Milestones for hybrid-catalysis in Cascade Reactions

Applications of heterogeneous Flow-Photochemistry in transparent capillaries

C. Deckers[1,*], E. Cermjani[1,2], T. H. Rehm[1], A. Schmitt[3] , G. Ulm[3], J. Prieschl[3], D. Hanselmann[3], B. Herbig[3]
[1] Fraunhofer Institute for Microengineering and Microsystems IMM, Carl-Zeiss-Straße 18-20, 55129 Mainz, Germany
[2] Johannes Gutenberg-University Mainz, Duesbergweg 10-14, 55128 Mainz, Germany
[3] Fraunhofer Institute for Silicate Research ISC, Neunerplatz 2, 97082 Würzburg, Germany
* christoph.deckers@imm.fraunhofer.de

Fraunhofer IMM

Fraunhofer ISC

Abstract & Vision

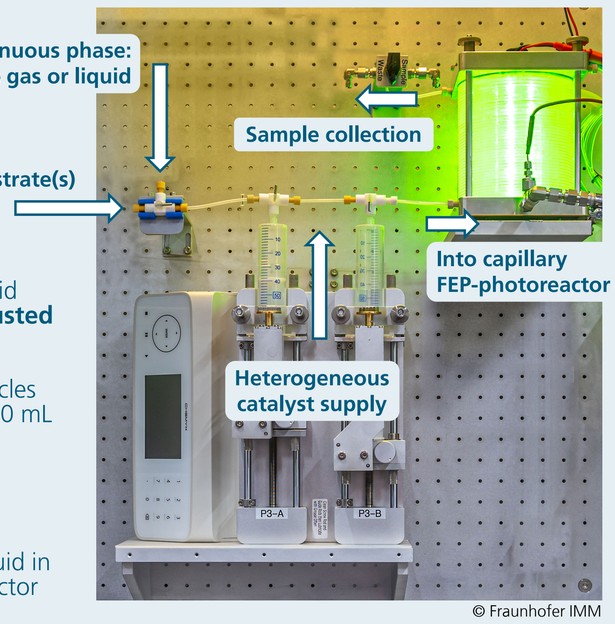
The synthesis of many **fine chemical products** for the pharmaceutical and the agrochemical industry often relies on catalysis. To achieve an **easy recycling** of those catalysts, **heterogeneous** materials are preferred. This is of particular interest, as filtration or other separation techniques can be used to **simplify down-stream** processes immensely.
Here, implementation in Flow Chemistry is realized via the **SMBR**-concept (**S**erial **M**icro **B**atch **R**eactor).[1] A transparent, inert FEP-capillary provides optimal conditions to build up a slug flow-like pattern with (supra-)particles to conduct flow-photochemistry.
Particular attention must be paid to the preparation of the SMBR as catalytic **activity must be maintained**. Moreover, the solvent of the liquid phase can lead to a catalyst **separation**. Both requirements can have a negative impact on each other. This pitfall is eliminated by choosing an **appropriate continuous phase** (gases or liquids). Multiple products are prepared via the SMBR-concept to **realize cascade reactions**.

Heterogeneous Catalysis via SMBR - More than a Slug Flow

Following these fundamentals will keep solid catalyst particles moving, prevent clogging and deposition along the capillary.[2]

Technique	Guidelines against clogging
▪ Prevent cluster formation	▪ Stabilize particles sterically or electrostatically (e.g. correct solvent) ▪ Avoid narrow radii and inertial deposition
▪ Microchannel design	▪ Select materials that inhibit attraction of particles
▪ Process procedures	▪ Clean microchannel occasionally ▪ Use flow pattern that prevent particle-wall contact (e.g. by an inert continuous phase)
▪ External forces	▪ Apply external forces to maintain uniform dispersions, e.g. by ultrasound

Implementation

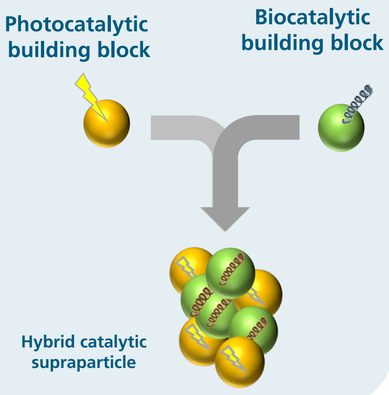


© Fraunhofer IMM

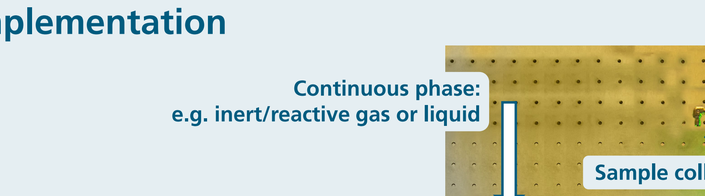
Key to success:
- Capillary, continuous phase, liquid phase and solid catalyst are **adjusted to each other**
- **Active mixing** of the solid particles for a **constant slurry feed** (in 20 mL or 50 mL syringes)
- Feasibility to **integrate** different **capillary photoreactors**
- Complete **irradiation** of the liquid in comparison to a packed bed reactor

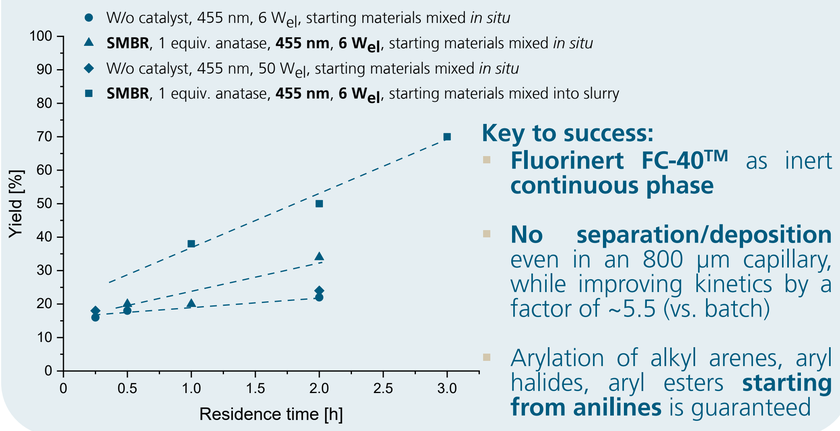
Conclusion & Next steps

- The SMBR-concept, an intelligent catalyst supply and correct stabilization of the flow pattern guarantee effective heterogeneous (photo-)catalysis
- The surface tension between the continuous and liquid phase is essential to stabilize the catalyst and prevent deposition
- Nanoparticulate or heterogeneous catalysts in supraparticle form individually designed for a specific reaction are featured by Flow Chemistry
- Spray-drying allows the combination of different particle types (● & ●) to form hybrid supraparticles for catalytic cascade reactions
- Confirm hybrid-catalyst activity



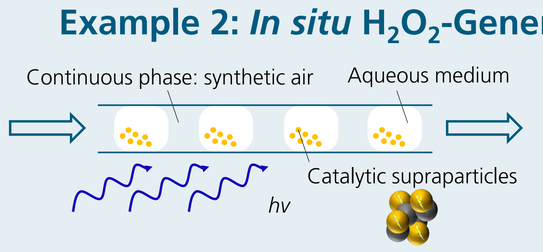
Example 1: Mild Photoarylation of Arenes

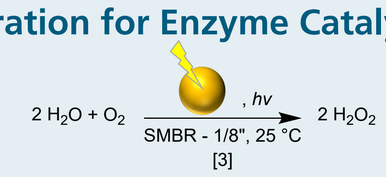


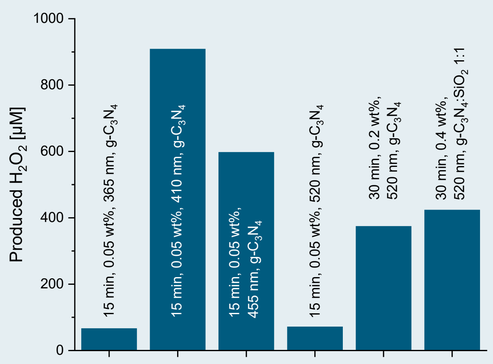


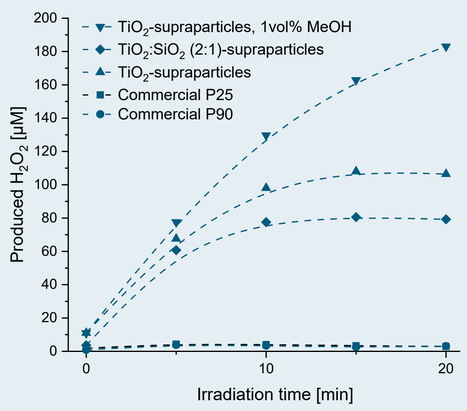
Key to success:
- **Fluorinert FC-40™** as inert **continuous phase**
- **No separation/deposition** even in an 800 µm capillary, while improving kinetics by a factor of ~5.5 (vs. batch)
- Arylation of alkyl arenes, aryl halides, aryl esters **starting from anilines** is guaranteed

Example 2: *In situ* H_2O_2-Generation for Enzyme Catalyzed Oxidations



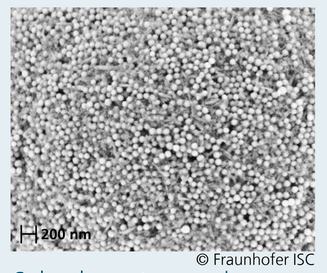






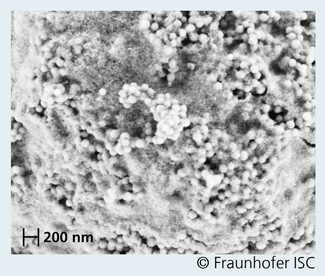
Conditions:
- **Left:** SMBR-concept, 100 mM Tricine buffer + 1vol% MeOH, ~40-50 W_{el}
- **Right:** MQ-water, 365 nm, ~12 W_{el}, 0.05wt% catalyst

Key to success:
- **Effective interaction** of the catalyst, the liquid and the gas



© Fraunhofer ISC

Sol-gel routes and spray-drying gives photocatalytic **g-C_3N_4** (top) and **TiO_2** (bottom) supraparticles. The REM-images show mixtures with SiO_2 nanoparticles (top-1:1, bottom-2:1) prior to enzyme modification.



© Fraunhofer ISC

[1] B. Pieber, M. Shalom, M. Antonietti, P. H. Seeberger, K. Gilmore, *Angew. Chem. Int. Ed.* **2018**, *57*, 9976.
[2] F. Scheiff, D. W. Agar in Biological and medical physics, biomedical engineering (Eds.: M. Köhler, B. P. Cahill), Springer-Verlag, Berlin, Heidelberg, **2014**, 103–148.
[3] Y. Guo, X. Tong, N. Yang, *Nano-Micro Lett.* **2023**, *15*, 77.

SPONSORED BY THE
Federal Ministry of Education and Research

In cooperation with

Fraunhofer IGB

Fraunhofer IME

www.cascade-reactions.de