Improve FCCU Profitability - Bottoms System Upgrades

A review of process flow scheme fundamentals and basic equipment operating and design principles that have improved unit operating profitability through better use of capacity, higher conversion and lower cost maintenance

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Many refiners continue to face significant problems with reliability of the FCCU main column bottoms (MCB) system. Poor reliability reduces unit capacity, lowers conversion and increases the cost of maintenance. Reliability troubles include MCB pump head-flow loss, exchanger tube-side fouling, debutanizer reboiler shell-side fouling, and coke accumulation in the bottom of the main column. Because many FCCU product recovery sections are based on inherently unsound process and equipment design, only rarely can operating changes alone materially improve reliability. Thus, a revamp involving some capital expense is almost always needed to correct the basic shortcomings that lie at the root of the problem. This paper discusses process flow scheme fundamentals and basic equipment operating and design principles that have improved unit operating profitability through better capacity utilization, higher conversion, and lower cost of maintenance.

MCB System

Superheated vapor enters the main column at 930-1025°F (500-550°C) where it contacts a portion of the main column bottoms stream. The MCB system removes heat from and scrubs catalyst fines from the reactor effluent stream. Consequently, the system operates at high temperature and contains solids that can erode and plug equipment not specifically designed for such difficult conditions (Figure 1).

MCB is pumped from the liquid pool in the bottom of the main column through an exchanger network where the temperature is reduced from 680-700°F (360-370°C) to 440-560°F (225-295°C) to meet the main column overall heat balance requirements. Typical MCB heat sinks include FCC riser feed, steam generation, gas plant reboilers, and in a few instances BFW preheat. These exchangers can be piped in parallel or series. Exchanger outlet streams (Total MCB) are split into slurry pumparound, quench, and decant oil product.

Cold slurry pumparound, routed to the top of the heat transfer internals located directly above the reactor feed, heats up as it flows down through the column internals, while vapor cools down to approximately 650°F (343°C). Temperature of liquid exiting the heat transfer internals is about 700-770°F (370-410°C), depending on fractionation efficiency and operating column pressure (Figure 2). The quench stream is fed directly into the liquid pool in the bottom of the main column. Most refiners maintain constant pool temperature by varying the quench stream flow rate. A small portion of the circulating MCB stream is yielded as decant oil product.

Process Flow Scheme

The process flow scheme influences total MCB circulation rate, temperature, and pressure as well as equipment sizing and selection. The exchanger network can be designed with either all- parallel or partial-

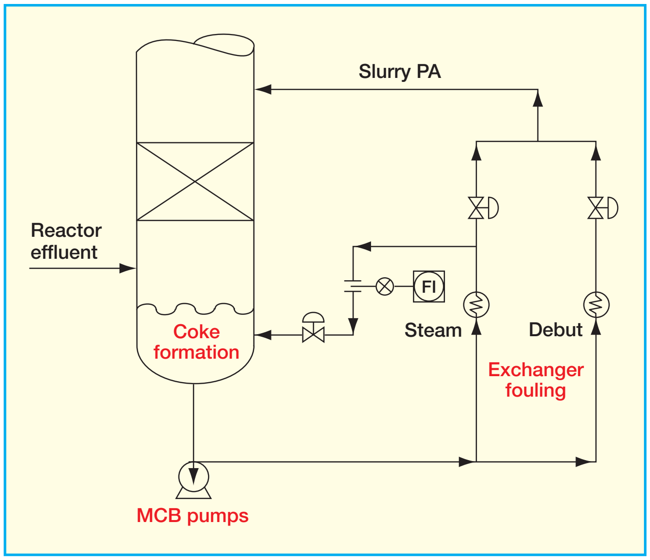

Figure 1. MCB System and Problem Areas

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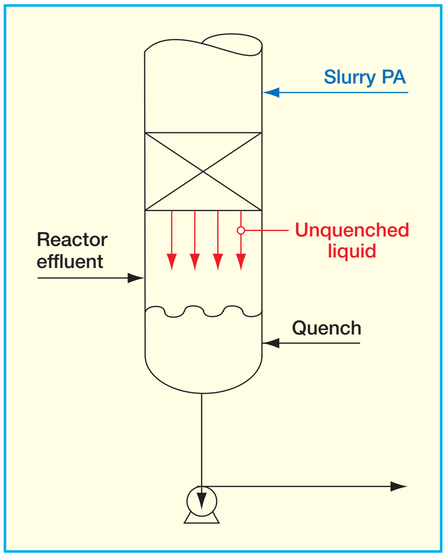

Figure 2. Main Column Slurry PA and Quench Systems

ly in series (Figure 3). Using exchangers configured all in parallel reduces system pressure drop and lowers pump capital and operating costs. It has the disadvantage of high MCB temperature – approximately 680-700°F (360-370°C) – when employed for Debutanizer reboiler heat. In this service minimizing tube wall temperature is essential to control shell-side fouling. Series-piped exchangers lower the MCB temperature to 560°F (293°C) for reboiler service but raises system pressure drop, increases pump head, pump speed, and rate of pump erosion from particulates. MCB equipment design and selection thus need to address conflicting criteria.

Equipment Design

Historically, MCB exchangers have been designed for all-parallel exchanger configurations with tube-side velocities of 4 - 8 ft/sec (1.2 - 2.4 m/sec) that generate pressure drops of 25 psi (1.7 bar) or less. Therefore, many refiners have MCB pumps that will operate at 1200-1400 rpm, generating less than 150 feet (45 meters) differential head. In many instances, this causes rapid tube- and shell-side fouling. Good design practice will specify series heat exchangers operating at 9-12 ft/sec (2.7 – 4.0 m/sec) tube velocity. This greatly reduces (and in some cases has eliminated) tube- and shell-side fouling. But whether the exchangers operate in series or in parallel, the MCB pump must fulfill its head-flow performance requirements while pumping erosive fluid throughout the duration of the run. Degradation of pump performance will increase the rate of exchanger fouling and limit MCB heat removal. To minimize pump erosion from catalyst and coke particles, an API fully lined pump is often required when operating with higher pump head and operating speeds in the MCB circuit.

Exchanger Fouling

Tube-side exchanger fouling is caused by coke and catalyst deposition inside the tubes, coke plugging the openings in the tube sheet, or by deposition of varnish-like material inside the tubes (Photo 1). Varnish-like material is formed in the bottom of the main column from thermal decomposition of polynuclear aromatics. In some instances, high MCB pool temperature causes coke to accumulate in the bottom of the main column.

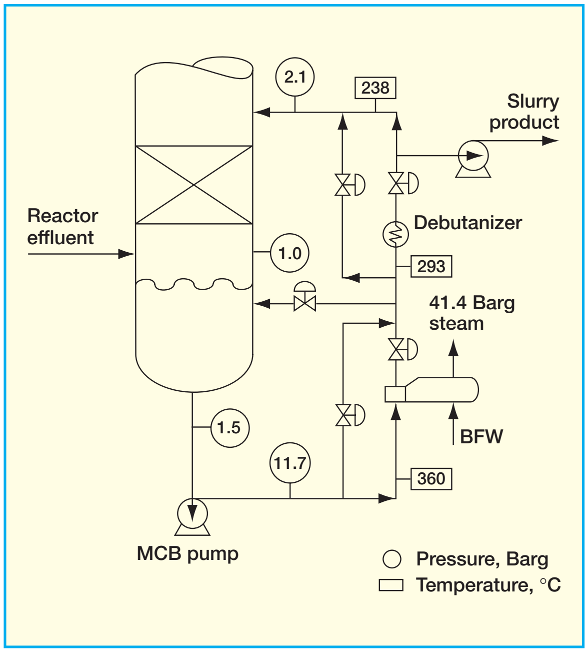

Figure 3. MCB Series Heat Exchanger Configuration

Both localized MCB liquid pool operating temperature and residence time contribute to fouling, the former being the main factor. Because most refiners measure bottom temperature in the suction line to the MCB pump, they incorrectly assume that it reflects MCB liquid pool temperature. This is only true if the quench is uniformly distributed across the column cross-sectional area.

Typically, the unquenched liquid leaving the column internals and the quench are not thoroughly mixed, causing localized MCB pool temperatures equal to the unquenched stream leaving the column internals (Figure 4). Quench must be evenly distributed to suppress formation of the fouling material. Because main fractionators are 12-28 feet (3.6-8.5 meters) in diameter, an improper design will not ensure that the quench is distributed across the column cross-sectional area. Localized bottom temperature can thus be as high as the unquenched temperature of 750°F (400°C), resulting in rapid exchanger fouling and coke accumulation in the bottom of the main column.

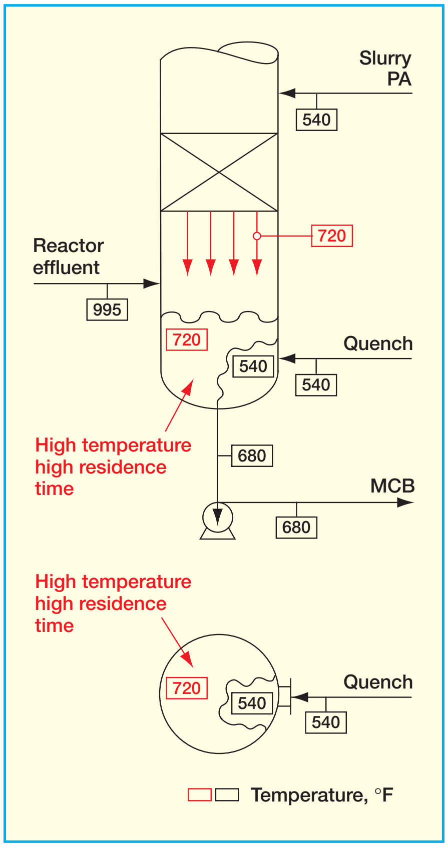

Figure 4. Poor Quench Distribution

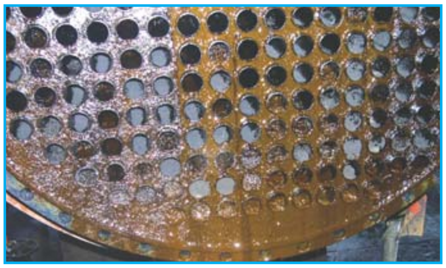

Photo 1. Exchanger Fouling

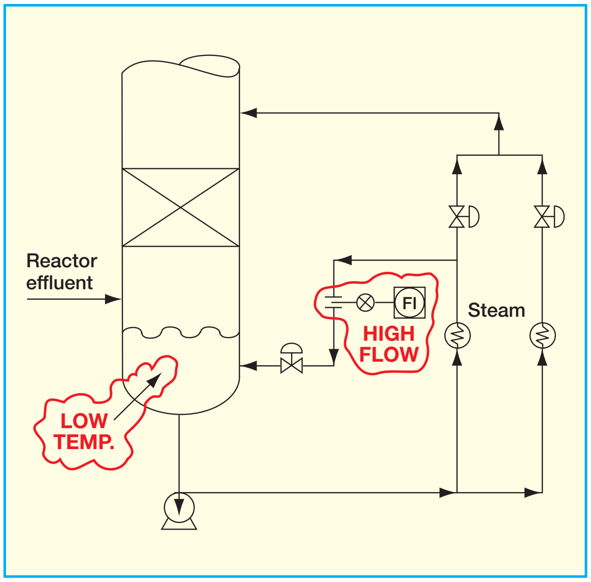

Figure 5. Start-of-run Operation, Constant Exchanger Velocity

Tube-side fouling from coke, catalyst fines, and varnish-like material increases not only as temperature increases and velocity drops, but also as API gravity decreases. Low velocity increases the fouling rate because solid particles more easily drop out of the stream. The fouling layer is resistant to heat transfer, thus lowering heat transfer coefficient and impairing heat removal. Because the MCB heat removal can account for 30-40% of total main column heat removal, MCB duty limits can reduce unit feed rate, reactor temperature, and conversion.

Equation 1

$$\frac{1}{U_c} = \frac{1}{h_i} + \frac{1}{h_i} + \frac{L_m}{k_m}$$

Where: h_i = inside film coefficient
h_o = outside film coefficient
L_m = tube thickness
k_m = tube thermal conductivity

Dirty heat transfer coefficient (U_D) is calculated by the following equation 2:

Equation 2

$$\frac{1}{U_D} = \frac{1}{U_C} + R_F$$

Where: U_D = heat transfer coefficient, dirty
U_C = heat transfer coefficient, clean
R_F = overall fouling factor

For a clean heat exchanger, the heat transfer coefficient is determined by the inside and outside film coefficients and the thermal conductivity of the tubes. For example, when the MCB steam generators are clean and operating at 6 ft/sec (1.8 m/sec) the service U-value will be 150 btu/hr-ft2-°F (733 kcal/hr-m^2-°C). When operating at 12 ft/sec (3.7 m/sec) the heat transfer coefficient is 220 btu/hr-ft^2-°F (1075 kcal/hr-m^2-°C). As fouling increases, the layer on the inside of the tubes progressively increases the resistance to heat transfer. For a fouled MCB exchanger, the fouling resistance is between 50-85 percent of the total resistance to heat transfer.

For a clean heat exchanger the thermal conductivity of the tube is typically small compared to the film coefficients. The clean heat transfer coefficient (Uc) is calculated by Equation 1.

A heavily fouled (Equation 2) steam generator U-value is 75 btu/hr-ft^2-°F (366 kcal/hr-m^2-°C), while for a clean one it is 150-220 btu/hr-ft^2-°F (733-1075 kcal/hr-m^2-°C).

Most tube-side fouling in the MCB exchangers typically occurs during the first few weeks of service and is usually due to using MCB temperature as the control parameter. Even if quench distribution is good, maintaining constant MCB temperature at start-of-run is flawed because it results in very low exchanger velocity when the tubes are clean and heat transfer is high. As fouling increases, pressure drop increases because the inside diameter of the tube gets smaller because of the fouling layer build-up. This slows the rate of fouling, even though fouling continues to increase. Velocity continues to increase until a terminal value of 9-12 ft/sec (2.7–4.0 m/sec) is reached, but by this time the exchanger is badly fouled and duty is degraded.

Rather than using temperature as the control parameter, the system should be designed to have the exchangers operate at constant velocity. At start-of-run the quench flow rate should be increased (Figure 5). By lowering MCB pool temperature, exchanger inlet temperatures are reduced. Required flow rates to meet the duty requirement are therefore higher. Because heat transfer coefficients are high when exchangers are clean, the exchanger log mean temperature difference (LMTD) must be kept low. This will dramatically reduce fouling and increase length of run. Some exchanger fouling will still inevitably occur but MCB temperature can be increased by reducing quench flow rate so heat removal can be met.

Plant performance data show that when an MCB steam generator operates at 13 ft/sec (4.0 m/sec) the tube-side fouling factor is reduced to virtually zero. However, high velocity generates approximately 65 psi (4.5 bar) pressure drop. Thus, MCB pumps must be able to generate approximately 290 feet (88 meters) of differential head when the system is designed with all-parallel exchangers operating at terminal velocity and 450 feet (137 meters) or more when series exchangers are specified. This requires an API fully lined slurry pump to ensure a high degree of reliability.

Parallel and Series Debutanizer Reboiler

When MCB is used as heat for the debutanizer reboiler, it can be supplied hot at 680-700°F (360-370°C) either directly from the MCB pumps or downstream of the steam generators or FCC feed exchangers. Series design has the advantage of lowering the MCB temperature to 550 - 600°F (288-315°C). Debutanized gasoline contains C_5^+ di-olefins that can polymerize to form coke when the shell-side tube wall temperature is high enough. But series exchangers require higher head pumps if tube velocity is maintained at 10 ft/sec (3.3 m/sec) or more. In one instance, the process design was changed from parallel to series to lower the tube wall temperature. Changes included:

- Tube-side passes were decreased from 8 to 4 on upstream steam generators
- Tube-side passes were reduced from 4 to 2 on the downstream reboiler
- MCB flow control valve sizes were increased
- MCB pump impeller size was increased and speed raised from 1800 to 2300 rpm

The result was rapid pump erosion, shortening of exchanger cleaning cycles from 18 months to 3 months, and reduced duty on all exchangers. Decreasing the number of tube passes is therefore not a reliable revamp strategy for this service. Higher head pumps are needed to operate exchangers in series, yet before increasing speed of a standard API 610 pump, this step must be evaluated thoroughly.

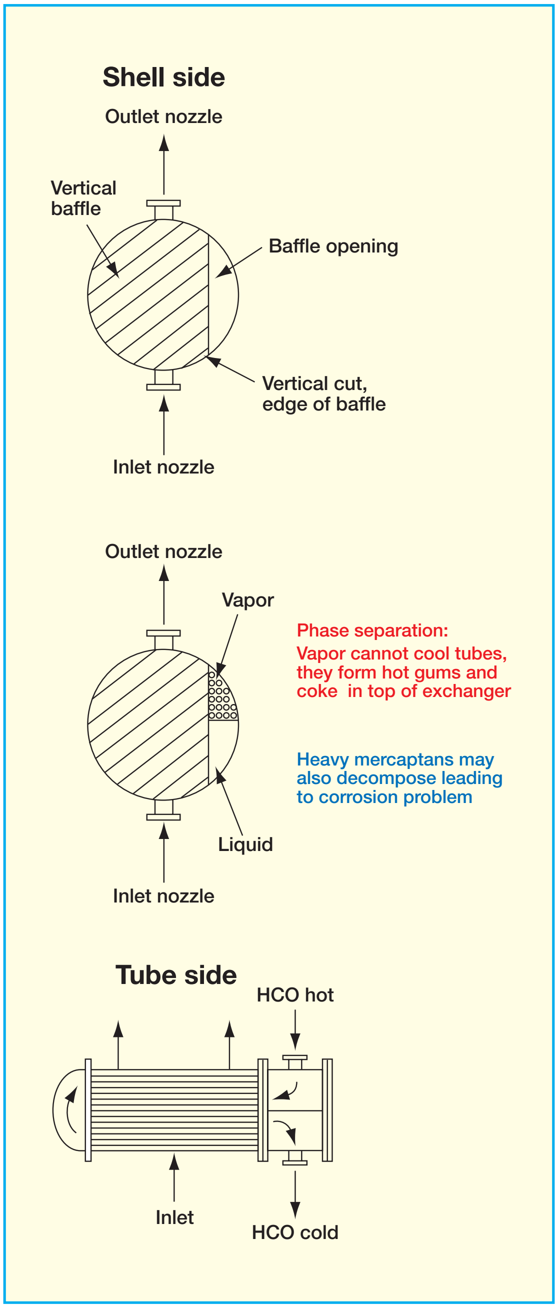

Figure 6. Phase Separation and Fouling

Debutanizer Reboiler Shell-side Fouling

FCC Debutanizer reboiler shell-side fouling is becoming more common. Existing exchanger designs that have operated without major problems are now causing unscheduled shutdowns. Severe shell-side fouling is characterized by dramatically lower heat transfer coefficient that results in very poor fractionation in the debutanizer. If the exchanger is not taken out of service to clean the shell-side, the fouling material eventually turns into hard coke that can deform the exchanger bundle and shell. Once this occurs, the tube bundle is difficult or impossible to remove from the shell and the entire exchanger must be replaced. The coke forms from iron-catalyzed polymerization of C_5 and heavier diolefins. Reactor feedstock quality, reactor temperature and reactor hardware can influence the amount of diolefins. These concentrate in the FCC gasoline. Concentration and tube wall temperature control the severity of fouling. Shell-side tube wall temperatures are set by the heating medium temperature and reboiler design. Common sources of heat are the MCB or heavy cycle oil (HCO). When the heat source is at 600°F (315°C) or higher it can cause high shell-side tube wall temperature and heavy fouling.

Often, refiners assume that fouling is mainly on the tube-side because both MCB and HCO streams have a high fouling tendency. If, during shutdowns the tubes are cleaned in place, but the shell-side is not, when the exchanger is returned to service, heat transfer coefficients are still low and debutanizer performance suffers. Typically J-type shell reboiler system using main fractionator HCO and/or MCB streams for heat will be 560 - 700°F (293-370°C) depending on the process flow scheme, column heat balance, and operating philosophy. As MCB streams contain catalyst fines, coke, and a high concentration of asphaltenes that can contribute to low heat transfer, it is natural to assume tube-side fouling is the major cause of poor reboiler performance.

Localized High Tube Wall Temperature

When shell-side fouling occurs, it is important to inspect the tube bundle to determine the exact location of the fouling. It often tends to be localized. One part of the bundle may be severely fouled but the rest of the bundle may be relatively clean. When this is the case, rigorous heat exchanger modeling with a program such as Heat Transfer Research Institute's (HTRI™) IST model can help pinpoint areas of localized high tube wall temperature.

In a J-type thermosyphon reboiler the shell-side feed enters the bottom in the middle of the shell and flows toward outlets at both ends, not from one end to other as with an E-type shell. The J-type shell is favored because it generates low shell-side pressure drop. This comes at a cost, however. Low pressure drop means low mass velocity, and low mass velocity removes less heat from the outer tube wall. It is common practice for the tube-side to be in countercurrent flow. Hot heating medium enters the top of the exchanger and cold tube fluid leaves the bottom. Therefore, the highest outer tube wall (shell-side of the exchanger) temperature should occur where the hot fluid enters. Sometimes, though, this is not the case.

Often, J-type thermosiphon reboilers have vertically-cut baffles. If vapor/liquid phase separation occurs in the baffle window, vapor flows through the top of the bundle and liquid through the bottom (Figure 6). Due to low mass flow in the upper part and to the fact that heat transfer coefficients are low for superheated vapor, high localized temperature develops at the top. Coke will form rapidly. Additionally, tubes in the top part of the bundle will expand more than those at the bottoms, causing bowing and damage to the tubes and shell. Eliminating phase separation by using horizontal baffles and spacing them so that the dead zones are minimized will reduce outer tube wall temperature. Yet, this increases pressure drop and decreases circulation, so that a complete hydraulic evaluation must be carried out to make sure that no other problems are created.

MCB Pumps

MCB pumps play a critical role in ensuring the reliability of the MCB system. Since high exchanger tube velocity generates a higher exchanger pressure drop, the impeller diameter or the pump speed must be increased to compensate for the increased head requirements. As pump head and speed increase, pump life is reduced unless other design parameters are adjusted. A report done by the U.S. Government Department of Energy in 1987 on centrifugal slurry pump wear shows that pump life can be related to several design variables. This pump life equation is shown in equation 3.

Equation 3

$$\text{LIFE} = \frac{k_g P V_f}{\left\{ \rho_f \left[\frac{\rho_s}{\rho_f} - 1 \right]^2 C_V G H S^2 D_P^2 \right\}}$$

Where: k_g = a geometry constant
P = pump material hardness
V_f = carrier fluid viscosity
ρ_f = carrier fluid density
ρ_S = particle density
C_V = concentration of particles
G = gravitational constant
H = head generated by the pump
S = speed
D_p = particle size

Once the impeller diameter and speed to meet the system head requirements are determined, pump geometry and material hardness are the only factors that can be adjusted to improve pump life.

Standard API 610 Process Pumps

Reliability of the Standard API 610 process pumps handling MCB bottoms has always been a problem due to their susceptibility to internal erosive wear (Photo 2).

Photo 2. Erosion of Standard API 610 Pump

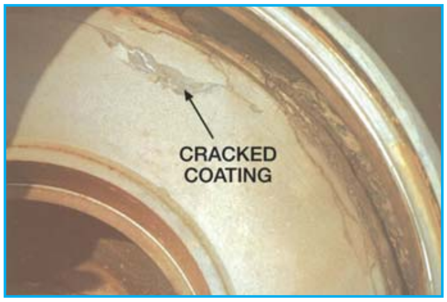

Photo 3. Coating Failure on Suction Disc

In the extreme cases, erosion caused by coke and catalyst particles can erode the pressure-containing casing itself. API pump manufacturers and refiners have had only limited success in trying to improve the wear resistances of the ductile pressure-containing casings through the use of thermal spray coatings, diffusion alloy coatings, weld overlays, and hard metal wear plates. At high temperatures thermal spray coating have a tendency to crack and chip off as shown in Photo 3, leaving substrate material open to corrosion and abrasive attack.

Diffusion alloy coating provides an erosion-resistant intermetallic surface alloy with excellent bond strength that will not flake off. However, this coating has limited wear resistance because the coating thickness is only 4 to 10 mils. Weld overlays provide a significantly thicker coating but they must be ground smooth to obtain maximum life.

If re-machining is needed to remove the distortion that happens to the base material during welding and subsequent heat treatment, costs will approach that of a new component. Hard metal wear plates are sometimes used to form a Partially Lined Slurry (PLS) Pump. The 25 % chrome iron liners protecting the casing walls work well. However, the coated pressure containing volute section of the casing can be eroded away as shown in Photo 4.

Photo 4. Casing Failure

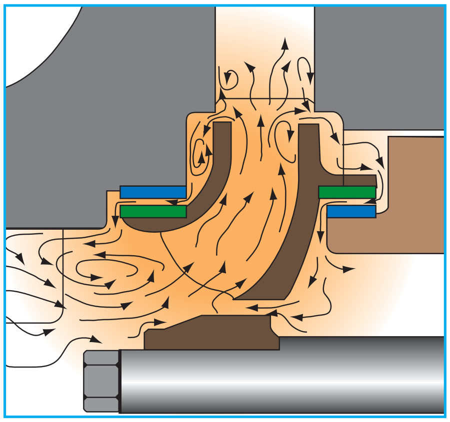

Figure 7. Tight Clearance Wear Rings

API Fully Lined Slurry Pump

Fully Lined API 610 pumps have been used successfully in MCB service. These pumps incorporate the same design features of an API process pump:

- 300 # Raised Faced flanges
- Confined Gaskets
- Vent & Drains
- Cartridge Seals
- Enclosed Impellers
- Heavy Duty Shafts
- Bearing life in excess of 25,000 hrs

The API fully lined pump design allows the wear resistant 25 % chrome iron liner material to be used in the high velocity areas to resist the erosive attack of the catalyst and coke particles. The liners offer 4-6 times the wear life of a coated part. They can be re-machined to remove worn surfaces, replaced if worn out or upgraded for additional life. The softer ductile pressure-containing casing material is fully protected from the high velocity slurry.

Standard API process pump geometry includes an enclosed impeller with tight clearance wear rings as shown in Figure 7.

A large clearance area exists between the sealing ring and impeller periphery where recirculation takes place. Catalyst and coke particulates in the fluid stream are caught in the eddy currents and vortices, causing very intensive wear to the casing wall in this region. Once wear occurs, recirculation accelerates and a perforated casing on the suction-side may result. The combination of grinding and vortex action in the close-fitting axial wear rings will open the clearances, causing excessive leakage. This uncontrolled leakage back to

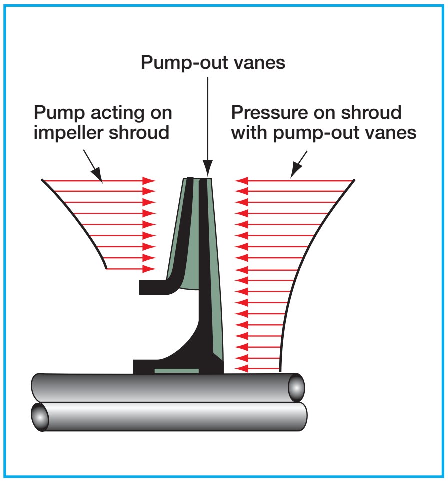

Figure 8. Slurry Impeller with Pump Out Vanes

Courtesy of Lawrence Pumps, Inc.

Photo 5. Fully Lined API Pump

the pump suction reduces the pump head-flow characteristics.

This situation can be eased by the use of pumping or expeller vanes on the external surfaces of the impeller shrouds, as shown in Figure 8. The repelling vanes create a pumping gradient with lower pressure towards the center. The pump-out vanes work to slow down the swirl component of the leaking inflow, to control secondary flows, and to reduce the leakage itself. Reduced leakage means longer life for the front radial sealing ring. The combination of repelling vanes and a front radial seal ring allows the front clearances of the impeller to increase due to wear without having a significant impact on pump performance. Impeller clearance adjustment to take up for wear can be made with the pump at full operating temperature simply by changing the shim thickness between the thrust bearing housing and bearing frame.

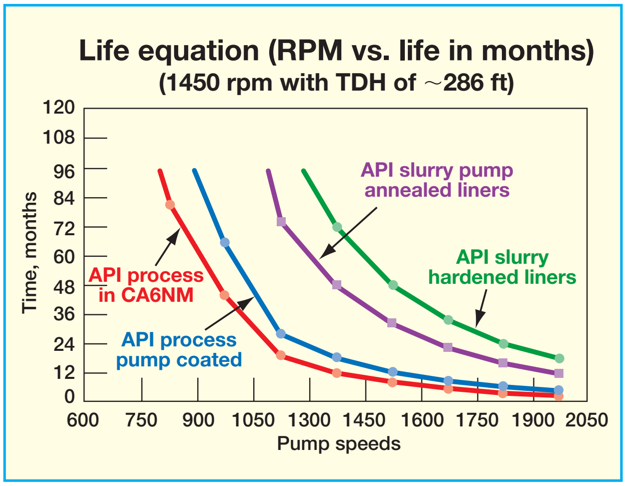

Figure 9. Pump Operating Life

Examination of Equation 3 will clarify why API fully lined slurry pumps offer improved operating reliability. Speed plays a critical part in determining pump life, as wear increases with the square of the speed. To develop the same total dynamic head, larger diameter impellers allow pumps to run at lower speeds. The chart on Figure 9 shows that for a pump speed of 1450 rpm and a total dynamic head of 286 feet, the operating life of a standard API process pump will be approximately 12 months. There is an exponential increase in wear as the speed increases. An API fully-lined slurry pump with 350 BHN liners running at the same conditions, however, will provide an operating life of 4 years.

If the liners and impeller are hardened, pump operating life will increase to 6 years, therefore, a fully-lined API 610 slurry pump in MCB service can be operated continuously between schedule unit shutdowns.

Summary

Lost production between real and target service factor can be the difference between profit and loss especially during low margin periods. To attain- and maintain targeted service factor in an FCC's Product Recovery Section operating for 4-6 years, MCB system reliability is critical. Important considerations are quench system design, high exchanger velocity from start-of-run, exchangers in series when MCB is used for debutanizer heat, and the use of API fully-lined pumps to maintain their flow-head characteristics throughout the duration of the run (Photo 5).

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