HS-FCC for propylene: concept to commercial operation

A FCC process provides a high light olefin yield from a wide variety of feedstocks utilising high severity reaction conditions and a novel down flow reaction system

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The fluid catalytic cracking (FCC) process has undergone a long evolution of hardware and catalyst changes, from bed cracking with amorphous catalyst to short contact time riser cracking with sophisticated zeolite catalyst systems. Improvements to the process have provided a wide degree of flexibility to selectively target the production of distillates or gasoline, or propylene from VGO and residue feeds, thereby making FCC the most widely used conversion process.

More generally, the objective of the process is to produce high valued products, and increasingly this includes fuels and petrochemicals, such as light olefins and aromatics. At present, over 30% of the worldwide propylene supply comes from FCC-related processes (FCC, RFCC, DCC). Fluctuating product demand and price have caused most new project developers to demand product flexibility for long-term profitability and process integration with petrochemical facilities for added synergy and cost savings.

Figure 1 HS-FCC semi-commercial unit

In order to respond to these market demands, a new high severity down flow FCC (HS-FCC) process has been developed by an alliance of Saudi Aramco, JX Nippon Oil & Energy (JX) and King Fahd University of Petroleum and Minerals (KFUPM), culminating in a 3000 b/d semi-commercial unit in operation since 2011 in Japan (see Figure 1). The process provides a high light olefin yield from a wide variety of feedstocks utilising high severity reaction conditions, a novel down flow reaction system and proprietary catalyst. HS-FCC is now available for licence from a Global Alliance by Axens and Technip Stone & Webster Process Technology.

Features of HS-FCC

FCC utilises acidic zeolite catalysts to crack heavy hydrocarbons into lighter fuels such as gasoline and distillate and, under more severe conditions, into lighter olefins such as propylene and butylene (and, to a lesser extent, ethylene). Complex secondary reactions that can degrade the primary products to less valuable components should be limited to retain product selectivity and refinery profitability. For HS-FCC, the objective is to not only improve the selectivity for normal fuels production, but also to maximise the potential of light olefin and petrochemical production at high severity. HS-FCC provides a total system to maximise product selectivity and, in particular, propylene yield. Three key elements are required to attain this objective:

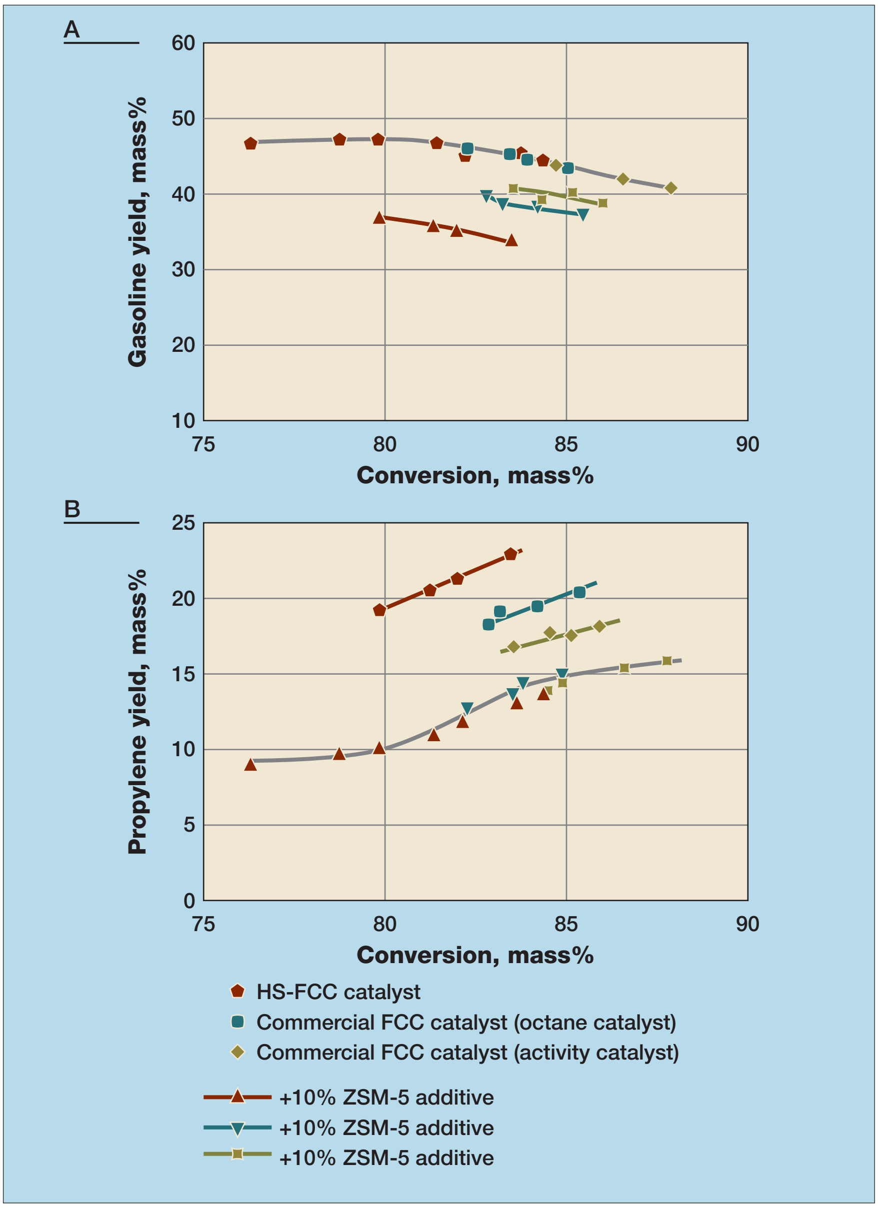

Figure 2 Proprietary catalyst boosts ZSM-5 effectiveness for more propylene

Reaction conditions and advantages of HS-FCC in petrochemicals production		
	Advantages	**Challenges**
High temperature	High conversion and olefins selectivity	Increased thermal cracking, product degradation
Short contact time	Reduced secondary reactions and thermal cracking	Reduced conversion, rapid mixing and separation required
High catalyst/oil	Increased catalytic cracking	Very high catalyst circulation, uniform flow, mixing and separation

Table 1

- Highly selective catalyst and additive system
- Optimised reaction conditions
- Down flow, short contact time reaction system with rapid catalyst separation.

The balance of these elements and realisation at commercial scale is the key to success.

Catalyst system

The catalytic cracking reaction pathways are complex, with the primary formation of olefinic products and parallel bi-molecular hydrogen transfer reactions leading to paraffin formation and aromisation of naphthenes. Managing the acid site density of the catalyst can suppress hydrogen transfer and isomerisation reactions to maximise olefins production. When coupled with ZSM-5 pentasil cracking catalyst additives, the increased olefins in the gasoline cut can be selectively cracked to further increase the propylene yield.

The HS-FCC catalyst uses a high USY zeolite content system with very low acid site density, formulated to minimise hydrogen transfer reactions for high olefin selectivity, and low coke and gas selectivity. This catalyst has been shown to be more effective for propylene production when coupled with ZSM-5 additives (see Figure 2). Commercial catalysts and HS-FCC catalyst exhibited a similar trend in gasoline and propylene yield as a function of conversion (severity), but the customised HS-FCC catalyst was much more effective in 'feeding' the ZSM-5 additive with more olefins, and more accessible linear olefins, to produce more propylene.[1]

Typical operating conditions for FCC and HS-FCC		
	FCC	**HS-FCC**
Reaction T,°C	500-550	550–650
Contact time, s	2–5	0.5–1.0
Catalyst/oil, wt/wt	5-8	20–40
Reactor flow	Up flow	Down flow

Table 2

Optimised reaction conditions

When targeting maximum petrochemicals production, HS-FCC operates under more severe conditions than conventional FCC. The main reaction conditions applied and the advantages and challenges presented are shown in Table 1.

High reaction temperature coupled with short contact time increases the primary reactions towards olefins, while limiting the unwanted secondary reactions of hydrogen transfer and thermal degradation. A consequence of the increased severity and short time is the need for higher catalyst circulation (catalyst-to-oil mass ratio, or

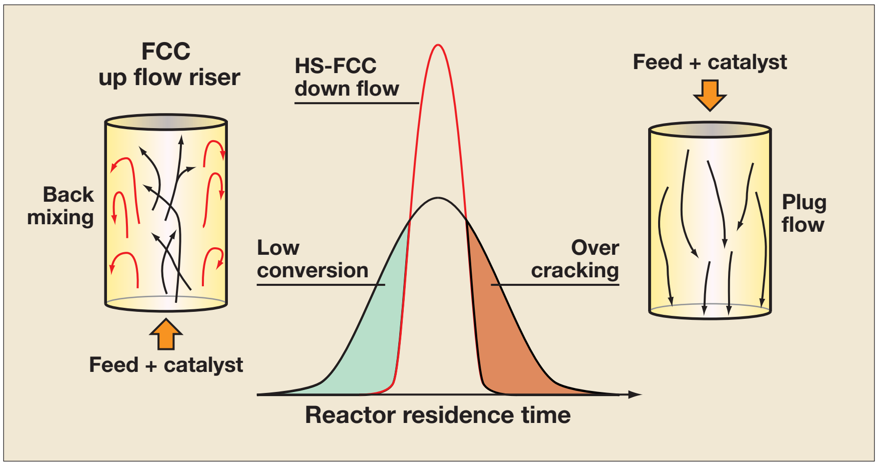

Figure 3 Up flow vs down flow residence time profiles

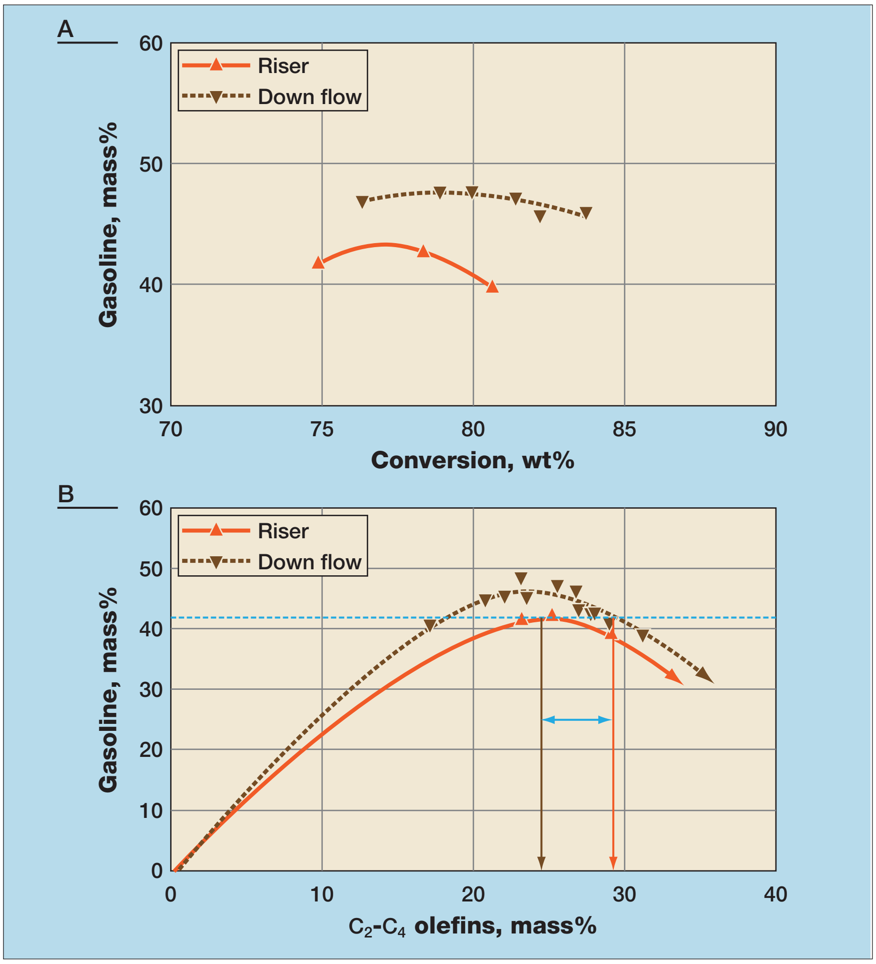

Figure 4 Selectivity benefits of a down flow reaction system[4]

C/O) to provide the required heat to the reactor and sufficient catalyst activity to achieve high conversion at short contact time. The range of operating conditions for a conventional FCC and HS-FCC are summarised in Table 2.

Down flow reaction (DFR) system

The specific reaction conditions with very high C/O result in certain challenges in a conventional up flow FCC riser reactor system, where the catalyst required for the reaction is lifted up the reactor pipe or riser by the vaporised and cracked hydrocarbon feed. In up flow fluid-solid systems, the solids or catalyst are conveyed upwards against the force of gravity by drag forces from the rising gases (hydrocarbons). As a result, all riser reactor systems have varying degrees of catalyst back-mixing and

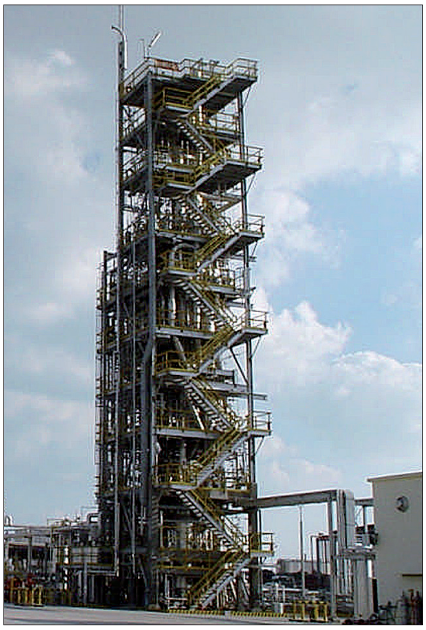

Figure 5 HS-FCC demonstration unit

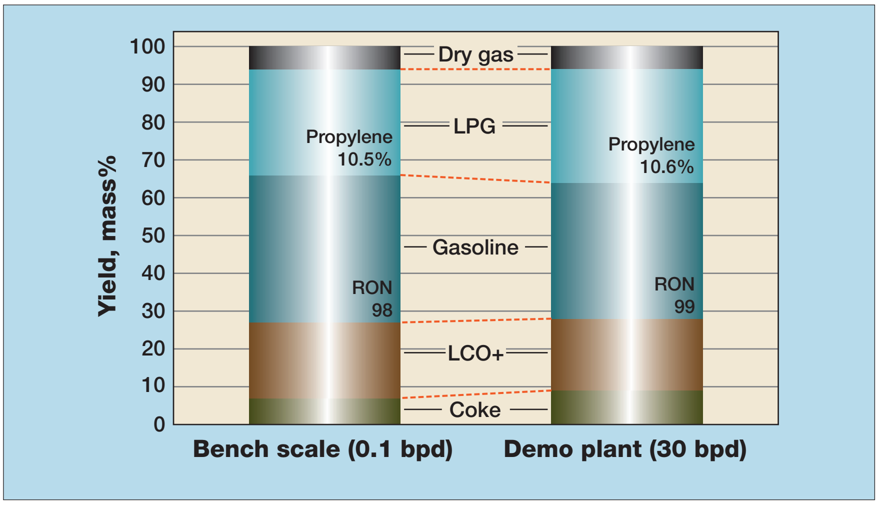

Figure 6 Bench scale vs demonstration scale results on low sulphur VGO at high severity without ZSM-5

reflux along the walls, particularly in the feed injection or catalyst pick-up zone at the bottom of the riser reactor. At very high C/O, significant back-mixing is unavoidable. This problem is overcome in a down flow reactor (DFR), where both the catalyst and feed flow downwards together (see Figure 3).

Down flow fluid-solid reaction systems have been of increasing interest in recent years to achieve plug flow reaction conditions, as summarised by Cheng.[2] When plug flow conditions are achieved, more selective primary cracking results in greater selectivity. FCC pilot work demonstrating the effects of short contact time and down flow have been reported by Del Poso[3] and Abul-Hamayel[4] (see Figures 4a and 4b). The general trend is that of greater gasoline selectivity at short contact time down flow, with a maximum yield achieved at a higher conversion level. This effect is seen in Figure 4a, where the maximum gasoline yield is about 5 wt% higher in the down flow system. When olefins are of interest, the more selective down flow reaction environment can produce substantially more light olefins (C_2-C_4) at the same gasoline yield compared to a conventional up flow system (see Figure 4b).

Although the idea of a controlled high severity, short contact time down flow reaction has been considered for some time, achieving this successfully on a commercial scale has been elusive. Extensive

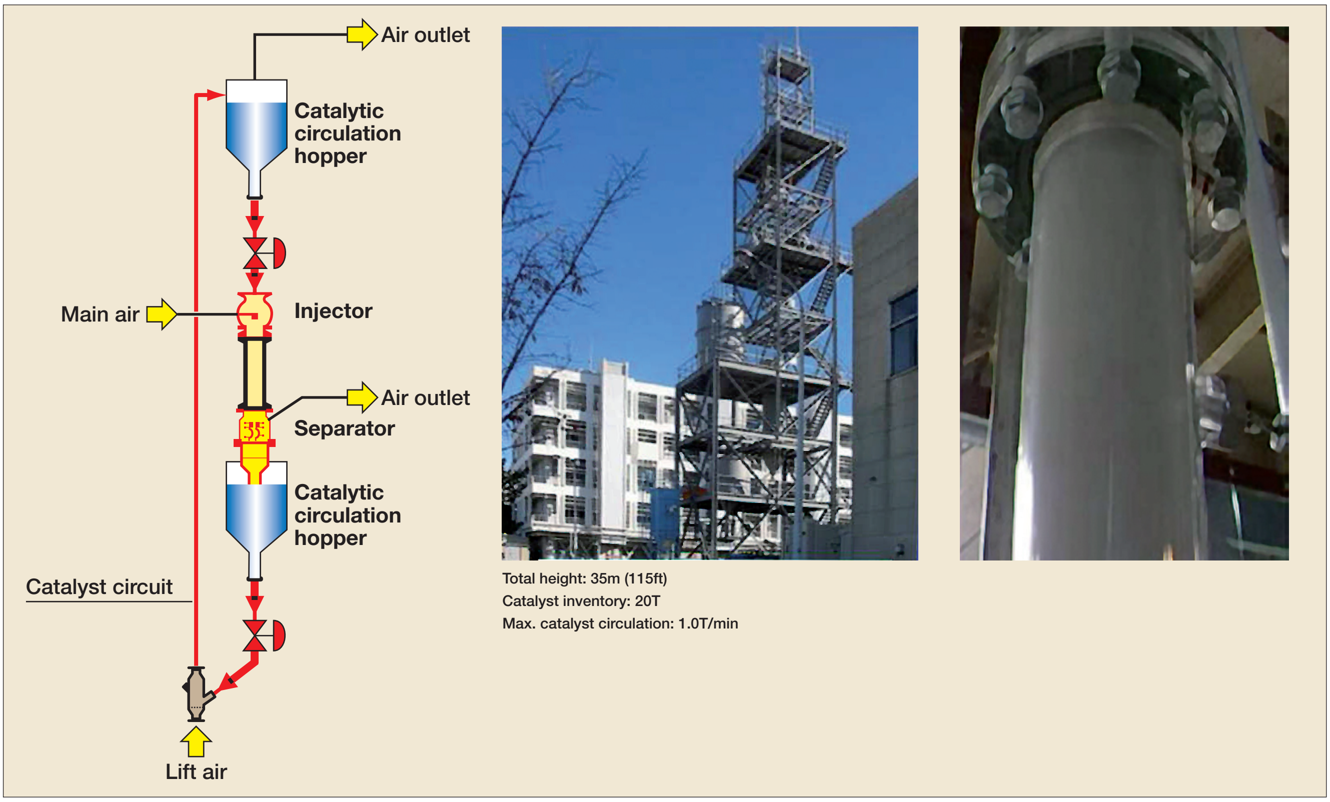

Figure 7 500 b/d equivalent cold flow testing to scale up and optimise the reaction system pilot work at the 0.1 b/d scale demonstrated the principle, catalyst system and operating conditions, but did not address how rapid mixing, reaction and efficient catalyst/gas separation can be achieved at a large scale with a target residence time on the order of 0.5 seconds. On a commercial scale, equipment design for very short contact time with the mechanical integrity to withstand high-velocity catalyst circulation in a coking environment requires extensive research, development and demonstration.

Semi-commercial unit performance

	VGO + HC Btm	HDT VGO	VGO + DAO	VGO+ AR
Feed SG	0.845	0.879	0.891	0.915
Reactor T, °C	575	595	580	600
Conv, w%	93.2	83.7	83.0	82.4
Light olefins, wt%	39	34	31	31
C_2=	4	4	3	3
C_3=	19	17	15	15
C_4=	16	13	13	12
C_5-220 gasoline, wt%	35	34	34	34
RON	98.5	98.1	98.1	98.4

Table 3

R&D history

The challenges of developing this new technology required a systematic research program undertaken by JX, KFUPM & Saudi Aramco with the support of Japan Cooperation Center, Petroleum (JCCP). Early pilot work by both JX and KFUPM in 1996-2000 demonstrated the benefits of high severity operation at controlled short contact time in down flow mode. Aramco became an active participant in the scale-up effort to design a 30 b/d demonstration unit. JX conducted large-scale, 30 b/d equivalent, cold flow testing of the catalyst circulation loop and reactor-separator equipment to validate the design of the demonstration unit.

The demonstration unit (see Figure 5) was operated from 2003-2004 at the Aramco Ras Tanura refinery. Results from the demonstration unit validated the HS-FCC concept, with good agreement between 0.1 b/d pilot results and 30 b/d demonstration (see Figure 6).[5,6]

A low sulphur VGO was cracked at high severity in both the pilot and demonstration units using only the new HS-FCC catalyst without ZSM-5 additive. A very high propylene yield, over 10%, was obtained along with a very high octane gasoline.

Work immediately began on scale-up to a commercial unit. Important lessons were learned concerning equipment design, and larger-scale cold flow work was undertaken by JX in Japan at the 500 b/d equivalent scale to optimise the feed injection zone and separator design (see Figure 7). This work was coupled with CFD simulations to assist in larger-scale equipment design.[6]

Semi-commercial unit

With the successful demonstration of HS-FCC technology at the 30

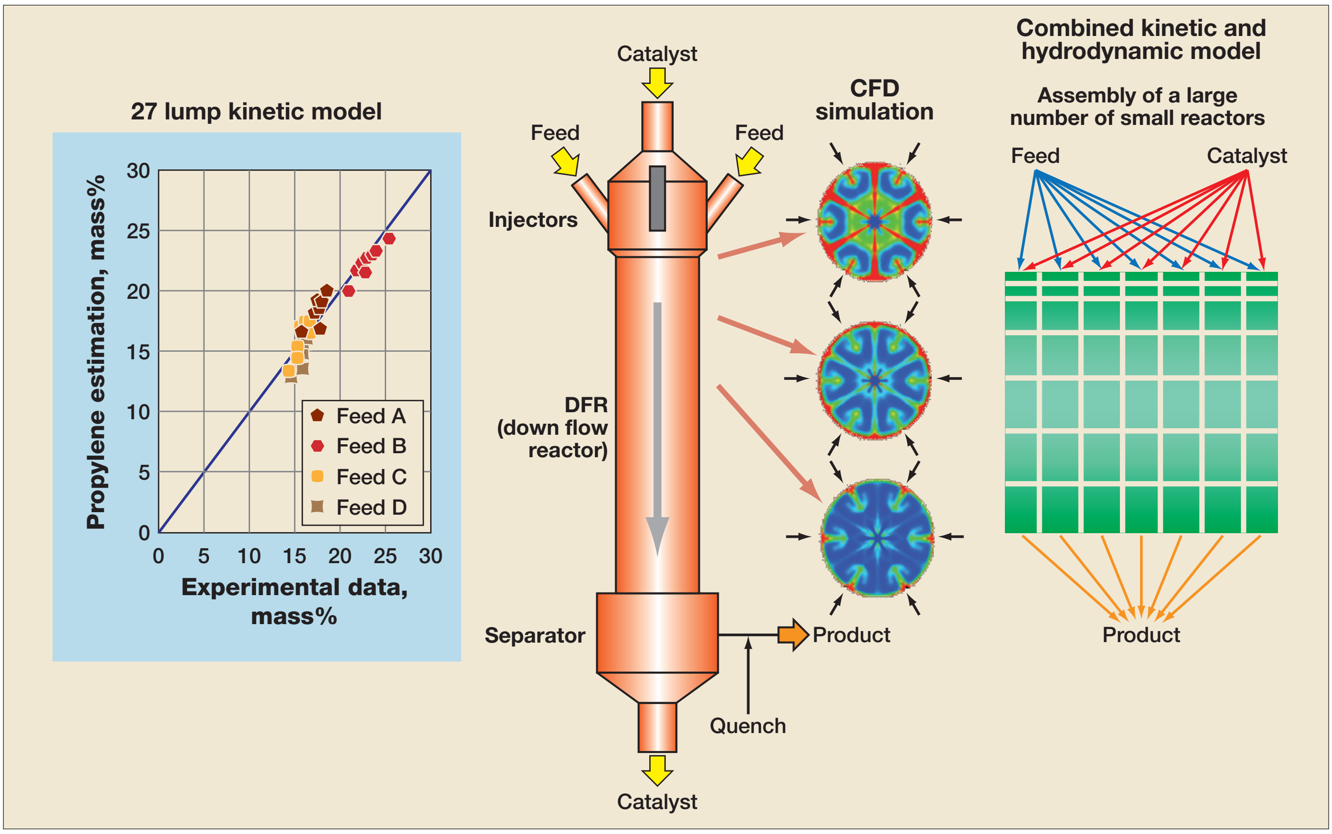

Figure 8 Combined kinetic and hydrodynamic modelling assists design and scale-up

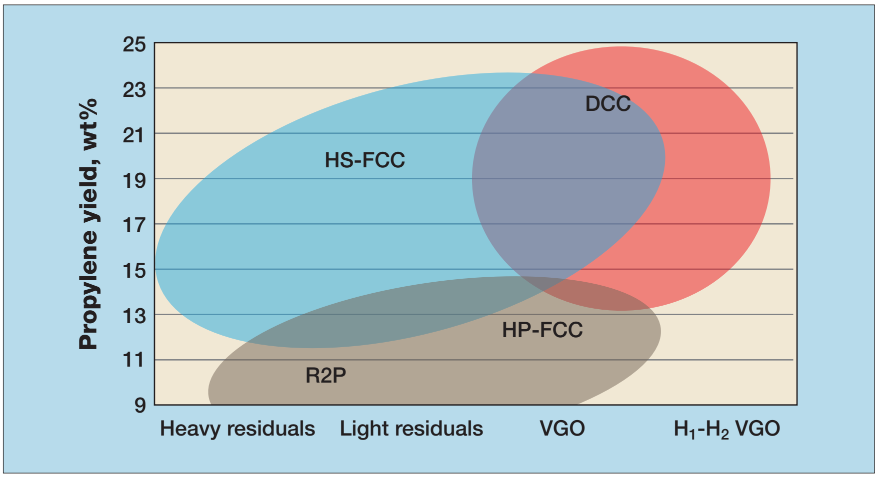

Figure 9 Family of high-propylene catalytic cracking processes

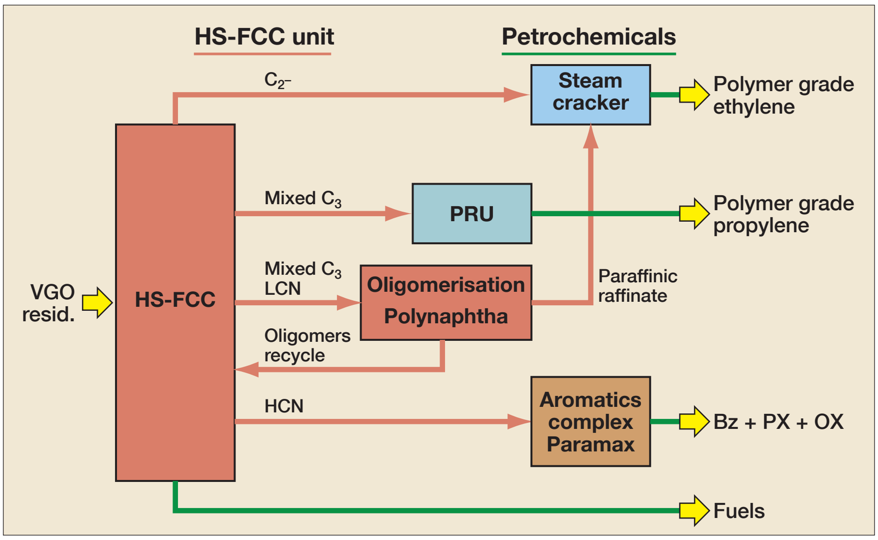

Figure 10 Integrated refinery-petrochemical complex

b/d scale completed, it was time to look forward to scaling up to a full-sized commercial unit and to plan for future licensing of the technology. Several FCC licensors were interviewed and evaluated before Axens and Technip Stone & Webster Process Technology were selected to assist in the design of a 3000 b/d semi-commercial unit, plan for a larger commercial unit, and serve as exclusive licensor for the HS-FCC technology, relying on its extensive knowledge in FCC and RFCC design.

A complete 3000 b/d HS-FCC unit with main fractionator, gas plant and flue gas treatment was designed for the JX Mizushima refinery. Chiyoda Engineering performed the detailed engineering and construction of the plant (see Figure 1), which was put on stream in early 2011.

Performance trials are on-going to evaluate yields and product properties for widely different feeds and to demonstrate equipment reliability. Preliminary results showing yields for several blends of VGO, hydrocracker (HC) bottoms, DAO and atmospheric residue are shown in Table 3. Combined light olefin (C_2-C_4) yields of 30-40 wt% have been demonstrated with 15-19 wt% propylene and 4 wt% ethylene. The yield of butenes is similar to propylene and offers opportunities for greater petrochemical integration, including oligomerisation and the FlexEne configuration for even higher propylene production.[7] These results are without the use of post-separator quench injection, which will improve olefin selectivity further. The catalyst system continues to be optimised for the various feeds.

When viewed from a petrochemicals perspective, the ethylene produced becomes a significant boost to the economics. The gasoline also has value beyond fuels, with an octane of 98-99, olefin content of 25-40 wt% and 35-50 wt% aromatics.

The testing programme will continue, with 100% residue cracking trials to begin soon. With a controlled short contact time, high C/O and p lug flow reaction system, HS-FCC is well adapted to be highly selective for both light and residue feed conversion to petrochemicals.

Throughout the programme, equipment evaluation, inspection and reliability data continue to be gathered to guide further development and scale-up to a fully commercial scale of at least 30 000 b/d. In parallel to this work, CFD simulation of the DFR and separator hydrodynamics are being combined with a kinetic model to analyse the results, validate the kinetic models, and enable accurate predictions at commercial scale for future feeds and reactor configurations.

HS-FCC in the family of catalytic cracking processes

The HS-FCC process expands the operating window of catalytic cracking to encompass heavier feeds and greater propylene potential. Commercial processes for high propylene production from light distillate feeds and residue feeds include DCC,[8] high-propylene FCC (HP FCC) and resid to propylene (R2P). More severe conditions for residue feeds to attain a higher propylene yield have proven challenging in the past due to undesired secondary reactions. High severity, combined with an optimised catalyst system and a controlled short contact time DFR reaction system, allows the new HS-FCC technology to provide selective conversion with lower fuel gas production and a greater olefin and petrochemicals yield even with heavy residue feeds. Indeed, the selectivity of the system presents opportunities to crack a wide range of conventional and unconventional feedstocks.

The technology mapping by severity and feedstock is shown in Figure 9.

With the option to operate at conventional severity or high severity, the refiner will have the ability to select an operating mode and feedstock best suited to the prevailing economic conditions. A high severity product slate rich in olefins and aromatics also makes integration with petrochemicals plants more attractive so that the natural synergy of shared intermediate products and recovery schemes can be realised.[9] An example of HS-FCC integration with a petrochemical complex is shown in Figure 10.

Global Alliance for commercialisation

The HS-FCC technology is the product of systematic process research, catalyst development, pilot work, 30 b/d demonstration unit testing, and ongoing semi-commercial operation and testing at the 3000 b/d scale. These successful results and the modelling tools developed for further scale-up make the technology ready for commercialisation. Axens and Technip Stone & Webster Process Technology are now offering HS-FCC technology on behalf of the HS-FCC Global Alliance team.

FlexEne is a mark of Axens.

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