Lower operating costs with liquid phase hydroprocessing

Liquid phase hydroprocessing demonstrated its economic and environmental advantages over trickle bed technology in a Chinese refinery

TONY CHEN, SANDEEP PALIT and SAMANTHA PRESLEY
DuPont Clean Technologies

Air quality concerns have led to increasingly stringent environmental legislation globally. In the case of China, diesel sulphur specifications have seen a marked change in the last 10 years. The country made drastic cuts to sulphur levels in diesel and introduced a limit of 10 wppm in densely populated areas in 2010. As a result, refiners face strict national regulations both for grassroots and existing plants. When the government-owned China National Offshore Oil Corporation (CNOOC), the largest offshore oil and gas producer in China, received approval to construct Phase II of its expansion project at the Huizhou refinery, the organisation turned to DuPont Clean Technologies to help it achieve not only the desired increase in crude processing capacity, but also to enable it to produce high quality, low sulphur fuel efficiently, safely and in compliance with local environment regulations. Implementing IsoTherming hydroprocessing technology allows CNOOC to meet all of these goals as well as decrease energy consumption and operating costs compared to conventional trickle bed hydroprocessing technologies.

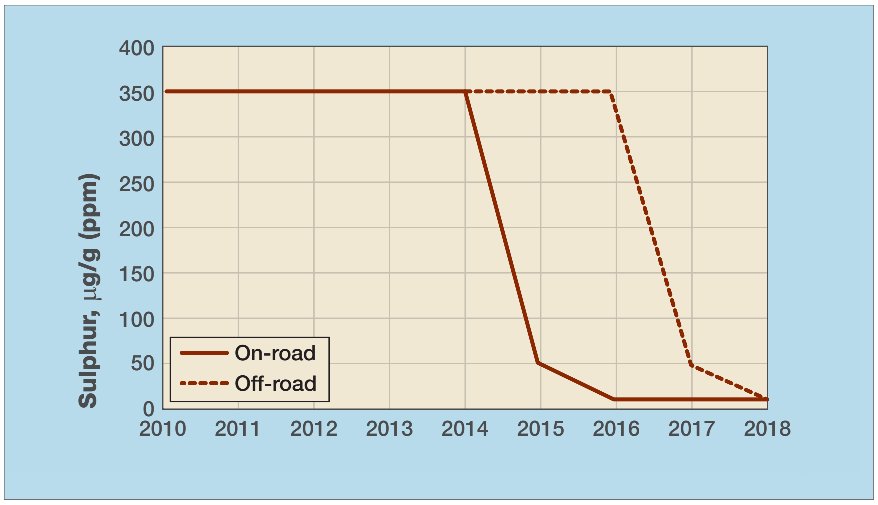

Figure 1 China's historical diesel sulphur specifications

Project parameters

Phase II of the Huizhou refinery was designed to more than double crude processing capacity at the plant from 11 million t/y (220 000 b/d) to 22 million t/y (440 000 b/d). CNOOC also wanted to improve its flexibility in processing a wider range of more economically attractive sour Arabian Gulf crudes. In October 2017, after three years of construction, the refinery successfully started up and tested 15 processing units, auxiliary production units, and supporting public works for the Phase II refinery project. These included new and modified units from a crude unit to an FCC unit, diesel hydrotreating, VGO hydrotreating, residue hydrotreating and a gasoline hydrotreating unit. Among them were a China National V diesel compliant (≤10 wtppm sulphur) 3.4 million t/y (71 637 b/d) grassroots diesel hydrotreater and a 2.6 million t/y (51 419 b/d) grassroots vacuum gas oil hydrotreater for the FCC feed, designed for output of <1000 wtppm sulphur and <600 wtppm nitrogen, both licensed by DuPont Clean Technologies.

At the outset of the refinery expansion, the CNOOC Phase II project included grassroots diesel and VGO hydrotreating units, which presented the company with an opportunity to evaluate its options, including IsoTherming technology which has been commercialised since 2005. Trickle bed hydroprocessing technology has been demonstrated globally for decades in numerous refinery applications. However, trickle bed technology relies on maintaining a high hydrogen gas to oil ratio. This leads to high energy consumption and capital investment arising from the considerable amount of hydrogen gas circulation needed for maintaining hydrogen partial pressure, controlling temperature rise, and providing the necessary hydrogen for the reactions. CNOOC wanted to explore IsoTherming technology as it is characterised by low energy consumption, low capital investment, low operating costs, ease of maintenance and simple operation. In addition, at the time of the CNOOC technology evaluation, there were more than 10 IsoTherming units in commercial operation processing kerosene through 100% light cycle oil feeds in a variety of hydroprocessing applications.

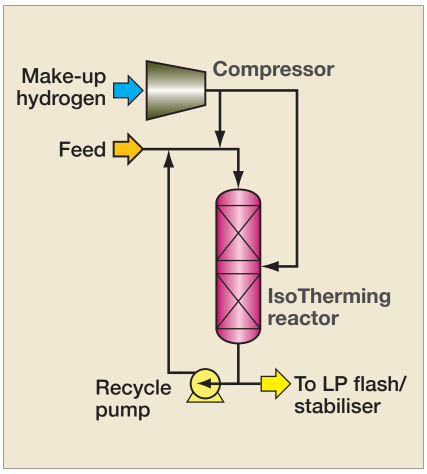

Figure 2 IsoTherming process

CNOOC undertook a thorough investigation of the technology, basing its final selection on confirmed process, environmental and safety benefits, commercially proven results, as well as capital and operating costs. The process of evaluating, selecting and commissioning this technology at the Huizhou refinery therefore spanned a five-year time frame and included technical discussions, an evaluation of IsoTherming and trickle bed hydroprocessing technologies in terms of process, investment and operating costs, and visits to existing commercial unit installations.

CNOOC's technology evaluation

In IsoTherming hydroprocessing technology (see **Figure 2**), the hydrogen required for the reaction is supplied using a saturated liquid stream rather than a recycle gas stream. The liquid recycle rate is set so that the amount of hydrogen dissolved in the combined (fresh and product liquid) feed is much greater than the reaction requirements. This liquid-full design ensures excess hydrogen availability at the reactor inlet/outlet. To replace hydrogen that has been consumed throughout the catalyst bed, hydrogen is continuously injected between each catalyst bed to re-saturate the feed prior to the next catalyst bed. A nominal, continuous flow of excess hydrogen/off-gas is vented from each catalyst bed as an indicator that sufficient hydrogen is flowing to the inter-bed resaturation point. Liquid distribution differences between IsoTherming and trickle bed reactors are illustrated in **Figure 3**.

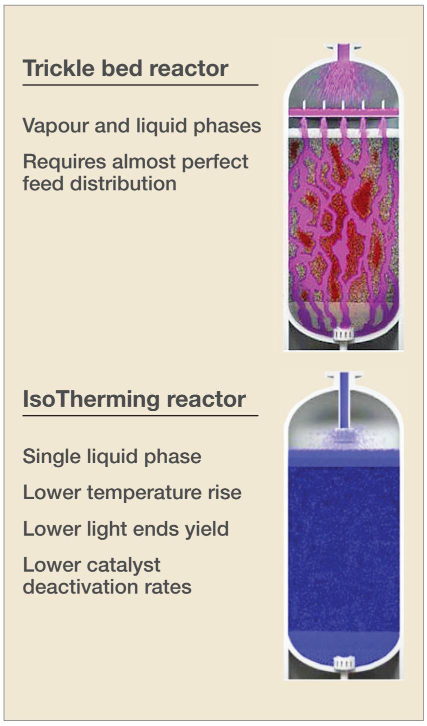

Figure 3 Liquid distribution differences between trickle bed and IsoTherming technologies

CNOOC realised the reactor design of IsoTherming technology would address areas of concern related to conventional trickle bed technology including multiphase flow, pressure drop and maintenance of the correct flow regime. In the IsoTherming reactor, the lack of a vapour phase and resultant reduced volumetric flow rate results in significantly lower pressure drop. In addition, the liquid-full reactor and even distribution of reactants minimises the possibility of forming isolated pockets of low flow and resultant 'hot spots' within the reactor bed. With the more efficient use of catalyst and a more uniform distribution of bed temperature due to the total liquid reactor feed, CNOOC concluded that IsoTherming technology is inherently safer and simpler than trickle bed technology.

Comparison summary

In summary, CNOOC viewed IsoTherming as offering the following advantages over conventional hydroprocessing technology:

- Lower capital requirements for both high pressure (HP) related equipment and the IsoTherming feed/effluent exchanger. **Table 1** provides a summary of differences in high pressure equipment requirements for IsoTherming and trickle bed technologies. Depending on the application, IsoTherming's capital cost savings can be as much as 25% compared to a conventional trickle bed design.

Another key part of the IsoTherming design is direct reactor feed/effluent heat exchange which recovers much of the heat of reaction energy by heating the reactor feed directly by combining it with the reactor effluent. Direct heat transfer enables the unit to recover high-level energy without the heat loss associated with indirect heat exchange (use of a heat exchanger), and this leads directly to significant fuel gas savings. Further, CNOOC opted to incorporate a twisted-tube bundle type heat exchanger design for the feed/effluent exchanger, proving for the first time that this type of heat exchanger can be reliably operated in an IsoTherming unit.

CNOOC's comparison of high-pressure equipment requirements for IsoTherming and trickle bed technologies

Key equipment	IsoTherming	Trickle bed
Reactor	√	√
Amine scrubber		√
Amine scrubber knockout drum		√
Reactor feed/product heat exchanger	√	√
Hot HP separator gas cooler		√
Hot HP separator gas/recycle H_2 heat exchanger		√
Hot HP separator		√
Cold HP separator		√
Recycle H_2 compressor knockout drum		√
Recycle hydrogen compressor		√
Recycle canned motor pump	√	

Table 1

- Lower maintenance and operating costs by eliminating the hydrogen recycle gas compressor and its ancillary recycle loop equipment.
- Reduced energy consumption as IsoTherming has consistently demonstrated 40-60% utility savings over trickle bed technology, for the following reasons:
  - By using a canned motor pump for hydrogen delivery which consumes substantially less energy than a comparable trickle bed recycle gas compressor, the unit power consumption is reduced, on average, by 30-40% for any application.
  - By eliminating the hydrogen recycle gas loop, the low-level energy loss to cooling water or air that is associated with the hydrogen recycle loop is eliminated.
  - By direct heat exchange (vs indirect heat exchange) using a liquid recycle, the high-level energy is recovered fully and leads directly to fuel gas savings at the reactor charge heater. The technology has consistently demonstrated a 30-60% drop in fuel gas costs.
- Any excess reactor bottoms heat, beyond what is required to preheat the reactor feed, can be used to generate steam. This results in a net reduction of steam usage within the unit and, in some extremely exothermic applications, the unit becomes a net producer of steam.

Overall, IsoTherming not only offers significant utility cost savings as well as substantial capital cost reductions compared to trickle bed technology but also a reduction in CO_2 emissions (due to minimal reactor charge heater duty). At the same time as comparing technologies, CNOOC also considered past commercial experience with IsoTherming. Since its first commercialisation in 2003 and at the time of the CNOOC evaluation, it has been licensed for more than 20 units around the world, of which seven were located in China. Today, IsoTherming hydroprocessing technology has 28 licences globally with 15 of these in commercial operation.

In view of these benefits, CNOOC concluded that the technology would be able to operate with lower investment and lower operating cost. CNOOC therefore decided that it was feasible for the Huizhou Refining & Chemical Project (Phase II) to utilise it in its ULSD and VGO hydroprocessing units.

CNOOC ULSD hydrotreating engineering and equipment cost analysis

Total engineering and bare equipment cost estimate	Trickle bed	IsoTherming	Difference
	¥362 759 800	¥279 628 000	¥83 131 800
	$54 413 970	$41 944 200	$12 469 770
Bare equipment cost breakdown	**Trickle bed**	**IsoTherming**	**Difference**
Static equipment	¥108 132,000	¥64 910 900	¥43 221 100
	$16 219 800	$9 736 635	$6 483 165
Mechanical equipment	¥62 560 300	¥43 857 700	¥18 702 600
	$9 384 045	$6 578 655	$2 805 390
Process pipe	¥57 255 200	¥32 280 500	¥24 974 700
	$8 588 280	$4 842 075	$3 746 205
Automation	¥32 639 900	¥26 406 500	¥6 233 400
	$4 895 985	$3 960 975	$935 010

Total savings approx. 25 MM USD (Chinese installation factor = 2-3 x equipment)

Table 2

Operational highlights

CNOOC broke ground for the ULSD unit on 16 October 2014, followed by a successful start-up in September 2017. At the time of start-up, the ULSD unit's operation complied with the design specifications and the ULSD product met or exceeded the China V standards at a lower than design feed rate due to available feedstock limitations. The ULSD unit underwent a performance test at the full design feed rate in September 2018. During the performance test, all the product's properties and waste emissions met or exceeded unit design specifications and performance guarantees indicating that IsoTherming operated as intended.

CNOOC broke ground on the VGO hydrotreating unit on October 16, 2014 and initiated a successful start-up in October 2017. Due to reduced refinery throughput due to market conditions, the IsoTherming VGO hydrotreater ran at reduced rates until recently. A successful performance test for this unit was completed in July 2020, where the results exceeded performance guarantees. In particular, the unit demonstrated that it maintained catalyst activity over the three-year period, demonstrating one of the advantages of the technology in its ability to reduce catalyst coke formation, compared to conventional trickle bed technology.

CNOOC indicated that it has demonstrated successful applications of the technology at the Huizhou refinery, with all technical indicators showing that the technology works well.

Economic and social benefits analysis

CNOOC developed estimates for engineering and bare equipment costs during the company's evaluation of hydroprocessing technology. The results are summarised in **Table 2**. It should be noted that these results do not represent the full capital cost or savings associated with either technology as the information is for the cost of bare equipment only, plus engineering fees (and does not include any installation related costs).

The total capital cost savings associated with IsoTherming for the CNOOC ULSD hydrotreating unit were approximately $25 million (Chinese installation factor = 2-3 x bare equipment). It is worth noting that the actual cost savings would be greater outside of China where installation factors are typically in the range 4-6 x bare equipment.

CNOOC determined that an average IsoTherming ULSD hydrotreater requires approximately 50% of the energy used by a comparable Chinese conventional trickle bed design. A portion of the IsoTherming unit's operating cost

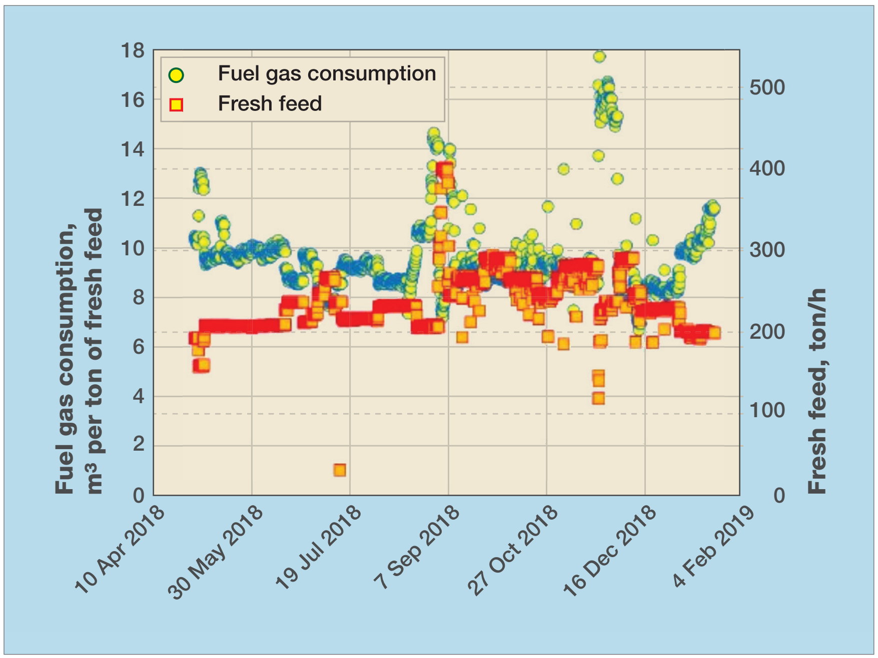

Figure 4 CNOOC Phase II ULSD feed heater fuel gas consumption

advantage comes from reduced fuel gas use due to optimised feed/product heat integration. The remainder comes from the method for delivering hydrogen to the catalyst beds. For many IsoTherming units, the reactor charge heater duty is determined by start-up conditions when there is insufficient product heat to exchange with the feed. As a result, the charge heaters typically operate with significantly lower duty than design conditions once the unit is stabilised. For the CNOOC ULSD hydrotreater, the reactor charge heater operates at approximately 23% of the design duty, leading to annual fuel gas savings of ¥7.854 million ($1 168 360) compared to an equivalent trickle bed design.

Figure 4 shows the unit total fuel gas consumption on a per-ton basis of fresh feed plotted against the unit total fresh feed rate. The graph demonstrates that greater energy savings can be realised (within design limits) when more feed is processed. CNOOC believes this to be one of the advantages of IsoTherming. Overall utility consumption including power and steam generation for the IsoTherming ULSD hydrotreater is 4.19 kg EO/t (kilogram oil equivalent per metric ton) whereas data on energy consumption for a conventional diesel hydrotreater in China showed an average energy consumption of 9.71 kg EO/t for 2016. As such, the CNOOC ULSD hydrotreater energy consumption is 5.52 kg EO/t less, equating to a total annual operating cost savings of 65.7 million CNY/year (US $9 853 200/year).

Overall, the company achieved significant capital and operating cost savings while meeting or exceeding the expected product yields of conventional trickle bed technology

CNOOC carried out a similar evaluation for the Phase II IsoTherming VGO hydrotreater. CNOOC determined an average IsoTherming VGO hydrotreater requires approximately 60% of the energy consumed in a comparable Chinese trickle bed design. While a portion of the unit's operating cost advantage comes from reduced fuel gas consumption, the VGO hydrotreater realises total annual operating cost savings of ¥27.3 million ($4 095 000) compared to a conventional trickle bed design.

CNOOC concluded that the projects, when built and put into operation, yielded a high reduction in energy consumption. The anticipated savings of large amounts of fuel gas and steam were realised along with a considerable reduction in emissions. Overall, the projects had a positive impact on environmental protection.

Conclusion

Currently, two hydroprocessing options are available for the production of ULSD and the treatment of FCC feeds. These include conventional trickle bed and liquid phase (IsoTherming hydroprocessing) technologies. CNOOC selected IsoTherming, enabling the company to realise both economic and social benefits. Overall, the company achieved significant capital and operating cost savings while meeting or exceeding the expected product yields of conventional trickle bed technology. CNOOC benefits from a safer, simpler, more efficient, and cost-effective process with lower emissions as compared to conventional trickle bed technology.

Tony Chen is Senior Technical Manager with DuPont Clean Technologies for IsoTherming hydroprocessing technology. Prior to joining DuPont, he spent 20 years in the oil refining industry, with most of his time in hydroprocessing. He holds a PhD in chemical engineering from Oklahoma State University.

Sandeep Palit is a Senior Technical Sales Manager with DuPont Clean Technologies for IsoTherming hydroprocessing technology. He graduated from Worcester Polytechnic Institute then held positions in process engineering in refining and chemicals, hydrocracking and dewaxing.

Samantha Presley is Global Licensing Manager with DuPont Clean Technologies for IsoTherming hydroprocessing technology and is responsible for the technical and commercial sale of the technology. She holds a bachelor of science degree in chemical engineering and a minor in business from the University of Kansas.