Specifications – importance of getting them right

Faulty equipment specifications sometimes carry unforeseen penalties, with loss of performance. But do not blame the original equipment manufacturer, say the authors – it is the process design engineer's responsibility to meet the objectives

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When process equipment does not meet the refiner's expectations, millions of dollars of profits can be lost due to lower feed rate, less than optimum product recovery, or unscheduled shutdowns. Original equipment manufacturers (OEM) are often targeted when this occurs.

Yet all process equipment has limitations that are based on fundamental design and operating principles, which should not be violated if the equipment is to work reliably.

In some cases, the equipment selected does not suit the purpose and in others the equipment specifications result in unintended consequences that were not apparent to the designer.

It is the process design engineer's responsibility, not the OEM's, to ensure the equipment selection and specifications meet the processing objectives. Furthermore, because equipment is often installed in severe services such as the FCC main column bottoms system where the fluid temperatures are as high as 700°F, available net positive suction head (NPSH) is often low, flow variability from start-of-run (SOR) to end-of-run (EOR) can be large, and the fluid contains catalyst fines and chunks of coke. Thus, even the best-designed equipment can be severely stressed.

Where possible, cost effective process flow scheme changes should be adopted to allow the equipment to operate within inherent limits, rather than simply placing blame on the OEM for poor process unit performance.

Three case studies review some common examples where equipment specification and selection reduced unit profits.

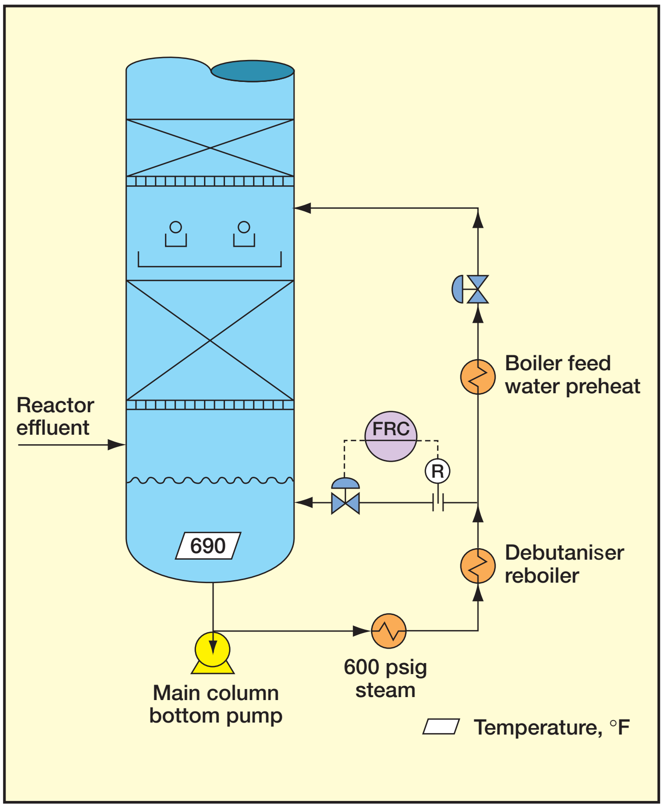

Figure 1 Main column bottoms system

Case study 1

Low NPSH pumps

An FCC main column bottoms (MCB) pump was recently specified with an NPSH available of 8ft. Thus, a low NPSH-required pump was selected and installed. When equipment reliability was poor, the contractor and operator blamed the OEM. Yet the root cause was the design engineer's ultra-conservative specification of the NPSH available.

If the NPSH available is low, the pump selected will always result in reduced turndown. Thus, when the refiner operated the pump over the range of flow rates required to operate the unit, the flow rates occasionally fell below the minimum. This below minimum flow rate damaged the pump due to low-flow induced cavitation.

Initially, the design engineer needs to appreciate the penalty for being ultra-conservative when calculating NPSH available. It forces the refiner to accept a pump with little operating flexibility. The selected pump will have a large impeller eye opening to reduce fluid pressure loss. Yet, this decreases the stable operating range for the pump.

As pump impeller eye diameter increases with decreasing NPSH available, the pumped fluid has a tendency to re-circulate at the entrance to the impeller. Fluid circulation in the impeller eye causes vortices that result in fluid cavitation. Operating the pump below minimum flow leads to seal and bearing failures, casing erosion, impeller erosion, and other unwanted problems such as extreme suction line vibration.

While pump NPSH required is a familiar term to most refinery process engineers, the affect of NPSH required on the impeller design and pump performance is not commonly known. Today, most pump suppliers report suction specific speed (N_{ss}) somewhere on the performance curves. As pump NPSH required decreases, the N_{ss} increases, and the pump stable operating range decreases.

A pump having an N_{ss} of 18 000 may turndown to only 85% of best efficiency point (BEP) before it begins to cavitate due to re-circulation in the pump impeller eye. In high-energy high head pumps, pump damage can occur rapidly and maintenance cost can be very high.

Although selecting high N_{ss} pumps and the resultant narrow operating range is known to rotating equipment engineers, process designers need to understand the penalty associated with specifying an ultra-conservative NPSH available. In some instances, low NPSH pumps must be selected, but in those cases where it is absolutely necessary, design engineers need to ensure the process flow scheme will give operating personnel the flexibility to maintain the pump flow within a narrow range without adversely affecting the FCC unit operation.

MCB system review

New pumps are frequently installed during revamps where they must fit into an existing process system and operate properly within constraints. Therefore, the designer does not have a "clean sheet" of paper and must find cost effective solutions working with the existing equipment. When trying to install new pumps, plot space will determine location rather than ideals, such as minimum suction piping run.

Figure 1 (previous page) shows a typical FCC main column bottoms (MCB) system. Reactor effluent enters the column at temperatures of 980–1015°F where the MCB system must remove up to 35% of the heat so the reactor products can be fractionated. Fluid mixed with catalyst and coke fines is withdrawn from the bottom of the main column and pumped through heat exchangers, then back to the column as sub-cooled pumparound return (PAR) and quench.

PAR liquid flows down the column through internals such as shed trays or grid where heat is transferred from reactor effluent to the PAR liquid. To prevent coke formation, most refiners maintain a constant temperature in the bottom of the main column by varying quench flow rate. However, MCB circulation rate depends on the system design, and the operating philosophy can cause large flow variability from start-of-run (SOR) to end-of-run (EOR).

Prior to making detail pump hydraulic calculations, the process engineer determines the total (PAR plus quench) heat removal requirements from the design basis heat and material balance around the column. Next, MCB circulating rate is calculated based on the exchanger configuration and the exchangers' tendency to foul. But this is simply the pump design point, which ideally matches the real operation. Yet the system design needs the flexibility to meet realistic process variability. Moreover, operating philosophy influences SOR and EOR conditions, which determine maximum and minimum flow.

If main column bottoms temperature is held constant from SOR to EOR, then flow rate will be low at SOR when exchangers are clean and increase as the exchangers foul. The rate of exchanger fouling depends on velocity through the exchanger tubes and fluid temperature throughout the main column bottoms pool.

Pump fundamentals

The selected pump requires a certain amount of net positive suction head required (NPSHR) to operate properly and the NPSH available (NPSHA) needs to be higher than NPSHR for stable and reliable pump performance throughout the run. NPSHA is the amount of head available at the pump suction above the fluid vapour pressure. Liquid level, suction piping pressure loss, and fluid vapour pressure determine the NPSHA.

When the designer specifies the NPSHA, this value plays a critical role in the pump selection and it determines stable operating range for the MCB pump.

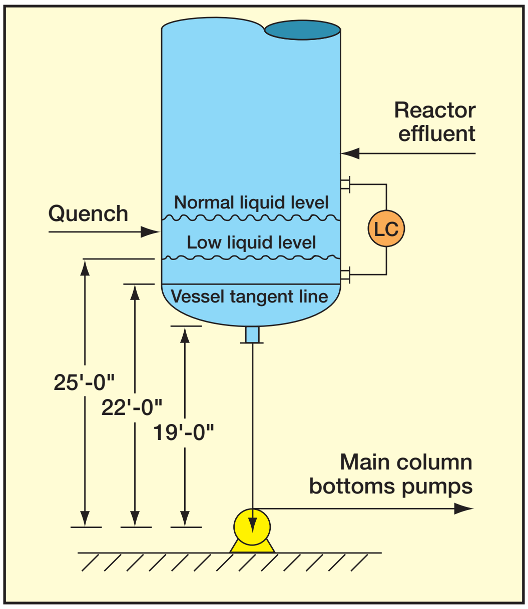

Figure 2 *MCB pump level*

Pump impeller eye design is characterised by the dimensionless variable N_{ss} shown in the equation:

$$N_{ss} = (Q^{0.5} X N)/NPSHR^{.75}$$

N_{ss} = Suction specific speed, dimensionless

Q_{bep} = Flow at the best efficiency point (BEP), GPM

NPSHR = Net positive suction head required at BEP

N = Pump speed, rpm

Because NPSHR is in the denominator, as its value decreases, suction specific speed increases. Consequently, pump stable flow range also decreases. When constant MCB temperature is the operating objective, MCB flow rate can easily be less than 60% of design flow rate at SOR when MCB exchangers are clean. Nevertheless, a pump selected to operate with only 8ft of NPSHA will not turndown to 60% of BEP.

NPSH available

NPSHA is based on the pump system configuration and the fluid flow rate and properties. Liquid level above pump centreline, fluid vapour pressure, and system pressure drop all influence NPSH

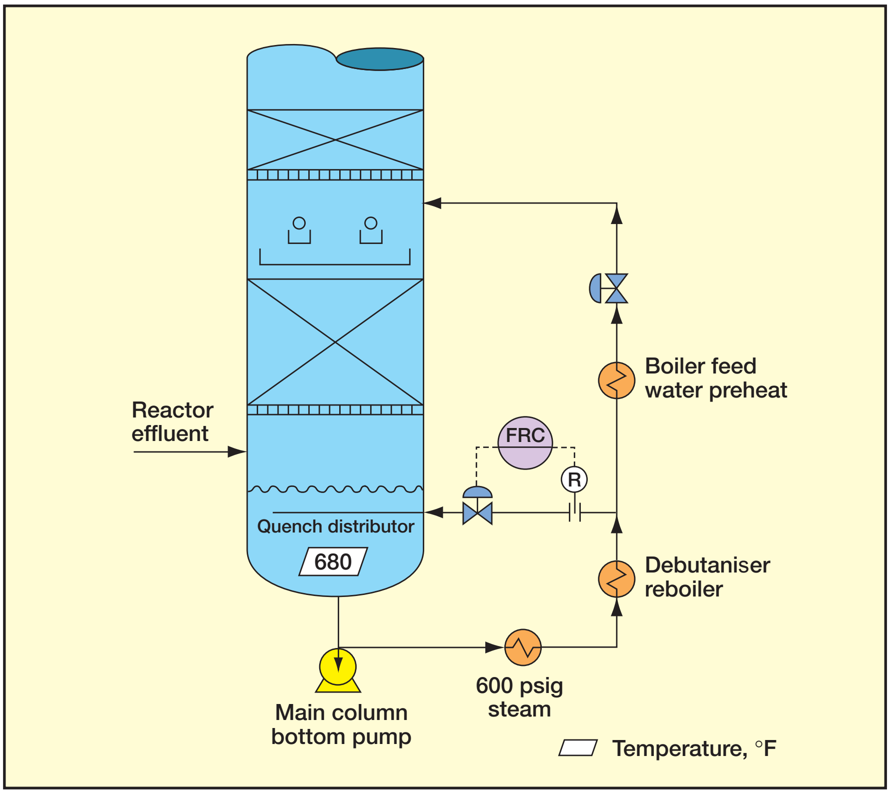

Figure 3 *MCB quench system*

available. Once the plot space for the pump is selected and pipe routing set by pipe stress considerations, system pressure drop cannot be materially lowered by the designer.

First, the designer needs to define minimum acceptable liquid level. Is it the bottom of the head, vessel tangent line, or low liquid level? Figure 2 illustrates how there can be a 6ft difference between the most conservative method, which uses the bottom of the head, and least that uses the low liquid level. This is the difference of between 8ft and 14ft NPSHA, and more importantly, allows the refiner to select a pump that turns down to 65–70% BEP flow rate rather than one that turns down to only 80–85% of BEP flow.

Furthermore, fluid vapour pressure can be reduced by 5ft for every 10ºF reduction in the main column bottoms pool liquid temperature. Reducing pool temperature from the 690ºF to 680ºF increases NPSHA from 14ft to 19ft (Figure 3).

Operating philosophy

Rather than maintain constant MCB temperature, the exchanger velocity should be controlled by allowing the temperature in the bottom of the main column to vary from SOR to EOR by manipulating quench flow rate. As the exchangers foul, the PAR rate increases and the quench flow decreases so that exchanger velocity is maintained. By using this approach, exchanger fouling is reduced, MCB pump erosion decreases, and the rate of coke formation in the bottom of the main column goes down.

MCB exchanger tube velocity should be maintained between 10–13ft/sec to minimise fouling. When the MCB system is operated to maximise exchanger velocity at SOR, NPSHA is very high because the main column temperature is low resulting in low fluid vapour pressure. Lowering MCB temperature has many benefits.

MCB pump specification

MCB pump reliability is an essential part of FCC unit profitability. Before selecting a MCB pump the process engineer should look for opportunities to improve MCB system performance. Selecting a pump that operates as close as possible to the BEP flow minimises pump erosion and maximises operating flexibility. Furthermore, MCB pump specifications should not use an ultra-conservative NPSH available.

Process designs that permit higher quench flow rates at SOR minimise pump flow variation and maximise exchanger velocity. Operating philosophy should be changed from constant main column bottoms temperature to constant MCB circulation rate by varying quench flow from SOR to EOR. Furthermore, lowering bottoms temperature reduces fluid vapour pressure and increases NPSHA without significant changes in pump flow rate or exchanger performance. Thus, a more reliable, lower N_{ss} pump can be selected with better turndown.

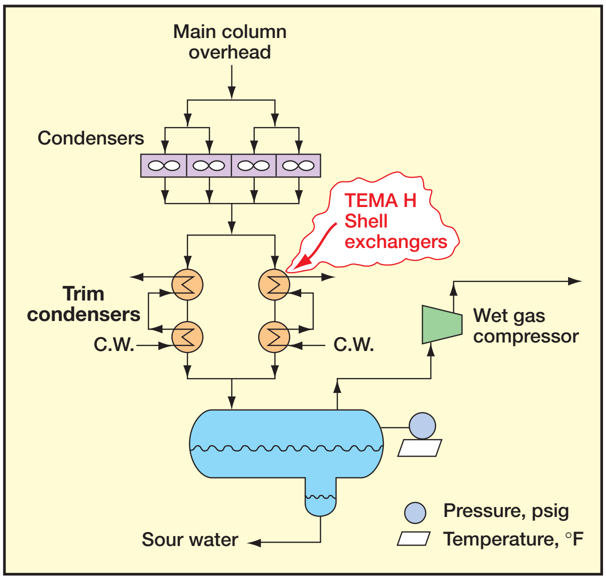

Figure 4 *FCC main column condenser system*

Case study 2
Overhead trim condensers

During a revamp, a Tube Exchanger Manufacturers Association (TEMA) H-shell was selected to reduce pressure drop through the trim condensers of an FCC main column overhead system. Figure 4 shows a typical overhead system with fin-fan condensers followed by shell and tube exchangers that use cooling water. One of the biggest challenges on the FCC is to maximise performance of the existing wet gas compressor, therefore the designer selected an H-shell because it generates very low-pressure drop.

Reducing system pressure drop from the reactor overhead to the compressor inlet raises suction pressure and generally lowers wet gas make. Spare compressor capacity is then used to increase FCC feed rate or raise reactor temperature to increase conversion. In this case, the refiner replaced the trim condensers to reduce pressure drop from 4psi to less than 1psi. After startup, the exchangers met the design pressure drop and the wet gas compressor suction pressure increased by 3psi, but wet gas production was 10% higher than expected.

Prior to the modifications, the overhead receiver operated at a pressure and temperature of 4psig (18.7psia) and 105°F, respectively. Raising overhead receiver pressure by 3.0psi should have reduced wet gas production by 25% if the 105°F temperature had been maintained. Yet even though more surface area was added to the trim condensers, the receiver temperature actually increased from 105°F to 117°F. Evaluation showed the service heat transfer coefficient was only 22Btu/hr-ft^2-°F (108 kcal/hr-m^2-°C). Therefore, overhead temperature increased and the wet gas rate was higher than expected.

FCC trim condensers

Commonly TEMA J-shell exchangers are used in this service to achieve the best balance of pressure drop and heat transfer coefficient. Less frequently, TEMA E- and H-shells have been installed. TEMA E-shell exchangers have the highest heat transfer coefficients, but they also generate very high-pressure drop. Conversely, while H-shell exchangers can be designed for very low-pressure drop by eliminating the baffles, they also achieve very low heat transfer coefficients. Balancing pressure drop and the resultant heat transfer coefficient is essential when optimising main column overhead exchanger design because both receiver pressure and temperature impact wet gas production.

After the revamp, evaluations showed the calculated heat transfer coefficient was only 22Btu/hr-ft^2-°F. Therefore, receiver temperature increased by 12ºF.

Figure 5 shows the fluid flow path through an H-shell exchanger with no vertical baffles other than the support baffles. Process fluid flows through two inlet nozzles around the horizontal baffles to the two outlet nozzles. Because there is very little resistance to flow and the path is relatively smooth, there is very little pressure drop. However, because the shell-side heat-transfer coefficient is also very low due the lack of turbulence, the exchanger overall heat transfer coefficient is very low.

Trim condenser specifications

The exchanger designer needs to strike a balance between pressure drop and heat transfer coefficient. While the new exchanger generated only 0.6psi pressure drop, the heat transfer coefficient was only 22Btu/hr-ft^2-°F. Higher-pressure drop will increase the heat transfer coefficient, but the resulting exchanger outlet temperature must result in lower wet gas rate. Otherwise, higher pressure drop has no benefit.

Overhead receiver temperature and pressure set gas flow rate to the wet gas

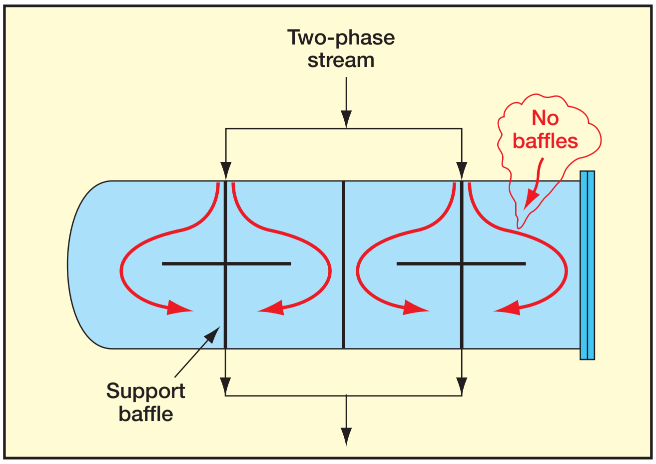

Figure 5 *H-shell exchanger (no baffles)*

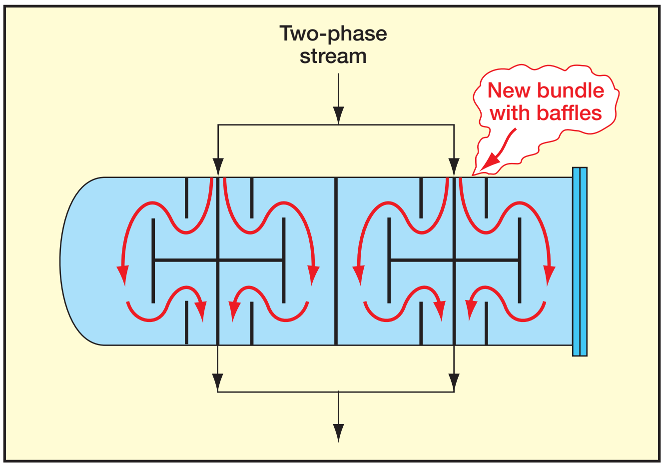

Figure 6 *H-shell exchanger (with baffles)*

compressor. A good rule of thumb is that for every 1.4psi increase in receiver pressure the wet gas rate should decrease by 10% when receiver pressure is low in psig. And for every 10ºF reduction in temperature the wet gas production will drop by approximately 10%.

Ideally, TEMA J-shells should be used in this service, because it is easier to balance pressure drop and heat transfer coefficient. However, once the H-shell was installed, a more practical alternative was to design a new exchanger bundle. An exchanger programme such as Heat Transfer Research Institutes (HTRI) IST should be used for detailed exchanger thermal design because accurate pressure loss and heat transfer coefficients are needed to find the optimum design.

By modifying the bundle and designing it with a double segmental baffle, it was possible to raise the heat transfer coefficient from 22 to 50Btu/hr-ft^2-°F (245 kcal/hr-m^2-°C) while increasing the pressure drop from 0.6 to 1.0psi (Figure 6).

Overhead receiver temperature dropped from 117ºF to 103ºF, which lowered wet gas production by about 7%.

Case study 3

Heavy oil service

Shed trays are used in several heavy oil services including delayed and fluid coker fractionators, FCC main column, visbreaker fractionator, shale oil vapour scrubber, and others. These trays have high vapour and liquid capacity and are fouling resistant when liquid rates are high. But, to function properly, they need a high liquid flow rate to create a uniform curtain of liquid for the vapour to flow through. Also, initial liquid and vapour distribution needs to be uniform because sheds will not correct either.

In many instances, baffle trays are selected solely based on their perceived lower fouling tendency. Yet, in low liquid rate services such as the delayed coker, they chronically coke. Many refiners have removed them from service because they do not function properly. Yet, several delayed coker licensors continue to misapply the tray in the bottom of the coker fractionator.

A heavy oil vapour scrubber was designed to remove solids while sustaining a high on-stream factor without excessive plugging or coke formation due to high temperature. First, the solids and coke from the upstream processor must be scrubbed to remove particulates and cooled prior to fractionation. High temperature hydrocarbon vapours leave the upstream processor and enter the vapour scrubber at approximately 505°C where the vapour stream is cooled to approximately 275°C.

A small heavy bottoms stream is produced, and the solids are removed. Bottom product is recycled. Therefore, it should contain the minimum amount of hydrocarbon needed to control vapour scrubber bottoms temperature, and essentially all the particulate and coke particles. Vapour scrubber bottoms temperature is controlled by varying the flow of sub-cooled liquid from the fractionator bottom pumparound system to the spray header that distributes liquid to the wash section grid bed.

After initial startup, solids removal efficiency was low, overhead vapour feeding the downstream fractionator contained solids, the vapour scrubber internals plugged rapidly with solids and coke fines, and temperature control was difficult. The intent of the vapour scrubber design was for the bottoms circulating slurry pumparound (recycle) stream to scrub the majority of the coke fines, and then the wash section above it would provide for final clean up and heat removal (Figure 7).

In theory, the bottoms slurry recycle was to provide most of the solids removal. Yet, in practice, it was the wash section that did most of the clean-up. Reviewing fundamental shed tray design and operating principles help provide an understanding of the shortcomings of the initial vapour scrubber internals design.

Shed tray fundamentals

Shed (baffle) trays are used in fouling hydrocarbon services including FCC slurry pumparound, delayed coker wash, fluid coker scrubbers, visbreaker atmospheric column steam stripping, residue hydrocracker atmospheric steam stripping, tar sands steam stripping, ethylene quench towers and shale oil vapour scrubbers.

Although shed trays are designed to prevent fouling, they also are very inefficient and require high liquid flow rates to function properly. Because they are non-fouling at high liquid rates, they are often misapplied in low liquid rate services because fouling resistance is the main selection criteria. A common example is the delayed coker main fractionator wash or clean-up section

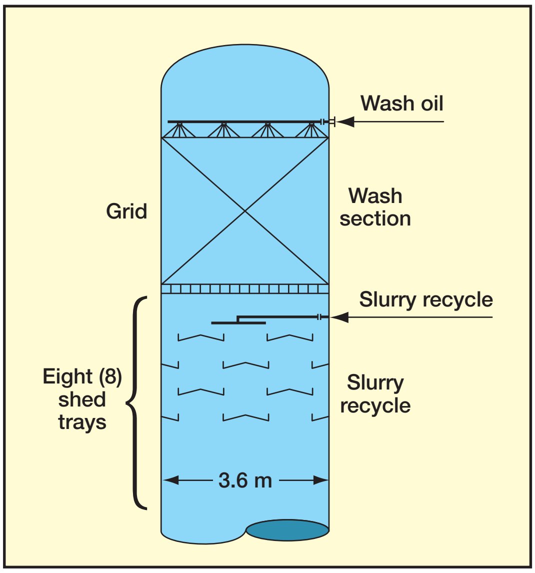

Figure 7 *Vapour scrubber column*

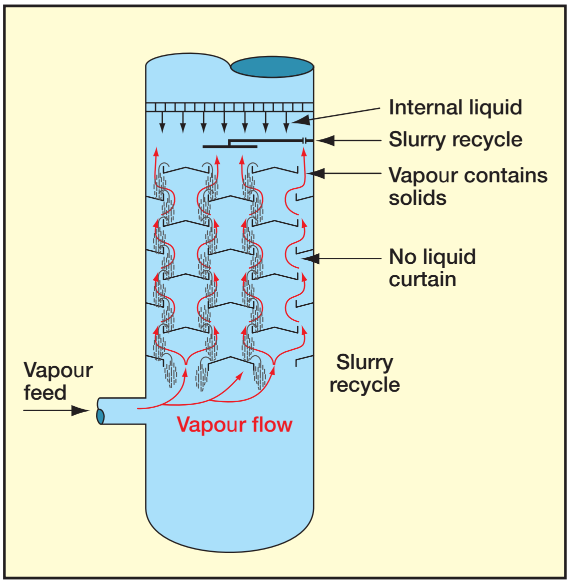

Figure 8 *Shed tray operation*

directly above the drum line vapour feed (Figure 8). While good fouling resistance needs to be the primary selection criterion, shed trays will not work at low liquid rate. The delayed coker wash section liquid rate is less than 5% of the rate needed for shed trays to operate properly.

Proper shed tray performance requires high liquid rate, good initial liquid distribution, and adequate levelness to create a sheet (or curtain) of liquid for the vapour to flow through . First and foremost, there must be sufficient liquid flow to create a curtain of liquid along the complete length of each edge of the shed tray. For example, a 5.8m diameter delayed coker main fractionator using an eight-pass tray would have approximately 30m of weir length (liquid curtain length). Thus, a coker unit operating at 600m^3/h feed rate and 5% recycle would have approximately 20m^3/h hot flow or 0.66m^3/h /m of weir.

The Francis weir equation shows that 22m^3/h/m of weir of liquid overflowing the tray will generate less than 13mm liquid height over the weir.

Thus, a tray that is 6mm out of level will flow a large portion over the low point of the edge of the tray. A tray operating at 0.66m^3/h/m of weir generates essentially no crest; hence it is impossible to create a curtain of liquid. Shed trays should not be used in delayed cokers or other low liquid rate services because they fundamentally cannot operate properly. Yet they continue to be misapplied in delayed coker service.

When delayed cokers were first used, shed trays were the correct solution because the vacuum bottom feed stream was routed to the top shed tray, thus they operated at extremely high liquid rates. This generated high flow rates over the edges of the shed creating a curtain of liquid. Today, coker feed goes directly into the bottom of the column.

Liquid distribution

Good initial liquid distribution is critical to create adequate vapour and liquid contacting, but is very difficult to accomplish in practice. The larger the column diameter the more challenging because there are three or more shed decks (six-passes or more) requiring equal amounts of liquid flow.

Ideally liquid flow to each shed deck should be based on percentage of total weir length of the individual shed deck. Furthermore, many towers have both liquid flowing from internals located directly above the top shed tray as well as external pumparound liquid to distribute to each shed.

In many instances, the external pumparound and internal liquids have large composition and temperature differences. Hence, when the internal liquid stream is more than 15–20% of the total flow, the two streams feeding the top shed deck need to be either mixed or the internal and pumparound streams must each be uniformly distributed to each of the shed passes. In practice, poor initial liquid or vapour distribution causes large radial temperature variations above the top shed tray. If external and internal liquids are not uniformly distributed or worse, if portions of the weir have no liquid flow, then there will be no contacting between the liquid and vapour.

The slurry pumparound (desuperheating) section of the FCC main fractionator has internal and external liquid streams that must be distributed. Most of these columns have at least six-pass shed trays and operate at high liquid rates. Often the wash section internal liquid flow rate is more than 20% of the total flow to the top shed tray. Thus, good distribution of both the external pumparound and internal streams is needed to ensure proper shed tray operation.

For example, a 7.3m column will have 10-pass shed trays having approximately 51m of weir length and 1000–2000m^3/hr of total liquid to distribute to the top shed tray. Thus, initial distribution is challenging because there are five shed decks and the internal and external stream must be split to each pass based on weir length. Furthermore, even at these high liquid flow rates, flow over the edge of each shed is only 20–40m^3/h/m of weir length. Thus the height of liquid flowing over the weir is only 13-20mm. Because the longest shed is 7.3m and there is a relatively low height of liquid over the weir, levelness is important because liquid will flow towards to the low points no matter how good the initial distribution. It is very difficult to level a shed tray to better than ±3mm in a large diameter column. Therefore, in practice, good shed tray operation is very difficult to accomplish.

Scrubber tower shed trays

The vapour scrubber has eight four-pass shed trays in the slurry recycle section. Total shed tray weir length is approximately 12.2m. Design liquid flow rate to the top shed tray consists of 12.2m^3/hr slurry recycle and approximately 10m^3/hr internal liquid flow from the wash section above the sheds. Thus the design basis liquid rate was only 1.8m^3/h/m of weir length. While many designers believe that installing V-notch weirs along the sheds allows them to operate at much lower liquid rate, in practice it does not work (Figure 9).

Revisiting fundamental performance of V-notches helps understanding why they are largely ineffective on shed trays. Although V-notches will reduce the effective weir length to approximately half of a straight weir as shown in Figure 9, liquid height in each notch is still very low due to the low liquid rate. Because flow through a V-notch varies with the 2.5 power of the height of liquid in the notch, any level variation will cause all the liquid to flow to the notches at the low point.

Scrubber wash section

The vapour scrubber wash section was designed to provide heat removal to cool the 505°C vapour feed from the upstream processor, scrub the remaining particulates and coke fines not removed in the slurry recycle section, and control the bottom temperature in the column. The wash section has a 2.6m bed height of grid and a spray-header type liquid distributor. Wash section heat removal is accomplished by contacting the cold liquid from the bottom of the fractionator column with hot vapour leaving the

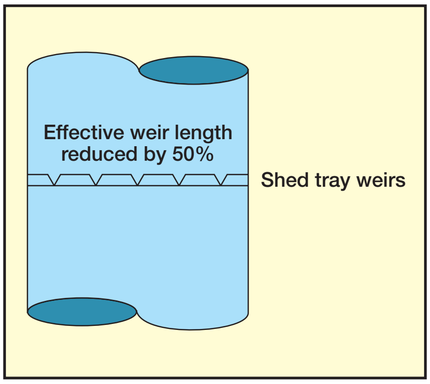

Figure 9 *Shed tray V-notch weir*

sheds. The original spray header design used seven 120° full cone spray nozzles located 480mm above the bed. Spray header design criteria vary. However, it is generally accepted that the area covered by the projected nozzle footprint from all the spray nozzles should sum to at least 150% of the column cross-sectional area to properly wet the complete column area. Furthermore, oil flow rate through the nozzles needs to be high enough to generate at least 0.35 bar pressure drop in order to develop the nominal spray angle. In this case, 120° nozzle angle was specified. Thus, if the distributor receives less flow than needed, it will not create the design footprint.

After the unit started up, the bottoms stream from the downstream primary fractionator contained coke and other solids, vapour scrubber bottoms temperature could not be controlled, and the scrubber rapidly fouled with solids. This required frequent shutdowns for cleaning. Review of the spray header design showed that the height of the nozzle above the grid did not cover the complete cross-section of the column. Thus, some of the vapour entering the wash section did not contact liquid. Furthermore, the distributor nozzle size was too large which reduced the nozzle angle well below the design.

Vapour scrubber modifications

The vapour scrubber slurry recycle and wash section internals designs both had fundamental shortcomings that needed to be addressed. Slurry recycle section performance could not easily be corrected because the slurry recycle pump was not large enough to provide sufficient flow rate to create a curtain of liquid from each shed. Therefore, a new wash section spray header was installed. The nozzles were properly sized to have adequate flow to develop the full 120° spray angle.

The new design ensured the complete cross-sectional area was wetted. Solids removal was dramatically improved. Even though the recycle section continued to perform poorly, the wash section changes allowed the vapour scrubber to meets its overall goals. Ultimately, the shed trays should be removed and the slurry recycle eliminated because the sheds maldistribute vapour to the grid, thus resulting in lower performance. Furthermore, the shed trays have a large amount of surface area to grow coke. The empty vessel space would actually produce better particulates removal than the shed trays. In this service, as in delayed cokers, removing the shed trays improves product quality and reduces turnaround maintenance costs associated with shed tray fouling, coking, and normal damage.

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