

Advances in delayed coking heat transfer equipment

Designs are evolving to meet changing process needs, while improving the onstream factor and extending run-length

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The delayed coking process is used to crack heavy oils, normally vacuum residue, into more valuable light liquid products, with less valuable gas and solid coke as byproducts. The first delayed coking plant was built in 1930. While the delayed coking process has been evolving for 78 years, the past few years have seen changes in feedstock that have had a major impact on the design and operation of delayed coking units. These changes are affecting the heat transfer equipment and coker heater in particular.

The increasing worldwide demand for liquid petroleum products, the resulting increase in the crude oil price, the differential cost between light and heavy crudes, and the shift toward processing lower quality, lower cost crudes and tar-sands bitumen have created a need to convert larger quantities of vacuum residue to higher valued liquid products. This has resulted in an increase in the application of delayed coking.

These lower cost feedstocks typically have higher metals and asphaltenes, and some have higher total acid numbers. The impurities in the crude tend to concentrate in the residue streams, making the resulting coker heater feed “dirtier,” with a higher fouling tendency.

Economics are driving coker operations toward lower coke drum pressures and lower recycle rate (throughput ratio) to increase liquid yields. Economics are also dictating larger diameter coke drums (9.15 m). Totally enclosed, fully automated top and bottom unheading devices have shortened coke removal time. This has resulted in shorter cycle times, which then require higher severities to produce coke with the same volatile combustible material. All of these factors have contributed to the need for larger capacity and higher severity coker heaters.

Delayed coking is an endothermic thermal cracking process that requires large quantities of heat to be supplied to the reacting feedstock at temperatures of 500°C+. All the process heat is supplied by the coker heater. The fluid must move through the heater to the coke drum as quickly as possible to minimize the amount of coke that is deposited in the heater tubes and downstream piping. The coke deposited inside the heater tubes causes increased tube metal temperature and pressure drop. Moreover, the rate of coke deposition determines coker heater run-length. Heater design must therefore consider feedstock quality, operating conditions, need for future expansion and possible changes in feedstock characteristics.

Changes in heater design. A delayed coker heater design dating back to 1940 consisted of small, box-shaped heaters with

double rows of tubes suspended from the roof and a single row of tubes on each wall (Fig. 1). The process fluid was heated only in the radiant section. The double row of tubes was backed with tiles that increased heater efficiency by increasing the convective heat transfer to the tubes. This general design was used for more than 20 years. Even though the shape of the heater later evolved, the double row of tubes suspended from the roof (with tiles backing them) continued to be used until about 1990.

During this period, delayed coking units were small: few were larger than 1.1 million metric tons/year (MMtpy). Most had a single pair of coke drums, one being filled while the other was de-inventoried. All the heaters were single-fired (i.e., tubes were heated from one side only). Firing from only one side results in a large difference between the peak heat flux and the average heat flux. The subsequent high peak heat flux results in high film temperature, which leads to accelerated laydown of coke inside the heater tubes.

The average heat flux rates for coker heaters was therefore lower than for general refinery process heaters, in the range of 24,400 kcal/hr m². The low average heat flux rates required relatively high residence times, which also promote coke deposition. Early designs had a number of small liberation gas burners in the floor and the height of the furnace could be small because the

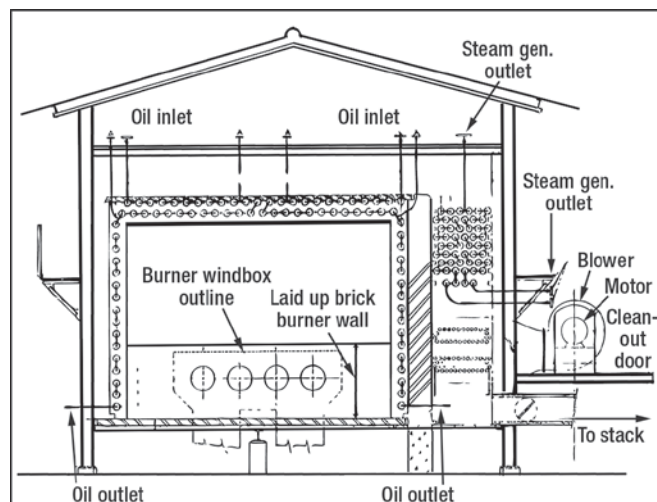


FIG. 1 Coker heater, circa 1950: box heater with double row of roof tubes.

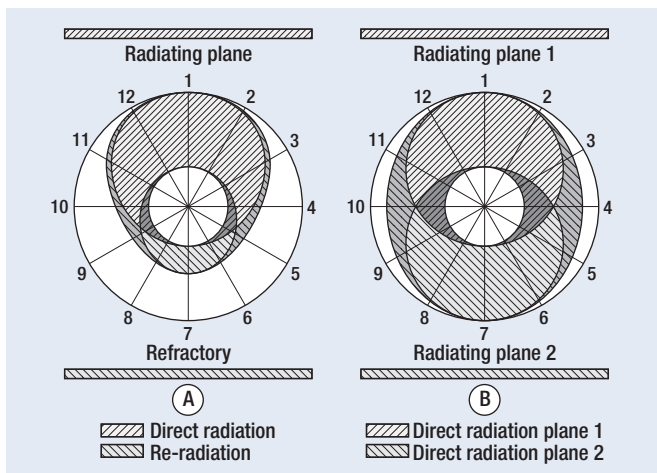


FIG. 2 Flux distribution around circumference of tubes.²

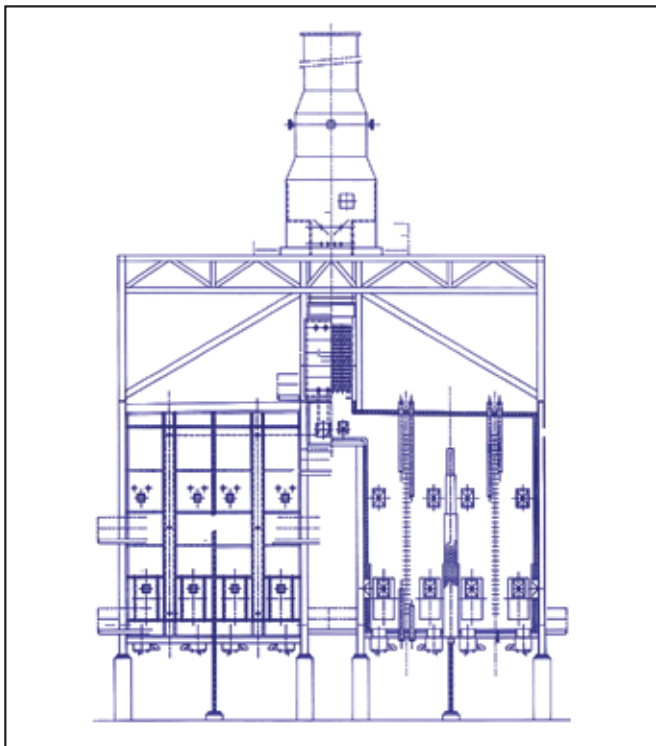


FIG. 3 Contemporary four-cell heater with internal walls.

flame lengths were only about half as long per unit heat release as modern, staged-fuel, low- NO_x burners.

After 1990, there was a significant new development in the design of the coker heater—the double-fired coker heater design. This patented delayed coking heater design¹ put the coil in the center of the box and the burners against the wall so that the tubes could be heated from both sides. The average heat flux rate could then be increased by 50% with no increase in peak heat flux or film temperature (Fig. 2). When the heat flux at points 1 and 7 of the tube heated from both sides equals the heat flux at point 1 of the tube heated from one side, the average is 50% higher. The resulting reduction in coil length reduced pressure drop and residence time and allowed for increased capacity per coil. Reducing the residence time in the coker heaters requires a slightly higher

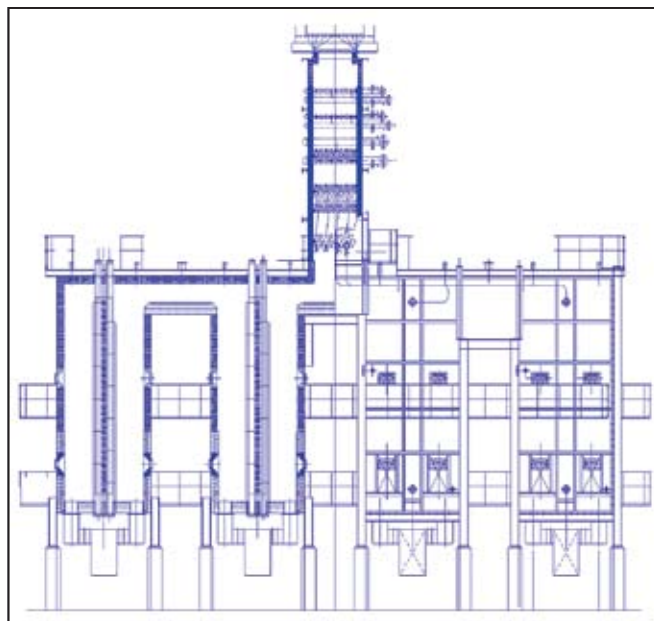


FIG. 4 Contemporary four-cell heater with air-cooled walls.

outlet temperature for the same conversion and yields. The patent has been licensed by a select group of furnace designers.

Contemporary heater designs. Contemporary delayed coking units have been designed for capacities larger than 6 MMtpy and have multiple pairs of large-diameter coke drums. These coker heaters are designed for very high capacity (Figs. 3 and 4) to limit the number of heaters per pair of coke drums. The resulting heater designs therefore have higher mass velocity and pressure drop. The heater tube diameter has not increased because increasing the tube diameter would raise the film temperature and tube metal temperature, thus accelerating radiant coking and reducing heater run-length. In the resulting tall, narrow firebox designs, the burner operation and flux profile become critical to achieving the required run-length.

Coil materials. Coke deposition inside the heater tubes leads to an increase in the tube metal temperature and pressure drop. The heater run-length will normally be controlled by the end-of-run (EOR) metal temperature.

Older units that processed clean feedstocks generally used 2¼ Cr-1 Mo or 5 Cr-½ Mo tubes. The majority of contemporary units have been engineered with 9% Cr-1% Mo (T9) tubes due to higher sulfur and higher EOR temperatures. Other alloys have been considered and selectively used. TP317L has been considered for feedstocks high in naphthenic acids, but only if the heater operating temperatures are in the corrosion range. Other austenitic alloys have been used to extend run-length due to their strength at higher temperatures, which enables setting the EOR temperature higher. Due to the high sulfur content in the feeds, stabilized austenitic alloys such as TP347H or TP321H would be required. However, if there is any chance that present or future feedstocks contain chlorides, austenitic alloys cannot be used. Allowable rupture stress values of the various tube materials are plotted in Fig. 5.

As evidenced in the curves, the stress values for 9 Cr-1 Mo plus vanadium (T91) are much higher than for 9 Cr-1 Mo (T9). However, the most recent edition of API 530 has set the limiting design metal temperature for alloy T91 at 650°C because of lack

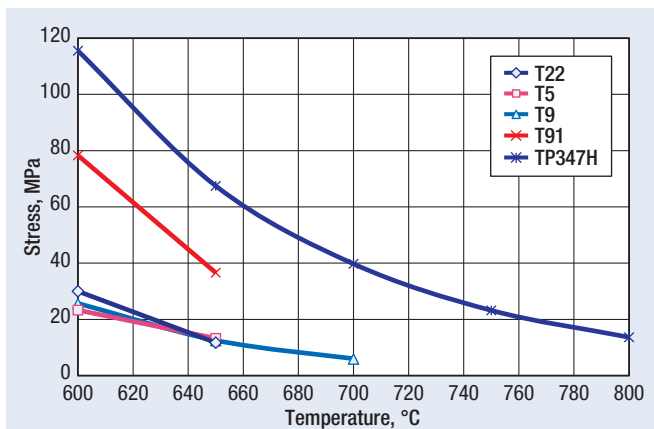


FIG. 5 Rupture stress curves for various tube materials.³

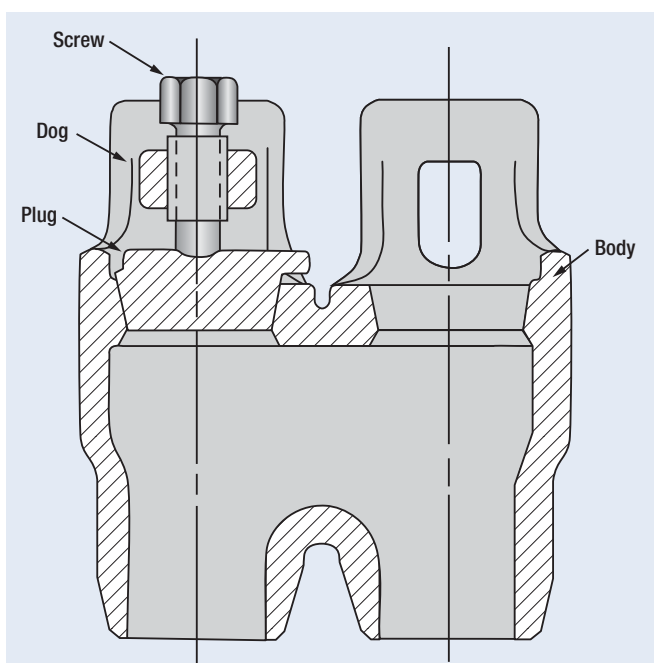


FIG. 6 "Mule ear" type return header has removable plugs.

of reliability for the rupture strength above this temperature. Since this material is also difficult to fabricate, its use has been limited.

Cleaning methods. When the design metal temperature or EOR pressure drop is reached, the heater coil must be decoked. Originally, the only method of decoking the tubes was mechanical cleaning by turbinizing. Heater tube ends had headers such as "mule ear" or "bull nut" types for return fittings. These were H-shaped headers with removable plugs that frequently leaked (Fig. 6). Tubes were expanded or rolled into a tube sheet in the fitting. Later, the fittings were designed to be welded to the tube ends. The headers had to be located outside the radiant chamber in header boxes. When it was time for decoking, the furnace was cooled, plugs were removed, and each tube was mechanically cleaned with a tool that cut the coke from the tube's inside.

Introducing steam-air decoking reduced the time required for decoking and made it possible to replace the headers with 180° U-bends welded to the tubes and located inside the firebox. This



FIG. 7 Piggging options for quick and easy mechanical decoking. (Photo courtesy of Eveready Energy Services)

lowered the cost and decreased the coil pressure drop during normal operation. Some users kept the headers on one end of the coil or near the outlet end for inspection after decoking.

A more recent development is "pigging," where a soft plastic plug (or "pig") with sharp cutting blades is forced through the coil using hydraulic pressure, cutting the coke as it travels along the tube length (Fig. 7). Pigging has been adapted as a quick and easy method of mechanical decoking. If return headers with plug fittings are used in the coil, the plugs must be contoured to prevent the pig from lodging in the bends. Pigging results in cleaner heater tubes compared to steam-air decoking and is less harmful to the coil since it is done at lower temperature and is less erosive. The heater must still be taken out of service, flushed and cooled before it can be pigged.

Increased onstream factor by online spalling. As the feeds became heavier, run-lengths were getting shorter. To increase the on-stream factor of the units, on-line spalling was developed. The on-line spalling method uses steam and/or condensate combined with modulating tube skin temperatures and steam flow rate to effectively break the coke off the tube wall, sweeping the spalled coke into the coke drum.

This method relies on the difference between the coefficient of thermal expansion of the deposited coke and steel. During online spalling, one individual coil of a heater is cleaned by spalling while the other pass(es) remains in operation. Normally, the capacity of the passes not being spalled can be increased to minimize the impact on unit capacity. Online spalling has been successfully conducted on most modern double-fired coker heaters. It has been done on two-pass heaters, where one pass operates while the other is spalled, as well as on four-pass heaters.

Cleaning by online spalling is almost as effective as mechanical cleaning or steam-air decoking. Several cycles of online spalling can be tolerated before offline cleaning is required. Online spalling is erosive—particularly when performed aggressively—and requires some protection for the fittings, especially near the outlet of the coil. This has been accomplished using cast return bends, with heavier back walls near the outlet of the coil. Some plants have also tried fittings with hard face coatings made of high-cobalt metallurgy.

Online pigging. Continuous disposition of vacuum residue is critical in refinery operations. A delayed coker processing a

large quantity of vacuum residue cannot be shut down without a major impact on refinery operations. There has been a push to increase delayed coking unit onstream intervals to a minimum of four years to coincide with refinery turnaround schedules. A cold shutdown to decoke the heaters would require an extended outage, impacting upstream and downstream units. While online spalling has already extended heater run-length, "online pigging" has resulted in a further extension.

The concept of online pigging was developed at a plant in South America in the early 1990s. In this concept, the heaters are designed so that one cell of a heater can be taken offline to be pigged while the other cells continue to operate in hydrocarbon service. This requires that the cell be isolated from the rest of the heater or, preferably, that multiple smaller heaters be installed instead of a single large heater. In the case of heaters with air preheat, individual air preheaters are preferred to single combined units for the ease of online pigging.

Online pigging has proven to be particularly effective in bitumen processing. Bitumen is derived from tar sands and is processed in facilities known as upgraders. Many upgraders use delayed coking to upgrade the bitumen into synthetic crude oil. The bitumen contains inorganic material (clay) that tends to deposit on the heater tube wall together with the coke and cannot be removed by spalling or steam-air decoking. Inorganic solids must be removed mechanically by pigging. The ability to pig online is critical in keeping these upgraders onstream.

Heater efficiency. The efficiency of the heater is limited by the amount of heat that can be added to the process in the convection section. The feed to the heater typically comes from the coker fractionating column bottoms operating in the range of 280°C to 300°C. Considering the nature of the fluid, the flue gas cannot be cooled lower than about 370°C by preheating the feed alone. Limiting the fluid crossover temperature is necessary to prevent reaction in the convection or shock tubes. Typically, the only other use for waste heat is steam superheating; however, this duty is relatively small. Therefore, the maximum efficiency achievable is approximately 80%, based on the lower heating value of the fuel.

Steam can be generated with the waste heat, but this requires additional pieces of equipment such as steam drums, pumps, piping, controls, etc., and a demand for the steam. More typically, combustion air preheating has been used to raise the efficiency to a minimum of 90% on contemporary designs.

Designing the unit for combustion air preheating requires making provision for fan failure and/or air preheat system maintenance. Typically, a bypass of the flue gas around the air preheater (APH) to the stack is necessary in case the induced draft fan fails. Some units specify ambient air doors to provide natural draft operation in the event of combustion air (forced draft) fan failure. In other cases, a spare forced draft fan is provided together with a full-size combustion air bypass around the APH. Electrical power must be reliable for the multiple-fan scheme to work.

The choice of individual air preheat systems versus a combined air preheat system should be based on economics and comparative analysis. The individual air preheat system offers better flexibility and the ability to isolate an individual heater for online pigging or steam-air decoking. If there is a future need to increase unit capacity, having heaters designed with individual air preheat systems simplifies expansion.

Oil firing. Most coker heaters fire fuel gas. The delayed coking process produces coker offgas, which is normally used to fire the

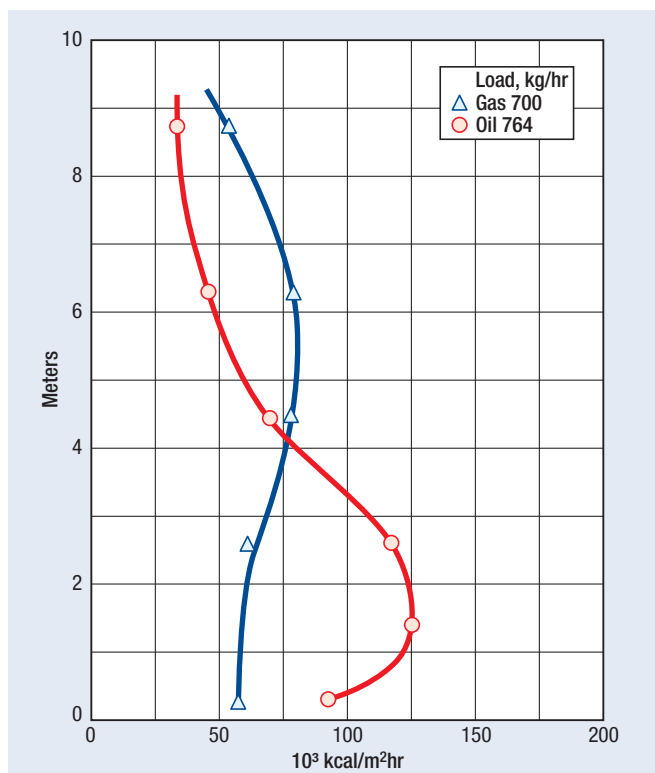


FIG. 8 Typical vertical flux profile for gas burner and oil burner.⁴

heaters. However, in refineries where natural gas is in short supply, the coker offgas is often used to balance the overall refinery fuel gas requirement. In these cases, the coker heater needs to be designed to fire fuel oil. This creates new challenges for coker heater design, particularly for the double-fired design.

The double-fired design uses a large number of small liberation burners fired upward and against the side wall of the radiant chamber. While the objective is to create uniform heating without alternating hot and cold areas along the tube length, this is not possible with oil firing. The minimum capacity for an oil burner is limited by the tip size in the oil gun: If the tips are too small, particles contained in the oil will plug the tip. As a result, there are fewer oil burners, but of higher capacity. The oil flame cannot be directed at the wall, and the flame length—and hence flux profile—is different from a low-NO_x gas burner of similar liberation.

All new gas-fired delayed coker heater designs have low NO_x burners; some have ultra-low NO_x burners. These gas burners generally have relatively flat flux profiles that are compatible with the process. The area of minimum heat flux is located near the floor, where the outlet tubes are located, while the highest heat flux is in the top of the furnace, where the feed is cooler. Vertical flux profiles from oil burners will be highest near the floor.

Fig. 8 shows the relative vertical flux profile for a gas burner and an oil burner. The non-uniform horizontal flux and the vertical flux profile difference associated with oil fuel firing have a negative effect on heater run-length.

If the coker heater is to burn dual fuels simultaneously, the heat input to a given coil must be uniform and the combustion air distributed in a manner that allows each burner to get a sufficient amount of air. Schemes where some burners burn fuel oil and others burn gas are difficult to control because the liberation per burner is never equal. The combustion air distribution results in

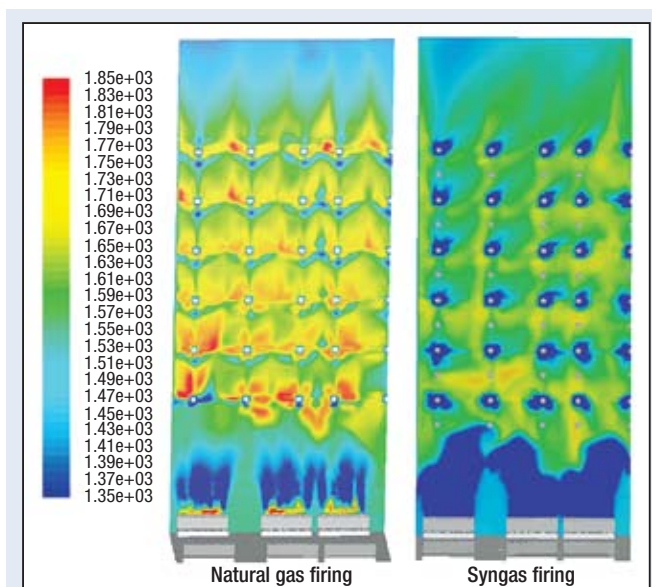


FIG. 9 CFD simulation of refractory wall temperature, K.

too much or too little air, or some combination of both, resulting in secondary combustion and flame impingement on tubes.

With oil burners, other issues need to be considered:

- Turndown is limited to one-third of maximum liberation.
- Convection tubes must be designed for soot removal, and may require the use of studded rather than finned tubes.
- Heater efficiency may be limited by acid dew point.

Liquid firing emissions are greatly increased when compared to gas firing, including increased NO_x , CO, SO_x and particulates. Finally, if the fuel is a heavy oil containing sulfur and vanadium, the tube support system and refractory may have to be designed using different materials depending on the level of these contaminants in the fuel oil.

A double-fired coker heater with burners firing a combination of fuel gas and heavy fuel oil has been operating successfully for more than two years.

Alternative fuels. Although the cost of solid fuels (coal) has risen recently, petroleum coke demand has not kept up with the increase in supply. The rise in natural gas price has been much greater, and new grassroots coker designs sometimes consider exporting the coker offgas to upgrade the value. Several gasifier projects have been built and/or are planned using petroleum coke as feed, mainly to produce syngas fuel for power production via gas turbines in integrated gasification combined cycle (IGCC) arrangements.^{5,6} With the increasing size of delayed coking plants, it will become feasible to integrate the delayed coker and gasifier so that syngas can be used to fire the delayed coker heater, using a less valuable byproduct to allow export of the higher valued fuel gas.

The use of syngas as fuel will impact the furnace design as well as other critical components (e.g., burners, flue gas handling equipment). A typical delayed coker will produce sufficient petroleum coke to generate enough syngas to fire the furnace as well as export syngas for IGCC or other uses. However, to start up the delayed coker or operate it with the syngas unit down, the furnaces will need to be fired on an imported fuel. This requires burner flexibility to meet the liberation requirements based on the fuels' differing molecular weights and heating values. Table 1

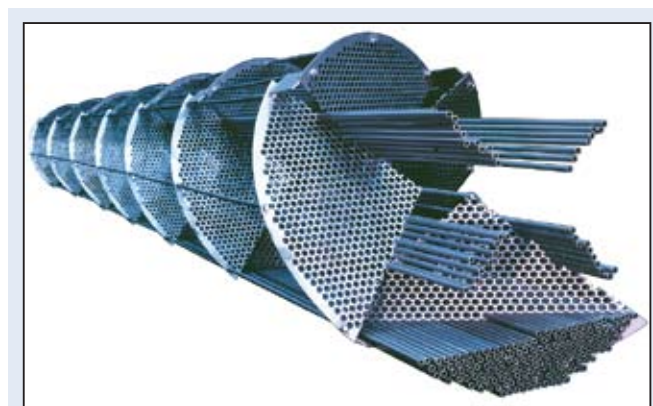


FIG. 10 A helically baffled heat exchanger tube bundle.

TABLE 1. Comparison of offgas and syngas

	Offgas fuel	Syngas fuel
Molecular weight	21.0	22.4
Lower heating value, kcal/kg	11,500	2,365
Lower heating value, kcal/Nm ³	10,190	2,155
Comb. air/fuel mass ratio	18.5	3
Flue gas/liberation, Nm ³ /Gcal	1,358	1,245

compares the properties of a typical syngas fuel generated from petroleum coke versus a typical coker offgas.

Burners must meet the range of operation required for both fuels, and such burner technology is being developed. Computational fluid dynamics (CFD) studies of these burners and associated firing patterns (Fig. 9) confirm that the expected flux profiles will meet the requirements needed to maintain unit run-lengths for delayed coker heaters.

NO_x emission regulations. NO_x emission regulations are becoming more stringent worldwide. Further reductions in NO_x levels will require coker heaters to be designed with selective catalytic reduction (SCR) units. The decision to add an SCR unit to a delayed coker heater must consider whether or not the unit will be permitted to operate with the SCR bypassed in an emergency situation, such as loss of the induced draft fan or air preheater.

Although delayed coking unit stack heights are normally determined by the cutting deck elevation, it would require a much taller stack to operate on natural draft if the gas would have to pass through the SCR before going to the stack. If bypassing is not permitted, a low-pressure-drop SCR reactor combined with a taller stack or steam ejector to temporarily generate the necessary draft can be used. The future trend is expected to favor the use of air preheating, low- NO_x burners and SCR units for NO_x reduction.

Process heat integration. With longer achievable run-lengths between offline cleaning of the coker heaters, focus can shift to other heat transfer equipment that may become the limiting factor for unit onstream availability and turnaround planning. The coker preheat exchanger train handles the heavy, viscous feed (which has been bitumen in some current designs) and is subject to significant fouling. A helically baffled heat exchanger (Fig. 10) has been developed⁷ and proven to provide a significant decrease in the fouling rate in several coker services (Figs. 11 and 12). It has



FIG. 11 Conventional exchanger in bitumen service—fouled after nine months.



FIG. 12 Replacement helically baffled heat exchanger bundle, inspected at annual turnaround after one year of operation in bitumen service.

been applied in coking service and equivalent viscous fouling services in crude and vacuum preheat trains. Operators have reported achieving a minimum two to three times longer run-lengths between cleaning than earlier segmental-baffle exchangers.⁸

The new exchanger exhibits reduced fouling characteristics compared to segmental-baffle exchangers as a result of several inherent design features:

- Helical flow path allows shellside velocities significantly higher (approximately two to three times higher) than the average cross-flow velocities associated with equivalent segmental baffle designs. The average velocities are higher, and the velocity distribution profile is more uniform.
- Shellside flow impacts the tube wall at an angle, causing shear forces acting on the tube wall to be significantly higher.
- Uniform flow velocities through the tube bundle—associated with the relatively constant shellside flow area—result in no abrupt changes in direction, no corners, and few dead spaces for eddy recirculation and fouling accumulation. This, in turn, translates into more uniform tube wall temperatures and tubewise temperature distribution.

As most delayed coker exchangers are of floating head construction because of fouling considerations, tube bundle change-out to a helically baffled bundle design is a low-cost and low-downtime option for increased heat recovery, reduced pressure drop and

reduced fouling for existing delayed coking plants. Such improvements have been noted for exchangers in bitumen service applied in other upstream units (e.g., crude and vacuum distillation units' preheat exchanger trains shown in Figs. 11 and 12).

Proven applications in delayed coking services include:

- Coker feed preheat exchangers (reduced surface required; reduced shellside pressure drop and fouling)
- HCGO product/pumparound coolers (reduced surface required; reduced fouling)
- Coker fractionator overhead condenser (reduced surface required; reduced shellside pressure drop)
- Debutanizer overhead and stripper overhead condensers (reduced surface required)
- Debutanizer reboiler and stripper reboiler (reduced surface required; reduced shellside fouling)
- Compressor interstage and discharge coolers (reduced surface required; reduced shellside pressure drop). **HP**

ACKNOWLEDGMENT

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- ⁴ Diagram supplied courtesy of John Zink Company. Original source: C. J. Hoogendoorn, C. M. Ballintijn and W. R. Dorresteyn, *Journal of the Institute of Fuel*, Dec. 1970, Vol. 43, p. 515, Fig. 8. Vertical heat-flux distributions for oil firing and gas firing with standard burners in bottom. Diagram reproduced with the kind permission of the Energy Institute, U.K.
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