Organisation profile

Heidrun Gruber-Woelfler*, Hans Schnitzer, Michael Narodoslawsky and Johannes G. Khinast

IPPE-TU Graz: green engineering inside and beyond the borders of process technology

DOI 10.1515/gps-2014-0099

Areas of expertise

The Institute of Process and Particle Engineering (IPPE, ippt.tugraz.at) at Graz University of Technology consists of five independent research areas, each committed to high-level basic and applied research:
- Pharmaceutical engineering and particle technology
- Mechanical process engineering
- Process evaluation
- Energetic biomass utilization, and
- Zero emissions techniques and systems.

The research of these groups covers the areas of pharmaceutical product and process development, particle manufacturing and flow processes, sustainable regional development, thermal biomass utilization and sustainable energy on the basis of renewable resources. We see ourselves as the interface between nature, engineering sciences, society and economics and are very much aware of our responsibility for future generations – the human being is always in the focus of our research.

Green process engineering

Process engineering is arguably one of the disciplines that are at the frontline of human impact on the environment. Green process engineering is therefore one of the most important tasks of any process engineering research and development institutions. This mission is a major pillar of the activities of the IPPE.

According to this mission, research at our institute focuses in part on chemical and pharmaceutical processes that are more intense, efficient and thus greener. One pathway followed here is the development and application of heterogeneous catalysis and micro-reactors that are capable of intensifying reactions considerably in order to achieve smaller footprints, to reduce costs, unwanted byproducts and energy consumption. Research at IPPE is, however, not restricted to the development of technologies that help to reduce the impact of process industries on the environment. IPPE also provides strategic decision support for industry to become greener. It also uses experiences and methods from chemical engineering to help beyond the confines of process engineering, providing innovative solutions for smart cities and regions.

Continuous processes for API production

The research of the group "Continuous Processes" focuses on the synthesis and purification of active pharmaceutical ingredients (APIs) and specialty chemistries in continuous flow mode (Figure 1). In particular, the activities cover (a) the preparation of heterogeneous catalysts, (b) the implementation of these catalysts into continuous flow processes and (c) the development of functionalized monolithic stationary phases for continuous (electro-)chromatography.

In the area of heterogeneous catalysis, palladium compounds and titanocenes are immobilized via organic ligands on different solid supports, such as functionalized silica gel [1, 2], silicon wafers and particles as well

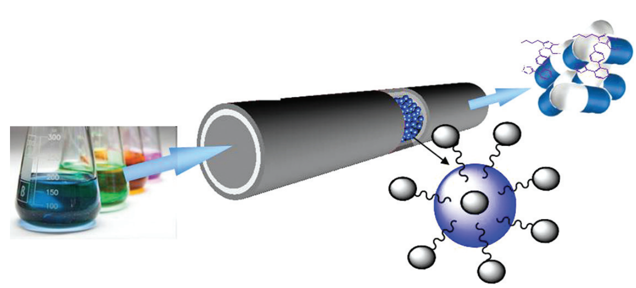

Figure 1 Scheme of the production of APIs in continuous flow mode.

***Corresponding author: Heidrun Gruber-Woelfler,** Institute of Process and Particle Engineering, Graz University of Technology, Inffeldgasse 13, 8010 Graz, Austria, e-mail: woelfler@tugraz.at
Hans Schnitzer, Michael Narodoslawsky and Johannes G. Khinast: Institute of Process and Particle Engineering, Graz University of Technology, Inffeldgasse 13, 8010 Graz, Austria

as modified cellulose. Additionally, palladium supported cerium-tin-oxides (general formula $Ce_xSn_yPd_{1-(x+y)}O_{2-\delta}$), that can be easily prepared via solution-combustion synthesis [3], have been established. The titanocenes are used for the production of chiral amines via hydrosilylation of imines [4], whereas the palladium compounds are used for Suzuki-Miyaura cross-coupling reactions [5, 6].

In addition to recycling and heterogeneity studies in batch experiments, the heterogeneous Pd-compounds are implemented in a packed bed micro-reactor system. The reactions are carried out in aqueous media at moderate temperatures. The Pd-leaching into the product was analyzed to be below the detection limit of inductively coupled plasma optical emission spectrometry (ICP/OES).

Applied microreactor system

The applied microreactor system is the so-called plug & play reactor, which was developed together with the company OneA Engineering GmbH (Figure 2). The system is a versatile tool that includes flexible modules for heating/cooling and mixing as well as an exchangeable reaction segment, which is a commercially available HPLC column filled with the catalytic active particles. The applications of the plug & play reactor include gas/solid, liquid/solid as well as gas/liquid/solid reactions. Furthermore, it allows the monitoring of the reaction progress and the reaction parameters in- and online and can be easily implemented in existing (industrial) processes.

Additionally to the heterogeneous Suzuki-Miyaura reactions, the performance of this new reactor is currently tested for the continuous production of acetyl salicylic acid (the API of aspirin) using a fixed bed of commercially ion-exchange particles as heterogeneous catalysts.

Continuous (electro)-chromatography

Another research focus is the development of functionalized monolithic stationary phases for continuous (electro)-chromatography. Chromatography is a powerful tool used in analytical chemistry as well as in preparative purification processes. However, chromatographic processes are costly and are performed mostly as batch processes on an industrial scale. One reason for that is the necessity to use different stages in a chromatographic separation process due to the high purification grade needed. To obtain a more sustainable method, trends towards continuous processes have emerged, such as simulated moving bed chromatography (SMB) [7] and continuous annular chromatography (CAC) [8, 9].

A novel approach in this area includes continuous annular electro-chromatography, which combines the advantages of HPLC and electrophoresis, thus achieving high theoretical plates and high throughput. As a consortium member of the FP 7 project "Continuous Annular Electro-chromatography (CAEC)" (https://caec.bci.tu-dortmund.de/), we developed functionalized monolithic stationary phases for the CAEC prototype (Figure 3). The novel

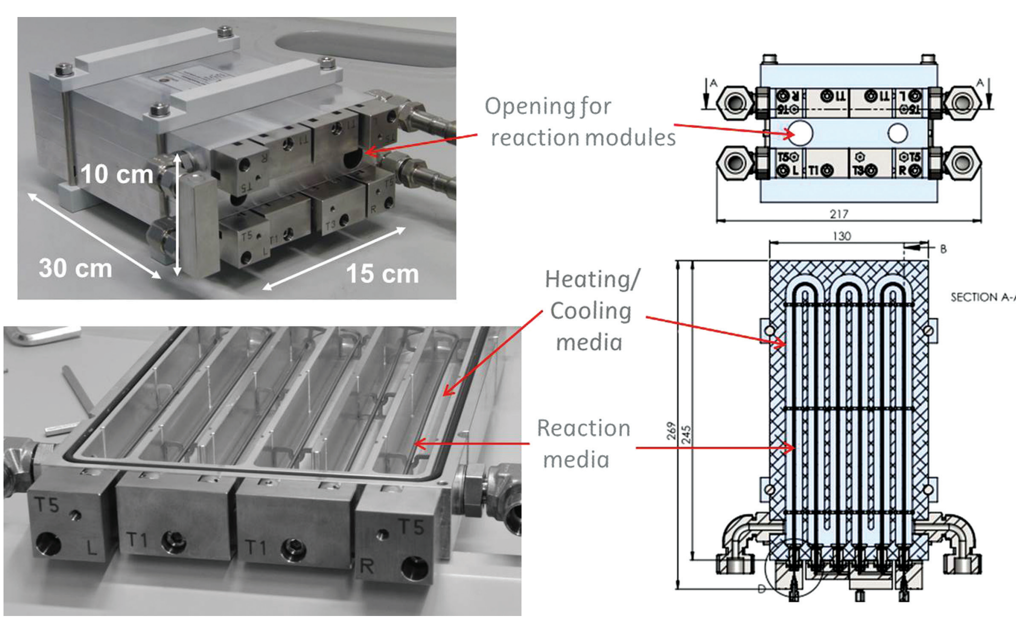

Figure 2 Pictures and scheme of the plug & play reactor.

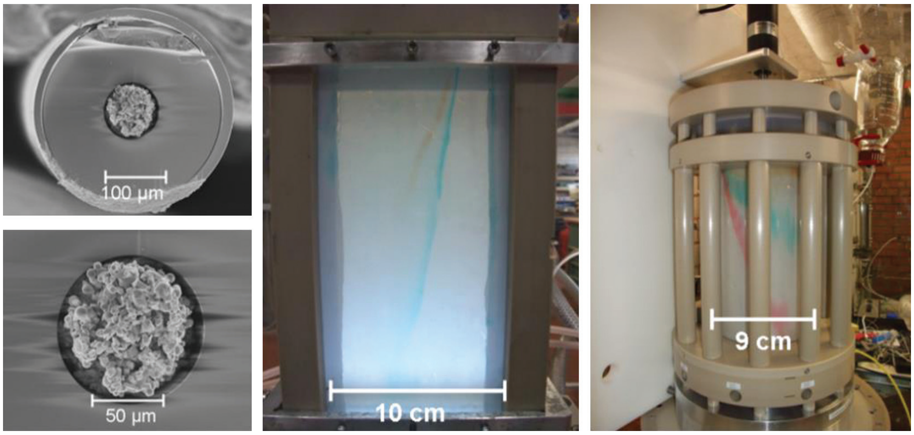

Figure 3 Pictures of a CEC capillary (right), the planar test system (middle) and the annular prototype (left) filled with monolithic stationary phase.

materials were successfully implemented in (a) capillaries for capillary electro-chromatography (CEC), (b) a planar test cell and (c) a prototype for CAEC. Although these geometries implied a scale-up of the filling procedure by the factor of 40, very homogeneous stationary phases without any shrinkage or cracks could be produced. The reversed phase materials were tested for the separation of different model compounds, such as polycyclic aromatic hydrocarbons, alkylbenzenes and phenols, and high separation performances with theoretical plate numbers of up to 30.000 m^{-1} could be achieved at every scale.

All in all, the approaches including the applications of recyclable, non-leaching heterogeneous catalysts for continuous flow chemistry in an aqueous environment as well as the reduction of the amounts of organic solvents used for purification approaches definitely contribute to a "green processing" of APIs.

Process analysis and emerging technologies for material and energy efficiency in production processes

Research on climate change showed that industry has to contribute to a reduction of 80% of the emissions of greenhouse gases until 2050.

In order to reach this ambitious goal the following approaches have to be made [10]:

- increase in the efficiency of energy use
- shift to renewable forms of energy sources
- new process units
- change the products to lower energy consumption and longer lifetime.

The research group focusses on the analysis and evaluation of production processes as a basis for the following [11]: process modifications, process integration and process intensification. In order to enable the access to the latest developments, a database (wiki.zero-emissions.at) has been designed and is continuously updated with the results of different projects [12]. The database includes basic production data, benchmarking numbers and latest developments in energy efficiency for important production processes. The main activities are currently in food industry within the Intelligent Energy Europe project Greenfoods (www.green-foods.eu). Examples of organic waste from food industry are shown in Figure 4 [13].

Figure 4 Organic waste from food industry prepared for biogas tests.

Other international projects are the ASEN-Uninet with the Ho Chi Minh University in Saigon, Vietnam, on water and energy issues as well as two TEMPUS projects: GIEP (www.giep.eu) and TRINEX (www.trinex.eu). Similar process optimisations focus on membrane distillation in wastewater cleaning.

Smart energy systems and ecological evaluation

Energy and greenhouse gas emissions are however not only problems for process industry, they are also of general importance to society on its way towards sustainable development. Process engineering is not only a part of the solution by greening industrial production but also by providing planning and decision support methods that may be used in other areas way beyond the confines of the process engineering discipline [14].

A research group at IPPE therefore focuses on the planning of optimal energy systems as well as on the exploitation of renewable resources in smart cities and regions of the future, drawing on the experiences with process synthesis in chemical engineering [15]. Using Process Network Synthesis methods based on the biparted graph representation of industrial processes spearheaded by Friedler et al. [16], the group helps regions and cities to develop optimal energy systems that combine greenhouse gas reductions with exploitation of local/regional renewable resources and economic benefits. Particular interest is put on the integration of industries into the energy systems of cities and regions. The software package RegiOpt, developed in cooperation with the University of Pannonia in Hungary and accessible from www.fussabdrucksrechner.at allows lay persons to estimate the optimal energy system for their particular regional setting.

Decisions towards sustainable development in industry as well as in other areas requires solid knowledge about ecological performance from the vantage point of sustainability. The Sustainable Process Index (SPI) developed by this research group at IPPE allows the comprehensive evaluation of ecological sustainability with an ecological footprint that also takes into account the difference between fossil, nuclear and renewable energy forms and the impact of emissions [17]. This measure has been successfully applied to many industrial processes over the course of the last 20 years. It has been applied however also outside the process industry to agriculture, energy systems, even to life styles, regions and cities. The SPI is the base of the freely available software SPIonWEB (www.SPIonWEB.tugraz.at) that allows process engineers to evaluate their processes based on mass and energy balances, drawing on a large database of processes to allow for life cycle assessment. More software on the SPI as well as case studies and literature can be taken from this web page and the web page www.fussabdrucksrechner.at.

References

[1] Gruber-Woelfler H, Radaschitz PF, Feenstra PW, Haas W, Khinast JG. *J. Catal.* 2012, 286, 30–40.
[2] Gruber-Woelfler H, Neubauer C, Lichtenegger GJ, Polo E, Khinast JG. *Dalton Trans.* 2012, 41, 12711–12719.
[3] Sanyakumar SR, Mukri BHAS, Patil S, Madras GIRI, Hegde MS. *J. Chem. Sci.* 2011, 123, 47–54.
[4] Gruber-Woelfler H, Flock M, Fischer RC, Sassmannshausen J, Stanoeva T, Gescheidt G, Khinast JG. *Organomet.* 2009, 28, 2546–2553.
[5] Miyaura N, Suzuki A. *Chem. Rev.* 1995, 95, 2457–2483.
[6] Suzuki A. *J. Organomet. Chem.* 1999, 576, 147–168.
[7] Rajendran A, Paredes G, Mazzotti M. *J. Chrom.* A 2009, 1216, 709–738.
[8] Uretschläger A, Jungbauer A. *Bioprocess Biosyst. Eng.* 2002, 25, 129–140.
[9] Wolfgang J, Prior A. In *Modern Advances in Chromatography*, 76th ed., Freitag R, Ed., Springer: Berlin Heidelberg, 2002, pp 233–255.
[10] Köppl A, Kettner C, Kletzan-Slamanig D, Schleicher S, Damm A, Steininger K, Wolkinger B, Schnitzer H, Titz M, Artner H, Karner A. *Energ. Environ.* 2014, 25, 281–304.
[11] Do TTH, Schnitzer H, Le TH. *J. Clean. Prod.* 2014, 78, 112–120.
[12] Muster-Slawitsch B, Weiss W, Schnitzer H, Brunner C. *Appl. Ther. Eng.* 2011, 31, 2123–2134.
[13] Nguyen Ngoc U, Schnitzer H. *Int. J. Environ. Sust. Dev.* 2010, 9, 149–180.
[14] Bramsiepe C, Sievers S, Seifert T, Stefanidis G, Vlachos D, Schnitzer H, Muster-Slawitsch B, Brunner C, Sanders J, Bruins M, Schembecker G. *Chem. Eng. Process.* 2012, 51, 32–52.
[15] Kettl KH, Niemetz N, Sandor N, Eder M, Heckl I, Narodoslawsky M. *21st European Symposium on Computer Aided Process Engineering – ESCAPE 21*, Pistikopoulos EN, Georgiadis, MC, Kokossis AC, Eds., Elsevier B.V., 2011.
[16] Friedler F, Varga JB, Fan LT. *Chem. Eng. Sci.* 1995, 50, 1755–1768.
[17] Stoeglehner G, Niemetz N, Kettl KH. *Energ. Sust. Soc.* 2012, 1, 2, doi:10.1186/2192-0567-1-2.