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Petrochemical Intensity of Future Refineries and Crude-to-Chemicals

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Introduction

As the global energy landscape undergoes a seismic shift driven by sustainability goals, economic pressures, and evolving consumer demands, the refining industry faces a pivotal challenge: how to maximize the value of crude oil while minimizing environmental impact. India too has pledged to achieve Net Zero targets by 2070. This along with the growing domestic demand of energy and polymers has put a tremendous pressure on the industry to seek an optimal pathway of achieving higher petrochemical intensity for existing as well as future refineries. While conventional methods of integrating refineries with petrochemical units provides an improvement in petrochemical intensity, it does so at higher capital expense and higher operating cost leading to significant carbon emissions.

Thermal Crude to Chemicals Technology (TC2C™) is a transformative technical innovation for crude to chemicals conversion developed jointly by Saudi Aramco Technologies Company, Lummus Technology and Chevron Lummus Global (CLG). TC2C™ redefines the traditional refinery model by converting crude oil directly into high-value chemicals, bypassing many conventional steps and unlocking unprecedented efficiency and profitability.

TC2C™ is a modern intensification of traditional processes, by taking the key technological features of commercially proven technologies and fusing them together to meet new processing objectives. The technology integrates desalting, targeted crude separation, crude conditioning, and steam cracking to maximize the yield of high value chemicals. Crude is a mixture of millions of molecules. TC2C™ relies on advanced analytical techniques to first segregate easy to convert and high chemical yielding molecules and then selectively treat the heavier molecules with the optimum addition of hydrogen so that the mixed feed stream cracker (MFSC) section of the TC2C™ produces the optimal chemicals at minimum energy. Lummus' extensive experience in cracking wide range of liquid feeds in MFSC is the foundation for optimizing the front end crude conditioning configuration and tailoring the operating conditions to prepare the feedstocks for steam cracking.

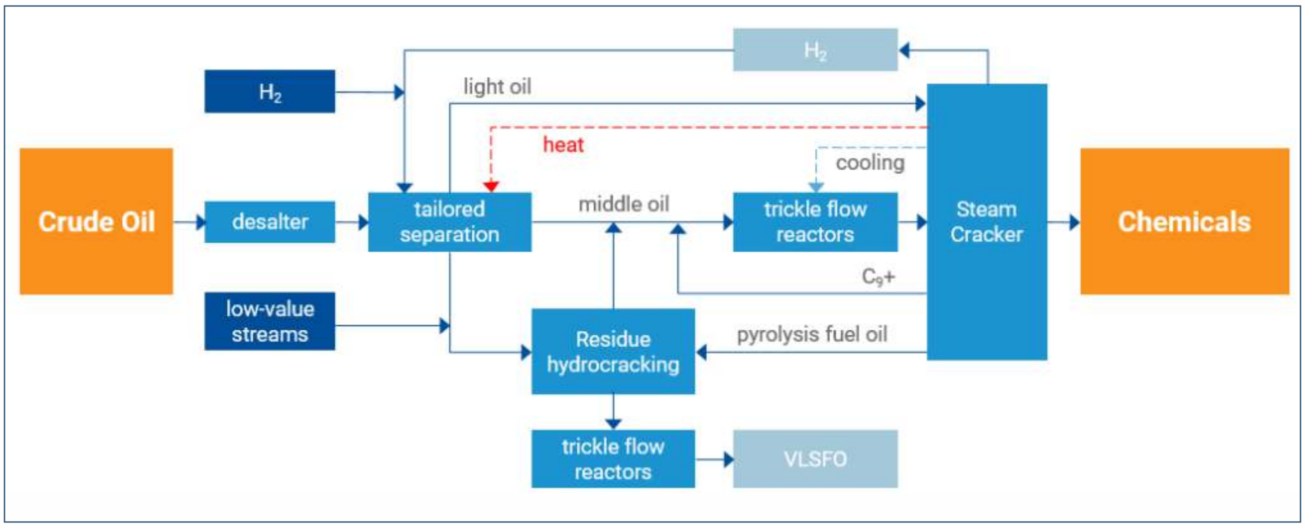
TC2C™ is derived from fundamental research in the areas of process technology, process chemistry, and catalyst technology through a robust, multi-year R&D program. This R&D program led to the development of novel, groundbreaking enhancements for crude to chemicals applications , including these key features, to name a few:

- ✓ Use of new novel proprietary separation devices which eliminates the need for energy intensive, conventional crude atmospheric and vacuum distillation units.
- ✓ Breakthrough hydrocracking catalyst with a tailored mesoporous zeolite for crude to chemicals application
- ✓ TC2C™'s fixed bed and liquid circulation reactors, which are smartly configured to selectively condition crude for MFSC to produce petrochemical building blocks such as ethylene and propylene along with other chemicals
- ✓ TC2C™ also provides the benefit of utilizing the low value orphan streams of refinery and petrochemical complex providing high chemical yield. For instance, Pyrolysis fuel oil is a highly hydrogen deficient material, rich in multi-ring aromatics with low market value, and TC2C™ upgrades this material to high value chemicals products.

TC2C™ as Advanced Refining Approach

Whole crude oil is typically fractionated in a crude oil refinery into a variety of fractions such as naphtha, kerosene, diesel, gas oil (vacuum or atmospheric) and high boiling residuum. Some of these fractions are used as starting feedstock for olefin production in petrochemical industry. Therefore, the starting feedstock for conventional olefin production is first subjected to substantial, expensive and energy demanding refining processes. TC2C™ technology redefines crude to chemicals pathways in an economically viable manner without passing through the conventional refining steps thus providing economically better route for crude to chemical conversion.

TC2C™ is a concept and a technology platform, not a fixed flow scheme. Depending upon the feeds, products and the targeted product slate, the details on the configuration are selected to meet the processing objectives.. One such configuration of TC2C™ is shown below:



In TC2C™, a normal paraffin rich light oil stream is recovered from starting feedstock (wide API range of crudes and/or condensates) using a novel separation device. This approach eliminates heavier molecules from the intermediate stream that is directly routed to the steam cracker. This step uses dilution steam to recover the n-paraffin rich lighter cut. Bottoms from the separation device are routed to another separation device that recovers a middle oil stream which is sent for fixed bed hydroprocessing for contaminant removal and hydrogen addition, using a carefully selected catalyst system. The severity of the reactions are adjusted depending on the feedstock and operating objectives, and optimizes the hydrogen consumption required to optimize the chemicals conversion. Hydroprocessing upgrades the quality of middle oil which results in improved yield of high value products and reduced fuel oil make from steam cracker.

The heaviest portion of the crude, which contains the highest concentration of contaminants such as metals, CCR, and asphaltene, is routed to a liquid circulation (LC) reaction platform utilizing either extrudate or slurry catalyst. The most critical technology component is these residue hydrocracking reactors as they deal with conversion of asphaltenes from crude. The LC reaction section converts the asphaltene and recycle pyrolysis oil from the steam cracker along with other low value stream available from refinery. The remaining unconverted oil is filtered and sent over a fixed bed reactor system to meet IMO-compliant very low sulfur fuel oil (VLSFO) specification (<0.5 wt% S). Products from converted products LC reaction section are further treated in fixed bed reactor which further improves the quality of cracker feed for optimal cracking heater run length and chemicals yield. This system ensures that no heavy polynuclear aromatics (HPNA) reach the steam cracker.

Thus, TC2C ensures that no part of the converted crude is wasted while maximizing the yield of chemicals. While simultaneously ensuing that the reliability of the refinery components matches the reliability of the cracker in terms of on-stream factor.

Key Benefits of TC2C™ for Chemicals and Fuels

One of TC2C™'s most compelling advantages is its ability to convert up to 80 wt% of crude oil into chemicals, including olefins and aromatics. This high yield is crucial in a market where petrochemical demand is outpacing GDP growth, especially in developing economies like India. A comparison of chemicals make of TC2C™ against conventional chemical refinery and naphtha cracker complex is provided below. The comparison is based on generating 2000kTA Ethylene product from the complex along with other incidental products. As evident from this comparison, TC2C™ provides significantly high chemical yield compared to a typical refinery while generating no low value streams such as PFO or LSFO. As compared to the naphtha cracker, TC2C™ provides benefit wrt naphtha vs crude price spread while maximizing the high value products make.

Flowrates in kta	TC2C Complex	Chemical Refinery	Naphtha Cracker
Crude	6262	8355	0
Naphtha	0	0	4806
Ethylene	2000 (32%)	2000 (24%)	2000 (42%)
Propylene	1396 (22%)	1664 (20%)	824 (17%)
Other chemicals	1295 (21%)	2163 (26%)	806 (17%)
VLSFO	567 (9%)	0	0
LSFO / PFO	0	1348 (16%)	248 (5%)
Total chemicals	4691	5827	3630
Total high value products	5258	5827	3630
% Chemicals / High Value Products	75.0 / 84.0	69.7 / 69.7	75.5 / 75.5

By eliminating several energy-intensive refining steps and optimizing hydrogen usage, TC2C™ significantly reduces greenhouse gas emissions. The process is designed to be energy-efficient, aligning with global decarbonization goals and ESG mandates. Comparison of Specific energy and carbon emission is provided below for TC2C complex vs typical refinery and Naphtha cracker is provided below. As evident from the table below, TC2C consumes lowest energy and therefore generates least quantity of carbon emissions per kg of high value chemicals make from the unit.

Specific Energy	TC2C Complex	Chemical Refinery	Naphtha Cracker
kcal/kg ethylene	7243	10075	5156
kcal/kg chemicals	3024	3458	2841
kcal/kg high value products	2553	3458	2841
CO2 emissions			
kg/kg ethylene	1.45	2.09	1.08
kg/kg chemicals	0.61	0.72	0.6
kg/kg high value products	0.51	0.72	0.6

TC2C™ offers 30–40% savings in capital and operating expenditures compared to conventional refining setups. This is achieved through elimination of atmospheric and vacuum distillation units, significantly reduced equipment count, and lower utility consumption. This upfront saving improves the project returns on investment and make the profits sustainable for the operator.

Historically, crude to chemicals complexes have been designed around very light crudes and condensates, which require little to no conditioning prior to feeding into petrochemicals complex. The technology platform breaks through the traditional feedstocks limitations and extends technology solutions/offerings to a wider feed basis with the ability to upgrade the bottom of the barrel and optimize the hydrogen consumption to improve the overall yield of chemicals.

TC2C™ can process a wide API range of crude and condensate feedstocks, including low-value orphan streams such as high sulfur fuel oil, slurry oil and light cycle oil (LCO) from FCC and low-value recycle stream from Mixed Feed Steam Cracker (MFSC). In the development of TC2C™, a major focus area was on the PyOil processing, including testing of different types of pyrolysis oils at a wide range of pyoil proportions in the feed mix to ensure that the concept was robust. Pyrolysis fuel oil is a highly hydrogen deficient material, rich in multi-ring aromatics with low market value. Adding the pyrolysis oil to the liquid circulation reactors where asphaltene conversion takes place, permits higher conversion of asphaltenes, while maintaining product stability.

This flexibility enhances operational resilience and feedstock optimization. This feature also makes it a technology of choice for refiners who are willing to improve their chemical footprint while getting rid of the low value streams.

Integration Benefits of TC2C™

Unlike typical refinery and petrochemicals set up, TC2C™ offers a seamless Integration within the crude conditioning section reactor platforms and between the crude conditioning and steam cracker sections of the unit. This integration allowed the joint team of various SME's to reimagine the process configuration and eliminate processing equipment which is not required to meet the new processing objectives. TC2C™ is designed to tailor the hydrogen content of crude components to create an optimal feed for mixed-feed steam crackers, which boosts the production of ethylene, propylene, and other valuable olefins. Hydrogen generated in the steam cracker can be utilized in the hydroprocessing reactors.

Low value cracker streams such as PGO and PFO can be processed in the crude conditioning fixed and/or ebullated bed reactors to improve the overall chemicals yield. Not only materials such as recycles, hydrogen and utilities are exchanged between crude conditioning section and steam cracker, processing conditions are also optimally utilized within and between these sections which is essential for improved carbon intensity of the process.

TC2C™ utilizes the CLG's commerically proven experience of integrating multiple fixed-bed and liquid circulation reactors in crude conditioning section, enabling selective conditioning of crude and efficient conversion of crude molecules to a full boiling range of feed molecules which can be routed directly to the steam cracker. This intensification reduces the number of processing steps and improves profitability of the unit.

Strategic Implications for Refiners

With global fuel demand plateauing and petrochemical consumption surging, TC2C™ enables refiners to pivot toward chemicals, capturing higher margins and future-proofing their operations. By reducing emissions and improving energy efficiency, TC2C™ helps refiners align with sustainability targets, regulatory requirements, and investor expectations.

The ability to process diverse feedstocks and produce multiple high-value outputs makes TC2C™ a strategic hedge against market volatility, feedstock price fluctuations, and geopolitical risks.

Despite its innovative nature, TC2C™ is built on commercially proven components, minimizing the risk associated with new technology adoption. This ensures high on-stream factors and operational reliability. The first license for TC2C™ was granted to S-OIL for their SHAHEEN project in early 2020, which is being constructed in Ulsan, Republic of Korea, marking a significant milestone in the technology's commercialization journey. The S-OIL SHAHEEN project is scheduled to begin operations in the second half of 2026. Since then, several grassroots and brownfield opportunities have emerged, demonstrating the technology's adaptability and market appeal.

Conclusions

TC2C™ technology represents a paradigm shift in refining, offering a smarter, cleaner, and more profitable way to convert crude oil into chemicals. With its high yield, integration flexibility, and sustainability credentials, TC2C™ is poised to become a cornerstone of next-generation refineries. As the industry in India and elsewhere navigates the twin challenges of energy transition and economic uncertainty, TC2C™ provides a robust, future-ready solution that maximizes value from every barrel of crude. Optimal consumption of crude will help reduce the ForEx outgo in importing crude for the domestic demands making this a technology of choice for a cleaner, sustainable and self-reliant energy future.