Engineering 56 (2026) 244–256

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Green Chemical Engineering—Article

Diameter-Transformed Fluidized Bed-Based Catalytic Reaction Engineering and Industrial Application

Youhao Xu [a,*], Bona Lu [b,c,*], Mingyuan He [a], Wei Wang [b,c]

[a] State Key Laboratory of Petroleum Molecular and Process Engineering, Research Institute of Petroleum Processing, Sinopec, Beijing 100083, China
[b] State Key Laboratory of Mesoscience and Engineering, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China
[c] School of Chemical Engineering, University of Chinese Academy of Sciences, Beijing 101408, China

ARTICLE INFO

Article history:
Received 25 July 2024
Revised 24 November 2024
Accepted 8 February 2025
Available online 1 November 2025

Keywords:
Diameter-transformed fluidized bed
Catalytic cracking
Maximizing *iso*-paraffins
Multi-scale simulation
Catalytic reaction engineering

ABSTRACT

In response to the critical national demand for upgrading automotive gasoline quality, the concept of dual reaction zones was developed to intensify both olefin generation and conversion. The successful large-scale implementation of this process has yielded substantial economic benefits and spurred the invention and systematic study of the diameter-transformed fluidized bed (DTFB) reactor, leading to a suite of new catalytic processes. This study begins with the conceptual origins of the DTFB reactor. By analyzing unimolecular and bimolecular mechanisms in hydrocarbon catalysis, the key conditions necessary for maximizing target products are identified. Furthermore, it elucidates the scientific and technological challenges in applying diameter variation to partition the reaction section, highlighting that the primary challenge lies in achieving precise coupling between flow and reaction multimodalities, which necessitates a generalized drag model for accurate prediction of flow regime transitions. Since flow structure is influenced by both macroscopic parameters and local dynamics, a two-way coupled energy minimization multi-scale (EMMS) drag model and a corresponding multi-scale computational fluid dynamics (CFD) approach have been proposed, laying a theoretical foundation for quantitative design of diameter-transformed sections. The subsequent development of ancillary technologies has provided the necessary engineering safeguards for flexible control of temperature, density, and gas–solid contact time in each zone, ultimately enabling the industrialization, large-scale operation, and long-term stability of DTFB-based catalytic technology. Finally, the study outlines several typical processes and their application performance, and prospects future work.

© 2025 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

Fluidization refers to the operation of solid particles under the action of a fluid, primarily driven by the drag force, which causes them to exhibit fluid-like behaviors. Once fluidized, the particles are easily in contact with the surrounding fluid, exhibiting exceptional efficiency in momentum, mass, and heat transfer. Therefore, within a fluidized bed, temperature distribution can be maintained uniformly and easily regulated, making it ideally suited for processes characterized by significant endothermic and exothermic reactions. By virtue of these advantages, fluidized beds prevail in a wealth of industrial applications including fluid catalytic cracking (FCC), base chemicals production, coal/biomass combustion and gasification, ore calcination, granulation, powder drying, and so on [1–3]. They play an important role in various process industries, including energy, chemical industry, metallurgy, and pharmaceutical manufacturing, particularly in the development of chemical reaction engineering.

The industrial use of fluidization technology dates back to 1926, with BASF in Germany pioneering the gasification of coal in a fluidized bed. The coal combustion and gasification technologies that emerged subsequently in the energy sector were primarily designed to handle coarser particles. However, a significant leap occurred in the 1940s with the development of the FCC process, which was designed to increase gasoline production to meet the demands of World War II. The advent of high-activity, fine-particle catalysts, along with the improvements in large-scale processing capacity and the need for rapid circulation between the

* Corresponding authors.
E-mail addresses: xuyouhao.ripp@sinopec.com (Y. Xu), bnlu@ipe.ac.cn (B. Lu).

https://doi.org/10.1016/j.eng.2025.02.024
2095-8099/© 2025 THE AUTHORS. Published by Elsevier LTD on behalf of Chinese Academy of Engineering and Higher Education Press Limited Company.
This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

reaction and regeneration stage, propelled the explosive growth of FCC technology. This advancement not only yielded substantial economic benefits but also catalyzed the widespread adoption of fluidized bed reactor technology across a diverse array of industries. It is worth noting that the inception of FCC technology is closely linked to pioneering research in the "fast regime" within the field of fluidization, making the fluidization become one of the most extensively studied areas in chemical engineering [4,5]. Since then, fluidization studies spanning theory, engineering technique, and industrial applications have flourished into a prominent research focus and become one of the most important branches of catalytic reaction engineering (CRE).

Gas–solid fluidization is intrinsically aggregative, displaying non-uniform multi-scale structures [6]. The fluidization with coarse particles has a relatively narrow window of operation, and the research in this area is primarily focused on gas-rich bubbling mesoscale phenomena [7]. In contrast, fine particles are well aerated and can be operated with high processing capacity over a much wider range, even exhibiting normal fluidization when gas velocity far exceeds the terminal velocity, thereby sparking extensive applications after the invention of FCC process. Unlike traditional gas-rich bubble structures, the FCC process represents high-velocity, high-solid flux fast fluidization, primarily characterized by particle-rich clusters. The dynamic behaviors of these mesoscale structures, including their formation, evolution, and stability, impact momentum, mass, and heat transfer and subsequently, reaction, thus attracting a vast amount of attention in fluidization field. By regulating operating gas velocity and solid flux, many new fluidized bed reactors such as turbulent fluidized bed, fast beds, and downer have been developed [1,2,4,8]. These various types of fluidized reactors developed during that period typically have only one reaction zone, each designed to operate at a specific flow regime. For instance, the methanol-to-olefins (MTO) fluidized bed reactor developed by the Dalian Institute of Chemical Physics is designed to operate at turbulent fluidization [9]; the heat carrier (fine ash particles) in the circulating bed boiler is fast fluidized to circulate through the full loop, and the coarse coal particles, introduced into the furnace via the bottom inlet, are subjected to either bubbling or turbulent fluidization regimes. This operational approach ensures that the particles have an adequate residence time within the furnace, allowing them to absorb heat effectively [10]. For these types of reactors, the relationship between dynamic flow structures and reactor performance is relatively easy to manipulate.

Around 2000, the Sinopec Research Institute of Petroleum Processing (RIPP) astutely recognized the difference between thermodynamic and kinetic properties of olefin generation (through cracking reactions) and those properties of olefin conversion (via isomerization and hydrogen transfer reactions). To produce high-quality gasoline with low olefin content and high octane rating, RIPP proposed a new fluidized bed design for the FCC process. This reactor features dual reaction zones, each tailored to create optimal conditions for both olefin generation and olefin conversion. This new catalytic cracking process was also called maximizing *iso*-paraffins (MIP) process in later published literature. The MIP process can substantially suppress formation of olefins in gasoline while preserving high octane number, so it was quickly accepted by many refineries to replace the traditional FCC process. This unexpectedly big success inspired the researchers to have serious contemplation on the fluidized bed reactor itself, that is, how to quantitatively design multiple reaction zones with respective favorable flow regime and then how to keep them steady and regulate their parameters flexibly in a feasible engineering manner. Subsequent fundamental research and extensive industrial trials jointly nurtured the invention of diameter-transformed fluidized bed (DTFB) reactor. During ongoing extended applications to more heterogeneous catalytic reaction processes, a suite of CRE technology based on DTFB was gradually formed. Particularly if the innovation in fluidized bed reactor can bring an order-of-magnitude change in catalyst density, residence time, temperature, and so forth, it will achieve a contribution commensurate with new catalyst development to the catalytic reaction process, propelling the fluidization discipline into a new era of revitalization [11–13].

The DTFB-based CRE technology is an innovative development stemming from the critical national demand for clean gasoline and growing out of persistent research at the interdisciplinary frontier of heterogeneous catalytic reaction processes and fluidization technology. Compared to the traditional FCC process, which operates its reaction zone at a single given flow regime, the MIP process with a DTFB reactor simultaneously holds multiple reaction zones. Maintaining a steady flow state while smoothly transitioning from one flow regime to another largely depends on the reactor geometry (e.g., diameter change ratio and bed height) and operating parameters. Accurate manipulation of these distinct flow regimes coexisting in the same reactor requires a unified understanding of mesoscale structures within the diverse flow regimes, as well as the mesoscale effects on momentum, mass and heat transfer, and reaction behaviors. As long as one acquires the law of flow regime transition, it becomes possible to manage reactor performance by altering mesoscale structures in a quantitative manner. This aligns with a research boom in the fluidization scientific community, which focuses on areas such as the quantitative determination of flow regime transitions [14–18] and the pursuit of a generalized structure-dependent approach to develop drag, mass transfer, and heat transfer coefficients [19–22].

This study initially delves into the inception of the DTFB reactor concept and addresses the pivotal scientific and technical challenges encountered during its industrialization and scaling-up phases. It then encapsulates the theoretical and engineering research milestones and the culmination of DTFB-based CRE technology, highlighting its success in eight distinct industrial applications. Finally, the study showcases three exemplary processes, demonstrating the application effects and the economic benefits achieved through the implementation of DTFB technology.

2. Inception of the DTFB reactor

Approximately 90% of processes in energy production, environmental management, and chemical manufacturing are characterized by intricate catalytic reactions. These reactions involve a multitude of elementary reactions that proceed through a network of interconnected series and parallel pathways. Achieving high conversion rates alongside high selectivity represents a significant challenge in complex catalytic reaction systems. Precise control over the desired reaction pathways necessitates a profound understanding of the kinetic and thermodynamic properties of various reaction pathways, as well as the interplay and coordination among them. The FCC process stands as the largest and most economically efficient catalytic reaction process globally [23]. It is a typical heterogeneous catalytic reaction system, involving cracking, isomerization, hydrogen transfer, alkylation, and other series of reactions [24]. According to thermodynamic data [25], an environment of high temperature and short contact time is conducive to endothermic cracking reactions. Conversely, exothermic processes such as hydrogen transfer, isomerization, and alkylation benefit from lower temperatures and longer contact time to optimize yield and selectivity. If the above reaction pathways can be intensified separately by creating a favorable reaction environment with suitable temperature and residence time, it is expected that highly selective transformation of the desired products can be achieved.

The traditional FCC reactor uses a high-velocity riser where a uniform temperature distribution can be achieved with high mass and heat transfer rates. Typically, a specific set of conditions—once the gas velocity and solid flux are established—corresponds to a singular operational state or flow regime within the system. Thus, the most straightforward concept for constructing a spectrum of reaction environments is to employ a strategic combination of several fluidized beds, each tailored to distinct operating states. However, it has been observed that the material residence time within the connecting pipelines between different fluidized beds is excessively prolonged, which can divert intermediates away from the preferred reaction pathways. On the other hand, it also increases the catalyst wear and construction cost. Consequently, in the design of a specialized fluidized bed reactor with multiple flow regimes, the first consideration is to ensure that the transition time between these flow regimes is short enough not to influence the reaction pathway.

The hydrocarbon catalytic reaction proceeds through distinct phases: the initiation stage, the transfer stage, and the termination stage [26]. During the initiation stage, alkane molecules are adsorbed onto the active sites of the catalyst, leading to the formation of a non-classical carbenium ion in an intermediate transition state. This state subsequently decomposes into classical carbenium ions, smaller alkane molecules, and hydrogen, which then transition into the next stage of the process. Fig. 1 [26] depicts the network of acid-catalyzed chain reactions, grounded in the carbenium ion mechanism. It can be seen that the carbenium ion reactions can proceed via β-scission and isomerization when adhering to a unimolecular mechanism, or alternatively, they may engage in disproportionation and hydrogen transfer reactions following a bimolecular mechanism.

To achieve maximum conversion of hydrocarbon reactants into the desired products [26], three key conditions must be meticulously met: ① The formation of various desired products from the intermediate transition state requires tailored reaction environments that are conducive to the formation of each specific product. ② The generation and transformation of intermediate transition states should be a continuous process. If the intermediate transition state is prematurely terminated, resulting in an undesired product, further conversion to the desired product through reaction condition adjustments would not only increase process energy consumption but also lead to reactant loss. This is a primary reason why the combination of different fluidized bed reactors sometimes falls short of targeted regulation. ③ Fine-tuning the reaction depth, which includes parameters such as the catalyst-to-oil ratio and contact time, should aim to align the size of intermediate molecules with that of the desired product molecules. This alignment is crucial for enhancing the selectivity towards the desired product, thereby improving the overall efficiency of the whole process.

The concept of two reaction zones in series respectively for olefins cracking and olefins conversion proposed by RIPP [25,27] capitalizes on the acid-catalyzed chain reaction network and leverages the thermodynamic data specific to the various types of reactions involved. As depicted in Fig. 2, the cracking of feedstock oil (heavy hydrocarbon) into smaller hydrocarbon molecules is highly endothermic. During this process the gas density changes very significantly, which in turn brings about a substantial increase in gas velocity. The catalyst particles coming from the regenerator after coking burning introduce a significant amount of heat to the feedstock oil, enabling it to vaporize and crack. In this way, the first reaction zone operates in high-temperature, dilute-flow environment, driving the reactions predominantly through the unimolecular mechanism, similar to the operation of a traditional equal-diameter FCC reactor. As the feedstock oil becomes heavier, the catalyst-to-oil ratio can be increased to enhance the depth of reaction. The second reaction zone is designed to intensify the conversion of olefins through isomerization and hydrogen transfer, which prefer low-temperature, dense-flow conditions. Therefore, first, the gas velocity is reduced by expanding the reactor diameter, allowing the second reaction zone to operate under fast fluidization regime. This can form coexistence of a dense bottom region and a more dilute top region, thereby significantly increasing the residence time for gas and solid particles. The extended contact time is crucial for facilitating the necessary reactions within the catalyst particles. The operating temperature in the second reaction zone is intentionally reduced for several reasons. First, the endothermic reactions in the first reaction zone have already consumed a significant amount of heat. Additionally, the strategic use of refrigerants further lowers the temperature. This temperature reduction is particularly beneficial for intensifying the isomerization reactions. While all isomerization, hydrogen transfer, and alkylation reactions favor lower temperatures, the cooling down plays a more pronounced role in isomerization. This is because, among these three parallel reactions, the equilibrium constant for isomerization is the largest, making it the most temperature-sensitive [25]. As a

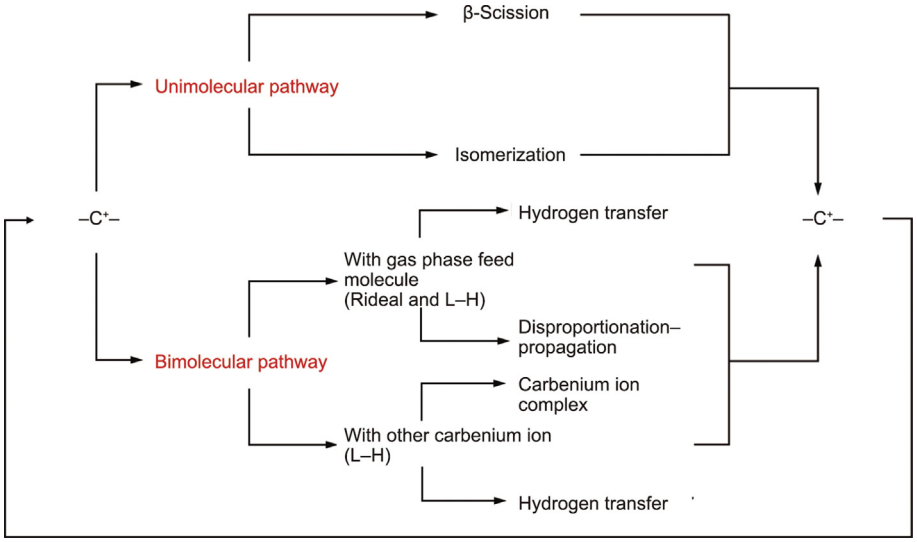

Fig. 1. Acid-catalyzed chain reaction network based on carbenium ions. L–H: Langmuir–Hinshelwood mechanism. Reproduced from Ref. [26] with permission.

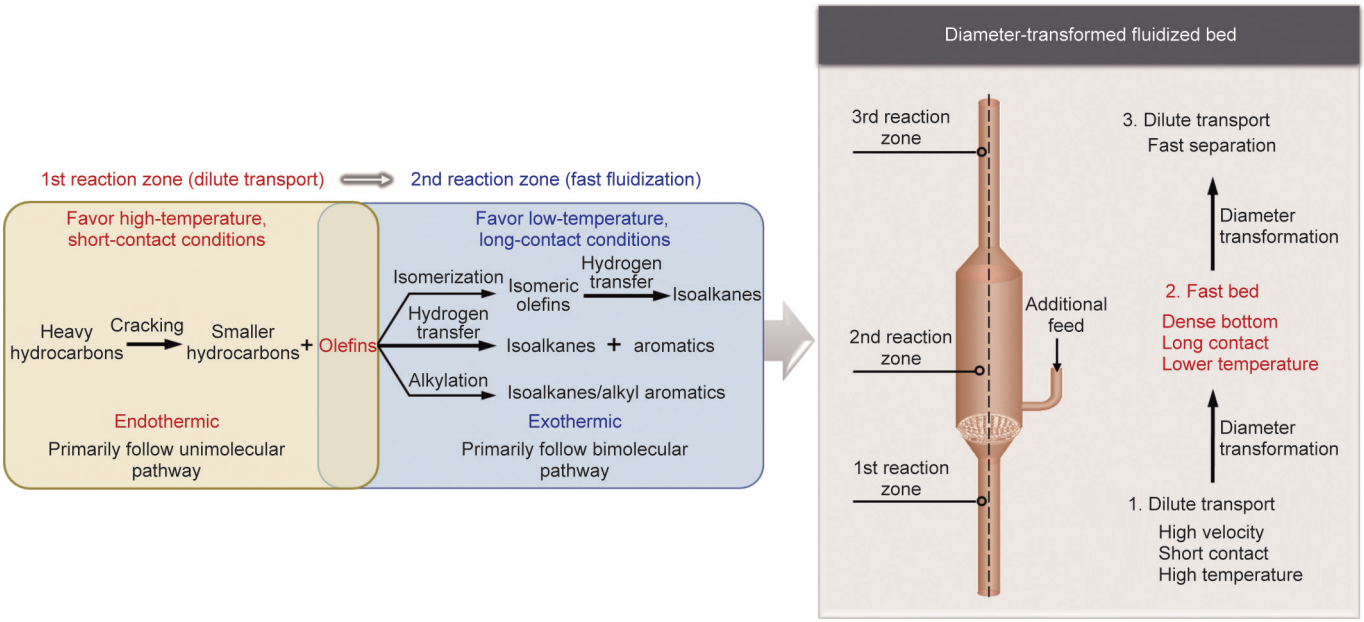

Fig. 2. The concept of two reaction zones based on cracking and conversion in series.

result, the reactor can stably manage the coexistence of markedly different flow regimes. Meanwhile, the gas–solid two-phase flow coming from the first reaction zone, due to its inherent inertia, can still maintain its original flow pattern for a certain period of time. This allows for the continuous production and conversion of intermediates, meeting the three key conditions previously discussed. Consequently, the innovative catalytic cracking process, aimed at MIP process, has been successfully developed.

Based on the analysis of the ratio of the characteristic product (olefins) of the unimolecular reaction to the characteristic product (*iso*-paraffins) of the bimolecular reaction, it was found that the unimolecular reaction and the bimolecular reaction take place in series, and the transition between two types of reactions can be completed within a second-order time frame. Table 1 shows the yield ratio of butane to butene, gasoline yield, the content of olefins in the gasoline, and coke yield at the end of both the first and second reaction zones. Here, butane and butene are considered indicative products of bimolecular and unimolecular reactions, respectively. The data reveal that after increasing of the reactor diameter, there is a significant enhancement in the prevalence of bimolecular reactions, corresponding to an approximate 24% reduction in the olefin content of the gasoline. In this context, the innovative concept of modulating the reactor diameter to create multiple distinct reaction zones arises, which sparked the conception of the DTFB.

3. Challenges in DTFB industrialization

Fluidized beds are typical nonlinear non-equilibrium systems, whose macroscopic heterogeneity is heavily influenced by geometric factors, with a typical example being choking behavior [28–30]. As illustrated in Fig. 3, when gas–solid fluidization is not confined by geometric boundaries, Fig. 3(a) presents an intrinsic flow regime phase diagram. It can be observed that as the gas velocity increases, the plateau section—where the solid flux (G_s) remains constant under varying solid concentration—becomes progressively shorter. At a superficial gas velocity (U_g) of approximately 12 $m \cdot s^{-1}$, this plateau vanishes, marking the operational point at the choking threshold. The plateau region formed by various operating velocities is known as the fast bed region, where a coexistence of the dilute region at the top and the dense region at the bottom is observed. By adjusting the dilute and dense phases, an operational environment with varying residence times and densities can be achieved. However, when the reactor dimensions and structure are fixed (for example, using a fluidized bed with a 90 mm inner diameter and 10.5 m height), the actual operational flow regime diagram, as shown in Fig. 3(b), is formed. The fast bed region not only has a significantly reduced operational area but also undergoes a substantial change in shape. Correspondingly, the critical choking velocity decreases from the original approximately 12 to 2.8 $m \cdot s^{-1}$, indicating that the likelihood of encountering choking behavior in actual operation is greatly increased. More studies about geometrical effects can be found in our previous reports [28–30].

Traditionally, the concept of diameter expansion has commonly been applied in the sedimentation section of fluidized bed design. The primary objective is to decrease the particle velocity, thereby reducing the load on the cyclone separator and mitigating its pressure demands. The MIP dual-zone reactor, which incorporates diameter changes in the reaction zone, introduces a multitude of challenges that are critical for its engineering and scalability, as illustrated in Fig. 4. Firstly, the abrupt change in the gas–solid fluidization state leads to a significant variation in gas velocity, from approximately 15–20 $m \cdot s^{-1}$ before the expansion to 0.5–3.0 $m \cdot s^{-1}$

Table 1
Selectivity of the unimolecular reaction and the bimolecular reaction at the outlets of different reaction zones.

Sampling location	Butane to butene yield ratio	Gasoline yield (%)	Olefin content in gasoline (%)	Coke yield (%)
The end of the 2nd reaction zone	2.08	49.3	34.1	8.6
The end of the 1st reaction zone	0.49	31.4	58.0	7.5

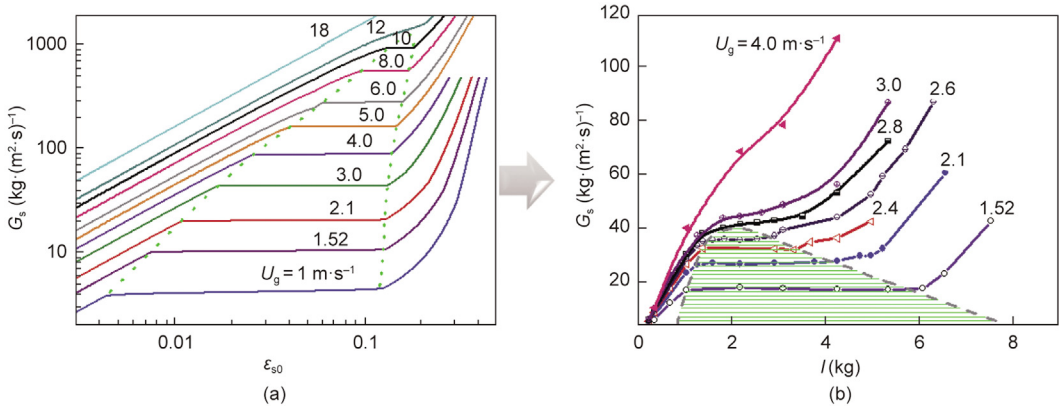

Fig. 3. The effect of geometry on the flow regime diagram in the FCC/air system. (a) Independence of geometrical effects; (b) constrained by reactor geometry. G_s: solid flux; U_g: superficial gas velocity; ε_{s0}: mean solid volume fraction in the bed; I: solid inventory mass.

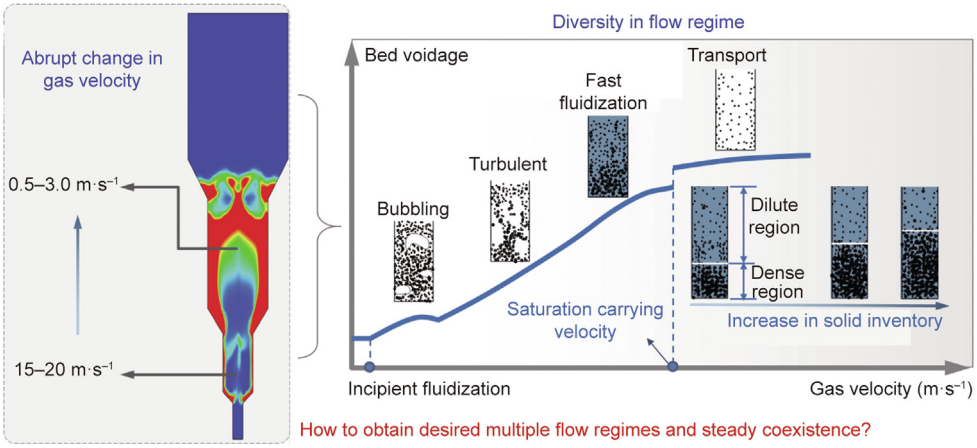

Fig. 4. The challenging problems during the diameter transformation of the fluidized bed.

after expansion. Such a drastic change in velocity leads to continuous fluctuations in the catalyst density within the bed, making it difficult to form a stable dense layer of the expanded reaction zone. Therefore, it is very necessary to design a suitable distributor, which should not only help form a steady dense bottom but also prevent serious abrasion from the high-velocity multiphase flows. Secondly, the bed expansion causes a sudden change in the flow regime, especially after the expansion where the reduced gas velocity increases the risk of choking. As discussed above, the critical choking velocity is reduced to a lower value under the restriction of the real riser geometry, especially the bed height and outlet structure. If not operated properly, this can lead to a multimodal switch in the catalyst particle concentration distribution, potentially resulting in either a completely dense or a completely dilute state. This not only affects the distribution and quality of the products at the outlet but can also lead to equipment shutdowns, a situation that has occasionally occurred in the early operational stages of catalytic cracking units [31]. Therefore, the gas velocity at the second reaction zone should not be close to the critical choking velocity. Here, the prediction in the critical choking velocity is key to the design of the DTFB.

Furthermore, when the reactor and regenerator are coupled, the interplay between the operational units increases the number of adjustable variables, further complicating the control of the DTFB reactor. Therefore, only by simultaneously addressing the aforementioned challenges—especially by achieving precise prediction of the flow regime and obtaining the phase diagram—can the industrialization, large-scale operation, and long-term operation of the DTFB reactor be realized.

4. Theoretical progress for the DTFB reactor

4.1. Pivotal scientific issues

As discussed above, the quantitative design of the DTFB depends on the precise prediction of the flow regime structure. Gas–solid fluidization possesses a diversity in flow regimes, where a continuous medium (gas) is superimposed with a discrete medium (particles) [2]. As shown in Fig. 4, with an increase in gas velocity beyond incipient fluidization, the bed typically exhibits bubbling, turbulent, fast fluidization, and dilute transport states in sequence [2]. The properties of particles/gas and the reactor geometry will both affect the flow regime structure. The inherent multi-state nature of the flow regime structure, combined with the multi-state coexistence induced by diameter changes and the characteristics of catalytic reaction pathways, makes precise prediction and control of the DTFB particularly challenging.

To overcome these challenges, two pivotal scientific issues must be addressed. First, the mesoscale structure—situated between the single particle and reactor scales—is governed by both chemical reactions and reactor operations. It exhibits a complex spatiotemporal, multi-scale dynamic distribution within the bed, profoundly influencing gas–solid flow and reaction behavior. Therefore, precise quantification of this mesoscale structure and the

development of a universal gas–solid drag model are essential for accurately predicting flow regime structures and the coexistence of multiple states. Second, when particles are mobilized by the fluid, they participate in reactions which in turn alter the fluid flow and velocity distribution. Consequently, establishing a multi-scale coupled simulation framework for reaction and transport processes, along with the seamless integration of diverse flow regimes with multi-state reactions, is key to achieving precise control over selectivity in complex catalytic reactions.

4.2. Drag modeling and choking prediction

The energy minimization multi-scale (EMMS) model [32], proposed by the Institute of Process Engineering, Chinese Academy of Sciences, provides a robust framework for accurately predicting multi-scale structural parameters and exploring a universal model for multiphase flow reactors. Recognizing the pivotal role of drag force in fluidization hydrodynamics, a novel two-way coupling approach for EMMS drag modeling has been established [33,34]. This method is grounded in the analysis of the mutual influence mechanism of macroscopic parameters and local dynamics on flow structure, particularly the changes in superficial gas velocity and solid flux due to diameter variations. The model posits that the average behavior of the flow structure is predominantly influenced by macroscopic operating conditions, while its dynamic behaviors are constrained by local hydrodynamics. A drag model that integrates the dynamic structure, balancing overall stability with local dynamics, has been developed, as depicted in Fig. 5. Compared to the traditional approach that uses solid concentration as the sole variable for the heterogeneity index of drag, this model adopts a dual-variate heterogeneity index in which an additional slip velocity is introduced to quantify the dynamic changes of the mesoscale

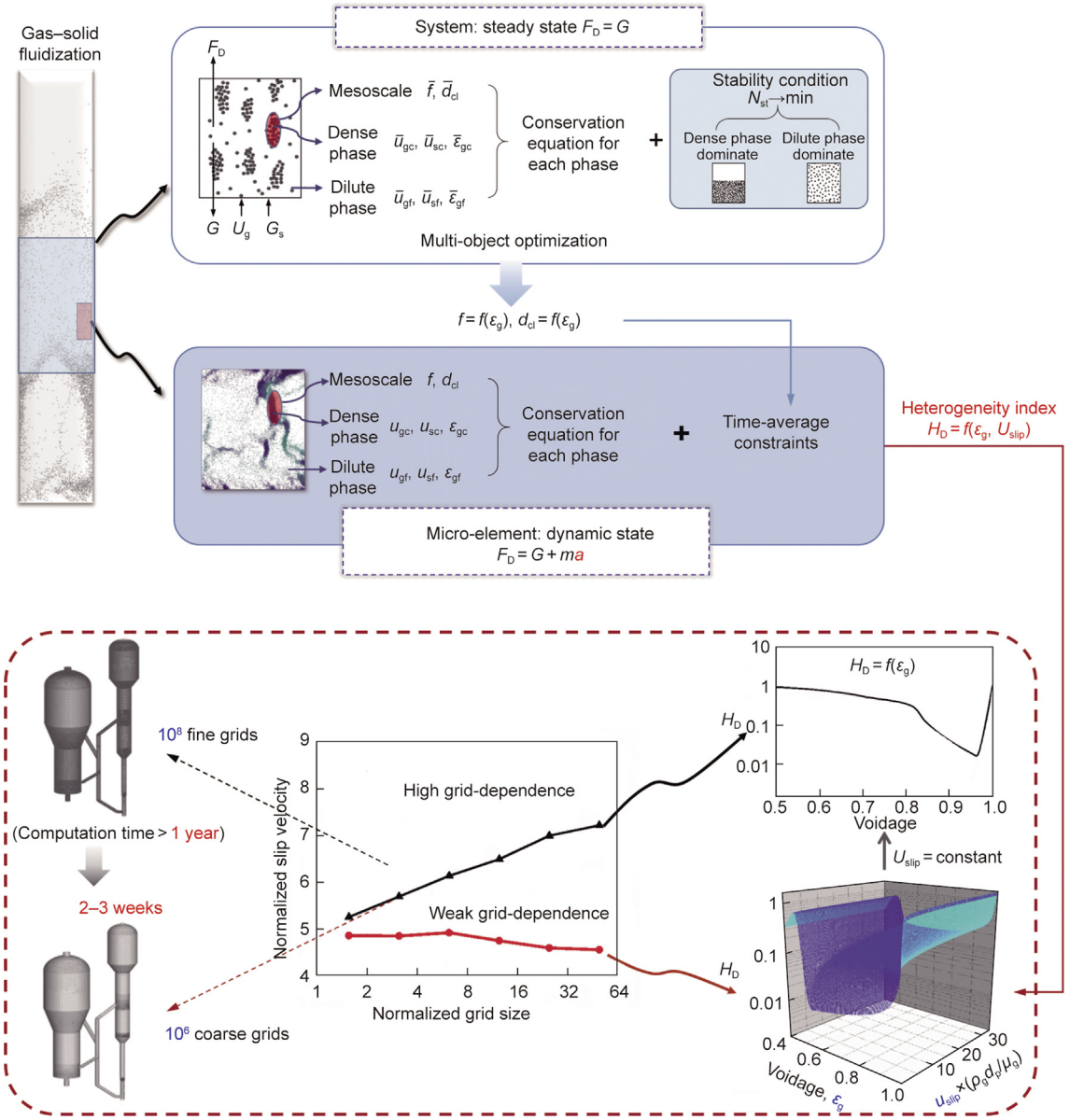

Fig. 5. Two-way coupled drag model with the expression of the drag heterogeneity index and its effects in CFD simulations. f: volume fraction of dense phase; d_{cl}: diameter of particle clusters; u_{gc}, u_{sc}, and ε_{gc} are the superficial gas velocity, solid velocity, and voidge in dense phase, respectively; u_{gf}, u_{sf}, and ε_{gf} are the superficial gas velocity, solid velocity, and voidge in dilute phase, respectively; the bar symbol "–" placed above a variable denotes its mean value; U_{slip}: superficial slip velocity; H_D: heterogeneity index of drag coefficient; F_D: drag force; G: gravity; N_{st}: mass-specific energy consumption for suspending and transporting particles; m: mass of particles per unit volume; a: inertial term; u_{slip}: real slip velocity; d_p: particle diameter; ρ_g: gas density; μ_g: gas viscosity.

structure, offering detailed micro-element flow field information for coupling with reactions. The use of the dual-variate heterogeneity index enables computational fluid dynamics (CFD) simulations to exhibit insensitivity to computational grids, allowing for the use of coarse grids in simulating large-scale fluidized bed reactors with a reduction in grid numbers by several orders of magnitude [35–38]. The dual-variate EMMS drag model [33,39] has been integrated as a built-in option in internationally recognized CFD software such as Ansys Fluent® and Siemens Simcenter Star-CCM+®.

Traditional multiphase flow modeling methods, such as the two-fluid model (TFM), rely on the assumptions of uniformity and local equilibrium within a microscopic control volume, which are not suitable for describing fluidized systems that are far from equilibrium [40–42]. It is noteworthy that integrating TFM with the EMMS-based drag model effectively captures the two typical transition behaviors of the DTFB from dilute pneumatic transport to fully dense transport: "choking" phase transition [16,18] and continuous, monotonic phase transition (as illustrated in Fig. 6). Using traditional homogeneous drag model, which tends to overpredict solid flux, is limited to identifying "continuous phase transitions." Therefore, based on a series of simulations by changing gas velocity and solid inventory, we established a quantitative relationship between choking and key parameters such as the expansion ratio (D/d, where D and d are different bed diameters), the solid inventory in the expanded section, and the bed height. In addition, according to the changes in physical properties before and after cracking reactions, the maximum mean gas velocity achievable in the first reaction zone ($U_{g1,max}$) can be evaluated. To ensure the expanded reaction zone operates at a steady fast bed regime (not close to choking critical point), the design of the expanded region and operating parameters should satisfy the condition, $U_{g2} = U_{g1,max}/(D/d)^2 < U_c$, where U_c is the critical choking velocity, and U_{g2} is the superficial gas velocity of the expanded reaction zone. Furthermore, based on the flow regime phase diagram, strategies like external catalyst supplementation can adjust the catalyst inventory in the second reaction zone. This adjustment can regulate the temperature and space velocity requirements for hydrocarbon catalytic reactions. This is one of the earliest reports on using CFD simulation to predict the choking phenomenon [16].

4.3. Flow-reaction coupling and full-loop simulation

The occurrence of reactions significantly increases the complexity of industrial reactor simulation. For the gas phase, the change in the number of molecules, accompanied by heat transfer, severely affects catalyst concentration, residence time distribution, and gas–solid backmixing behavior. For the solid phase, changes in solid concentration affect local reaction rates, while coke deposition reduces catalytic activity and alters pore size, thereby affecting product selectivity.

Traditional heat transfer models assume that catalysts are uniformly dispersed in the form of single particles within a micro-element, and the reaction heat is directly transferred to the surrounding flow field through single particles. This causes heat transfer to be instantaneously completed with reactions, leading to sudden local density or temperature changes and posing a significant challenge for the convergence of numerical solutions. In actual fluidized bed systems, particles tend to form clusters to reduce friction dissipation with the surrounding fluid [39–41]. Based on the aforementioned two-way coupled drag force model, by analyzing the multi-scale distribution structure within the micro-element, parameters describing the dilute phase, dense phase, and mesophase within the micro-element can be determined and then taken into account in the heat transfer modeling [38,43]. Since the mass transfer process is closely coupled with the reaction [43], when considering the impact of non-uniform structures on the mass transfer process, the type of reaction must also be taken into account [44]. For heterogeneous catalytic reactions, such as FCC reactions, if a reaction kinetic model is established at the particle scale, the effects of flow structures on mass transfer and reaction models can often be neglected [43–45]. This is because internal diffusion within the catalyst particle is typically the rate-limiting step. Therefore, within the framework of TFM and by incorporating EMMS-based drag and heat transfer models along with a reaction kinetics model, the simulation can accurately predict solid concentration, temperature distribution, and reaction behaviors, including coke content and total conversion [38,43,45], as illustrated in Fig. 7. When the reaction rate is comparable to or slower than the external mass transfer rate, the impact of mesoscale structures on the mass transfer process becomes significant [46]. Consequently, a multi-scale CFD simulation approach based on

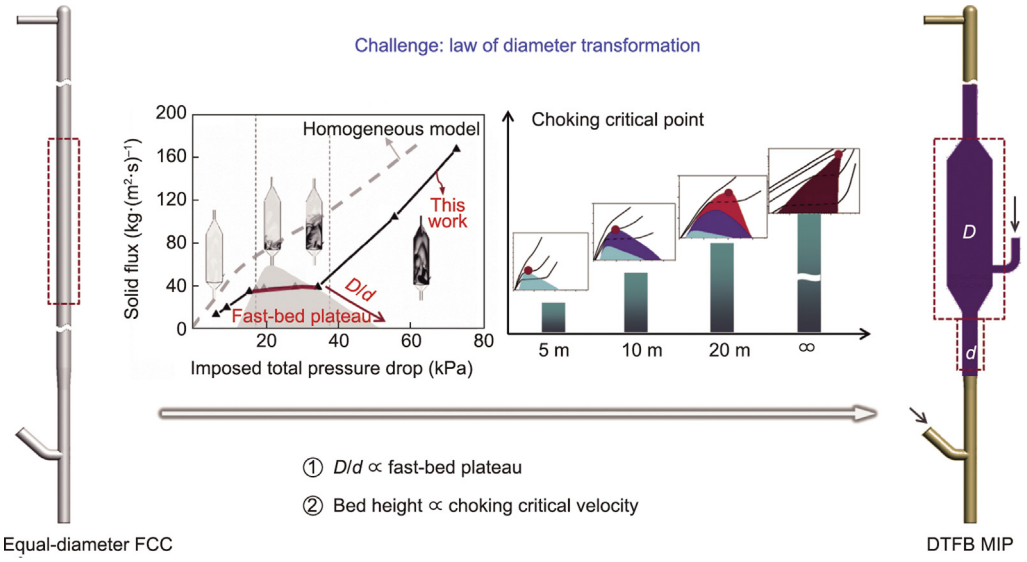

Fig. 6. Relationship between the choking phenomena and the D/d ratio (diameter change) as well as the choking phenomena and the height of the diameter-expansion section.

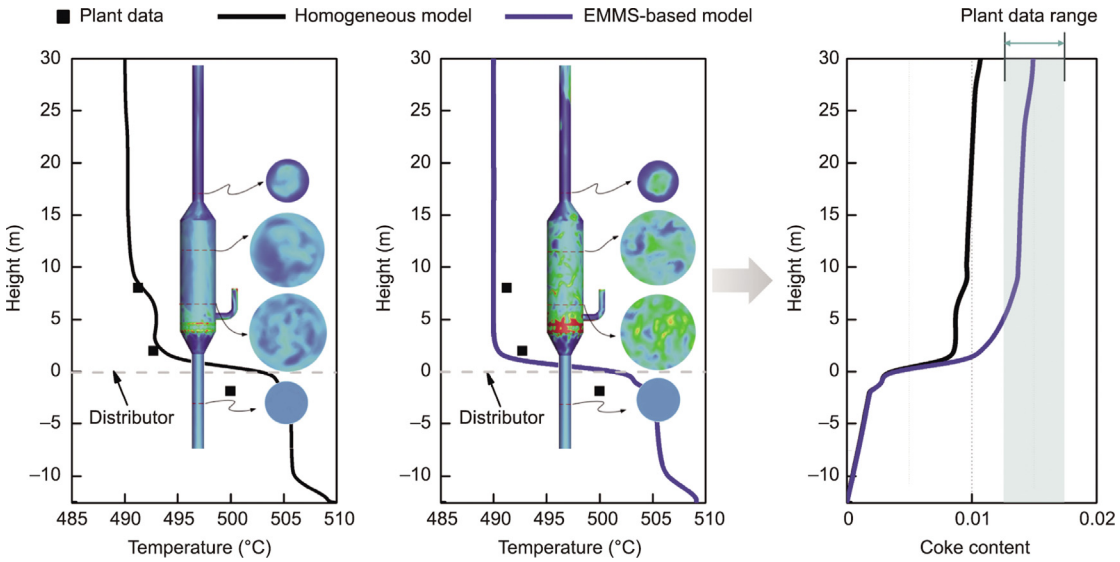

Fig. 7. The comparison in predictions in solid concentration, temperature, and coke content of catalysts by using EMMS-based model and homogeneous model.

consideration of the effects of dynamic mesoscale structures in the constitutive relations has been established [29,38].

Accurate flow regime prediction has laid a solid theoretical foundation for the quantitative design of DTFB reactors. However, regulating these reactors within the entire reaction–regeneration system demands a holistic approach, given the strong interplay between operational units. The control of pressure and thermal balance is integral to the stable circulation of catalyst particles in the regeneration system, which in turn affects the efficacy of both reaction and regeneration processes. The full-loop circulation system of reaction and regeneration encompasses various units, including conveying, reaction, sedimentation, and regeneration. This system operates across a broad spectrum of flow regimes and under complex physical property conditions, making it an exemplary application for validating the applicability of the model. By incorporating artificial neural networks (ANNs) with the dual-variate drag model, the EMMS–ANN drag supermodel has been developed [47], which takes into account the diverse variables associated with the operational flow regimes in each unit under reaction conditions. This model has been validated to demonstrate that, under reaction conditions, the slip velocity remains a pivotal variable for characterizing the dynamic behaviors of mesoscale structures [48]. It facilitates unified calculations across multiple flow regimes and physical property conditions.

The full-loop hydrodynamic simulation of the reaction–regeneration system based on the DTFB reactor represents the most industrially aligned approach in the literature on full-loop simulation studies [49]. This simulation spans a range of operations from bubbling beds and turbulent beds to multiple fast bed operations with varying velocities. It captures the fluctuation characteristics inherent in cyclic operations, and it shows the fluctuation frequency is an order of magnitude lower than that of the riser-only simulation. Furthermore, it can reveal the interactions between disparate operational units, and thus serve as a tool for diagnosing system instabilities and forecasting safety risks. As shown in Fig. 8, the full-loop reactive simulation can evaluate both the amount of heat released by external devices and the variation in product distribution. It also predicts solid concentration more accurately than full-loop flow simulations. Moreover, conducting a full-loop simulation for the reaction–regeneration system provides essential data to extract a network of microscopic reactors. This, combined with artificial intelligence (AI)-enhanced spatial–temporal data-mining technology [50–54], serves as the initial seed for developing an industrial large-scale model. This model can integrate industrial data as well as a vast amount of CFD data, allowing for continuous improvement, and is thus expected to aid in more innovations in catalytic reaction technologies harnessing DTFB reactors.

5. Development of ancillary technology and industrial applications

The DTFB catalytic reactor introduces additional variables by altering the bed diameter, achieving a sophisticated integration of operational and geometric parameters. This creates the prerequisite for the coexistence of multiple reaction zones and enables rapid transitions between flow regimes. To realize its full potential in industrialization, large-scale application, and long-term operation, the development of complementary ancillary engineering technologies is imperative. These technologies must provide the means for agile control over a spectrum of variables within each zone, including temperature, density, and gas–solid contact time, ensuring optimal reaction conditions across the bed.

5.1. Specialized distributors for transition sections

In conventional fluidized bed reactors, distributor plates are typically designed for single-phase flow or low-velocity multiphase flows. However, in the case of DTFB reactors, the distributors in the transition sections are subject to the challenging condition of high-velocity gas–solid mixture flow. This scenario introduces significant difficulties in achieving a stable transition between distinct flow regimes, forming a dense phase region layer in the secondary reaction zone, and ensuring long-term operation. Particularly, long-term operation is very challenging because the distribution plate is susceptible to deformation under the prolonged impact of high-speed fluids, and high catalyst-to-oil ratios cause more severe abrasion to both the catalysts and the distributor plate.

To tackle the above problems, the distributor design has evolved several generations, with development alternating between CFD studies and industrial trials. In 2000, a perforated plate with large orifices was first employed. The industrial trials

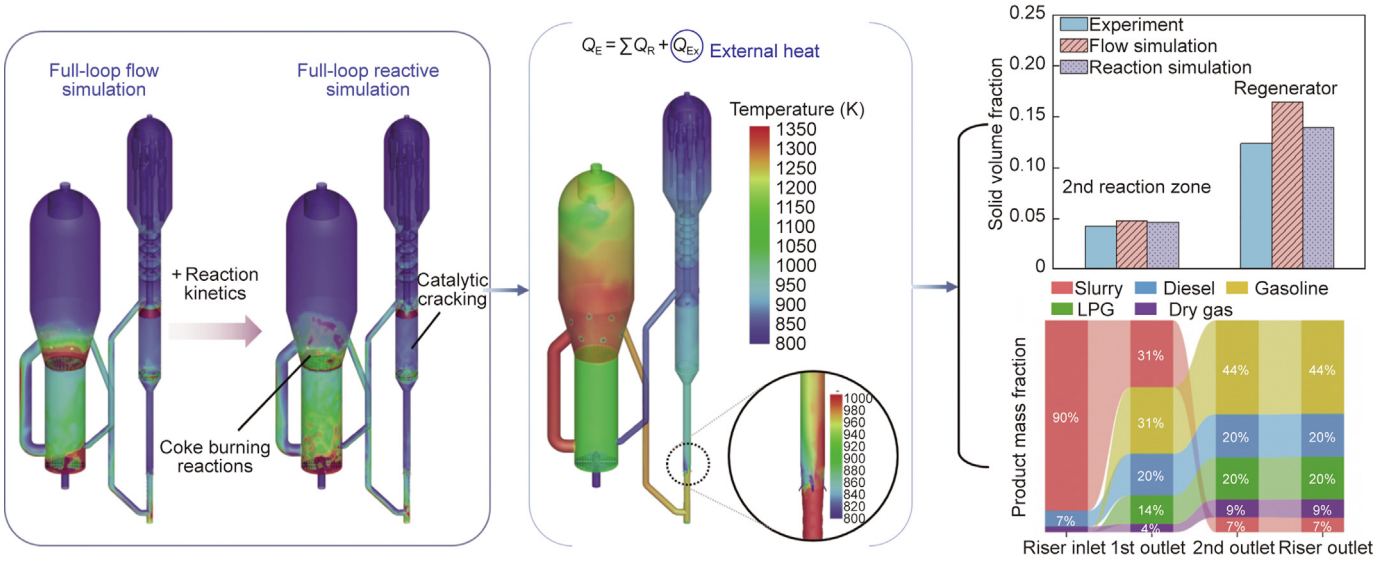

Fig. 8. The capability of reactive simulation of the industrial-scale reaction–regeneration full-loop FCC system. Q_E: heat from regenerator; Q_R: heat for reactor; LPG: liquefied petroleum gas.

indicated that such a plate could evenly divide the fluid flow into small jets, but this resulted in the formation of a layer with relatively low catalyst density just above the plate, which hindered effective control over the reaction depth. To address this, a specially shaped distribution plate was engineered, with a design concept that transitions the fluid flow direction from axial to radial. This scheme allows the fluid to initiate movement above the distributor with zero axial velocity, facilitating the formation of a denser catalyst particle layer. Further advancements were made to address the long-term operational challenges of catalyst wear and distributor deformation. Concave distributors and mushroom-headed distributors were developed to enhance durability and performance. The comparative application effects of these four distributor types are detailed in Table 2, showcasing their respective impacts on reactor operation and efficiency.

Concave distributors and mushroom-headed distributors have been successfully implemented in long-term operations on large-scale DTFB catalytic cracking units, with diameters reaching up to 5.5 m. Especially, the type with mushroom head can significantly minimize the catalyst consumption and wear. The new distributor technology excels not only in facilitating seamless transitions between diverse flow patterns but also in overcoming the persistent challenge of severe wear on distributors, typically caused by high-velocity gas–solid two-phase flows.

5.2. Ancillary technology for regulation of diameter-transformation section

FCC units have diverse configurations, such as co-axial arrangements of the reactor and side-by-side layouts. To accommodate these various designs and to make the most of existing equipment, the development of a range of ancillary engineering technologies is essential when utilizing DTFB in the upgrade process to replace the original reactor.

In the co-axial layout of the reactor and regenerator, an overflow hopper is strategically positioned below the dipleg of the primary cyclone separator to extract the spent catalyst. For the side-by-side arrangement, particularly with externally-mounted DTFB reactors and regenerators, a cyclonic fast separation device is installed at the reactor outlet to separate spent catalysts. A portion of these catalysts is then conveyed to the lower part of the second reaction zone via an additional return pipeline equipped with a plug or sliding valve. The remaining catalysts are transported from the pre-steam stripping section to the steam stripping section of the disengager. In the case of an overlapped layout with internally-mounted DTFB reactors and regenerators, spent catalyst can be directly extracted from the steam stripping section and supplemented to the second reaction zone.

This has led to the development of a suite of technologies, including methods for extracting high-temperature catalysts, withdrawal spent catalysts, and their forced cooling, as well as techniques for transporting them to the bottom of the second reaction zone. These technologies are complemented by operational principles for the design and regulation of reaction modes. For instance, enhancing heat transfer through the injection of liquid coolants, cooling catalysts, or hot catalysts, to modulate local temperatures, and determining various injection locations based on the characteristics of different reactions.

In 2004, a 1.5 Mt·a^{-1} catalytic cracking unit at a domestic oil company transitioned from a single riser to a dual-riser configuration. A further modification was made in 2010 with the adoption of a DTFB system. As detailed in Table 3, the DTFB unit demonstrated a marked reduction in energy consumption, decreasing by 6.93 kg of oil equivalent per tonne (kgOE·t^{-1}) compared to the single riser

Table 2
Distributor types, performance, and characteristics.

Distributor type	Fluid distribution	Ease of forming dense solid layer	Catalyst wear level	Long-term/large-scale operation difficulty
Large orifice plate	Very good	Difficult	High	Difficult
Special-shaped plate	Good	Easy	High	Difficult
Concave plate	Good	Easy	Low	Moderate
Mushroom-headed plate	Average	Easy	Low	Easy

Table 3
Characteristic product yields and energy consumption before and after the retrofit of a catalytic cracking unit (with equivalent feedstock properties).

Reactor type	Feedstock ($t \cdot d^{-1}$)	Dry gas yield (%)	Coke yield (%)	Liquid yield (%)	Plant energy consumption ($kgOE \cdot t^{-1}$)
Single riser	4812.3	4.78	7.62	82.55	63.37
Double risers	4761.4	5.50	7.93	79.70	69.60
DTFB	4999.0	2.95	6.92	86.07	56.44
Δ(DTFB – single)	186.7	−1.83	−0.70	3.52	−6.93
Δ(DTFB – double)	237.6	−2.55	−1.01	6.37	−13.16

and by 13.16 $kgOE \cdot t^{-1}$ compared to the dual risers. Concurrently, the raw material processing capacity of the unit expanded; the dry gas yield was reduced by 1.83 and 2.55 percentage points, respectively; the coke yield dropped by 0.70 and 1.01 percentage points, respectively; and the liquid yield saw an increase of 3.52 and 6.37 percentage points, respectively. These enhancements notably improved the yield of desired products.

5.3. Industrial applications of DTFB reactors

The ongoing expansion of the MIP process application scale, coupled with diverse market demands, has driven profound fundamental research on the synergy between complex catalytic reactions and fluidized bed operations. This has led to the emergence of a suite of innovative technologies harnessed on the DTFB platform. The following outlines three such exemplary processes.

5.3.1. Petroleum hydrocarbon catalytic cracking

In the production of low-olefin gasoline, hydrogen transfer reactions, which are governed by bimolecular mechanisms, are crucial. In contrast, for the production of olefins, unimolecular cracking reactions are key. When a catalytic cracking process is designed to be versatile and accommodate multiple production schemes, it requires not only the ability to rapidly switch between unimolecular cracking and bimolecular reactions but also precise control over different types of bimolecular hydrogen transfer reactions. Additionally, it demands that once intermediates have achieved sufficient conversion, their transition state should be capable of shifting reaction directions in a controlled manner.

Utilizing the DTFB platform along with complementary techniques, a series of innovative catalytic cracking processes have been developed. These include the efficient utilization of heavy hydrocarbons, the production of clean gasoline, and the maximization of propylene and marine fuel oil [55–61]. In the technology designed for the efficient utilization of heavy hydrocarbons, pre-cracking of these hydrocarbons occurs in the first reaction zone, while the conversion of saturated hydrocarbons is completed in the second reaction zone. Industrial trials have demonstrated a significant increase in liquid yield of over 10.04%, a substantial reduction in coke yield by 21.05%, and a reduction in dry gas yield by 45.51%. For the production of clean gasoline, hydrocarbon molecules undergo cracking in the first reaction zone, and olefin bimolecular conversion takes place in the second reaction zone. This process has played a pivotal role in the upgrade of gasoline quality in China from National III to National VI standards. Lastly, the process for maximizing propylene and marine fuel oil has achieved a several-fold increase in propylene yield while significantly reducing the production cost of marine fuel oil.

5.3.2. Olefin-to-ethylene and propylene

Olefins are subjected to confined thermal catalytic reactions on a catalyst to generate ethylene and propylene [62,63]. This process necessitates the promotion of unimolecular cracking reactions of olefins while concurrently inhibiting thermal cracking and bimolecular polymerization reactions. By employing the DTFB platform, a turbulent fluidized bed with an elevated catalyst density is designated as the primary site to favor the compromise between catalytic cracking and thermal cracking reactions within the shaped pore channels between the molecular sieve crystals and the catalyst particles. The post-reaction fluid then enters the reduced-diameter area where rapid cooling and temperature reduction are implemented to further suppress thermal cracking reactions. Pilot-scale experiments [64] have demonstrated a significant enhancement in both the yield and selectivity of ethylene and propylene, alongside a notable reduction in methane yield. This technology holds the promise of offering a more competitive production method, potentially reshaping the refining industry.

5.3.3. Methanol-to-light olefins

Methanol rapidly transforms into ethylene and propylene on the surface of SAPO molecular sieves, driven by the hydrocarbon pool mechanism, while simultaneously being accompanied by the production of minor quantities of butene and higher olefins. Leveraging the DTFB platform, a fast bed section is designed as the primary site for the catalytic conversion of methanol into ethylene and propylene. These products are then swiftly directed into a reduced-diameter outlet. Given that methanol conversion is an exothermic process, it generates elevated temperatures in the outlet region. This increase in temperature, coupled with the reduced reaction time, effectively inhibits the oligomerization of ethylene and propylene and simultaneously promotes the cracking reactions of butene and larger olefins [65].

To date, leveraging the DTFB reactor platform, eight processes have been successfully industrialized, and one process is projected to reach industrialization by 2026, as illustrated in Fig. 9. This technological advancement has been particularly impactful in the realm of clean gasoline production. Through persistent fundamental research on the DTFB reactor, coupled with the development of complementary support technologies, significant milestones have been achieved. For instance, the requirements for National I and National II gasoline standards were met in 2002, followed by the successful production of National III gasoline standard in 2007, and the fulfillment of National IV gasoline standard in 2011. This has solidified a dominant market position, capturing over 70% of the domestic market share in the production of catalytic cracking gasoline. Furthermore, patents related to DTFB technology have been licensed to foreign countries such as Brunei, Uzbekistan, and Kyrgyzstan.

Over two decades of research have culminated in the development of an array of innovative processes on the DTFB catalytic reactor platform. This innovative reactor has successfully achieved precise control over the selectivity of complex catalytic reactions within a single fluidized bed, and has also resolved the historical trade-off between selectivity and conversion rate. As Werther et al. [12] remarked in the special issue celebrating the 100th anniversary of the Ullmann's Encyclopedia of Industrial Chemistry, "As has been demonstrated by the development of the MIP process, the fluidization principle still provides room for innovation."

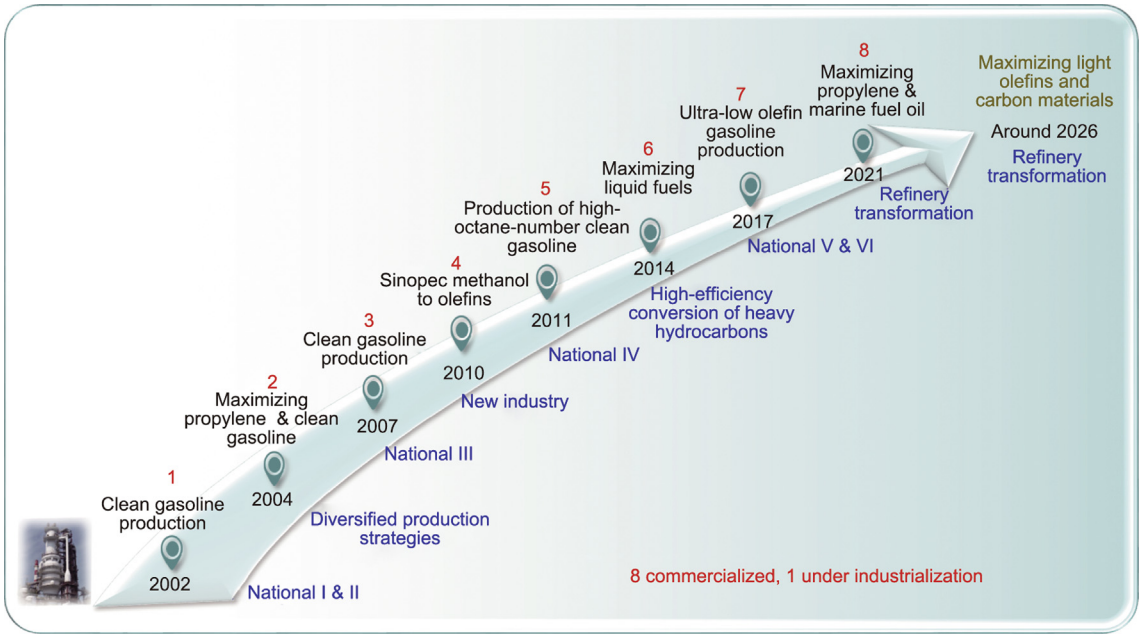

Fig. 9. Industrialization of a series of processes based on DTFBs.

6. Conclusions and prospects

The development of the MIP process with dual reaction zones and its substantial impact on the continuous upgrading in automotive gasoline in China from National II to National VI standards have spurred the invention of the DTFB reactor. The DTFB catalytic reactor introduces new variables by changing the bed diameter, resulting in a high coupling between operational variables and geometric variables, thus providing the prerequisite for the coexistence of multiple reaction zones and rapid transitions between distinct flow regimes. The subsequent development of theoretical models and ancillary technologies help realize the flexible control of temperature, density, and gas–solid contact time in each zone, thereby jointly forming a suite of DTFB-based CRE technology. The quantitative design of the DTFB is highly dependent upon the accurate prediction of the flow regime structure; thus, the key scientific issue is focused on the development of a universal drag model and the underlying mechanism governing the interplay between various flow regimes and the multitude of reaction types. Addressing these scientific issues leads to engineering challenges, including the novel distributor technology for realizing rapid and smooth transitions between different flow regimes and flexible parameter control technologies. The scientific and technological challenges highlighted above have been effectively tackled, to varying extents, across a spectrum of catalytic reaction processes, exemplified by the technique of petroleum catalytic cracking.

As the catalytic cracking process with the DTFB reactor continues to expand in both scale and application scope, the regulatory mechanisms and theoretical models for the diameter-transformed multiple reaction zones have reached a higher level of sophistication. In response to evolving market demands and national strategic imperatives, there is a pressing need for continuous enhancement of existing catalytic reaction processes and the innovation of new processes on the DTFB platform. This imperative calls for deeper fundamental research in several key areas:

(1) Matching mechanisms: A thorough understanding of the mechanisms that govern the compatibility between diverse reaction types and multiple flow regimes is essential.

(2) Reaction kinetics: A systematic approach for jointly optimizing catalyst and reactor design should be developed combining multi-scale molecular dynamics approaches, thermodynamic models, and reaction kinetic experiments at different scales.

(3) AI-driven modeling: The network of microscopic reactor models developed from the multi-scale CFD simulations can be used as the initial core to develop the industrial large-scale model. With continuous AI-driven learning with new CFD data and industrial operation data, it is expected to form a control and design industrial software that will accelerate the birth of new technologies.

By embracing these advancements, DTFB-based CRE technology stands not only to meet current needs but also to adapt to future challenges, solidifying its role as a cornerstone of innovation in the field of catalytic reactions.

CRediT authorship contribution statement

Youhao Xu: Writing – original draft, Supervision, Methodology, Funding acquisition, Data curation, Validation, Project administration, Investigation, Formal analysis, Conceptualization. **Bona Lu:** Writing – review & editing, Validation, Methodology, Funding acquisition, Writing – original draft, Supervision, Investigation, Formal analysis. **Mingyuan He:** Supervision, Investigation, Methodology, Formal analysis. **Wei Wang:** Validation, Writing – original draft, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to acknowledge the financial supports from the National Key Research and Development Program (2022YFB4101403) and the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA0390502).

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used Kimi AI in order to improve the language, grammar, and overall readability of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

[1] Jin Y, Zhu JX, Wang Z, Yu ZQ, editors. Principles of fluidization engineering. Beijing: Tsinghua University Press; 2001. Chinese.
[2] Kwauk M, Li H. Handbook of fluidization. Beijing: Chemical Industry Press; 2008. Chinese.
[3] Jin Y, Cheng Y, Bai D, Zhang C, Wei F. Fluidization research and development in China. Chem Ind Eng Prog 2023;42(6):2761–80. Chinese.
[4] Squires AM, Kwauk M, Avidan AA. Fluid beds: at last, challenging two entrenched practices. Science 1985;230(4732):1329–37.
[5] Kwauk M. Fluidization—idealized and bubbleless, with applications. Beijing: Science Press; 1992.
[6] Wilhelm RH, Kwauk M. Fluidization of solid particles. Chem Eng Prog 1948;44:201–18.
[7] Davidson JF, Harrison D, editors. Fluidization. Waltham: Academic Press; 1971.
[8] Grace JR, Avidan AA, Knowlton TM, editors. Circulating fluidized beds. Dordrecht: Springer; 1997.
[9] Tian P, Wei Y, Ye M, Liu Z. Methanol to olefins (MTO): from fundamentals to commercialization. ACS Catal 2015;5(3):1922–38.
[10] Yang H, Lv J, Yue G. Design theory of circulating fluidized bed boilers and determination of the design parameters. J Power Eng 2006;26(1):42–8. Chinese.
[11] Xu Y, Wang W, Lu B, Xu H, He M. China's oil refining innovation: MIP development strategy and enlightenment. Chem Ind Eng Prog 2023;42(9):4465–70.
[12] Werther J, Hartge EU, Heinrich S. Fluidized-bed reactors—status and some development perspectives. Chem Ing Tech 2014;86(12):2022–38.
[13] Treese SA, Pujadó PR, Jones DSJ. Handbook of petroleum processing. Cham: Springer; 2015.
[14] Kim SW, Kirbas G, Bi H, Lim CJ, Grace JR. Flow behavior and regime transition in a high-density circulating fluidized bed riser. Chem Eng Sci 2004;59(18):3955–63.
[15] Du B, Warsito W, Fan LS. Behavior of the dense-phase transportation regime in a circulating fluidized bed. Ind Eng Chem Res 2006;45(10):3741–51.
[16] Lu B, Wang W, Li J, Wang X, Gao S, Lu W, et al. Multi-scale CFD simulation of gas–solid flow in MIP reactors with a structure-dependent drag model. Chem Eng Sci 2007;62(18–20):5487–94.
[17] Sun Z, Zhu J. A consolidated flow regime map of upward gas fluidization. AIChE J 2019;65(9):e16672.
[18] Han C, Xu Y, Lu B, Wu H, Wang W. Numerical exploration of the flow regime transition of a novel catalytic cracking reactor and operation mode analysis. Powder Technol 2022;398:117137.
[19] Igci Y, Sundaresan S. Verification of filtered two-fluid models for gas–particle flows in risers. AIChE J 2011;57(10):2691–707.
[20] Wang W, Lu B, Geng J, Li F. Mesoscale drag modeling: a critical review. Curr Opin Chem Eng 2020;29:96–103.
[21] Li Y, Han S, Yu Y, He X, Huang Z, Zhou Q. Modeling filtered heat transfer model by considering dimensionless temperature difference between gas and solid phases. AIChE J 2023;69(1):e17917.
[22] Hardy B, Rauchenzauner S, Fede P, Schneiderbauer S, Simonin O, Sundaresan S, et al. Machine learning approaches to close the filtered two-fluid model for gas–solid flows: models for subgrid drag force and solid phase stress. Ind Eng Chem Res 2024;63(18):8383–400.
[23] Ancheyta-Juárez J, López-Isunza F, Aguilar-Rodríguez E, Moreno-Mayorga JC. A strategy for kinetic parameter estimation in the fluid catalytic cracking process. Ind Eng Chem Res 1997;36(12):5170–4.
[24] Ancheyta J. Modeling and simulation of fluidized-bed catalytic cracking converters. In: Ancheyta J, editor. Modeling and simulation of catalytic reactors for petroleum refining. Hoboken: John Wiley & Sons, Inc.; 2011. p. 368–473.
[25] Xu Y, Zhang J, Long J. A modified FCC process MIP for maximizing *iso*-paraffins in cracked naphtha. Pet Process Petrochem 2001;32(8):1–5. Chinese.
[26] He MY. The development of catalytic cracking catalysts: acidic property related catalytic performance. Catal Today 2002;73(1–2):49–55.
[27] Xu Y, Zhang J, Long J, He M, Xu H, Hao X. Development and commercial application of FCC process for maximizing *iso*-paraffins (MIP) in cracked naphtha. Eng Sci 2003;5(5):55–8. Chinese.
[28] Wang W, Lu B, Dong W, Li J. Multi-scale CFD simulation of operating diagram for gas–solid risers. Can J Chem Eng 2008;86(3):448–57.
[29] Wang W, Lu B, Zhang N, Shi Z, Li J. A review of multiscale CFD for gas–solid CFB modeling. Int J Multiph Flow 2010;36(2):109–18.
[30] Lu B. EMMS-based meso-scale model and its application in simulating gas–solid two-phase flows [dissertation]. Beijing: Institute of Process Engineering, Chinese Academy of Sciences; 2009. Chinese.
[31] Sinopec. Catalytic cracking accident analysis and prevention. Beijing: China Petrochemical Press; 2007. Chinese.
[32] Li J, Kwauk M. Particle-fluid two-phase flow: the energy-minimization multi-scale method. Beijing: Metallurgical Industry Press; 1994. Chinese.
[33] Lu B, Wang W, Li J. Searching for a mesh-independent sub-grid model for CFD simulation of gas–solid riser flows. Chem Eng Sci 2009;64(15):3437–47.
[34] Wang W, Li J. Simulation of gas–solid two-phase flow by a multi-scale CFD approach—extension of the EMMS model to the sub-grid level. Chem Eng Sci 2007;62(1–2):208–31.
[35] Lu B, Zhang N, Wang W, Li J, Chiu JH, Kang SG. 3-D full-loop simulation of an industrial-scale circulating fluidized-bed boiler. AIChE J 2013;59(4):1108–17.
[36] Luo H, Lu B, Zhang J, Wu H, Wang W. A grid-independent EMMS/bubbling drag model for bubbling and turbulent fluidization. Chem Eng J 2017;326:47–57.
[37] Lu B, Zhang J, Luo H, Wang W, Li H, Ye M, et al. Numerical simulation of scale-up effects of methanol-to-olefins fluidized bed reactors. Chem Eng Sci 2017;171:244–55.
[38] Lu B, Niu Y, Chen F, Ahmad N, Wang W, Li J. Energy-minimization multiscale based mesoscale modeling and applications in gas-fluidized catalytic reactors. Rev Chem Eng 2019;35(8):879–915.
[39] Lu B, Wang W, Li J. Eulerian simulation of gas–solid flows with particles of Geldart groups A, B and D using EMMS-based meso-scale model. Chem Eng Sci 2011;66(20):4624–35.
[40] Wang W, Chen Y. Mesoscale modeling: beyond local equilibrium assumption for multiphase flow. In: Marin GB, Li J, editors. Advances in chemical engineering. Volume 47: mesoscale modeling in chemical engineering, part II. Waltham: Academic Press; 2015. p. 193–277.
[41] Wang H, Chen Y, Wang W. Scale-dependent nonequilibrium features in a bubbling fluidized bed. AIChE J 2018;64(7):2364–78.
[42] Tian Y, Geng J, Wang W. Structure-dependent analysis of energy dissipation in gas–solid flows: beyond nonequilibrium thermodynamics. Chem Eng Sci 2017;171:271–81.
[43] Lu B, Cheng C, Lu W, Wang W, Xu Y. Numerical simulation of reaction process in MIP riser based on multi-scale model. CIESC J 2013;64(6):1983–92. Chinese.
[44] Liu S, Xu F, Lu B, Wang W, Liu Z, Wang Y. Porous-media model based particle-resolved simulation of a fixed bed with olefin catalytic cracking reaction. Powder Technol 2024;431:119099.
[45] Han C, Xu Y, Lu B, Wang W. Two-phase and three-phase modeling of an industrial fluidized bed for maximizing *iso*-paraffins. Chem Ing Tech 2023;95(1–2):97–106.
[46] Liu C, Wang W, Zhang N, Li J. Structure-dependent multi-fluid model for mass transfer and reactions in gas–solid fluidized beds. Chem Eng Sci 2015;122:114–29.
[47] Yang Z, Lu B, Wang W. Coupling artificial neural network with EMMS drag for simulation of dense fluidized beds. Chem Eng Sci 2021;246:117003.
[48] Du C, Han C, Yang Z, Wu H, Luo H, Niedzwiecki L, et al. Multiscale CFD simulation of an industrial diameter-transformed fluidized bed reactor with artificial neural network analysis of EMMS drag markers. Ind Eng Chem Res 2022;61(24):8566–80.
[49] Wu Y, Liu S, Xu Y, Lu B, Wu H, Wang W. Hydrodynamic full-loop simulation of an industrial fluid catalytic cracking fluidized bed system with mechanical valves. Ind Eng Chem Res 2024;63(7):3324–35.
[50] Wang F, Yao D, Li Y, Sun T, Zhang Z. AI-enhanced spatial-temporal data-mining technology: new chance for next-generation urban computing. Innovation 2023;4(2):100405.
[51] Xu Y, Liu X, Cao X, Huang C, Liu E, Qian S, et al. Artificial intelligence: a powerful paradigm for scientific research. Innovation 2021;2(4):100179.
[52] Guo L, Meng F, Qin P, Xia Z, Chang Q, Chen J, et al. A case study applying mesoscience to deep learning. Engineering 2024;39:84–93.
[53] Yuan Y, Chaffart D, Wu T, Zhu J. Transparency: the missing link to boosting AI transformations in chemical engineering. Engineering 2024;39:45–60.
[54] Zhao Y, Zhu Z, Chen B, Qiu S, Huang J, Lu X, et al. Toward parallel intelligence: an interdisciplinary solution for complex systems. Innovation 2023;4(6):100521.
[55] Zhu Y. Application of MIP technology and proprietary catalysts in RFCC processing hydrotreated heavy oil. Pet Process Petrochem 2015;46(10):72–6. Chinese.
[56] Wang X, Li M, Xu Y, Hao Z. Research and industrial application of catalytic cracking technology for producing ultra-low olefin gasoline. Pet Process Petrochem 2022;53(2):5–22. Chinese.
[57] Yu F, Song Y, Bai X, Yu B, Zhao Y, Chen Z, et al. Industrial test of MFP technology in FCC unit. Pet Process Petrochem 2022;53(7):18–22. Chinese.
[58] Xu Y, Liu T, Wang Y, Sun L. Development and commercial application of IHCC technology for maximizing liquid yield. Pet Process Petrochem 2016;47(7):1–8. Chinese.
[59] Xu Y, Cui S. A novel fluid catalytic cracking process for maximizing *iso*-paraffins: from fundamentals to commercialization. Front Chem Sci Eng 2018;12(1):9–23.

[60] Xu Y, Yang W, Wang X. Development and application of core technology and technical route supporting continuous upgrading of gasoline quality in China. 1. Theoretical basis and industrial practice of olefin content control in FCC gasoline. Pet Process Petrochem 2022;53(9):1–9. Chinese.
[61] Zhou Y, Liu B, Ma M. MIP process technology reformation of 3×10^6 t/a heavy oil catalytic cracking unit. Chem Eng Oil Gas 2020;49(4):32–6. Chinese.
[62] Xu Y, Zuo Y, Bai X, Du L, Han Y. Development background, development idea and conceptual design of FCC process for targeted cracking to light olefins. Pet Process Petrochem 2021;52(8):1–11. Chinese.
[63] Xu Y, Zuo Y, Yang W, Shu X, Chen W, Zheng A. Targeted catalytic cracking to olefins (TCO): reaction mechanism, production scheme, and process perspectives. Engineering 2023;30:100–9.
[64] Wang Q, Bai X, Xu Y, Yu F. Study and application of flexible fluid catalytic cracking process to meet changing market demand. Pet Process Petrochem 2024;55(7):1–7. Chinese.
[65] Liu H, Ding J, Shen X, Wang C, Qi G, Wang Y, et al. The practice from fundamental research to commercial application—research and development of SMTO technology for methanol-to-olefins. Pet Process Petrochem 2024;55(1):122–9. Chinese.