Heater Tube Cleaning and Verification: The Effect of Fouling on Heater Services That Are Prone to Coking From a Process Engineer's Perspective

By Tom Gilmartin, Zerosumheater and retired fired heater and flare advisor for BP

EXECUTIVE SUMMARY

Heater tube inspection is almost exclusively looked after by the inspection team at a facility. And quite appropriately too — making sure the tubes are suitable for the next run is crucial. Innovative tube inspection techniques such as intelligent pigging and, most recently, Quest Integrity's Advanced Decoking and Cleanliness Verification (ADCV™) inspection offer additional information that is particularly useful to a process engineer to avoid production slowdowns or unplanned mechanical cleaning outages.

Even a small amount of fouling in the radiant section of a vacuum heater adversely affects NOx, production run times and overall performance of the fired heater. What is sometimes not realised is that even a localised area of 5mm of coke left in a coil can have a very significant impact on margin capture. Examples are given where this could lead to a yearly loss in production of $12.6 million USD or significantly more. The results in this paper show the benefit in knowing where fouling (e.g., coke and scale) has formed in a heater coil and why being confident that the coils are cleaned properly after a decoke or descale is crucial.

The consequences of some strategies that may be used to alleviate high tube temperatures caused by fouling are given, from running the furnace inefficiently to cutting coil outlet temperature and finally throughput. The commercial impacts are shown for these cases. Using a more advanced cleaning method, as is now offered with the Quest ADCV™ service as compared to convection mechanical decoking, can provide many benefits.

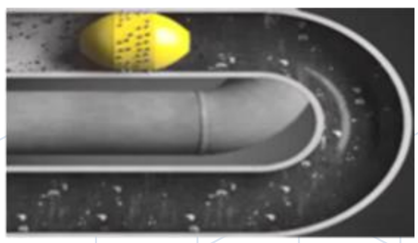

Figure 1. Quest Integrity ADCV™ service

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INTRODUCTION

In a production plant, process engineers are typically responsible for optimizing the plant to meet production and commercial demands. This is complemented by integrity inspections and the know-how of the integrity team responsible for ensuring the plant is maintained and safe. New smart pigging technology is now available that offers extensive insights on fouling that is useful for a process engineer as they optimize the plant.

It is sometimes said to process engineers, “You did not push your vacuum heater hard enough during the run if it has no coke.” By the same token, it is perhaps rather truculent to not clean your heater properly at a turnaround — especially when you do so for the preheat train before the heater. This paper is designed to allow you to refine that judgment and avoid the pitfalls of not knowing if a coil has been properly cleaned.

Take a vacuum heater. Any vacuum heater. You will find this workhorse heater in most refineries. It’s a low-pressure heater compared to most but a critical link for other units that provide the added margin capture for a refinery.

Vacuum, visbreaker, coker and sometimes crude heaters belong in a class of fired equipment that have a propensity to form coke in the heater coils. To achieve an acceptable run time between decoking, the heater design is used to limit the process tube oil temperature. Heat flux, flow regime and process coil outlet temperature are some of the factors used to control this. For vacuum heaters, run times can be anywhere from 18 months to 6 years depending on the feed being processed.

SIMULATIONS AND CASES CONSIDERED

A vacuum heater has been simulated to show the effect of coke laydown on heater tubes and its impact on heater performance in terms of three metrics: fired and process duty and environmental emissions. A range of coke thermal conductivities and thicknesses is used.

Note that no furnaces were harmed in these simulations…

A 27.9MW process duty vacuum furnace has been used to demonstrate the effect of fouling on the overall heater performance. The heater coils are horizontal with four passes and incremental tube sizes increasing in size towards the outlet. Tube material used is 5% Cr with a maximum design temperature of 650℃. A coil outlet temperature (COT) of 383℃ has been selected since this temperature bridges the temperature range used in vacuum and crude heaters.

As a reference, lower thermal conductivity is bad for heat transfer. Coke thermal conductivity is about 20 times lower than the tube metal and is a significant barrier to effective heat transfer.

- Nine cases are considered:
  — Base case (no internal fouling)
  — 1mm and 5mm fouling throughout the entire radiant section tubes with coke thermal conductivities of 1.5 and 3 W/mK (watts per Kelvin metre)
  — Localised fouling with 1mm and 5mm coke again in the radiant section with coke thermal conductivities of 1.5 and 3 W/mK
- Fouling thickness is held constant at 1 mm and 5 mm for widespread and localised fouling using the previously mentioned coke thermal conductivities. This reflects the thermal properties of coke which changes with the temperature and morphology of the accumulated coke. As a comparison, the thermal conductivity of 5% Cr is around 40 W/mK at 20℃.
- The process duty is maintained during this exercise with firing rate adjusted to compensate.

The effect of the fouling on key aspects of the fired heater radiant and convection section performance is shown in Table 1 for fouling throughout the entire radiant section.

TABLE 1. FOULING THROUGHOUT RADIANT SECTION ONLY (NO FOULING IN CONVECTION)									
		1.5 W/mK Thermal Conductivity				3 W/mK Thermal Conductivity			
	No fouling (base)	1mm thick	change	5mm thick	change	1mm thick	change	5mm thick	change
Firing rate (MW)	33.55	33.56	+0.1%	33.7	+0.4%	33.57	+0.1%	33.6	+0.1%
BWT (°C)	736	746.3	+10.3	789.6	+53.6	741	+5.1	762.3	+26.3
Tube Skin Temp (°C) *	419	463	+44	635	+21	441	+22	530	+111
NOx (ppm)	25	25.6	+2.4%	28.2	+12%	25.3	+1%	26.5	+6%
Absorbed fire box duty (%)	74.6	73.9	-0.7%	71.1	-3.5	74.2	-0.4	72.9	-1.7
Stack temp (°C)	324.6	325.9	+1.1	330.4	+5.6	326.8	+0.6	327.6	+2.8
Total heater fired efficiency (%)	82.9	82.9	-	82.6	-0.3	82.9	-	82.7	-0.2
A constant process duty of 27.9 MW used for all cases									
*A bulk process temperature of 383°C is calculated at the referenced skin thermocouple location									

REVIEW OF DATA FOR HEATER PERFORMANCE

1. **Environmental:**

   a. For the 1.5W/mK case a 2.4% increase in NOx with 1mm of fouling and 12% increase for 5mm in the radiant section.

   b. For the 3 W/mK those values show a 1% and 6% change. Driving source of this is the added fire box temperature.

   Note: On some units there may be a fixed maximum environmental permitted NOx limit that may lead to a consequential reduction in firing.

2. **Fired duty increases but not significant with fouling added:** The overall heater efficiency decreases a small amount with fouling – though there is a more significant decrease in radiant section absorbed duty with a 0.7% to 3.5% reduction in radiant for the 1.5W/mK case and 0.4% to 1.7% for the 3W/ mK case. The reason for this is less effective heat pick up in the radiant section. It is not unusual for a vacuum heater to have a process derived max fired duty using previous experience of how hard the heater can be fired and give an acceptable run time.
   In theory this would suggest that the heater will not be duty limited, but there is more to that as shown in the following points.

3. **As the radiant section fouls several things happen:**

   a. **Radiant section efficiency drops.** The effective heat pick up in the radiant section decreases. Overall, there is a reduction of process duty absorbed in the radiant section, dropping from a base level of 74.6% to 71.1% in the most fouled condition. This radiant duty decrease shows up as an increase in flue gas temperature going to the convection section with a corresponding increase in NOx production.

   b. **Tube skin temperatures increase.** For the worst case above (1.5W/m/K, 5mm) a very significant impact occurs here even though the fouling thickness is still minor. Tube metal temperatures increase from 419℃ to 635℃ to achieve the same COT with a less effective radiant section. This is close to the tube temperature limits for a 5% Cr tube (650℃). It will be discussed later why some end users may use a lower temperature limit of 593℃.

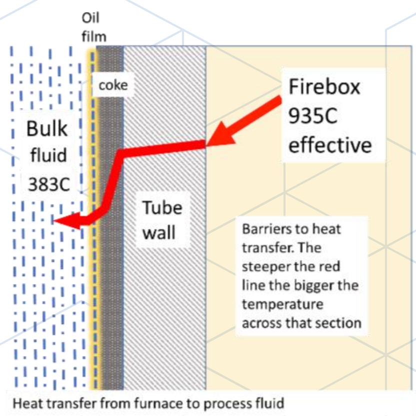

Figure 2. Heat transfer

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Tube skin temperatures: simulated vs. actual. The results above are from a process simulation. In the actual furnace, tube temperatures are measured by thermocouples attached to the heater tube. The design of these thermocouples can add a 20-40°C difference in recorded metal temperature compared to a simulation.

A simplified explanation for this is the way thermocouples are installed. They are externally attached to the tube, and as a consequence receive less cooling than the actual tube, absorbing more heat compared to the actual process tube. These thermocouples will read higher than the metal temperature from a simulation.
Visually you can see this effect if you look in a furnace and spot the tube thermocouples. They appear brighter than the tube - less cooling. This detail is one a good thermocouple manufacturer addresses - up to a point.

Typically, a simulation matches the skin temperature reported by changing the thermal conductivity of the coke and or thickness to match the field results.

4. **Radiant section fire box temperature is still acceptable at maximum case of 789.6°C.** Typically fired heaters have a maximum fire box temperature of 850-900℃ in this service, partially to protect the tube hangers and also to reduce coking tendency of the feed in the radiant coil. This limit (which indi- rectly is a proxy for heat flux) is important when processing opportunity feeds, which may be more sensitive to thermal breakdown. Fouling is driving the radiant section closer to these limits.

5. **Process Engineer perspective on these numbers.**
What can you see from the control room or data analysis in the office?

   - Tube skin temperatures — shows the largest noticeable change from a monitoring perspective but assumes you have the thermocouples in the correct location
   - Bridgewall or firebox temperature — next indicator with a significant change
   - Fired duty and heater efficiency — changes too small to notice in day-to-day monitoring

   There is one other metric that can be used. Visual inspection of the firebox (see Figure 3). It is possible to see advanced cases of fouling (the 5mm coke case). Thermography adds even more quantitative information.

6. **Impact on tube temperature limits and heater performance.** In this service, tubes are typically 5% Cr to 9% Cr and occasionally stainless steel. Tube metal limits are usually 650℃ (5%Cr), 705℃ (9%Cr) and 815℃ for stainless steel, which is typically used for more acidic feeds. In this simulation, where 5% Cr is used, API530 gives a limiting design temperature of 650℃, however this is for creep properties. A more commonly used limit is 593℃ which may be used to avoid rapid oxidation of the tube external surface. In this case, if 593℃ was used instead of 650℃, a cut back in heater operation may be required. Options are considered in the next section.

At 635°C an operator looking in the furnace will not need tube thermal indicators (TIs). They will visually see a dark red to cherry color on the tubes (best seen at night).

Figure 3. Visual tube inspection

OPTIONS TO DEAL WITH THE HIGH TUBE SKIN TEMPERATURES

a. **Material choice:** 9Cr steel with a limit of 705℃ would provide some headroom, but not much. Even with stainless steel tubes, the effect of fouling is to push the heater operation to traditional material limits with potential commercial / safety considerations coming into play.

b. **Special operational techniques:** These are sometimes used to mitigate and maintain run time- sometimes they work, sometimes they don't. Increasing O_2, cutting COT and cutting rate are discussed. The first one addressed is increasing O_2.

Increasing O_2 to reduce tube temperatures. An operational move sometimes used to alleviate skin temperatures is to run the furnace at max O_2, simply to move furnace duty from the radiant to the convection section. Example below:

TABLE 2	4% O_2 No Fouling	4% O_2 5mm Thick 1.5W/mK	9.7% O_2 5mm Thick 1.5W/mK
Firing rate (MW)	33.5	33.7	37.1
BWT (°C)	736	790	768
Skin (383°C bulk)	419	635	606
NOx (ppm)	25	28.2	34.4
Absorbed fire box (%)	74.6	71.1	62.3
Stack temp (°C)	324.8	330.4	364.2
Efficiency (%)	82.9	82.6	74.9

Success! Skin temperatures have indeed dropped by around 30℃ but at the cost of a very significant increase in fired duty.

Downside. Additional fuel duty, furnace efficiency has a significant drop off. Unsaid in this little simulation is: Do you have enough draft in the furnace to accommodate this increase in firing? What happens to the flame shape – is this firing increase enough to cause flame impingement, making the coking rate higher? A process model cannot predict that aspect. The NOx is likely to go up as well which has to be corrected.

SOME CRITICAL COMMENTS ON THESE RESULTS

This is just a simulation. It's unrealistic to lay coke down through the whole radiant section.

That is correct with two exceptions:

1. There are, however, times where an entire coil can be coked very quickly. Examples of this include: a low flow situation occurring in a coil including tripping to minimum fire, an individual coil control valve closing or jamming, incorrectly set low flow trips or excess time to respond to a low flow event- seconds make the difference!
2. The heater has never been pigged and does not suffer from high skin temperatures. In this situation, coke may be present but has been accepted as the normal baseline for heater operation.

What's more commonly the case:

Although coking or fouling across an entire heater coil is not typically seen, there tends to be specific areas that are most exposed to coke formation in terms of heat flux. Data is reviewed again in Table 3, and this time ignoring all the changes apart from skin temperatures. Local heat transfer (which in effect cools the tube) is still dominated by the coke layer thermal conductivity compared to other components. The localised coke is driving the high skin temperatures seen in this simulation. An important thing to note is tube temperatures are controlled by the effective heat transfer across the tube.

TABLE 3. LOCALISED FOULING IN RADIANT SECTION ONLY EXCERPT (NO FOULING IN CONVECTION)

Tube skin temperatures only		1.5 W/mK Thermal Conductivity				3 W/mK Thermal Conductivity			
Constant process duty	0mm Thick (no fouling)	1mm Thick	change	5mm Thick	change	1mm Thick	change	5mm Thick	change
Tube Skin Temp for a 383°C bulk process feed temperature	419°C	463°C	+44°C	635°C	+216°C	441°C	+22°C	530°C	+111°C
Adding allowance for thermocouple design +20°C	439°C	483°C	+64°C	655°C	+236°C	461°C	+42°C	550°C	+131°C
Adding allowance for thermocouple design +40°C	459°C	503°C	+84°C	675°C	+256°C	481°C	+62°C	570°C	+151°C

DEALING WITH THIS CASE OF LOCALISED FOULING

Here only the simulated cases are used without the additional allowance for skin thermocouple type.

The 1.5W/mK Case. We need to bring the tube temperature down below the oxidation temperature of 5% Cr- a value of 593℃ rather than the API 530 limiting metal temperature of 650℃. We tried increasing O_2 in the previous section; it worked a little bit but ran out of draft. We don't want to shut down for a mechanical cleaning to remove this coke, what else can I do?

1. Dropped the COT by 10℃ – this reduced the tube temperature by 10℃ to 625℃ – that did not help much and column cuts may be going off spec.
2. Try cutting rate: A 20% rate cut required to bring tube temperatures back to the tube limit – 590℃ vs limit of 593℃

TABLE 4	Condition	Skin (°C)	BWT (°C)	Average heat flux (W/m²)	Peak Film Temp (°C)
Start COT	383°C	636	789	32,777	402
COT reduction	10°C cut	626			
Rate reduction	-10%	612	761	30,078	400
Rate Reduction	-20%	590	731	27,275	398

WHAT ARE THE COMMERCIAL CONSEQUENCES OF THAT 20% RATE CUT?

3,250 bpd rate cut example @ $10 per bpd margin. $12million per year.

A key point is that a unit must be ready to take advantage of margin capture whilst it lasts. From the above case, even a little bit of fouling affects the overall ability of the heater to take advantage of a margin opportunity or to extend the run time of a heater.

A special case is given in Table 5 - here the coking thickness is increased to 7mm. On heaters with significant localised coking, this is not an abnormal thickness to find (in fact 10-15mm is more common). It is usually found and measured when tubes have been removed after a coking event and can be measured directly. This case is offered as it shows how just 2mm of added coke can have a dramatic effect on heater operation.

TABLE 5. LOCALISED FOULING IN RADIANT SECTION ONLY EXCERPT (NO FOULING IN CONVECTION)				
Tube skin temperatures only		1.5 W/mK Thermal Conductivity		
Constant process duty	0mm Thick (no fouling)	5mm Thick	change	7mm Thick
Tube Skin Temp for a 383°C bulk process feed temperature	419°C	635°C	+216°C	727°C
Adding allowance for thermocouple design +20°C	439°C	655°C	+236°C	747°C
Adding allowance for thermocouple design +40°C	459°C	675°C	+256°C	767°C

Figure 4. Coked tube

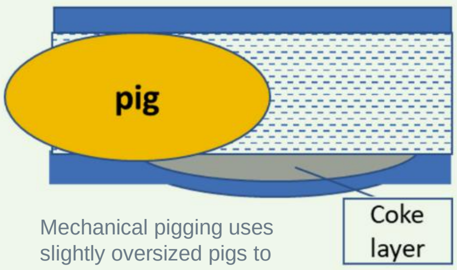
Note: That for the case of 7mm coking, there will be no sensible process moves available at this tube temperature. Heater will need to be scheduled for an unscheduled pigging run to clear the coke. At 730-750 C the affected tubes would be readily observable by an operator. Estimated time of the unit outage would be 10 days. This time does not include the removal and replacement of damaged tubes. Commercial cost would be a multiplication of the rate cut example.

WHAT ABOUT LOCALISED COKE THEN? THE HEATER IS PIGGED ROUTINELY

Have you removed all the coke?

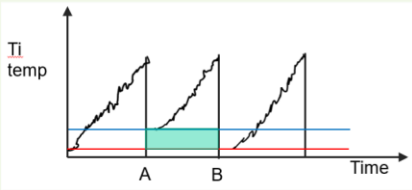
Consider the way coke laydown affects the tube. For a 5% Cr tube, the coke layer increases the metal temperature. Above 593℃ the external surface of the tube starts to oxidize, removing tube thickness. Over time the tube develops a classic bulge profile. The coke sits in that bulge (see illustration). This is well documented, check API 573. **Leaving this coke in place or in other places on the tube wall where conventional mechanical decoking cannot detect and remove it can lead to instant regret at start up** since tube temperatures have not recovered (see Figure 6)

Of course, there is a more banal way of leaving fouling even if you regularly pig a heater and have done so for many years. How do you know that the coil is clean? Pressure drop and coke fines during a pigging operation is a very subjective method of verification and rarely supervised by plant personnel.



Mechanical pigging uses slightly oversized pigs to clean the tubes. Too small and they don't remove coke, too large and risk damaging the tube (pigs have metal studs designed to remove the coke) Coke in this bulged area may not be removed.

Figure 5. Coke in bulged tube



Indicative example of tube temperature skin trends over three shutdown cycles. Tube temperatures increase over run, which is normal. At point A, a turnaround happens with pigging. Unfortunately, the tube temperatures did not return to their previous low starting points. Much consternation. At the next turnaround, B, a more extensive clean was carried out. Full recovery of starting tube temperature realised.

Figure 6. Tube temperature over three shutdown cycles

LOCALISED COKE — LEAVING IT IN PLACE

5mm of coke does not seem like a lot. Many operators consider leaving any coke as an initiation point /catalyst for additional coke to collect in those areas. There are complex models of this available in open source literature. Whether those models are credible is a moot point, however the impact of even a thin layer of coke on tube temperatures is not. Coke forms where heat flux levels are highest in a furnace. Flame impingement greatly increases the localised heat flux and hence tendency to form coke in a tube.

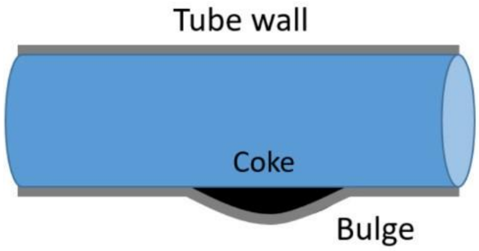


Figure 7. Coke in a bulge

We Do an Ultrasonic Intelligent Pigging Run After the Mechanical Pig Cleaning That Confirms the Tubes Are Clean — Doesn't That Work?

This works. But it does not capture very useful process engineering data. You have no idea where the fouling was and what tubes were exposed to it before the start of mechanical cleaning. Knowing this information provides insights on the firing profile, where the skin TIs should be and if there are any unusual fouling mechanisms in play. This information also helps direct where thermography readings should be taken and provides future forecasting for run times and projects (e.g., should you retube, upgrade metallurgy or burners, move the velocity steam injection point or upgrade the preheat train). Finally, for the inspection team knowing where the fouling has occurred is useful for material checks in those areas. Any sign of carburization / oxidation damage?

ADVANCED DECOKING AND CLEANLINESS VERIFICATION (ADCV™) IN DETAIL

Standard mechanical pigging uses cleaning tools that are oversized (made of hard plastic with scrapping studs inserted). There is a limit to how much these pigs can be oversized by. Too much and you can get tube scoring – essentially removing tube material. How does a pigging contractor know if tubes are clean?

Monitoring water quality during cleaning o peration, looking at the pressure traces for each pass. This approach leaves a lot of doubt. If there are bulges in the tube, these will not show as being significantly different from other areas. Those areas may have coke present. Hard fouling left over from previous cleanings can be left behind in areas of non-deformed tubing going completely unnoticed during current mechanical cleaning operations. It takes real expertise to review these traces and is particularly difficult to review and interpret if they are not graphically presented. Quest Integrity provides both the expertise and software tools to accomplish this.

Figure 8. Severe tube bulging

Insufficient cleaning …leaving coke.

Prior to the advent of mechanical pigging, the standard technique for coke removal was to burn it off. Steam air decoking, SAD. This was achieved with the heater off line by introducing air and steam into the heater coil and firing the heater. This technique required careful control of parameters to avoid damaging the tubes. Indeed, during this operation, the tubes could be seen to glow orange as the burn proceeded. With the temperatures involved, external tube oxidation typically formed. Ironically this oxide layer acted as a barrier to heat transfer. This SAD technique had two main benefits: coke removal could be visually seen as the burn proceeded through the coil and it could be done without external specialists. As a technique, this has fallen into disuse (apart from special cases) since mechanical pigging can deliver tube cleaning results in a shorter time with less risk of tube damage.

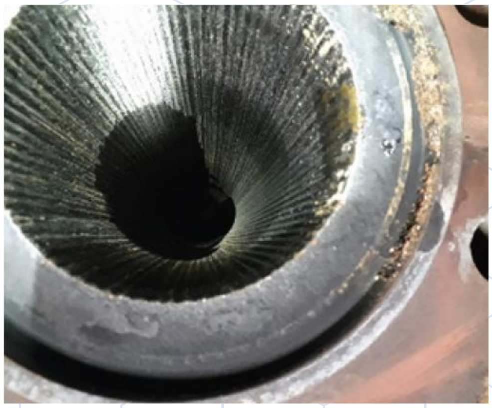


Figure 9. Damage (grooving) on tube internal surface from over-cleaning

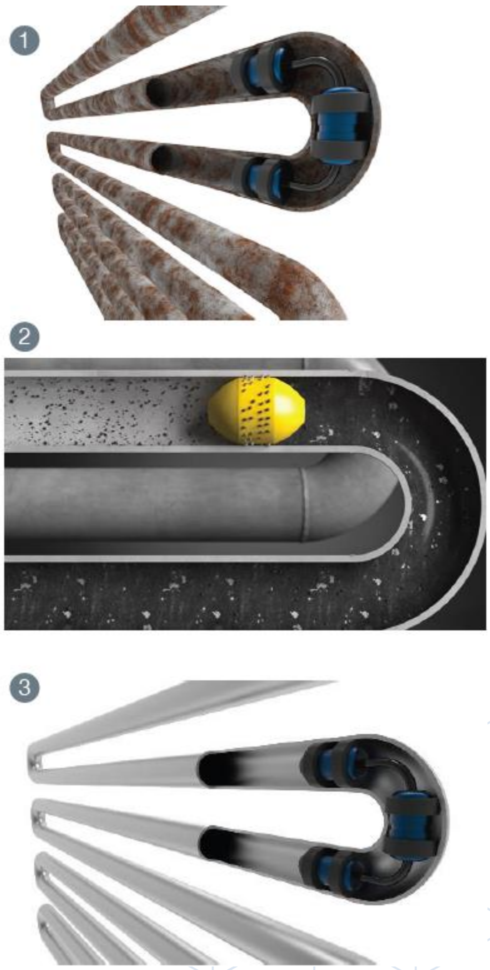
Aggressive cleaning or *risking damaging the tubes.*

The ability of a mechanical pig to clean tubes is typically based on two things.

- Size and type of mechanical pig (studs)
- Number of cleaning cycles used (500-1000) circuits by the pig, essentially grinding any coke out

For stubborn areas of coke, there is a risk of damaging the actual tube in clean areas - leaving scored grooves in the tubes. For stainless steel in particular, this can be a problem because the material is softer than a Cr steel and may have a different corrosion allowance compared to a ferritic material (1mm compared to 3mm with 5Cr). Advanced Decoking and Cleanliness Verification (ADCV™) has the advantage of identifying the key areas of coke and allowing close attention of the pigging cycle to only those areas.

ADCV™ replicates the one key benefit that the burn technique had and adds a new one: it provides a detailed map of where the coke was in the coil together with positive verification that coke has been removed at the end of the cleaning process.



Initial results from ADCV™ inspections

Localised areas of 5mm coke were found in several crude and vacuum heaters. ADCV™ was used to identify these areas and selectively target them for coil cleaning, completely removing the coke in these areas. The process impact of these areas was not reported by the end users, however the simulations above give a good indication of potential consequences. **Integrating the ADCV™ results with heater process data before and after will assist with the optimisation of the heater.**

Outline of the ADCV™ process steps

1. Initial ADCV™ survey – where is the fouling located? Ultrasonic-based intelligent pig maps the location and thickness of the fouling.
2. Mechanical cleaning team removes the bulk of the fouling using studded pigs.
3. Cleanliness verification using the intelligent pig then checks the result, fine tuning the mechanical pigging work with additional cleaning that identifies tubes or spots with fouling. Additional cleaning is performed as needed based on the intelligent pig results. Once it's confirmed all fouling has been removed, tube integrity data is collected using an FTIS™ tool to determine the thickness of the pipe wall and whether any deformations exist such as bulging or creep.
4. Any areas that were not able to be cleaned are reported to the client for further investigation. These are important areas - any bulging or major deformation in a tube caused by overheating may not be cleanable by a mechanical pig.

IN CLOSING

Fouling in a heater makes a significant difference to a heater's safety, environmental and commercial performance.

Since coke is the dominant reason for high tube skin temperatures for normal furnace parameters, the thickness of the coke matters. Knowing that all of the fouling has been removed and where it initially formed- and where it did not- allows an informed view on past and future heater operations and most importantly avoids running the heater sub optimally until the next turnaround.

Tom Gilmartin

Tom (Bsc, Msc, C.Eng) is a 30-year BP veteran and the company's former fired heater and flare advisor.
Now semi-retired, he enjoys walking and cycling.

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