Coke formation in industrial furnaces

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Abstract

There are several thousand hydrocarbon furnaces located in world refineries and petrochemical plants. In general, these furnaces vary in size and style but each contains fired heating or reaction coils most often of a serpentine configuration commonly called furnace tubes, which transport the hydrocarbon charge stock being heated and processed. During normal operation a solid carbon material, commonly referred to as coke, is formed adjacent to the inner wall of the tubing. The formation, which is a result of continuous heating of the zero velocity fluid layers immediately adjacent to the fluid boundary, grows in thickness in a continuous manner with time. Eventually, removal of the coke deposits becomes necessary due to excessive pressure drop across the tubes, reduced throughput through the tubes, or reduction in thermal efficiency below some allowable minimum.

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 minimize the rate of coking. Several methods for internal cleaning or decoking of hydrocarbon furnace tubes are currently employed, the most common of which are mechanical cleaning, hydro blasting, and steam-air decoking. But by good operation like suitable reflux, increasing flow of fluid in the coils and minimizing flame impingement can prolong run lengths and increase the period time between decoking and increase reliability and safe operation of furnaces.

Keywords:decoking, flame, refining, oil film temperature, hydrocarbon, furnaces

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1- Introduction:

Process heaters are critical pieces of equipment in the refining and petrochemical industries, and monitoring the working condition of these heaters is essential. The traditional method of heater monitoring is visual, using viewing windows and peepholes, to ensure proper flame pattern and burner management, and to make sure that no flames impinge on the tubes.

Oil thermal stability varies depending on crude type. Some crude oils are simply less stable than others. Some crude oils have poor thermal stability and begin to generate gas and coke at relatively low temperatures. Coking occurs when the hydrocarbons inside the heaters are heated above a certain temperature. Essentially, it is the result of the polymerization reaction of hydrocarbons. The coke layers are poor conductors of heat and also obstruct flow inside the tubes, causing pressure drop and operational problems.

An effective tube management program can reduce equipment costs at a medium-size refinery by one million dollars per year or more.

Gas composition often changes inside the heater depending on process parameters. The percentage transmission of radiation of a certain wavelength or band through the gaseous environment also varies with the composition, which affects the recorded temperature.

2- Experimental theory

Fired heaters are used considerably in the chemical process industries, for heating crude oil in the petroleum refining and petrochemical sectors. Unfortunately, fired heaters are often taken for granted and neglected more than other equipment in terms of operation and maintenance. Proper care and attention to these heaters can prolong run lengths and increase reliability and safe operation.

There are several thousand hydrocarbon furnaces located in world refineries and petrochemical plants. In general, these furnaces vary in size and style but each contains fired heating or reaction coils most often of a serpentine configuration commonly called furnace tubes as shown in Figure1, which transport the hydrocarbon charge stock being heated and processed. During normal operation a solid carbon material, commonly referred to as coke, is formed adjacent to the inner wall of the tubing. The formation, which is a result of continuous heating of the zero velocity fluid layers immediately adjacent to the fluid boundary, grows in thickness in a continuous manner with time. Eventually, removal of the coke deposits becomes necessary due to excessive pressure drop across the tubes, reduced throughput through the tubes, or reduction in thermal efficiency below some allowable minimum [1].

Several methods for internal cleaning or decoking of hydrocarbon furnace tubes are currently employed, the most common of which are mechanical cleaning (commonly known as turbine), hydro blasting, and steam-air decoking.Turbine essentially consists of cutting or reaming the coke deposits from the tube wall by passing a cutting head through each straight section. This method requires that the furnace be disassembled to the extent that the inlet and outlet of each individual straight section of tube is exposed to allow entry of the cutting head. For those furnaces of welded return bend design this means that return bends must be initially cut off and welded back in place after cleaning. Commercial sandblasting is usually employed to clean the return bends. This method has several major drawbacks, including: (1) it results in substantial downtime; (2) it is labor intensive; (3) it results in substantial tube wall wear and subsequent premature tube failure as a result of improper alignment of cutting head and furnace tube; and (4) causes severe erosion of return bends.

Probably the most common method of decoking furnace tubes is by injecting metered amounts of steam and air into the tubes with the furnace fired. The solid coke is thus removed by a highly exothermic reaction between the solid coke and air which generates a gas-solid stream of coke particulate, CO, CO2, SO2 and NOx. The steam is used to cool the products of reaction. Process steps include: (1) removing the furnace from hydrocarbon service; (2) connecting decoking lines to the furnace; and (3) introducing steam and air to induce controlled burn out. Though furnace downtime is considerably less than the above two processes, this process can result in serious and costly furnace damage. During the process the tube skin temperature must be maintained within very narrow limits so as to both sustain the temperature required to support the reaction and yet limit the reaction temperature below the tube melting point. This highly exothermic reaction frequently results in ruptured tubes and fittings and hence costly downtime. In addition, the high temperature reaction of oxygen can leave an oxide layer on the inner tube wall which will inhibit heat transfer. Mechanical cleaning or polishing must be used to remove the deposits subsequent to steam air decoking operations. Finally, a further disadvantage of this process is that the effluent gases are highly toxic and thus create serious environmental problems, if not properly handled.
Another way which can be used for removing coke from tubes is spalling as shown in figure 2. In this case super heat steam with high pressure and temperature can pick up scale and coke from surface of tubes. The rising temperature procedure is shown in figure 3.
Some experimental work can be done to protect the fire heaters as follows:

2-1- Temperature profile monitoring

The tube skin and box temperatures of some of the most important furnaces in petroleum refineries are listed as shown in figure 4 .Thermography is the best tool for analyzing the relative temperature distribution on the tubes. In absolute scale, this method can be used to find out the exact temperature on the tube and also to validate the thermocouple readings. This can be done quite accurately in gas-fired furnaces and reformer heaters. In oil-fired furnaces, however, the images sometimes show higher temperature than the actual one due to flame effect and tube external surface condition.

2-2- Detection of scaling and hot spots

Scaling is a high temperature phenomenon caused by oxidation or sulfidation of heater tubes. Normally, it occurs in the fire-side of the heater tubes. Scale is a poor conductor of heat and thus increases the skin temperature of the tubes.Detection of coking inside the heater tubes**.** Coking occurs when the hydrocarbons inside the heaters are heated above a certain temperature. Essentially, it is the result of the polymerization reaction of hydrocarbons. The coke layers are poor conductors of heat and also obstruct flow inside the tubes, causing pressure drop and operational problems [2].

2-3- Changes in the gas composition inside the heaters

Gas composition often changes inside the heater depending on process parameters. The percentage transmission of radiation of a certain wavelength or band through the gaseous environment also varies with the composition, which affects the recorded temperature. In the furnaces natural gas and fuel gas can be used and vendors usually design heaters with both of them. Nevertheless if fuel gas contains a lot of light component like H_2 , the flame volume will be bigger and thus the flame contact to the tubes of heater and coke formation occurs.

2-4- Minimize coking

Radiant section localized 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 minimize the rate of coking.

2-5- 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 pot still, 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 test have proven that rapid coke and gas formation in the vacuum heater can be caused by the upstream equipment. The operation of process heaters requires exacting control of process fluid coil outlet temperatures and the heat flux distribution to the coils in order to prevent overheating which will accelerate the formation of coke on the inside walls of the process coils. Also, variations in coil outlet temperatures over time and from coil to coil are detrimental to process efficiency [3].

2-6- Minimizing flame impingements

A common reaction to the need for more heat duty is to pump more fuel into the burners of a fired heater, without cross checking its heat-release design limits. This can cause long-term problems like flame impingement, tube bowing, sagging, leakage, rupture, damage and even explosion. Flame impingement is when a flame actually touches or engulfs the tubes or their supports. This condition is one of the major problems encountered in hard-firing heaters, and it can occur due to inadequate design, poor operation or poor maintenance. When flame impingement occurs for even a short duration, damage is done. Consequences can include failures in tubes that carry process fluids, tube supports, refractory, burners, casing and structural integrity. This article uses a horizontal-tube, up-fired, box-type, natural-draft heater with multiple burners as an example. Most of the discussions are, however, applicable to the majority of fired-heater configurations where a flame is present [4].

We will define a bad flame as one whose dimensions cannot be well defined. Such flames can be long, loose, lazy, cloudy, erratic or smoky. The actual or full-flame shape is beyond the dimensions or contours that can be seen with the naked eye. In a bad flame situation, it may be difficult to see if enough clearance is provided between the flame and the tubes in the heater. Baking soda, in powder form, can be used to help make the flue-gas circulation and flame behavior visible inside the fire box. To do this, a very small quantity (less than 1 oz) of baking soda can be tossed or sprayed into the area of interest through the nearest peep doors. Several types of flames are depicted in Figure 5 for comparison. Case 2 shows long and loose flames and Case 3 indicates cloudy flames. As opposed to Case 1, the second and third cases are situations that do require an operator's attention. Case 4 shows clear and visible flame impingement, which may be due to damaged burner parts, misalignment or poor operation. This situation needs immediate attention.

2-7- Effects of flame impingement

Typically, the theoretical adiabatic or maximum flame temperature of fuel gas in air ranges between 3,000 and 4,000°F. The actual flame temperature inside the fire box — after losing heat to the surroundings — is in the range of 2,000 to 3,000°F. Impingement of this high-temperature flame subjects the tubes and tube supports to very high rates of localized heat flux (the amount of heat absorbed per unit area). This can cause coking inside the tube, as well as leakage, sagging, bowing and ultimately, premature failure of the tube and tube supports. Hot spots on tubes from flame impingement may glow in colors of cherry red or orange, indicating very high tube-metal temperatures. These high temperatures can cause hydrocarbon cracking, which results coke formation at the hot spots as shown in Figure 6. When coke forms inside the tubes, it acts like an insulator and doesn't allow the flowing process fluid to cool the tube walls. The tube-metal temperature starts to increase, while the heat transfer across the coke-coated tube wall decreases. This can ultimately result in tube rupture and leakage. In a two-phase-flow heater, flame impingement promotes more vapor generation resulting in a higher pressure drop across the heater. The increased vapor levels may reduce the heat-transfer coefficient inside the tube and lead to an increase in the tube-metal temperature. A tube's life is reduced rapidly at higher temperature levels. Temperatures that rise above the creep-rupture design temperature, particularly, can lead to a shorter tube life and rupturing. Flame impingement can lead to heavy oxidation of the tube metal, which forms a hard scale around the tube surface. This can affect radiant heat absorption and tube life.

2-8- Preventing flame impingement

A common cause for flame impingement is either damaged burner parts (tips and tiles, for example) or poor combustion. Poor combustion generally results from an inadequate supply of air, or poor mixing of fuel and air at the burner throat. Additional causes for flame impingement include over firing of the burners and air leakage. In some instances, irregular flue-gas flow patterns inside the fire box can lead to flames throughout the fire box.The design of the heater's fire box should be adequate enough to contain the flame. The box should not be too narrow or too short. Table 1 indicates the minimum required tube-to-burner clearance, as recommended by the American Petroleum Institute (API), for a natural-draft heater. Choosing the number of burners for a fired heater is usually left to the design engineer's experience. More burners, spaced equally in the fire box, will provide a more uniform heat flux and relatively shorter flame lengths. The trade off is in increased costs for the burners, instrumentation, operation and maintenance. Considering the potential losses due to shorter run lengths or reliability issues, it may be wise to make the greater initial investment. Flame heights for good heater and burner design are, as a guideline, less than one-third to one-half of the firebox height. Practical experience shows that flames higher than 12 ft are not always stable and can lean towards the tubes. Current NOx-reducing burners utilize air and/or fuel staging, and internal flue-gas recirculation techniques to reduce NOx emissions. These techniques tend to elongate and delay the combustion process, leading to a longer flame, as compared to conventional burners. The fire-box dimensions and tube configuration need to be adequate to justify the installation of such NOx-reducing burners. The analysis usually leads to the installation of more, smaller burners. For forced-draft burners, flame heights can be reduced by increasing the air-pressure drop across the burners. This increases the turbulence between air and fuel to provide adequate mixing energy for shorter flames. In natural-draft heaters, however, this is less likely to be an option because the draft available for the burner is relatively low when compared to forced-draft systems. Another option to lower the flame height is to modify the angle of the gas/oil tips. This technique can also be used to decrease the width of a flame, if, for example, the fire-box configuration is better suited for long and slender flames. These adjustments to the flame shape and size can avoid flame impingement on the tubes. The burner type and design play vital roles in reducing flame-impingement problems. Premix burners normally produce shorter flame lengths than raw-gas burners. Installing premix burners in short fire boxes, therefore, can reduce the possibility of flame impingement. Burners should be designed in such a way that a minimum of 90% of the available draft is consumed across the burner. Additionally, a minimum of 75% of the total draft consumed in the burner should be consumed at the burner throat. This will ensure adequate mixing energy for the air and fuel to produce stable flames for the specified conditions. Fuel quality also plays a major role in burner maintenance. Fuel containing particulate matter, liquid condensate or heavy metals such as Na, Va, or Ni, can lead to frequent fuel-tip damage. Installing a good fuel-filtration system can reduce or eliminate such damage. For a multi-burner system, the design of the air plenum and individual combustion air ducts plays a significant role in providing uniform air distribution to the system. When air distribution is poor, some burners will seek air from the fire box to combust their fuel, creating a fuel-rich zone or longer flames. Symmetrical air-duct arrangements and adequate flow-directing baffles in the air plenum can improve the air-flow distribution.Operationaspects damage to the burner fuel tips results in a cloudy or erratic flame, which as we have seen, may lead to flame impingement. Particulates and heavy metals in the fuel can either plug or erode fuel-tip ports. In multi-burner heaters, an experienced operator or engineer can determine if a particular tip is damaged or misaligned by comparing flame shapes from other burners. When a damaged tip is identified, it should be replaced as quickly as possible [5].

3- Results and discussion

Process heaters are critical pieces of equipment in the refining and petrochemical industries, and monitoring the working condition of these heaters is essential. The traditional method of heater monitoring is visual, using viewing windows and peepholes, to ensure proper flame pattern and burner management, and to make sure that no flames impinge on the tubes.During visual observation, any bowing, bulging, scaling, discoloration, etc. of the tubes is noted. In parallel, the skin temperature of the tubes also is monitored by skin thermocouples and sent as real-time data to the control panel. Tube metal temperature always must be maintained within design limits to avoid overheating.

The three dimensional simulation of turbulent combustion and heat transfer within process heaters provides for a detailed examination of the effects of design and operating changes on process side conditions. Since the fireside conditions are coupled with the process side conditions, nonlinear effects associated with changing firing rates, coil and furnace geometry, firing distribution, feedstock, and process flow rates can be examined in a rigorous manner. In this paper, it was shown how these parameters can be used to improve performance and efficiency in process heaters.

Impingement of this high-temperature flame subjects the tubes and tube supports to very high rates of localized heat flux (the amount of heat absorbed per unit area). This can cause coking inside the tube, as well as leakage, sagging, bowing and ultimately, premature failure of the tube and tube supports. Hot spots on tubes from flame impingement may glow in colors of cherry red or orange, indicating very high tube-metal temperatures. These high temperatures can cause hydrocarbon cracking, which results in coke formation at the hot spots.

As mentioned some works can be done to protect the fire heaters; with temperature profile monitoring, detection of scaling and hot spots, changes in the gas composition inside the heaters, minimize coking, oil thermal stability, minimizing flame impingements and not over loading from heaters ,the condition of heater can be optimized.

4- CONCLUSIONS

In a typical petroleum refinery, there may be a lot of fired heaters with different configurations, and each heater may have different types of burners. Frequent monitoring, proper maintenance, and the design and operational aspects mentioned, can reduce or

eliminate flame impingement, which in turn can increase the run length, reliability and safety of fired heaters.
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. As tube metal temperatures increase, the heater firing must be reduced will progressively increase until the tube metallurgical temperature limit is reached. Then the heater must be shut down to remove the coke. Rapid coke formations caused by a combination of high oil film temperature, long oil residence time, and inherent oil stability. Heater design affects the localized coke formation rates through its influence on oil residence time and film temperature.
An effective tube management program can reduce equipment costs at a medium-size refinery by one million dollars per year or more.
With temperature profile monitoring, detection of scaling and hot spots, changes in the gas composition inside the heaters, minimize coking, oil thermal stability, minimizing flame impingements and not over loading from heaters, the condition of heater can be optimized.

Figures:

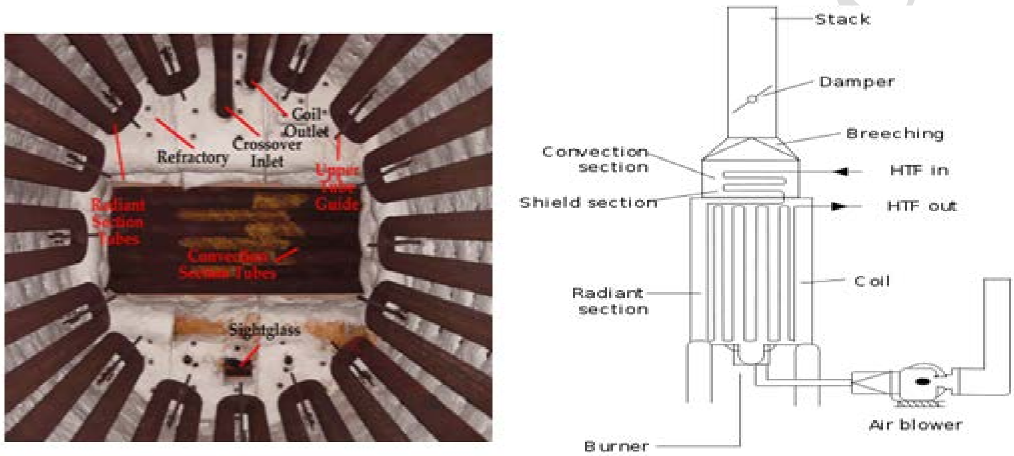

Figure1: Furnace tube overview

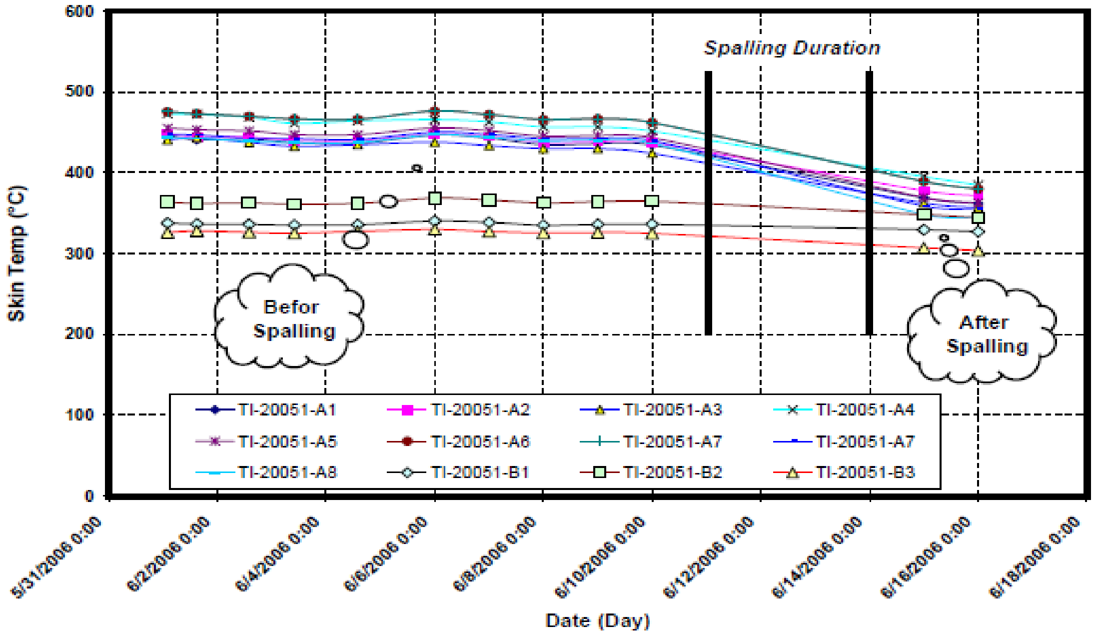

Figure 2: Spalling analysis temperature

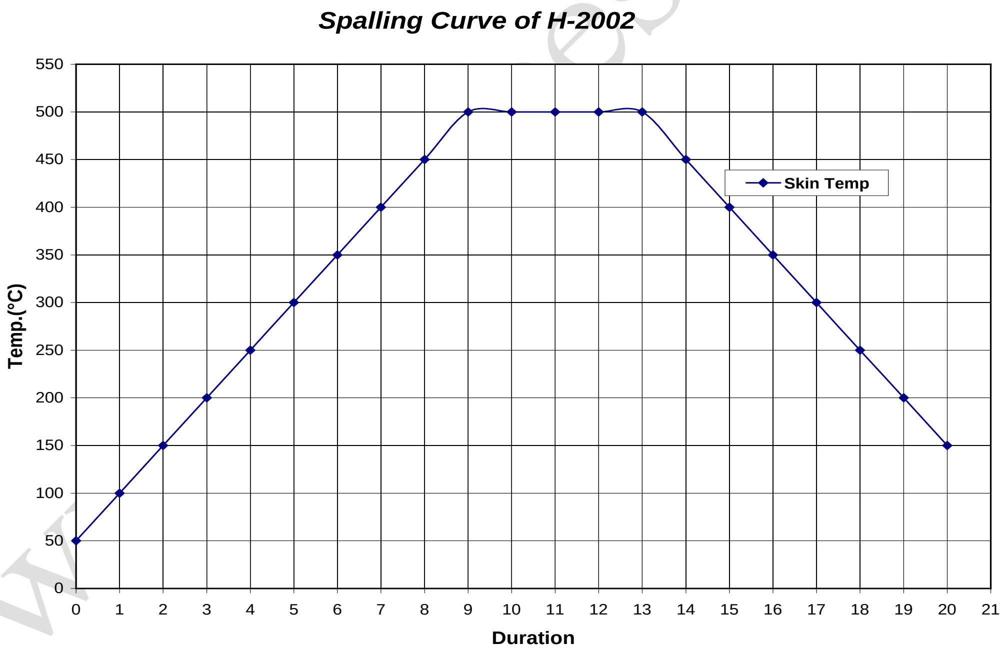

Figure 3: Spalling procedure curve

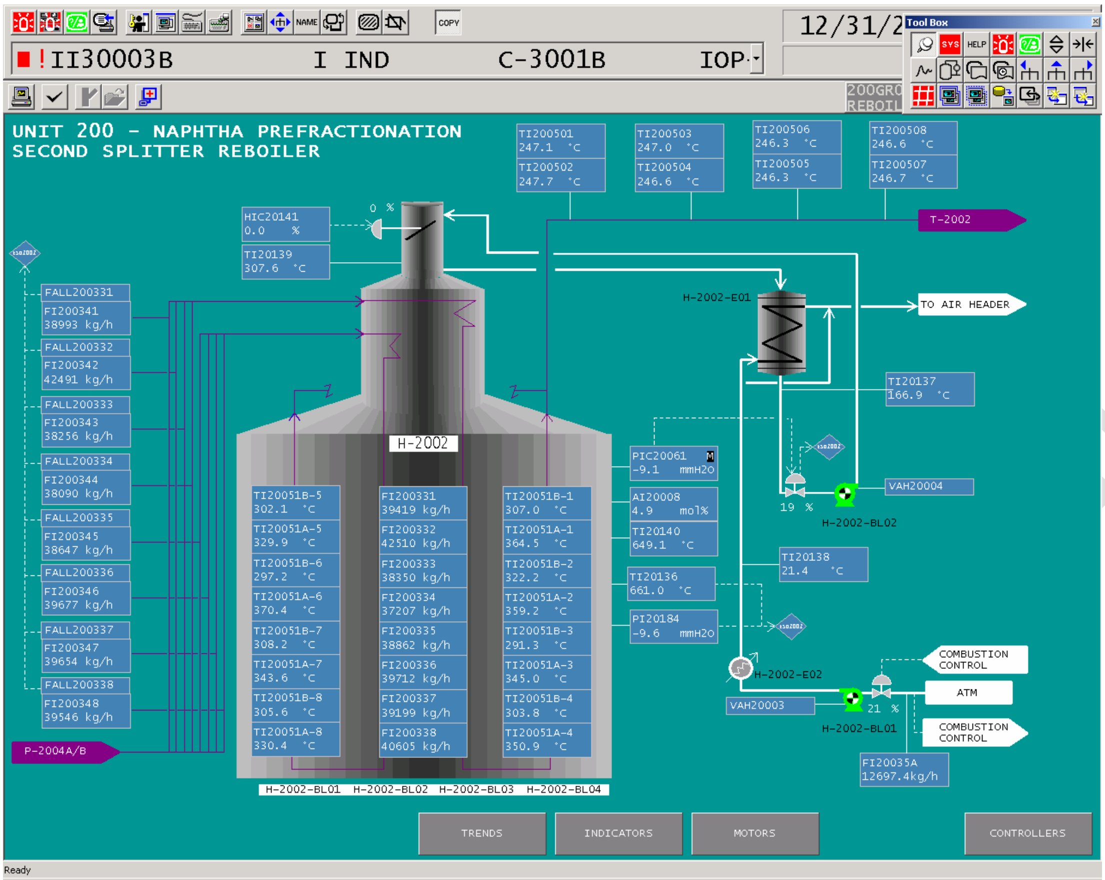

Figure 4: Heater tube skins temperature

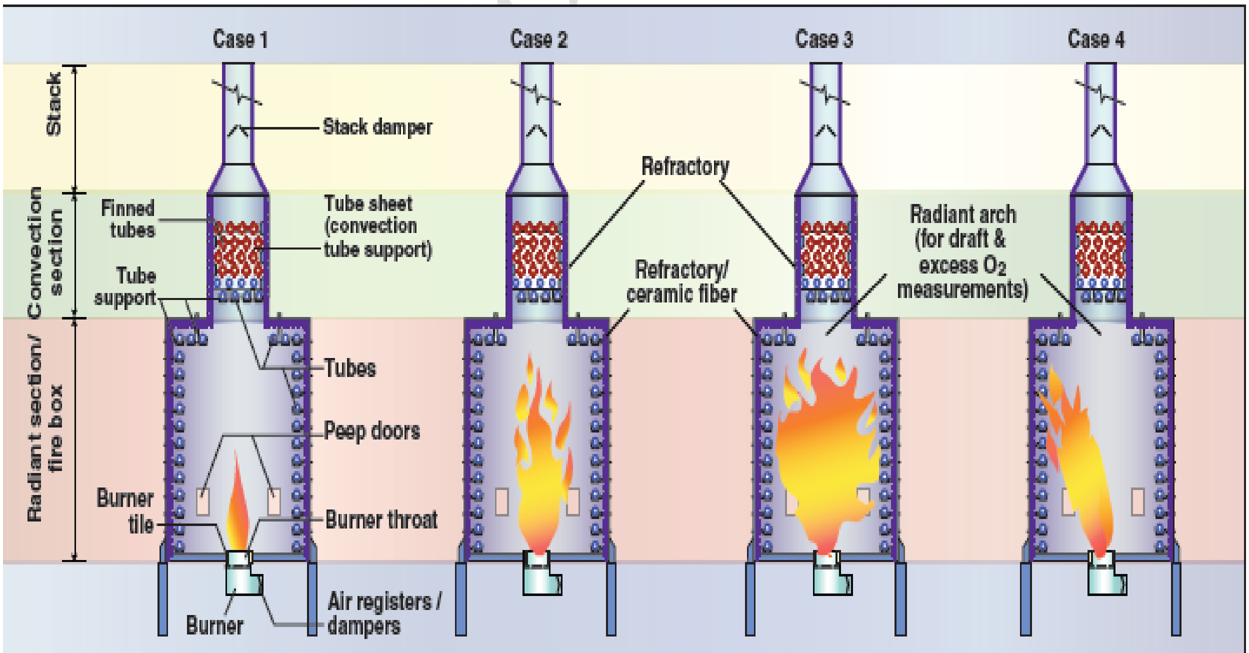

Figure 5: Several types of flames

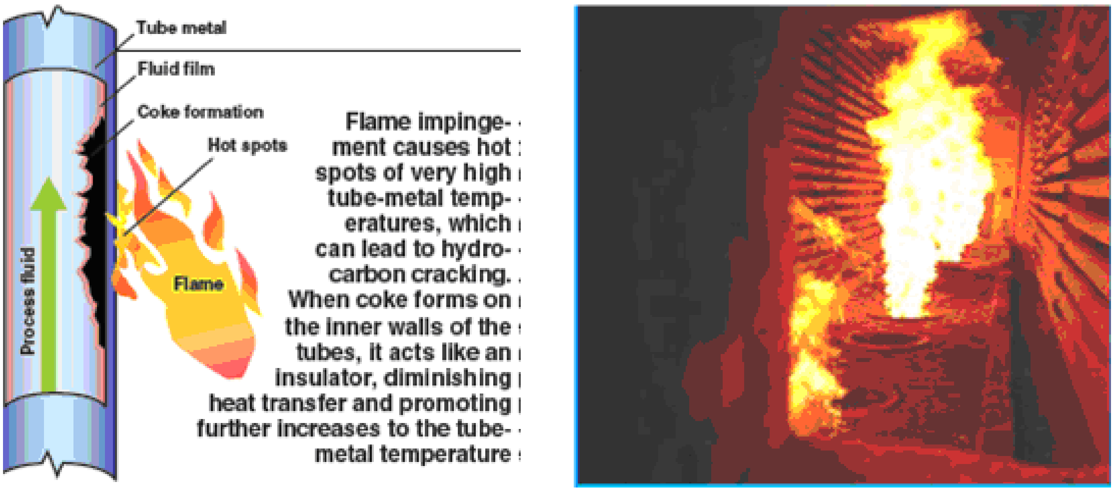

Figure 6: Flame impingement causes hot spots

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