Flexible upgrading of heavy feedstocks

Adding tailor-made options for upgrading heavy crudes to existing assets can adapt refineries to changes in market conditions and regulatory demands

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With the commercial introduction of delayed coking in 1929 by Standard Oil of Indiana, the refining industry achieved 100% conversion of vacuum residue to distillates and coke. For the next 40 years crude oil prices remained low (less than $20/bbl) and the US became the world’s largest market for delayed coking. As crude oil prices started to climb after the first oil shock in 1972, refiners started to shift their focus away from conversion and towards technologies that could maximise the liquid yield of transportation fuels. With crude oil prices today around $60/bbl, a 20% increase in liquid yield could net a refiner more than $175 million per year for a 40 000 b/d residue hydrocracker relative to a delayed coker of the same capacity. This has been the driving force behind the hydrotreatment of atmospheric and vacuum residues around the world.

The introduction of stricter regulations concerning marine fuel oil by the International Maritime Organization means that demand for high sulphur residual fuel oil will continue to decline in the near future because of difficulty in meeting the new low sulphur standard for residual fuel oil. Consequently, refiners will now have an incentive for complete residual oil destruction for heavy high sulphur crudes. The PIRA energy consulting firm forecast the net supply of high sulphur fuel oil could decline by 1.4 million b/d from 2020 and low sulphur (0.5 wt% or less) fuel oil will grow by 900 000 b/d. Upgrading margins have not recovered in recent years but could do so in the future. However, refiners must look at a wide range of alternatives to meet their target return on investment in light of this uncertain market.

One option available in today’s market includes integration with downstream petrochemicals to increase the margin over the entire upgrading chain from crude oil to finished products. Another option includes the development of tailor-made solutions that take advantage of existing assets at specific refinery locations along with local market opportunities for fuel outlets and environmental regulations.

The approach
Axens has developed a standard technology screening methodology that helps refiners to define the basis of a feasibility study. Key criteria to consider are existing assets at the refinery (delayed coker, residual fuel oil boiler, solvent deasphalting (SDA) unit, and so on), types of crudes to be processed in the future, source of hydrogen and its cost. During the feasibility study, in close collaboration with the petroleum refiner and technology provider, alternative schemes are defined and carefully evaluated. The most appropriate option is selected taking into account the price of crude oil, finished and intermediate products, local market outlets for the products, local and national environmental regulations, capex, operating cost and plant operability.

Tailor-made solutions for achieving high conversion
The H-Oil suite of technologies is based on the proven H-Oil platform and provides a refiner with many options to increase overall liquid yield while meeting a good rate of return on its investment. Figure 1 illustrates the relative performance of the H-Oil process, the H-Oil+ and the H-Oil2-stage configuration that make up the suite of hydrotreatment technologies available to a refiner. Each technology option
of catalyst that is added on a daily basis. The conversion of vacuum residue is normally set between 75 wt% and 90 wt% when production of a stable residual fuel oil is desired from the unconverted residue. A typical configuration is shown in Figure 2.

The unconverted vacuum residue has other commercial applications, including fuel for an on-site boiler for steam and power production, which is applied commercially at PKN Orlen refinery in Plock, Poland; for gasification for hydrogen production at Shell Convent, LA refinery; or as feed to a delayed coker for production of either fuel grade or anode grade coke, an option followed at the Husky Energy Upgrader in Canada.

In many cases, conversion can be increased to higher levels depending on the application and the types of crudes being processed. In the application of feeding unconverted vacuum residue to a gasification unit, the optimal conversion level is sometimes set at 86% in order to produce enough unconverted oil to the gasification unit to put the complex in hydrogen balance. This operation was economically attractive when margins were high. When margins shrank, the refinery took advantage of spreads between low sulphur and high sulphur opportunity crudes. During this period, throughput was maximised and the unconverted oil was routed to the residual fuel oil pool.

Research by Nova Husky Research Center has also demonstrated that unconverted bottoms from high conversion operation could be successfully blended to make road grade asphalt. The level of blending is determined by two main factors: the conversion level, and the grade of road asphalt desired by the end user.

It has been 50 years since the start-up of the first large scale commercial plant. During this time, Axens has been working to enhance the operation and reliability of this technology through innovative designs, the use of improved equipment and the development of catalysts. Some of the technology improvements include:

- Improved recycle cup design inside the reactor to reduce gas hold-up and to improve the efficiency of the ebullated-bed reactor
- Inter-stage separation (ISS) for a design which includes two reactors in series. By off-loading the gas from the first reactor, the hydrogen partial pressure can be increased in downstream reactors or the hydrogen partial pressure can stay the same by lowering the overall system pressure. This allows for a decrease in overall capex
- Catalyst cascading whereby the spent catalyst from the lag reactor is cascaded to the front reactor, thus reducing the overall catalyst addition rate, which results directly in a reduction in operating costs. This is an effective tool for feedstocks with low to medium levels of metals in the crude oil
- High performance catalyst has enabled refiners to raise conversion with minimal increase in sedimentation or decrease in stability of the unconverted oil. In addition, catalyst can now be tailor-made for specific crude oils in situations that are tied to those crude oils
- Automated weighted average bed temperature (WABT) controlled by adjusting the feed oil temperature to the reactor in the control panel
- Automated ebullated bed level
control by detecting the bed level through nuclear detectors on the reactor and then adjusting the variable frequency drive that controls the speed of the ebulliating pump.

The majority of these new technology features were built into the latest commercial plant at LukOil’s Burgas refinery in Bulgaria which started operations in 2015 (see Figure 3). In addition, an advanced hydrogen management scheme using membranes and pressure swing adsorption (PSA) to minimise hydrogen losses and reduce the number of compressors was incorporated into the design of this plant. This H-Oil unit is designed to process 46 000 b/d of vacuum residue from Urals crude. The plant started operations in 2015. The design allowed for a staged investment whereby a new VDU and VGO hydrotreating unit would be integrated and added to this existing unit at a later time. In 2016, the unit passed all performance objectives thereby validating the technology advances incorporated into the design. Achieving high conversion on this difficult crude was a major achievement while also attaining high on-stream time with over 96% availability. Feedback from prior commercial units is incorporated into all new units which helps ensure safe and reliable operation.

**H-Oil** suite of technologies

The ‘+’ in H-Oil stands for additional technology features that work with the basic platform of the H-Oil process. Several options are available to meet the needs of a refiner that requires additional conversion for a modest increase in capital investment.

Some additional technology features used commercially inside the H-Oil process include the use of:

- Vacuum bottom recycle (VBR) to reduce reactor severity and conversion per pass, thus reducing the formation of sediment downstream of the reactor
- A low space velocity design that allows for deep hydrogenation and improved catalytic conversion while reducing the sediment levels in the unconverted residue
- HCAT is a new liquid catalyst precursor that reduces product sediment and allows refiners to operate at higher conversion levels

The innovative technology features are gaining wide acceptance in the industry. Many of these features have expanded the slate of heavy crudes that can be processed in an H-Oil unit. The VBR feature has been used at Shell’s Convent, LA refinery in the USA since its start-up in 1984. This unique application has allowed the refiner to run in several different modes including high conversion and maximum throughput, depending on market conditions.

The low space velocity design...
option is a powerful way to boost conversion and hydrogenation reactions. The effluent quality is improved and sedimentation/fouling levels are reduced downstream of the reaction section. In a recent industrial demonstration, the feed rate was reduced which allowed for a significant increase in conversion while the sediment levels in the downstream fractionator bottoms decreased (see Figure 4). This demonstration validated earlier research work which indicated conversions up to 95 wt% could be achieved with production of a stable unconverted oil (UCO) on an ebullated bed pilot unit. As expected, conversion of asphaltenes, Conradson carbon residue (CCR) and hydrodesulphurisation (HDS) also increased during this demonstration test.

Increasing catalytic activity is another way to improve performance in both conversion and heteroatom removal. The classic way to achieve this improvement in activity is by either increasing the residence time (in larger reactors) or by increasing the catalyst addition rate. The former increases capital investment while the latter increases the refiner’s operating costs through the use of more catalyst. An alternative is adding a liquid catalyst precursor to the oil feed entering the reactor.

The HCAT catalyst complements the solid supported catalyst and allows the ebullated bed reactor system to operate more efficiently by facilitating the transfer of hydrogen to the asphaltenic molecule (see Figure 5). This liquid catalyst is finely dispersed in the feed oil to the ebullated bed reactor by a specially designed mixing device. The hydrogenation of asphaltenes leads to higher asphaltenic conversion at lower levels of sediment in the unconverted residue. The impact on sediment formation is shown in Figure 6. During a pilot plant test in support of a commercial plant, the use of small concentrations of HCAT allowed for a 14 percentage points increase in conversion while maintaining the IP-375 sediment level at or below the standard level typically used in commercial operations. Sediment level measured downstream in the fractionator bottoms is used as an indication of fouling tendencies in the vacuum tower as well as the stability of the unconverted vacuum residue from the unit. HCAT is suited to upgrading heavy crudes but it is also effective in achieving very high conversion with easier feed. This novel catalyst additive is now in use at several commercial hydrocracking ebulliated bed plants around the world, including non-Axens licensees.

Some features of the H-Oil® process include the use of additional technologies downstream of the H-Oil unit. As an example, routing unconverted vacuum residue from the H-Oil unit to an existing delayed coker completely eliminates residual fuel oil production and achieves 100% conversion overall. An alternative is to route the unconverted oil to a new or existing SDA unit to remove the asphaltenes and improve the quality of the distillates for further treatment. Both schemes are shown in Figure 7. The concept of H-Oil followed by a second conversion unit helps the refiner minimise technical risk, lower investments cost by utilising existing assets and most importantly achieve high on-stream time which is necessary to pay off the original investment and achieve good economic results.

The first use of this combination was achieved by Husky Energy in Canada. In a detailed study performed with Axens, an optimum conversion level was achieved in both conversion units that balanced technical risks and minimised capex. Both units could operate separately to achieve higher plant reliability while making a high quality synthetic crude oil and a finished transportation fuel. In addition, Axens confirmed that fuel grade or anode grade coke could be made with this technology by optimising the design and operating conditions of the plant.

The latest design of an H-Oil unit
followed by a delayed coker is the scheme selected by ZRCC for its complex in China. By adding the residue hydrocracker upstream of the existing delayed coker, the amount of petroleum coke was reduced by 32% due to the conversion of CCR in the H-Oil unit. The overall conversion is 92 wt% with this configuration. In addition, the quality of the new coke produced was improved due to the removal of impurities in the upstream residual hydrocracker. This unit is due to start up in the first semester of 2019 and will be the latest ebullated bed unit designed for high conversion.

The key driver of the H-Oil/delayed coker combination is the increase in overall liquid yield compared to using the delayed coker by itself. In addition, the vacuum residue feed rate can be increased since a substantial amount of CCR conversion occurs in the residue hydrocracker. Figure 8 shows an overall increase in liquid yield of 30% with strong selectivity towards the production of diesel fuel. With the increase in liquid yield and high oil price, the payback for this type of plant can be economically very attractive.

Another example includes the use of sequential deasphalting (H-Oil + SDA) which paves the way for major increases in conversion through the removal of asphaltenes from the unconverted oil. The deasphalted oil (DAO) can either be hydrotreated for increased yield in diesel production or cracked in an FCC unit for additional gasoline production, depending on local market conditions. The unconverted pitch from the SDA has many potential outlets ranging from blending into road grade asphalt to burning or gasifying to produce power and hydrogen.

The Hengli project in China is an example of the option that integrates upgrading heavy oil at the refinery with a petrochemical plant downstream (see Figure 9). This large complex was optimised by a team of engineers from Axens and Hengli. This resulted in a configuration that includes the high conversion H-Oil suite of technologies; the H-Oil process, SDA (Solvahl), and hydrocracking (HyK) of vacuum gas oil (VGO) and DAO for the maximum yield of naphtha for processing in a downstream petrochemical plant. Hengli is able to maximise its overall margin by producing petrochemicals. This 110 000 b/d plant uses two parallel trains with two ebullated bed reactors in series for each train. The design feedstock is a blend of Arabian and Marlin crudes. Pitch from the SDA unit is routed to a gasification unit. Axens provided the major technologies for both the refining and petrochemical plants. This unit is scheduled to start-up in the first semester of 2019. More than 92 wt% conversion will be achieved with no production of fuel oil.

**H-Oil two-stage configuration**

The deep conversion of very refractory feeds faces many challenges, some of which have adverse effects on reactor stability. To overcome these issues, a first stage of moderate conversion is set in a two-stage
configuration. The heaviest fraction from the first stage is routed to an SDA unit to remove unconverted asphaltenes while the clean effluent undergoes additional conversion in the second stage. The second stage consists of one H-Oil reactor (see Figure 10). High levels of performance are achieved with this configuration. The SDA section prevents the asphaltenes-rich and instability-promoting fraction of the effluent from being processed in the second stage. By segregating DAO from first stage effluent, stability is maximised in the whole complex. Conversion levels are in the range 65-90 wt% with this scheme.

The highest investment is associated with the H-Oil two-stage configuration. This application is limited and most appropriate for processing high refractory feedstocks, found in Venezuela for example.

A case study
To understand the potential economic benefits of each of the schemes described in the H-Oil Suite, Axens undertook an in-house study based on the processing of a Urals vacuum residue feedstock with a capacity of 2.6 million t/y (46 000 b/d). Three configurations were evaluated: H-Oil process; standard processing scheme, H-Oil+ process, two ebullated bed reactors in series, followed by an SDA unit; and the H-Oil two-stage configuration for maximum conversion. In all cases, VGO was routed to a downstream hydrocracking unit.

A gross margin (the difference between the selling price of products and the cost of feedstocks of vacuum residue and hydrogen) was calculated for each scheme. The results of this analysis are shown in Figure 11. As expected, each of the schemes showed an increasing benefit in gross margin as the conversion level was increased. High gains in economic benefit will pay substantial benefits to refiners as oil margins increase. The final economic benefit measured by internal rate of return will be a strong function of the final capital investment. In many cases, the high incremental capital investment required for achieving higher conversion does not result in the best return on investment. Having a tailored solution based on existing local assets at the refinery and local conditions will determine which scheme maximises the internal rate of return for each refinery.

Technology innovations
Technology innovation has been a cornerstone of improvements to the H-Oil process. Improvements come from feedback from commercial operating units and IFPEN’s R&D support. IFPEN is ranked in the Reuters Top 100 global innovation organisations and over 100 000 hours of operating data have contributed to the following breakthroughs:

- Inter-stage separation (ISS) provides the ability to debottleneck limitations in gas velocity and increase feed rate in a single train, which reduces capex
- Implementation of advanced process control greatly improved the operation and reliability of the plant
- Development of a new analytical tool that can measure extremely low levels of C₇ asphaltenes led to a major breakthrough in producing a ‘clean DAO’ in SDA
- Developing inter-stage sampling techniques provides the ability to measure the composition of effluents across each reactor stage in order to precisely determine individual reactor exotherm and optimise the overall design of the unit
- The use of spiral heat exchangers greatly improved efficiency and reduction in downstream fouling
- A new predictive model enables refiners to predict performance and sedimentation in unconverted bottoms based on crude properties. This helps the refiner maximise profitability by targeting the acquisition of distressed crudes on the open market.

IFPEN is continuing to pursue developments at its research facilities. R&D is continuing in the areas of oil stability, high conversion, process fundamentals and process modelling.

With IFPEN and HTI, Axens is the only technology provider that can provide pilot testing to customers in a real ebullated bed pilot unit. This pilot plant has the capability to produce results which can be used as a direct comparison with an industrial unit with regard to fouling (sedimentation in the fractionation bottoms).

Commercial experience
Fifty years ago, the first large scale H-Oil plant was inaugurated. The latest H-Oil unit was started in 2015 at LukOil’s refinery in Bulgaria. Throughout the world, H-Oil units have accumulated more than 230 years of operating experience, which is the highest level of experience for any residue hydrocracking technology, and licensed units represent a total capacity of more than 1.02 million b/d.

Of the 21 licensed H-Oil units, most are located in North America, followed by Europe and the Far East (see Figure 12). Growth in North America came as the result of refiners requesting technologies that...
could improve liquid yield once oil prices started to increase from $20/bbl in the 1970s to over $70/bbl today. As **Figure 13** shows, most of the unconverted oil from these licensed units is directed towards residual fuel oil. There has been a substantial shift in recent years to eliminate residual fuel oil altogether by routing the bottoms to delayed coking and SDA to increase overall liquid yield.

A key advantage of a mature technology is its ability to achieve high unit availability or on-stream time. A review of nine commercial plants over the years has resulted in an average unit availability of 97%. Even the newest unit to start up (in 2015), which includes all of the latest technology innovations, is operating at this level. In a recent internal study, a reduction in on-stream time from 96% to 90% can cost a refiner $45 million per unit in lost revenue. This explains why so many of the older plants are requesting updated operating simulators. The cost of training new operators can easily pay for itself when this plant operates one extra day a year.

**Reducing capital investment**

One of the most pronounced trends over the past 20 years has been the reduction in capital investment in commercial H-Oil units. With advances in technology, the processing capacity per unit train has increased substantially. This has provided significant cost advantages for the refinery industry. The train capacity has gone from 14,000 b/d of vacuum residue in the 1960s to over 60,000 b/d currently. The most striking example is the commercial plant constructed at the Shell refinery in Convent, LA, which started operations in 1984 with a design capacity of 35,000 b/d. The H-OilRC plant consisted of two parallel trains with two reactors in series for each train. Both trains had their own dedicated catalyst handling sections with a common fractionation section. About 10 years later, Axens was able to design a 34,000 b/d plant for PKN Orlen in Poland in one train with two reactors in series. With virtually the same feed capacity, the number of pieces of major equipment and associated capital costs were substantially reduced. As **Figure 14** shows, innovation has led to substantial reductions in capital cost by taking advantage of economies of scale and reduction of major equipment. Today, commercial plants are being designed to process up to 70,000 b/d in a single train plant.

**Impact of IMO 2020 regulations**

With updated MARPOL regulations starting in 2020, the sulphur level in marine fuel oil will drop from the current 3.5 wt% to 0.5 wt%. A recent internal study has discovered a couple of viable options using the H-Oil+ process for making low sulphur residual marine fuel oil (RMO). Some options include:

- Route VGO from the H-Oil unit to the marine gas oil (MGO) pool: if the price of MGO rises above the price of diesel fuel, then it is profitable.
- H-Oil followed by SDA: in this case, DAO from the SDA is blended with VGO from the H-Oil unit to meet the 0.5 wt% sulphur specification.
- SDA followed by the upgrading of the DAO in the H-Oil unit: the unconverted residual oil meets the sulphur specification and pitch from the SDA unit is routed to a delayed coker, bitumen pool or also used as a liquid or solid fuel.
- An H-Oil unit processing low to medium sulphur feedstocks and using a low sulphur cutter-stock like light cycle oil (LCO) from a FCC unit.

**Figure 12** Geographic distribution of H-Oil units

**Figure 13** Routing of unconverted oil from commercial plants

**Figure 14** Achieving breakthroughs in processing capacity
with a yield in the range of 25-30 vol% of the fresh feed to the unit. As one might expect, distillate products from a residue hydrocracker would be more refractive because the most reactive sulphur and nitrogen compounds have already been converted. Figure 15 shows the results of characterising a typical H-Oil diesel product compared to a straight run mid-distillate material. The straight run diesel contains more than 50% benzothiophene which is easy to convert, while the H-Oil diesel contains more than 50% dibenzothiophene, which is a more refractory compound and consequently more difficult to convert. The same analysis was conducted on nitrogen compounds. Distillates which contain larger quantities of basic nitrogen create difficulties for sulphur removal because they inhibit hydrodesulphurisation reactions. The removal of high levels of nitrogen compounds typically requires greater reactor severity in comparison to desulphurisation reactions.

It is worthwhile also comparing H-Oil diesel reactivity to other cracked feedstocks from delayed coking, such as light coker gas oil (LCGO) and from an FCC unit, such as LCO. Figure 16 shows results from pilot tests that were conducted for the purpose of producing ultra-low sulphur diesel fuel with 10 wtppm sulphur. The key variable was liquid hourly space velocity (LHSV) which relates to the amount of catalyst volume required to achieve this result. A lower LHSV means substantially more volume of catalyst is required in the reactor to achieve the same result. In these tests, the H-Oil diesel was found to be the most reactive compared to LCGO and LCO.

Several refineries today process
H-Oil diesel in existing low/moderate pressure units as well as dedicated units added to an existing unit. The latest application is the H-Oil unit at PKN Orlen’s Plock refinery. A dedicated diesel unit was added after the original H-Oil unit started operations in order to produce low sulphur diesel fuel. Several options were examined by both parties and an optimal design was agreed and implemented in 2007. The details of the design and successful operation were presented and later published. New units under design have considered integrated hydroprocessing units for both initial start-up or as part of a phased investment.

VGO is another major distillate product that has been routed in the past directly to an FCC unit without any pretreatment. In recent designs the VGO is routed to a hydrocracker to maximise production of high quality diesel fuel. In some cases the VGO is pretreated with straight run VGO in a hydrotreater before routing to the FCC unit to increase the yield and conversion to gasoline. As a rule of thumb, a 0.1 wt% increase in the hydrogen content of the VGO will result in an increase of 1-2% in gasoline yield.

Detailed characterisation (sulphur, nitrogen and aromatic compounds) is required to develop optimal hydroprocessing conditions along with selecting the best catalyst to meet the performance objectives. In many cases the VGO is routed to standalone hydrotreating units but in recent years refiners have been looking at adding new integrated units with the residue hydrocracker. Several configurations have been examined including the use of an in-line hydrocracker taking the entire overhead from the H-Oil hot high pressure separator, which is mainly naphtha and diesel, and then adding VGO recovered from the downstream fractionation column. This high pressure unit suffers from lower hydrogen purity and high levels of hydrogen sulphide and ammonia compounds in the feed which inhibit catalyst activity. In addition, overcracking of the diesel fraction leads to increases in production of light gases (C_1 to C_4) which in turn increases hydrogen consumption.

A better scheme would use the optimal hydrogen partial pressure levels for each processing unit (residue and VGO) which could result in capital and operating cost savings. Figure 17 shows the scheme developed by Axens for integrating H-Oil with VGO hydrocracking. The two units use the same make-up hydrogen compressor and share the same high pressure amine absorber and hydrogen purification system. The high pressure purge from the VGO hydrocracker is routed to the common high pressure amine absorber, thus resulting in a higher purity hydrogen and correspondingly lower operating pressure for the hydrocracker. There are several references utilising this design today.

Flexibility in an uncertain market
With uncertainty in the market, refiners need tailored solutions which can take advantage of utilising existing units while meeting local and national regulations, local market outlets for products, and achieving high reliability. The H-Oil suite of technologies provides a range of applications that can be utilised in today’s market. These technologies have been accepted worldwide by the refining industry as providing low risk and high return on investment.

Further reading
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