Max-Planck-Innovation

Technology Offer

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

File no.: MI1402-5768-LC

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:

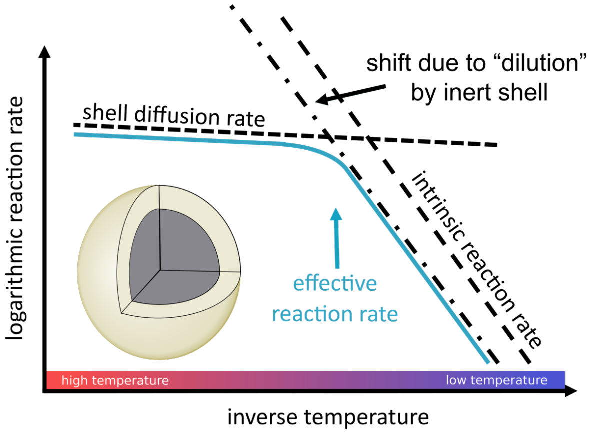

Figure 1: The basic principle of core-shell catalyst pellets (Arrhenius plot): At high temperatures, the mass transport through the inert shell becomes rate-determining, which decreases the effective reaction rate and thus limits hot-spot temperatures and prevents reactor runaways.

- 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.

Max-Planck-Innovation GmbH
Arnulfstr. 58
80335 München
www.max-planck-innovation.de

Scalability and Customization

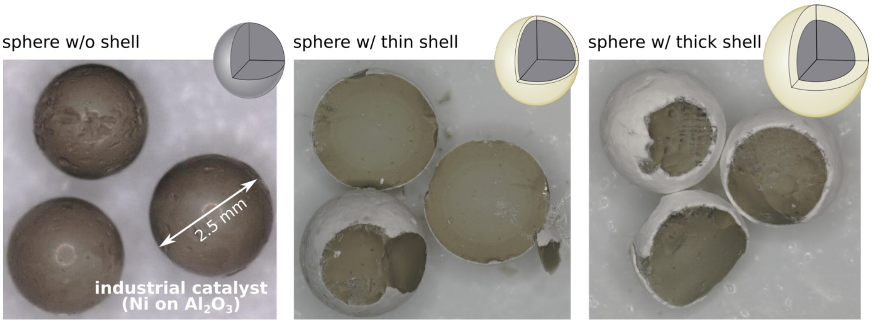

Figure 2: Core-shell catalyst pellet samples produced by fluidized-bed coating.

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.

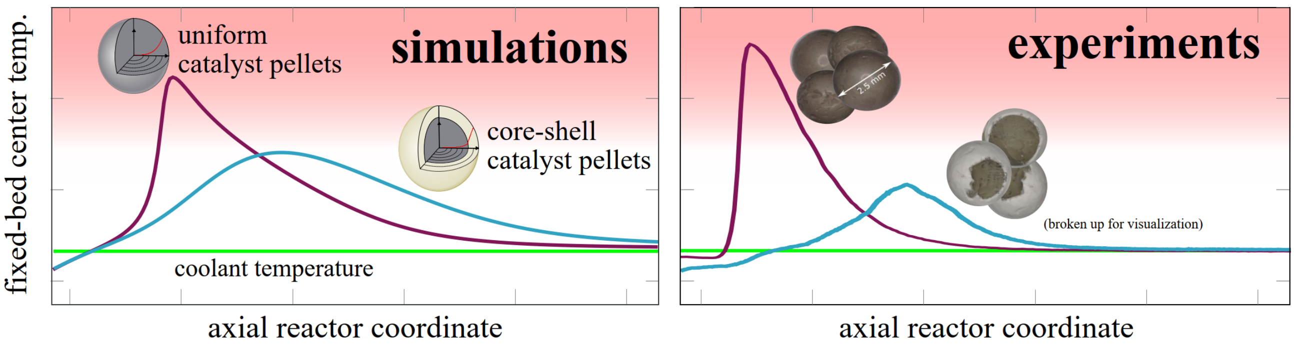

Figure 3: The core-shell catalyst pellet concept applied to CO_2 methanation: Simulation studies (left) and pilot-reactor experiments (right) (tube length: 2 m; tube diameter: 2 cm). In both cases, a significant decrease of the hot-spot temperature is observed.

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

Max-Planck-Innovation GmbH
Arnulfstr. 58
80335 München
www.max-planck-innovation.de

- 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

Literature

[1] R. Zimmermann, J. Bremer, K. Sundmacher: "Optimal catalyst particle design for flexible fixed-bed CO_2 methanation reactors", *Chemical Engineering Journal* 387 (2020) 123704

[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: "Core−Shell Catalyst Pellets for Reaction Heat Release Control in Fixed-Bed Reactors", *Ind. Eng. Chem. Res.* 2024, 63, 7556−7564

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

Contact

Dr. Lars Cuypers,
Diplom-Chemiker
Senior Patent- & Lizenzmanager
E-Mail: cuypers@max-planck-innovation.de

Max-Planck-Innovation GmbH
Arnulfstr. 58
80335 München
www.max-planck-innovation.de