Column Heat Input Limit Reveals Design & Operating Issues

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As refiners work to increase unit production or accommodate feed composition changes with minimal capital investment, existing equipment design and operating conditions should be evaluated for opportunities. In many cases throughput limitations can be resolved through review and modification of existing equipment design.

A recent examination of Alkylation plant fractionation illustrates design and operating issues that should be considered for capacity increases and operating efficiency improvements.

An existing Sulfuric Acid Alkylation plant had excess feed and reaction zone capacity. Unit fractionation was restricting throughput; Deisobutanizer reboiler input was at its maximum with its reboiler steam supply valves wide open. A new Alkylate RVP specification of 5.0 psia was also constraining operation. An engineering review suggested minor design modifications and maintenance items that, after implementation, increased fractionation capacity ____%.

Deisobutanizer Operation

The Alkylation unit is fed Isobutane and olefinic C4's which react with a Sulfuric Acid catalyst to produce a primarily C8+ Alkylate. The reactor effluent containing excess Isobutane, n-Butane, residual olefinic C4's, and Alkylate is sent to the Deisobutanizer (DIB) after caustic and water washing. Figure 1 illustrates the DIB. The DIB fractionates the effluent into Isobutane in the column overhead which is recycled to the plant reaction section, and Alkylate in the column bottoms which is sent to gasoline blending. In our case the column has a vapor side-draw which removes n-Butane; other plants utilize a separate Debutanizer column to remove the n-Butane. Table 1 details the initial DIB operation.

Initial operation in the winter months allowed column operation at lower pressures due to lower than maximum design cooling water temperatures . This boosted column throughput. However, excess feed and reaction capacity remained and the reboiler steam supply valves were still wide open. In addition, summer temperatures and the higher cooling water temperatures they bring would eliminate the lowered column pressure operating option for increased capacity.

With the help of unit operators, operating data were gathered and analyzed. The following possible opportunities for improved operations were found:

- Both reboilers are recirculated thermosyphons. However, neither reboiler had internals that preferentially fed light material from the tray immediately above.
- The Medium Pressure steam supply to the bottom reboiler was superheated by 70 °F.
- Reboiler heat transfer coefficients back-calculated from operating data were significantly below design.

Reboiler Review

Thermosyphon reboilers may be once-through or recirculated. The outlet from a once-through thermosyphon returns to the column so that none of its liquid effluent enters the reboiler inlet sump. This is usually accomplished by returning the effluent to the column below the inlet draw location. The inlet temperature to a once-through reboiler is lower than a recirculated reboiler in the same service yielding a greater temperature driving force and therefore a greater duty for the same area. A once-through reboiler functions as approximately one theoretical stage in the tower.

Recirculated thermosyphons return their outlet to the column such that part of their liquid effluent returns to the reboiler inlet to be mixed with the light feed from the tray above. Recirculating a thermosyphon has the advantage of lowering the percent of the reboiler outlet that is vapor. Thermosyphon reboilers are typically limited to an outlet vapor content of 30 to 50% by weight to reduce the potential for liquid slugging and to provide a liquid wash for the tube surface. Increasing the reboiler effluent liquid concentration in the reboiler feed reduces the outlet vapor fraction. Recirculation can also help ensure a consistent liquid height feeding the thermosyphon. Having a constant liquid head on the reboiler inlet generally results in more stable reboiler operation. However, recirculating a thermosyphon increases equipment size due to higher flow rates and a lower temperature driving force. The lower driving force results from the mixed feed entering the reboiler at a higher temperature than the light liquid feed from the tray above would be if fed alone. A recirculated thermosyphon equates to some fraction of a theoretical stage.

Recirculated thermosyphons are often designed such that even though there is recirculation of the exchanger outlet to its inlet, all of the light liquid from the tray above is preferentially fed to the reboiler. This way the lowest reboiler inlet temperature can be achieved thereby maximizing the temperature driving force and the exchanger duty for a given heat transfer area. This preferential reboiler feed is typically accomplished by installation of appropriate internal baffles which direct the light liquid flow to the reboiler inlet. For the case we are reviewing, neither reboiler had a preferential flow design.

The operating data in Table 1 suggest the magnitude of the impact this lack of preferential reboiler feed had. The Table's Initial Operation data column indicates that the DIB reboiler inlet temperature was actually higher than the DIB bottoms product (Alkylate) temperature! This surprising observation was checked and rechecked. If true, it meant that a large part of the light liquid feed to the reboiler was actually bypassing the reboiler inlet and leaving the column directly with the Alkylate. The primary effect of this bypassing would be to increase the bottom reboiler inlet temperature thereby lowering the exchanger's temperature driving force and its capacity. A process simulation was developed to match the operating data. This simulation was able to match plant operation with reasonable accuracy by sending 50% of the light liquid from tray 1 directly to the Alkylate product. Half the normal reboiler feed was not entering the exchanger.

The DIB side reboiler is also recirculated and also does not posses preferential feed. However, the internal geometry and exchanger operating conditions are such that the deleterious effect on exchanger capacity is not as great as that for the bottom reboiler. Calculations suggest that 5% of the exchanger design capacity is lost due to the non-preferential feed arrangement.

Superheated Steam

The steam supply to the DIB bottom reboiler had 70 °F of superheat. Unfortunately, hotter is not always better for heat transfer. While this higher steam temperature increases the temperature driving force as defined by the Log Mean Temperature Difference (LMTD), it had a negative affect on the heat transfer coefficient (U). Equation 1 is the common heat exchanger operating equation where the exchanger area (A) and configuration correction factor (Ft) are multiplied by the LMTD and U to calculate the exchanger duty (Q).

$$Q = Ft * U * A * LMTD \qquad (1)$$

The U in Equation 1 varies over the length of the exchanger and is a function of many factors including fluid physical properties, velocities, and the heat transfer regime . Saturated steam condensing on tube surfaces has a very high heat transfer coefficient. However, superheated steam must first be cooled to its saturation temperature before it can begin condensing. Much of the cooling occurs through dry-wall desuperheating for which the heat transfer coefficient can be 50% of the condensing steam U or less. It was estimated that steam superheating reduced the reboiler capacity by approximately 10% through lower heat transfer coefficients in part of the bundle.

Superheated steam can also lead to a mistaken impression of the available temperature driving force. Figure 2 illustrates typical heating and cooling curves for a steam reboiler. If we assume saturated steam, Equation 2 defines the standard LMTD for points on Figure 2.

$$LMTD_{sat} = \frac{(T_{h6} - T_{c1}) - (T_{h1b} - T_{c6})}{\ln\left(\frac{T_{h6} - T_{c1}}{T_{h1b} - T_{c6}}\right)} \qquad (2)$$

This typical LMTD calculation uses the inlet and outlet temperatures of the heat exchanger. Using superheated steam, the calculated LMTD calculated would be significantly larger. However, this does not accurately reflect exchanger operation. The majority of the heat transfer occurs through condensation of saturated steam. The LMTD calculation can also be skewed because the steam is boiling a fluid. Much of the heat transfer associated with boiling a liquid may occur at a nearly constant temperature. In this case the standard LMTD does not accurately reflect the temperature driving force along the length of the exchanger.

To correct for the inaccuracies inherent in the standard LMTD calculation, a weighted LMTD ($LMTD_{wtd}$) can be used as defined by Equation 3, where j is the zone number.

$$LMTD_{wtd} = \frac{Q_{total}}{\sum\left(\frac{Q_j}{LMTD_j}\right)} \qquad (3)$$

Figure 2 depicts the heating and cooling curves split up into zones. Typically these zones are in equal duty increments. The $LMTD_{wtd}$ calculates the standard LMTD of each zone, weights the LMTD by the duty of its zone, and then sums these weighted LMTD values. Equation 4 details the Zone 2 LMTD equation.

$$LMTD_2 = \frac{(T_{h5} - T_{c2}) - (T_{h4} - T_{c3})}{\ln\left(\frac{T_{h5} - T_{c2}}{T_{h4} - T_{c3}}\right)} \qquad (4)$$

The greater the number of zones, the more closely the calculated driving force matches actual conditions. The weighted LMTD accounts for the effects of the unusual temperature curves associated with boiling and condensing fluids and, in our case, for the effects of superheated steam. Replacing the LMTD of Equation 1 with the $LMTD_{wtd}$ value provides for a more accurate exchanger evaluation.

Fouling

Data from the unit were analyzed to calculate heat transfer coefficients (U's) for the overhead condensers, and for both the bottom and side reboilers. The calculated overhead condenser U matched design very well. However, the U's calculated from unit data for both reboilers were approximately 70% of design. The bottom reboiler's reduced U is partially due to the dry-wall desuperheating discussed previously. However, the substantial heat transfer coefficient reductions from design suggest fouled exchangers.

Although the original design had included typical fouling factors for both reboiler services, the effect of extreme fouling that can occur in an Alkylation plant was not accounted for in the final design. Often it is impractical, or at least costly, to design for unusual or upset operating conditions. However, design and construction costs should be weighed against future operating penalties when the design basis is reviewed. The solution may not lie in increased surface area for exchangers at risk. An answer which reduces the likelihood of extreme fouling might be less costly while improving unit operation at the same time.

Improvements

A short plant shutdown was scheduled to implement the following improvements:

1. A baffle and modified seal pans were installed in the column to ensure that Tray 1 liquid was preferentially fed to the bottom reboiler.
2. Both reboilers were found to be fouled and were cleaned.
3. A steam header desuperheater was put into service.

An internals modification to provide preferential feed to the side reboiler was deferred due to its design and installation complexity, and due to its relatively minor impact.

Revised Operation

Unit performance on startup, post improvements, is detailed in column two of Table 1. Alkylate production increased _______%. A more typical column bottoms temperature profile is seen where the reboiler inlet temperature is lower than the column bottoms product temperature. Additionally, calculated reboiler heat transfer coefficients were found to be at design.

Examination of existing operating conditions and equipment design can often reveal opportunities for higher throughput, improved operation, and increased profits. After taking a look, new equipment may still be required. Brushing away the leaves from the nearest ground may uncover rich soil, or tangled roots. However, without looking before you dig, you don't know whether to use a spade or a pick. A shovel may not pierce the roots, while a pick takes quite a swing just move soft earth. Without turning back the ground-cover you can choose to search for the easiest ground for your shovel to strike purchase. That may be a long journey. And the roots may still remain.

Brief Biographies of the authors:

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Table 1 - Unit Operation

	Initial Operation	After Modifications
Feed, BPSD	56,800	
Recycle Isobutane, BPSD	35,700	
Normal Butane, BPSD	3,900	
Alkylate Product, BPSD	17,200	
Reflux, BPSD	15,400	
Overhead Temperature, °F	122	
Overhead Pressure, psig	83	
Condenser Duty, MMBtu/hr	82.2	
Side Reboiler Duty, MMBtu/hr	70.0	
Bottom Reboiler Duty, MMBtu/hr	32.1	
Alkylate Product Temperature, °F	336	
Bottom Reboiler Inlet Temperature, °F	346	
Bottom Reboiler Return Temperature, °F	355	