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Convert bottom-of-the-barrel into diesel and light olefins

Integrating residue hydrocracking operations with advanced fluid catalytic cracking optimizes upgrading of heavy crude oils

M. RAMA RAO, D. SONI, and **G. M. SIELI,** Lummus Technology, Bloomfield, New Jersey;
D. BHATTACHARYYA, Indian Oil Corp. Ltd., R&D Center, Faridabad, India

Global demand for diesel is projected to grow from approximately 23 million barrels per day (MMbpd) in 2006 to 37 MMbpd by 2030, while the demand for gasoline is expected to increase from 22 MMbpd to 27 MMbpd over the same period.[1] This increase in diesel demand (14 MMbpd) is almost three times the increase in gasoline demand (5 MMbpd).

Gasoline demand in the US and Western Europe is expected to stay flat or even decrease. These trends have led refiners to consider various options for maximizing diesel production from current operations and/or adding new units targeted at meeting this projected new demand for diesel while improving margins.

Olefin demand trends. Demand for light olefins (ethylene, propylene and butylenes)—the building blocks for the petrochemical industry—is also growing significantly. Several announced steam-cracker projects are expected to produce sufficient ethylene to meet new petrochemical demand. While the propylene production—a byproduct of liquid-feed steam crackers—will also increase, it will be insufficient to meet the growing future demand. In looking ahead, catalytic cracking is expected to continue to be the prominent propylene source.[2]

Adapting to market conditions.

The decline in fuel oil demand and tighter fuel specifications, coupled with more stringent environmental regulations, have compressed refinery margins. There is a growing drive to cost-effectively maximize production of high-value products from every barrel of crude oil processed. In addition, the considerable price differential between light/sweet and heavy/sour crudes is driving the market to process larger quantities of heavier crudes. There are many options on how to upgrade the "bottom of the barrel."

Carbon rejection. Among the carbon rejection processes, delayed coking has been quite popular recently. Solvent deasphalting (SDA) is used to separate residue from deasphalted oil (DAO), which is a feedstock for fluid catalytic cracking (FCC) or hydrocracking units. Although this process maximizes DAO, the pitch (bottoms of the SDA unit) contains very high levels of Conradson carbon residue (CCR) and metal contaminants, thus posing serious concerns for disposal and/or utilization. Visbreaking is also used to reduce residue viscosity while maximizing distillate production. Products from all of these processes require a substantial degree of post treatment to improve quality and to meet desired fuel specifications.

Hydrogen addition. Conversely, hydrogen addition technologies, such as atmospheric residue desulfurization (ARDS) and vacuum residue desulfurization (VRDS), produce better quality products. However, because of the high investment and high hydrogen addition requirements, these technologies are used for only about 20% of the global residue upgrading capacity.

New challenges.

When determining which process(es) to implement, it is necessary to broadly examine the refiner's many challenges, including possible changes in product demand, quality and pricing, and the need for the refinery to be able to process heavy/sour crudes. Advancements in process technologies play a crucial role. Now, more than ever, the ability to upgrade the bottom of the barrel and to produce high-quality products while processing a heavy crude slate are key drivers for better margins.

Several options have the capability not only for handling heavy crudes using various residue upgrading technologies, but also for tailoring schemes to maximize high-demand products such as diesel and light olefins. The scheme described here involves the integration of the innovative ebullated-bed hydrocracking process and advanced fluidized catalytic cracking (FCC) processes.

The ebullated-bed residue hydrocracking process is a highly effective hydrogen-addition process that upgrades heavy residue feeds to good-quality diesel and FCC feed. The advanced FCC process is a catalytic cracking process that maximizes light olefins from various feedstocks such as vacuum gasoils (VGO), atmospheric residues, etc. This scheme is also flexible enough to shift the product slate to meet fluctuations in the marketplace with respect to the required products and/or the type of crude processed.

New hydrocracking process.

The ebullated-bed residue hydrocracking process[a] features high distillate yields while efficiently removing feed sulfur, CCR content and metal contaminants from vacuum residues. It is safe, reliable and easy to operate. Over the years, advances in the ebullated-bed residue hydrocracking process have significantly reduced capital investment and operating costs while extending the conversion and process capabilities, including:

- Hydrogen purification systems
- Low treat-gas rates
- Integrated hydrotreating/hydrocracking
- Inter-reactor separator/stripper
- Third-generation bottoms recycle pan
- Onstream catalyst addition and withdrawal
- Maintaining constant pressure drop across the reactor
- Isothermal reactor operation
- Ability to process heavy, high-metals, high-solids content feedstocks.

Integrating the ebullated-bed residue hydrocracking unit with hydroprocessing results in significant cost savings. The recycle of high-temperature vacuum bottoms to the reactor and the use of aromatic diluents, such as FCC slurry oil, help in controlling coke and sediment formation, which could otherwise lead to potential difficulties in maintaining proper catalyst bed ebullation. The advent of membrane purification systems has resulted in very high-purity recycle gas and reduced recycle gas rates to the ebullated-bed residue hydrocracking reactor. This enhances the total reactor operation since internal liquid recirculation is increased as a result of reduced superficial gas velocity and holdup. This also helps in better back-mixing of liquid and catalyst bed, thereby minimizing incidences of hot spots, catalyst-bed slumping, channeling and flow maldistribution.

TABLE 1. Crude oil slate comparison

Crude name	Base Case, bpsd	Case 1, bpsd	USD/bbl
Maya	35,000	80,000	60.39
Urals	35,000	80,000	64.48
Bonny Light	65,000	20,000	70.57
Sarir	65,000	20,000	66.74
Total	**200,000**	**200,000**	

The ebullated-bed residue hydrocracking process has great inherent flexibility to meet variations in feed quality and throughput, product quality, and reaction operating severities (temperature, space velocity, conversion, etc).[3,4] This is a direct result of the ebullated catalyst-bed-reactor system. Online catalyst addition and withdrawal capabilities facilitate in the controlling the catalyst consumption and activity in response to variations in feed quality (metals, sulfur, asphaltenes, etc.) Depending on feed quality, diesel and gasoil (FCC feed) yields in the range of 19 vol%–43 vol% and 30 vol%–40 vol%, respectively, can be produced in the ebullated-bed residue hydrocracking unit. Typical operating parameters, feed quality and product yields can be found elsewhere.[3]

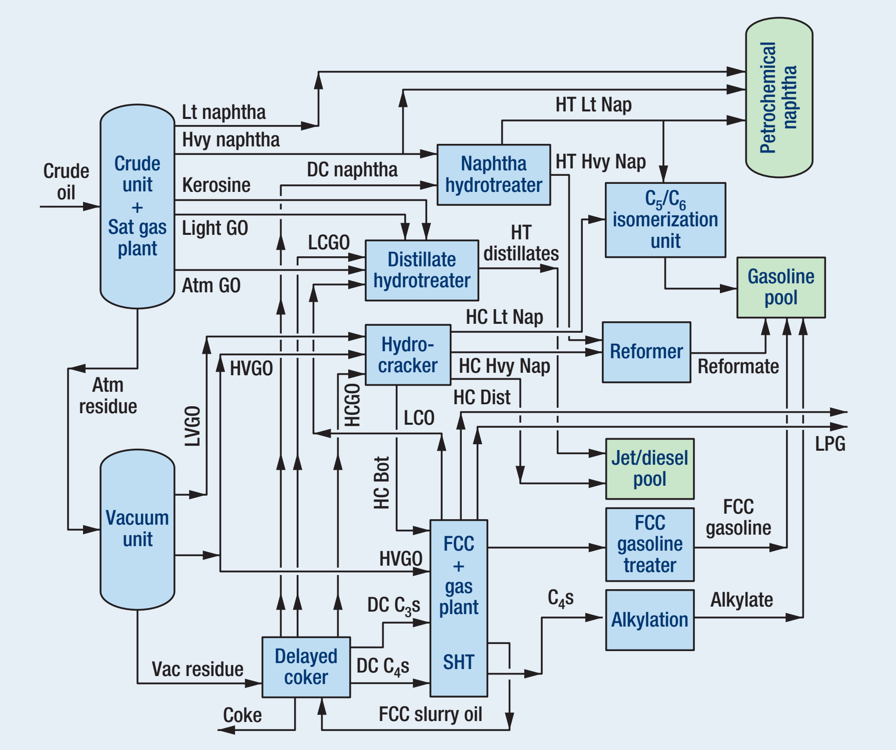

FIG. 1 Simplified flow diagram of the Base Case refinery.

New advanced FCC process. This process combines a proprietary advanced FCC catalyst with proprietary state-of-the-art FCC/RFCC technology.[b] The advanced FCC process is unique for its direct conversion of heavy feeds, such as VGO and residue oils, to high yields of light olefins. It features:

- A proprietary advanced FCC catalyst formulation that is:
  - o Very selective in cracking molecules of different shapes and sizes to produce high yields of light olefins
  - o Highly tolerant of metals and can operate with a high vanadium concentration on the equilibrium catalyst. This feature is very important for residue-feed processing as it minimizes the fresh catalyst consumption rate.
- A highly selective reaction system that involves only riser cracking without any recycle of the spent catalyst.
- Easy adjustment of operating conditions and catalyst formulation to meet the changing requirements of product demands and feedstock quality.

The reactor regenerator section equipment and hardware pieces are designed to utilize the maximum potential of the advanced FCC catalyst with the specific feedstock to produce light olefins. This FCC process utilizes higher riser reactor temperature (530°C–600°C), higher catalyst-to-oil ratio (12–20), and lower hydrocarbon partial pressure to achieve high conversion and selectivity for light olefins. Since all the cracking reactions take place in the short-contact-time riser reactor, with very high catalyst-to-oil ratio and all high-activity catalyst, the selectivity to light olefins is very high. The LPG produced contains about 45 wt%–50 wt% propylene. Total olefins in LPG can be as high as 80 wt%.

The major concerns when processing heavier feedstocks having high CCR and metals are: excessive coke make, high regenerator temperature, high dry-gas make and high catalyst makeup rates. The advanced FCC catalyst's low selectivity to delta coke and dry gas and its high tolerance to metals, in conjunction with the advanced hardware design, allow this unit to easily handle these difficult feedstocks. Demonstrating the full flexibility of the advanced FCC process, it can accept feedstocks ranging from hydrotreated VGO to heavy residue oils and can be designed and operated to maximize propylene, or propylene plus ethylene,

TABLE 2. Comparison of FCC feedstock quality

	Base Case	Case 1
Gravity, °API	22.1	18.7
Sulfur, wt%	1.12	2.0
Con. carbon content, wt%	1.35	2.5
Nickel, ppmw	0.73	6.2
Vanadium, ppmw	1.6	13.8
Total nitrogen, ppmw	1,495	2,557

or propylene plus gasoline.[5]

Process integration/reconfiguration. The refinery considered in this study plans to improve its capability to process heavier crudes and also maximize diesel, jet fuel and light-olefin products. The consequences of processing higher quantities of heavy crude are:

- A substantial reduction in middle distillate yields or a higher yield of atmospheric bottoms, leading to limitations in vacuum tower capacity
- Inferior product quality:
    - o Requiring additional treating facilities and/or
    - o Resulting in secondary processing units, such as hydrocracking and FCC units, to utilize more hydrogen and/or catalyst.

Such a plan is likely to require a significant level of capital investment. To optimize the refinery configuration, an in-house linear programming (LP) model was used that captures the changes in crude quality, optimizes product blend to meet the desired product specifications and estimates the incremental utilities required. The model also features economic evaluation capabilities that account for new investments, incremental utility costs, cost of feed/product, imports/exports, etc.

The LP model initially was configured for a base refinery operation, and then reconfigured to account for changes in crude slate and associated effects on the product yields and quality, and changes in costs. These parameters were used in the LP modeling study:

- In both cases, refinery crude throughput capacity is 200,000 bpsd
- Base refinery is currently processing a blend of 35 vol% heavy and 65 vol% light crudes; the reconfigured refinery is expected to process 80 vol% heavy crude
- Capacity potential of all existing process units is to be fully utilized
- Production of diesel, jet fuel and propylene is maximized while processing the heavy crude slate
- Fuel quality is to meet Euro-IV specifications
- Crude and product prices are based on Rotterdam 2007 average spot prices.

Several configurations were investigated to meet the objectives of the refinery in a cost-effective manner. It was found that incorporating an ebullated-bed residue hydrocracking unit and revamping the FCC unit to an advanced FCC process

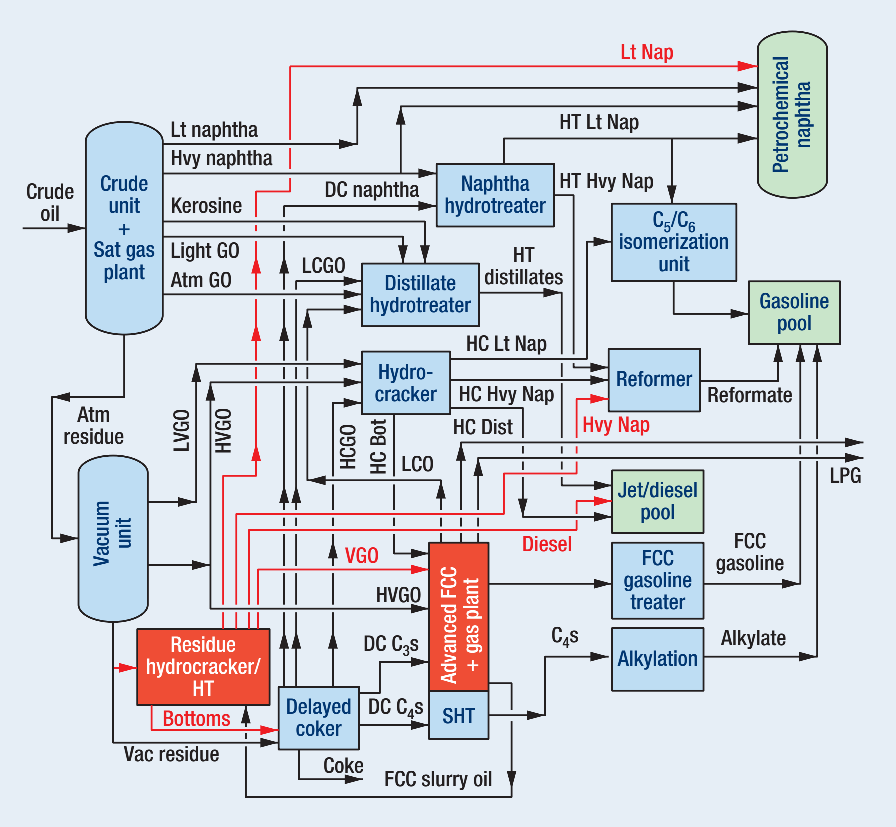

FIG. 2 Simplified flow diagram of an upgraded refinery with ebullated-bed residue hydrocracking process and advanced-FCC unit.

TABLE 3. Comparison of process unit capacity

	Base Case		Case 1 Incremental	
Process unit	bpsd	Ktpy	bpsd	Ktpy
Crude unit	200,000	9,450	0	340
Vacuum unit	87,554	4,591	9,430	660
Delayed coking unit	29,570	1,701	0	0
Ebullated–bed residue hydrocracking process	—	—	20,005	1,173
FCC (advanced FCC unit)	27,325	1,401	–3,080	–130
Hydrocracker	44,810	2,285	6,300	335
Naphtha hydro treater	27,246	1,159	590	0
Reformer	40,651	1,710	–3,160	–160
Hydrogen plant, MMscfd	61		47	
Amine regeneration, gpm, DEA	1,177		415	
SRU + TGT, metric tpd	285	—	77	—
C_5 isomerization	5,113	195	140	1
FCC gasoline HT	15,671	669	–6,680	–290
Alkylation	4,365	171	–115	–4
C_4 SHT unit	4,335	142	–520	–16
Diesel HT unit	67,028	3,180	180	6

TABLE 4. Product prices and comparison of product rates and imported feeds

		Base Case		Case 1	
Products	**USD/bbl**	**bpsd**	**Ktpy**	**bpsd**	**Ktpy**
Propylene-PG	74.7	2,401	70	6,316	183
Euro-IV 92 RON gasoline	76.93	69,511	2,938	63,405	2,664
Petrochemical naphtha	72.78	33,669	1,319	31,935	1,263
Euro IV diesel	82.26	87,023	4059	88,370	4,106
Jet fuel	85.01	7249	328	10,000	453
Sulfur	25 ($/metric ton)	190 (metric tpd)	67	435 (metric tpd)	152
Coke	30 ($/metric ton)	1,303 (metric tpd)	456	1,525 (metric tpd)	534
Diesel + Jet fuels		94,272	4,387	98,370	4,556
Imported feeds					
Natural gas ($/MMBtu)	7	444 (metric tpd)	155	364 (metric tpd)	127
MTBE	90.07	6,750	281	7,038	294

TABLE 5. Total installed cost, gross revenue and simple payback

Investments costs, MMUS$	Base	Case 1
ISBL	—	590.4
Utilities + offsites	—	178.3
Total installed cost, MMUS$	—	768.7
Gross revenue, MMUS$/yr	576.7	780.7
Increase in gross revenue, MMUS$/yr	—	204.0
Simple payback, yr	—	3.77

would provide significant advantages, especially if a refinery is geared to process heavy crudes for the cost advantage. This combination of processes provides the refinery with greater flexibility to accept wider variations in crude quality while optimizing refinery margins. For a better understanding of the proposed scheme, several case studies are presented here.

Base Case. The Base Case represents the base refinery configuration, which uses a delayed coking unit for residue upgrading as shown in Fig. 1. As indicated in Table 1, the crude blend consists of 35 vol% heavy crude (mix of Maya and Urals) and 65 vol% light crude (Bonny Light and Sarir).

Case 1. The refinery upgrade (Fig. 2) involves adding a new ebullated-bed residue hydrocracking unit and revamping the existing FCC unit to an advanced FCC design. This case is based on the refinery processing 80 vol% heavy crude, as listed in Table 1. The increased volume of heavy crude results in a higher volume of atmospheric tower bottoms (ATB) and vacuum residues (VR). Part of the VR is routed to the ebullated-bed hydrocracking process to maximize diesel product and to produce feed for the advanced FCC unit. The LP modeling studies suggest that a blend of 80 vol% heavy and 20 vol% light crude is optimal because it maximizes the amount of diesel and light olefins. Even though increasing the heavy crude portion beyond 80% lowers feed cost, it poses limits on yields and in meeting Euro-IV diesel quality.

The delayed coker capacity is maintained equivalent to the Base Case by processing a blend of virgin VR and ebullated-bed residue hydrocracker bottoms. The feed to the advanced FCC unit consists of the heavy vacuum GO (HVGO) cut from the ebullated-bed residue hydrocracking unit and virgin VGO, which is significantly less than the Base Case feed to the FCC unit. To supplement the advanced FCC unit feed, ATB is included as one of the feed constituents. Typically, the inferior feed quality of this stream (Table 2) would adversely affect the FCC product yield pattern and catalyst makeup rate. However, this effect is minimized in the advanced FCC unit as the process can efficiently handle inferior feedstocks without a catalyst cooler and huge catalyst makeup rates. Despite the inferior feed, propylene and butylenes production is increased from 5.1 wt% and 4.1 wt% to 17 wt% and 8.2 wt% in the advanced FCC unit, respectively.

The propylene from the advanced FCC unit, after treatment, can be used as a petrochemical feedstock. A portion of the C_4s is used to produce alkylate for the gasoline pool. Light cycle oil (LCO) from the advanced FCC unit is processed in the existing hydrotreater. Distillate from the ebullated-bed residue hydrocracker is processed in an integrated hydrotreater/hydrocracker reactor arrangement, with the hydrocracker processing incremental virgin VGO. Slurry oil (CLO) is recycled to the ebullated-bed residue hydrocracker as aromatic diluent to minimize coke and sediments formation. This scheme has the flexibility to process a higher quantity of heavy/opportunity (i.e., lower cost) crudes and still produce Euro-IV quality fuels and petrochemical feedstocks.

Table 3 summarizes the feed capacities of all the processing units. As shown in Table 3, the revised configuration is able to effectively utilize the capacities of most of the existing process units. The FCC gasoline hydrotreating unit and C_4 selective hydrotreating (SHT) unit capacities are under-utilized, as the current objective is to reduce gasoline production. As expected, hydrogen consumption is increased considerably and has been considered in the evaluation of the refinery upgrade.

Table 4 shows that diesel and jet fuel product increase from a total of 4,387 Ktpy in the Base Case to 4,556 Ktpy in Case 1. Although it is possible to increase jet fuel production, it was limited to the projected demand of 33% over the Base Case (i.e., equivalent to 453 Ktpy). **Note**: Revamping the existing FCC unit to an advanced FCC design resulted in an increase in propylene from 70 Ktpy (Base Case) to 183 Ktpy in Case 1. Even though the heavy crude content was increased from 35 vol% (Base Case) to 80 vol% (Case 1), it was possible to increase the quantity of diesel, jet fuels and propylene by incorporating the ebullated-bed residue hydrocracking and advanced FCC units. Otherwise, the middle distillates yield/quantity would have been much lower than that of the Base Case. The incremental butylenes (98 Ktpy) produced from the advanced FCC unit are used to produce alkylate, meeting the internal fuel requirements and minimizing natural gas imports, which is a specific requirement in this case. Alternatively, the incremental butylenes can also be sold separately as a petrochemical feedstock.

Economic benefits. The estimated total installed cost for Case 1 is presented in Table 5, together with the gross margin for the Base Case and Case 1 and the simple payback for Case 1. The economics of the project are attractive, with an estimated simple payback period of less than

3.8 years. The proposed scheme results in significant incentives for refiners aiming at improving crude blend flexibility with increased diesel and propylene production.

Conclusions: Several recent factors have influenced the refinery outlook:

- Demand and growth of diesel compared with gasoline, coupled with stringent automotive fuel specifications
- The use of the refinery as an alternate source for petrochemical feedstocks, leading to integration of refinery operations with a petrochemical complex
- Shrinking refinery margins due to higher/volatile crude oil prices, which increase the need to process opportunity/inferior feedstocks into useful products while enhancing yields, product quality and selectivity.

To address these issues, many existing refinery configurations include an FCC unit and delayed coker to maximize gasoline production and to upgrade the bottom of the barrel, respectively. However, adding a new ebullated-bed hydrocracker and revamping the FCC unit to an advanced design can result in:

- Increased diesel and light-olefins product yields and quality
- Process integration via feed/product stream sharing
- Improved feed quality for FCC unit
- Ability to handle heavier crudes efficiently and more cost effectively.

These advantages make the combination of the ebullated-bed residue hydrocracking process and the advanced FCC units an attractive option for refiners. **HP**

LITERATURE CITED

For complete literature cited, visit HydrocarbonProcessing.com.

NOTES

[a] The process is licensed by Chevron Lummus Global (CLG), a joint venture between Chevron U.S.A. Inc., a wholly owned subsidiary of Chevron Corp., and Lummus Technology, a CB&I company.

[b] Process developed by Indian Oil Corp. Ltd.'s Research & Development center, with the state-of-the-art FCC/RFCC technology and know-how of Lummus Technology.

Rama Rao Marri is a principal process technology engineering specialist at Lummus Technology in Houston, Texas. He has more than 17 years of experience in the area of FCC process design, development and technical services. He was the co-inventor of the Indmax FCC process developed by IOC R&D center for converting heavy feeds, including residue to light olefins, i.e., propylene and ethylene. He has about 11 patents and 20 publications/papers to his credit. Mr. Marri has a MS degree in chemical engineering from Indian Institute of Technology, Kanpur, India.

Dalip Soni is the director, FCC Technology, at Lummus Technology in Houston, Texas. He has 30 years of experience in process design, research, development and evaluation of petroleum refining and synthetic fuel processes. The majority of his experience has been related to FCC technology having worked on several design and development projects. He has BS degree in chemical engineering from Panjab University, India, and an MS degree in chemical engineering from Oklahoma State University.

Gary Michael Sieli is the director of process planning for Lummus Technology's Process Planning Group in Bloomfield, New Jersey, and has been with Lummus since 2002. He has a BS degree in chemical engineering from the New Jersey Institute of Technology and an MS degree in chemical engineering from Rutgers University. Mr. Siele has authored several papers on refinery planning, heavy oil upgrades and delayed coking, and has more than 32 years of experience in the refining industry.

Debasis Bhattacharyya is a senior research manger in the R&D Center of Indian Oil Corp. Ltd. He holds a B. Tech degree in chemical engineering from Calcutta University and M. Tech degree from Indian Institute of Technology, Kanpur. He joined Indian Oil in 1991 and has been engaged in providing technical services to refineries on catalyst selection, process optimization, troubleshooting, revamping various refining processes and also the development and commercialization of new technologies. He holds 10 US patents and authored more than 35 papers in national and international journals and symposiums. He is a member of Indian Institute of Chemical Engineers.