Refinery expansion and oil quality upgrading

Optimisation of resources and effective integration of clean fuels technology enable older refineries to better match the economic performance of new plants

SUN LILI
Sinopec Engineering Incorporation

This article analyses the differences between older refineries and advanced refineries with respect to policy requirements, target market demand, advanced process technology, resource utilisation, energy conservation, environment protection and economic benefit. Through case analysis, some effective measures are taken by exploiting the potential to enhance comprehensive refining capacity, improve oil product quality, optimise the product mix, and achieve economies of scale.

China's refining industry has accelerated its restructuring since the beginning of the 21st century. Production of clean oils has been increased through the wide adoption of clean fuels production technologies. Measures to continuously increase depth of oil processing, adapt to sour, heavy oil processing and further improve light oil yield have been pursued. Also, competitive, integrated refining and petrochemical complexes have been established in coastal areas to ensure the requirements of energy supply to support national economic development are met.

Currently, Sinopec owns a large number of coastal and inland refineries that were built in the 1970s and the 1980s. Since the "10th Five-Year Plan", the refineries have accelerated their technical transformation, optimised their allocation of resources, adjusted the product mix, notably improved their overall strength and competitiveness, and have achieved a refining capacity of about 5.0 million t/y. However, there are still some differences between these refineries and advanced refineries. These differences, in particular, relate to industrial policy requirements and target market demand, the level of advanced process technology, resource utilisation, energy conservation, environment protection and economic benefit. Therefore, it is necessary to enhance their performance in a number of respects: raising refining capacity; improving oil product quality, optimising the product mix; achieving economies of scale; and exploring a process route with the characteristics of old refineries by exploiting their potential.

Refinery expansion and oil quality upgrading

Goals for the development of older refineries

To comply with the newly issued Circular Economy Promotion Law of the People's Republic of China and the Cleaner Production Promotion Law of the People's Republic of China, petrochemical plants or refineries, especially older refineries, need to improve their immediate environment to establish a clean performance for sustainable development. As pipeline oil becomes poorer in quality, refineries need to improve their capacity for — and adaptability to — low-quality crude oil processing, to create the conditions for further improving their environmental protection measures and increasing their profitability. The Chinese government aims to adopt tougher quality standards for gasoline and diesel; hence, refineries need to improve measures for gasoline and diesel production by means of technical transformation and improvement, so as to upgrade the quality of crude oils and to supply the market with cleaner oil products. Refineries need to work out an optimal combination of oil, gas and coal, so as to take full advantage of the extensive resources of China.

Development roadmap for older refineries

The quality of crude oils needs to be upgraded by phasing out outmoded process units and technically transforming and improving older refineries. Relying on existing facilities in the older refineries, production needs to be raised to increase oil throughput, so as to provide cleaner oil products for the local economy. Resource allocation needs to be optimised and product costs reduced by adjusting unit configuration and product mix, to further increase the overall competitiveness of the refineries.

Plan for refinery expansion and oil quality upgrading

Optimisation of process technology

Crude oil structures and product demand need to be analysed in relation to problems in the existing process flow of the older refineries. These problems include low adaptability to sour crude oil processing, low heavy oil conversion, poor quality of oil products and single product mix. Relying on the existing crude oil processing capacity of the older refineries, a clean vacuum residue desulphurisation (VRDS) FCC process for heavy oil processing is recommended, based on a process comparison to increase adaptability to sour crude oil processing and to improve heavy oil conversion. A catalytic reformer (CCR) unit, an S-Zorb unit and a diesel hydrogenation unit are to be installed to upgrade comprehensively the quality of gasoline and diesel to national III/IV/V standards. While ensuring oil production, the process schemes and operating conditions of the FCC and CCR units are optimised, the production of raw materials such as propylene, benzene and paraxylene are increased appropriately, and the product mix is optimised, thus creating the conditions for the development of a downstream petrochemical industry. A light ends recovery unit and a hydrogen-rich gas purification unit are also to be installed. For example, FCC dry gas is sent to the styrene unit as the feed to recover and produce high-value products and to increase the resource utilisation rate.

The application of such measures for integrating refining and petrochemical production can not only lower the production costs of the refineries, but can also significantly increase the added value of their products and enhance their profitability and overall competitiveness.

Comprehensive energy utilisation

Refinery-wide energy utilisation controlled by complex systems engineering organises heat integration between units as well as the distribution of cold and hot sources based on the actual conditions of each production unit and utility, so as to ensure the smooth operation of closely grouped units and to maximise operational efficiency and value.

Taking advantage of a centralised arrangement of units, an integrated study of refinery-wide energy utilisation is carried out. The focus is shifted from energy optimisation of a single unit to a combination of unit optimisations with refinery-wide optimisation, in order to improve the energy utilisation level of the refineries.

By adopting low-temperature heat utilisation technologies, a low-temperature heat utilisation plan can be further optimised and the application of low-temperature heat power generation or refrigeration technology can be enhanced.

Optimisation of general plot plan

The principle behind the general plot plan design is to achieve smooth and compact process flows. The number of blocks is reduced to shorten logistical distances and so minimise the floor area. Those units whose production characteristics are the same and production processes that are closely related in terms of logistics are grouped into a complex unit. Process equipment in units is located according to process flows to enable deep integration. Auxiliary facilities are located as close to production units as possible, to minimise the space between them. Auxiliary rooms of production units such as control rooms and power distribution rooms should be located together in a single building. The increase in floor area occupied should be less than 0.2 hectare per 10 000 tonnes of crude oil, to achieve the level of land use of more advanced refineries.

Optimising and integrating storage and transportation

The configurations and process flows of storage and transportation systems must be integrated and optimised. Control systems and automation levels are optimised and tank capacity is determined to ensure a stable, flexible and advanced operation. Based on the arrangement of existing and new units, full consideration is given to system configuration and the balance of utilities, including refinery-wide hydrogen, fuel gas and flare systems. Based on unit layout, consideration is given to the layout of tank farms in order to optimise the process flows of storage and transportation facilities, to save investment costs and to reduce energy consumption.

Water resources

Process technologies for units are optimised to control water consumption. Drainage systems are designed based on the principle of effluent segregation, while classified treatment is adopted for the effluents from various units, and pretreatment and centralised treatment is integrated to ensure the appropriate sewage recovery level. Different wastewater treatment technologies are used to achieve cascaded use of effluent as much as possible, and integrated processes for wastewater treatment are used to maximise effluent recycling and water conservation.

Steam system

Based on the principle of determining power output according to steam, the steam balance and power balance are optimised. Critical power equipment in units and systems is driven by steam turbines as much as possible, so as to improve the safety and capacity utilisation rate of units. The design of the steam system is optimised by analysing the requirements of units and taking into consideration the factors influencing the waste heat steam generation capacity of units and refinery-wide energy consumption.

Case study: modification of an older refinery

Current situation

The refinery has a crude oil processing capacity of 5.0 million t/y. Its CDU/VDU consists of two trains. One processes Luning pipeline crude oil and the other processes sweet crude oil. A delayed coking-FCC process has been adapted for heavy oil processing. Vacuum residue is sent to the delayed coker, and vacuum gas oil (VGO) is sent directly to the FCC unit. FCC gasoline is the main product, for which a 200 000 t/y semi-regenerative catalytic reformer is installed (see Figure 1).

In general, the inability of the older refinery to process sour crude oil is a result of four factors. The first factor is the issue of environmental protection. The quality of FCC gasoline and SO_2 emissions in FCC flue gas restrict the level of sulphur in the crude oil for processing. An increase in the sulphur content of the crude oil would lead to bottlenecks in the throughput of environmental protection units, including the desulphurisation unit, the sulphur recovery unit and the sour water stripper, which are in need of modification.

The second factor is the metallurgical constraints of the refinery's original design. For example, low-grade material used in the equipment and pipelines of the CDU/VDU cannot meet the requirements of sour crude oil processing, and the carbon steel used for the fractionator and stripper of the FCC unit limits the sulphur level of crude oil. The third factor is the challenge of upgrading the oil quality. The refinery lacks measures for reducing the sulphur content of oil products, especially gasoline,

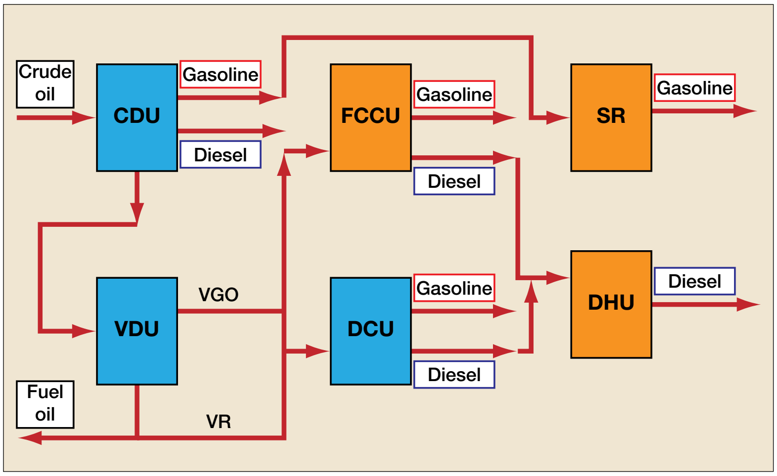

Figure 1 Older refinery: existing process flows

Changes in the properties of crude oil before and after modification			
No.	**Item**	**Before modification**	**After modification**
1	API	20.8	29.5
2	Density (15.6°C), g/cm^3	0.9291	0.8805
3	Sulphur, wt%	>0.85	>1.0
4	Nitrogen, ppm	4400	2180
5	Acid number, mg KOH/g	>0.5	>1.5
6	Carbon residue, wt%	4.11	4.22
7	Nickel, ppm	22. 6	11.48
8	Vanadium, ppm	1.70	14.02
9	Viscosity(40°C), cst	320.0	17.0 (50°C)
10	Yield, wt%		
	Gas	0.13	0.51
	<165°C	3.59	13.06
	165~220°C	4.30	5.21
	220~365°C	16.17	23.31
	365~580°C	41.50	32.67
	>580°C	34.31	25.24

Table 1

because high-quality and clean blending components for reformate are unavailable. Low capacity and outmoded technology in the reformer present a bottleneck for upgrading the oil quality. In order to meet current quality standards for gasoline, the sulphur content of the FCC feedstock has to be controlled; this, in turn, restricts the sulphur content of the crude oil. Therefore, the refinery has structural defects in terms of sour crude oil processing and oil quality upgrading.

Selection of process scheme

Changes in the properties of crude oil before and after modification

The quality of pipeline oil is becoming worse as crude oil supplies become markedly poorer in quality (see Table 1).

Table 1 shows that although the API of crude oil improved markedly after modification, the quality of crude is markedly lower and its heavy metal content, which influences heavy oil conversion, changes significantly. The acid number of crude oil increases from 0.5 to 1.5 (a 200% increase), and its sulphur content increases from 0.85 to 1.0 (a 17.5% increase). There is a small increase in heavy metal content, from 24.3 ppm to 25.5 ppm (a 5% increase), but the vanadium content increases significantly, from 1.7 ppm to 14.02 ppm.

Table 1 and Figure 1 show that the current process scheme cannot meet the demands of low-quality crude oil processing and the economic benefits of scale in terms of upgrading oil quality, meeting environmental protection requirements and realising the safe and long-term operation of units.

Selection of an oil processing scheme

The quality of crude oil is even lower following modification. The increase in sulphur content of crude oil not only leads to problems concerning environmental protection and safety, but also lowers the profitability of the refinery. Therefore, a clean process flow, which increases heavy oil conversion, should be selected following modification.

VRDS and residue fluidised catalytic cracking (RFCC) units are required for the pretreatment of low-quality residue, in order to remove impurities such as sulphur and metals. The residue is then sent to the FCC unit for secondary conversion. In this way, heavy oil processing capacity is increased, heavy oil processing measures and conversion depth are improved, the yield of oil products and the utilisation rate of crude oil resources are increased, and the ability to adapt to sour crude oil processing is strengthened significantly.

The residue processing scheme combines hydrogenation with decarbonisation. A new VRDS unit is installed and the existing delayed coker unit (DCU) is used to improve the properties of feedstock to the VRDS unit.

Heavy oil conversion is increased by improving heavy oil processing measures. It has been verified that the capacity of the CDU/VDU needs to be expanded to 5.0 million t/y offsite. The crude oil processing capacity of the refinery will reach 8.0 million t/y after modification. In order to improve light oil yield, deep cut technology is used for the CDU/VDU to reduce the residue yield. Vacuum residue (>580°C) is mainly used as feed to the DCU. The existing units, including a coker, are fully utilised, and the properties of the feed to the VRDS unit are improved (see Figure 2).

By improving heavy oil

processing measures, FCC feedstock is hydrotreated to reduce the sulphur content in FCC gasoline, thus lowering the content of impurities such as sulphur in gasoline.

An advanced and environmentally friendly, ultra-low pressure continuous catalyst regeneration (CCR) process, which enables high product yields, is used to increase the production of high-octane gasoline blending components and to improve the blending of gasoline products structurally.

For diesel production, a liquid-phase bed straight-run diesel hydrofining unit is installed for desulphurisation of straight-run diesel oil, so as to meet the sulphur content requirements of automotive diesel fuel. The existing 1.0 million t/y hydrofining unit is used for FCC diesel oil and coker diesel oil (see Figure 3).

The quality and quantity of oil products are considerably increased by improving heavy oil processing measures, using clean and environmentally friendly processes, and increasing the amount of crude oil processed. A full hydrogenation process is selected to lower the sulphur content in oil products and to control and reduce pollutant emissions from the source. In spite of a low-quality crude oil feed, complicated process flows and an increase in the energy factor, energy consumption per unit of energy factor falls by more than 15%. Water demand per tonne of crude oil for refining decreases to 0.41 m^3/t, the recycling rate of water increases to 97.9%, and the water discharge per tonne of crude oil decreases from 0.5 m^3/t to 0.22 m^3/t, thus significantly improving and protecting the natural water body (see Table 2).

The comparison of results shows that increases in gasoline and diesel production after modification are 1.3125 million t/y and 1.4026 million t/y respectively, and both gasoline and diesel meet National IV emissions standards. After modification, propylene, LNG and mixed xylene production increases by 139 900 t/y, 347

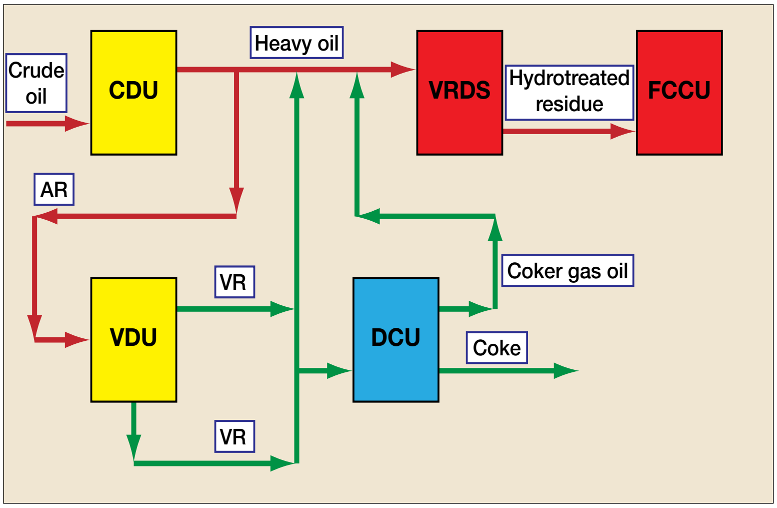

Figure 2 Process flows for heavy oil processing following modification

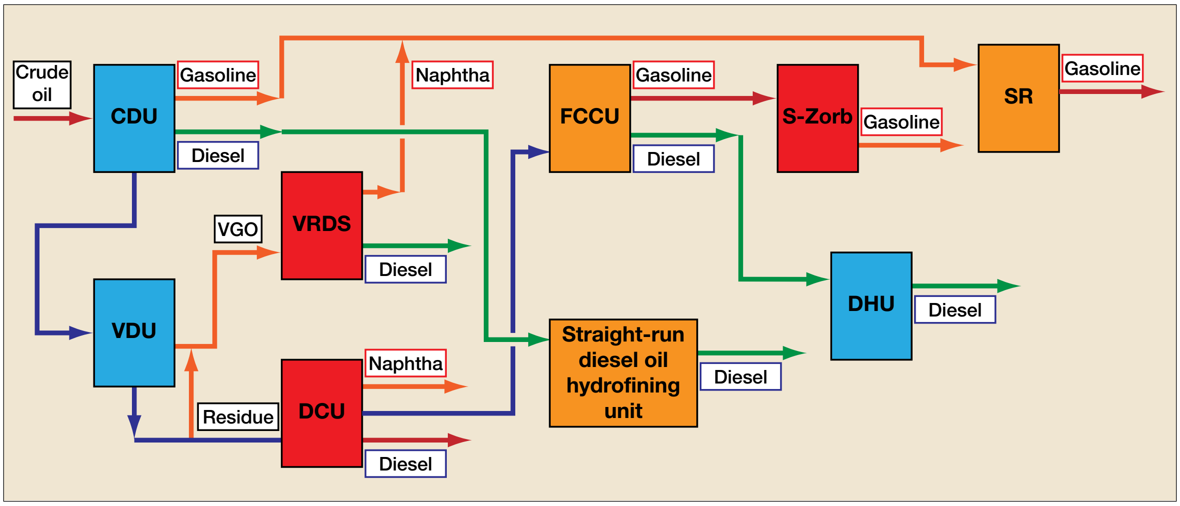

Figure 3 Process flows for clean fuels production following modification

Comparison of main products before and after modification (Unit: 104 t/a)

No.	Item	Before modification	After modification	Increase	Remarks
A	Main outsourcing raw material				
1	Crude oil	500.00	800.00	300.00	Ratio of Shengli crude oil to imported crude oil is 3:7
2	Natural gas	/	11.48	11.48	
B	Main products				
1	Propylene	/	13.99	13.99	For downstream butyl alcohol and 2-ethyl hexanol project
2	LNG	33.25	68.00	34.75	including propane
3	Mixed xylene	/	21.17	21.17	
4	Gasoline	78.20	209.45	131.25	
	including 93# ethanol gasoline		139.45		After modification, all gasoline meets national III standard, and some meets national IV standard
	97# ethanol gasoline		70.00		
5	Diesel	199.75	340.01	140.26	
	including automotive diesel		130.00		After modification, automotive diesel meets national IV standard
	ordinary diesel		210.01		
6	Petroleum coke	37.87	26.54	-11.33	
11	Sulphur	4.05	7.76	3.71	

Table 2

500 t/y and 212 700 t/y respectively, providing raw materials for the development of a petrochemical industry.

Using advanced technologies, this project strives to: increase the homemade ratio of process technology and equipment; reduce project investment; avoid investment risk; and improve the return on investment. Tables 3 and 4 show a comparison of production indicators and a comparison of economic indicators before and after modification.

Tables 3 and 4 show that the yield of clean oil products, including gasoline, kerosene and diesel, increases by 13.09%, and the diesel-to-gasoline ratio decreases by 0.93 after modification, better suiting the growth in market demand for clean gasoline. After modification, the yield of light oil increases to 74.56%, 7.27% higher than before, and the overall commodity availability increases to 95.41%, 3.3% higher than before. The incremental after-tax internal rate of return on total investment is 22.75%, the net present value is RMB 3232.19 million ($500 million) and the payback period is 5.92 years. It can be seen that the modification can not only improve the environment and increase the production and yield of clean oil products, but can also achieve good economic benefits.

Comparison of production indicators before and after modification

No.	Item	Before modification	After modification	Difference
1	Diesel to gasoline ratio	2.55	1.62	-0.93
2	Yield of gasoline, kerosene and diesel, %	55.59	68.68	13.09
3	Yield of light oil, %	67.07	74.56	7.27
4	Overall commodity availability, %	92.11	95.41	3.30

Table 3

Comparison of economic indicators before and after modification

No.	Item	Value	Note
1	Internal rate of return, %	22.75	Total investment, after income tax, incremental
2	Net present value, million Yuan	3232.19	Total investment, after income tax, incremental
3	Payback period, year	5.92	Total investment, after income tax, incremental

Table 4

Conclusions

In the expansion of existing refineries, the utilisation of available resources must be optimised first. By adopting a clean VRDS-FCC process for heavy oil processing, hydrogenation is combined with decarbonisation for integrated application. Light oil yield and overall commodity availability can be greatly increased, and effective utilisation of crude oil resources can be achieved.

Based on the present situation and by exploiting the refineries' potential, clean oil production technologies including VRDS, diesel hydrotreating, CCR and

S-Zorb were optimised in an integrated fashion to upgrade oil quality and improve the environment. After a number of projects were put into operation, the quality of all oil products was able to meet national IV standards, marking a step forward in the refineries' development into advanced refineries, and a process route for low-quality crude oil processing with the characteristics of old refineries was established.

Sun Lili is Vice President of Sinopec Engineering Incorporation in charge of processing solution study, engineering, construction and startup of grassroots refinery and refinery modification projects. She has over 20 years' experience in engineering design and startup of various hydroprocessing units and has won several prizes of National Scientific and Technological Progress. She holds a BS in petroleum refining from China University of Petroleum and has released over 30 papers.
Email: sunlili.sei@sinopec.com

LINKS

More articles from the following categories:
Revamps, Shutdowns and Turnarounds