Chapter 13

ADVANCED REACTOR INTERNALS FOR HYDROPROCESSING UNITS

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1. INTRODUCTION

Since the introduction of fixed bed hydroprocessing technology in the early 1950's, catalyst suppliers have made significant advances in improving the relative activities of hydroprocessing catalysts. As illustrated in Figure 1, the activities of current commercial hydrotreating catalysts are an order of magnitude higher than those initially introduced.

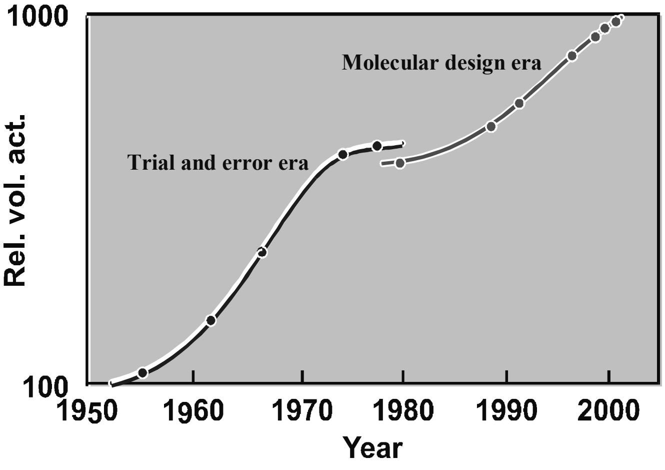


Figure 1. Development of Hydrodesulfurization Catalysts

In the mid 1990's it became apparent that the design of hydroprocessing reactors had not advanced at the same pace as the development of hydroprocessing catalysts, and that the existing reactors were not capable of utilizing the benefits of the high activity catalysts. As a result, licensors began to develop high performance reactor internals to address the demands of ultra-low sulfur diesel production.

2. ELEMENTS OF HYDROPROCESSING REACTOR DESIGN

The following describes the reactor internals elements that should be considered in the design of hydroprocessing reactors:

- Inlet Impingement Device: The purpose of the inlet impingement device is to diffuse the velocity profile of the fluids entering the reactor inlet nozzle and create an even pattern of liquid dispersion across the top liquid distribution tray.
- Top liquid distribution tray: The top liquid distribution tray evenly distributes the liquid charge across the surface of the top catalyst bed.
- Catalyst support: Multiple beds are often utilized in reactors that have high temperature rises or would benefit from re-distribution of the reactants. These reactors would have catalyst support grids and beams to carry the weight of each catalyst bed.
- Quench distributor: In multibed reactors, quench fluids are introduced into a quench zone through a quench distributor for cooling purposes or replenishment of depleted reactants.
- Quench Mixing Chamber: In multibed reactors, the mixing chamber insures that liquid and vapor phases entering the quench zone make sufficient contact to reach an equilibrium temperature and composition.
- Liquid re-distribution tray: The re-distribution tray evenly distributes the quenched liquid and vapor exiting the mixing chamber across the surface of the subsequent catalyst bed.
- Thermocouples: Thermocouples monitor the temperature of the fluids reacting throughout the catalyst bed. They should be located to provide sufficient data to indicate that the reaction in each section of the catalyst bed is even.
- Outlet collector: The outlet collector supports the bottom catalyst bed and is designed to promote even flow in the bottom of the reactor.

Although the entire reactor internals elements listed above are important to the performance of the hydroprocessing reactor, the distribution trays and mixing chambers are critical to insuring the efficient utilization of the hydroprocessing catalyst.

3. LIQUID DISTRIBUTION TRAY DESIGN

Liquid distribution trays are typically used to establish good flow distribution in hydroprocessing reactors. By obtaining even distribution of the liquid reactants over the entire reactor cross sectional area, all the catalyst at a given level is evenly wetted. Thus all the catalyst at a given level operates at the same efficiency, which increases the overall efficiency of the reactor. Additionally, even liquid distribution minimizes the radial temperature profile across the reactor. This minimizes the occurrence of hot spots which, over time, causes coking and high catalyst deactivation. Consequently, the reactor operates more efficiently, which enables a longer cycle length. Value is achieved by reduced catalyst requirements, higher processing capability and/or longer cycle lengths.

Most liquid distribution devices are proprietary designs developed by process licensors and internals fabricators. Most of the known designs fall into one of four categories.

The first is a series of troughs and overflow weirs that systematically subdivide the liquid into multiple streams before it contacts the bed. This type is often used in liquid contactors or counter-current absorbers. The trough type distribution device is mechanically complex and very sensitive to levelness. Depending on the design of the troughs, the quality of the distribution may be susceptible to fouling. An example of this type is U.S. Patent 5,192,465 by Petrich, et al, assigned to Glitsch, Inc.

A second type of liquid distribution device is a perforated tray. This may or may not have notched weirs around the perforations. The tray may also have chimneys for vapor flow. This type of distribution device is often used for rough liquid distribution in conjunction with a more sophisticated final liquid distribution tray. A perforated tray is possibly the least expensive design with regard to materials and fabrication cost, and it can offer a large number of distribution points. However, it is not an efficient primary distribution device because it must be absolutely level to provide even distribution of liquids, and it is very prone to plugging by debris collecting on the tray. Examples of this type are U.S. Patent 4,836,989 by Ali, et al, assigned to Mobil Oil Co. and U.S. Patent 3,824,080 by Smith, et al, assigned to Texaco.

A third common type of liquid distribution device is a chimney tray. This device uses a number of standpipes laid out typically on a regular square or triangular pitch pattern on a horizontal tray. The standpipes typically have holes or notches cut through the sides for the passage of liquid. The tops of the standpipes are open to allow vapor flow down through the center of the chimneys. Some designs use special vapor chimneys to handle the bulk of the vapor flow. Functionally, the chimney tray design is very similar to the perforated tray design, except the holes or perforations are elevated above the surface of the tray to allow some capacity to maintain a liquid level and hold debris that may collect of the tray. The chimney design is an improvement over a perforated tray, since it can be designed for a wider range of liquid/vapor loadings and is less susceptible to fouling. However, the spacing of the chimney risers typically reduces the number of distribution points compared to a perforated tray. A properly designed chimney must either become taller or have smaller holes drilled in the side to maintain a liquid level on the tray as the liquid rate changes. At turndown, it is possible that some holes will be covered with liquid and others will not. This results in uneven liquid distribution over the surface below the tray. Examples of this type are U.S. Patent 4,126,540 by Grossboll, et al., assigned to ARCO, and U.S. Patent 3,353,924 by Riopelle assigned to Shell Oil Co.

The fourth type of liquid distribution device is a bubble cap tray, originally designed for application in fractionation towers. This device employs a number of bubble caps laid out on a regular pitched pattern on a horizontal tray. The bubble cap distributor works on a vapor-assist principle that offers a relatively stable operation compared to a chimney device. The bubble cap is a cap centered concentrically over a standpipe. The sides of the cap are slotted for vapor flow. Liquid flows under the cap and is aspirated by the vapor, flowing upward in the annular area between the cap and the standpipe, and then down through the standpipe.

The advantage of a bubble cap device over a chimney type design is the wider turndown range possible with the bubble cap. As the liquid charge rate drops the level drops on a bubble cap tray and the slot area increases, resulting in a reduced vapor velocity through the slots. The reduced vapor velocity pulls less liquid through the distributor, and the liquid level is re-established. Another advantage of the bubble cap over the chimney type design is that the bubble cap is less sensitive to an out-of-level tray. Due to fabricating tolerances, installation difficulties and deflection due to operating load, not all of the distribution devices will be at the same level in the vessel. With proper design, the bubble cap device will minimize the liquid flow differences between bubble caps at different elevations better than can be achieved with a chimney type design. A final advantage of the bubble cap over the chimney type design is the increased contacting of the liquid and vapor phases. The intimate contacting that occurs in the up flow portion of the device provides closer approaches to thermal and compositional equilibrium than would be achieved in the chimney tray.

The primary disadvantage of a bubble cap tray is the comparatively large size of the bubble caps relative to a chimney device. The large size and necessarily wider spacing of the bubble caps reduces the number of distribution points over the cross section of the tray and catalyst bed below. The wide spacing and pitched array of the bubble cap tray also results in poorer distribution coverage adjacent to the reactor wall, further reducing catalyst utilization. An example of this type is U.S. Patent 5,158,714 by Shih, et al., assigned to Union Oil Co.

A comparison of the performance characteristics of a typical multi-port chimney type distributor and a standard bubble cap distributor is illustrated in Figure 2.

The performance parameter, Sensitivity %, is a measurement of the difference in the liquid delivered by adjacent distributors at different elevations. This parameter is described by the following formula:

$$S = [(F_l - F_h) / F_{ave}] * 100$$

Where: S = Performance Sensitivity
F_l = Liquid flow through low distributor
F_h = Liquid flow through high distributor
F_{ave} = Average flow through all distributors

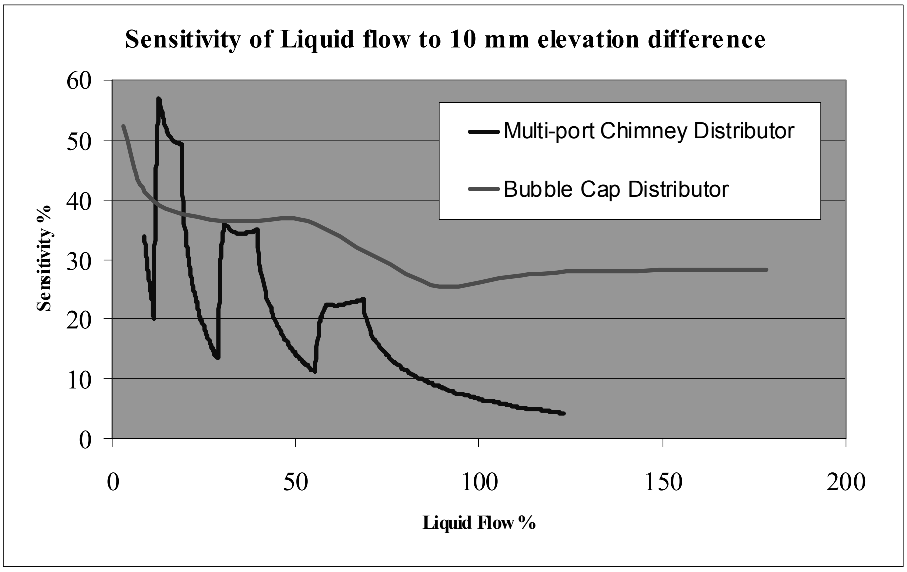


Figure 2. Liquid Distributor Performance Sensitivity

Figure 2 illustrates the deterioration in performance of a nonlevel chimney type tray as the liquid rate is reduced and the liquid level drops. Each time the liquid level reaches the nominal elevation of one of the chimney's holes, holes of the low chimneys may be covered with liquid while holes of the high chimneys are dry. Thus some distributors deliver more liquid. This causes flow mal-distribution across the catalyst bed.

When Haldor Topsøe began to investigate the design of a high performance distribution tray, several parameters were recognized as critical to achieve the desired performance efficiency. These are as follows:

1. **Spacing Density**: Because of the difficulty to visualize the performance of the distribution devices under actual operating conditions of a hydroprocessing reactor, assumptions as to the effectiveness of overlapping spray patters, or deflection splash patterns, should be discounted. The only positive approach to insure adequate liquid distribution is to achieve a high number of liquid drip points across the surface of catalyst by reducing the spacing of the distribution devices as much as is practically possible. Increasing the spacing density also enables a greater number of distribution points in the area adjacent to the reactor wall. This is very important to improved catalyst utilization, because over 35% of the catalyst in the reactor is contained within an annular ring between the reactor wall and 80% of the reactor diameter.

2. **Sensitivity to Levelness:** An out-of-level condition should have a very low impact on the operation of a high performance distribution tray. As described earlier, a distributor device operating on a vapor-assist principle will have a greater tolerance to levelness compared to a chimney type distributor device. In addition, the geometry of the distributor device can further improve the sensitivity to levelness. Leveling devices can also be incorporated into the tray design to compensate for out-of-levelness due to ring warpage, beam deflection, or plumbness of the reactor.
3. **Operating Stability:** A distribution tray may have very good performance at the design conditions. However, as the operation diverges from the design point due to changes in the charge rate or changes in vaporization due to temperature or feed quality, the performance of the distribution tray can deteriorate rapidly. A high performance tray should be capable of maintaining a relatively level height of liquid and an even flow rate through the distributor devices as the operation of the reactor changes.

The distribution device developed through the research and development efforts undertaken by Haldor Topsøe is a combination of bubble cap and chimney devices referred to as a Vapor-Lift Tray, or VLT. The VLT device has an operating concept similar to a bubble cap device but has several advantages. The VLT device has a smaller footprint and closer spacing which enables an increase in the number of liquid distribution points across the tray area. Furthermore, since the spacing pattern has a square rather than triangular pitch, gaps in liquid distribution coverage along beams and near the vessel wall are minimized. Overall wetting efficiency of the catalyst below the tray is improved when the liquid distributors have a smaller pitch compared to a larger pitch.

A standard bubble cap tray design is limited by the relatively large spacing and modifications have been attempted to improve the dispersion pattern of the liquid exiting from the cap, e.g. the shear plate described in the Shih patent or the turbine baffles described in the Jacobs patent. Increasing the number of bubble caps by reducing the spacing would increase the number of distribution points. However, doing so would negatively impact the liquid/vapor flow relationships through each cap. Smaller bubble caps with fewer slots will not be as efficient as a VLT due to the geometry of the concentric caps. The geometry of the VLT enhances the stability over a wide operating range compared to a bubble cap. A further advantage for the VLT device is that its simplicity makes it easier and less costly to fabricate in the optimal size prescribed by the process conditions. The performance characteristics of a VLT compared to bubble caps and chimney tray designs are illustrated in Figure 3.

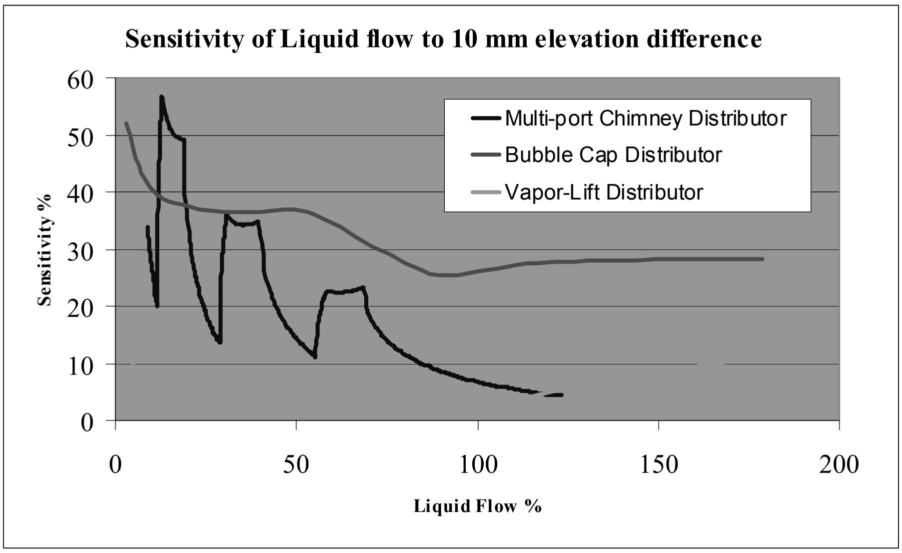


Figure 3. VLT Distributor Performance

Sensitivity is, as described previously, a gauge of the difference in the liquid flow measured from adjacent liquid distributors positioned at different elevations. These plots show that the percentage difference in the liquid flow from VLT distributors is much smaller compared to other distributor types. This ensures an even distribution of liquid over a broad range of operations, even though the tray may not be perfectly level. Poorly designed distributor devices can become very unstable and sensitive to differences in elevation as the liquid level on the tray drops. At very low liquid levels, a poorly designed distributor can actually cause mal-distribution of liquid across the catalyst bed beneath the tray.

4. QUENCH MIXING CHAMBER DESIGN

The catalyst in hydroprocessing reactors with high temperature rises or large catalyst volumes is separated into multiple catalyst beds. A quench section separating each of the catalyst beds is designed to mix the reactants and introduce a quenching medium to typically reduce the equilibrium temperature before the reactants are distributed over the following catalyst bed. Since distributor trays are basically plug-flow devices, an apparatus is needed to mix the liquid into a homogeneous blend before it is delivered onto the distribution tray. Several different mixing chamber designs have evolved during the development of hydroprocessing reactor internals.

Baffle mixer designs such as ribbon blenders and disc-and-donut type mixers promote mixing by changing the direction of the fluid streams. These designs can be effective mixing devices, but they usually have comparatively high differential pressures to achieve mixing and they can be comparatively large, requiring more reactor shell length to accommodate the quench section.

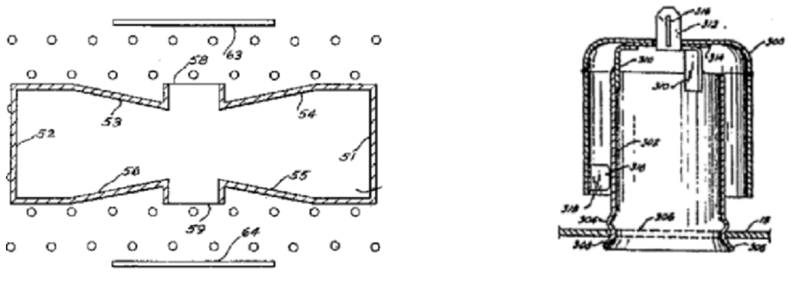
Impingement type quench boxes promote mixing by injecting or directing separate portions of the reactant fluids and impinging them against one another in a small area. This type of mixer can be designed with a reduced depth. However, test work has shown that it is difficult to achieve an equilibrium temperature with an impingement type mixer. In a low pressure drop design, the vapor and liquid phases typically follow separate paths through the mixing chamber and can segregate and inhibit the mixing of liquid collected from different quadrants of the reactor.

A preferred type of mixing chamber is a centrifugal or vortex type design, typical of the design introduced by U.S. Patent 4,836,989 by Ali, et al., assigned to Mobil Oil Co. This mixer collects liquid and vapor from all quadrants of the reactor and introduces them close to the perimeter of a circular chamber where they make several rotations before being ejected out through a central exit port. This design can have a comparatively shallow depth, a very low pressure drop, and can achieve an equilibrium temperature of the liquid passing through the mixer. Several licensors skilled in the design of hydroprocessing reactors employ a vortex type mixing chamber.

5. EXAMPLE OF REACTOR INTERNALS REVAMP

The following is an example of improved performance that has been realized by replacing a classic reactor internals design with a recently developed high performance design.

The original reactor internals included bubble-cap liquid distribution trays and impingement-type, quench mixing chambers similar to those described in U.S. Patent No. 3,218,249 and U.S. Patent No. 3,502,445 –Ballard, et al., Union Oil of Cal. (Figure 4). The original thermometry comprised three vertical thermowells running the length of the reactors and horizontal thermowells traversing the top and bottom of each of three catalyst beds.



Impingement-Type **Bubble-Cap**

Figure 4. Pre-Revamp Reactor Internals

5.1 Reactor Internals Performance (Pre-revamp)

Due to changes in the plant operation subsequent to the initial installation, the performance of the impingement-type quench mixing chambers deteriorated and the distribution trays could no longer maintain an even flow distribution across the catalyst beds. The degradation in performance of the reactor internals resulted in wide radial temperature variations ranging from 7– 10°C at the catalyst bed inlets to 15 – 40°C at the catalyst bed outlets. The flow/temperature mal-distribution is documented by temperature profiles plotted from thermocouple measurements (Figure 5).

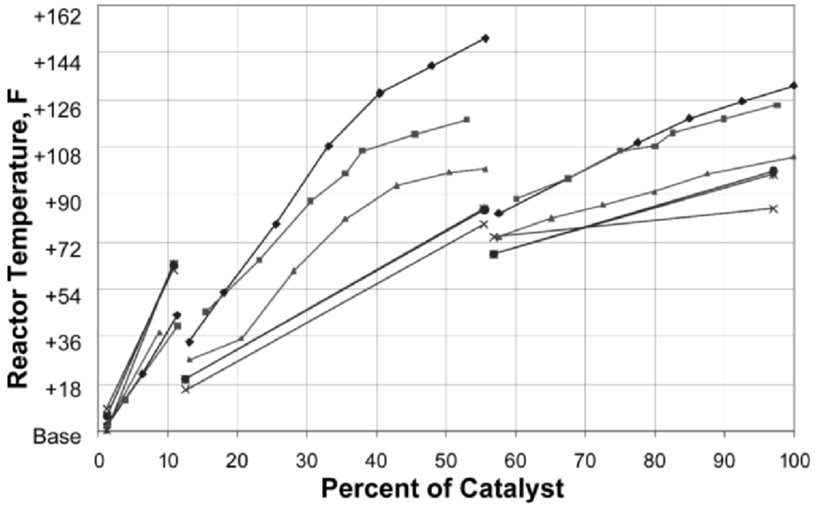


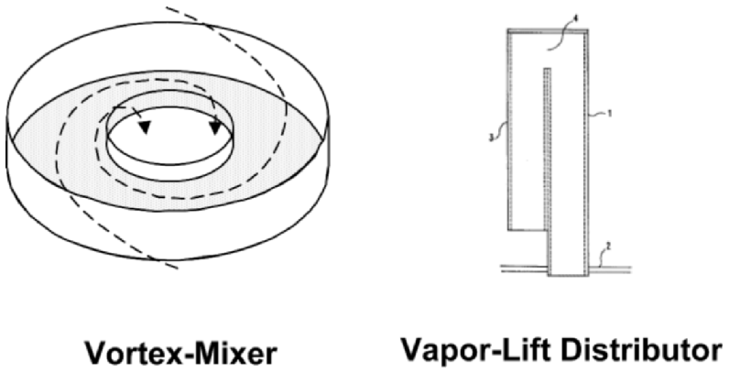
Figure 5. Pre-Revamp Performance

As seen, significant radial temperature differences were measured by the thermocouples in the vertical thermowells, especially at the bottom of the second catalyst bed in the reactor. The temperature difference measured at the top of the middle and lower catalyst beds is an indication that the quench boxes were not adequately mixing the liquid to an equilibrium temperature before passing it on to the re-distribution trays. Further, the vapor-liquid mixing through the distributors was not sufficient to evenly quench the liquid before it was distributed onto the next bed. In addition to the temperature mal-distribution, the original re-distribution trays were not providing an even liquid flow onto the following catalyst beds. This flow mal-distribution is indicated by the widening of the radial temperature differences measured by thermocouples descending through the beds.

Large radial temperature differences are problematic because they reduce the length of the operating cycle between turnarounds. High peak temperature areas adjacent to the reactor wall lead to premature unit shutdown as the temperature approaches the reactor design limit. Furthermore, because of limited thermocouple coverage, there is real concern that the existing temperature indicators might not record the actual hot spot in the catalyst bed, and that damage to the reactor wall could occur unknowingly.

5.2 New Reactor Internals Modifications and Improvements

To improve unit performance, the existing reactor internals were replaced by high performance vortex type mixing chambers to optimize liquid-liquid mixing and VLT distribution trays to increase the number of drip points and minimize the dead flow zones adjacent to the reactor wall (Figure 6). The VLT distribution trays also offered low sensitivity to tray levelness and improved stability over a wide operating range.



Vortex-Mixer **Vapor-Lift Distributor**

Figure 6. High Performance Reactor Internals

To improve monitoring of the temperature profiles, the existing thermocouple arrangement was replaced by 84 flexible-type thermocouples in the catalyst beds.

5.3 Performance Improvement Results

Following the restart of operations, the temperature profile across the reactor with the new internals is plotted in Figure 7. The improved performance of the new internals is readily seen when comparing this plot with that previously shown in Figure 5.

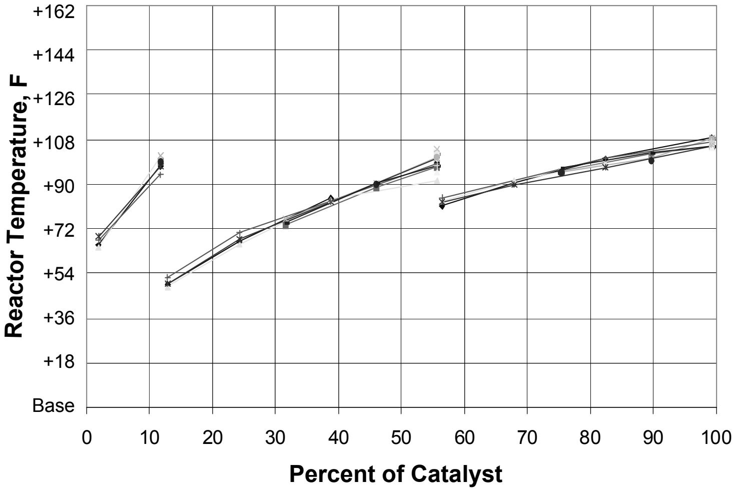


Figure 7. Revamped Reactor Performance

Several observations from such a comparison are immediately apparent:

5.4 Radial Temperature Differences

The radial temperature spreads for the revamped operation are significantly improved compared to the original equipment. At the start of the operating cycle conditions, the actual deviation in bed inlet temperature is approximately 1°C. With the old internals, the temperature deviation at the bed inlets ranged from 7-10°C. With the new internals, the radial temperature spread at the bed outlets ranges from 2-4°C. This is significantly lower than the 15-40°C bed outlet temperature deviation experienced with the old internals.

5.5 Weighted Average Bed Temperature

A reduction in average bed temperature is typically observed when less efficient distribution trays are replaced. This is due to more efficient utilization of the catalyst resulting from improved liquid flow distribution. It appears that a directional 2-4°C reduction in weighted average bed temperature (WABT) may have been achieved. However, it is difficult to estimate the degree of improvement with any precision because the widely divergent temperatures measured by the three vertical thermowells during the pre-revamp operation makes estimating the actual WABT very speculative.

6. CONCLUSIONS

Hydroprocessing reactors originally designed for low severity service typically are not adequate to handle increased severity with high activity catalysts or to achieve the operating efficiency demanded by the current and future fuels specifications.

High performance reactor mixing chamber and distribution tray designs have been developed by some licensors which can often be incorporated into existing reactors to improve their performance.