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Research on Upgrading Path of Efficient Conversion Process for Refining and Chemical Catalytic Cracking Feedstock

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Abstract: This study addresses critical challenges in the refining and petrochemical industry, including low feedstock conversion efficiency and poor feedstock adaptability in catalytic cracking processes. Through systematic analysis of feedstock physicochemical properties and key process constraints, the research explores three strategic dimensions: feedstock pretreatment optimization, reaction process control, and process-catalyst synergy enhancement. By refining pretreatment parameters, precisely regulating operational metrics, and establishing integrated process-catalyst coordination systems, the study proposes targeted process upgrades for efficient catalytic cracking feedstock conversion. These innovations enable directional feedstock transformation and increased light oil yields, providing actionable technical solutions for improving catalytic cracking process performance, energy efficiency, and operational optimization in the refining sector.

Keywords: Refining and chemical industry; Catalytic cracking; Efficient feedstock conversion; Process upgrading

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1. Analysis of physical property characteristics of catalytic cracking feedstock and transformation constraints

1.1. Hydrocarbon composition and structural characteristics of different categorization catalytic cracking feedstocks

The feedstocks for catalytic cracking in refining and chemical processes encompass various categories such as atmospheric heavy oil, vacuum residue, and coking waxy oil, each exhibiting significant differences in hydrocarbon composition and molecular structure. Atmospheric heavy oil contains relatively high proportions of saturated hydrocarbons and naphthene, features a relatively simple molecular chain structure, and exhibits low aromatization degree, making it an ideal base feedstock for catalytic cracking. Vacuum residue is rich in polycyclic aromatic hydrocarbons and gum-like asphaltenes; its molecular structure is complex with limited branching and high degree of aromatic ring condensation, rendering its macromolecular structure resistant to rapid cleavage during catalytic cracking reactions, a major challenge for feedstock conversion. Coking waxy oil contains elevated proportions of olefins and aromatic hydrocarbons, along with certain heteroatom compounds; its structural instability increases the tendency for coking during reactions, thereby compromising overall conversion efficiency.

There are significant differences in the carbon chain length and branching degree of hydrocarbon molecules among various refining and petrochemical feedstocks. Straight-run feedstocks exhibit relatively uniform carbon chain distribution and moderate branching, making them prone to chain scission and isomerization reactions during catalytic cracking. Secondary processed feedstocks such as coking waxy oil and deasphalting oil have broader carbon chain distributions, with a higher proportion of large-molecule heavy hydrocarbons and fewer branched structures, resulting in reduced effective chain-scission efficiency and decreased production of light hydrocarbon products during catalytic cracking. Additionally, the distribution of heteroatom substituents varies among feedstock hydrocarbons; compounds containing sulfur, nitrogen, or oxygen heteroatoms can adsorb onto the catalyst's active sites, reducing catalytic efficiency and indirectly affecting the feedstock conversion process.

1.2. Mechanism of influence of residual carbon and heavy metal content in raw materials on the conversion process

The residual carbon content in feedstock is a critical parameter influencing the catalytic cracking process. Residual carbon primarily consists of refractory components such as colloids and asphaltenes. Under the high-temperature conditions of catalytic cracking, residual carbon readily forms coke deposits on the catalyst surface, covering the active sites and thereby reducing catalyst activity and selectivity, which ultimately decreases overall feedstock conversion efficiency. In feedstocks with high residual carbon content, the coking rate is rapid and the coke layer exhibits a dense structure. This not only hinders contact between feedstock molecules and catalyst active sites but also increases mass transfer resistance within the reactor, resulting in insufficient reaction depth, higher reprocessing rates of heavy products, and reduced plant productivity.

The heavy metals present in the feedstock primarily include nickel, vanadium, iron, and sodium. These metals deposit on the catalyst surface as metal ions or oxides during catalytic cracking reactions, forming heavy metal contamination centers that exert significant toxic effects on the process. Heavy metals such as nickel and vanadium exhibit dehydrogenation catalytic effects, promoting excessive dehydrogenation of feedstock molecules, which increases the production of dry gas and coke while reducing light oil yield. In contrast, heavy metals like sodium and iron react with the molecular sieve components in the catalyst, disrupting its crystalline structure and decreasing the catalyst's specific surface area and pore volume. This leads to a substantial decline in the catalyst's cracking activity and selectivity, severely limiting the effective conversion of feedstock and the improvement of product quality [1].

1.3. Core bottlenecks and restraining factors in raw material conversion under current processes

Current catalytic cracking processes suffer from inadequate targeted pretreatment strategies. Most petrochemical plants employ standardized pretreatment protocols for raw materials with varying properties, failing to implement customized adjustments based on hydrocarbon composition, residual carbon content, and heavy metal levels. This results in suboptimal pretreatment efficiency, where harmful impurities remain unremoved and subsequently compromise catalytic cracking reaction efficiency. For instance, existing pretreatment technologies demonstrate low removal rates when processing inferior feedstocks with high residual carbon and heavy metal concentrations, failing to meet subsequent reaction requirements. This critical bottleneck ultimately hinders efficient material conversion processes.

Current catalytic cracking processes lack dynamic parameter tuning capabilities. Core parameters such as reaction temperature, pressure, and feed-to-oil ratio predominantly operate under fixed-value control modes, failing to adapt dynamically to real-time variations in feedstock properties. This results in the reaction process consistently operating suboptimal conditions. When feedstock quality fluctuates, fixed parameters may lead to insufficient reaction depth or excessive cracking. Insufficient reaction depth causes elevated heavy product ratios, while excessive cracking increases dry gas and coke formation rates. Both phenomena ultimately reduce feedstock conversion efficiency and light oil yield.

2. Optimization and upgrading of pre-treatment process for catalytic cracking feedstock

2.1. Precise control method for process parameters of raw material hydrogenation refining and modification

Hydrofining and modification of feedstocks is the core technique for enhancing catalytic cracking feedstock quality. Precise control of process parameters directly determines the pretreatment efficiency, with key parameters including reaction temperature, hydrogen partial pressure, liquid space velocity, and hydrogen-to-oil ratio. The reaction temperature must be precisely adjusted according to the aromatization degree of the feedstock: for high-aromatic feedstocks, raising the temperature to 380–420 ℃ promotes aromatic hydrogen saturation and the cracking modification of gum and asphaltene, while reducing the condensation degree of aromatic rings; for low-aromatic feedstocks, maintaining the temperature between 360–380 ℃ prevents excessive hydrogenation-induced hydrogen consumption and loss of light components, achieving optimal modification efficiency while controlling energy consumption.

The synergistic regulation of hydrogen partial pressure and liquid space-time velocity is crucial for feedstock hydrogenation refining. For feedstocks with high carbon residue and heavy metal content, increasing the hydrogen partial pressure to 6.0–8.0 MPa enhances hydrogen solubility in the feedstock, promoting hydrogenation decontamination and hydrocracking reactions while effectively removing sulfur, nitrogen heteroatoms, and heavy metals. Simultaneously, reducing the liquid space-time velocity to 1.0–1.5 h^{-1} prolongs the contact time between feedstock and catalyst, improving hydrogenation reaction depth and impurity removal efficiency. The hydrogen-to-oil ratio should be optimized based on feedstock processing capacity and reaction conditions, maintained at 500–800:1 to ensure adequate hydrogen supply, promptly remove reaction-generated light components, inhibit coking reactions, and maintain stable catalyst activity.

2.2. Improvement of high-efficiency pretreatment technology for raw material demetallization and residual carbon removal

To address heavy metal removal in catalytic cracking feedstocks, we have optimized the catalyst system for existing hydrotreating demetallization technologies. The specialized demetallization catalyst employs alumina as the support material, supported with nickel-molybdenum and cobalt-molybdenum bimetallic active components. Through enhanced pore structure design, the catalyst achieves increased specific surface area and pore volume, significantly improving heavy metal ion adsorption and removal efficiency. Additionally, a pre-treatment filtration unit is integrated before hydrotreating demetallization processes, utilizing high-precision ceramic membrane filtration technology to remove solid particulate impurities and certain macromolecular asphaltenes from feedstocks. This step reduces impurity load on subsequent hydrotreating systems and enhances demetallization performance.

To achieve efficient removal of residual carbon from feedstock, the delayed coking and solvent deasphalting combined process was optimized. The solvent ratio in solvent deasphalting was adjusted by using a propane-butane mixed solvent with a mixing ratio of 3:7, enhancing solvent selectivity for extracting colloidal asphaltenes and effectively removing heavy residual carbon components from feedstock. Simultaneously, delayed coking process parameters were optimized to maintain furnace outlet temperature at 490–510 ℃ and coke tower operating pressure at 0.15–0.25 MPa, promoting cracking and condensation reactions of heavy hydrocarbons in feedstock while reducing residual carbon content.

2.3. Personalized pretreatment process matching strategies for raw materials with different physical properties

For high-quality catalytic cracking feedstocks with low residual carbon and heavy metal content, such as atmospheric heavy oil and light vacuum residue oil, a simplified pretreatment process is employed, primarily involving mild hydrofining. The reaction temperature is maintained at 360–380 ℃ with a hydrogen partial pressure of 4.0–5.0 MPa. This approach effectively removes trace heteroatom compounds while maximizing the retention of light fractions, thereby reducing energy consumption and hydrogen demand in the pretreatment process, improving efficiency, and meeting the quality requirements for subsequent catalytic cracking reactions. Such feedstocks require no deep desulfurization or residual carbon removal treatments, and the simplified process significantly lowers operational costs while enhancing overall production efficiency [2].

For low-quality catalytic cracking feedstocks with high residual carbon and heavy metals, such as heavy and light vacuum residue oil and deoiled asphalt, the deep composite pretreatment process is employed. The treatment follows a sequence of “filtration for impurity removal–hydrogenation for demetallization–hydrogenation for residual carbon removal–hydrogenation for refining”. All process parameters are optimized through advanced control modes. During the demetallization stage, the hydrogen partial pressure is elevated to 7.0–8.0 MPa, while the liquid space-time velocity in the residual carbon removal stage is reduced to 0.8–1.0 h^{-1}, ensuring thorough removal of harmful impurities such as heavy metals and residual carbon from the feedstock.

3. Optimization and control of process parameters for catalytic cracking reaction process

3.1. Regulatory patterns of reaction temperature and pressure on raw material conversion efficiency

Reaction temperature is the core regulatory parameter in the catalytic cracking process, directly influencing reaction rate and product distribution. Within a certain range, increasing the reaction temperature significantly accelerates the cracking rate of feedstock molecules, promotes the chain-breaking decomposition of macromolecular hydrocarbons, and enhances feedstock conversion efficiency. When the reaction temperature rises from 480 °C to 520 °C, the cracking rate increases by 30–40%, leading to higher light oil yield. However, temperatures exceeding 530 °C may trigger over-cracking, resulting in substantial increases in dry gas and coke production, a decrease in light oil yield, accelerated catalyst coking and deactivation, and higher plant energy consumption.

Reaction pressure regulates the conversion efficiency of catalytic cracking feedstock by influencing the concentration of hydrocarbon molecules and reaction residence time within the reactor. Since catalytic cracking reactions predominantly occur in the gas phase, operating at low pressure conditions facilitates reaction progression. Maintaining reactor pressure between 0.15–0.25 MPa reduces the partial pressure of hydrocarbons, enabling rapid desorption of light fractions from catalyst surfaces, minimizing side reactions, and enhancing light oil yield. Conversely, excessively high pressure increases hydrocarbon concentrations and prolongs reaction residence time, exacerbating secondary cracking and coking reactions, reducing feedstock conversion selectivity, and increasing the proportion of dry gas and coke products.

3.2. Optimization matching and control pathway of dosage oil ratio versus reaction time

The feed-to-catalyst ratio, defined as the mass ratio of catalyst to feedstock, serves as a critical parameter for controlling the depth of catalytic cracking reactions. Increasing this ratio enhances the contact probability between feedstock molecules and the catalyst’s active sites, thereby improving reaction depth and feedstock conversion efficiency. For heavy, refractory catalytic cracking feedstocks, raising the feed-to-catalyst ratio from 5:1 to 8:1 increases feedstock conversion efficiency by 20–25% and significantly boosts light oil yield. However, when the ratio exceeds 9:1, it leads to excessive catalyst consumption, increased catalyst regeneration load and energy consumption, and may cause over-cracking of feedstocks, resulting in reduced product selectivity.

Reaction time, defined as the residence duration of feedstock in the reactor, requires coordinated optimization with the oil-to-feedstock ratio. Tailored control strategies should be implemented based on material properties. For high-quality feedstocks prone to cracking, the “high oil-to-feedstock ratio + short reaction time” approach is adopted, maintaining a ratio of 7:1 to 8:1 with reaction times reduced to 2–3 seconds. This enhances feedstock conversion efficiency while minimizing side reactions and improving light oil yield. For low-quality feedstocks resistant to cracking, the “moderate oil-to-feedstock ratio + balanced reaction time” strategy is employed, controlling the ratio at 6:1–7:1 and extending reaction times to 3–4 seconds. This ensures complete molecular cracking while preventing coking and excessive cracking caused by prolonged reaction durations.

3.3. Process optimization design for flow field distribution in lift tube reactor

The flow field distribution in the riser reactor directly determines the contact and mixing efficiency between raw materials and catalyst. Existing reactors suffer from uneven flow fields at the feed end and inadequate mixing between catalyst and raw materials. The core of optimization lies in enhancing atomization and mixing performance at the feed end. By installing high-efficiency atomization nozzles at the reactor's feed inlet and employing dual-fluid atomization technology, the atomization fineness of raw materials is improved, enabling them to enter the reactor as micron-scale droplets and thereby increasing the contact area with the catalyst.

Optimize and enhance the internal structure and operating parameters of the tubular reactor to improve the flow field distribution between its middle and upper sections, thereby boosting overall reaction efficiency. Multiple baffle plates are installed in the middle section to direct the flow direction of the catalyst and reaction materials, preventing back mixing and dead zones and ensuring uniform material distribution within the reactor. The upper section features a gradually expanding tube design that reduces material flow velocity, prolongs contact time between raw materials and catalyst, and enhances reaction depth.

4. Process synergistic upgrade path for efficient conversion of catalytic cracking feedstock

4.1. Parameter synergistic optimization strategy for pretreatment process and reaction process

The synergistic optimization of pretreatment process parameters and reaction process parameters is crucial for achieving efficient feedstock conversion in catalytic cracking. It requires dynamic adjustment of reaction parameters based on the physicochemical characteristics of pretreated feedstocks, establishing a parameter linkage system integrating "pretreatment modification and reaction cracking". When deep hydrogenation modification is employed in pretreatment processes, resulting in significant reductions in residual carbon and heavy metal content while enhancing cracking performance, the reaction process can appropriately lower operating temperatures and feed-to-oil ratios. Maintaining reaction temperatures between 480–500 ℃ and feed-to-oil ratios of 6:1–7:1 ensures optimal feedstock conversion efficiency while reducing system energy consumption, catalyst coking tendencies, and product selectivity.

For feedstocks with high light component content after pretreatment, the reaction process adopts a "low temperature, low pressure, and short reaction time" strategy, maintaining reaction temperatures at 470–490 ℃, reactor pressures at 0.15–0.20 MPa, and reaction durations of 2–3 seconds to prevent excessive cracking of light components and maximize light oil yield. For feedstocks still containing residual heavy hydrocarbons post-pretreatment, the process employs a "moderate high temperature, moderate pressure, and appropriate reaction time" approach, controlling reaction temperatures at 500–520 ℃, reactor pressures at 0.20–0.25 MPa, and reaction durations of 3–4 seconds to facilitate complete cracking of heavy hydrocarbons and enhance overall feedstock conversion efficiency.

4.2. Research on the compatibility of high-efficiency specialized catalysts with raw materials and processes

To develop high-performance specialized catalytic cracking catalysts tailored for specific feedstocks and optimized process parameters, the research focuses on optimizing catalyst active components, support structure, and shape selectivity. For heavy aromatics and heavy catalytic cracking feedstocks, specialized catalysts are engineered with ultra-stable Y-type molecular sieves as active components and composite alumina supports. Rare earth element-modified molecular sieves are introduced to enhance hydrocracking activity and anti-coking performance, while pore structure optimization increases mesopore proportion to facilitate diffusion and cracking of large-molecular-weight heavy hydrocarbons. These catalysts are specifically designed to meet reaction process parameters including “medium-high temperature ranges and moderate catalyst-to-oil ratios”.

To address low-residue and high-quality catalytic cracking feedstocks, we developed specialized catalysts with shape-selective molecular sieves as core active components. This innovation enhances the catalyst’s shape-selective cracking performance, facilitating directional molecular cracking of feedstocks to produce light oil products such as gasoline and diesel while reducing dry gas and coke formation. The catalysts are optimized for reaction process parameters including “low temperature, high oil-to-agent ratio, and short reaction time”. Concurrently, compatibility studies between catalysts and pretreatment processes were conducted. For hydrorefined modified feedstocks, we increased hydrogenation-active component content in the catalyst to improve cracking adaptability. For solvent deasphalted modified feedstocks, we enhanced the catalyst’s resistance to heavy metal contamination to ensure stable activity, achieving comprehensive compatibility across catalysts, feedstocks, and processes.

4.3. Integrated upgrading solution for energy conservation and efficiency enhancement in the full process of catalytic cracking technology

The integrated energy-saving and efficiency enhancement upgrade for the full catalytic cracking process focuses on achieving cascaded energy utilization across process units and optimized material circulation to reduce overall plant energy consumption. In heat recovery, residual heat from high-temperature flue gas in the reactor-regenerator is captured through a waste heat boiler, with the generated steam powering plant fans and pumps. Simultaneously, high-temperature oil slurry waste heat from the distillation column is utilized for feedstock preheating and water softening, enabling cascaded heat recovery that reduces comprehensive energy consumption by 15–20%. Regarding material circulation, optimized operating parameters for the distillation column and absorption-stabilization system improve light hydrocarbon recovery efficiency. Recovered dry gas and liquefied gas are reintroduced as fuel gas into the regenerator, achieving material recycling and enhanced feedstock resource utilization rates [3].

By leveraging intelligent technologies to achieve intelligent control and integrated upgrading of the entire catalytic cracking process, an intelligent monitoring system for the entire process is established. This system collects real-time data on raw material properties, operating parameters, and product distribution from each process unit. Through big data analysis and intelligent algorithms, it enables coordinated intelligent regulation of parameters across all process units, including pretreatment, reaction, fractionation, and absorption stabilization, ensuring the entire process remains in an optimal operating state at all times.

5. Conclusion

This paper focuses on the core topic of efficient conversion of catalytic cracking feedstocks in the refining and chemical industry. It systematically analyzes the physical properties of different types of catalytic cracking feedstocks and elucidates how residual carbon content, heavy metal levels, and improper regulation of existing process parameters constrain the conversion process. By addressing three key aspects, optimization of feedstock pretreatment processes, precise control of reaction parameters, and synergistic coordination between processes, the study proposes targeted improvement strategies. These strategies enable customized matching of pretreatment processes, accurate regulation of reaction parameters, and effective parameter synergy between pretreatment and reaction processes.

Disclosure statement

The authors declare no conflict of interest.

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