Choosing quench interbed technology

A design for hydroprocessing interbed internals favours separate mixing of gas and liquid phases before contacting of the two phases occurs

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The performance of a hydroprocessing reactor is determined not only by the loaded catalyst but also by the design of its internals. The internals positioned at the interbed have the combined function of:
- Remixing reaction fluids in order to eliminate radial maldistribution
- In-mixing of liquid and/or gas quench streams
- Redistribution of gas and liquid over the catalyst bed below.

A wide range of different types and designs of equipment has been developed. Assessment of the validity of the different designs against the functionalities listed above has been hampered by insufficient understanding of the mixing process and consequential uncertainty in scale-up from small-scale laboratory experiments to industrial operation with reactor dimensions over 5m in diameter. Furthermore, the feedback loop from the implementation of these designs to actual practice is often long.

The Ultra-Flat Quench (UFQ) technology is based on separate mixing of gas and liquid phases. This technology combines the advantage of centrifugal mixing for gas with the efficiency of impingement for liquid mixing. It provides a superior and well-described mixing process that is robust in a wide range of operating conditions and dimensions.

The Shell Group has developed, tested and optimised this technology as the owner/operator of hydroprocessing units and as a leading licensor of these technologies over a significant number of years. Multiple case studies show the actual performance of the technology. Further illustration of the advantages of UFQ designs is offered by advanced computational flow dynamics (CFD) in industrial conditions. CFD is also used to optimise quenching and mixing between catalyst beds, with optimum reduction in temperatures.

Catalytic hydroprocessing
Catalytic hydroprocessing is a technology that has been applied for more than 50 years to upgrade hydrocarbon streams. The reactions are typically carried out in a co-current, adiabatic, fixed-bed reactor. Recent advances in catalyst technology, including the Centera catalysts supplied by Criterion, have made it possible to optimise the operation of these reactors and to meet tight new specifications.

The performance of such reactors is determined not only by the loaded catalyst, but also, to a large extent, by the design of their internals. In the last 15 years, considerable attention has been given to the issue of maldistribution in gas/liquid (G/L) applications: insufficient distribution of gas and liquid inside the reactor leads to, for instance, under-utilisation of the catalyst and the formation of local hotspots. This has detrimental effects on catalyst cycle length, product quality, unit reliability and process safety. In a number of articles, successful revamps have been presented, showing how the installation of state-of-the-art internals has had positive effects.

Figure 1 Schematic overview of internals in a hydroprocessing unit

0 High dispersion tray to provide ideal distribution of gas and liquid over the entire cross-sectional area of the catalyst bed below the tray
1 Inlet device and predistribution tray to optimise the entry of the reactants into the reactor
2 Filter tray or scale catching tray to prevent fouling from entering the catalyst bed and thus limit pressure build-up over the reactor
3 Quench internals to ensure uniform process and quench mixing at the interbeds
4 Catalyst support grid to support the catalyst bed
5 Bottom basket to support the lowest catalyst bed and prevent catalyst migration to downstream units, while maximising catalyst volume in the bottom dome

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Liquid quenches are applied that have higher heat capacities and so more easily lower the reactor temperature, while not increasing the (gas) compression cost. However, this is at the expense of an added quench oil pump. The choice between gas and liquid quench is mainly dictated by the availability of the quench stream, the overall economics of the process, and product quality and production requirements. In a few cases, a combination of both a gas quench and a liquid quench can be applied. In all cases, high-performance internals are required in the interbed in order to:

- Thoroughly mix a hot process stream with a cold quench stream
- Remove any radial temperature and concentration maldistributions in the liquid and gas entering from above
- Distribute the gas and liquid streams evenly over the catalyst bed below.

Many companies have developed their own proprietary designs to accomplish this. The demands on these quench internals are high. Ideally they should:

- Be able to mix process fluids delivered from all radial locations in the bed above
- Be able to effectively mix both gas and liquid quenches
- Have high operational flexibility to handle changes in G/L ratio, quench and total flow
- Be compact to maximise the catalyst volume inside the reactor
- Be easy to install, inspect and clean during turnaround
- Be robust, with a relatively small footprint on these parameters, as well as providing an economic way of debottlenecking units for refiners, including Naftan, Repsol, Preem, Norco, North-Atlantic and Petrobras.

The focus of these articles has often been on the distribution tray at the top of the catalyst bed. Shell Global Solutions’ HD trays have been able to improve the performance of units by effective distribution of gases and liquids over the catalyst bed. The robustness of these distribution trays against a wide range of operating conditions, combined with a high tolerance against tray tilt and a boltless, weldless and ergonomic design, has made these trays a desirable choice for refiners in revamps and for new units, with more than 1500 trays supplied to customers in the last ten years.

Besides the Shell Global Solutions HD tray (marked “0” in Figure 1), a number of other internals contribute to the success of these revamps and grass-root units (see Figure 1).

This article focuses on the quench internals for fixed-bed reactors to:

- Show the importance of well-functioning quench internals
- Provide insights into the quench mixing process obtained from laboratory work, advanced CFD techniques and field experience
- Formulate the main criteria for quench equipment and assess different quench concepts against them
- Demonstrate the superior performance of UFQ technology in multiple case studies.

### Quench interbed internals

The catalyst in hydroprocessing units can be separated into multiple catalyst beds to limit temperature rises and limit the total bed length. Typically, the temperature increase per bed is limited to 30–40°C, and the bed length is 3–6 m for hydrotreaters and 12 m for hydrotreating units. Quench zones are positioned between beds, facilitating the addition of quench gas and/or liquid to the reaction medium. These quench flows play a key role in ensuring product quality. They contribute to process safety and provide a built-in capability to handle a variety of feeds so that the feedstock slate can be adjusted in response to market conditions.

Conventionally, cold quench hydrogen is introduced to reduce the reaction temperature, improve product quality and reduce catalyst deactivation. Increasingly, cold liquid quenches are applied that have higher heat capacities and so more easily lower the reactor temperature, while not increasing the (gas) compression cost. However, this is at the expense of an added quench oil pump. The choice between gas and liquid quench is mainly dictated by the availability of the quench stream, the overall economics of the process, and product quality and production requirements. In a few cases, a combination of both a gas quench and a liquid quench can be applied.

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number of parts with high reliability of operation.

We will demonstrate in the following sections that not all designs are equal — a result of the fundamental choices made in mixing philosophy. Furthermore, we will argue that there is some trade-off between different demands.

Mixing in quench trays
Collecting reactant, injecting quench fluid, mixing and distribution are the separate steps that can be distinguished in a quench internal. The last step, distribution, does not differ from distribution over the first catalyst bed at the top of the reactor. Shell Global Solutions provides the HD tray for this purpose; the most important difference for the interbed is that the distributor can be integrated with other functions into a single quench tray, leading to more savings in occupied volume.

Although there are differences in the way reactant is collected and quench fluid is injected, the main difference is in how the different streams are mixed. There are three basic mixing technologies:9 (two of these are shown in Figures 2a to 2b)

- Baffle mixer type, including ribbon blenders and disc-doughnut-type designs; mixing is accomplished by changing the direction of process liquid
- Impingement type: mixing is accomplished by injecting/directing part of the reactants and impinging this with another portion of the reactants in a small area
- Vertical, vortex or centrifugal type: mixing is achieved by letting the process fluid make several rotations in a circular chamber before being ejected out of a central exit port.

Table 1 scores these general design types against formulated requirements. Although it is difficult to generalise, it can be said that baffle types of equipment usually have a high DeltaP and a relatively high occupied volume. For impingement mixing, it has been observed that vapour and liquid follow separate paths in the mixing chamber, leading to poor interphase contacting. In addition, these paths can inhibit effective radial mixing within each of the phases.9 As a
result of these drawbacks, these more conventional approaches to interbed mixing have lost popularity.

Vortex mixing has become more dominant, with clear advantages over conventional mixers, such as reduced height and lower pressure drop. There is a variety of vortex mixer types, each with varying arrangements of vanes and baffles within the mixing chamber and variable orientation of the quench liquid injection point, with patents applying to these differing configurations. It has been demonstrated that gas mixing is near-perfect in such equipment. Although liquid mixing should be acceptable, it is difficult to achieve effective mixing because of large differences in density between the phases. Even the difference in density between hot and cold gas might lead to imperfect vortex mixing in some circumstances. In the 1980s and 1990s, there were a number of vortex applications within the Shell Group. Our experience is that this technology, when properly designed, provides satisfactory operation with low amounts of liquid. However, an assessment combining experience in the field and laboratory work revealed some major drawbacks in the vortex concept:

- Less effective mixing in the presence of larger amounts of liquid
- Uncertainties about the adequacy of the design for larger industrial applications due to the absence of good scale-up rules. The main reason for this is complicated G/L mixing phenomena during centrifugal mixing and how these interact with the configuration
- Less flexibility towards changing densities, flow changes or changes in the G/L ratio.

These drawbacks triggered the development of UFQ interbed internals, which has since become the standard for all of our interbed designs for hydrocracking, luboil units, ULSD and other hydrotreating units, residue conversions units, dewaxing, and pygas and aromatics saturation units.

**Design of UFQ interbed internals**

The UFQ concept is based on the separate mixing of the gas and liquid phases before contacting of the phases is executed. It is a patented design whereby gas-gas and liquid-liquid interactions are first effected separately to provide equilibrated, homogeneous gas and liquid phases. Figure 3 shows a UFQ geometry featuring a collection tray (1), several jet pipes (2), swirler vanes (3) and a central opening (4). Not shown in the figure are a quench ring to introduce gas and/or liquid above the collection tray and a predistribution and HD tray for G/L distribution below the jet pipes.

Gas passes through the central opening (4) in a downwards direction to the lower section. The swirl vanes (3) impart a swirling motion to the gas so that good gas mixing is achieved with minimum pressure drop. Liquid builds up on the collection tray (1) and enters several liquid jet pipes (2) via openings located in the bottom of the tray. Turbulence inside the jet pipes mixes the liquid. The liquid jets that exit the jet pipes impinge the centre of the flow field. The impingement of these liquid jets is key to achieving full radial, thermal mixing.

Thus, the UFQ concept combines the advantages of impingement technology for liquid mixing with the efficiency of vortex technology for gas mixing. Other advantages include:

- High flexibility of liquid flow rate

At higher liquid throughput, the jets will completely fill up and the liquid height on the tray starts to increase. The additional static height of the
liquid will increase the liquid flow through the pipes. The design also has tolerance for even higher liquid flow rates, with some liquid being entrained with the gas swirl when the gas chamber is overflowing. Thus, operational performance is independent from the quench load over a wide range of conditions:

- High flexibility of gas flow rate. The vortex mixer is a versatile device to facilitate gas mixing at a wide range of gas operating loads. Note that this is only possible in the absence of liquid; if a large amount of liquid is present, a change in gas velocity can have a detrimental effect on liquid mixing. In a UFQ, gas and liquid mixing has been decoupled and its performance is therefore insensitive to the gas load.
- Predictability of operation. Separate G/L mixing leads to a well-characterised mixing process. Scale-up and/or application of different operating conditions is reliable and straightforward. Complicated G/L interphase phenomena are avoided and a reliable set of equations are available for the design.

Flexibility of UFQ internals is typically between +30% and -40% of the design gas and liquid feed rates, and basically independent of the quench load. Many other interbed internals will perform only in a narrow operating range.

Laboratory and field experience

Experimental

The basis of the UFQ design was established in cold-flow test facilities dedicated to benchmarking the performance of conventional interbed internals, as well as to develop and optimise the UFQ concept. The experimental unit enables quantitative measurement of operating parameters, such as pressure drop, liquid hold-up, gas-gas mixing performance, liquid-liquid mixing performance, quench performance, liquid and gas flow rates, as well as visual observation of performance on a 1m diameter scale. In those experiments, the concept of separate gas and liquid mixing was developed and confirmed over a wide range of operating conditions. A typical experiment has been described: a radial Delta T of 30°C was imposed on one radial quadrant. The UFQ reduced it to below 4°C, whereas more conventional quenches were only able to lower the Delta T to 16°C.

Commercial operation

The current UFQ design is the result of more than ten years of installation experience and ongoing improvements. Over 500 quench trays are operational and provide satisfactory performance. The range of applications is wide, featuring reactor diameters of 1–6m. Incorporating the feedback from operations in the design is not always easy, as often there is a considerable lead-time between design and start-up. Furthermore, fewer data are available than in the laboratory and there may be other parameters affecting performance. However, the commercial data do show the reliability of our design methodology, as well as the superiority of the separate mixing concept. The most important feedback from operations is related to ease of installation and operator safety.

Focus on shallow design

Before the 1990s, only 60–70% of the total reactor volume could be filled with catalyst due to the presence of large internals. Reactor utilisation has been considerably increased with the introduction of shallow internals such as the UFQ design, which is typically less than 1m in height. We have found, in experiment and in the field, that further reducing the size of internals can have a serious negative effect. Reduced-height internals compromise flexibility when operating at variable liquid-gas loads, especially at high loads where flooding may occur or the residence time in the mixer is not enough. Furthermore, installation of such internals is difficult, leading to longer turnarounds. Lastly, accessibility of such internals is difficult, making maintenance more difficult and risky for personnel.

Ease of installation

Significant savings in time and maintenance costs can be achieved by optimising the design of internals. Some customers have
justified replacing their internals with UFQ technology only on the basis of the benefit achieved during opening/closing in turnaround. Best practices for interbed design are considered to be:

- Prefabrication of interbed tray and support in modular parts, allowing entry through the central manhole
- Minimum retrofit impact by maximising the use of existing hardware, such as support beams and reactor rims
- Use of wedges and split keys to prevent welding on the reactor wall and no, or minimal, use of bolts
- Inclusion of a large central manway for easy downstream access
- Extension of the catalyst support beams upwards into the catalyst bed rather than downwards into the interbed itself
- Attachment of specific clips for thermocouple connections.

Typically, one interbed can be installed within one work shift. In more complicated situations, such as the revamp of a unit without the presence of a support rim, more time is required, although welding can still, in many cases, be avoided.

Design validation using CFD
CFD is used to demonstrate the advantages of UFQ designs, as well as to further optimise the design and test it for scale-up and operation over a wide range of operating conditions.

The results of CFD model calculations show an excellent fit with visual and experimental observations: similar pressure drop, similar liquid build-up on the upper deck of the UFQ and similar liquid flow field.

One result of a two-phase simulation of the UFQ is shown in Figure 4. The image shows liquid from the tray descending the jet pipes and mixing with other jet outlets at the centre.

Another design parameter is the quench injection: angle and velocity can be varied to optimise mixing by utilising the momentum of the quench gas. An example is shown in Figure 5.

Table 2 shows that for a specific configuration there is an optimum angle of quench gas injection, leading to minimum radial T-variation. Note that the radial distribution is the result of gas injection at a temperature of more than 300°C below reaction temperature and that, even at unfavourable injection angles, the variation in temperature below the UFQ is already small.

Another important finding is that results from water-air mixtures at ambient conditions, commonly applied in cold flow experiments, can in some cases be misleading for phenomena that may arise with hydrocarbon/hydrogen mixtures in industrial conditions. For example, differences in density, surface tension, thermal conductivity and viscosity can have an effect on gas-liquid interactions.

Usually, the UFQ design allows such interactions to take place further downstream, at the predistribution tray and in the nozzles of the HD tray. Reliable design requires keeping such interactions to a minimum upstream. One example of an undesired interaction is shown in Figure 6.

The figure shows a suboptimal design that is unable to cope with a
very low liquid load. The resulting low level on the tray leads to choking, with gas entering the jet pipes and bypassing the swirler. This leads to insufficient gas mixing. The entry of gas via the jets also breaks up the jet streams, so they impinge less effectively and radial mixing is reduced.

Case studies
New hydrocracker
A hydrocracker in Europe was equipped with seven UFQ internals at each of the interbed stages. HD trays were installed above the first bed and at all interbeds. Since startup, the unit has experienced no problems with radial temperature gradients or temperature excursions as a result of the uniformity of distribution of a combination of UFQ and HD trays.

Figure 7 shows daily average radial ΔTs measured over a period of two months above and below the bottom two UFQ internals under typical operating conditions. The lowest interbed would be expected to experience the most severe duty, requiring premium mixing performance. Radial ΔTs of about 2–3°C above the UFQ are reduced by the mixing performance of the UFQ internal to <1°C below the internal.

Replacing internals in a luboil unit
Conventional quench trays (combined gas-liquid chimney downcomers with liquid-immersion quench system) were in place in an Indonesian luboil unit. The unit experienced severe radial temperature gradients, particularly at the bottom two beds. For example, radial temperature gradients of 50–60°C were observed at the bottom of the lowest bed.

The unit was retrofitted with UFQs, and current radial temperature gradients at the bottom of the lowest bed vary typically between 5°C and 8°C, depending on feed type. Note that this bed is nearly 9m long, so some radial temperature gradients may be expected at the bottom of the bed, depending on the loading method. Radial temperature gradients at the inlet to the last bed are reduced to around 1°C by the UFQ; previously, they approached 10°C.

Eliminating hotspots
A hydrocracker in North America faced a recycle gas compressor failure for about 10 minutes. During this period, a runaway occurred in the bottom half of Bed 2 of the cracking reactor and a hotspot of nearly 150°C developed. This hotspot was almost eliminated at the top of Bed 3 because of the UFQ mixing and redistribution trays: the radial spread at the inlet of the bed below was reduced to about 10°C (see Figure 8). Note that conditions during this incident were significantly different from normal operation. Effective mixing over a wide range of operating conditions is an important element contributing to process safety.

Conclusions
The installation of high-performance quench internals is a key element in achieving the main objectives of quench technology: enhancing product quality, increasing process safety and building in the capability to handle a variety of feeds. Over the years, UFQ interbed internals have been demonstrated in more than 500 trays installed globally for a wide range of operating conditions. The basis of their design combines the benefits of vortex and impingement technology. The main differentiators for this technology are high flexibility in operating conditions for both gas and liquid and reliability of design over a wide range of sizes and conditions.

These are the results of a design favouring separate mixing of gas and liquid phases before contacting of the two phases takes place over complicated and often undefined two-phase devices. The concept has been developed and validated in an experimental programme and in CFD simulations.

The track record of UFQ internals and feedback from operations has enabled a balance between optimal mixing and quenching performance on the one hand and minimal maintenance effort, personnel safety and robust operation on the other.

References
1. Artuch, Shishov, Yakubenka, Samaolienko, Scheffer, Kalospiros, McNamara, Increased upgrading at low cost: customised revamp of a distillate hydrotreater into a mild hydrocracker, 1st Russian & CIS Bottom of the Barrel Technology Conference & Exhibition, Moscow, April 2005.
3. Egby, Larsson, Leading edge technology combined with team approach achieves

4 Olson, Shah, Gobert, Himmelfarb, Jlijstra, Green, Revamp of pygas unit to meet new sulphur regulations, AIChE, Houston, Spring 2007.

5 Sharp, Jones, Hruska, Baumgartner, Anderson, Adarome, Hu, Ouweh, Boer, A success story: a significant improvement in hydocracker profitability with ULSD production through customised catalyst system, state of the art reactor internals and outstanding technical cooperation, NPRA 2007.


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