Gaining Insights into the Fouling Rates of Delayed Coker Heaters

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Introduction

Delayed Coker Technology licensors make design decisions ensuring that new heaters are capable of running ten to twelve months before a shutdown for decoking is necessary. This typical run length target is met while ensuring the heater operating severity is such that the unit will meet overall product yield and quality performance guarantees.

As the unit operation deviates from the original feedstock and design operating conditions, heater fouling rates often accelerate. As suggested in Figure 1, at fouling rate of 1-2°F/day, a typical industry benchmark for a heater run length between decoking shutdowns is half of the original design basis.

![Figure 1: Start and End of Run Conditions: Industry Typical vs Design 9Cr Tubes](image)

A Delayed Coker unit engineer should be able to quantify the impact that the unit operating conditions is having on heater coking rates to ensure that the economic penalty associated with accelerated heater coking is considered when calculating the unit operating margin.

The root cause of accelerated heater fouling can generally be determined by comparing the current operation against the original design basis.

New Design Considerations

To minimize coking potential, a Delayed Coker heater typically features the general attribute of a cabin style furnace with horizontal fired radiant tubes. Where warranted, rather than natural draft, a balanced draft combustion air system with / without air preheat can be utilized. To provide even heat distribution along the length of the radiant tube sheet, Delayed Coker heaters utilize a large number of low capacity burners rather than a few high capacity burners as seen in Crude and Vacuum unit furnaces. The advent of double fired radiant tubes in the late 1980’s to early 1990’s marked a significant change in the design.
basis of Delayed Coker heaters. While initially limited to units processing unstable feedstocks, the double fired radiant tube sheet is now a common attribute of new Delayed Coker Unit design. As suggested in Figure 2, the utilization of double fired radiant tubes offers configuration opportunities that can improve the effectiveness of online decoking procedures and even provide the ability for independent heater pass operation. By increasing the heater on stream factor, the latter could be an extremely desirable attribute for a two drum Delayed Coker.

![Figure 2: General Arrangement Options for a 2-Pass Single and Double Fired Coker Heater](image)

A target cold oil inlet velocity and process mass flux rate guideline are used as the basis for developing the number of tube passes and the required tube internal diameter in a new heater design. In establishing the required process convection and radiant section tube surface area, guidelines with respect to the process crossover temperature and the radiant section tube by tube bulk temperature profile are followed. Some of the parameters taken into consideration when optimizing the heater design involve evaluating the impact of; velocity steam injection rate and location(s), increasing the radiant section tube diameter, and increasing the radiant section tube by tube center line spacing. The overall goal of the optimization work is to achieve an acceptable tube by tube inner film temperature profile through the radiant section with minimum cracking residence time. Table 1 provides a summary of typical new Delayed Coker Heater design guidelines.

Table 1: Typical Critical Coker Heater Design Criteria

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Typical Design Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold oil inlet velocity</td>
<td>ft/s</td>
<td>6.0</td>
</tr>
<tr>
<td>Velocity steam injection</td>
<td>wt% on feed</td>
<td>1.0</td>
</tr>
<tr>
<td>Process mass flux rate</td>
<td>lb/sec-ft²</td>
<td>350 – 400 (double fired)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 – 300 (single fired)</td>
</tr>
<tr>
<td>Average radiant tube heat flux</td>
<td>BTU/hr-ft²</td>
<td>12,500 – 13,500 (double fired)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9,000 – 10,000 (single fired)</td>
</tr>
<tr>
<td>Maximum radiant tube heat flux</td>
<td>BTU/hr-ft²</td>
<td>16,000 – 18,000</td>
</tr>
<tr>
<td>Radiant outlet velocity</td>
<td>ft/s</td>
<td>150 max</td>
</tr>
</tbody>
</table>

Of those listed in Table 1, the radiant tube heat flux is the most critical specification in the design of a new Coker heater. An average heat flux rate significantly lower than that indicated would typically
translate into higher coking rates due to an excessive cracking residence time. An average heat flux rate significantly higher than that indicated would result in increased coking rates due to excessive inner film temperatures. As suggested by Figure 3, the duty absorbed by tubes in the radiant section of a single fired heater is a function of both radiant and convective heat transfer.

![Figure 3: Mechanism of Radiant Section Heat Transfer: Single Fired Tubes](image)

In the case of double fired tubes as depicted in Figure 4, re-radiation off of the refractory to the back side of the heater tube is replaced by direct radiation to the tube from a secondary burner lane. At a similar maximum heat flux, with two side direct radiation, double fired radiant tubes exhibit a higher average radiant heat flux rate than single fired tubes.

![Figure 4: Mechanism of Radiant Section Heat Transfer: Double Fired Tubes](image)

Typically the maximum to average heat flux ratio for double fired tubes is 1.20 compared to 1.80 for single fired tubes. The exact heat flux ratio is a function of the combustion gas flow patterns in the radiant section as influenced by the tube to tube spacing, along with the tube center line to radiant wall offset distance for single fired tubes.
The specification of double fired radiant tubes provided the opportunity to increase the design process mass flux rate from 200-300lb/sec-ft\(^2\) to 350-400lb/sec-ft\(^2\). As a result of increased inner film shear stress and reduced fluid cracking residence time, a high mass flux rate heater with double fired radiant tubes will exhibit lower fouling rates than single fired low mass flux rate heater.

A Delayed Coker heater operates under two phase flow conditions due to feed vapourization and fluid cracking. To initiate vapourization and improve the in tube fluid velocity profile through the convection section, velocity steam is typically injected at the heater inlet. A common way to control the overall heater pressure drop under fouled conditions is to incorporate multiple velocity steam injection points into the heater design. Zero, or inadequate, velocity steam injection could adversely impact the heater run length by increasing the oil film cracking residence time. The recommended outlet fluid velocity guideline of less than 150ft/s at the heater outlet is based on minimizing the potential for outlet piping erosion. Tube velocity is controlled by optimizing the process fluid mass flux rate and if necessary increasing tube diameter. In addition to following the velocity guideline, the outlet piping layout should be designed in a manner to further minimize erosion potential.

Fundamentally, a well-designed Delayed Coker heater increases the temperature of the feed to the required outlet temperature as quickly as possible while minimizing the cracking residence time. To minimize coking, cracking should be initiated well within the radiant section and the tube by tube bulk fluid temperature profile should rise continually through the radiant section. A stalled temperature profile is indicative of meeting only heat of reaction requirements and can lead to accelerated coking. As in the case of the bulk fluid, the tube by tube inner film temperature should steadily increase across the radiant section at a controlled rate of approximately 10-15°F reducing to 5-10°F towards the outlet of the heater. Rates higher than this would be indicative of excessive tube flux rates and can lead to accelerated coking. As shown in Figure 5, this design guideline is best exemplified by comparing the profiles of a Delayed Coker heater to a Visbreaker heater.

![Figure 5: Comparing Delayed Coker and Visbreaker Heater Profiles](image)

In Visbreaking, targeted conversion occurs either strictly based on the cracking residence time in the heater or the combined cracking residence time in the heater and the outlet soaking drum. In either case, Visbreaker heaters exhibit significantly higher coking rates than Delayed Coker Heaters. The stalled profile of the Visbreaker heater in Figure 5 is evidence of the required cracking residence time to
achieve the targeted unit conversion. Cracking residence time can be defined as the total time at which the inner film temperature exceeds the cracking threshold. An appropriate temperature used to define the cracking threshold would be between 800°F-825°F.

**Heater Simulation Modeling**

In an operating unit, as a minimum, the coil inlet flowrate, steam injection rate, inlet temperature and pressure, outlet temperature, and discrete tube metal temperature readings are available for monitoring purposes. In some instances combustion air and fuel gas flow rates, along with flue gas measurement such as the bridgewall temperature, may also be available. Although sufficient for day to day performance monitoring, routinely available information is insufficient to gain insight into the factors influencing heater fouling.

To gain a detailed understanding into the operation of a fired heater requires the use of a fired heater simulation program such as FRNC-5PC from PFR Engineering Systems or Xfh® from Heat Transfer Research, Inc.

Simulating a Delayed Coker heater presents challenges above that of other process heaters. For the heater modeling program to accurately predict the total absorbed duty, the heat of cracking must be accounted for. This is achieved by the direct input of physical property grids of the heater inlet and outlet streams that reflect compositional changes occurring across the heater due to cracking. A general purpose process simulation program should be used to generate the required physical property grids.

As indicated in Figure 6, the heater inlet physical property grid (stream #3) is generated from a blended stream comprised of a recycle oil generated in the Coker fractionator (stream #2) and the fresh feed analytical properties (stream #1). This physical property grid defines the convection section inlet fluid properties in the heater simulation model.

**Figure 6: Heater Inlet Property Grid Definition**

At a minimum, a second physical property grid representing the heater outlet stream needs to be generated. Generating this physical property grid requires the user to define the feed cracking profile.
that occurs across the heater. As suggested in Figure 7, cracking estimates can be developed based on the relationship between the heater cracking residence time and the overall unit product yield profile.

Figure 7: Example Heater Cracking Profile

As a modeling simplification, with cracking reactions typically limited to the radiant section, the heater outlet grid defines the radiant section inlet fluid properties in the heater simulation model. As indicated in Figure 8, this simplification assumes heat of reaction requirements are met across the radiant inlet tube with latent and sensible heat requirements met across all of the tubes in the radiant section.

Figure 8: Delayed Coker Heater Modeling Assumptions

Distributing heat of reaction requirements across other tubes in the radiant section is limited only by the ability of the user to generate multiple cracking profiles, and the capability of the heater modeling program to allow the input of multiple fluid property grids.

Comparing the predicted heater fired duty against that calculated from metered combustion gas rates provides a basis for validating the accuracy of the cracking assumptions built into the physical property grids. If significantly different, cracking estimates should be reviewed. Likewise, the predicted vapourization at the heater outlet should be compared to that of the general purpose simulation. If
different, the fluid property grids should be reviewed to ensure that they have been transferred correctly from the general purpose simulation program to the heater modeling program. Once satisfied that the fluid properties grids have been accurately defined, as identified in Figure 9, the predicted radiant section absorbed duty should be checked against actual performance by comparing the predicted process cross over temperature (point #2) and flue gas bridgewall temperature (point #1) against actual values.

![Figure 9: Tuning Radiant Section Absorbed Duty](image)

If the model is under predicting the crossover and bridgewall temperatures, the calculated radiant section absorbed duty is higher than actual. Likewise, if the model is over predicting the crossover and bridge wall temperatures, the calculated radiant section absorbed duty is lower than actual. A degree of caution should be taken with the measured bridgewall temperature as the accuracy of the value may be questionable due to the possibility of irregular flue gas flow profiles and the elevated fluid temperature the thermocouple is exposed to. The radiant section absorbed duty is influenced by combustion air rates as well as tube outside fouling resistance. As appropriate, in the modeling either of these can be used to tune the predicted radiant section absorbed duty to match plant data.

As was the case for the radiant section absorbed duty, the predicted convection section absorbed duty should also be tuned to match plant data. As indicated in Figure 10, this is achieved by specifying the correct level of outside tube fouling resistance in the convection section such that the predicted stack inlet temperature (point #1) matches available plant data.
The final aspect of model tuning involves the correct specification of the convection and radiant section tube inside fouling resistance and thickness in order to achieve a close match between the predicted overall heater pressure drop and tube metal temperatures with actual values.

**Benchmarking the Heater Operation**

Once tuned to match the current operation, the result of the general purpose heater simulation model is an extremely useful tool for benchmarking and trouble-shooting heater performance, evaluating the impact of heater revamp projects, and conducting heater coking rate studies.

In benchmarking the current heater operation, tube by tube profiles of; the inner film and bulk fluid temperature, average and maximum heat flux, bulk velocity, pressure drop, vapourization, flow regime, and cracking residence time should be compared against design conditions and historical results. The following is an example of benchmarking a heater operation against typical design standards.

Figure 11 depicts the tube by tube vapourization and bulk fluid velocities for two different Delayed Coker heaters. In the case of the heater depicted in the left of Figure 11, the sudden increase in vapourization and fluid bulk velocity at the inlet to the radiant section is due to the combined effect of velocity steam injection into the Convection / Radiant cross over header and the change in fluid properties reflecting cracking assumptions. Approaching 200ft/s, the bulk fluid velocity at the heater outlet exceeds the typical design basis target and as a result there is an increased potential for pipe erosion.
In the case of the heater depicted in the right of the Figure 11, although still exhibiting a step change in both profiles at the radiant section inlet due to fluid property cracking assumptions, vapourization is initiated at the convection section inlet by velocity steam injection and as a result bulk fluid velocities through the convection section are higher.

Figure 12 is an example of the tube by tube average and peak heat flux profiles through the convection and radiant sections of a Delayed Coker heater. Through the finned tubes of the convection section the tube by tube average heat flux increases from approximately 3,000BTU/hr-ft$^2$ to 8,100BTU/hr-ft$^2$. Across the bare convection section tube sheet the average heat flux rate increases from approximately 4,500BTU/hr-ft$^2$ to 5800BTU/hr-ft$^2$.

Through the radiant section the peak heat flux decreases from 17,300BTU/hr-ft$^2$ to 14,000BTU/hr-ft$^2$. These values are slightly lower than the typical design guideline setting the peak heat flux level between 16,000 BTU/hr-ft$^2$ to 18,000BTU/hr-ft$^2$. The general trend of a decreasing heat flux profile through the radiant section is a result of the heater design, (constant radiant tube diameter and spacing) and modeling assumptions built into the simulation program (constant radiant section combustion gas temperature). With a peak to average heat flux ratio of approximately 1.30, from the plot it is evident that this is an example of a heater with double fired radiant tubes. The typical design basis for double fired radiant tubes is an average flux rate between 12,500BTU/hr-ft$^2$ to 13,500BTU/hr-ft2. In this
example the average tube heat flux decreases from 13,500BTU/hr-ft\(^2\) to 11,000BTU/hr-ft\(^2\). Benchmarking the developed peak and average heat flux rates against design standards suggests that for the rated operation the radiant tube surface area is slightly greater than required.

Figure 13 shows the bulk fluid and inner film temperature tube by tube profile for the same heater. In this example, the oil film temperature exceeds the cracking threshold temperature of 800\(^\circ\)F for nearly the entire radiant section tube surface area. In addition, for over fifty percent of the radiant section surface area, the bulk fluid temperature exceeds the cracking threshold temperature. With increased vapourization, towards the outlet of the heater, the fluid flow regime transitions from Bubbly to Annular Mist.

![Figure 13: Tube by Tube Oil Film and Bulk Fluid Temperatures](image)

The above tube by tube flux profiles, developed fluid flow regime, and cracking residence times suggest that for the modeled operating conditions, heater coking rates would be higher than expected for an optimized design. From this base model, step cases can be considered to gain further insights into heater fouling and to predict the impact that changes in operating conditions will have on heater run length before the changes are implemented in the field. Examples of these studies would include changing the process inlet or outlet temperature, velocity steam injection rate and location, the unit recycle rate, and finally the amount of excess air in the flue gas.

Whether evaluating minor projects such as changes to the convection / radiant section surface area, or a major project such as the inclusion of air preheat, by comparing base modeling results against the predicted revamped operation, the impact on the overall heater operation, including the change in coking rates, can be estimated to provide valuable input to the project economics.

**Modeling Limitations**

When working with any process simulation tool it is important that modeling limitations are fully understood. In the case of general purpose heater simulation programs, examples of these limitations
include a limited understanding of the impact of feed quality changes and no ability to model air/fuel mixing and combustion.

Through the direct input of the physical property grids, the model accurately predicts the impact of changes to feed cutpoint, critical assay properties such as density and viscosity, and the unit recycle rate. Importantly, the model will not be able to predict the impact that contaminants such as sodium, metals, inorganic compounds, crude production additives or changes in fluid solvency which impact asphaltene stability will have on the heater operation.

General purpose heater models typically calculate the burner adiabatic flame temperature, and the resulting radiating gas temperature, based on the input combustion air and fuel characteristics while assuming combustion gas flow patterns within the radiant section are approaching well stirred conditions. Not modeled explicitly are the burners, or radiant box flue gas flow patterns. As a result, the model cannot provide insight into issues arising from poor burner performance, flame to flame interactions, flame impingement on the radiant tubes, or highlight irregular radiant box combustion gas flow patterns.

Insights into the degree that burner performance and radiant box combustion gas flow patterns have on heater coking rates can be gained by using the heater modeling software in conjunction with the general purpose process simulation program and computational fluid dynamics (CFD) simulation software. Through the use of CFD, the identified modeling limitations with respect to Air / Fuel mixing and combustion are eliminated. Figure 14 is an example of a study evaluating burner performance in a radiant box with vertically orientated double fired tubes.

![Figure 14: Developed Flame Patterns Based on CFD Modeling](image)

In this study, the geometry of the burners and the radiant fire box was modeled to the necessary level of detail to ensure that an accurate representation of the developed flame pattern with respect to the tube sheet was obtained. The modeling suggested the burners were developing a well-formed tight flame with no indication of tube impingement. As seen in Figure 15, by expanding the study area beyond the burners, the influence of the off centre flue gas take-off on the radiant box combustion gas fluid flow pattern was obtained as was evidence of back mixing.
Summary
The results of heater simulation modeling can be used to benchmark key performance indicators of an operating heater against design standards to identify and correct the root cause for accelerated Delayed Coker heater fouling. From a fouling standpoint, this would include comparing tube by tube average heat flux rates, bulk and inner film profiles, and the inner film cracking residence time. On a proactive basis, by incorporating detailed heater modeling into monitoring activities, heater run lengths can be extended by optimizing operating conditions. Last, but not least, a well-tuned heater model will allow a more accurate prediction of the impact of changes in design and/or operating conditions on heater fouling rates and run length, therefore improving decision making for capital expenditure in and around the Delayed Coker Heater.

Literature Sources
1. Images of heater modeling utilizing CFD software courtesy of Tridagonal Solutions Inc. (www.tridiagonal.com)