptible to creep damage, such as chrome alloy drums, Bottom Growth which is a mostly uniform increase in average diameter up to coke fill level is observed, as shown in Figure 5.

Outage Growth is another type of uniform bulging that is concentrated at the coke fill (outage) level, as shown in Figure 6. This type appears to be caused by "top quenching" in which water and/or anti-foam liquids are inserted at the top of hot drums causing extremely high bending and membrane stresses in the shell at the outage level above which the wall is free to contract and below which it is not.

The above three types of bulging can hardly be explained using thermal gradients or hot spots. Coke resistance appears to be the only possible explanation.

CONCLUSION

The authors believe that data presented in this paper provide clear and irrefutable evidence of the significance of the role that coke resistance plays in coke drum failures. Authors also believe that the combination of coke resistance and thermal gradients - particularly hot / cool spots - are responsible for most plastic shell distortions in coke drums. The only exception is fabrication-induced damage such as Mid-height Growth and Accordion bulging.

This paper is a first step of trying to convince industry of the significance of coke stiffness using available evidence. It would be very valuable to quantify the impact of process parameters on coke stiffness and resulting damage. It is our goal, and we certainly hope, that this paper would stir enough interest and discussion to justify the effort needed to conduct necessary tests, instrumentations, and simulations to turn these observations into operational and design tools.

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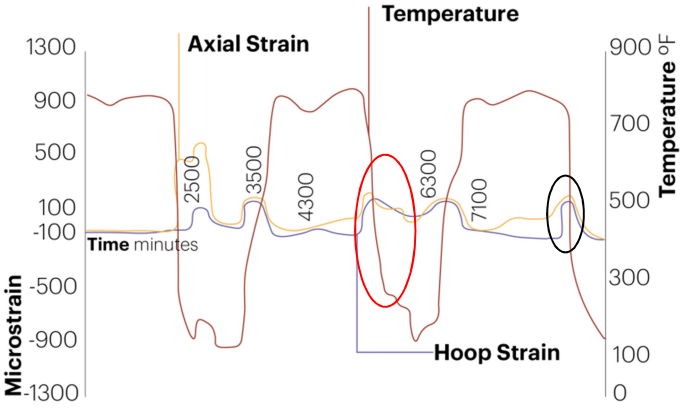

Figure 1: Strain and temperature measurements during three operating cycles

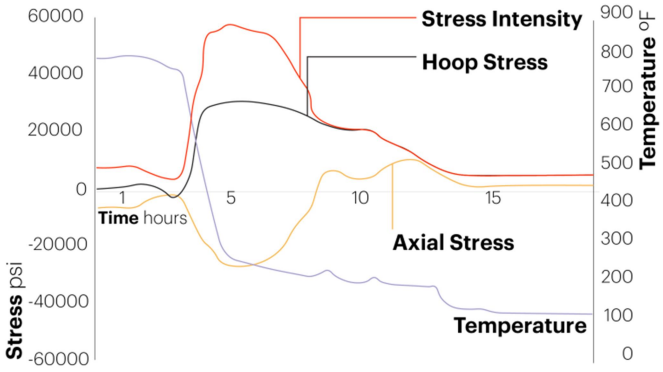

Figure 2: Stresses calculated from strain measurements during a quench

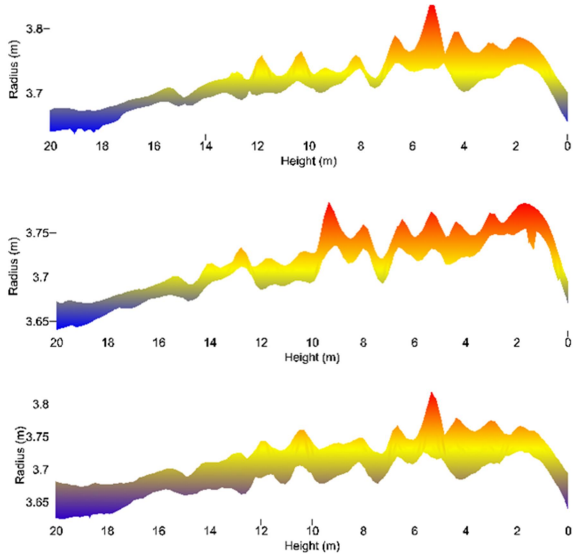

Figure 3: Tapered Growth

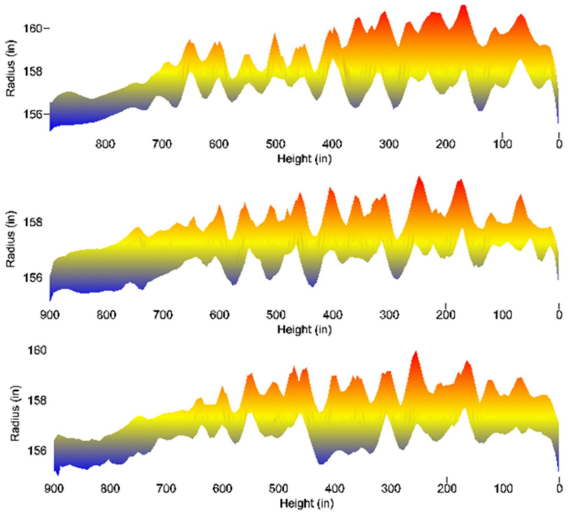

Figure 4: Bottom Growth

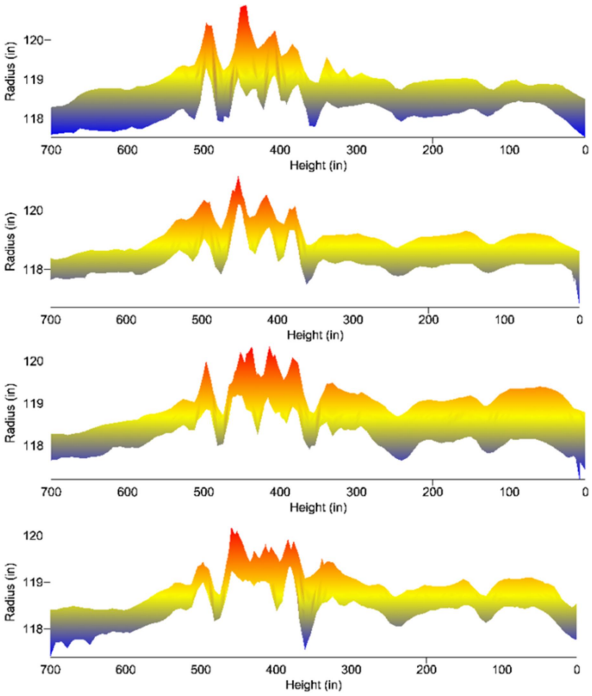

Figure 5: Outage Growth