Why vacuum unit fired heaters coke

A description of the internal workings of vacuum heaters and the causes of coke formation within them. Case studies show how to avoid localised hot spots in order to maintain yield targets and increase run lengths

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Some refinery vacuum heaters have chronic problems with coking and short run-lengths. Several of these heaters operate at coil outlet temperatures of only 750–760°F and average radiant section heat flux of 8000Btu/hr-ft^2-°F or less. Why do these seemingly mild operations have run-lengths less than two years between decokings, while others operate for four years at coil outlet temperatures of 790°F and average flux of 11 000Btu/hr-ft^2-°F? Common heater monitoring parameters such as coil outlet temperature, average heat flux, and fired duty are generally of little value in determining why a heater develops hot spots. Hot spots are typically localised phenomena. Often, they are a consequence of decisions made to reduce the heater initial investment.

When revamping, the designer should apply fundamental design principles to meet short term product yield targets and long term run-length objectives. Common heater design considerations that affect the rate of coke lay-down are radiant section tube layout, process coil design, and burner performance. This article reviews how heater design influences localised conditions that promote rapid coke formation. Two case studies show how fundamental principles can be applied to eliminate hot spots and increase run-length.

Coke forms because conditions in the shock or radiant tubes cause the oil to thermally decompose to coke and gas. Coke lay-down on the inside of the tube increases the tube metal temperatures (TMT). As tube metal temperatures increase, the heater firing must be reduced or TMT will progressively increase until the tube metallurgical temperature limit is reached. Then the heater must be shutdown to remove the coke. Rapid coke formation is caused by a combination of high oil film temperature, long oil residence time, and inherent oil stability.

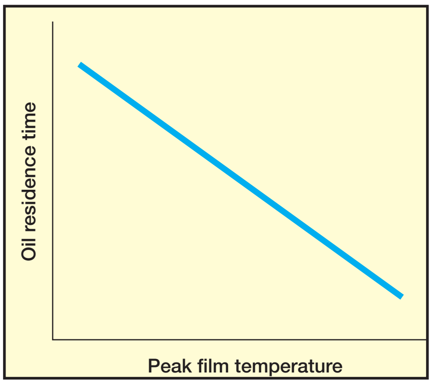

Figure 1 *Oil cracking: showing time and temperature*

Heater design affects the localised coke formation rates through its influence on oil residence time and film temperature. The lower velocity oil film flowing along the tube wall will be 25°F to over 200°F higher than the oil temperature. For instance, the oil film temperature in the outlet tube may be over 950°F even though the bulk oil temperature is only 790°F. Coke formation begins in the oil film flowing on the inside tube wall because its temperature is higher.

Oil film temperature is highest at the front of the tube facing the burner and lowest on the rear of the tube facing the refractory. This peak oil film temperature is where coking starts. The temperature rise through the oil film depends on a number of design factors. Heater tube layout, process coil design, and burner performance all have an effect on the oil film temperature.

Figure 1 represents the relationship between peak oil film temperature, oil residence time, and the rate of coke formation. Operating above the cracking line will cause rapid coke and gas formation that eventually leads to hot spots. Oil stability will move this line up or down. Heater tube layout, process coil design, and burner performance control localised peak film temperatures and oil residence time. Peak film temperature can vary significantly on a single tube due to fire box flue gas temperature gradients.

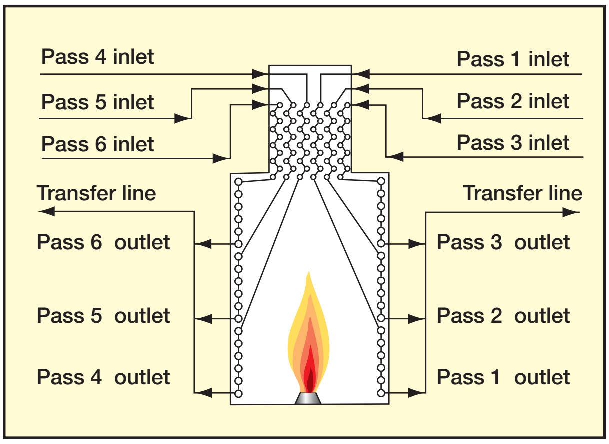

Figure 2 *Six-pass box type, stacked passes*

Heater design

Vacuum heaters are typically cabin, box, or vertical cylindrical type design with firing on one side of the heater tube. Occasionally double-fired designs are used in tar sand, high bitumen crude, or hydrocracking vacuum residue services where oil stability is poor. Although vertical cylindrical designs are common, they should be avoided because the vertical tubes cause the oil to flow repeatedly through the high heat flux zone. In addition, the sizing of the last two to three tubes in each pass is complicated by pressure variations in the up-flow and down-flow tubes. Box and cabin type heaters are the most common in refinery vacuum units.

Most cabin or box type heaters have four or six passes in a single radiant cell. The height-to-width ratio (L/D) varies from 2.2 to 3.5. The number of burners, flame length, and the distance from the burners to the tubes are all design variables. Figure 2 shows a six-pass box heater with the coils stacked along each wall. Oil flows downward in each pass. This six-pass design will be used to review what happens inside a heater and

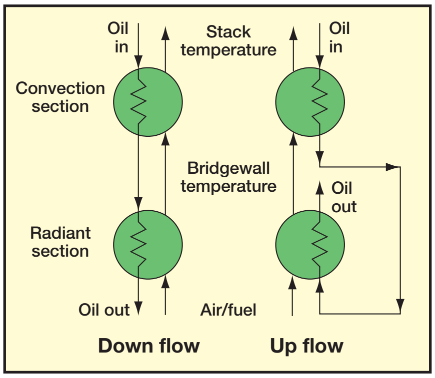

Figure 3 *Simplified heater model*

some of the design considerations (stacked tubes, oil down-flow or up-flow, tube size, location of coil outlets, etc) that influence the rate of coking.

There are many different heater designs. Pass layout, process coil design, and burner performance vary from one heater to the next. While computer models are necessary tools to design and troubleshoot vacuum heaters, these models need to correctly represent actual heater operation. Often, heater models assume ideals that do not exist in the real world. Heater model results and the application of basic fired heater design principles should be used when revamping a vacuum heater.

Fired heater basics

Fired heaters consist of a convection and radiant section (Figure 3). The convection section recovers heat from the flue gas leaving the radiant section (bridgewall) and transfers it to the cold process fluid in the tubes. Convection duty depends on the equipment design, bridgewall temperature, and the flue gas rate. Maximising convection section duty decreases the radiant section duty, which always reduces the rate of coke formation. Once the convection section design is set, the radiant section must provide the remaining heat needed to meet the required coil outlet temperature.

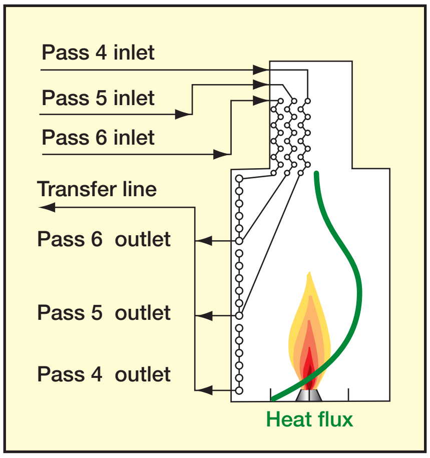

Figure 4 *Heat flux gradient with elevation*

The box heater shown in Figure 2 has horizontal tubes on the radiant section side walls. Three passes are located on each wall. Each pass consists of a number of tubes with the oil flowing downward in each pass from the convection section outlet. Most cabin and box heaters have the passes stacked because this reduces initial heater cost. However, stacking the tubes always results in heat absorption differences between the individual passes.

Today, most refiners vary pass flow rates to achieve equal coil outlet temperature. Hence, high pass flow rate variation indicates large heat absorption differences. Stacked tubes and other factors contribute to localised coking conditions. Radiant section localised film temperature and oil residence times depend on the heat flux, bulk oil temperature, and tube mass flux rates. All are design variables which can be manipulated. Understanding the relationship between the oil film temperature, heat flux, bulk oil temperature, mass flux, and oil residence time allows the designer to choose cost-effective solutions to minimise the rate of coking.

Heat transfer

The radiant section typically provides more than 60% of the heat added to the reduced crude. Heat transfer from the hot flue gas to the oil occurs primarily by radiation. Equation 1 is the Lobo-Evans method for estimating the overall amount of heat transferred in the radiant section as a function of flue gas temperature leaving the radiant section (T_g), tube metal temperature (T_t), and the radiant section surface area (αAcp).

Equation 1
Radiant Section Duty:
$Q_r = 0.173(\alpha A_{cp})(F)[(T_g/100)^4-(T_t/100)^4]$
= Btu/hr

Although this equation makes several assumptions to simplify what happens in an actual heater, it highlights that the heat transfer rate is controlled by flue gas and process fluid temperature differences. Because the flue gas absolute temperature is so much higher than the process fluid, localised flue gas temperature largely determines how much heat is transferred at any location within the fire box. Thus, increasing the flue gas temperature in the fire box (T_g) will increase the rate of heat transfer.

The Lobo-Evans method assumes the fire box is well mixed and that flue gas temperature is uniform throughout. Every heater will have both longitudinal and transverse temperature gradients that depend on the design. Burner design, number of burners, burner operation, and flue gas flow patterns all influence the flue gas temperature and the localised heat flux.

Localised heat flux

Average radiant section heat flux is the total radiant section absorbed heat duty divided by the total outside surface area (Equation 2) of the radiant section tubes. Localised heat flux varies depending on the specific heater design.

Equation 2
Heat Flux:
= Quantity of heat absorbed (Btu/hr)/Outside tube area (ft^2)
= $Btu/hr\text{-}ft^2$

Flue gas temperature is not uniform throughout the fire box. Hot flue gas flows upward between the tubes in the heater while cold flue gas flows downward between the tubes and refractory. This recirculating flue gas may be only 1000°F at the heater floor while the flue gas entering the convection section will be 1450–1750°F. The air/fuel mixture does not burn instantly. Burner heat release is a function of the flame height and volume. Therefore, at some elevation above the heater floor there is a maximum flue gas temperature. This is where heat flux is the highest. Figure 4 represents the heat flux distribution in a high height to width ratio (L/D) box heater.

Localised oil film temperature

Figure 5 represents the temperature difference between the bulk oil and the oil film. Equation 3 shows how the temperature drop across the oil film is calculated. The D_o and D_i are the outside and inside tube diameters, respectively. Flue gas temperature largely determines the amount of heat transferred at any given point (Q_{local}).

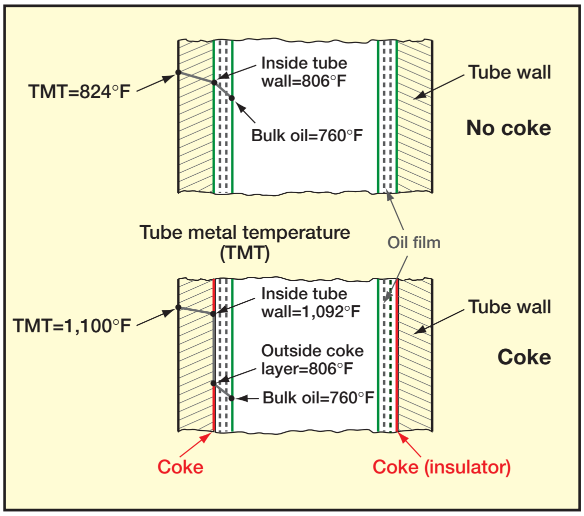

Figure 5 *Oil film temperature*

Equation 3

^3t_f = Temperature drop across the oil film
= $Q_{local}\ D_o/D_i\ h_i$
= °F

For a given heat flux (Q_{local}), temperature drop through the oil film temperature is set by the process fluid convection coefficient (h_i) inside the tube.

Oil mass flux

Equation 3 shows that increasing the convection coefficient decreases the temperature drop through the oil film. Cost-effective design changes that reduce the oil film will reduce the rate of coke formation. Since the majority of the tubes have little or no oil vaporisation and the Reynold's number is greater than 10 000, the heat transfer coefficient (h_i) can be calculated using the Seider and Tate equation shown in Equation 4.

Equation 4

Inside tube heat transfer coefficient:
= $(0.023)k/D(DG/\mu)^{0.8}(c_p\mu/k)^{0.33}\ (\mu/\mu_w)^{0.14}$
= Btu/hr-ft^2/°F

The only term the heater designer can control is tube diameter (D) and it determines the oil mass velocity (G). Decreasing the tube diameter increases mass velocity. Oil transport properties and oil mass velocity are the also terms in the equation. Transport properties viscosity (μ) and thermal conductivity (k) are controlled by crude type and atmospheric column operation. The $(\mu/\mu_w)^{0.14}$ term is 1 because the ratio of viscosity of the bulk oil and oil film is near 1.

Mass flux is the mass flow rate in the tube divided by the tube inside cross-sectional area (Equation 5). Reducing the tube diameter increases the oil mass flux. Increasing mass velocity not only decreases oil film temperature, but it reduces the oil residence time. Conversely, as the tube diameter increases, the mass flux rate decreases, inside heat transfer coefficient decreases, and the film temperature increases.

Equation 5

G (mass flux):
= Mass rate of oil/Inside cross-sectional area of heater tube
= lb/sec-ft^2

Outlet tube sizing is a trade-off between maintaining mass velocity and the influence of tube pressure drop on the bulk oil temperature. High mass flux reduces temperature drop through the oil film, but, it increases tube pressure drop, which raises the peak bulk oil temperature inside the heater. Higher bulk oil temperature raises film temperature.

Oil residence time

Oil residence time depends on heater charge rate, tube size, steam injection rate, and coil steam injection location. Residence time can vary from less than 10 seconds for a heater with velocity steam to over 90 seconds in dry heater. Residence time is a significant factor in the rate of coke formation, yet many designers ignore it.

Dry heater oil residence time depends only on feed rate and tube size. The smaller the tube sizes for a fixed radiant section outside tube-surface-area, the lower the oil residence time. Radiant sections use between two to five tube sizes from the inlet to the outlet due to oil vaporisation. Steam can be used to lower oil residence time. Steam should be injected upstream of the tube where high coking rates are expected. For instance, if the shock tubes are coking, injecting all the steam downstream at the crossover will not stop the coking. Some heaters are designed with 5in shock tubes and 4in radiant section tubes. The 5in tube oil residence time and peak film temperatures are high; therefore coking will occur at this location.

Oil thermal stability

Oil thermal stability varies depending on crude type. Some crude oils are simply less stable than others. For instance, some Canadian and Venezuelan crude oils have poor thermal stability and begin to generate gas and coke at relatively low temperatures. During laboratory testing in the ASTM D5236 potstill, the thermal stability can be inferred from the maximum still temperature before cracking starts.

Another factor that reduces oil stability is the upstream heater and column severity. Several refiners operate crude column heaters at 750–780°F outlet temperatures. High outlet temperature crude heaters combined with high residence time in the crude column bottom decrease oil stability. Field tests have proven that rapid coke and gas formation in the vacuum heater can be caused by the upstream equipment.

Heater design considerations

Heater pass layout, process coil design, and burner performance all play a key role in the rate of coke formation. Figure 2 shows the design of a six-pass box heater with stacked tubes. Three passes are stacked on each wall. It is floor fired and it is a narrow heater with an L/D ratio of 3.2. Using this heater design to review fundamental principles helps highlight the difference between good and bad design practices.

The majority of vacuum heaters have the tube passes stacked on the wall. Some have one or two rows of roof tubes and the tube passes stacked. Each pass

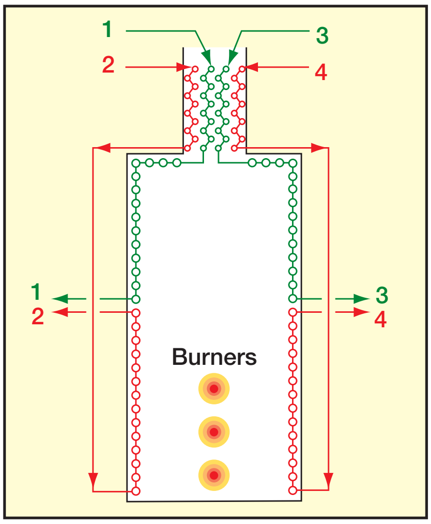

Figure 6 *Stacked passes and poor burner layout*

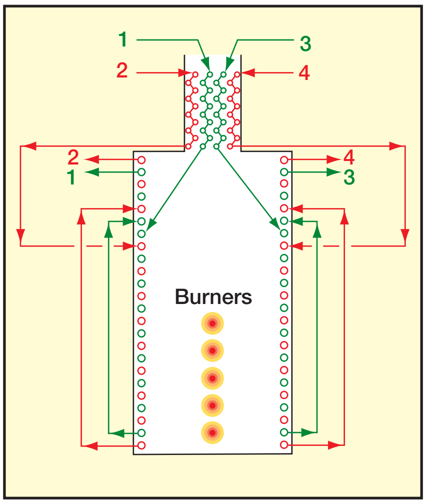

Figure 7 *Balanced pass flux, lower film temperatures*

has been designed with identical outside tube surface areas. Therefore, the stacked passes will absorb different amounts of heat. Figure 4 shows the heat flux variation. Tube passes 5 and 2 absorb the most heat. The pass 5 and 2 outlet tubes are located in the high heat flux zone. The 10in outlet tubes in each pass receive high heat flux and low mass flux; hence the temperature drop through the film is very high. These tube passes will have chronic problems with coking.

High L/D heaters have high heat flux gradient from the floor to the roof (bridgewall). The elevation with the highest heat flux will be directly related to flame length and stability. High L/D heaters with short flame length burners also have higher heat flux variation. Low NO$_X$ burners tend to have longer flame lengths, hence the bottom of these heaters will be cold with the maximum heat flux moving further from the floor than a heater using conventional burners. Another consequence of many low NO$_X$ burners is poor flame stability. Hence, the flames tend to move around and lick the tubes.

Ideally, the oil leaving the convection section should first be routed to the elevation in the radiant section having the highest heat flux. This minimises film temperature because of a lower bulk oil temperature. The heater shown in Figure 2 should be revamped by using external jump-overs to route the oil leaving the convection section to the middle of the heater. Heat absorption per pass can be balanced by using external jump overs. Balancing the average heat flux to each pass is critical to improving run-length in any vacuum heater.

Case history 1

Burner modifications and pass layout changes

A high L/D four-pass heater was designed with stacked passes. The upper and lower passes had very large differences in heat flux. All four heater pass outlet tubes exited the middle of the heater where the flue gas temperature and heat flux were very high. Coke was forming in the high heat flux lower passes. While the average radiant section flux rate was only 8500Btu/hr-ft^2, the heater had run-lengths of less than 18 months.

Burner location, number of burners, and flame length, in addition to the stacked pass layout, all caused extremely high localised heat flux. The end-fired heater had three burners on each end wall (Figure 6). The burner flame length was very long resulting in extremely high heat flux where the flames met in the middle of the heater. All six burners were located below the outlet tubes for the lower pass.

Outlet tube location is important because the oil mass flux is low. Therefore, the temperature drop through the oil film is high. All four outlet tubes (10in) were located in the middle of the radiant section wall. The outlet tubes should never be located in the middle of the heater. Heat flux is always high at this location.

Improving run-length required complete re-tubing of the radiant section and replacing both burner end walls (Figure 7)**.** Burner location, number of burners, burner size, and flame length were all changed. Tube layout changes balanced the heat absorption in each pass. Oil from the convection section was first routed to the middle of the heater. Oil flows downward through wrapped tubes to the floor of the heater where external jump overs routed the oil to the top of the radiant section. The four outlet tubes exited the top of the radiant section.

All the existing burners were replaced and two additional burners were added. This reduced the flame length and spread the heat release over a larger portion of the radiant section. Localised heat fluxes were dramatically reduced because the flue gas temperature gradients were reduced.

Case history 2

Balancing pass heat flux and reducing oil residence time

Figure 8 shows a four-pass side fired cabin heater with stacked passes. The convection section was designed with both process and steam coils. The side burner fired onto the brick fire wall between the two sides of the heater. Again with the stacked pass design, the individual heater passes had significantly different heat flux rates. The lower passes absorbed considerably more heat than the upper passes. Heater run-length was less than one year.

Heat flux was highest half-way up the radiant section. Yet, all four passes' outlet tubes exited this section. The oil mass flux was only 150lb/sec-ft^2 in the smallest diameter tubes and less than 50lb/sec-ft^2 in the outlet tube. Therefore, the temperature drop through the oil film was very high throughout the

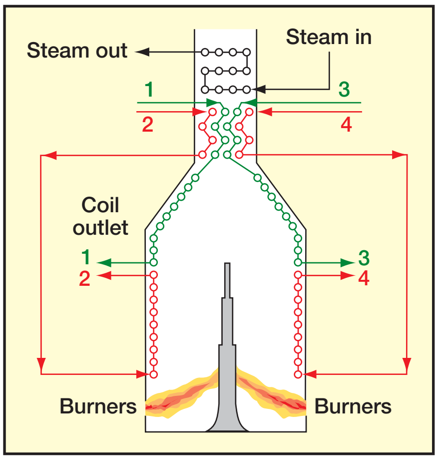

Figure 8 *Stacked passes and high oil residence time*

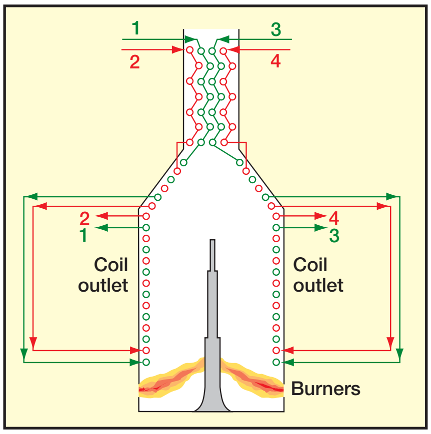

Figure 9 *Balanced flux, residence time reduction*

heater and extremely high in the outlet tube due to high heat flux and low oil mass flux. Coil steam was injected three tubes back from the coil outlet. Thus, the majority of the radiant section tubes had only oil and low velocity (low mass flux). Radiant section oil residence time was very high.

Prior to the revamp, this heater as with most cabin and box heaters, used a stacked tube layout. It is always cheaper to stack the tubes. Yet it always causes heat flux imbalances between the passes. The heater was essentially rebuilt. A new convection section using only process coils was installed. The radiant section tube layout was changed to ensure equal heat flux in each pass. External jump-overs were used to route the oil from hip tubes to the bottom of the radiant section. Oil flow is upward through wrapped passes. The outlet tubes were relocated to the top of the cabin wall (Figure 9).

The revamp objectives were to increase process absorbed duty without increasing the heater firing rate and to increase run-length. The convection section steam coils were removed and new process coils added. Radiant section tube sizes were decreased to raise the oil mass flux rate to 400lb/sec-ft^2. Coil injection steam was increased from 800lb/hr to 1600lb/hr. Coil steam rate was limited by vacuum column overhead system. Steam was injected into the first radiant section tube and travelled through all the tubes. Higher mass velocities, higher coil steam rate, and steam injection location reduced oil residence time from 60 seconds to less than 15 seconds.

Tube sizes, diameter transitions, and transition locations were modified based on evaluation of residence time and peak film temperature from rigorous modelling. Comparing oil residence time when the peak oil film temperature exceeds 850°F is important. Prior to the revamp the heater had residence time of 15 seconds when oil was above 850°F. After the revamp it decreased to less than three seconds.

Conclusion

Minimising oil film temperature and oil residence time decreases the rate of coke formation and improves run-length. Minimising oil film temperature starts by ensuring the radiant section tube layout results in equal heat flux per pass (each pass absorbs the same amount of heat). The individual tube-pass layout should consider routing the convection section outlet to tubes with the highest heat flux. Low bulk oil temperature and high oil mass flux rate will minimise film temperature in the high heat flux section of the heater.

The radiant section coil outlets from each pass should be located at the top of the radiant section unless heat flux is very high. Low L/D heaters using low NO_x burners will sometimes have very high heat flux in the top of the radiant section. Oil residence time should be minimised by selecting the smallest tube size possible and coil steam injection should be used whenever the ejector system sizing permits.

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