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Technology Offer

Smart Heat Management with Core-Shell Catalyst Pellets: Preventing Hotspots, Maximizing Yield

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Background

Efficient heat management remains one of the most critical challenges in fixed-bed reactors operated with exothermic reactions. Uncontrolled local temperature excursions (hotspots) can lead to irreversible catalyst degradation due to sintering or structural breakdown - jeopardizing long-term performance, safety, and profitability. Traditional mitigation strategies such as feed dilution or fixed-bed dilution are widely applied, but they come at a reduction in space-time yield, increased operational complexity, and higher energy consumption.

These trade-offs become especially critical in dynamic operation modes, as increasingly required in Power-to-X applications driven by fluctuating renewable energy sources. In such cases, thermal runaway events and local overheating can occur unpredictably, making robust heat control not just a design consideration but a fundamental requirement for process viability.

Technology

Prof. Kai Sundmacher and Dr.-Ing. Ronny Zimmermann, together with their team at the Max Planck Institute for Dynamics of Complex Technical Systems, have developed and patented a novel core-shell catalyst pellet that fundamentally redefines how exothermic reactions are controlled at the pellet scale.

The core-shell pellet consists of a highly active catalytic core sourounded in an inert, low-permeability shell. The design adapts to the thermal operating regime of the reactor:

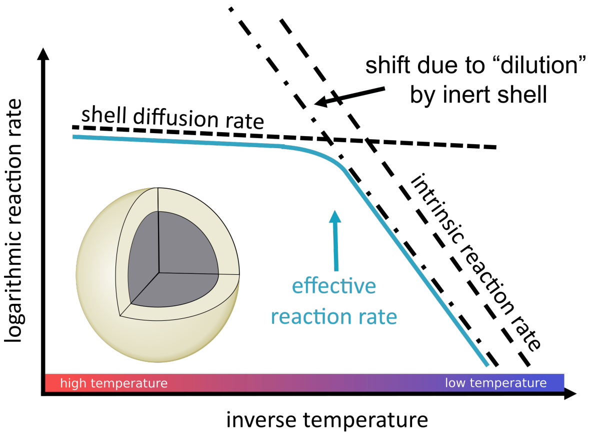

Figure 1: The basic principle of core-shell catalyst pellets (Arrhenius plot): At high temperatures, the mass transport through the inert shell becomes rate-determining, which decreases the effective reaction rate and thus limits hot-spot temperatures and prevents reactor runaways.

- At low temperatures, the shell has minor influence, and the full catalytic activity of the core is utilized - ensuring high reaction rates and space-time yields.
- At elevated temperatures, the shell becomes a mass transport barrier, limiting gas transfer into the active core and thus actively suppressing hot-spot formation.

This **self-regulating mechanism** of the pellets offers a robust and passive safety feature against thermal runaway, especially for -but not limited to- dynamic operating scenarios. As a result, the novel pellet design combines **high performance with intrinsic thermal stability** - without the need for conventional trade-offs such as feed or fixed-bed dilution.

Scalability and Customization

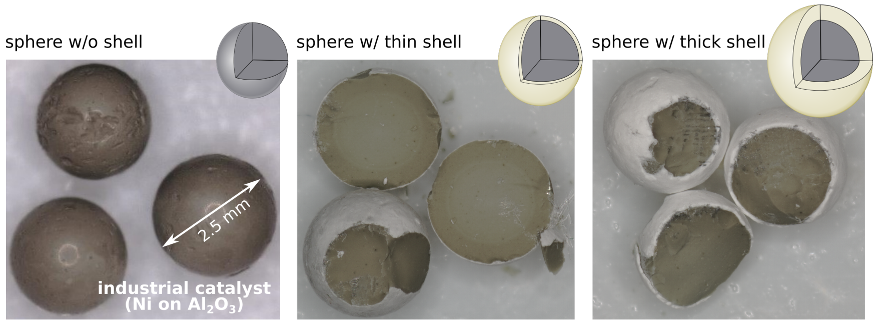

Figure 2: Core-shell catalyst pellet samples produced by fluidized-bed coating.

The core-shell catalyst pellet design is practically and economically viable. It can be manufactured cost-effectively at pilot and industrial scale using established coating methods such as fluidized-bed coating. This ensures ‘’drop-in” integration into existing production lines.

The shell properties (e.g., porosity, pore size, and thickness) can be tuned to meet the specific requirements of a given reaction system (see Fig. 2). This opens up a wide application range, from thermally sensitive lab-scale studies to high-throughput production in large-scale fixed-bed reactors.

Case Study: CO_2 Methanation

To demonstrate the performance and technical feasibility of the core-shell catalyst pellet concept, a series of computational and experimental studies [1–5] were conducted using CO_2 methanation as a showcase. This reaction is highly exothermic and is widely recognized as a benchmark process where thermal management is critical to ensure selectivity, stability, and catalyst lifetime.

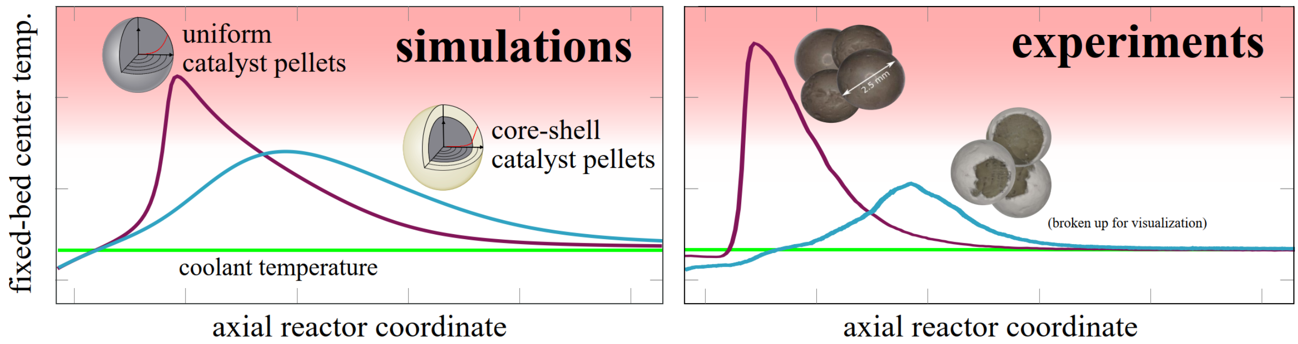

Figure 3: The core-shell catalyst pellet concept applied to CO_2 methanation: Simulation studies (left) and pilot-reactor experiments (right) (tube length: 2 m; tube diameter: 2 cm). In both cases, a significant decrease of the hot-spot temperature is observed.

Simulation results and pilot-scale experiments consistently confirm the temperature-limiting function of the core-shell catalyst pellets at elevated operating conditions. The shell’s mass transport resistance significantly reduces hotspot temperatures, leading to stable and well-distributed temperature profiles across the fixed-bed - while still achieving high methane yields.

Compared to conventional methanation process concepts - such as fixed-bed dilution, recycle loops, intercooling or distributed feed injection - the core-shell pellet demonstrates multiple key advantages [2,4]:

- Up to 3× higher space-time yield (vs. fixed-bed dilution)
- Up to 3× lower pressure drop (vs. fixed-bed dilution)
- >90% CO_2 conversion already in the first reactor stage
- Process simplification: reduced or no need for recycle compressors, intercoolers, feed distribution systems
- Hotspot suppression: reliable protection against catalyst sintering and thermal runaway
- Dynamic robustness: stable operation even under fluctuating conditions
- High flexibility: fast start-up/shutdown, ideal for Power-to-X load scenarios

With this performance, the core-shell concept enables product qualities comparable to multi-stage systems, but within a single-stage, multi-tubular fixed-bed reactor. Ultimately, the simpler process configuration will lead to **lower capital and operating costs**, as well as significantly **higher load flexibility**.

Additional so far unpublished methanation data is available, that could be provided under a CDA.

Further Applications

The core-shell catalyst pellet design is not limited to CO_2 methanation. As a generalizable heat management concept, it holds strong potential for a wide range of highly exothermic catalytic processes, where thermal runaway and hotspot formation pose significant challenges. Promising application fields include: Fischer-Tropsch synthesis (GTL processes), sulfuric acid production (SO_2 oxidation), methanol synthesis, ammonia synthesis.

Get in touch with us to discuss how this technology can be tailored to your specific process challenges.

Patent Information

European priority patent application filed in May 2019

PCT patent application filed in May 2020, nationalized in EP, US, CN

EP3972735B1 granted (validated as Unity Patent, CH, GB, ES, IE, NO)

CN114126757B granted, US20220266235A1 under examination

Literature

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[2] R. Zimmermann, J. Bremer, K. Sundmacher: "Load-flexible fixed-bed reactors by multi-period design optimization", *Chemical Engineering Journal* 428 (2022) 130771

[3] R. Zimmermann, J. Bremer, K. Sundmacher, L. Mörl et al.: "Core–shell catalyst pellets for effective reaction heat management", *Chemical Engineering Journal* 457 (2023) 140921

[4] R. Zimmermann, K. Sundmacher: „Kern-Schale-Katalysatorpellets: Das Gelbe vom Ei für den lastflexiblen Festbett-Reaktorbetrieb?“, *Chemie Ingenieur Technik* 97.5 (2024) 411-420.

[5] A. Geschke, R. Zimmermann, J., Bremer, K. Sundmacher, „Core-Shell Catalyst Pellets for CO_2 Methanation in a Pilot-Scale Fixed-Bed Reactor”, *Chemie Ingenieur Technik* 96.12 (2024) 1718-1725