

Roadmap Chemical Reaction Engineering

an initiative of the DECHEMA/VDI Subject Division
Chemical Reaction Engineering

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Preface

This 3rd edition of the Roadmap on Chemical Reaction Engineering has been completely revised, putting more focus on three main trends in Technical Chemistry and Process Engineering:

- » Integrated approach to product and process design
- » Process diagnostics based on models, operando investigations and process data
- » Electrification of chemical conversion processes and large-scale implementation of electrochemical and chemical energy storage

Chemical reaction engineering plays a key role in product properties and quality. For this reason, it is intimately involved in the development of innovative product features. As an example, certain microstructures of polymers or functionalities of nanoparticles can only be achieved if the process and the reactor are designed using the tools of chemical reaction engineering. To an increasing extent, chemical reaction engineering is also the key to process and product development in sectors outside the chemical industry, such as energy technology or automotive engineering.

With the help of additive manufacturing, chemical reactors will become tailor-made devices with an optimized design for the specific reaction. This translates into more efficient fluid and particle flow, heat and mass transport, better structural properties and traceable reaction trajectories.

To achieve Germany's greenhouse gas reduction goals, a rapid energy transition (i.e. from fossil fuels to renewable sources) is imperative. The large-scale transition to intermittent electrical energy from sun and wind power will generate increasing interest in the electrification of chemical processes and new approaches for electrical energy storage.

Chemical reaction engineering is not only driven by the need for new processes and products (market pull), but also by a rational utilization of technologies (technology push). The combination of laboratorial experiments and novel digital tools, such as multiscale modeling and simulation, opens the way to a systematic approach, in which in situ measurements at a molecular level assist to improve product properties.

In short, chemical reaction engineering is no longer just about understanding, designing and optimizing classical chemical reactors in terms of yield, energy and efficiency. It is also an important enabler for sustainable solutions, product innovation and new business concepts.

The roadmap contains a total of six case studies, which are intended to provide insights into current chemical reaction engineering tasks based on practical examples.

Finally, we hope the 3rd edition provides stimulating and enjoyable reading. We would really appreciate getting your feedback, suggestions and comments for the next edition, so do not hesitate to contact us.

The Board of the DECHEMA/VDI Subject Division Chemical Reaction Engineering

1 What is Chemical Reaction Engineering?

Chemical reaction engineering lies at the interface between chemistry and process engineering, spanning the development of new synthesis routes in the laboratory and the industrial-scale manufacture of chemicals. The end products of the chemical industry, such as polymers, colorants, adhesives or detergents found in many of today's consumer goods, have become an indispensable part of everyday life and make a substantial contribution to our high standard of living. In addition to these classic chemical products, chemical reaction engineering also enables products and processes for chemical energy conversion and storage and therefore contributes to the transformation of our current predominantly fossil energy system towards a totally renewable energy system. Finally, chemical reaction engineering also holds indispensable scientific fundamentals for the production of synthetic foods to help feed the world's population.

The evolution of chemical reaction engineering is closely linked to the development of the ammonia synthesis by the Haber-Bosch process at the beginning of the 20th century. From around the middle of the 20th century, chemical reaction engineering became recognized as a separate scientific field and, as such, became firmly established in the curricula for chemical engineering education. DECHEMA (Gesellschaft für Chemische Technik und Biotechnologie e.V., the German expert network for chemical engineering and biotechnology) and VDI (Verein Deutscher Ingenieure) should be mentioned as key organizations that played a major role

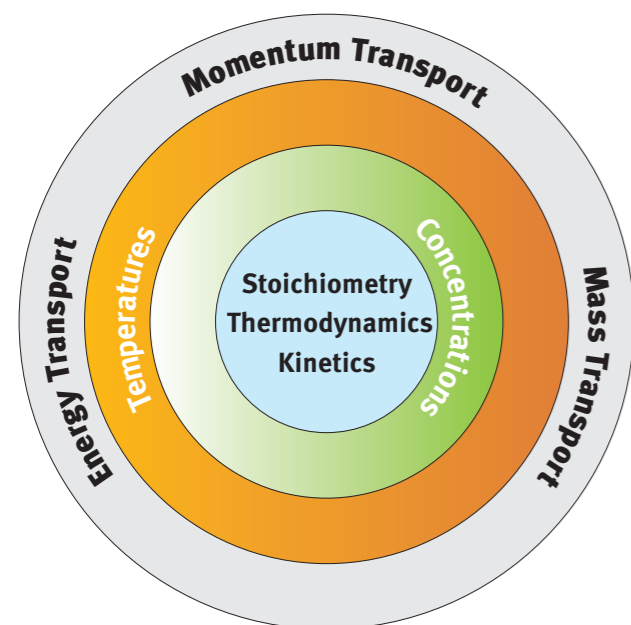


Figure 1.1: Fundamental Aspects of Chemical Reaction Engineering.

in the development of chemical reaction engineering as a vigorous and independent discipline in Germany. In 1956, the DECHEMA Expert Committee "Chemical Reaction Engineering" was founded and in 1961 the DECHEMA Working Group "Technical Reactions (Technische Reaktionen)" was established under its patronage. Also in 1956, the Working Group "Technical Reaction Engineering (Technische Reaktionsführung)" was set up under the auspices of the former VDI division "Process Engineering". In 2007, DECHEMA and VDI-GVC bundled all their previous activities in process and plant engineering, chemical engineering and technical chemistry in the joint initiative ProcessNet. The working groups in chemical reaction engineering were consequently merged into the Working Group "Technical Reactions". In 2015, as part of a reorganization and consolidation, the Working Group "Technical Reactions" ceased operations and its activities were integrated into the ProcessNet Subject Division "Chemical Reaction Engineering". From 2023, the activities are continued within the DECHEMA/VDI Subject Division "Chemical Reaction Engineering". Chemical reaction engineering as an independent scientific discipline is based on two pillars: "reaction analysis" and "reactor design".

In reaction analysis the stoichiometry, thermodynamics and kinetics of chemical reactions are scrutinized. Stoichiometry provides the framework to account for the possible interactions between the various chemical species in a reaction network; thermodynamics indicate the limits imposed on conversions, while kinetics describe how fast individual reactions proceed and thus provide the reaction engineer with the basis for modeling and reactor design. Today, mechanistic kinetics derived from detailed knowledge of the molecular processes are generally preferred over formal kinetic descriptions based on fitting empirical rate of reaction expressions to experimental data from kinetic measurements. Establishing mechanistic kinetics also makes use of several chemical disciplines such as physical chemistry, solid-state chemistry and theoretical chemistry, and even physics may be involved in the relevant surface science.

Reactor design can be carried out empirically by scaling down the technical reactor envisaged to a representative laboratory reactor system and then using this to identify optimal reaction conditions (temperature, pressure, concentrations and catalyst), and even a comparison of alternative reactor types (fluidized-beds, plug-flow reactors, batch reactors, ...) is thus possible. Distributed parameter measure-

ments are playing an increasingly important role in this process, since they provide revealing insights into the locally prevailing conditions. Rational reactor design, based on reliable kinetics, taking into account both chemical reactions and the transport processes for mass, heat and momentum involved in the system under consideration, is becoming the norm, with reactor modeling and simulation making an indispensable contribution. New reactor concepts and variations in the reactor operating conditions can be predicted reliably by this means. The conceptual basis for the reactor modeling is the balancing of energy, matter and momentum. Solving these balance equations leads to temperature and concentration fields and reaction rate profiles in the chemical reactor. In addition to reaction kinetics, heat and mass transport as well as fluid dynamics can have a decisive influence on reactor performance.

Figure 1.1 provides a schematic illustration of the fundamental aspects of chemical reaction engineering. From a more practical point of view, these fundamental aspects are applied to the corresponding reaction systems, which results in three typical approaches:

1. Experimental Reaction Engineering (see Chapter 3)
2. Mathematical Modeling and Simulation (see Chapter 4)
3. Reactor Design and Process Development (see Chapter 5)

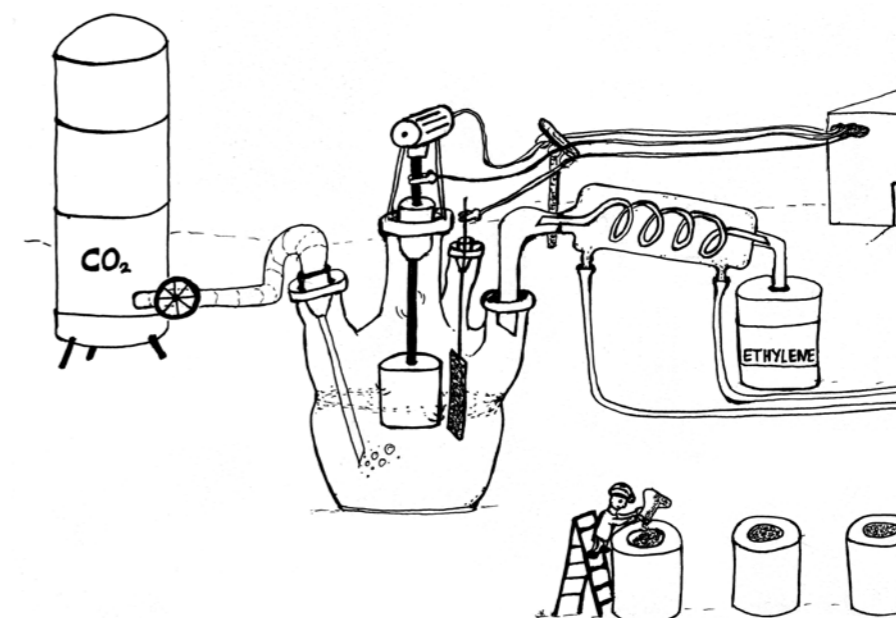


Figure 1.2: How not to scale-up: The scale-up by simply increasing the size of the laboratory apparatus is not possible. (E. Kollé-Görgen, B.J.M. Etzold, DOI: 10.48328/tudatalib-662, Reproduced with permission under the term of CC BY 4.0)

Since the diversity of chemical reactions is enormous, e.g. catalysed or non-catalysed, single- or multiphase, exo- or endothermic, thermo-, photo- or electrochemical, etc., case studies have been selected to demonstrate the underlying principles and the typical approaches of chemical reaction engineering for various applications (see Chapter 6).

Since the ultimate goal of chemical reaction engineering is either the improvement of existing chemical processes or the development of new chemical processes, a scale-down or a scale-up is needed in order to bridge the scales between lab investigation and industrial production. So typically, a chemical reaction engineer always has a chemical process in mind, meaning that all the investigations done in the lab need to be scalable. Knowing the fundamental aspects and choosing suitable approaches, one can handle the scalability and the transfer of knowledge between the scales. Figure 1.2, for instance, visualizes a scale-up-method which does not work. The example is taken from the field of electrocatalysis, where rotating disc electrodes are often used for catalyst screening, e.g. for electrocatalytic conversion of CO₂ to ethylene. However, this type of electrode as well as its operating mode cannot be scaled-up as shown in Figure 1.2. Thus, based on the knowledge of fluid dynamics, mass and heat transport an appropriate reactor and process design can be devised and scaled-up based on the aforementioned chemical reaction engineering approaches, i.e. suitable experimental investigations and appropriate modeling and simulation studies.

2 Relevance of Chemical Reaction Engineering

Chemical reaction engineering contributed significantly to one of the key achievements of the 20th century like the ammonia production by the Haber-Bosch process. This process enabled the mass production of agricultural fertilizers and led to a massive increase in growth of agricultural yields. Without this process almost half the world's population would not be alive today. However, it is estimated that 828 million people currently suffer from chronic hunger and that global food production needs to double by the time that the global population stabilises at around 10 billion in 2050 [1,2,3]. In the 21st century global climate change has become the greatest threat facing mankind, e.g. through causing increased flooding, extreme heat, loss of biodiversity, and – as already in the 20th century – food insecurity. CO₂ produced by human activities is the greatest contributor to global warming due to its greenhouse effect. By 2020, its concentration in the atmosphere had risen by 48 % of its pre-industrial level (before 1750). Chemical reaction engineering can significantly contribute to reduce fossil CO₂ emissions and convert CO₂ from a threat to an asset by closing the carbon cycle. Figure 2.1 summarizes how the chemical industry, and thus chemical products, can become greenhouse gas neutral. Three general possibilities are available to reach this goal:

1. Chemical recycling
2. Bioeconomy
3. CO₂ utilization

While bioeconomy relies on the catalytic efficiency of enzymes that often allow for comparatively mild reaction conditions, classical chemical processes such as chemical recycling and CO₂ utilization are energy intensive [6]. To ensure sustainability, their energy demand needs to be covered by renewable energy, preferably renewable electricity. Chemical reactions can be driven directly or indirectly with electricity, e.g. by electro-, plasma-, and photochemistry or by electrical heating via resistive, inductive or dielectric heating. All these possibilities of using renewable electricity are subsumed under the term “electrification of the chemical industry” [4,5,6]. Chemical reaction engineering is more important than ever before to develop new reactors and processes utilizing renewable electricity.

However, apart from the technological transition towards non-fossil raw materials and renewable energy, the economic feasibility of a chemical production route must still be considered with respect to:

- » Investment costs
- » Operational costs
- » Process safety
- » Environmental impact

Investment costs can be calculated based on the process flowsheet from major items such as reactors, separation equipment, compressors and pumps. The type, number and size of the major units are influenced significantly by the temperature and pressure operating conditions required for the chemical reaction, by the selectivity-conversion behaviour and by the potential space-time-yield of the reactor. While selectivity dictates the complexity of downstream separation, conversion determines the recycle flow rate and the space-time-yield defines the size of the reactor. Therefore, both the selectivity-conversion diagram and the space-time-yield are critical criteria for process development and optimization.

Operational costs are also strongly dependent on the selectivity-conversion behavior, since selectivity dictates the raw material efficiency and a combination of selectivity and conversion stipulates the energy required for separation.

Chemical reaction engineering principles, mainly focusing on reactor operation, are also used to enhance process safety. A runaway reaction or the ignition of a reaction on a solid catalyst can be described by a heat balance (Semenov diagram), in which diffusion phenomena and fluid dynamics can play a key role. In such cases, micro-reaction engineering, for example, can provide significantly safer production process.

Furthermore, chemical reaction engineering makes essential contributions to reducing the environmental impact by following the 12 principles of green engineering [7] and sustainable process design [8]. A so-called life cycle assessment (LCA) not only considers the impact category “climate change” but also the other remaining 14 impact categories according to the EU standard EU15804.

Last but not least, it is important to emphasize that the relevance of chemical reaction engineering is not only a key to sustainable production of chemicals but can contribute to the sustainability in other sectors as well, e.g. to the

- » energy sector by providing energy storage solutions such as liquid organic hydrogen carriers (LOHCs), redox flow batteries, etc.
- » transport sector by providing sustainable aviation and marine fuels
- » steel sector by providing hydrogen-based metallurgic processes
- » construction sector by providing sustainable construction materials
- » life science like pharma sector and food sector eg. by providing synthetic food
- » establishing circular economy, see fig.2.1

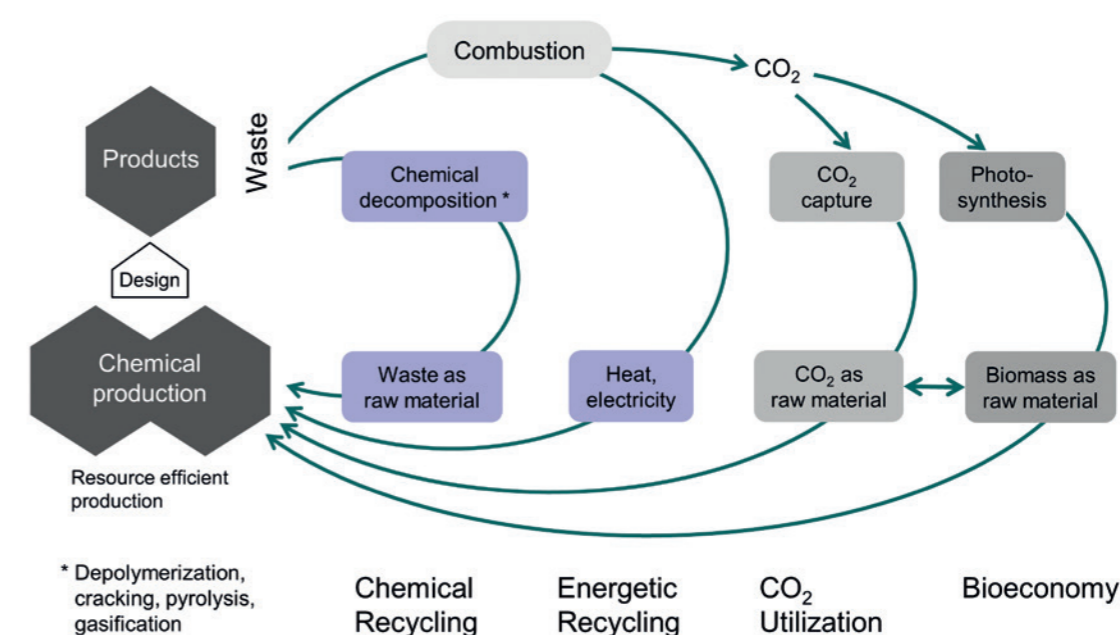


Figure 2.1: Closing the carbon cycle. (According to: Verband der Chemischen Industrie e.V. – VCI (2018) and M. Carus and A. Raschka nova-Paper #10, nova-institute, Hürth, Germany)

REFERENCES

- [1] FAO Food and Agriculture Organisation of the United Nations, UN Report: Global hunger numbers rose to as many as 828 million in 2021.
- [2] I. Tomlinson, Doubling food production to feed the 9 billion: A critical perspective on a key discourse of food security in the UK, *J. Rural Studies* 29 (2013) 81–90. <https://doi.org/10.1016/j.jrurstud.2011.09.001>.
- [3] P.R. Ehrlich, J. Harte, Opinion: To feed the world in 2050 will require a global revolution, *PNAS* 112 (2015) 14743–14744. <https://doi.org/10.1073/pnas.1519841112>.
- [4] J.L. Barton, Electrification of the chemical industry, *Science* 368 (2020) 1181–1182. <https://doi.org/10.1126/science.abb8061>.
- [5] E. Klemm, C. Lobo, A. Löwe, V. Schallhart, S. Renninger, L. Waltersmann, R. Costa, A. Schulz, R.-U. Dietrich, L. Möltner, V. Meynen, A. Sauer, K.A. Friedrich, CHEMampere: Technologies for sustainable chemical production with renewable electricity and CO₂, N₂, O₂, and H₂O, *Can. J. Chem. Eng.* 100 (2022) 2736–2761. <https://doi.org/10.1002/cjce.24397>.
- [6] R. Geres, A. Kohn, S. Lenz, F. Ausfelder, A. M. Bazzanella, A. Möller, Summary of the DECHEMA and FutureCamp study “Roadmap Chemie 2050” for the VCI: Working towards a Greenhouse Gas Neutral Chemical Industry in Germany, FutureCamp Climate GmbH, München, Germany 2019. ISBN: 978-3-89746-223-6.
- [7] P.T. Anastas and J.B. Zimmerman, Design Through the 12 Principles of Green Engineering, *Environ. Sci. Technol.* 37 (2003), 94A–101A. <https://doi.org/10.1021/es032373g>.
- [8] D.J.C. Constable, M. Gonzalez, S.A. Morton, Towards more sustainable chemical engineering processes: integrating sustainable and green chemistry into the engineering design process, *Sustainability in the Design, Synthesis and Analysis of Chemical Engineering Processes*, in: G. Ruiz-Mercado and H. Cabezas (Eds.), Oxford, UK: Butterworth-Heinemann, 2016, 1–34. <https://doi.org/10.1016/C2014-0-00535-7>.

3 Experimental Reaction Engineering

Experimental research is essential for the correlation, validation and optimization of mathematical models and technical process simulations. The coupling between experiments and reaction modeling approaches provides a reliable basis for designing more efficient chemical process technologies.

A LABORATORY REACTORS

Researchers in the field of reaction engineering have a large number of laboratory scale reactors available to perform experimental studies under a variety of controlled conditions. Standard reactors described in literature [1, 2] provide infor-

mation regarding conversion, productivity, selectivity and catalyst lifetime. With recent advances in instrumentation, it is possible to exercise precise control over the reaction conditions, i.e. temperature, partial pressure, time-on-stream, residence time, feed composition, etc. Laboratory and pilot plants can now be controlled via easily configurable process

control systems, so that an automated operation is possible over long periods of time. Systems for acquisition and processing of laboratory data also enable the computerized archiving and analysis of such information, which further facilitates the interpretation of experimental results [3]. Systematic process automation strongly relies on computer science techniques. These techniques can help manufacturers to find efficient solutions and improve the existing products, as well as to optimize process efficiency and the overall use of resources, minimizing waste and avoiding costly downtimes of the production line [4].

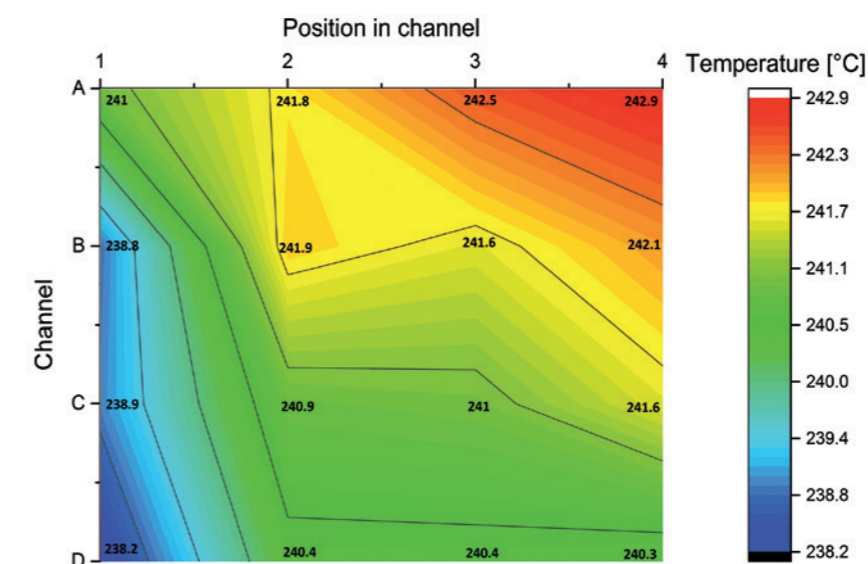


Figure 3.1: Compact modular Fischer-Tropsch reactor of the KIT spin-off INERATEC GmbH. Nearly isothermal conditions were achieved with the innovative evaporation cooling. (source: INERATEC GmbH)

Along with process automation, flow chemistry is also a trending research topic. It has become an important tool in chemical research, with studies focused on the design and development of novel catalytic reactors and manufacturing techniques. Microfluidic reactors with specially tailored features are increasingly employed for the synthesis of advanced materials, e.g. nanoparticles with narrow size distributions or particular morphologies. Such microstructured reactors can improve heat and mass transfer during a chemical reaction.

Larger microstructured reactor systems are currently being developed for energy-related applications, such as the

use of excess renewable electrical energy for the production of synthetic carbon-neutral hydrocarbons (e.g. oxygenated hydrocarbons) or high-value chemicals – the so-called Power-to-X (PtX) approach [5] (see Figure 3.1). Such applications benefit from the excellent heat transfer performance of microstructured reactors and from the resulting potential for higher space-time-yields, selectivities and longer catalyst lifetimes. Their modularity and superior dynamic operation, i.e. including more rapid start-up and shut down, makes them particularly attractive for decentralized energy generation and utilization, within the context of a future energy system largely based on renewables. Several companies, including Inerotec, go beyond the utilization of microstructured reactors as a tool for experimental reaction engineering. They are working on the scale-up of microstructured reactors and their implementation in commercial production plants.

Additive manufacturing (AM), also known as 3D printing, combines the possibility of both an innovative reactor design and precise coupling of sensors for reaction control. Three-dimensional structures of an almost unlimited geometrical complexity are achievable, with full integration of additional functionalities: dosing, phase contact, heating, cooling, in-line analysis and reaction monitoring [6]. Such features can

be exploited in the design of customized reactor and process equipment with greatly enhanced performance.

So far, industrial applications of AM are mainly found in prototyping and tool part manufacturing of components in the fields of architectural, dental and medical technologies, as well as in the automotive and aerospace sectors. Contrary, in the chemical and pharmaceutical industries AM is still mainly in the research phase. Nevertheless, a sharp rise in innovative applications has been registered over the last few years involving single-phase [7] as well as multiphase reaction systems [8]. A broad range of industrial applications of AM in chemical reaction engineering still requires extensive research, starting from fluid dynamic simulations and moving to experimental validation of the design ideas. An important goal is the additive manufacturing of porous structures (see Figure 3.2), which can be used as a heat transfer surface or as a catalyst support. For the latter, the structure needs to be subsequently functionalized and coated with catalytically active layers. Another possibility which has been commercialized recently is the direct additive manufacturing of the catalyst itself. The goal is to achieve high outer surface areas of catalyst structures in combination with low pressure drop of the catalyst packing in conventional reactors.

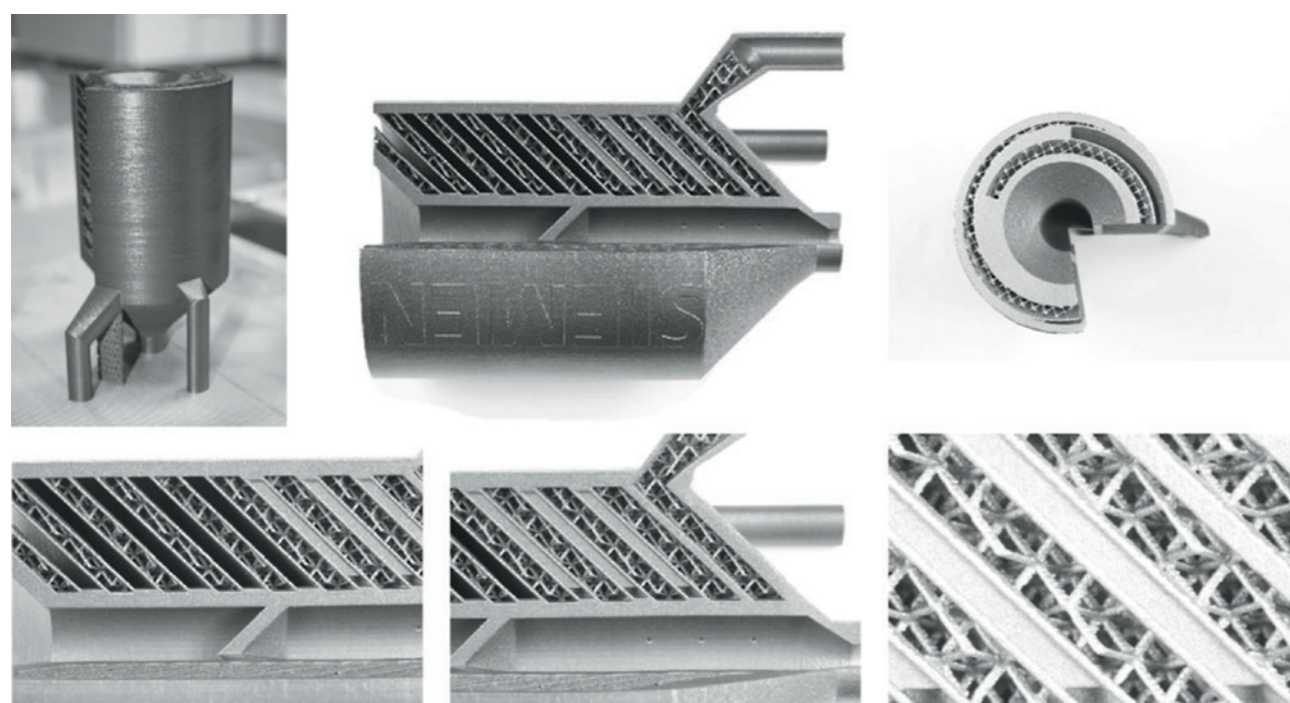


Figure 3.2: Segment of reactor demonstrative model printed via powder bed fusion by laser beam, from Jastram et al [9] (with permission from Wiley).

B HIGH THROUGHPUT TECHNOLOGY

High throughput experimentation (HTE) is a technique that allows the rapid sequential execution and parallelization of experiments with complex sequences of operations (see Figure 3.3). This technique also allows an efficient integration of hardware and software components into the complete workflow [10, 11]. In particular, knowledge of the procedures to scale down functional units has led, in many cases, to ingenious experimental procedures and a range of novel experimental possibilities. Today, nearly all technically relevant reactor configurations and modes of reactor operation can be investigated by a highly parallelized approach in HTE. Improved reactor designs and more precise and faster analytics are critical for obtaining high precision experimental results [12].

Enhanced precision and the increasingly predictive character of the results with regard to scale-up has directly led to three new fields of application for HTE:

- I) Determination of large amounts of kinetic data within a short timeframe using parallel reactors,
- II) evaluation of ramp-up and shut down procedures,
- III) quality control in catalyst production and benchmarking studies.

A new field in reaction engineering is the evaluation of catalysts in complex fluid flows. Downscaled bubble columns, fluidized beds, trickle bed reactors and riser reactors working in parallel are currently used for catalyst evaluation in petrochemical applications. In addition, the testing of technically relevant feedstocks and the evaluation of full-sized shaped catalysts have become important technological linchpins [13, 14].

Two aspects can be highlighted here: First, a fully modular concept for the construction of test units that leads to scalable adaptation from bench to pilot-scale. Second, the use of software platforms that allow complete data integration, coupled with modeling and data-driven methods. High throughput experiments have reached the status of an indispensable tool in the industrial environment, and increasingly also in academia, in order to develop a detailed understanding of reaction kinetics based on large amounts of data, and for identifying new approaches for developing and optimizing processes on this basis [15–18]. This opens up new opportunities for collaboration across industrial and academic research boundaries to use the data for optimization tasks and the search for new reactor and process concepts.

C DYNAMIC METHODS

In current chemical production, most reactors are operated at steady-state, preferably close to their optimal operating

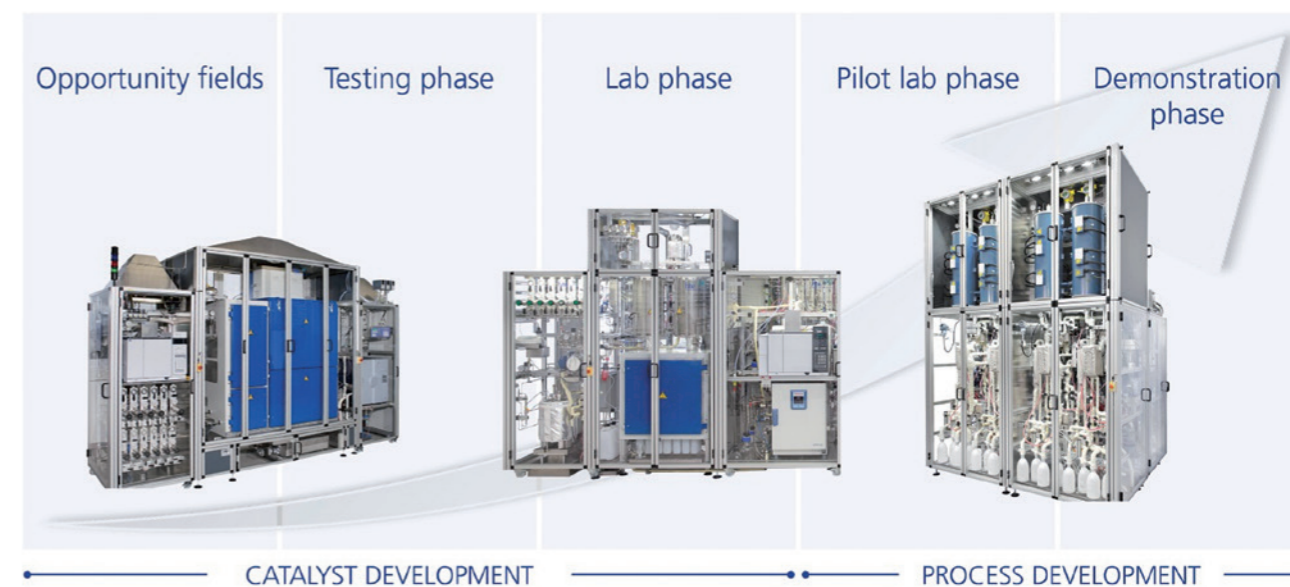


Figure 3.3: High Throughput Technology (source: hte GmbH).

point. Reactors may, however, be operated with dynamic variation of inlet variables, such as feed concentration and temperature [19]. In the case of electrochemical reactors, current and voltage are also typical dynamic variables [20]. The reason for such operation may be either fluctuating external conditions, such as in catalytic converters for cars [21], or the volatile availability of renewable energy for concepts like power-to-chemicals [22]. Some reactors or the reactions themselves may also cause intentional or unwanted natural dynamic behavior of the reactor, such as degradation or periodic oscillations, which need to be carefully controlled. As has been shown in several investigations, the catalyst structure may change depending on the reaction conditions [23]. Therefore, apparent kinetics determined from steady-state experiments are insufficient to describe catalytic processes that may be constantly changing. Intrinsic reaction kinetics determined via transient techniques can provide not only more accurate kinetic models, but also an improvement of reactor performance [24]. Complex nonlinear analysis methods, such as frequency response analysis, have been employed re-

cently, as they can be combined with modeling tools to provide a deep insight into process interactions [25].

Reactor design and scale-up, as well as optimization of operating conditions, require an understanding of chemical reaction kinetics and their coupling with mass and heat transport. Dynamic analysis methods are used to identify time constants for the individual processes, process interactions and optimal operating points. These methods consist of interpretation of the reactor's response to dynamic input signals, such as sinusoidal current or inlet concentration. Various detection methods may be employed simultaneously to determine the response of several variables, yielding a deeper insight from various perspectives [26].

A variety of experimental methods has been developed to analyze the state of the catalyst in situ and spatially resolved, together with concentration and temperature profiles inside the reactor.

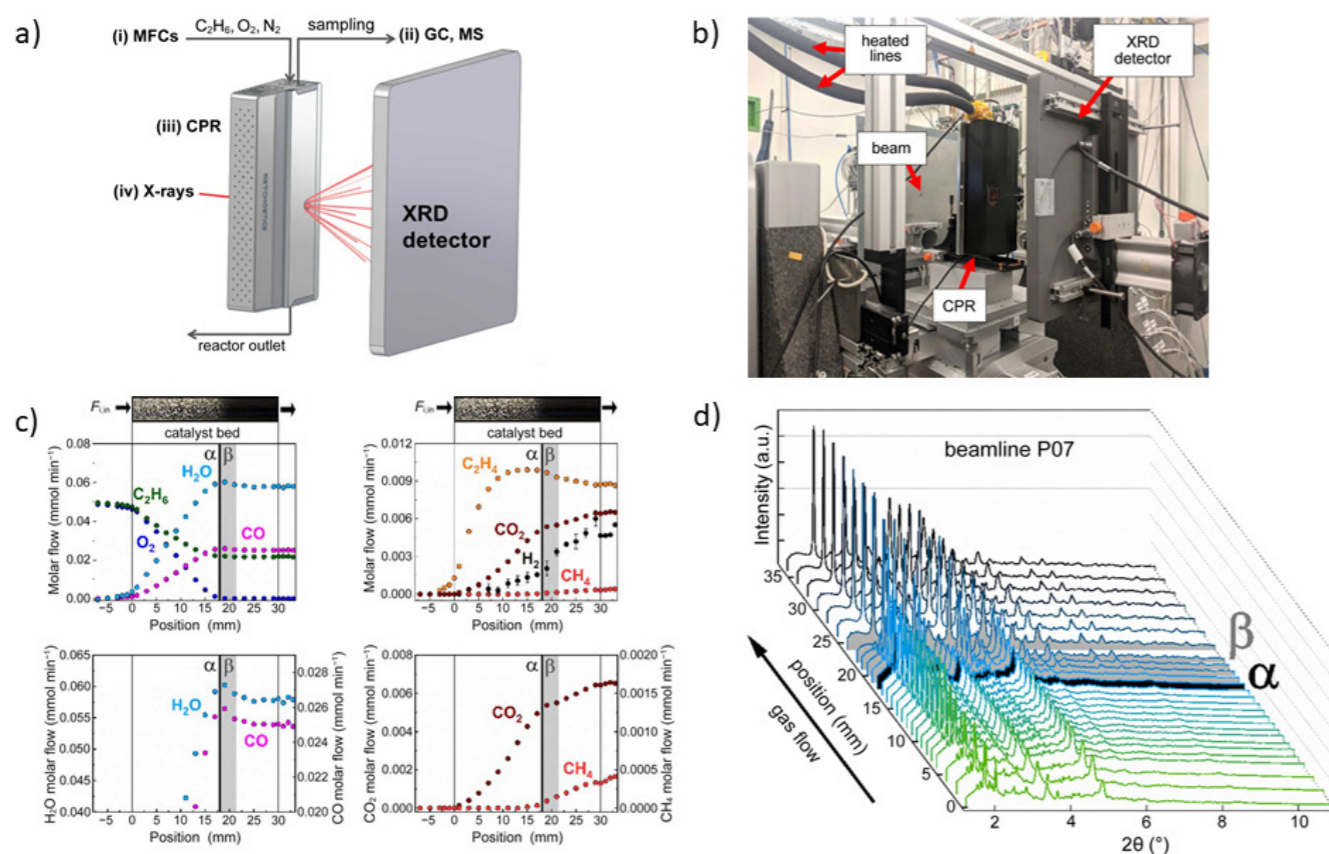


Figure 3.4: Reactonics Compact Profile Reactor (CPR) for operando X-ray diffraction studies at the Hamburg Synchrotron DESY (Beamtime P07, PETRAIII). a) Schematic of experiment. b) CPR mounted at beamline. c) Species profiles for oxidative dehydrogenation of ethane to ethylene on a $\text{MoO}_x/\text{Al}_2\text{O}_3$ catalyst. d) Spatially resolved XRD profiles at 100 keV [33] (with permission from International Union of Crystallography).

A number of these methods are now firmly established in the field of reaction technology, such as temperature programmed desorption (TPD), temperature programmed oxidation (TPO), temperature programmed reduction (TPR), temperature programmed surface reaction (TPSR), steady-state isotopic transient kinetic analysis (SSITKA) and the temporal analysis of products (TAP). These techniques are often coupled with spectroscopic methods, such as X-ray spectroscopy [27], nuclear magnetic resonance imaging [28], and laser spectroscopy methods [29] to non-invasively visualize the catalyst, porous media and gas phase, respectively (see below).

Profile reactor techniques extend the experimental portfolio to measure species concentrations and temperatures inside reactors and within particles [30]. Furthermore, multiscale modeling has led to computational tools for the transient three-dimensional simulation of the flow field, species and temperature profiles, and state of the catalyst [31]. The combination of both surface and gas phase experimental methods with multiscale modeling techniques is expected to yield new insights for understanding the interactions of kinetics and transport in catalytic reactors, leading to an improved knowledge-based design and optimization procedure in chemical reaction engineering [32]. The combination of concentration measurements in profile reactors with

spatially resolved X-ray operando investigations allows the correlation of material properties and reaction kinetics under dynamic conditions [31]. These novel catalytic profile reactors (Figure 3.4) are capable of simultaneously measuring spatially resolved temperatures, concentrations, and X-ray absorption spectroscopy (XAS) profiles through a catalytic fixed-bed, providing a quantitative link between catalyst structure and reactivity. This permits detailed studies under realistic and well-defined reaction conditions, thus significantly improving the accuracy of kinetic models [33].

D IN SITU SPECTROSCOPIC METHODS, VISUALIZATION OF PHASE INTERFACES

Rational development of catalytic processes requires an understanding of both the reactor environment and the catalyst itself [34]. It thus embraces spectroscopic monitoring of (a) the fluid phase (gas/liquid) including concentrations of substances and gradients at the solid/fluid interface and (b) the catalyst itself. These studies need to be preferentially conducted while the catalyst is working (“operando”). With respect to a solid catalyst, this means that the catalyst is studied under conditions representative of their real-life usage [23, 35]. Correlating structural changes with the catalytic performance is crucial for comprehending complex mechanistic aspects, and thus for providing a knowledge-

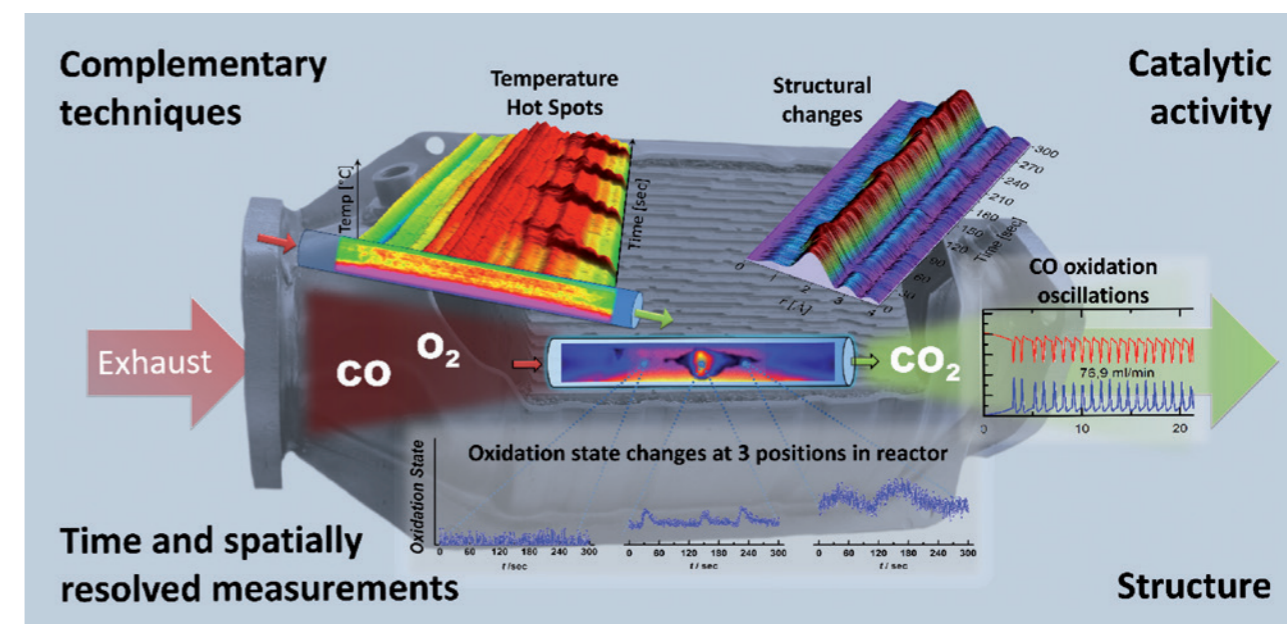


Figure 3.5: Operando spatially and time-resolved X-ray absorption spectroscopy and infrared thermography study of $\text{Pt}/\text{Al}_2\text{O}_3$ diesel oxidation catalyst during oscillatory CO oxidation activity (1000 ppm CO, 10% O_2 in He) at 125 °C. (Reprinted from [36] with permission from Elsevier)

based catalyst development. A good example are operando hard X-ray based methods, which provide information on the local structure. Moreover, they have been further developed towards monitoring the interaction of the active sites with reaction intermediates. The high penetration of X-rays allows the catalyst to be housed in specially engineered microreactor cells and to be studied under various temperatures and gas atmospheres while monitoring the catalytic performance. In addition, the highly dynamic structural gradients along the catalyst bed can be monitored by 2D or 3D X-ray tomography, by virtue of the high time and spatial resolution of these methods.

As illustrated in Figure 3.5 for a model Pt/Al₂O₃ diesel oxidation catalyst, the necessity for time and spatially resolved spectroscopic studies is decisive for unambiguously elucidating the catalytic behavior during temperature and gas-mixture transients, which lead to substantial dynamics in the reaction zone along the catalyst bed. Such dynamic studies will be of increasing importance in the future [36].

A further example of a powerful non-invasive analytical method is nuclear magnetic resonance (NMR) spectroscopy, which enables both qualitative (structure elucidation) and quantitative characterization. It is thus a valuable tool for in situ analysis of reactions and other processes.

Until recently, chemically high-resolution NMR spectroscopy was only possible with cryogenically cooled high-field spectrometers, which are expensive and need a special laboratory infrastructure. In the last years, so-called benchtop spectrometers, which are significantly cheaper and very easy to handle, have been increasingly used, especially for reaction analysis [37]. By using mathematical evaluation algorithms, it is possible to compensate for the disadvantages of the benchtop compared to the high-field spectrometer – for instance the lower chemical resolution – and to analyze complex reaction networks [38]. Further research is needed to be able to apply this analysis technique to in situ analysis of reactions under high pressure or at high temperature. The combination of different analysis methods into new types of soft sensors also has great potential for further development [39, 40].

simulations. The further improvement of existing tools, as well as new developments of imaging sensors and measuring methods, will enable the multi-dimensional measurement of local process and flow parameters (phase velocities, phase components and concentrations, temperatures).

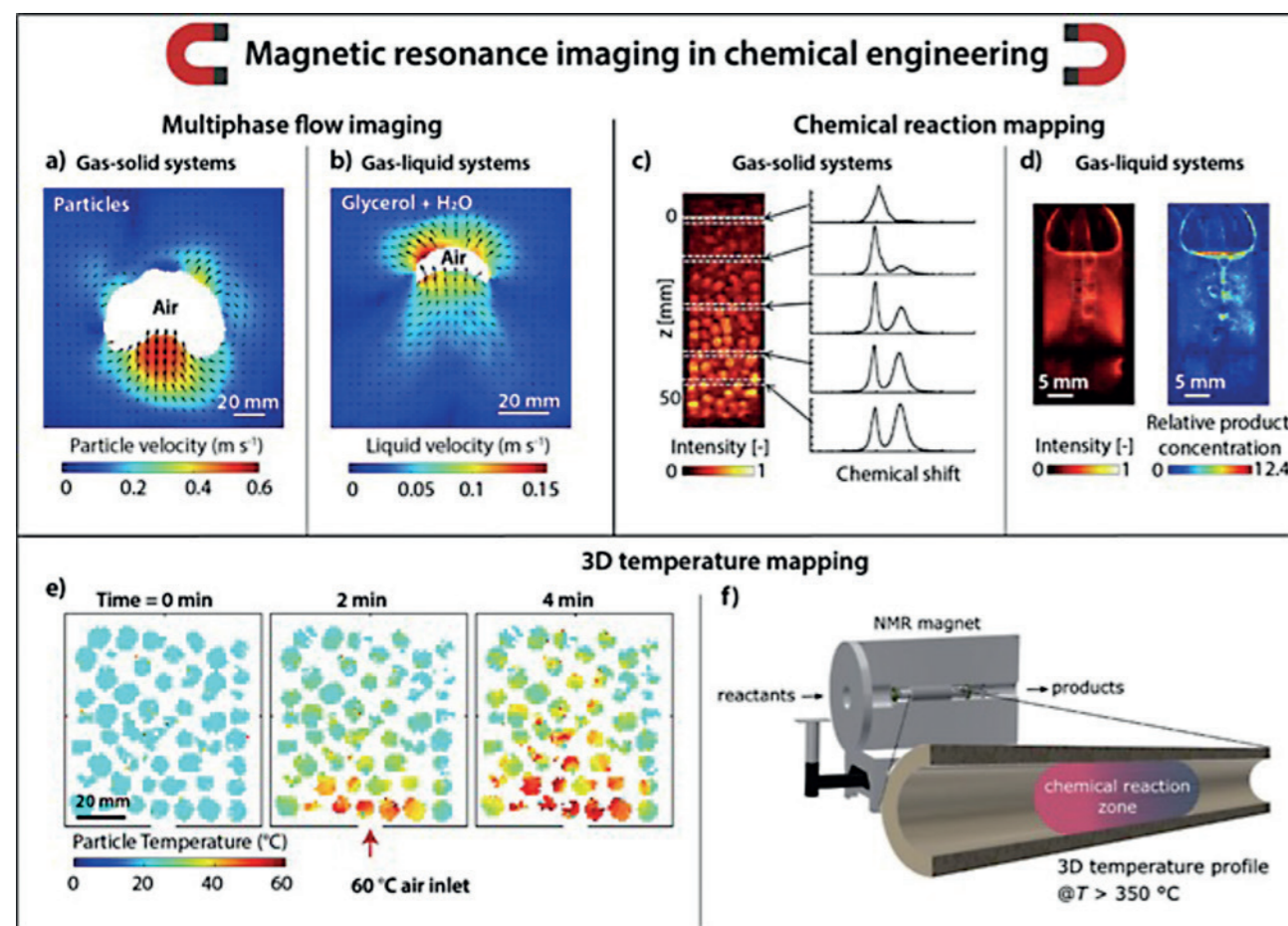


Figure 3.6: MRI of various chemical engineering systems. (a) MR velocimetry image of a single air bubble rising in a fluidized bed of dry particles captured at a temporal resolution of 20 ms (adapted from Penn et al. [42] with permission of American Association for the Advancement of Science). The direction of the arrows shows the direction of the particle flow. (b) MRI image of a single air bubble rising in a viscous liquid (adapted from Penn et al. [42] with permission of American Association for the Advancement of Science). (c) Operando MRI measurement of an oligomerisation reaction at 110 °C and 29 bar (image courtesy of Mick Mantle, University of Cambridge). (d) Copper oxygenation reaction occurring in the wake of an oxygen bubble rising in liquid copper(I)-based compound (image courtesy of Stefan Benders, Hamburg University of Technology). (e) MRI thermometry of a packed bed of beads heated by a stream of hot air (adapted from Serial et al. [45], with permission of Wiley-VCH). (f) In-situ MRI temperature measurements of gas-phase reactions at temperatures exceeding 350 °C (reproduced from Ridder et al. [46] with permission of Elsevier).

There have been new developments in the use of magnetic resonance imaging (MRI) in the field of reaction engineering in recent years. MRI is a tomographic technique that provides spatially and time resolved measurements of the internal structure of three-dimensional samples. This technique is currently used primarily in medical diagnostics, but it is increasingly being applied in the engineering sciences [41]. Similarly to NMR, MRI uses strong magnetic and radiofrequency fields, but applies additional magnetic field gradients to obtain spatial resolution. Compared to other 3D imaging techniques, MRI is very versatile: in addition to the local distribution of phases (i.e. liquids, solids, and gases) within a sample, it can quantify a range of other system properties including multiphase flow, temperature distributions, and chemical reactions (Figure 3.6). Until recently, one disadvantage of MRI for engineering systems was its low temporal resolution of several minutes per image. With the recent introduction of scan acceleration techniques, the temporal resolution has significantly improved, paving the way for real-time measurements of a variety of process parameters in the field of chemical reaction engineering research.

However, MRI is also subject to some limitations. Probably the strongest constraint on MRI in the field of chemical reaction engineering is the fact that, in standard MRI, the sample materials must be strictly non-ferromagnetic and ideally electrically non-conductive. Another disadvantage of the technique is the relatively high cost of MRI experiments. Extensive advances in experimental reaction technology are to be expected in the future due to the intense interplay between high-resolution experimental data and numerical

Research needs:

1. Further development and broader application of kinetic models determined via transient techniques
2. Provision of easy access to automated materials synthesis and automated laboratory reactor operation to make large data sets available for widespread use of research data
3. Development of tools for robust handling and analysis of large data sets in combination with a wide use of research data in reaction engineering according to jointly developed FAIR@CRT concepts. Setting up a legal framework for sharing of research data in academia and industry.
4. Broader utilization of the increased potential of additive manufacturing for laboratory reactors, especially in the development of new multi-functional concepts for process integration
5. Development of standardized set-ups (e.g. microreactors) that enable broad application of In situ and operando spectroscopy (e.g. NMR, XAS) and provide easier access to existing research infrastructures.
6. Application of more flexible, cost-efficient and compact “low-cost spectroscopic devices”, such as benchtop NMR spectrometers, for reaction and process monitoring
7. Improvement of the spatial and temporal resolution of MRI for Chemical Reaction Engineering systems by implementing acceleration techniques based on hardware, pulse sequences, and reconstruction algorithms.
8. Development of large vertically-oriented MRI systems based on modern MRI technology, dedicated specifically to chemical engineering applications.

REFERENCES

- [1] Manfred Baerns, A.B., Axel Brehm, Jürgen Gmehling, Hanns Hofmann, Ulfert Onken, Albert Renken, Technische Chemie. Vol. 1. 2006: Wiley-VCH. 757.
- [2] Fogler, H.S., Elements of Chemical Reaction Engineering. 2006: Prentice Hall PTR.
- [3] Breen, C.P., et al., Ready, Set, Flow! Automated Continuous Synthesis and Optimization. Trends in Chemistry, 2021. 3(5): p. 373-386.
- [4] Appel, J., et al., Comprehensive Analysis Competence and Innovative Approaches for Sustainable Chemical Production. Chimia (Aarau), 2016. 70(9): p. 621-7.
- [5] Banivaheb, S., et al., Recent Progress in Direct DME Synthesis and Potential of Bifunctional Catalysts. Chemie Ingenieur Technik, 2022. 94(3): p. 240-255.
- [6] Li, J., et al., In situ sensors for flow reactors – a review. Reaction Chemistry & Engineering, 2021. 6(9): p. 1497-1507.
- [7] Grinschek, F., et al., Getting Chemical and Biochemical Engineers Excited about Additive Manufacturing. Chemie Ingenieur Technik, 2022. 94(7): p. 931-938.
- [8] Lämmermann, M., W. Schwieger, and H. Freund, Experimental investigation of gas-liquid distribution in periodic open cellular structures as potential catalyst supports. Catalysis Today, 2016. 273: p. 161-171.
- [9] Jastram, A., S. Schaack, and C. Kiener, Simulation-Driven Design of an Additively Manufactured Reactor for Exothermic Liquid-Liquid Reactions. Chemie Ingenieur Technik, 2022. 94(7): p. 948-957.
- [10] Buglioni, L., et al., Technological Innovations in Photochemistry for Organic Synthesis: Flow Chemistry, High-Throughput Experimentation, Scale-up, and Photoelectrochemistry. Chem Rev, 2022. 122(2): p. 2752-2906.
- [11] Futter, C. et al., High Throughput Experimentation Applied in the Field of Technical Catalysis: Past, Present, Future, in Modern Applications of High Throughput R&D in Heterogeneous Catalysis, A.V.J. Hagemeyer, Anthony F., Editor. 2014, Bentham Science Publishers.
- [12] Schulz, C., et al., Preparation and High-Throughput Testing of TiO₂-Supported Co Catalysts for Fischer-Tropsch Synthesis. Catalysts, 2021. 11(3).
- [13] Pogaku, R., Transfer Learning Combined with High-Throughput Experimentation Framework for Integrated Biorefinery, in Horizons in Bioprocess Engineering. 2019. p. 343-351.
- [14] Maier, W.F., Early Years of High-Throughput Experimentation and Combinatorial Approaches in Catalysis and Materials Science. ACS Comb Sci, 2019. 21(6): p. 437-444.
- [15] Wulf, C., et al., A Unified Research Data Infrastructure for Catalysis Research – Challenges and Concepts. ChemCatChem, 2021. 13(14): p. 3223-3236.
- [16] Nguyen, T.N., et al., High-Throughput Experimentation and Catalyst Informatics for Oxidative Coupling of Methane. ACS Catalysis, 2019. 10(2): p. 921-932.
- [17] Foppa, L., et al., Learning Design Rules for Selective Oxidation Catalysts from High-Throughput Experimentation and Artificial Intelligence. ACS Catal, 2022. 12(4): p. 2223-2232.
- [18] Wild, S., et al., Experimental investigations and model-based optimization of CZZ/H-FER 20 bed compositions for the direct synthesis of DME from CO₂-rich syngas. Reaction Chemistry & Engineering, 2022. 7(4): p. 943-956.
- [19] Fischer, K.L. and H. Freund, Intensification of load flexible fixed bed reactors by optimal design of staged reactor setups. Chemical Engineering and Processing - Process Intensification, 2021. 159.
- [20] Rohe, M., F. Kubanek, and U. Krewer, Processes and Their Limitations in Oxygen Depolarized Cathodes: A Dynamic Model-Based Analysis. ChemSusChem, 2019. 12(11): p. 2373-2384.
- [21] Deutschmann, O. and J.-D. Grunwaldt, Abgasnachbehandlung in mobilen Systemen: Stand der Technik, Herausforderungen und Perspektiven. Chemie Ingenieur Technik, 2013. 85(5): p. 595-617.
- [22] Wentrup, J., G.R. Pesch, and J. Thöming, Dynamic operation of Fischer-Tropsch reactors for power-to-liquid concepts: A review. Renewable and Sustainable Energy Reviews, 2022. 162.
- [23] Kalz, K.F., et al., Future Challenges in Heterogeneous Catalysis: Understanding Catalysts under Dynamic Reaction Conditions. ChemCatChem, 2017. 9(1): p. 17-29.
- [24] Berger, R.J., et al., Dynamic methods for catalytic kinetics. Applied Catalysis A: General, 2008. 342(1-2): p. 3-28.
- [25] Armstrong, C.D. and A.R. Teixeira, Advances in dynamically controlled catalytic reaction engineering. Reaction Chemistry & Engineering, 2020. 5(12): p. 2185-2203.
- [26] Kubanek, F. and U. Krewer, A Cyclone Flow Cell for Quantitative Analysis of Kinetics at Porous Electrodes by Differential Electrochemical Mass Spectrometry. Electrochimica Acta, 2016. 210: p. 862-873.
- [27] Chen, Y., et al., A Theory-Guided X-ray Absorption Spectroscopy Approach for Identifying Active Sites in Atomically Dispersed Transition-Metal Catalysts. J Am Chem Soc, 2021. 143(48): p. 20144-20156.
- [28] Brächer, A., et al., Application of a new microreactor ¹H NMR probe head for quantitative analysis of fast esterification reactions. Chemical Engineering Journal, 2016. 306: p. 413-421.
- [29] Nilsson, A., et al., Catalysis in real time using X-ray lasers. Chemical Physics Letters, 2017. 675: p. 145-173.
- [30] Sosna, B., O. Korup, and R. Horn, Probing local diffusion and reaction in a porous catalyst pellet. Journal of Catalysis, 2020. 381: p. 285-294.
- [31] Wollak, B., et al., Exploring catalyst dynamics in a fixed bed reactor by correlative operando spatially-resolved structure-activity profiling. Journal of Catalysis, 2022. 408: p. 372-387.
- [32] Chawla, J., et al., Oxidative Coupling of Methane over Pt/Al₂O₃ at High Temperature: Multiscale Modeling of the Catalytic Monolith. Catalysts, 2022. 12(2).
- [33] Wollak, B., et al., Catalytic reactor for operando spatially resolved structure-activity profiling using high-energy X-ray diffraction. J Synchrotron Radiat, 2023.
- [34] Grunwaldt, J.-D., J.B. Wagner, and R.E. Dunin-Borkowski, Imaging Catalysts at Work: A Hierarchical Approach from the Macro- to the Meso- and Nano-scale. ChemCatChem, 2013. 5(1): p. 62-80.
- [35] Deschner, B.J., et al., Continuous-flow reactor setup for operando x-ray absorption spectroscopy of high pressure heterogeneous liquid-solid catalytic processes. Rev Sci Instrum, 2021. 92(12): p. 124101.
- [36] Gänzler, A.M., et al., Operando spatially and time-resolved X-ray absorption spectroscopy and infrared thermography during oscillatory CO oxidation. Journal of Catalysis, 2015. 328: p. 216-224.
- [37] Nestle, N., et al., Taking compact NMR to monitoring real reactions in large-scale chemical industries-General considerations and learnings from a lab-scale test case. Magn Reson Chem, 2020. 58(12): p. 1213-1221.
- [38] Steimers, E., et al., A comparison of non-uniform sampling and model-based analysis of NMR spectra for reaction monitoring. Magn Reson Chem, 2021. 59(3): p. 221-236.
- [39] Fricke, F., et al., Artificial Intelligence for Mass Spectrometry and Nuclear Magnetic Resonance Spectroscopy Using a Novel Data Augmentation Method. IEEE Transactions on Emerging Topics in Computing, 2022. 10(1): p. 87-98.
- [40] Behrens, R., et al., NMR spectroscopic method for studying homogenous liquid phase reaction kinetics in systems used in reactive gas absorption and application to monoethanolamine-water-carbon dioxide. Chemical Engineering Journal, 2019. 374: p. 1127-1137.
- [41] Pesch, G.R., H. Ridder, and C. Sinn, Operando characterization of heterogeneously catalyzed gas- and multi-phase reactions using nuclear magnetic resonance imaging. Chemical Engineering and Processing - Process Intensification, 2022. 179.
- [42] Penn, A., et al., Real-time probing of granular dynamics with magnetic resonance. Sci Adv, 2017. 3(9): p. e1701879.
- [43] Baker, L., et al., Operando magnetic resonance studies of phase behaviour and oligomer accumulation within catalyst pores during heterogeneous catalytic ethene oligomerization. Applied Catalysis A: General, 2018. 557: p. 125-134.
- [44] Benders, S., et al., Imaging of copper oxygenation reactions in a bubble flow. Magn Reson Chem, 2018. 56(9): p. 826-830.
- [45] Rotzetter, P., et al., Magnetic resonance thermometry of gas-solid systems. Chemie Ingenieur Technik, 2020. 92(9): p. 1180-1180.
- [46] Ridder, H., et al., Spatially resolved direct gas phase thermometry in chemical reactors using NMR. Chemical Engineering Journal, 2022. 433.

4 Mathematical Modeling and Simulation

Detailed modeling of a chemical reactor lays the foundation for an efficient and rational design based on insights into the relevant phenomena and processes within the equipment. Additionally, modeling unlocks potential for process intensification and optimization deduced from these insights and, as such, is seen as the key to reliably predicting economic and ecological process parameters for industrial-scale production systems.

While the descriptive quality, i.e. the physical and numerical fidelity of models and simulation methods, respectively, has been greatly improved over the last decade, there is still a strong need for (I) including machine learning tools, (II) providing FAIR (findability, accessibility, interoperability, and reusability) data, (III) including more rigorous multi-scale and multi-phenomena models and (IV) establishing a suitable modeling platform open to other researchers. Given the huge complexity of chemical reaction engineering problems, priority should be assigned to interdisciplinary research efforts, such as strategically focused programs and collaborative research centers.

A CHALLENGES

Mathematical modeling is of pivotal importance in the field of chemical engineering and plays a decisive role in the future development of a sustainable, resource-efficient chemical and process industry with net-zero greenhouse gas emissions [1, 2]. Modeling is especially challenging in the context of chemical reactor engineering, as a number of phenomena and processes need to be considered:

» Reactivity

of multicomponent chemical systems, especially networks of chemical reactions, that need to be described at a molecular level (i.e. with intrinsic kinetics).

» Multiphysics

is the intense interplay and mutual dependence (i.e. close coupling) of the diverse relevant processes, including fluid dynamics, solid mechanics, multiphase and particle flow, acoustics, heat transfer, reacting flow, electromagnetics, electrochemistry, and rheology.

» Multiscale approach

is the consideration of a wide range of relevant spatial and temporal scales, ranging from the molecular to the plant level.

» Multiphase

is the reciprocal interaction of multiple phases, including

the influence of phase dispersion, interfacial effects, and phase change.

» Turbulence

in particular the influence of turbulence on homogeneous chemical reactions – especially regarding their inherent nonlinearity and intimate interaction with various transport processes – as well as the influence of further phases on turbulence in multiphase systems (e.g. turbulence modulation, or cluster induced turbulence).

The characterization of these phenomena and processes can be accomplished experimentally or by simulations. However, these two strategies are often closely intertwined, since only experiments enable mathematical models to be scaled and numerical simulations to be validated. Thus, in the following discussion, it is assumed that all relevant phenomena can be captured using appropriate mathematical models supplemented with suitable boundary conditions. Three objectives are in focus: (I) establishing a common nomenclature for modeling and simulation, (II) identifying recent key achievements and trends, but also gaps in current models, simulation and post-processing tools, as well as (III) defining milestones to sketch out future progress in this field.

B WORKFLOW OF MODELING AND SIMULATION

In today's global chemical industry, objectives, such as high productivity and selectivity, process and product safety, environmentally compatible products, minimization of waste generation, investment and energy consumption, together with operability and control, are typically incorporated in a framework for chemical product design [1]. One crucial step of this framework is the product design model, see Figure 4.1, which includes model parameter constraints, economic factors, properties, process and product performance models, as well as objective functions with a multitude of constraints [2]. A thorough modeling approach provides opportunities to consider phenomena at different time and length scales of the specific chemical reaction system ranging from the

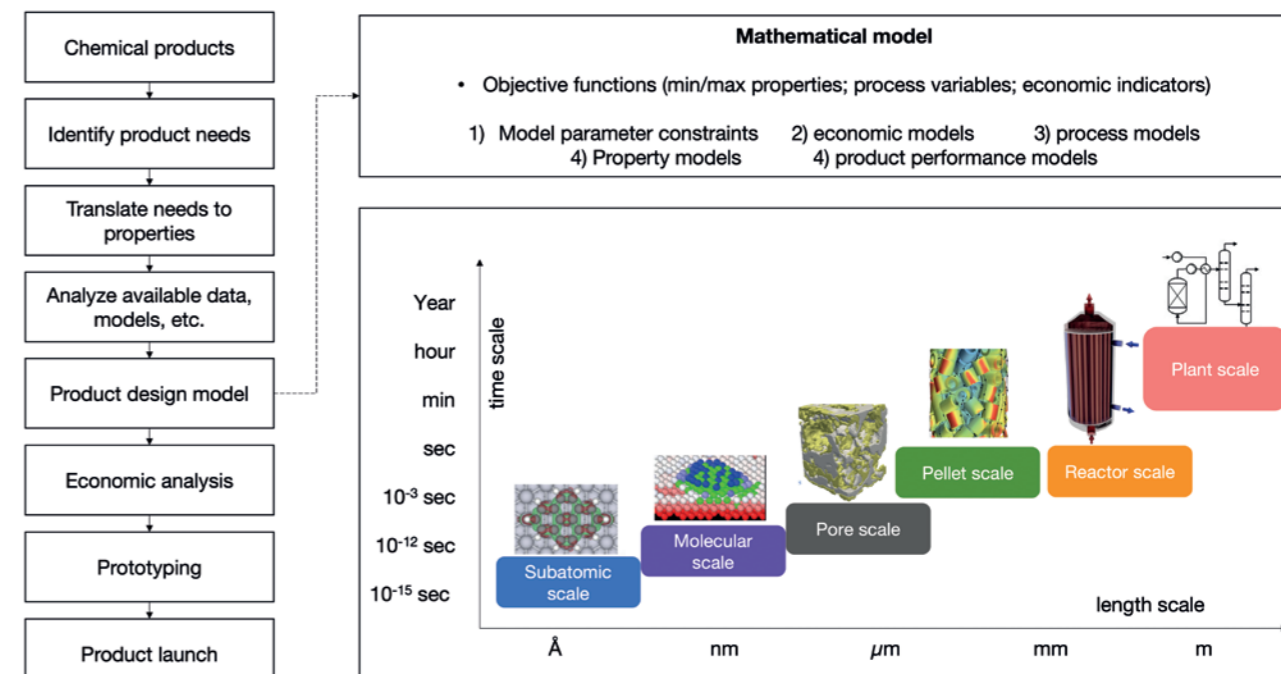


Figure 4.1: Framework for chemical product design. Partly adopted from [3], with permission from Elsevier.

electron level up to the plant level. Most relevant for chemical reaction engineering problems is the combination of the molecular scale, where the intrinsic reaction kinetics must be understood, with the micro- and mesoscales, where flow mixing and flow patterns must be captured using computational fluid dynamics (CFD) tools.

Every modeling workflow for a chemical reactor comprises several steps, which are illustrated schematically in Figure 4.2, and described in detail below. Each model is associated with costs, complexity, errors and uncertainties. The total costs consist of the individual costs for model creation,

computing time, validation and verification, data analysis, as well as the capital costs for hardware, direct operating costs, such as license and staff costs, and indirect operating costs, such as maintenance and information resources. The complexity of a model can be reduced by simplifications involving space, time, the occurring phenomena, as well as time and spatial resolution. Errors in models can be classified into (I) numerical errors, i.e. rounding errors, convergence errors, discretization errors, (II) bugs, which are errors in the code, and (III) user errors, which originate from incorrect use of code/software. Furthermore, models are typically uncertain, due to (I) input uncertainties, i.e. limited

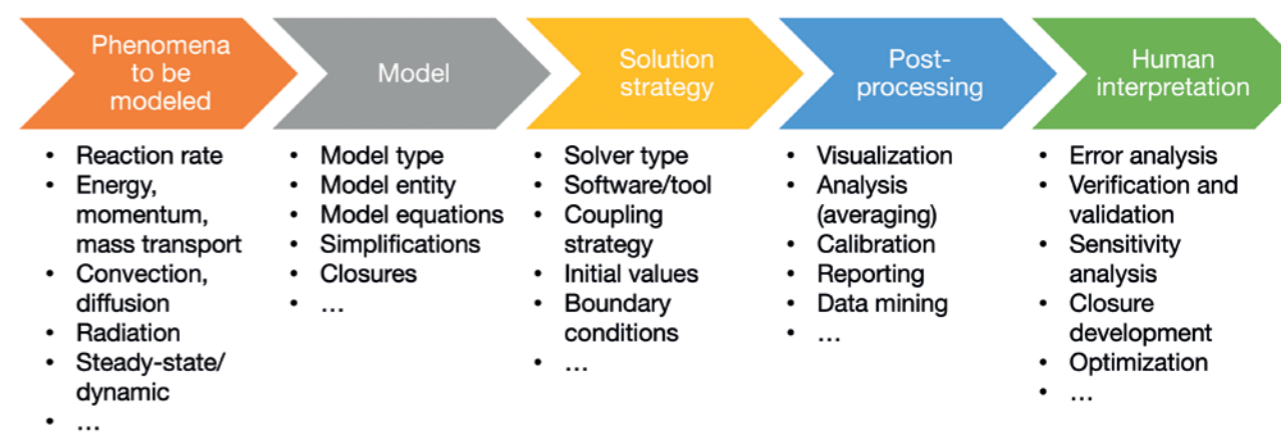


Figure 4.2: Details of the modeling workflow for a chemical reactor and its products.

information or approximation of geometry, boundary conditions, material properties, etc. or (II) model uncertainties, i.e. the difference between reality and simulation due to an inaccurate description of physical and/or chemical processes (turbulence, reactions, ...) or questionable simplifications (stationary, incompressible, ...).

B1 Processes and phenomena

Reactions

For chemical reactors a key quantity to be modeled is the reaction rate, which is typically of interest for more than one chemical reaction in the system. Most often, many reactions occur between the many participating species and the individual reaction rates for homogeneous reactions depend on local species concentrations, temperature, and pressure. For heterogeneous reactions, the catalyst significantly determines the productivity and selectivity of the process, since it influences both the reaction mechanism and the microkinetics. The latter links the processes at the atomic level with the performance of the catalyst in operation. The intrinsic reaction rates (i.e. without transport limitations)

must be accessed using computational chemistry tools, i.e. density functional theory (DFT) [4] and molecular dynamics (MD) [5]. Such microkinetics can include thousands of possible reaction intermediates and elementary steps [6], even if only small molecules are participating, such as in the steam reforming of methane [7] or in CO₂ methanation [8]. Three main challenges are related to the hierarchical microkinetic analysis of heterogeneous catalytic processes: (I) complexity and dynamic nature of the catalyst [9], (II) complexity of reaction mechanisms [6, 10, 11], and (III) complication and computational cost of energetic parameter estimation [12]. These challenges should be accounted for by an efficient multiscale modeling framework [13] (see Figure 4.3). The manual generation of microkinetics is, however, error-prone. Therefore, automated reaction mechanism generators (RMG) were established first for gas phase kinetics [14] and later extended to surface reactions [15]. RMG considers all possible reaction paths but selects only the kinetically relevant for the final thermodynamically consistent microkinetics. Energetic parameters are determined from databases and estimation methods, which automatically generate fully parameterized microkinetics within a few minutes.

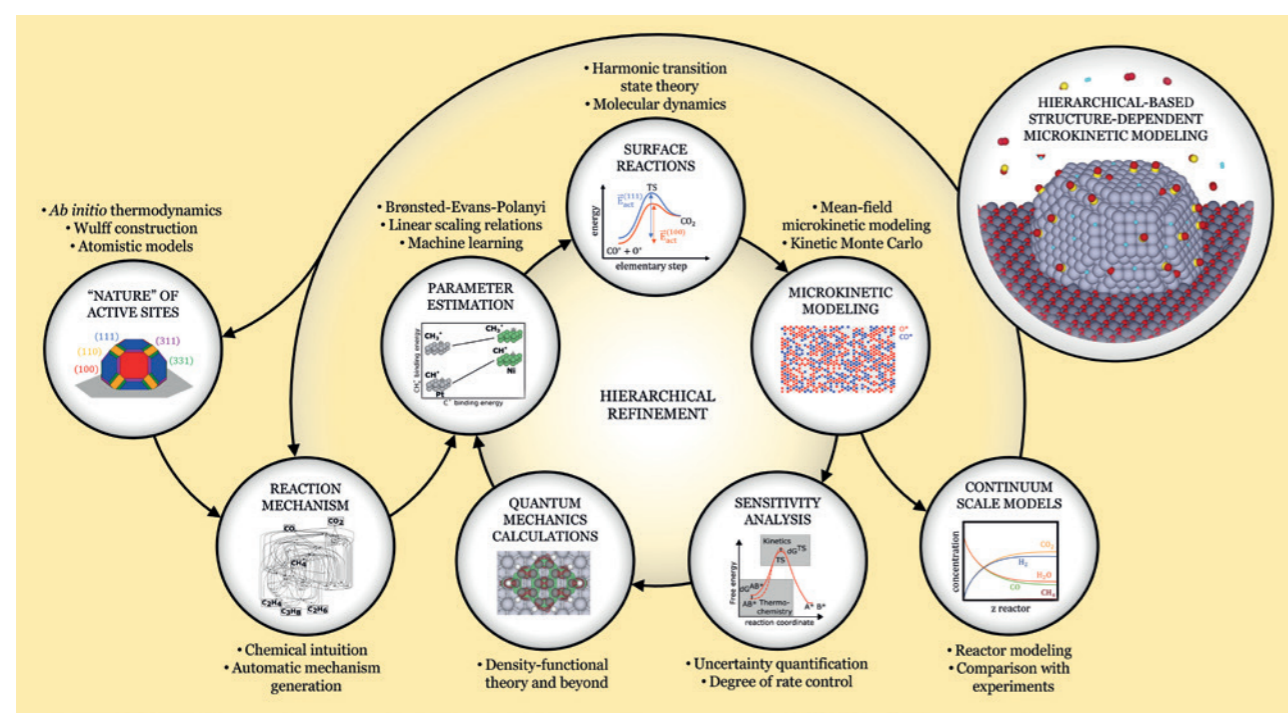


Figure 4.3: Hierarchical-based multiscale modeling approach for catalytic surface reactions [3]. The complexity of catalytic systems is tackled with a hierarchical refinement procedure: (I) Microkinetic simulations are performed with low-accuracy parameters, (II) the most relevant parameters are identified by sensitivity analysis techniques, and (III) those parameters are refined with high-accuracy quantum mechanical calculations [17]. These microkinetic simulations must be included in a multiscale framework, in which the effect of the reaction environment on the catalyst structure and the reaction mechanism is accounted for [18]. Reprinted from [3], with permission from Elsevier.

RMG was successfully applied to the microkinetics describing the catalytic partial oxidation of methane [16] and the CO₂ methanation [8], to name just a few.

Multiphysics problems

Very often, multiple chemical and physical processes within a chemical reactor are found to be strongly coupled, creating a so-called multiphysics problem, which can encompass fluid dynamics, solid mechanics, multiphase and particle flow, acoustics, heat transfer, reacting flow, electromagnetics, electrochemistry, and rheology. Appropriate software tools have to be selected. When dealing with multiphysics problems, software tools offering the simultaneous solution of coupled equations and implicit discretization techniques are to be preferred whenever coupling of transport processes is expected to be intense and/or to take place at very different scales (i.e. for strong coupling and/or stiff systems). Additional care should be taken in choosing a tool with an underlying flexible and extensible software design based on a mature (higher) programming language. Suitable multiphysics platforms, such as ANSYS Multiphysics, COMSOL, Simcenter STAR-CCM+ (proprietary software), and OpenFOAM (open-source software) are readily available and provide a substantial basis for further developments. Only such platforms will enable and efficiently foster the combination of conventional reaction engineering models and modern approaches of computational continuum mechanics, in particular, CFD for multiphase flows and/or multicomponent systems.

Multiscale problems

If multiple models characterizing distinct processes at different time and length scales are to be combined, one typically defines a “chain of models” to formulate a so-called hierarchical (or horizontal) multiscale modeling approach (see Figure 4.3). These models are executed simultaneously or sequentially in a side-by-side mode. For the modeling chain to work reliably over multiple scales of interest, consistency and interoperability within such a hierarchical multiscale approach play a central role. The linkage or coupling between scales is challenging in terms of reducing degrees of freedom (abstraction) and with respect to efficient computing (implementation). Over the last few years, various comprehensive reviews have been published concerning different aspects of this wide-ranging topic, such as multiscale modeling in reaction engineering [3], multiscale modeling in computational heterogeneous catalysis [19, 20], focusing on metal-catalyzed reactions [21], material-function relationships in heterogene-

ous catalysis [6], computational materials science and process engineering [22], gas/solid fluidization systems [23, 24], or more general aspects of multiscale modeling [25].

Apart from hierarchical concepts, integrated (or vertical) multiscale modeling strategies have emerged and made significant progress. These models aim to incorporate processes at multiple scales within a unified, typically more generic, modeling framework. The utilization of detailed (physico-) chemical knowledge on a molecular scale was addressed, for example, in order to bridge the gap in scales when describing the viscoelastic flows of polymer solutions or polymer melts [26]. Furthermore, spatial filtering supports closure development for models of dense fluid/particle systems [27], whereas coarse-grain discrete element method modeling (DEM) is based on the idea that only the collective behavior of the particles is of primary interest [28].

Multiphase flows

Multiphase flows very often occur in chemical engineering, where the gas/solid/liquid phases are contained within the same system, share distinct interfaces, and can be in contact with one another in various combinations. Typical examples of gas/liquid systems are bubble column reactors [29], sprays and thin film reactors [30], to name just a few; examples of fluid/solid systems are fluidized and spouted beds, pneumatic conveying, mixers and granulators, drying, agglomeration, coating, and combustion [31]. The modeling and simulation of multiphase flows presently involves a variety of different techniques and methodologies with varying levels of detail [32].

For industrial scale problems, the Eulerian–Eulerian model is often used, which does not resolve the exact interface between the continuous fluid and a dispersed phase (fluid or solid) but only takes into account the mutual interaction between the phases by means of closure models (e.g. drag force, lift force, etc.) [33]. The model is computationally economical, but the closures are not founded on rigorous derivation but rather on experimental observations. If the size distribution of the dispersed phase changes significantly, this can have an impact on the drag and buoyancy forces and thus on the velocity fields. Such changes can be modeled with population balance models coupled with CFD models [34]. Applications of this modeling strategy are, for example, bubble column reactors or reactive crystallization with bubble breakup and coalescence [35].

A very detailed modeling approach for fluid/solid systems is the combination of CFD for the fluid phase with the DEM for the particles, known as CFD-DEM [31,36]. This approach tracks both the fluid/particle and particle/particle interactions. Collision interaction can highly influence the transport phenomena in dense particulate flows. In this approach, the individual particle motion is described with a Lagrangian model, whereas particle/particle collision can be either modeled with a soft-sphere or hard-sphere approach [37]. To reduce the computational cost of CFD-DEM simulations, coarse grain DEM models have been developed extensively over the last years [28]. The basic idea is to lump together neighboring particles into a computational, representative element (grain) (see Figure 4.4 (A)). These grains then interact through collision with each other and with the fluid (see Figure 4.4 (B)). A key element is the linking of physical particles' properties to the properties of the grains [38]. Finally, the full resolution of interactions between the continuous and the dispersed phase, respectively, is referred to as CFD direct numerical simulation (CFD-DNS). With this approach it is possible to derive closure models, for example, for fluid/particle systems needed for the low-fidelity models mentioned above [39]. For fluid/fluid CFD-DNS, it is especially

challenging to track the interface in a computationally efficient and physically realistic manner. Several methods exist to do this, ranging from lattice Boltzmann, volume-of-fluid (VoF), level set, front tracking and phase-field methods including several modifications [40]. Examples are given by single droplet dynamic motion, droplet impingement, or mass transfer across a bubble interface. A special application of CFD-DNS is the particle-resolved CFD simulation of packed-bed reactors (see Figure 4.4 (B)), where the flow around each pellet is fully resolved and coupled with heat and mass transfer and chemical reaction inside the pellets [41]. Related challenges are the generation of a high quality mesh in the contact regions between particles [42], the efficient coupling between microkinetics and the CFD solver [43], the derivation of simplified model parameters (scale bridging) [44], as well as the accurate description of the chemical and transport processes inside the porous catalyst pellets [45].

Turbulence

Turbulence plays a major role in chemical reaction engineering, since it influences residence times and mixing, and therefore intensifies both heat and mass transfer. However,

the prediction of turbulent flows is rather complex, as it involves events over large time and length scales. The most rigorous modeling approach is DNS, which avoids the closure problem by considering all scales of turbulent motion. For many engineering problems, this level of detail is not necessary. It is less costly to solve for averaged (Reynolds-averaged Navier-Stokes (RANS) equation models) or filtered (large eddy simulation (LES) and detached eddy simulation (DES) models) quantities and to thus approximate the impact of the small fluctuating structures. These models are, however, only approximate representations of the physical phenomena of turbulence.

Turbulent particle-laden flows are very challenging, due to the differing particle and fluid properties, the multidirectional coupling, and the many scales involved [48]. Therefore, the influence of the particles on the dynamics of the overall flow is quite involved. Examples are the motion of a small number of isolated particles with complex shapes or the collective dynamics of particle swarms. Particle-resolved or interface-resolved DNS is the most rigorous modeling approach [49]. In addition, body-fitted methods, such as overset-grid approaches, should be mentioned. Although super-computing has enabled the simulation of systems with thousands of particles, post-processing of the huge data sets generated is not yet well developed. This makes it difficult to extract relevant quantities, such as mesoscale stresses and interphase energy fluxes.

Turbulence in fluid/gas systems, i.e. droplets or bubbles, arises due to gravity, buoyancy and mean shear. It is more challenging than for rigid particles, because the former can show surface deformation [50]. Hence, DNS for these systems differs from particle-laden DNS and can be classified into categories where the initial diameter of the bubbles is smaller or larger than the Kolmogorov length scale and where the surface deformation is fully resolved or approximated with phenomenological models [51]. Models offering a lower level of detail are Eulerian-Lagrangian and Eulerian-Eulerian approaches, and Reynolds-averaged turbulence models [52].

In wall-bounded flows, turbulence is influenced by the near-wall dynamics governed by the viscous scaling. The presence of walls introduces mean velocity gradients, anisotropies in the near-wall velocity field, variations in the level of fluctuations with the distance from the wall, and

distinct flow structures, such as quasi-streamwise vortices, low-speed streaks, and, at large Reynolds numbers, the so-called very-large-scale motions [53]. Furthermore, the behavior of chemically reacting flows is influenced decisively by the presence of walls. Applications are widespread, such as the formation of pollutants in combustion systems, the formation of process-disrupting deposits in energy or process engineering, or catalytic effects in general, see for instance [54, 55].

Turbulent motion in porous material occur quite frequently in chemical engineering, e.g. in packed-bed reactors, foams, structured reactors, electrode materials or heat exchangers. The difference between turbulent flows in a porous media to open flow is that true macroscopic turbulence is not possible because turbulent eddies are confined in the interstices between the solid walls/obstacles [56].

Due to the complex porous geometry, the averaging and closing approaches for the momentum balance cannot be directly applied, making DNS an appropriate tool to understand turbulence in porous media. Flow patterns, such as jets, helical vortices, and coherent structures, have been observed with DNS, which can, in principle, be used to develop macroscale momentum balance equations [57].

B2 Model definition

A useful nomenclature for modeling and simulation greatly facilitates the dialogue and mutual understanding between industrial chemical engineers, software developers and academia. Furthermore, such a nomenclature can be brought to bear at all modeling levels, irrespective of the scale being studied. It defines a model according to:

- » Its type (deterministic or stochastic, continuum or discrete, etc.),
- » the entity to be modeled (a finite volume, a particle, a cloud of bubbles, a compartment, etc.),
- » the model equation(s) to be solved (e.g. Newton's equation of motion, a species transport equation, or the radiative transfer equation to predict thermal fluxes), and
- » the constitutive equations (i.e. the respective closure models and physical principles formulated as correlations) that

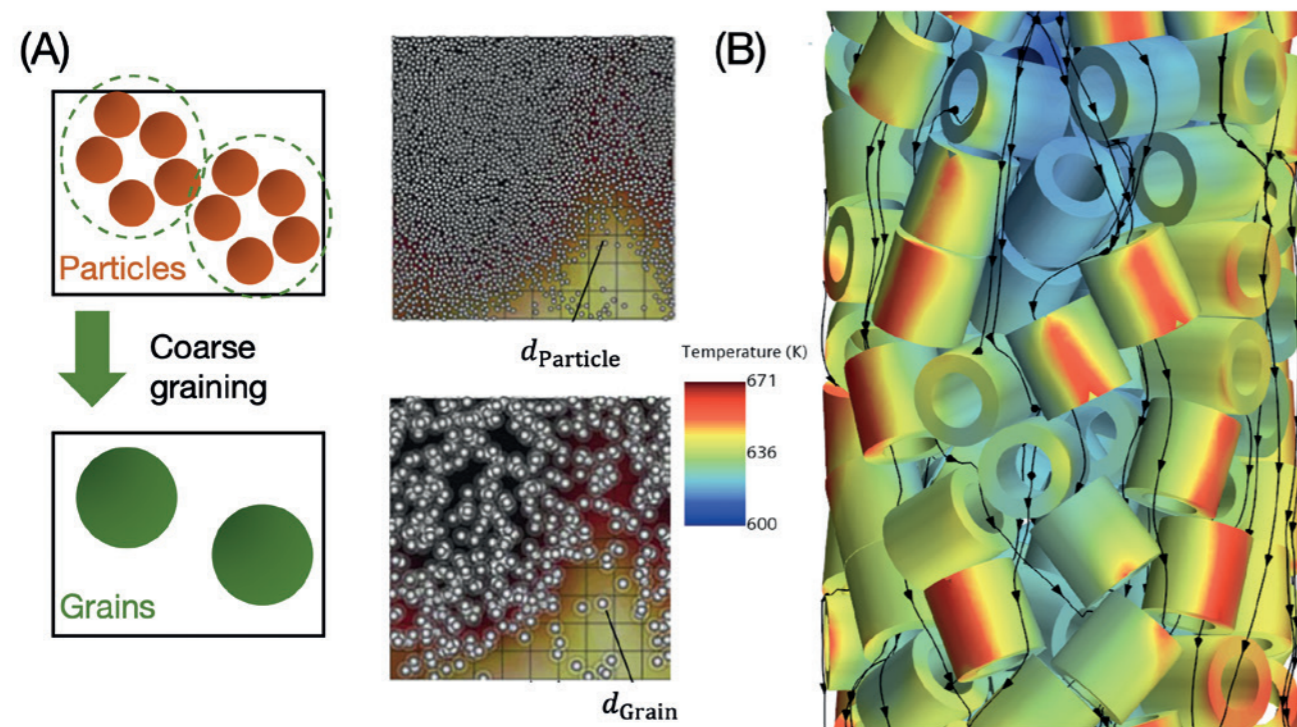


Figure 4.4: (A) Coarse-grain CFD-DEM, partly from [46]; (B) Particle-resolved CFD simulation of a packed bed reactor of rings (courtesy of G.D. Wehinger, TU Clausthal).

are used in the model (e.g. Fickian diffusion, or a kinetic expression for the reaction rate). This encompasses classical “static” correlations, the tabulation of closure relations (e.g. via pre-computed, or in situ adaptive tabulation [43]), as well as procedures that perform dynamic parameter adjustment (e.g. via neural networks [60]).

B3 Solution strategy

Model-based design of chemical reactors involves different fields of modeling, simulation and optimization. It includes forward simulations with models of different detail and complexity, model analysis, such as sensitivity and stability analysis, and rigorous optimization, such as parameter estimation and optimal design. Together these fields provide a fundamental understanding of the physical and chemical phenomena occurring. The model analysis and rigorous optimization allow one to design robust, intensified and efficient chemical reactors and processes. This is especially advantageous when dealing with complex reaction systems, since here the optimal reactor design can be quite counterintuitive due to the simultaneous occurrence of multiple phenomena in these systems. The exact solution strategy varies in different simulation fields. Yet, one can generally distinguish between the following:

- » Numerical approach and type of solver (e.g. a finite difference method, or a (semi-) analytical solution of a model),
- » software tool used (open-source or closed-source), including the parallelization strategy (i.e. MPI and/or SMP parallelization) and hardware requirements (CPU- or GPU-based),
- » coupling strategy between multiple model equations (e.g. explicit or implicit coupling, coupling interval), as well as
- » representation of the solution domain (0D/1D/2D/3D), including the initial and boundary conditions, together with a steady-state assumption or transient solution.

Software quality is decisive for its viability and special attention should therefore be paid to its support, upgrade, and compatibility features. A higher programming language and proven software design to strengthen these aspects of software quality are a key to guarantee computational per-

formance for future hardware architectures used in high performance computing (HPC) clusters. Thus, some of the most important points when it comes to software tools used for the solution of model equations are:

- » A hierarchical software design (i.e. reusability of individual software components),
- » a modular design that permits the extension and exchange of individual modules, as well as
- » a copious set of links (software interfaces) to enable on-line- and offline-hook-ups (e.g. with other software tools for co-simulation, or on-the-fly post-processing), as well as integration into modeling platforms (i.e. a workflow software that allows the connection of further software tools).

B4 Post-processing

With the increasing amount of raw data to be processed, efficient and effective post-processing has become a pivotal task. While post-processing is often included within the simulation tool, it is also useful to have both dedicated visualization tools (e.g. ParaView, TecPlot, EnSight, etc.) and modules that can be linked to the solver for on-the-fly post-processing. The most basic features of such tools are data analysis (e.g. spatial and/or temporal filtering, calculation of statistics), or the automated generation of reports. More sophisticated tools address the automated evaluation of outcomes, e.g. by comparing simulation and experimental data with, for example, matplotlib, seaborn, plotly, etc. Calibration workflows that dynamically adjust parameter values during a simulation run are becoming increasingly important, because of the increasing availability of data and computational resources. Furthermore, virtual reality (VR) has gained attention as a means for exploring CFD simulation results in chemical reaction engineering, both in research and teaching [61, 62].

B5 Human factor

Finally, human interpretation is still a critical factor when it comes to model verification and validation. For instance, it is essential to have access to workflows for automated testing (e.g. as realized by Jenkins) so that staff can focus on the interpretation of results. One important component in

a modeling workflow is the human brain itself. Recent work has therefore focused on assisting the end-user of the workflow by providing links to a database for data comparison and final development work (using software, such as KNIME, Orange, R, etc.). In addition, following state-of-the-art software engineering principles, such as agile development, is vital when developing or extending reaction engineering software. The typically complex model interaction necessitates test-driven development techniques to deal with complexity when devising or substantially extending software. Software development must also ensure its future compatibility and relevance, even if this sometimes entails re-writing the code, or even creating a new software tool.

C ACHIEVEMENTS AND TRENDS

The following achievements and trends can be identified in the field of modeling and simulation of chemical reactors:

- » Modeling in certain sub-genres (e.g. microreactors or lab-scale reactors) has made significant progress, where simplified models (ideal reactors or chemical reactor networks (CRN) [63]) are readily available or can be derived from detailed CFD simulations. Future activities may also incorporate analytical solutions or CRN models into simulation platforms. In addition, in many fields of chemical reactor modeling, DNS approaches have been developed for representative volumes/structures during the last decade. However, the main challenge remains how to effectively derive closures for simplified models from these DNS.
- » A large set of open- and closed-source software tools for describing chemical reactors has been established, which now serve as data generators. Consequently, focus has shifted from data generation to advanced data processing, including closure derivation.
- » The integration of models and simulation tools into information processing and modeling platforms is currently attracting attention to further optimize and control existing and future processes, as well as to enable knowledge-based decisions, taking economic and ecologic efficiency into account. This has fueled (even more) rigorous model validation schemes considering realistic process environments, research towards a more complete process understanding (i.e. more rigorous models) and very large-scale models that are able to cover the interaction

of full process chains at the plant level. The digital twin concept unifies product-process-resources models [64]. A key goal is to establish and manage the networking of partial models into an integrated information space [65] and to permanently hold (raw) data and algorithms and make them readily available to the people and technical systems authorized to access them. This interdisciplinary task requires complementary efforts from different scientific communities and industrial partners.

- » Nowadays, numerous cloud computing solutions are being offered: End users do not have to worry about hardware or software purchasing anymore, with applications instead being provided on a pay-per-use basis. This has significantly lowered the barrier for embarking upon modeling and simulation work. However, the challenges of model selection and the interpretation of simulation results still remain, requiring highly trained staff in the field of modeling and simulation. Finally, the results can be discussed with the various stakeholders using VR or augmented reality [66].
- » After an initial hype about graphical processing units (GPU)-based desktop computing some years ago, there has now been considerable progress and adoption of this promising technique throughout the CFD community. In the last few years, a number of particle-based CFD methods have been utilizing GPU-computing. In 2022, Ansys Fluent as well as Siemens Simcenter STAR-CCM+ introduced multi-GPU solvers for individual CFD solvers. Also, openFOAM can be run on GPUs via RapidCFD. In the coming years, GPU-based CFD codes will experience a further boost, since the hardware costs for GPU servers are already significantly less than for CPU and still falling. Power consumption for GPUs is also less than for CPUs, and GPU performance is by orders of magnitude larger compared to CPU. The progress of GPUs is closely connected with the increasing usage of Artificial Intelligence and data analysis/mining, hence a further speeding-up of GPU-based CFD codes can be expected in the future.
- » Machine learning (ML) is a data mining technique which is used to establish data-driven models. ML is already being used frequently in molecular modeling, e.g. for the discovery and design of new compounds or the prediction of chemical reactions [67] and surface reaction network complexity [68]. However, in chemical and process

engineering, ML has only just started to be applied in the various sub-disciplines [69], such as the modeling of processes [70] and the support for sensorial analysis. In contrast, ML is not extensively being used in the framework of CFD simulations, although there are some promising

applications, such as accelerating DNS or LES with ML [71], accelerating chemical source term calculation [72], ML approach for reconstructing discrepancies in RANS modeled Reynolds stresses [73], or uncertainty quantification in CFD with deep learning [74], to name just a few.

Research needs:

In the following section, we identify urgent research needs in the field of modeling and simulation of chemical reaction engineering:

1. The usage of machine learning tools could be applied over all the many disciplines in chemical reaction engineering. In particular, ML/surrogate models that appreciate physics and chemistry must be developed. Further challenges are optimal decision making, information and knowledge representation, heterogeneity of data, safety and trust in ML applications and, last but not least, creativity [70].
2. The availability of validation data is crucial for model development. Hence, the FAIR data principles (findability, accessibility, interoperability, and reusability) for scientific data management and stewardship [75] must be strictly complied with. In this regard, Zenodo is one example of a general-purpose open repository developed under the European OpenAIRE program and operated by CERN. Researchers can file research papers, data sets, software, reports, etc. for which a distinct DOI is generated [76]. Moreover, another example is the German National Research Data Infrastructure (NFDI), which provides valuable data from German science and research. These data have been systematically accessed, networked and made usable in a sustainable and qualitative manner.
3. The multiscale modeling approach is surely one of the most challenging and interdisciplinary research topics in chemical reaction engineering. Recently, Wehinger et al. [3] summarized the main trends and future research needs covering surface changes in reactors and cells, hierarchical microkinetic analysis, efficient coupling between detailed reaction mechanisms with CFD and efficient scale bridging from the molecular up to the plant level. Surrogate models based on ML seem to be promising for the last point.
4. Many research groups have developed their own specific codes for a subset of applications. This leads to difficulties in integrating such code into existing or new applications. It is therefore essential to have standardized tools that are independent of operating system and software. Standardized graphical user interfaces (GUI) or application programming interfaces (API) would allow researchers to build new models faster and more efficiently and to reduce the gaps between scales.
5. Since electrochemical processes will soon play a much larger role in the chemical and process industry, modeling and simulation approaches from chemical reaction engineering can be adapted to and further developed for electrochemical systems.

REFERENCES

- [1] J. Uhlemann, R. Costa, J.-C. Charpentier, Product Design and Engineering in Chemical Engineering: Past, Present State, and Future, *Chem. Eng. Technol.* 42 (2019) 2258–2274. <https://doi.org/10.1002/ceat.201900236>.
- [2] L. Zhang, H. Mao, Q. Liu, R. Gani, Chemical product design – recent advances and perspectives, *Curr. Opin. Chem. Eng.* 27 (2020) 22–34. <https://doi.org/10.1016/j.coche.2019.10.005>.
- [3] G.D. Wehinger, M. Ambrosetti, R. Cheula, Z.-B. Ding, M. Isoz, B. Kreitz, K. Kuhlmann, M. Kutscherauer, K. Niyogi, J. Poissonnier, R. Réocreux, D. Rudolf, J. Wagner, R. Zimmermann, M. Bracconi, H. Freund, U. Krewer, M. Maestri, Quo vadis multiscale modeling in reaction engineering? – A perspective, *Chem. Eng. Res. Des.* 184 (2022) 39–58. <https://doi.org/10.1016/j.cherd.2022.05.030>.
- [4] A.T. Bell, M. Head-Gordon, Quantum Mechanical Modeling of Catalytic Processes, *Annu. Rev. Chem. Biomol. Eng.* 2 (2011) 453–477. <https://doi.org/10.1146/annurev-chembioeng-061010-114108>.
- [5] K.E. Gubbins, Y.-C. Liu, J.D. Moore, J.C. Palmer, The role of molecular modeling in confined systems: impact and prospects, *Phys Chem Chem Phys.* 13 (2011) 58–85. <https://doi.org/10.1039/CoCP01475C>.
- [6] A. Bruix, J.T. Margraf, M. Andersen, K. Reuter, First-principles-based multiscale modeling of heterogeneous catalysis, *Nat. Catal.* 2 (2019) 659–670. <https://doi.org/10.1038/s41929-019-0298-3>.
- [7] M. Maestri, D. Vlachos, A. Beretta, G. Groppi, E. Tronconi, Steam and dry reforming of methane on Rh: Microkinetic analysis and hierarchy of kinetic models, *J. Catal.* 259 (2008) 211–222. <https://doi.org/10.1016/j.jcat.2008.08.008>.
- [8] B. Kreitz, K. Sargsyan, K. Blöndal, E.J. Mazeau, R.H. West, G.D. Wehinger, T. Turek, C.F. Goldsmith, Quantifying the Impact of Parametric Uncertainty on Automatic Mechanism Generation for CO₂ Hydrogenation on Ni(111), *JACS Au.* 1 (2021) 1656–1673. <https://doi.org/10.1021/jacsau.1c00276>.
- [9] K.F. Kalz, R. Kraehnert, M. Dvoyashkin, R. Dittmeyer, R. Gläser, U. Krewer, K. Reuter, J.-D. Grunwaldt, Future Challenges in Heterogeneous Catalysis: Understanding Catalysts under Dynamic Reaction Conditions, *ChemCatChem.* 9 (2017) 17–29. <https://doi.org/10.1002/cctc.201600996>.
- [10] J.T. Margraf, K. Reuter, Systematic Enumeration of Elementary Reaction Steps in Surface Catalysis, *ACS Omega.* 4 (2019) 3370–3379. <https://doi.org/10.1021/acsomega.8b03200>.
- [11] A.H. Motagamwala, J.A. Dumesic, Microkinetic Modeling: A Tool for Rational Catalyst Design, *Chem. Rev.* 121 (2021) 1049–1076. <https://doi.org/10.1021/acs.chemrev.0c00394>.
- [12] B.W.J. Chen, L. Xu, M. Mavrikakis, Computational Methods in Heterogeneous Catalysis, *Chem. Rev.* 121 (2021) 1007–1048. <https://doi.org/10.1021/acs.chemrev.0c01060>.
- [13] M. Maestri, Escaping the trap of complication and complexity in multiscale microkinetic modeling of heterogeneous catalytic processes, *Chem. Commun.* 53 (2017) 10244–10254. <https://doi.org/10.1039/C7CC05740G>.
- [14] C.W. Gao, J.W. Allen, W.H. Green, R.H. West, Reaction Mechanism Generator: Automatic construction of chemical kinetic mechanisms, *Comput. Phys. Commun.* 203 (2016) 212–225. <https://doi.org/10.1016/j.cpc.2016.02.013>.
- [15] C.F. Goldsmith, R.H. West, Automatic Generation of Microkinetic Mechanisms for Heterogeneous Catalysis, *J. Phys. Chem. C.* 121 (2017) 9970–9981. <https://doi.org/10.1021/acs.jpcc.7b02133>.
- [16] E.J. Mazeau, P. Satpute, K. Blöndal, C.F. Goldsmith, R.H. West, Automated Mechanism Generation Using Linear Scaling Relationships and Sensitivity Analyses Applied to Catalytic Partial Oxidation of Methane, *ACS Catal.* 11 (2021) 7114–7125. <https://doi.org/10.1021/acscatal.0c04100>.
- [17] M. Maestri, D. Livio, A. Beretta, G. Groppi, Hierarchical Refinement of Microkinetic Models: Assessment of the Role of the WGS and r-WGS Pathways in CH₄ Partial Oxidation on Rh, *Ind. Eng. Chem. Res.* 53 (2014) 10914–10928. <https://doi.org/10.1021/ie501570b>.
- [18] R. Cheula, M. Maestri, Nature and identity of the active site via structure-dependent microkinetic modeling: An application to WGS and reverse WGS reactions on Rh, *Catal. Today.* (2021) S0920586121002261. <https://doi.org/10.1016/j.cattod.2021.05.016>.
- [19] F.J. Keil, Molecular Modeling for Reactor Design, *Annu. Rev. Chem. Biomol. Eng.* 9 (2018) 201–227. <https://doi.org/10.1146/annurev-chembioeng-060817-084141>.
- [20] C. Chizallet, Achievements and Expectations in the Field of Computational Heterogeneous Catalysis in an Innovation Context, *Top. Catal.* 65 (2022) 69–81. <https://doi.org/10.1007/s11244-021-01489-y>.

- [21] M. Saliccioli, M. Stamatakis, S. Caratzoulas, D.G. Vlachos, A review of multiscale modeling of metal-catalyzed reactions: Mechanism development for complexity and emergent behavior, *Chem. Eng. Sci.* 66 (2011) 4319–4355. <https://doi.org/10.1016/j.ces.2011.05.050>.
- [22] N. Cheimarios, G. Kokkoris, A.G. Boudouvis, Multiscale Modeling in Chemical Vapor Deposition Processes: Models and Methodologies, *Arch. Comput. Methods Eng.* 28 (2021) 637–672. <https://doi.org/10.1007/s11831-019-09398-w>.
- [23] J. Li, W. Huang, From Multiscale to Mesoscience: Addressing Mesoscales in Mesoregimes of Different Levels, *Annu. Rev. Chem. Biomol. Eng.* 9 (2018) 41–60. <https://doi.org/10.1146/annurev-chembioeng-060817-084249>.
- [24] M.W. Baltussen, K.A. Buist, E.A.J.F. Peters, J.A.M. Kuipers, Multiscale Modeling of Dense Gas–Particle Flows, in: *Adv. Chem. Eng.*, Elsevier, 2018: pp. 1–52. <https://doi.org/10.1016/bs.ache.2018.02.001>.
- [25] A.G. Hoekstra, S. Portegies Zwart, P.V. Coveney, Multiscale modeling, simulation and computing: from the desktop to the exascale, *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* 377 (2019) 20180355. <https://doi.org/10.1098/rsta.2018.0355>.
- [26] C. Binetruy, F. Chinesta, R. Keunings, Multiscale Modeling and Simulation of Polymer Flow, in: *Flows Polym. Reinf. Polym. Compos.*, Springer International Publishing, Cham, 2015: pp. 1–42. https://doi.org/10.1007/978-3-319-16757-2_1.
- [27] S. Radl, F. Municchi, Spatial Filtering for Scale Bridging and Its Application to Transport in Dense Particle Beds, in: *Adv. Chem. Eng.*, Elsevier, 2018: pp. 153–237. <https://doi.org/10.1016/bs.ache.2018.03.001>.
- [28] A. Di Renzo, E. Napolitano, F. Di Maio, Coarse-Grain DEM Modeling in Fluidized Bed Simulation: A Review, *Processes*. 9 (2021) 279. <https://doi.org/10.3390/pr9020279>.
- [29] M. Schlüter, S. Herres-Pawlis, U. Nieken, U. Tüttli, D. Bothe, Small-Scale Phenomena in Reactive Bubbly Flows: Experiments, Numerical Modeling, and Applications, *Annu. Rev. Chem. Biomol. Eng.* 12 (2021) 625–643. <https://doi.org/10.1146/annurev-chembioeng-092220-100517>.
- [30] R.V. Craster, O.K. Matar, Dynamics and stability of thin liquid films, *Rev. Mod. Phys.* 81 (2009) 1131–1198. <https://doi.org/10.1103/RevModPhys.81.1131>.
- [31] P. Kieckhefen, S. Pietsch, M. Dosta, S. Heinrich, Possibilities and Limits of Computational Fluid Dynamics–Discrete Element Method Simulations in Process Engineering: A Review of Recent Advancements and Future Trends, *Annu. Rev. Chem. Biomol. Eng.* 11 (2020) 397–422. <https://doi.org/10.1146/annurev-chembioeng-110519-075414>.
- [32] J.B. Joshi, K. Nandakumar, Computational Modeling of Multiphase Reactors, *Annu. Rev. Chem. Biomol. Eng.* 6 (2015) 347–378. <https://doi.org/10.1146/annurev-chembioeng-061114-123229>.
- [33] G. Besagni, F. Inzoli, T. Ziegenhein, Two-Phase Bubble Columns: A Comprehensive Review, *ChemEngineering*. 2 (2018) 13. <https://doi.org/10.3390/chemengineering2020013>.
- [34] M. Shiea, A. Buffo, M. Vanni, D. Marchisio, Numerical Methods for the Solution of Population Balance Equations Coupled with Computational Fluid Dynamics, *Annu. Rev. Chem. Biomol. Eng.* 11 (2020) 339–366. <https://doi.org/10.1146/annurev-chembioeng-092319-075814>.
- [35] D. Ramkrishna, M.R. Singh, Population Balance Modeling: Current Status and Future Prospects, *Annu. Rev. Chem. Biomol. Eng.* 5 (2014) 123–146. <https://doi.org/10.1146/annurev-chembioeng-060713-040241>.
- [36] S. Golshan, R. Sotudeh-Gharebagh, R. Zarghami, N. Mostoufi, B. Blais, J.A.M. Kuipers, Review and implementation of CFD-DEM applied to chemical process systems, *Chem. Eng. Sci.* 221 (2020) 115646. <https://doi.org/10.1016/j.ces.2020.115646>.
- [37] W. Zhong, A. Yu, X. Liu, Z. Tong, H. Zhang, DEM/CFD-DEM Modeling of Non-spherical Particulate Systems: Theoretical Developments and Applications, *Powder Technol.* 302 (2016) 108–152. <https://doi.org/10.1016/j.powtec.2016.07.010>.
- [38] S. Sundaresan, A. Ozel, J. Kolehmainen, Toward Constitutive Models for Momentum, Species, and Energy Transport in Gas–Particle Flows, *Annu. Rev. Chem. Biomol. Eng.* 9 (2018) 61–81. <https://doi.org/10.1146/annurev-chembioeng-060817-084025>.
- [39] S. Tenneti, S. Subramaniam, Particle-Resolved Direct Numerical Simulation for Gas-Solid Flow Model Development, *Annu. Rev. Fluid Mech.* 46 (2014) 199–230. <https://doi.org/10.1146/annurev-fluid-010313-141344>.
- [40] M. Wörner, Numerical modeling of multiphase flows in microfluidics and micro process engineering: a review of methods and applications, *Microfluid. Nanofluidics*. 12 (2012) 841–886. <https://doi.org/10.1007/s10404-012-0940-8>.
- [41] N. Jurtz, M. Kraume, G.D. Wehinger, Advances in fixed-bed reactor modeling using particle-resolved computational fluid dynamics (CFD), *Rev. Chem. Eng.* 35 (2019) 139–190. <https://doi.org/10.1515/revce-2017-0059>.
- [42] M. Kutscherauer, S. Böcklein, G. Mestl, T. Turek, G.D. Wehinger, An improved contact modification routine for a computationally efficient CFD simulation of packed beds, *Chem. Eng. J. Adv.* 9 (2022) 100197. <https://doi.org/10.1016/j.cej.2021.100197>.
- [43] E.A. Daymo, M. Hettel, O. Deutschmann, G.D. Wehinger, Accelerating particle-resolved CFD simulations of catalytic fixed-bed reactors with DUO, *Chem. Eng. Sci.* 250 (2022) 117408. <https://doi.org/10.1016/j.ces.2021.117408>.
- [44] G.D. Wehinger, F. Scharf, Thermal radiation effects on heat transfer in slender packed-bed reactors: Particle-resolved CFD simulations and 2D modeling, *Chem. Eng. Res. Des.* 184 (2022) 24–38. <https://doi.org/10.1016/j.cherd.2022.05.034>.
- [45] P. Kočí, M. Isoz, M. Plachá, A. Arvajová, M. Václavík, M. Svoboda, E. Price, V. Novák, D. Thompsett, 3D reconstruction and pore-scale modeling of coated catalytic filters for automotive exhaust gas aftertreatment, *Catal. Today*. 320 (2019) 165–174. <https://doi.org/10.1016/j.cattod.2017.12.025>.
- [46] A. Ozel, J. Kolehmainen, S. Radl, S. Sundaresan, Fluid and particle coarsening of drag force for discrete-parcel approach, *Chem. Eng. Sci.* 155 (2016) 258–267. <https://doi.org/10.1016/j.ces.2016.08.014>.
- [47] M. Bagheri, B. Stumpf, I.V. Roisman, C. Tropea, J. Hussong, M. Wörner, H. Marschall, Interfacial relaxation – Crucial for phase-field methods to capture low to high energy drop-film impacts, *Int. J. Heat Fluid Flow*. 94 (2022) 108943. <https://doi.org/10.1016/j.ijheatfluidflow.2022.108943>.
- [48] L. Brandt, F. Coletti, Particle-Laden Turbulence: Progress and Perspectives, *Annu. Rev. Fluid Mech.* 54 (2022) 159–189. <https://doi.org/10.1146/annurev-fluid-030121-021103>.
- [49] M. Maxey, Simulation Methods for Particulate Flows and Concentrated Suspensions, *Annu. Rev. Fluid Mech.* 49 (2017) 171–193. <https://doi.org/10.1146/annurev-fluid-122414-034408>.
- [50] V. Mathai, D. Lohse, C. Sun, Bubbly and Buoyant Particle–Laden Turbulent Flows, *Annu. Rev. Condens. Matter Phys.* 11 (2020) 529–559. <https://doi.org/10.1146/annurev-conmatphys-031119-050637>.
- [51] S. Elghobashi, Direct Numerical Simulation of Turbulent Flows Laden with Droplets or Bubbles, *Annu. Rev. Fluid Mech.* 51 (2019) 217–244. <https://doi.org/10.1146/annurev-fluid-010518-040401>.
- [52] R.O. Fox, Multiphase turbulence, in: *Adv. Approaches Turbul.*, Elsevier, 2021: pp. 307–371. <https://doi.org/10.1016/B978-0-12-820774-1.00013-6>.
- [53] A.J. Smits, B.J. McKeon, I. Marusic, High–Reynolds Number Wall Turbulence, *Annu. Rev. Fluid Mech.* 43 (2011) 353–375. <https://doi.org/10.1146/annurev-fluid-122109-160753>.
- [54] A. Bender, P. Stephan, T. Gambaryan-Roisman, A fully coupled numerical model for deposit formation from evaporating urea-water drops, *Int. J. Heat Mass Transf.* 159 (2020) 120069. <https://doi.org/10.1016/j.ijheatmasstransfer.2020.120069>.
- [55] M. Börnhorst, C. Kuntz, S. Tischer, O. Deutschmann, Urea derived deposits in diesel exhaust gas after-treatment: Integration of urea decomposition kinetics into a CFD simulation, *Chem. Eng. Sci.* 211 (2020) 115319. <https://doi.org/10.1016/j.ces.2019.115319>.
- [56] Y. Jin, A.V. Kuznetsov, Turbulence modeling for flows in wall bounded porous media: An analysis based on direct numerical simulations, *Phys. Fluids*. 29 (2017) 045102. <https://doi.org/10.1063/1.4979062>.
- [57] B.D. Wood, X. He, S.V. Apte, Modeling Turbulent Flows in Porous Media, *Annu. Rev. Fluid Mech.* 52 (2020) 171–203. <https://doi.org/10.1146/annurev-fluid-010719-060317>.
- [58] A. du Cluzeau, G. Bois, A. Toutant, Analysis and modeling of Reynolds stresses in turbulent bubbly up-flows from direct numerical simulations, *J. Fluid Mech.* 866 (2019) 132–168. <https://doi.org/10.1017/jfm.2019.100>.
- [59] X. Shao, T. Wu, Z. Yu, Fully resolved numerical simulation of particle-laden turbulent flow in a horizontal channel at a low Reynolds number, *J. Fluid Mech.* 693 (2012) 319–344. <https://doi.org/10.1017/jfm.2011.533>.
- [60] Y. Jiang, X. Chen, J. Kolehmainen, I.G. Kevrekidis, A. Ozel, S. Sundaresan, Development of data-driven filtered drag model for industrial-scale fluidized beds, *Chem. Eng. Sci.* 230 (2021) 116235. <https://doi.org/10.1016/j.ces.2020.116235>.

- [61] G.D. Wehinger, S. Flaischlen, Studying Computational Fluid Dynamics in a New Dimension with Virtual Reality, in: *Comput. Aided Chem. Eng.*, Elsevier, 2020: pp. 2041–2046. <https://doi.org/10.1016/B978-0-12-823377-1.50341-4>.
- [62] S. Solmaz, T. Van Gerven, Interactive CFD simulations with virtual reality to support learning in mixing, *Comput. Chem. Eng.* 156 (2022) 107570. <https://doi.org/10.1016/j.compchemeng.2021.107570>.
- [63] G.D. Wehinger, B. Kreitz, C.F. Goldsmith, Non-Idealities in Lab-Scale Kinetic Testing: A Theoretical Study of a Modular Temkin Reactor, *Catalysts*. 12 (2022) 349. <https://doi.org/10.3390/catal12030349>.
- [64] A. Bamberg, L. Urbas, S. Bröcker, M. Bortz, N. Kockmann, The Digital Twin – Your Ingenious Companion for Process Engineering and Smart Production, *Chem. Eng. Technol.* 44 (2021) 954–961. <https://doi.org/10.1002/ceat.202000562>.
- [65] M. Graube, J. Pfeffer, J. Ziegler, L. Urbas, Linked Data as Integrating Technology for Industrial Data., *Int. J. Distrib. Syst. Technol.* 3 (2012) 40–52. <https://doi.org/10.4018/jdst.2012070104>.
- [66] W. Li, A. Nee, S. Ong, A State-of-the-Art Review of Augmented Reality in Engineering Analysis and Simulation, *Multimodal Technol. Interact.* 1 (2017) 17. <https://doi.org/10.3390/mti1030017>.
- [67] M. Haghghatlari, J. Hachmann, Advances of machine learning in molecular modeling and simulation, *Curr. Opin. Chem. Eng.* 23 (2019) 51–57. <https://doi.org/10.1016/j.coche.2019.02.009>.
- [68] Z.W. Ulissi, A.J. Medford, T. Bligaard, J.K. Nørskov, To address surface reaction network complexity using scaling relations machine learning and DFT calculations, *Nat. Commun.* 8 (2017) 14621. <https://doi.org/10.1038/ncomms14621>.
- [69] C. Trinh, D. Meimaroglou, S. Hoppe, Machine Learning in Chemical Product Engineering: The State of the Art and a Guide for Newcomers, *Processes*. 9 (2021) 1456. <https://doi.org/10.3390/pr9081456>.
- [70] A.M. Schweidtmann, E. Esche, A. Fischer, M. Kloft, J. Repke, S. Sager, A. Mitsos, Machine Learning in Chemical Engineering: A Perspective, *Chem. Ing. Tech.* 93 (2021) 2029–2039. <https://doi.org/10.1002/cite.202100083>.
- [71] D. Kochkov, J.A. Smith, A. Alieva, Q. Wang, M.P. Brenner, S. Hoyer, Machine learning–accelerated computational fluid dynamics, *Proc. Natl. Acad. Sci.* 118 (2021) e2101784118. <https://doi.org/10.1073/pnas.2101784118>.
- [72] B. Partopour, R.C. Paffenroth, A.G. Dixon, Random Forests for mapping and analysis of microkinetics models, *Comput. Chem. Eng.* 115 (2018) 286–294. <https://doi.org/10.1016/j.compchemeng.2018.04.019>.
- [73] J.-X. Wang, J.-L. Wu, H. Xiao, Physics-informed machine learning approach for reconstructing Reynolds stress modeling discrepancies based on DNS data, *Phys. Rev. Fluids*. 2 (2017) 034603. <https://doi.org/10.1103/PhysRevFluids.2.034603>.
- [74] K.O. Lye, S. Mishra, D. Ray, Deep learning observables in computational fluid dynamics, *J. Comput. Phys.* 410 (2020) 109339. <https://doi.org/10.1016/j.jcp.2020.109339>.
- [75] M.D. Wilkinson, M. Dumontier, I.J. Aalbersberg, G. Appleton, M. Axton, A. Baak, N. Blomberg, J.-W. Boiten, L.B. da Silva Santos, P.E. Bourne, J. Bouwman, A.J. Brookes, T. Clark, M. Crosas, I. Dillo, O. Dumon, S. Edmunds, C.T. Evelo, R. Finkers, A. Gonzalez-Beltran, A.J.G. Gray, P. Groth, C. Goble, J.S. Grethe, J. Heringa, P.A.C. 't Hoen, R. Hooft, T. Kuhn, R. Kok, J. Kok, S.J. Lusher, M.E. Martone, A. Mons, A.L. Packer, B. Persson, P. Rocca-Serra, M. Roos, R. van Schaik, S.-A. Sansone, E. Schultes, T. Sengstag, T. Slater, G. Strawn, M.A. Swertz, M. Thompson, J. van der Lei, E. van Mulligen, J. Velterop, A. Waagmeester, P. Wittenburg, K. Wolstencroft, J. Zhao, B. Mons, The FAIR Guiding Principles for scientific data management and stewardship, *Sci. Data*. 3 (2016) 160018. <https://doi.org/10.1038/sdata.2016.18>.
- [76] European Organization For Nuclear Research, OpenAIRE, Zenodo: Research. Shared., (2013). <https://doi.org/10.25495/7GXX-RD71>.

5 Reactor Design and Process Development

The basis for process development and associated reactor design is the precise knowledge of stoichiometry, thermodynamics, kinetics, transport phenomena and relevant safety data. This can be used to determine the characteristic reaction time scale and the heat being released or supplied.

These quantities must be matched to the transport processes in the reactor, so that the reaction can be carried out safely and with high yields. Miniplant studies are often imperative, because the process can only be implemented and investigated in the necessary detail with recycle streams, under partial loading and during start-up and shutdown. With the help of a good model, the process can be transferred directly to production plant scale, but a pilotplant is installed if the scale-up risk needs to be reduced further. The current state of chemical reactor development indicates that modern techniques for process intensification have in some cases already entered industrial practice.

A OPTIMIZATION OF TRANSPORT PROCESSES IN THE REACTOR

Transport phenomena can be categorized into momentum, heat and mass transport processes [1]. Furthermore, the phases involved (solid, liquid, gaseous, supercritical) and phase boundaries can be identified, as well as the interfaces on or at which a transfer process takes place with or without a chemical reaction. For a transport process one needs to distinguish between diffusion, laminar dispersion and turbulent exchange. This brief survey illustrates the complexity of the transport processes between the molecular and the plant equipment scale. In addition to the length scale at which the transport processes occur, the time scale is also relevant, due to the relative rates of transport and chemical reaction. For this reason, the transport phenomena for chemical species and energy form a bridge spanning molecular processes up to equipment implementation. Understanding them is essential for the successful future development of reaction technology.

Transport processes can, in some cases, be described analytically, for instance with laminar flow, boundary layer equations, heat conduction and diffusion. Other models are based on dimensionless numbers and their correlations. The description of turbulence is still based on concepts that are more than 50 years old. In the meantime, however, numerical methods have been established to the point where

they can make a significant contribution in determining turbulent exchange variables. The modeling of turbulence and the experimental validation on a fine scale nevertheless remain major challenges. Measurement methods for velocities, temperature and concentration fields at the micrometer scale in simple geometries have been developed and refined. The modeling of the residence time distribution is based on standard models, which, however, are only of limited use for real equipment. Local and integral measurements are therefore still essential.

The participating phases in chemical reactors are seldom homogeneously distributed. The majority of reaction systems are heterogeneous and must be described by multiphase flow concepts. The transport processes at phase boundaries have, up to now, been described by correlations and molecular dynamics simulations, but with a large gap between the continuum and the molecular levels. The same is true for catalysis on solid surfaces and in porous materials.

A promising path to intensify transport processes in reactors as well as to acquire an improved understanding of the fundamentals is the transition from random configurations to well-defined structures in the micro- and millimeter range. Substantial progress has already been made in the description of the transport processes with chemical reactions in small channels, in particular in the case of laminar, single-phase flows and clear-cut two-phase systems, such as the segmented Taylor flow in capillaries.

Further current lines of research are the use of mini- and micro-emulsions as microreactors, processes in micelles and vesicles in colloid chemistry, as well as the use of sponges and other novel porous media for various reaction-related applications. Another topical trend is the alternative activation of and energy supply for chemical reactions. These techniques include energy input by cavitation, ultrasound, micro or radio waves and light. Novel fluids such as ionic liquids and supercritical media also have considerable potential for applications in reaction technology. However, such approaches have, so far, few industrial applications.

The overall objective is to adapt the mass and heat transport processes to the chemical reactions taking place, so that a maximum selectivity is achieved with the highest possible conversion. The heat transport must always be carried out as efficiently as possible, so that the optimum temperature for the chemical reactions is guaranteed at every location in the reactor. In the majority of cases, the most intensive mass transport of substances is sought. However, there are interesting special cases, in which it is of advantage to hinder mass transport processes. This includes, for example, phase transfer catalysis or regio-selective catalysis, where the access of reactants to and/or the release of products from microporous systems are deliberately restricted. The limitation of mass transport can also be used to limit heat release, which might otherwise lead to hot spots.

The interaction of reaction kinetics and thermodynamics with the associated transport processes in the reactor is a highly coupled system, which is not yet fully understood, particularly in the case of multiphase reactors. Further experimental and theoretical advances are required in this field.

Research needs:

1. Use of micro- and millistructured reactors with well-defined channel dimensions as model systems, especially for multiphase reactions
2. Derivation of effective transport parameters in domains with complex microscopic structures
3. Experimental and theoretical treatment of turbulent flows in extended multiphase systems
4. Optimization of mass transport processes, for example, by tailor-made porous systems in catalysts, micellar systems and microemulsions.

B MINIPLANT TECHNOLOGY AND EXPERIMENTAL SCALE-UP

After identifying a promising new chemical synthesis route and devising the catalysts needed, the process development begins. Starting from the laboratory synthesis, process concepts are developed and the individual steps of the process are tested in the laboratory and by simulation. The interaction between the individual steps can also be analyzed very efficiently in process simulation environments. The influence of initially unknown by-products, which can

accumulate in recycle streams and possibly lead to fouling, i.e. plugging of pipelines, machines and equipment, but which cannot be entirely predicted by simulations, can be investigated and understood with the aid of a miniplant, comprised of laboratory apparatus items (separation columns, reactors, etc.). A miniplant is a small-scale, complete plant with production rates of 100 g h^{-1} consisting of raw material preparation, synthesis, downstream processing and all recycle streams and is thus one of the most powerful experimental tools of modern process development (see Figure 5.1). In addition, representative waste streams can be obtained and analyzed. A conceptual waste concept can be elaborated which is most often different for individual production sites.

After validation of the process concept in the miniplant, the next conventional step is the planning and construction of a pilot-plant with a significantly higher capacity. The scale of the pilot plant is between that of the miniplant and that of the subsequent industrial installation. Production capacities of several kg h^{-1} to t h^{-1} permit, for example, application tests or customer deliveries on a larger scale as well as the study of the long-term plant behavior under semi-production conditions. The operation of the pilot-plant is used to complete and verify existing data and documentation. It is one of the main cost drivers in the commercialization of technical processes and often leads to a considerable extension of development times. Hence, these days, the construction of a pilot-plant should be the exception rather than the rule.

With the improvement of the simulation programs for the modeling of processes, the so-called holistic “integrated miniplant technology” as a combination of experimental miniplant technology with process simulation has become the gold standard over the last few years, since the synergy between miniplant technology and mathematical simulation results in a scale-up reliability that is as good as that of a pilot-plant.

The basis for reactor scale-up is setting up and solving the mass, energy and momentum balances, represented by a system of coupled partial differential equations, which must then be solved numerically. In the early phases of process development, however, this rigorous method often lacks the necessary material data, kinetic data and clear boundary conditions. Therefore, one still needs to rely on dimensional analysis and dimensionless parameters, reflecting the ratio

of system-relevant terms in the above-mentioned balance equations. In later phases any remaining uncertainties of the data need to be considered. If no pilot-plant is built or for large scale-up factors, turbulent flow represents another uncertainty. CFD is a valuable tool for analyzing the related scale-up issues and quantifying sensitivities. All this relates to the industrial need for robust designs which consider uncertainties, and allow easy adjustments of process parameters or design changes during start-up.

The experimental scale-up is particularly simple in the case of multitubular or plate reactors, since the scale-up can be carried out from pilot experiments in the single-tube or one-channel reactor via a “numbering-up”. This strategy is also adopted in the case of microstructured reactors with multiple parallel flow channels. An appropriate design of the distributor is crucial to ensure an even distribution of flow to the individual channels. In addition, detrimental feedback mechanisms have to be considered. Maldistribution may cause increased viscosity or coking, which in turn can increase maldistribution. It might even cause equipment damage, e.g. by hot spots, or spark safety issues. Research needs to analyse self-reinforcing feedback loops and avoid them by equipment design or by measurement sensors control.

In chemical processes involving large reactor volumes with complex fluid dynamics, a scale-up is at present still only



Figure 5.1: Miniplant modular dosing unit for various liquids (source: HNP Mikrotechnik, MoDoS).

Research needs:

1. Increase the efficiency of the miniplant operation by
 - cost-effective automation,
 - employing reusable modules in laboratory systems with well-established control and safety concepts, the models of which are already accessible in the model libraries of the simulation environment,
 - improvement in the scalability of apparatus (for example for the processing of solids) from the laboratory to the technical scale,
 - facilitation and exploitation of additive manufacturing (3D printing) to accelerate toolset development and implementation in labs.
2. Avoidance or reduction of pilot tests by means of validated models for reactor scale-up and development of tools for the assessment and limitation of risks of transfer to the production scale. This should include the development of reliable CFD tools and models for use by non-CFD experts.
3. Development of process and plant concepts and reactor technologies, including accelerated and simplified scale-up, e.g. through numbering-up.
4. Analysis of self-reinforcing feedback loops in parallelized reactors and avoiding them by design or by monitoring and regulation.

possible in limited scale-up stages, in order to master the overall scale-up risk. Therefore, a first commercial plant of a new process is typically smaller than subsequent installations.

C EQUIPMENT DEVELOPMENT

Initial situation / state of the art

The development of the equipment technology for the construction of chemical reactors goes hand in hand with the development of new processes. A historical example of this is the development of high-pressure reactors for the ammonia synthesis more than a hundred years ago.

The range of equipment technology and reactor design is today as broad as the product range manufactured in chemical plants. Due to its flexibility, the stirred tank is the most commonly used reactor vessel. However, the equipment spectrum extends from classical fixed bed reactors with molten salt or

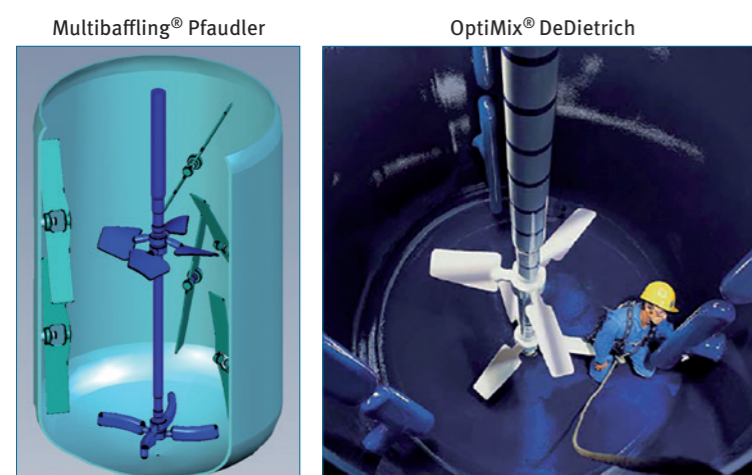


Figure 5.2: Stirred vessels of Pfaudler und deDietrich.

evaporative cooling, heat exchanger reactors through bubble columns, jet reactors, nozzle reactors, fluidized-bed reactors to high-temperature reactors and more complex reactors, such as microstructured reactors, photochemical reactors, electrochemical reactors, kneader reactors and hybrid systems, such as reactive distillation, extractions or gas scrubbers.

Although the stirred tank is one of the oldest chemical reactor designs, it is undergoing continuous refinement and reincarnation. In the enameled stirred tank (see Fig. 5.2), new solutions (in this case, flexible current baffle arrangements) have been developed, which have significantly increased the flexibility and energy efficiency in gas/liquid systems, despite the otherwise limited production potential of enameled devices.

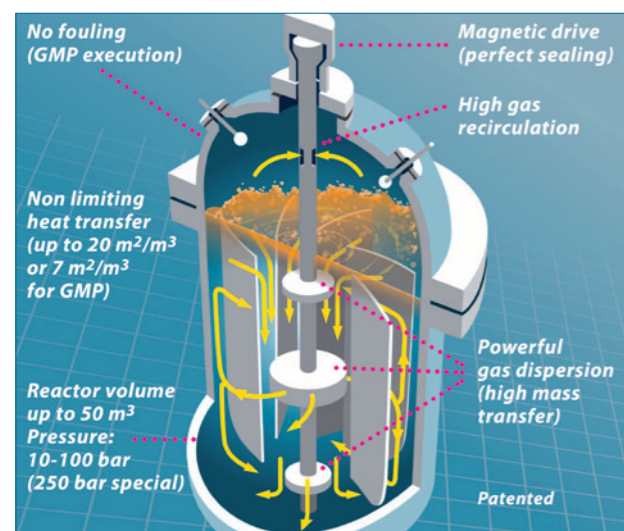


Figure 5.3: Gas/Liquid-Reactor with heat exchanger plates (Source: Biazzi SA).

To improve the heat removal in stirred vessels, heat exchanger plates (see Fig. 5.3) can be used, which offer larger heat exchange surfaces than internally installed heat exchanger coils. Thus, exothermic reactions in multiphase systems, e.g. suspension hydrogenations, may be better controlled.

Salt bath reactors are conventional fixed-bed reactors for exothermic, heterogeneously catalyzed gas phase reactions at high temperatures (see Figure 5.4). They are used for example for partial oxidation reactions, such as the synthesis of acrylic acid.

When the requirements for heat removal or temperature control become more stringent, so-called heat exchange reactors are used. Based on plate or tube-bundle heat exchangers, very high heat exchange performance can be achieved for single-phase systems.

In recent years, the development of microstructured reactors has shown that the intensification of heat transfer in manufacturing technologies was mainly confined to and driven by single-phase systems. Microstructured reactors (see Figures 5.5 and 5.6) are characterized by internal structures of ten to several thousand micrometers. With such structures, liquid heating and cooling rates in the range of milliseconds become feasible.



Figure 5.4: Salt-operated tubular reactors from DWE® (Source: MAN Energy Solutions).

In principle, microstructured reactors can also be used for multiphase systems. However, effects such as surface tension, wetting or maldistribution of flow in parallel channels point towards alternative equipment solutions for large reactors. Currently, such multiphase reactors are therefore limited to the laboratory scale.

For large-scale production, an integrated scale-up concept is necessary for the required throughput whereby only a minimal cross-sectional enlargement of the channels takes place. Thus, the advantages of microreaction technology, such as high mixing quality, excellent heat transfer and targeted process control can be retained. The required throughput is achieved, for example, by a parallel connection of channels to a channel bundle within a reactor (see Figure 5.6).

In 2016 the first large-scale production reactor was commissioned at Shaoxing Eastlake Hi-Tech Co. Ltd. (China) to produce an active ingredient for agriculture application. Meanwhile three of those reactors are running continuously with an overall throughput of 30.000 t/a.

In process intensification, the heterogeneously catalyzed reactive distillation initiated equipment development in order to optimize the interaction of catalysis, reaction and separation. The fixation of the solid catalyst in the reactive distillation column, for example, is realized by incorporating the catalyst into the separating column internals (see Fig. 5.7).

For the development and design of equipment, in addition to mechanical strength calculations, manufacturers employ complex CFD calculations to quantitatively describe the fluid dynamics as well as mass and heat transfer. Especially for single-phase reaction systems, these CFD calculations now achieve design quality.

Safety requirements normally lead either to a pressure-resistant design or to the use of pressure relief devices. Modern reactors can, however, also be operated in a safe mode with the help of measurement and control technologies using offline or online model calculations, which are process-adaptive and therefore economically more attractive. Reliable management of complexity and deep process comprehension is required for such an approach [3].

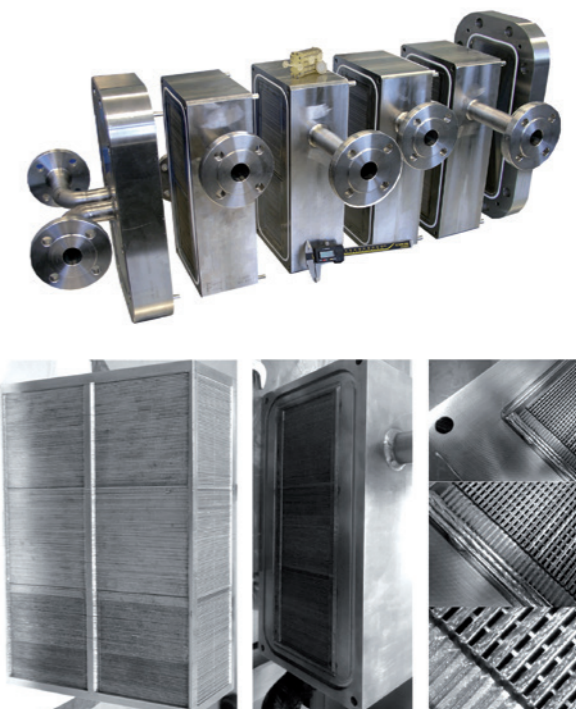


Figure 5.5: Microstructured production reactor of IMVT for the synthesis of diacetonacrylamide from diacetone alcohol and acrylonitrile. The plates with channels of 0.5 mm depth and 2 mm width are diffusion-welded. (Source: Institute for Microprocess Technology (IMVT), Karlsruhe Institute of Technology (KIT)).

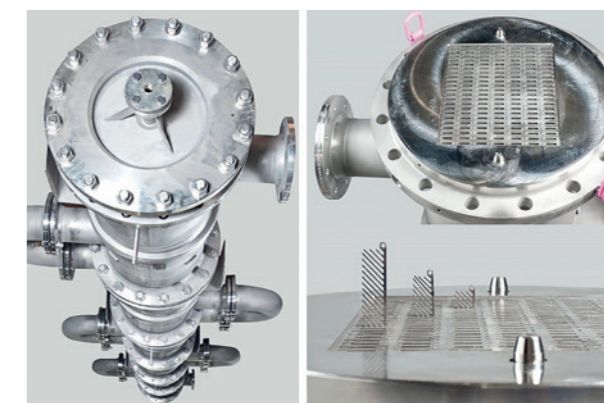


Figure 5.6: Millistructured production reactor of Ehrfeld Mikrotechnik. Left: Complete reactor, Top Right: 154 in parallel aligned process channels, Bottom right: Static mixing inserts for enhanced heat and mass transport (Source: Ehrfeld Mikrotechnik GmbH).

Technical scientific challenges

Better process control by In situ analytical methods and improved measurement techniques, e.g. heat flow sensors or in-line viscosity measurements, is desirable to significantly improve quality control, particularly in batch syntheses. In addition, batch processing times can be shortened, because part of the process optimization is shifted to the production

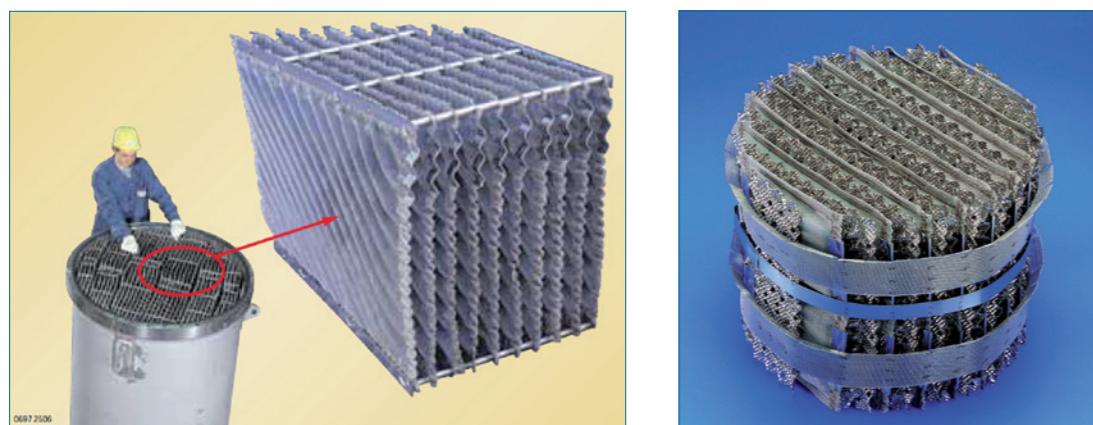


Figure 5.7: Wire mesh Katapak™ of Sulzer ChemTech. (L. Götze, O. Bailer, Sulzer technical review 1999).

phase through improved process control. This is particularly interesting in the case of agrochemicals and pharmaceutical products, since the constraints imposed on the development times are especially tight. Analytical techniques, e.g. online NMR or spectroscopic methods such as UV-VIS, IR and Raman spectroscopy, have already demonstrated huge potential for process optimization.

Some biotechnological processes require large reactor volumes of the order of more than 1000 m³ as well as high specific mass transfer rates, leading to motor power requirements in excess of 10 MW for conventional aeration systems, which are difficult to implement mechanically. It would be preferable to avoid such high drive torques by hybrid gasing devices and thus to increase the overall energy efficiency for this intensified mass transfer.

Directly coated heat exchanger elements in microreactors with highly active solid catalysts (see Fig. 5.8) can open up new possibilities for the control of strongly exothermic reactions. For this purpose, coating techniques providing reliable and reproducible coatings at the microreactor scale must be developed along with suitable characterization procedures for the quality control, and deactivation must be monitored carefully, due to the small catalyst mass present.

The development of novel equipment concepts is a complex process. Ideally, the reactor provides the optimal transport characteristics for heat, mass, and momentum needed for the best reaction yield and/or selectivity. This presupposes knowledge of the optimal operating profile for the reaction, which should be determined as an ideal benchmark without imposing any equipment restrictions. Subsequently, the

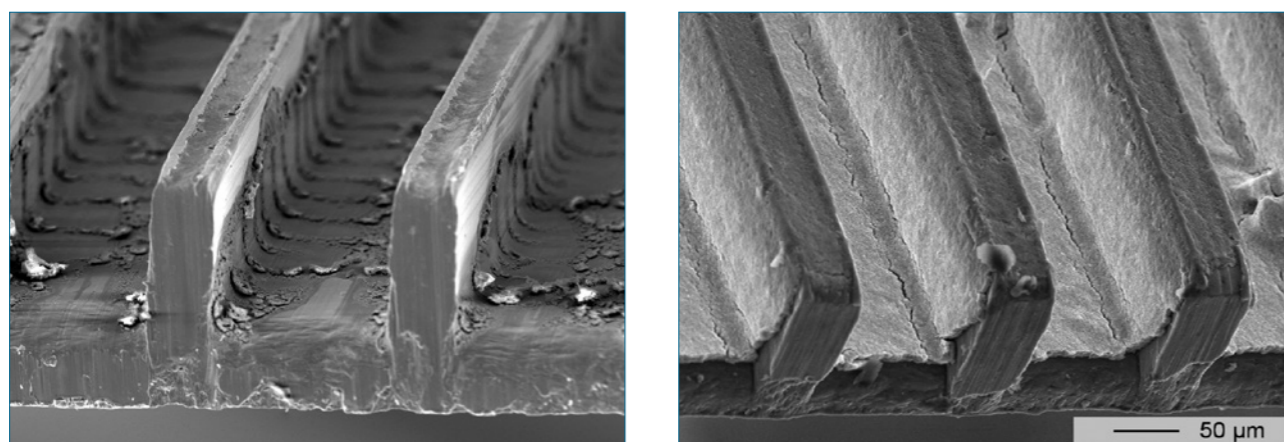


Figure 5.8: Left: Sol-gel coating of a microstructured stainless steel foil with 5 % Pt/CeO₂ for the water gas shift reaction. Right: Washcoat layer of a microstructured stainless steel foil with Cu/ZnO nanoparticles for methanol reforming. (Source: Institute for Microprocess Technology (IMVT), Karlsruhe Institute of Technology (KIT)).

optimum temperature and concentration profiles have to be approximated as far as possible within the constraints of a technical reactor. To attain a generally valid solution from a particular procedure, new optimization methods are necessary. In addition, further development of simulation tools for heat, mass and momentum transfer is required, especially in complex geometries and/or multiphase systems (see Chapter 4). On the other hand, uncertainties and sensitivities must be considered to ensure good operability and robust design. The latter becomes increasingly important for bio-based and recycled waste feedstocks, which are set to gain market share rapidly in the coming years, as their composition and physical properties are more variable than conventional petrochemical raw materials and as they typically contain more impurities. The dynamic supply of green power is pushing in the same direction.

Research needs:

1. New In situ analytical methods and new process measurement techniques to improve process control in production and to help shorten development times for batch processes.
2. Model-based control and safety concepts.
3. New methods for design and construction to allow model-based development of novel reactor concepts implementing optimal reaction management.
4. Tools for process and equipment design under uncertainties.
5. Optimization of lab equipment for the generation of accurate and reliable basic design data.
6. Development of robust catalysts, which are stable with respect to bio-based and recycled waste feedstocks and to high fluctuations in throughput.

D PROCESS INTENSIFICATION

Process intensification aims to achieve a clear economic and ecological improvement in the efficiency of chemical and biotechnological processes and the generation of new products or better product qualities. It makes use of an interdisciplinary, holistic approach, as well as a multiscale process analysis from the molecular level up to the global site network. It involves deliberately targeted measures for process structuring and integration, while promoting the effective exploitation of innovative equipment and technologies.

In connection with reaction technology, the following principal process intensification measures enable favorable spatial, temporal, thermodynamic and functional configuration of the reaction system:

- » Miniaturization
- » Hybridization
- » Structuring
- » Dynamic operation
- » Novel reaction media and energy supplies
- » Integration and rationalization

Miniaturization, i.e. the operation of ‘microreactors’ with characteristic dimensions in the millimeter or micrometer range, pursues the goal of eliminating mass and heat transfer limitations, which often stymie the purely chemical ‘reactivity’ performance. High specific heat exchange surface areas as well as increased mass transfer due to intensive mixing ensure well-defined near-optimal operating conditions. The stochastic processes in conventional reactors are largely eliminated and replaced by the uniform processing profile of the microscale operating mode. The low internal volume of microstructured devices is highly advantageous for both safety reasons and in the processing of expensive materials.

The successful exploitation of the potential performance enhancements of microreactors in technical production requires reliable parallelization strategies, which ensure an even distribution of the flow across numerous microchannels. The production of microstructured reactors also entails high costs, which must be justified by the improved reactor performance. In order to minimize the manufacturing expense, the structures used should be designed to be as fine as necessary but as coarse as possible.

Hybridization of the chemical reaction with separation units can open up synergies for both processes, as in the case of reactive distillation: Removal of a (by-) product from the reaction mixture allows to overcome conversion restrictions due to chemical equilibrium, while a reaction can circumvent formation of an azeotropic mixture. In principle, every separation operation can be integrated with a reaction in a multifunctional device. Reactive absorption is, for example, a mature technology for numerous gas purification processes and synthesis reactions. Reactive distillation is also commercially well-established for certain applications.

Chromatographic and membrane reactors have been researched extensively for decades and are already used technically in niche applications. From the perspective of the reaction engineer, the integration of additional unit operations offers a very useful tool for manipulating the concentration and temperature profiles in the reactor. However, the harmonization between the reaction and the separation process usually requires compromises, which can lead to sub-optimal operation of the individual processes, sacrificing degrees of freedom, or completely preventing a meaningful integration (see Fig. 5.9).

In the case of reactive distillation, special packings are required in order to meet the conflicting requirements of both processes with respect to residence time and interfacial area.

The macro- and microstructuring of the various functionalities in the reactor has proved to be a particularly effective means for resolving possible contradictions, rather than a simple unstructured combination. Catalytic packings can usually be expediently used in certain sections of reactive distillation columns, whereas in the other sections only distillation without reaction takes place. Identifying the optimum degree of integration and the possibilities for implementation are major challenges in the design of multifunctional reactors.

Local structuring of the reaction space of a solid catalyst often offer extensive potential for improving reactor operation. Thus, by diluting the catalyst in the region of the hot spot, a better harmonization between the reactive heat generation and heat removal by reactor cooling can be achieved. Owing to a non-uniform distribution of the catalytic activity in the catalyst core, deactivation phenomena can be retarded. Novel catalyst structures, such as catalytic sponges (see Figure 5.10), permit a deliberate adjustment of mass and heat transfer characteristics with low pressure loss. Although the optimization task appears to be very complex in structuring measures, it often leads to simple asymptotic solutions.

The dynamic operation of the reactor can be interpreted as a temporal structuring of the reaction regime and is by no means an unknown approach in conventional reactor technology, for example in semi-batch reactor processes. How-

ever, dynamic reactor operation must not interfere with the steady-state operation of the remaining plant items. By periodically modulating the liquid feed into a trickle-bed reactor, the accessibility of the catalyst surface for the gas phase, and thus the conversion rate, can be significantly enhanced. Similar advantages can be gained by using a rotating liquid distributor. Pressure pulsation can significantly accelerate diffusive transport processes by convective contributions. Furthermore, cyclic reactor regime utilizes storage effects and can thus provide temperature and concentration conditions which cannot be achieved in steady-state operation, as in the case of the reverse-flow reactor for oxidative waste gas treatment. The accurate manipulation of the concentration and temperature profiles in microreactors should facilitate the technical implementation of dynamic operations.

Novel reaction media, such as supercritical fluids and ionic liquids, enable a made-to-measure design of the reaction environment, a targeted influence on the activities of individual reaction partners and improved transport properties compared to conventional reaction systems. In addition, they often offer environmental benefits over conventional organic solvents. On the other hand, they are usually more expensive and can involve costly equipment, e.g. due to high pressure operation. So-called “rich” operation modes without inert diluents or solvents are regarded as promising, albeit ambitious, reaction technology targets, which could significantly reduce the extent of downstream processing. However, issues of safety engineering or product quality have to be clarified in advance.

For alternative energy supplies, plasma reactors are state-of-the-art for acetylene production. The volumetric energy input by means of microwaves or shear forces does not require temperature gradients and is therefore particularly suitable for temperature-sensitive liquids and solids. The use of ultrasound is especially appropriate for mass-transfer limited reactions or for heterogeneous catalysis because the reactive surface can be kept fresh by cavitation. Such unconventional energy forms are, of course, complex, and the uniform energy input on a larger scale is regarded as problematic. By means of centrifugal fields, a countercurrent flow of two fluids can be achieved, even in very finely structured packings, which may help overcome a significant shortcoming of microreactor technology.

Process intensification measures often complement one another, but this considerably increases the complexity of reaction management or reactor design. The use of continuous instead of batch operation at relatively low production capacities, as well as fast and flexible reaction management according to the market demand by process intensification techniques, can effectively achieve a rationalization of the entire production chain. Furthermore, process intensification opens up new horizons for direct synthesis and local process monitoring and control.

While many of these process intensification measures have been successfully demonstrated in research projects, the task now is to exploit these findings and results in industrial processes. For this purpose, it is necessary to evaluate the various options for process intensification even in an early

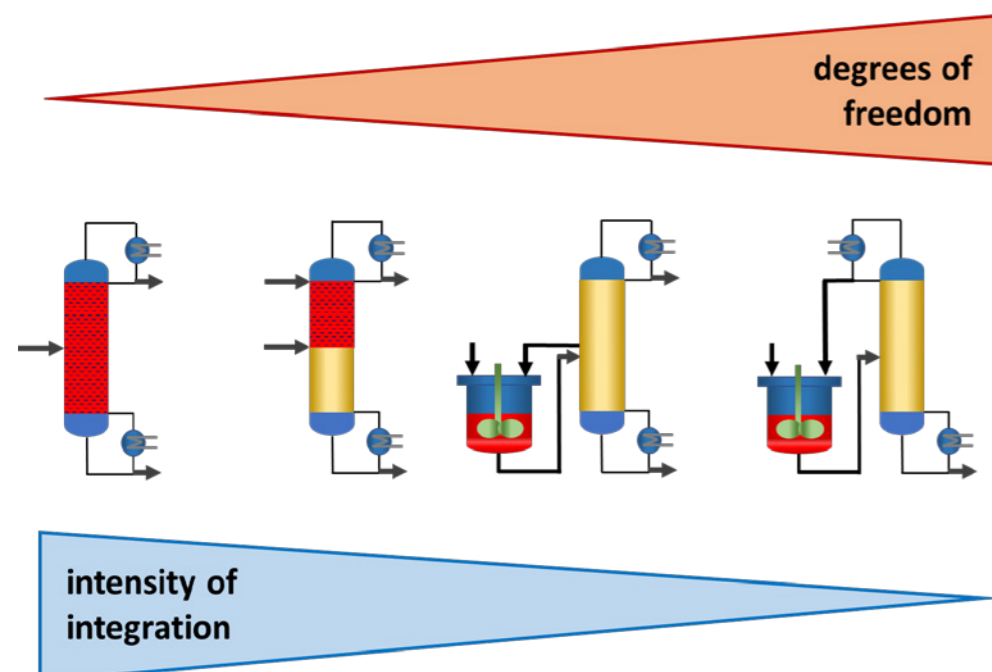


Figure 5.9: Degree of freedom vs. integration level of multifunctional reactors. (Source: Chair of Process Systems Engineering, Otto-von-Guericke University Magdeburg).

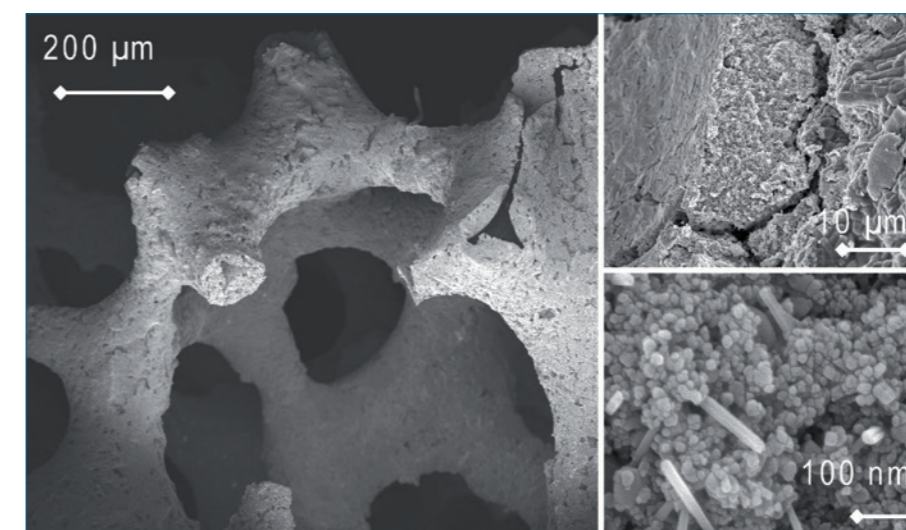


Figure 5.10: Ceramic sponge impregnated with SCR catalyst (left: sponge structure, top right: catalyst layer, bottom right: TiO_2 (spherical particles) and V_2O_5 (needles)). (source: Engler-Bunte-Institute, Karlsruhe Institute of Technology (KIT)).

phase of process development and to benchmark them economically against standard designs. This should include the increased effort for process and equipment development. To get from the current approach based on specific examples to a generalizable model-based methodology, however, further specialized fundamentals are required. The goal is to place the process intensification on a theoretically sound footing and to evaluate the suitability of process intensification measures by means of systems-analytical methods in the integrated plant environment.

Research needs:

1. Methodology for integrating process intensification measures in process synthesis and process development
2. Tools for the economic evaluation of process intensification measures.
3. Development of reliable parallelization strategies for microreactor technology.
4. Development of a corresponding micro-process technology to supplement microreactor technology.
5. Development of systematic approaches for the spatial and temporal structuring of different functionalities in the reaction zone.

E SYSTEMS ENGINEERING APPROACHES FOR REACTOR ANALYSIS, OPERATION AND CONTROL

Reactor analysis in a process-wide context

Each chemical reactor is embedded in a complex chemical production process, consisting of many other process units, such as separators, mixers, heat exchangers and compressors (see Fig. 5.11). Thus, the reactor cannot be designed, analyzed and optimized as an isolated component, but should be considered as a unit which is linked by many functional connections to the overall production system. The reactor communicates with the other process units via mass and energy fluxes. In particular, the reactor output defines the inlet conditions of the subsequent downstream processes. Non-converted reactants must be separated in the downstream process section and recycled back to the reactor. Recycle loops may enrich the levels of undesired by-products in the process, which can lead to severe operation-

al problems both in the reactor itself and other parts of the plant. It is thus imperative to analyze the reactor-separator-recycle systems rather than just the stand-alone reactors. In some cases, recycling of intermediates formed during the reaction can have a positive effect on productivity and selectivity. Analyzing the reactor-separator-recycle is also very important, as the effort for separating the reactor outlet mixture depends on its composition. In particular, the existence of azeotropic mixtures makes vapor/liquid separations difficult and thus must be considered carefully before stipulating the reactor performance. Furthermore, the thermal management of the reactor and its thermal integration with the downstream separation processes require a systems perspective, particularly with respect to the optimal design of the heat exchange network. The temperature and pressure levels of all units, including the reactor, must be set optimally, in order to maximize the energetic efficiency of the process as a whole. In doing so, not only performance indices, but also process-wide safety aspects must be taken into account. In the future, the electrification of heating and reuse of waste heat by heat pumps will become increasingly important in green- and brownfield sites.

Reactor operation and control

In the first step, the evaluation of the reactor performance within a chemical production process is often primarily based on the conversion-selectivity characteristics and the catalyst aging profile. However, for the rapid modification of production targets to market dynamics, load changes occur more frequently than in classical continuous reactor operation. Hence, the operational flexibility becomes an additional performance criterion in reactor optimization. The stability of temporary steady-state operational points, trajectory planning for load changes and real-time optimization are also aspects of increasing significance. Advanced control strategies have to be developed and implemented for industrially relevant reactors. To contribute effectively to enhanced process performance, these control strategies should be fed with a large amount of in situ operational data with reasonably high resolutions in time and space. Such data can be harvested via modern sensor networks installed in chemical reactors and other process units. This is part of the Process Industry 4.0 scenario, in which data-driven process control and operation is of paramount importance for smart chemical production. It is foreseeable that networks of decentralized processes and various production sites of different enterprises will communicate with one other via

the Internet of Things. This will lead to a qualitatively higher complexity of chemical production networks that can only be handled with the help of new data-driven computer models. Such models must be rapidly calibrated in real-time and used very flexibly for optimal process operation and control.

Research needs:

1. Advanced methods for model-based reactor analysis and optimization within process systems, accounting for performance, flexibility, parametric sensitivity and uncertainties.
2. Methods and tools for the operation and control of continuous reactors for frequent load changes and under dynamic conditions for use of fluctuating renewable energies and bio-based feedstocks with variable composition.
3. Data-driven approaches and tools for optimal operation and control using advanced sensor technologies.

F ELECTRIFICATION OF CHEMICAL PROCESSES

Elimination of greenhouse gas emissions is currently changing the chemical industry profoundly, leading to the replacement of fossil raw materials by biomass, recycled streams and carbon dioxide as well as the use of renewable power sources.

The first two alternative feedstocks are (today) characterized by a more diverse composition and physical properties together with a higher level of impurities [4, 5] compared to conventional feedstock. In principle, one can either refine the feedstocks by pretreatment or design more resilient processes, or even combine these strategies. From a chemical engineering point, the design principles remain unchanged and only the optimization criteria change.

Replacing fossil energy for heating by green power has a significant effect on process and equipment design. On the one hand, new design challenges have to be resolved, e.g. proper electrical insulation to prevent dangerous short-circuiting. On the other hand, electric power offers new degrees of freedom, such as heating to any temperature with

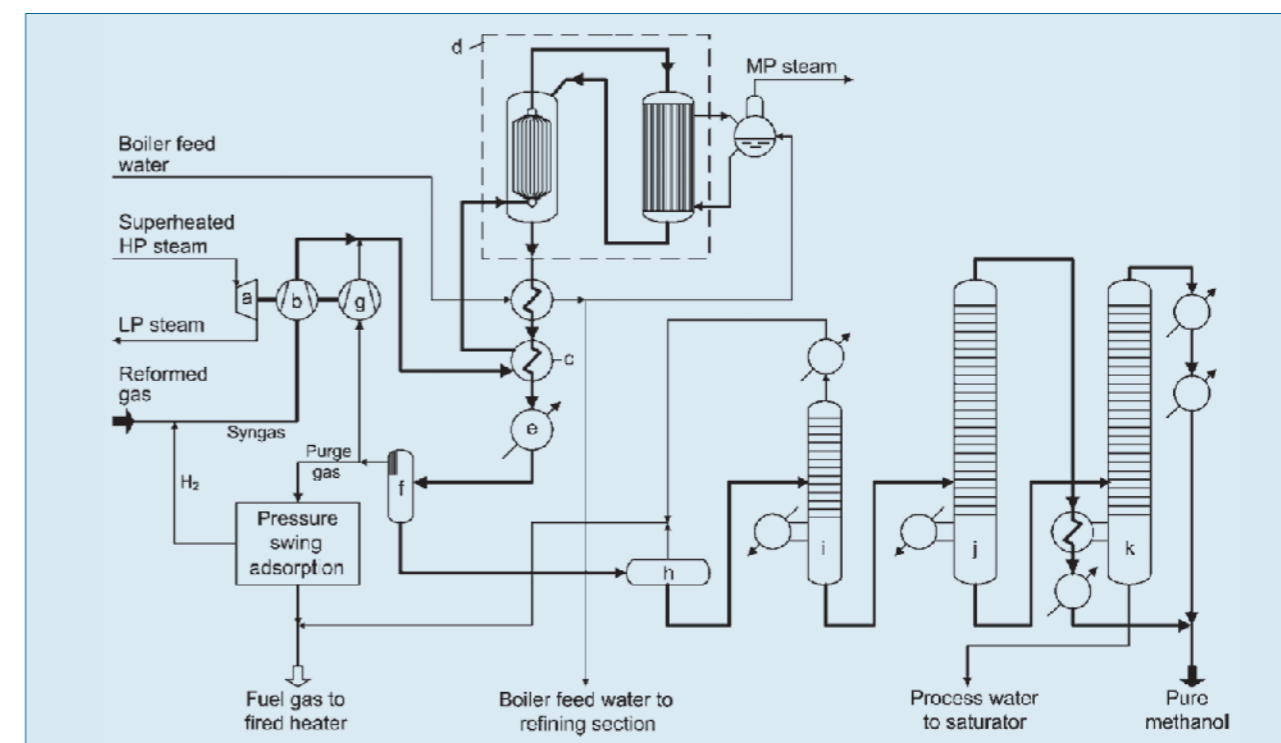


Figure 5.11: Flowsheet of the Lurgi MegaMethanol production process system. The two-stage reactor section has multiple interactions via the mass and energy fluxes to and from the feed pretreatment section and the downstream separation section. a) Turbine for synthesis gas and recycle compressor; b) synthesis gas compressor; c) trim heater; d) combined converter system; e) final cooler; f) methanol separator; g) recycle gas compressor; h) expansion vessel; i) light ends column; j) pure methanol pressurized column; k) atmospheric methanol column. (Reprint from Ullmann's Encyclopedia of Industrial Chemistry, 2012, with permission by Wiley-VCH, Weinheim).

no additional cost from a thermodynamic point of view, or the potential to overcome heat transfer limitations at surfaces by volumetric heating.

Electric heating can be implemented in four ways, all of which are being employed in current developments:

- » Indirect ohmic heating (current through heating elements with no direct contact to reaction space)
- » Direct ohmic heating of reaction space (see Fig. 5.12)
- » Inductive heating (see Fig. 5.13)
- » Microwave heating

By far the biggest and most important emerging electrified process is water electrolysis. Apart from this, organic electrochemistry and photochemistry represent further options for electrification of chemical processes, for which a growing role can be expected.

Indirect ohmic heating

Indirect ohmic heating aims to replace the combustion burners in conventionally heated processes by electrical heaters [6, 7]. The design of the reaction pathway and the reaction conditions will at first mirror the conventional mode of operation. This approach can, however, only be a stopgap introduction to electrification, in order to achieve the fastest possible reduction in greenhouse gas emissions. A direct benefit of electrical over conventional reactor heating is the elimination of the fuel-flue gas circulation and its associated energy losses. On the other hand, problems such as the supply and distribution of large amounts of electrical power, the electrical insulation of the heating section, the configuration and mounting of the heating elements, the control of the heating power and above all the operating conditions have to be solved. However, the potential of electrical energy to optimize reactor energy efficiency and operating behavior has so far barely been exploited. The savings in greenhouse gas emissions will be obtained at the price of higher costs.

Direct ohmic heating

Direct resistive heating of the reaction chamber has the potential to overcome the critical heat transfer limitations in endothermic reactions [8]. As a result, purely endothermic reactions can be realized with heat input and reaction rates that, in conventional processes, are only attainable by coupling with exothermic oxidation reactions. Reactor concepts with direct electrical heating can thus also be considered as alternatives to oxidative dehydrogenation or autothermal reforming processes, where the heat of reaction for endothermic reactions is generated by a simultaneous combustion reaction [9]. There are several inherent advantages associated with this principle:

1. Superior product yields can be realized. As a side-effect, considerable cost savings in product treatment are possible, e.g. for product separation and in raw material recovery.
2. Oxygen can be eliminated from the reaction system. This would have considerable advantages for both the product composition and for process safety.

Nevertheless, the implementation of these concepts requires a radical change in reactor design. In the periphery of the reaction section, a rapid heating of the feed streams and – more importantly – the quenching of the product streams is essential. This must be accomplished with a highly efficient heat integration. Furthermore, electrically conductive resistance elements must be integrated into the reaction section. These can be separate heating elements or multifunctional internals or packings that function both as chemical contactors and electrical resistors. Conductive ceramic composites provide a potential method for direct electric heating of reactors either in the form of honeycomb structures or multitubular reactors (see Figure 5.12). Ceramic materials are well-known for their high thermal stability, chemical passivity, corrosion resistance and coatability with catalytically active materials [10]. Problems such as the uniform connection of the electrical resistances with low contact losses, the regenerability and exchangeability of the catalyst, or the insulating bushing for electric power supply through pressure-bearing reactor walls must still be resolved. In addition, the interaction between the reaction and the electrical properties of the reaction section, in particular the electrical resistance, must be ascertained and regulated. Accordingly, the implementation of this concept requires developments in the following areas:

- » Reactor design suitable for highly efficient heat integration,
- » multifunctional materials as reactor internals, catalysts or catalyst carriers, additionally featuring a well-defined electrical conductivity,
- » adaptation of the catalysts to the modified reaction conditions without oxygen,
- » apparatus concepts for the introduction and distribution of the electric current in the reaction system,
- » adaptation of the materials for the internals and the housing of the reaction chamber to the pertinent reaction conditions. The applicability of previously proven materials must be reassessed. On the other hand, the use of refractory materials can be considered, which might not be feasible in conventional reactors due to their susceptibility to oxidation. In addition, electrically insulating materials must be integrated into the pressure-bearing reactor shell.
- » The determination of the specific ohmic resistance in the reaction section as a function of the packaging structure and the reaction conditions. In particular, correlations must be established for the effective ohmic resistance of randomly packed electrically conductive particles and for the contact between the packing and the electrodes. The interactions of these parameters with the reaction and their influence on the heat distribution over the reaction chamber must be analyzed and controlled.

The implementation of direct ohmic reactor heating offers the possibility of carrying out endothermic high-temperature reactions with high energy efficiencies and yields. This opens up the perspective of a significant improvement in energy efficiency and thus cost-effectiveness of these processes compared to the current state-of-the-art, in addition to significantly reduced greenhouse gas emissions [9,11].

Inductive and microwave heating

The heating of reactions through electromagnetic radiation, i.e. inductively, via radio frequencies or via microwaves – depending on the wavelength – can be considered as a further variant of direct electrical heating [12]. On the other hand, the often postulated catalytic effects of electromagnetic radiation are – if at all – of subordinate significance. The motivation for heating electromagnetically is linked to its potential to supply electrical energy without contact into the reaction space, eliminating the problems associated with the introduction and distribution of electrical energy, as well as catalyst handling mentioned in connection with direct ohmic heating. The implementation of these concepts requires suitable materials in the reaction chamber as susceptors for the electromagnetic radiation. Another essential prerequisite is a “transparent” shell of the reaction chamber [13,14]. This necessitates – especially for high-temperature reactions – the use of ceramic materials. Beside the development needs identified in connection with direct ohmic heating, the implementation of contactless electromagnetic energy input premises the following development steps:

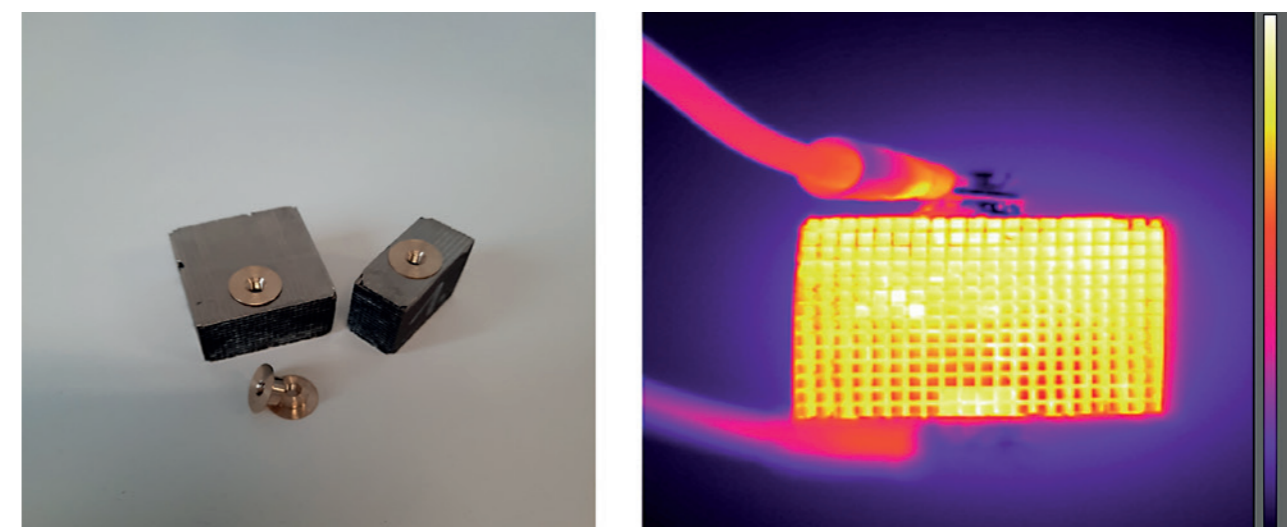


Figure 5.12: Conductive ceramic monolith samples with connection sockets (left), sample during electrical heat-up experiment (right) (source: MCI Innsbruck).

1. The determination and optimization of the absorption properties of the internals or the containment of the reaction chamber for electromagnetic radiation in conjunction with the development of novel structures and materials with specially tailored properties.
2. The modeling of the heat distribution induced and its interaction with the chemical reactions. The focus will be on a stability analysis in order to identify critical parameter constellations that might lead to hotspots, runaway, susceptibility or oscillating operating states.
3. The development of suitable scaling principles to adapt these heating concepts to the required production capacity of the processes. Especially in the case of microwave heating, modular concepts should be considered.

Water electrolysis

Water electrolysis will be a key future technology for transforming renewable electrical power into chemical energy. Hydrogen will play a decisive role, not only as a reactant for the chemical and the steel industries, but also as a versatile fuel and long-term energy storage medium at the terawatt-hour scale. Electricity can be conveniently and reasonably efficiently retrieved from hydrogen by means of a fuel cell. Thus, these two electrochemical technologies are central to this sustainable hydrogen cycle.

Water electrolyzers are typically stacked, plate-type millistructured reactors with up to several hundreds of individual modular cells consisting of electrodes and separators [15,16]. High-temperature (solid oxide) electrolysis (SOEL) is

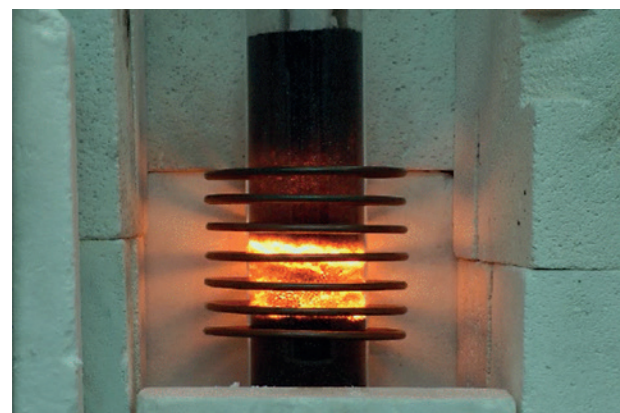


Figure 5.13: Laboratory experiment on methane pyrolysis in an inductively heated reaction section. (Source: VDEh-Betriebsforschungsinstitut GmbH, 2017).

operated with water vapor in a gas phase process. On the other hand, the two commercially available low-temperature electrolysis process variants (i.e. polymer electrolyte membrane, PEMEL, and liquid alkaline, AEL) are characterized by highly complex multiphase interactions between gases, liquids and solid structures (e.g. electrocatalysts, transport layers and ion conducting polymers). In these multiphase systems, only a thorough understanding of the nexus between transport phenomena and resulting electrochemical performance allows to achieve greatly increased efficiencies and space-time yields [17]. Although several commercial solutions are already available at the megawatt scale, further research and development effort is required to enhance the efficiency of water electrolyzers and to cut the investment costs significantly:

- » Development of diagnostic tools for monitoring concentration and potential distributions as well as multiphase-flow for both laboratory and technical electrolyzers.
- » Multiphysics modeling of reaction and transport phenomena in transport channels, porous electrodes and separators at the single cell level.
- » Development of stack models to minimize losses induced by flow maldistribution and stray currents.
- » Strategies for dynamic operation of electrolyzers directly coupled to fluctuating renewable energy sources taking safety aspects (gas contamination) into account.

Photoreactors

Initiating reactions with light gives access to reaction routes that are not accessible by conventional, thermally driven ground state chemistry. In recent years, the increasing availability of efficient high power LED light sources together with micro- and millistructured photoreactors has led to growing research activities towards industrially relevant photoreactions and the development of photoreactors [18-20]. The intrinsic electrification of light-driven reactions makes photochemistry a promising option to create chemical value chains based on green electricity. Despite this, the potential of light-based chemical manufacture has barely been exploited to date.

Photoreactions are characterized by a strong interaction between the radiation field and the transport processes in the

participating media, which significantly increases the parameter space that governs both activity and efficiency [21].

A particular characteristic of photoreactions is the steep gradient of the reaction rate along the beam trajectory in the reaction system. To deliver high-performance photoreactors, mass and heat transport have to be tuned to make allowance for this gradient of reaction rate [22] (see Figure 5.14). Providing photons efficiently to the reactants under various reaction conditions is crucial for energy efficient industrial implementation, which also requires the development of photoreactors that can be scaled [23-25]. Furthermore, a thorough consideration of the properties of the available light sources in terms of geometry, emission properties, electrical power consumption and heat generation is necessary. The scale-up of photoreactors is one of the major hurdles that have to be overcome on the road to industrial application. To establish large-scale photochemical production processes, advances in the following fields are required:



Figure 5.14: Modular miniplant photoreactor MISCOP developed by Ulm University and Peschl Ultraviolet GmbH equipped with static mixers for enhanced mass transport to improve reaction performance.

- » Development of photoreactors that are adapted to multiphase reaction systems, i.e. gas/liquid or gas/liquid/solid systems,
- » development and verification of scale-up strategies,
- » development of high-power light sources up to the MW range,
- » investigations of the potential of dynamic irradiation,
- » multiphysics modeling incorporating the (transient) radiation field,
- » development of safety concepts appropriate for high power light sources, and
- » development of experimental methods to screen large parameter spaces efficiently, including spectral and temporal changes of the radiation field, to identify optimal reaction conditions.

Research needs:

1. Develop scalable concepts and designs for electrothermal reactors, featuring well-defined heating profiles and highly efficient heat integration.
2. Develop multifunctional catalysts or catalyst carriers with material properties and geometrical structures adapted to the requirements of electrothermal operation.
3. Develop models to describe the dynamics caused by nonlinear interaction between electrothermal activation and chemical reactions, which help to identify controllable operating conditions.
4. Tuning of material properties and spatial control of heating power for inductive or microwave heating.
5. Develop materials and components for electrical insulation
6. Develop robust methods for large scale water electrolysis together with corresponding materials for electrodes and strategies for operation under fluctuating supply of renewable energy.
7. Deepen the reaction engineering knowledge about electro- and photochemical reactions and processes.
8. Develop high-performance reactor designs together with efficient scale-up strategies for electro- and photochemical reactions and transfer them into applications.
9. Adapt catalysts to the modified reaction conditions.

REFERENCES

- [1] Bird, R.B., Stewart, W.E., Lightfoot, E.N., Transport Phenomena, 2. Edition, Wiley, New York, 2007.
- [2] <https://ineratec.de/technologien/>
- [3] Journal of Loss Prevention in the Process Industries 72 (2021) 104494.
- [4] Tursi, A. (2019). A review on biomass: importance, chemistry, classification and conversion. *Biofuel Research Journal*, 6(2), 962.
- [5] Jiang, J. et al. (2022). From plastic waste to wealth using chemical recycling: A review. *Journal of Environmental Chemical Engineering*, 10(1), 106867.
- [6] Eder, K. (2015). Device and method for heating a fluid in a pipeline by means of three-phase current. PCT-application No. WO2015/197181A1.
- [7] Kochendoerfer, K.A.; Jenne, E.; Shustov, A. (2021). Electrically heated, hybrid high-temperature method. PCT-application No. WO2022/069711A1.
- [8] Appel, H. et al. (2019). Device packed with solid material for performing endothermic reactions with direct electrical heating. PCT-application No. WO2019/145279A1.
- [9] S. T. Wisman et al. *Science*, 2019, 364(6442), 756–759. doi: 10.1126/science.aaw8775.
- [10] E. Klemm, C. M. S. Lobo, A. Löwe, et al. CHEMampere: Technologies for sustainable chemical production with renewable electricity and CO₂, N₂, O₂, and H₂O. *The Canadian Journal of Chemical Engineering*, 2022, DOI: 10.1002/cjce.24397.
- [11] M. Ambrosetti, A. Beretta, G. Groppi, E. Tronconi, A Numerical Investigation of Electrically-Heated Methane Steam Reforming Over Structured Catalysts. *Front. Chem. Eng.*, 2021, 3:747636. doi: 10.3389/fceng.2021.747636
- [12] Kuhwald, C.; Tuerkhan, S.; Kirsching, A. (2022). Inductive heating and flow chemistry – a perfect synergy of emerging enabling technologies. *Beilstein Journal of Organic Chemistry*, 18(1), 688-706.
- [13] M. G. Vinum et al. *Angewandte Chemie International Edition*, 2018, 57(33), 10569–10573. doi: <https://doi.org/10.1002/anie.201804832>
- [14] H. M. Nguyen et al. *Applied Catalysis A: General*, 2020, 599. doi: <https://doi.org/10.1016/j.apcata.2020.117620>.
- [15] *Electrochemical Power Sources: Fundamentals, Systems, and Applications. Hydrogen Production by Water Electrolysis*, Tom Smolinka, Jürgen Garcke (Eds.), Elsevier 2021, ISBN: 9780128194249
- [16] Chatenet M. et al. (2022). Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments, *Chem. Soc. Rev.*, 51, 4583. DOI 10.1039/docso1079k
- [17] Etzold, B.J.M.; Krewer, U.; Thiele, S.; Dreizler, A.; Klemm, E.; Turek, T., Understanding the Activity Transport Nexus in water and CO₂ electrolysis: State of the art, challenges and perspectives, *Chemical Engineering Journal* 424 (2021) 130501, <https://doi.org/10.1016/j.cej.2021.130501>
- [18] M. Sender & D. Ziegenbalg, *Light Sources for Photochemical Processes – Estimation of Technological Potentials Chemie Ingenieur Technik*, Wiley-Blackwell, 2017, 89, 1159-1173, DOI: 10.1002/cite.201600191
- [19] L. Buglioni, F. Raymenants, A. Slattery, S. D. A. Zondag & T. Noël, *Technological Innovations in Photochemistry for Organic Synthesis: Flow Chemistry, High-Throughput Experimentation, Scale-up, and Photoelectrochemistry Chemical Reviews*, American Chemical Society, 2021, DOI: 10.1021/acs.chemrev.1c00332
- [20] B. O. Burek, A. Sutor, D. W. Bahnemann & J. Z. Bloh, Completely integrated wirelessly-powered photocatalyst-coated spheres as a novel means to perform heterogeneous photocatalytic reactions *Catalysis Science & Technology*, The Royal Society of Chemistry, 2017, 7, 4977-4983, DOI: 10.1039/C7CY01537B
- [21] D. Ziegenbalg, A. Pannwitz, S. Rau, B. Dietzek & C. Streb, Comparative Evaluation of Light-Driven Catalysis: A Framework for Standardized Reporting of Data *Angew. Chem. Int. Ed.*, 2022, 61, e202114106, DOI: 10.1002/anie.202114106
- [22] Z. Dong, Z. Wen, F. Zhao, S. Kuhn & T. Noël, Scale-up of micro- and milli-reactors: An overview of strategies, design principles and applications *Chemical Engineering Science: X*, 2021, 10, 100097, DOI: 10.1016/j.cesx.2021.100097
- [23] M. Sezen-Edmonds, J. E. Tabora, B. M. Cohen, S. Zaretsky, E. M. Simmons, T. C. Sherwood & A. Ramirez, Predicting Performance of Photochemical Transformations for Scaling Up in Different Platforms by Combining High-Throughput Experimentation with Computational Modeling *Organic Process Research & Development*, American Chemical Society, 2020, 24, 2128-2138, DOI: 10.1021/acs.oprd.0c00182
- [24] A. A. Bayly, B. R. McDonald, M. Mrksich & K. A. Scheidt, High-throughput photocapture approach for reaction discovery, *Proceedings of the National Academy of Sciences*, National Academy of Sciences, 2020, 117, 13261-13266 DOI: 10.1073/pnas.2003347117
- [25] F. Levesque, M. J. Di Maso, K. Narsimhan, M. K. Wismer & J. R. Naber Design of a Kilogram Scale, Plug Flow Photoreactor Enabled by High Power LEDs, *Organic Process Research & Development*, American Chemical Society (ACS), 2020, 24, 2935-2940, DOI: 10.1021/acs.oprd.0c00373

6 Case Studies

The following case studies were chosen to address research topics that are currently hot topics and illustrate the importance of the contributions of chemical reaction engineering. The first two case studies are devoted to high temperature processes, ceramic reactors for highly endothermic reactions on the one hand and thermolysis of plastic waste streams on the other hand. The following two case studies address the CO₂ utilization by dry reforming and CO₂ electrolysis. CO₂ utilization comprises also usually high temperature reactions. However, CO₂ electrolysis can also be carried out under mild conditions as shown in the corresponding case study. Last but not least, the last two case studies demonstrate the role of chemical reaction engineering for producing speciality chemicals, either high performance polymers or pharmaceutical active ingredients.

CASE STUDY 1:
HIGH TEMPERATURE PROCESSES

Background

Highly endothermic equilibrium syntheses such as reverse water-gas shift reaction, steam reforming or dry reforming require the addition of large amounts of heat and economic conversions can only be achieved at very high temperatures. The state-of-the-art is to carry out such processes in metallic tubes with internal flow, to which heat is supplied by a combustion reaction in the external space. The maximum temperature in the reaction chamber is limited to approximately 900 °C. The energy of the outflowing hot flue gases is used to heat the feed gas and to generate steam (usually at 15 bar, i.e. 200 °C). The energy demand of the chemical reaction is supplied by burning fossil fuels which comes with a tremendous corresponding CO₂ emission.

Today's reactor materials in high-temperature synthesis generally consist of elaborately manufactured stainless steel tubes. The operation of such reactors is limited to approx. 900 °C, due to the mechanical resistance of the tubes. In addition, metallic tubes are chemically attacked by carburization, by hydrogen embrittlement [1, 2] and by so-called metal dusting [3]. Conversely, the reactor wall may catalyze undesirable reactions, such as hydrocarbon decomposition to carbon, which is then deposited as a coke layer on the inner wall of the tube. To avoid the disadvantages imposed by metallic reactor material one approach is to replace it by ceramic materials.

Contribution of Chemical Reaction Engineering

There are three main challenges in applying ceramic materials where reaction engineering can contribute. Firstly, ceramic materials are brittle and thus sensitive to thermal

stress. Secondly, electrical heating must be employed in the high temperature range. Thirdly, electrical heating is only economic, if the reactors are highly thermally integrated.

Ceramic reactor material

The advantages of ceramic materials, especially oxide ceramics, include high temperature resistance, chemical passivity, high corrosion resistance and high strength. The main disadvantage of monolithic ceramic materials is high brittleness. Thermal stress often results in brittle failure, which is not acceptable in industrial reactors.

The application of newly developed oxidic fiber ceramics (OCMC – Oxide Ceramic Matrix Compound) allows to improve the fracture behavior considerably. For this purpose, the inner dense ceramic tubes are wrapped by multiple OCMC layers. During the kilning process the OCMC layer shrinks and applies a compressive stress on the inner tube, which considerably improves its resistance to thermal stress. The newly developed layered ceramics even withstand exposure to the flame of a cutting torch without brittle failure. Although this is encouraging, studies on long-term behavior are still lacking.

Electrical heating

Initial attempts have been conducted to apply resistive heating in reactor design [4]. Direct resistive heating of the reactor tubes would seem to offer a simple solution but must be rejected due to their high electric conductivity. Metallic heating elements thus need very low cross-sectional areas. First experiments have shown that embedding of a thin foil of metal in corrugated form between the inner tube and the outer OCMC layer allows the layered reactor tubes to be heated up to 1250 °C, see Figure 6.1 left [5, 6]. The mechanical stability of the metallic material, which normally delaminates at high temperatures, is ensured by compressive stress build-up due to the outer OCMC layer during sinter-

ing. The ceramic material serves as an insulator and protects the metal layer from direct exposure to reaction gases. Nevertheless, the OCMC ceramic layer is porous and thus the long-term stability must still be investigated. Application of protective coatings to the metal layer might be necessary. Close cooperation with material scientists is a prerequisite for further advances in this field.

Reactor concept with heat integration

Chemical reactions at high temperatures and with high energy supply can only be carried out economically if the heat of the product gas can be recovered by preheating the feed gas. This can be achieved by counter-current flow of the feed and product gases for maximized heat transfer. Intense counter-current heat exchange allows to maintain the in- and outflow to and from the reactor at low temperature levels and thus to use standard sealing techniques to connect the ceramic reactor material with metallic flow distributors. 3D printed gas distributors permit the introduction of feed gas and withdrawal of product gas in close vicinity to one another.

In Figure 6.1 (right) a case study is shown in which the reactor consists of an OCMC tube with an electrically heatable end section. Internally coating the heated section with catalysts ensures that the reaction takes place at the desired location.

On the inside of the tube, the temperature of the feed gas rises almost linearly before it reaches the catalytically active and electrically heated section of the OCMC tube. Here, a strongly endothermic reaction (e.g. the reforming of methane) takes place, causing a temperature drop in the tube wall. The gas flow is reversed at the end of the reactor tube and the hot product gas is cooled by heat exchange with the feed.

This case study shows that even with this straightforward construction the endothermic reaction can be sustained at high temperatures with a minimum of electric energy. Constructions with smaller channels and better heat transfer in addition to optimized structurization of heatable and catalytically active segments are able to create reaction conditions which provide high conversions and prevent side-reactions (e.g. coke formation).

The case study illustrates how an elaborate concept (heat integration) may be adapted to new challenges, such as electric heating. Close cooperation between materials scientists and appropriate modification of new material are a prerequisite for successful further developments.

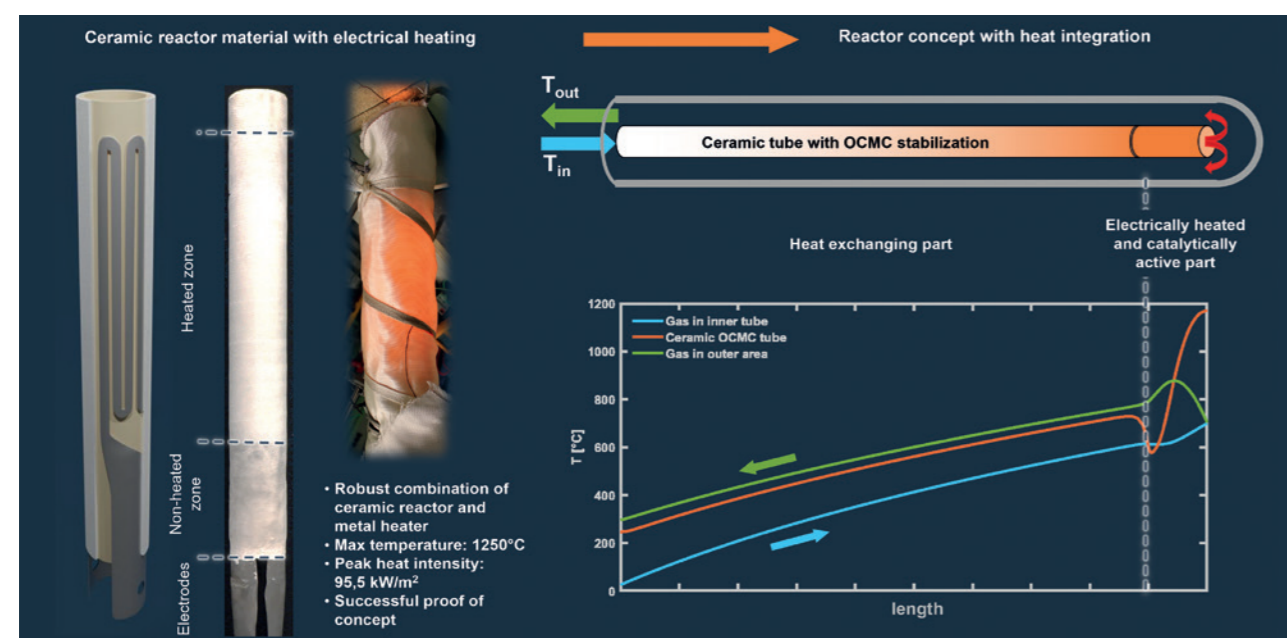


Figure 6.1: Combination of electrically heated ceramic tubes and a heat regenerative reactor concept (source: University of Stuttgart).

REFERENCES

- [1] S. Moran and H. Gräfen, "Construction Materials in the Chemical Industry" in Ullmann's Encyclopedia of Industrial Chemistry, Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA, pp. 1–49, 2016.
- [2] H. K. Birnbaum, "Hydrogen Embrittlement" *Enycl. Mater. Sci. Technol.*, pp. 3887–3889, Jan. 2001, doi: 10.1016/B0-08-043152-6/00690-2.
- [3] H. J. Grabke, R. Krajak, and E. M. Muller-Loren, "Metal dusting of high temperature alloys, Metal dusting" von Hochtemperaturlegierungen," vol. 97, pp. 89–97, 1993, doi: 10.1002/maco.19930440306.
- [4] Kunz, Ulrich; Turek, Thomas (2009): Flow through reactors for organic chemistry: directly electrically heated tubular mini reactors as an enabling technology for organic synthesis.
- [5] Kolios, Grigorios et al.: GASDICHTES, WÄRMEDURCHLÄSSIGES, KERAMISCHES UND MEHRLAGIGES VERBUNDROHR, Offenlegungsnummer: EP 3 835 639 A1
- [6] Kolios, Grigorios et al.: Gas-tight, heat-permeable, multilayer ceramic composite tube, Patent-Nr: US 10,865,151 B2

CASE STUDY 2: PYROLYSIS OF PLASTIC WASTE STREAMS

Background

Modern societies rely on a continuous stream of virgin plastic materials for a vast number of applications [1], which may involve long or short product life spans, as in construction or food packaging, respectively. At the same time, a waste stream is generated that can only partially meet the material and/or legal criteria for reutilization. Hygiene restrictions for foodstuffs, for example, prohibit the direct reuse of plastic containers. Avoiding the creation of (plastic) waste in the first place is, of course, expedient [2]; however, this is not always an easy option, as the application is usually associated with a specific function, as for example with packaging [3], for which plastic may often be the best choice in terms of the impact on the ecosystem [4, 5]. The reuse of small selected fractions of high quality waste plastic and "down-cycling" of the rest will fail to meet the legally required material recycling quota [6–8]. Larger polymer containing waste streams, even after sorting [9] and washing, still have a certain complexity in terms of polymer types, fillers and processing agents, stabilizing additives, inks, dyestuffs and other components used to enhance the performance and attractiveness of the products. This complexity can be reduced with the help of pyrolysis, i.e. thermal conversion in the absence of oxygen [10]. Thermolysis yields a product range comprised of solids (waxes), oils and gas, depending on the reaction conditions and waste source.

The decomposition back to monomers is usually the next best option for the material recycling of polymer, although the primary resources necessary for waste collection, transport, sorting, cleaning and thermal conversion and yield must be taken into consideration. The direct formation of monomers from sorted (homo)polymers may well be the material reutilization process with the smallest environmental footprint (Figure 6.2) [3, 11].

A breakdown to chemicals of lower complexity, such as syngas (using oxygen) or naphtha-like streams entails greater effort that will be necessary to reassemble the monomers. Such an indiscriminate decomposition may, however, be unavoidable for inseparable polymer mixtures, such as laminated film, or where the depolymerization to monomer is not very selective. The latter situation applies to many thermosets, but also to polyethylene, a polymer that can be prepared from any linear olefin, and in which the "information content" (the signature of the monomer) in the polymer backbone bears no trace of its synthetic history [12]. This is less true for polypropylene and not at all for polystyrene, from which the monomer can be regenerated easily [13]. Next to polymethyl methacrylate [14], a polymer extensively used in corona countermeasure products, the depolymerization of polystyrene to styrene is a typical objective for a consolidated recycling loop [12, 15, 16].

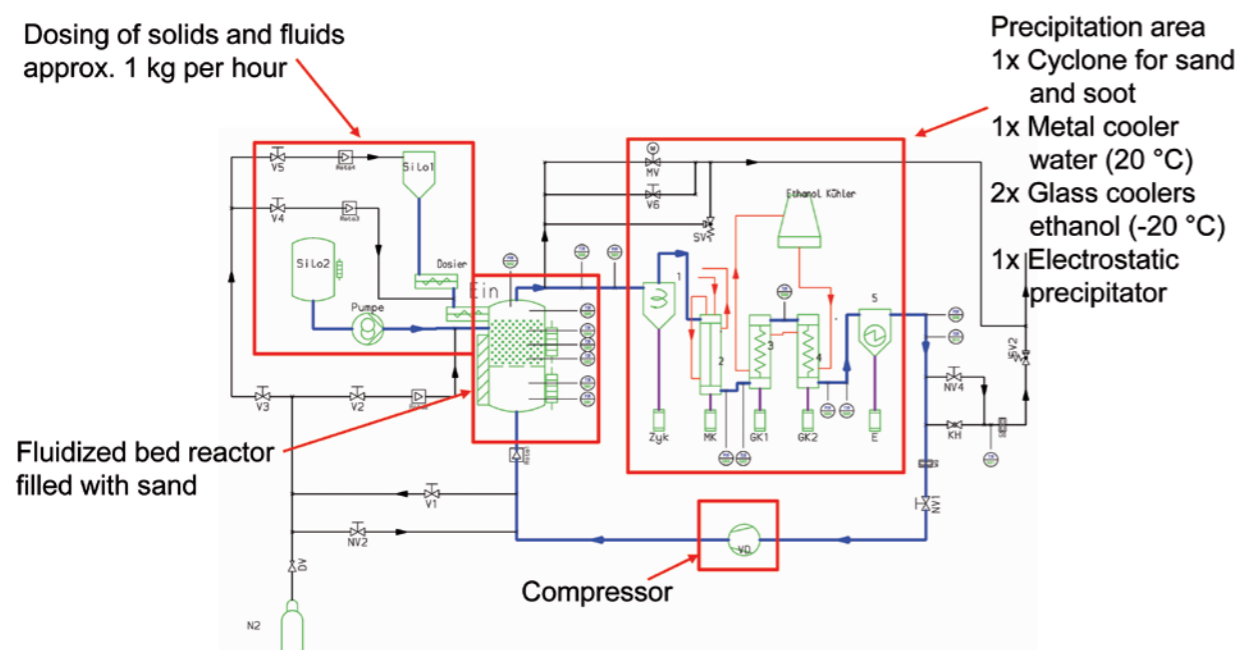


Figure 6.2. Flow chart of the pyrolysis miniplant of the Institute of Technical and Macromolecular Chemistry. (<https://www.chemie.uni-hamburg.de/institute/tmc/arbeitsgruppen/luinstra.html>)

Contribution of Chemical Reaction Engineering

The generation of pyrolysis oils containing valuable chemicals from diverse polymer containing waste streams (before and after sorting) is an original chemical engineering topic. The outcome of the pyrolysis will be a function of the waste source and the conversion technology, as both chemical and physical processes are of relevance. The heat transfer for heating and cooling, residence times, the interaction of various thermal processes, product collection/recycling and any catalysts [17] will influence the result. The stability of reactor operation in the context of thermal gradients, fouling in downstream equipment items (pressure build up) and the possible reactivity of mixtures with a multitude of components towards the materials of construction need to be carefully considered and close attention paid to the potential formation of hazardous chemicals. Although the number of studies published in this field has steadily increased and new insights have been acquired, it is still not possible to predict the product mixture composition from the constituents of the feed and the process used. The state-of-the-art has been summarized in recent reviews [7, 18].

A continuous fluidized bed miniplant operated at around 700°C and above enables an elucidation of the details of the pyrolysis for diverse feeds under various conditions. Detailed

online and offline analytics are a prerequisite for capturing the progress of the underlying thermal and chemical transformations. Such research work attempts to extend and to consolidate observations and insights into basic questions related to mass balancing, feed-process conditions-product-correlations, fouling and so on for actual waste streams.

The pyrolysis of polystyrene provides an example of such endeavors: a reference case was developed for the generation of virgin quality styrene from polystyrene, with a styrene containing pyrolysis oil as intermediate. The objective was to manufacture general purpose pyrolysis of polystyrene from the product obtained and thus offer a showcase of how chemistry might be applied to the circular economy of food packaging. Even so, a lot of research effort must still be invested in all steps of any specific recycling process. Apart from the pyrolysis process itself, the valorization of the products generated is crucial to assess the global cradle-to-grave environmental impact. An economically viable separation of monomers or their precursors, which yields maximum amounts and excludes downgrading, is a new and challenging task, for which only chemical reaction engineering expertise and technology can provide solutions [19]. This is also true for the subsequent polymerization of the reclaimed monomers with their specific range and levels of impurities, which should have no adverse impact on the environment or health compared to the status

quo [15]. Since the circular chemistry of polystyrene/styrene/polystyrene represents one of the easier tasks, considerable

work needs to be done in this area in the foreseeable future to extend the approach to other polymers [20].

REFERENCES

- [1] Conversio, Stoffstrombild Kunststoffe in Deutschland 2019: <https://www.conversio-gmbh.com/de>.
- [2] Waste Management in the EU, https://environment.ec.europa.eu/topics/waste-and-recycling_en.
- [3] Aufkommen und Verwertung von Verpackungsabfällen in Deutschland im Jahr 2015. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2017-11-29_texte_106-2017_verpackungsabfaelle-2015.pdf
- [4] Beiträge zu „Plastik in der Umwelt“. <https://bmbf-plastik.de/de/publikationen>.
- [5] DeArmitt, C. (2020) The plastics paradox: Facts for a brighter future, Phantom Plastics LLC, Terrace Park, OH. ISBN 978-0-9978499-6-7.
- [6] La Mantia, F.P. (2004) Polymer Mechanical Recycling: Downcycling or Upcycling? *Progress in Rubber, Plastics and Recycling Technology*, 20 (1), 11–24.
- [7] Li, H., Aguirre-Villegas, H.A., Allen, R.D., Bai, X., Benson, C.H., Beckham, G.T., Bradshaw, S.L., Brown, J.L., Brown, R.C., Cecon, V.S., Curley, J.B., Curtzwiler, G.W., Dong, S., Gaddameedi, S., García, J.E., Hermans, I., Kim, M.S., Ma, J., Mark, L.O., Mavrikakis, M., Olafasakin, O.O., Osswald, T.A., Papanikolaou, K.G., Radhakrishnan, H., Sanchez Castillo, M.A., Sánchez-Rivera, K.L., Tumu, K.N., van Lehn, R.C., Vorst, K.L., Wright, M.M., Wu, J., Zavala, V.M., Zhou, P., Huber, G.W. (2022) Expanding plastics recycling technologies: chemical aspects, technology status and challenges. *Green Chem.*, 24 (23), 8899–9002.
- [8] Sebastian, J. and Paul, L. (2021) Plastic recycling and regeneration, in *Sustainable Manufacturing*, Elsevier, pp. 339–365.
- [9] Woidasky, J., Moesslein, J., Wendler, P., Kirchenbauer, D., Wacker, D., Gao, G., Lang-Koetz, C. (2020) Kunststoffidentifikation und -sortierung in der Circular Economy durch Fluoreszenzmarker. *Chemie Ingenieur Technik*, 92 (4), 441–451.
- [10] Redshaw, J., O’Flaherty, M., Lake, A., Moreau, P. (2021) Chemical Recycling—Pyrolysis, in *Circular Economy of Polymers: Topics in Recycling Technologies* (eds D.I. Collias, M.I. James, J.M. Layman), American Chemical Society, Washington, DC, pp. 81–103.
- [11] Green Best Practice Community. <https://greenbestpractice.jrc.ec.europa.eu/node/197>.
- [12] Zhao, D., Wang, X., Miller, J.B., Huber, G.W. (2020) The Chemistry and Kinetics of Polyethylene Pyrolysis: A Process to Produce Fuels and Chemicals. *ChemSusChem*, 13 (7), 1764–1774.
- [13] Kaminsky, W., Predel, M., Sadiki, A. (2004) Feedstock recycling of polymers by pyrolysis in a fluidised bed. *Polymer Degradation and Stability*, 85 (3), 1045–1050.
- [14] Laviolette, J.-P., Leclerc, P., Kerenkan, A.E., Eslami, A., Doucet, J. (2021) Monomer Recycling of Addition Polymers, in *Circular Economy of Polymers: Topics in Recycling Technologies* (eds D.I. Collias, M.I. James, J.M. Layman), American Chemical Society, Washington, DC, pp. 105–128.
- [15] Liu, Y., Qian, J., Wang, J. (2000) Pyrolysis of polystyrene waste in a fluidized-bed reactor to obtain styrene monomer and gasoline fraction. *Fuel Processing Technology*, 63 (1), 45–55.
- [16] *Sustainable Manufacturing* (2021), Elsevier. ISBN 978-0-1281811-5-7.
- [17] Mark, L.O., Cendejas, M.C., Hermans, I. (2020) The Use of Heterogeneous Catalysis in the Chemical Valorization of Plastic Waste. *ChemSusChem*, 13 (22), 5808–5836.
- [18] Vollmer, I., Jenks, M.J.F., Roelands, M.C.P., White, R.J., Harmelen, T., Wild, P., Laan, G.P., Meirer, F., Keurentjes, J.T.F., Weckhuysen, B.M. (2020) Die nächste Generation des Recyclings – neues Leben für Kunststoffmüll. *Angew. Chem.*, 132 (36), 15524–15548.
- [19] Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J., Bardow, A. (2020) Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling. *Resources, Conservation and Recycling*, 162, 105010.
- [20] Collias, D.I., James, M.I., Layman, J.M. (eds) (2021) *Circular Economy of Polymers: Topics in Recycling Technologies*, American Chemical Society, Washington, DC.

CASE STUDY 3: REDUCTION OF CO₂ EMISSIONS BY DRY REFORMING OF METHANE

Background

Since CO₂ is considered the major greenhouse gas and contributes largely to the recent climate-change issues, the so-called carbon dioxide management with respect to carbon capture, utilisation and storage has become a very important topic. However, from an industrial point of view, CO₂ is not only a greenhouse gas and waste product, but it can also be considered as a valuable and well utilised C₁ carbon building block with the potential to open up new industrial value chains to sustainable high value chemical products and reduce the CO₂ footprint of chemical and other industries. One of the most promising technologies in the context of the chemical valorisation of CO₂ is the dry reforming of methane (DRM) [1, 2]. DRM refers to the chemical process in which methane and carbon dioxide are converted to synthesis gas, short syngas, a mixture of hydrogen and carbon monoxide with low H₂/CO molar ratios:



The term “dry” in dry reforming originates from the partial or full substitution of water in the steam reforming process by CO₂. It has been estimated that through DRM a decarbonization of petrochemical value chains at a scale of multi Gt CO₂ per year could be achievable [3]. DRM can be utilized in a number of industrial processes reaching from the chemical and steel industry to the energy sector. Carbon dioxide is accessible from point sources associated with electrical power generation, production of metals, cement, ceramics, ammonia as well as gas and naphtha crackers. The methane sources are natural gas, shale gas, synthetic natural gas and industrial off-gases. There are also quite a number of combined sources of CO₂ and CH₄ such as the off-gases of steel plants, biogas from anaerobic fermentation of biomass, or landfill gas from the digestion of municipal solid waste. DRM can be operated heterogeneously using advanced catalysts but also homogeneously in the gas phase in fixed bed and flow reactors, respectively, and even in internal combustion engines [4]. Two successful implementations of DRM in the chemical and steel making industry will be discussed in the following. The development of both technologies has been supported by a strong industry-academia collaboration.

Contribution of Chemical Reaction Engineering

Advanced DRM catalysts for the reduction of CO₂ emissions in the chemical industry: Catalytic dry reforming under industrially relevant conditions of high pressures and high temperatures faces several challenges concerning the catalyst materials and process engineering [5]. The deposition of coke on the catalyst such as Ni and Co is a limiting factor for catalyst activity and lifetime [6]. Therefore, thermodynamics [7] and kinetics [8] behind coke formation as well as the catalytic cycle have to be understood not only to provide an appropriate catalytic material but also to develop a sustainable reactor concept. The demanding conditions also lead to a coupling of reactions in the gas phase and on the catalyst. Gas phase reactions may initiate coke formation at the entrance of the catalyst bed [9]. In the DRYREF project, funded by the German Federal Ministry of Economic Affairs (FKZ 0327856 und 03ET1282), a strong collaboration between industry (hte, BASF, Linde) and academia (KIT, TU Munich, Leipzig University, DECHEMA) led to profound analyses of the mechanisms occurring in gas phase and on the catalysts, which was the basis for the development of a novel catalytic system with high coking resistance and lower catalyst deactivation (see Figure 6.3). In order to overcome the difficulties involved with the DRM technology, a very detailed knowledge of the DRM mechanism under industrially relevant operating conditions had to be established. Therefore a very broad range of catalytic materials were tested with the aim to prevent sintering of the active species and coking. The rational catalyst design is based on the modification of the active species, alteration of the particle

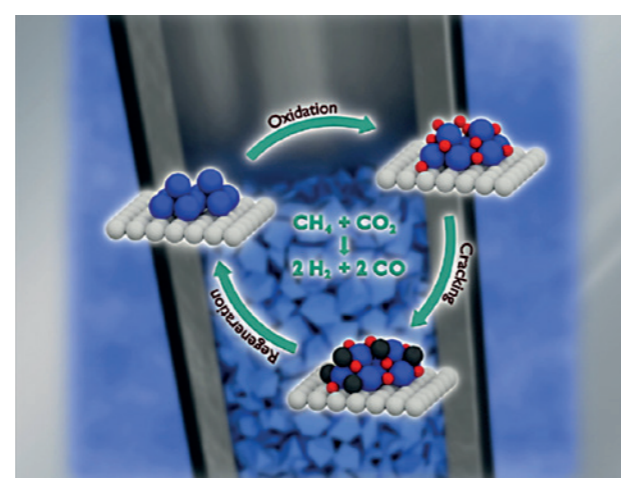


Figure 6.3: Sketch of catalytic cycle for dry reforming of methane, adapted from [8].

size, enhancement of the particle dispersion, adjustment of the properties of the support materials, design of the pore system and optimizing of further properties and operating conditions. Numerical simulation of the reactor behaviour supported the engineering process.

Dry reforming of methane is meanwhile offered on a commercial scale by Linde’s DRYREF™ syngas generation plant powered by BASF’s SYNSPIRE™ catalyst. This technology does not only shrink the carbon footprint of chemical industry but also improves process efficiency [10]. The technology received the ICIS Award 2019 for Best Process Innovation [11]. Recently, BASF, SABIC and Linde have started construction of the world’s first demonstration plant for large-scale electrically heated steam cracker furnaces. With Case Study 1 a possible concept of electrical heating, namely resistive heating, was introduced.

Reduction of CO₂ emissions from off-gases of the steel industry

The understanding of non-catalytic homogeneous reactions between natural gas and CO₂ [9] can also be employed to reduce CO₂ emissions in steel production, which contributes to ca. 8% of the world-wide direct CO₂ emissions. In steel plants, large streams of gaseous exhaust occur: the coke oven gas (COG) contains significant amounts of CH₄ and light hydrocarbons while the blast furnace gas (BFG) contains much CO₂. In a recently proposed technology [12, 13], these two gas streams are mixed and fed to the regenerative heat exchangers (Cowper’s type) of the steel plants, in which the CO₂ is used to reform the meth-

ane to syngas. The reducing potential of the resulting H₂/CO-rich mixture is then employed by feeding it into the blast furnace to support the reduction of the iron ore to iron, saving significant amounts of coke (see Figure 6.4). Since the Cowper’s type heat exchanger are periodically (ca. 30 min) cooled and heated, they exhibit strong spatial and temporal temperature variations (800°C to 1400°C), making the engineering of the process rather challenging. Based on detailed thermodynamic and kinetic simulations, followed by experimental evaluation on the lab scale, a window of suitable operating conditions was found to dry-reform synthetic mixtures of the steel-plant off-gases. In this proof-of-concept study, a maximal reduction of 78% of CO₂ and a CH₄ conversion of 95% could be achieved at 1350°C, 5.5 bar, and a COG/BFG ratio of 0.6 [12]. The application of this technology can result in up to 12% reduction of CO₂ emissions of a blast-furnace-based steel plant, which would correspond to a reduction of ca. 25% of Germany’s total CO₂ emissions, if the technology would be applied world-wide. First results from a pilot plant established by Saarstahl, Dillinger and Paul Wurth in the “H₂Syngas” project are very promising [13].

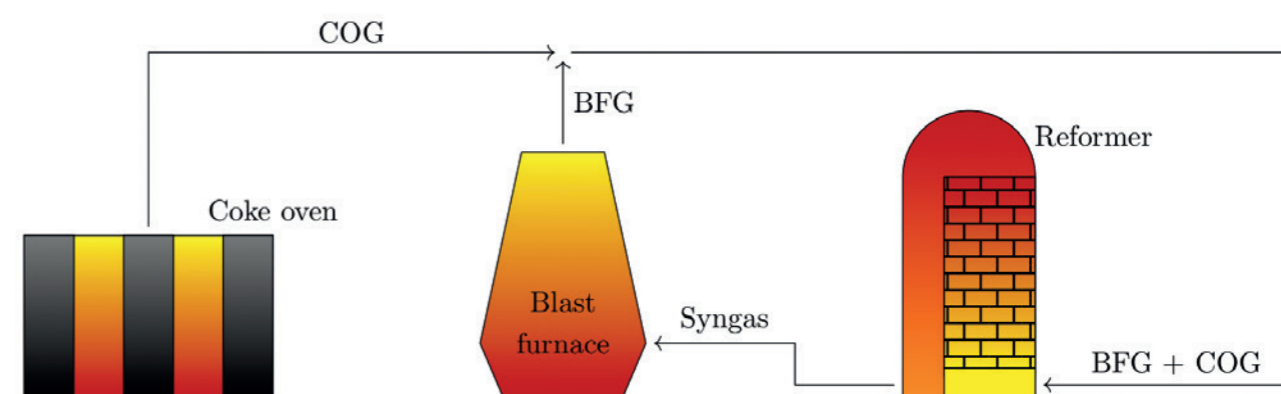


Figure 6.4: Utilization of ironmaking off-gases for syngas production by dry reforming of methane. (Courtesy of P. Blanck)

REFERENCES

- [1] E. Schwab, A. Milanov, S. A. Schunk, A. Behrens and N. Schödel, *Chem. Ing. Techn.* 87 (2015) 347–353.
- [2] S. Hanf, S. Angeli, D. Dussol, C. Fritsch, L. Maier, M. Müller, O. Deutschmann, S. A. Schunk. Methane Dry Reforming, Chapter 9 in *Chemical Valorisation of Carbon Dioxide*, ed. by G. Stefanidis, A. Stankiewicz. Green Chemistry Series, Vol. 74, The Royal Society of Chemistry, 2022.
- [3] R. K. Parsapur, S. Chatterjee and K. W. Huang, *ACS Energy Lett.*, 2020, 5, 2881–2885.
- [4] H. Gossler, S. Drost, S. Porras, R. Schießl, U. Maas, O. Deutschmann. *Combust. & Flame* 207 (2019) 186-195.
- [5] K. Wittich, M. Krämer, N. Bottke, S.A. Schunk, *ChemCatChem* 12 (2020) 2130–2147.
- [6] L.A. Schulz, L.C.S. Kahle, K. Herrera Delgado, S. Schunk, A. Jentys, O. Deutschmann, J.A. Lercher. *Appl. Catal. A: Gen.* 504 (2015) 599-607.
- [7] A. Giehr, L. Maier, S. Schunk, O. Deutschmann. *ChemCatChem* 10 (2018) 751-757.
- [8] A. Giehr, L. Maier, S. Angeli, S.A. Schunk, O. Deutschmann. *Ind. Eng. Chem. Res.* 59 (2020) 18790-18797.
- [9] L.C.S. Kahle, T. Roussière, L. Maier, K. Herrera Delgado, G. Wasserschaff, S.A. Schunk, O. Deutschmann. *Ind. Eng. Chem. Res.* 52 (2013) 11920-11930.
- [10] <https://www.engineering.linde.com/dryref>
- [11] <https://www.basf.com/global/de/media/news-releases/2019/12/p-19-420.html>
- [12] S. Angeli, S. Gossler, S. Lichtenberg, G. Kass, A. Agrawal, M. Valerius, K. P. Kinzel, O. Deutschmann. *Angew. Chemie Intl. Ed.* 60 (2021) 11852-11857.
- [13] <https://www.paulwurth.com/en/pilot-dry-reforming-plant-commissioned-in-dillingen-in-success-for-paul-wurth/>

CASE STUDY 4: REDUCTION OF CO₂ EMISSIONS BY CO₂ ELECTROLYSIS

Background

CO₂ electrolysis is a promising technology in the context of climate change, since it provides the possibility to store electrical energy in form of valuable chemicals, while consuming CO₂, therefore potentially even being a carbon negative technology (see Fig. 6.5). Depending on the electrode material used, a broad spectrum of products ranging from CO over CH₄ to multicarbon compounds is obtained [1]. These products are desirable intermediates which can be used in further chemical conversion processes, such as Fischer-Tropsch or methanol synthesis. Low temperature CO₂ electrolysis is usually carried out in aqueous electrolytes, allowing hydrogen evolution to occur in parallel to CO₂ reduction. Since green hydrogen can be produced more efficiently via water electrolysis, a high Faradaic efficiency towards carbon products is targeted [2].

Contribution of Chemical Reaction Engineering

Reaction engineering plays an important role in the development of the CO₂ electrolysis process. Before the process can be industrially implemented, several engineering questions need to be answered at electrode, cell and process levels. Currently, the research focus lies mostly on the development of efficient electrodes. Another challenge is related to the reaction temperature. Whereas most CO₂ electrolysis studies are presently carried out at ambient temperature, a large-scale technical electrolyzer would be operated at significantly higher temperatures due to lower ohmic losses and limited heat removal.

Early research on CO₂ electrolysis has mainly been conducted at planar electrodes in CO₂ saturated electrolytes. However, such systems are strongly constrained by the low solubility of CO₂ in water [3]. For the process to be conducted at industrially relevant current densities, the use of gas diffusion electrodes (GDEs) is beneficial to significantly reduce mass transport limitations [4]. GDEs are already commonly used in industrial applications such as oxygen depolarized

cathodes for chlor-alkali electrolysis [5], since they allow for intimate contact between gaseous reactants, liquid electrolyte and the solid electrocatalytic material. Optimizing these electrodes towards high Faradaic efficiencies for carbon products at elevated current densities is a major challenge to make CO₂ electrolysis feasible for industrial implementation, with the optimal electrode design constituting a trade-off between optimal CO₂ transport and wetting of the electrode area.

In the optimization of CO₂ electrolysis, a strong emphasis is placed on the local reaction environment in the porous system of the GDE. Since this data is so far experimentally unavailable, a description by mathematical models is crucial for a better understanding of the process. These models need to account for a variety of complex effects, such as electrowetting and its influence on the varying electrolyte distribution within the GDE. Another major factor is the local alkalization due to hydroxide formation in the electrochemical reactions, accelerating carbonate formation from CO₂ in homogeneous reactions. This leads to a limited carbon efficiency, since a fraction of the CO₂ consumed is unavailable for the electrochemical conversion. All of these factors

contribute to depleted CO₂ availability at the reaction front, and thus need to be overcome for efficient CO₂ electrolysis. Besides the previously mentioned phenomena, there may be further limitations to consider. For example, a product poisoning of silver catalysts by carbon monoxide has been highlighted in recent modeling studies [6].

Overall, progress at all scales from the electrochemical kinetics over the complex electrode reaction-transport interactions up to the entire electrolysis process is required to realize CO₂ electrolysis on an industrial scale.

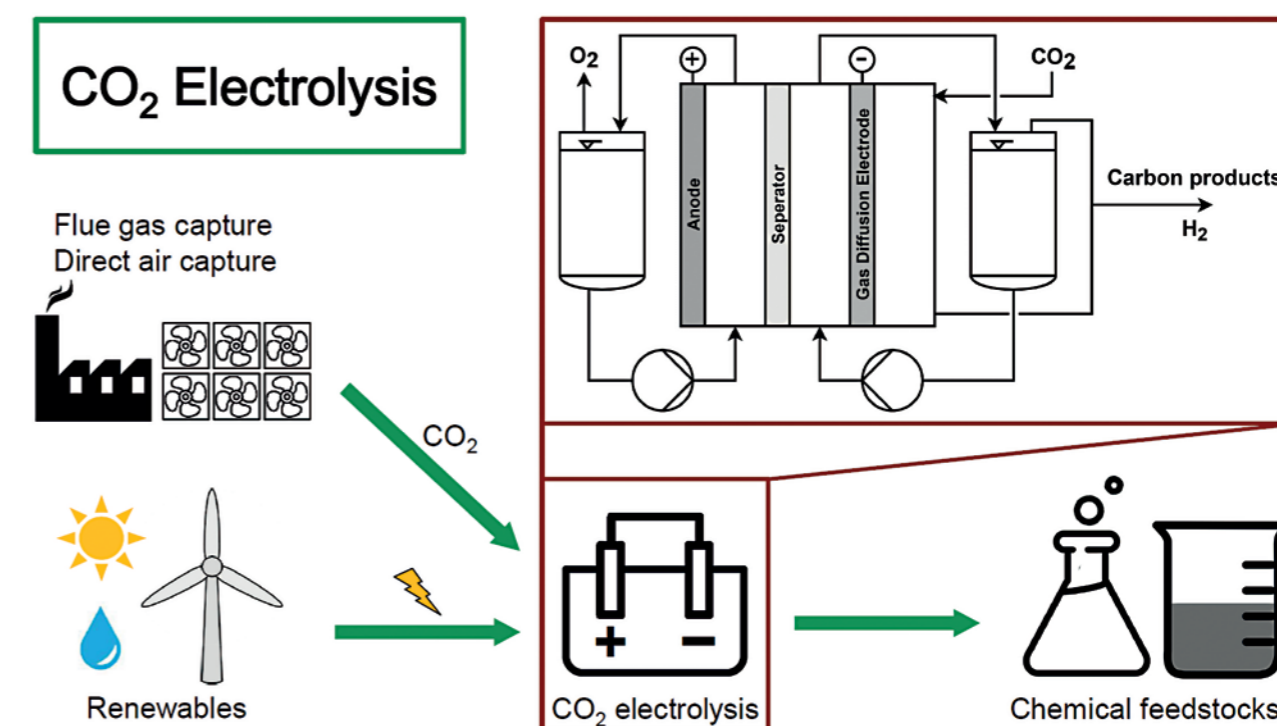


Figure 6.5: Process scheme of CO₂ electrolysis and its integration into a renewable energy economy.

REFERENCES

- [1] Y. Hori, H. Wakebe, T. Tsukamoto, O. Koga, Electrocatalytic process of CO selectivity in electrochemical reduction of CO₂ at metal electrodes in aqueous media, *Electrochim. Acta* 39 (11–12) (1994) 1833–1839, [http://dx.doi.org/10.1016/0013-4686\(94\)85172-7](http://dx.doi.org/10.1016/0013-4686(94)85172-7).
- [2] T. Burdyny, W.A. Smith, CO₂ reduction on gas-diffusion electrodes and why catalytic performance must be assessed at commercially-relevant conditions, *Energy Environ. Sci.* 12 (5) (2019) 1442–1453, <http://dx.doi.org/10.1039/c8ee03134g>.
- [3] B.J. Etzold, U. Krewer, S. Thiele, A. Dreizler, E. Klemm, T. Turek, Understanding the activity transport nexus in water and CO₂ electrolysis: state of the art, challenges and perspectives, *Chem. Eng. J.* 424 (2021) 130501, <http://dx.doi.org/10.1016/j.cej.2021.130501>.
- [4] A.J. Martín, G.O. Larrazábal, J. Pérez-Ramírez, Towards sustainable fuels and chemicals through the electrochemical reduction of CO₂: lessons from water electrolysis, *Green Chem.* 17 (12) (2015) 5114–5130, <http://dx.doi.org/10.1039/c5gc01893e>.
- [5] J. Kintrup, M. Millaruelo, V. Trieu, A. Bulan, E.S. Mojica, Gas diffusion electrodes for efficient manufacturing of chlorine and other chemicals, *Electrochem. Soc. Interface* 26 (2) (2017) 73–76, <http://dx.doi.org/10.1149/2.fo7172if>.
- [6] M. Löffelholz, J. Osiewacz, A. Lüken, K. Perrey, A. Bulan, T. Turek, Modeling electrochemical CO₂ reduction at silver gas diffusion electrodes using a TFFA approach, *Chemical Engineering Journal* 435 (2022) 134920, <http://dx.doi.org/10.1016/j.cej.2022.134920>.

CASE STUDY 5: CONTROLLED POLYMERIZATION IN CONTINUOUS FLOW

Background

Polymerization technology is a good example of applied reaction engineering in many respects [1]. On the bottom line this is due to the fact that polymers on their own are not a well-defined species. Instead, their application properties are determined by various characteristics, such as molecular weight, frequency and type of branching, and, in case of copolymers, the co-monomers and their organization. As a result, their properties are not described by specific values but rather by distributions that determine how a polymer behaves in subsequent processing and during its product lifetime. This almost infinite variety makes these materials virtually indispensable in modern life. They play a key role in many of the recent challenges facing humanity, such as energy harvesting from renewable sources, for instance either in terms of light-weight construction or functional materials, cell separating membranes in battery or fuel cell technology, encapsulation materials for solar cells or insulation material for ultra-high voltage power lines, not to mention a wide variety of applications in healthcare.

The microstructural properties of a polymer are the result of a complex interacting network of elementary reactions, that exhibit very specific dependencies on pressure and temperature on the one hand and the local reaction environment, such as species concentration, system viscosity and macromolecular characteristics, on the other hand. The behavior of the elementary reaction network is coupled to the local reactor environment. Figuratively speaking, the history of the technical reaction process is frozen in the microstructural properties of the macromolecular ensemble of the produced material. Achieving the desired polymer microstructure thus represents the first major challenge in (polymer) reaction engineering.

The second challenge is to meet the enormous demand for such materials, together with the need to supply them at high efficiencies and affordable prices. These requirements have driven the design of massive reactors with production capacities of 400 kt/a to 500 kt/a for typical state-of-the-art world-scale manufacturing facilities. Even small production facilities still have a capacity of about 80 kt/a. The production of α -olefin polymers or nylon are examples of production processes on this scale. Consequently, huge scale-up factors are involved when transferring processes from laboratory operation, generating just a few kilograms per run, up to commercial production levels.

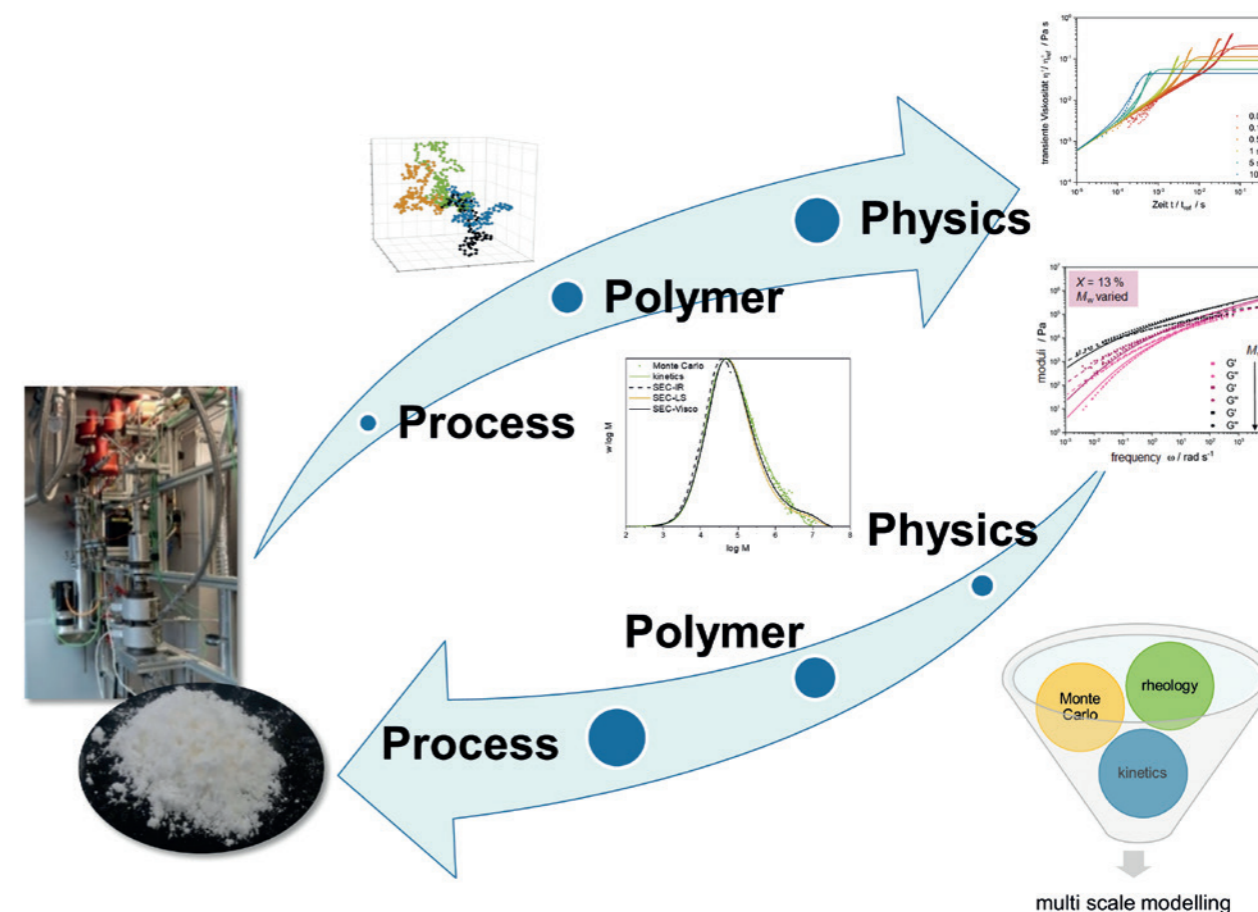


Figure 6.6: Multiscale approach to bridge from polymer synthesis to rheological properties utilizing the polymeric microstructure.

Contribution of Chemical Reaction Engineering

The pioneers of (polymer) reaction engineering, such as Ray [2], Hamielec [3] and Villermaux [4], understood early on the value of modeling and simulation for bridging the gap between well-defined laboratory experiments and industrial implementation, and the concepts they devised remain valid until today. A complex network of elementary reactions is used to describe the conversion of monomers to complex macromolecular structures, which provides the link to product application properties. The complexity, level of detail and precision of such models have developed significantly over the last few decades. This applies not just to the performance of simulation models, but also to the caliber of laboratory experiments and the insights acquired into industrial plant operation.

The examples considered in this section are taken from the high-pressure polymerization process for low-density poly-

ethylene (LDPE) but can be regarded as representative for any large-scale polymer product, since the needs and driving forces are the same. Whilst the exact objectives of investigations may vary, both the working principles involved, and the tangible benefits remain a common denominator. Figure 6.6 depicts the concept of the multiscale modeling approach as it is first applied to the reaction kinetics to ascertain the polymeric microstructure and from this, the rheological properties [5]. The data shown refer to laboratory scale experiments, but could equally be applied to industrial-scale production data to obtain qualitatively similar results. This feature can be illustrated by means of the molecular weight distributions acquired from the industrial process, shown in Figure 6.7. In both cases, the kinetic model and the kinetic and thermophysical properties are identical, but specific process data has been used, demonstrating the potency of modeling and simulation based on first principles.

With this toolbox, concepts such as digital twins have be-

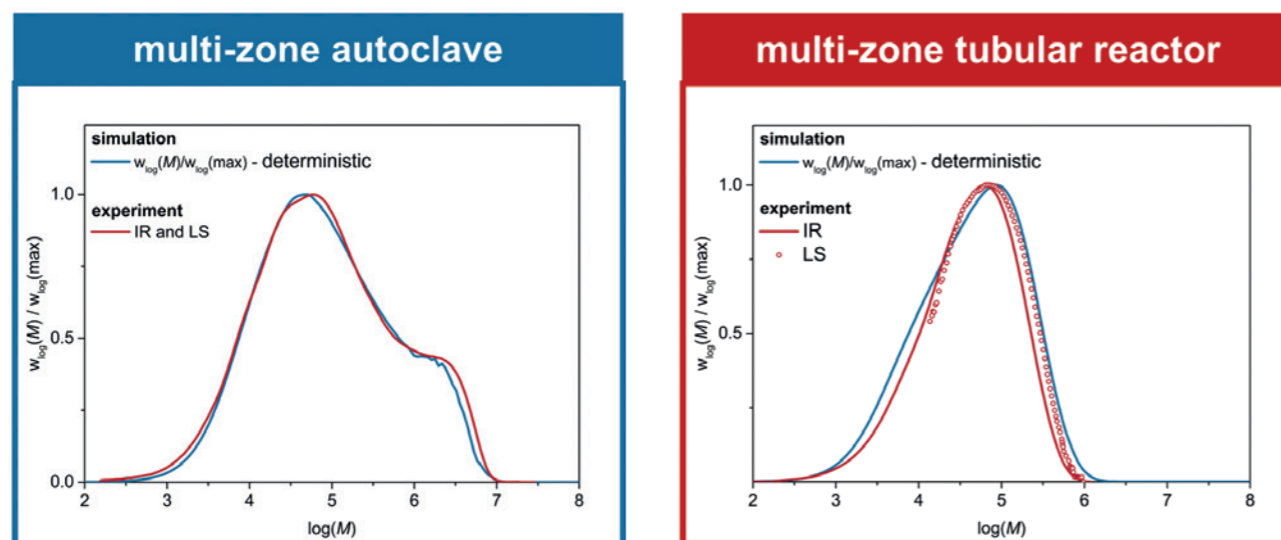


Figure 6.7: Quality of description for the molecular weight distribution in modeling industrial autoclave and tubular reactors utilizing a unified kinetic model.

come accessible that can be used to optimize processes, plan trials while minimizing their number and even train personnel. If computational speed and efficiency suffice, soft sensor and advanced process control strategies become practicable. The first makes available important parameters that may not be directly accessible online but are nonetheless relevant for running the process for good product quality. The latter allows to control and regulate the process with an element of foresight, and, in case the models run in multiple real-time scenarios, to test the effect of parameter

changes on the process before applying them. These concepts represent significant advances in operating the process more efficiently and sustainably.

Figure 6.8 depicts what is feasible by modeling based on first principles. The relationship between polymeric microstructure and process conditions via kinetics and thermo-physical properties is already well established. This microstructure then serves as the basis for estimating rheological properties [6]. A random walker provides the radii of gyra-

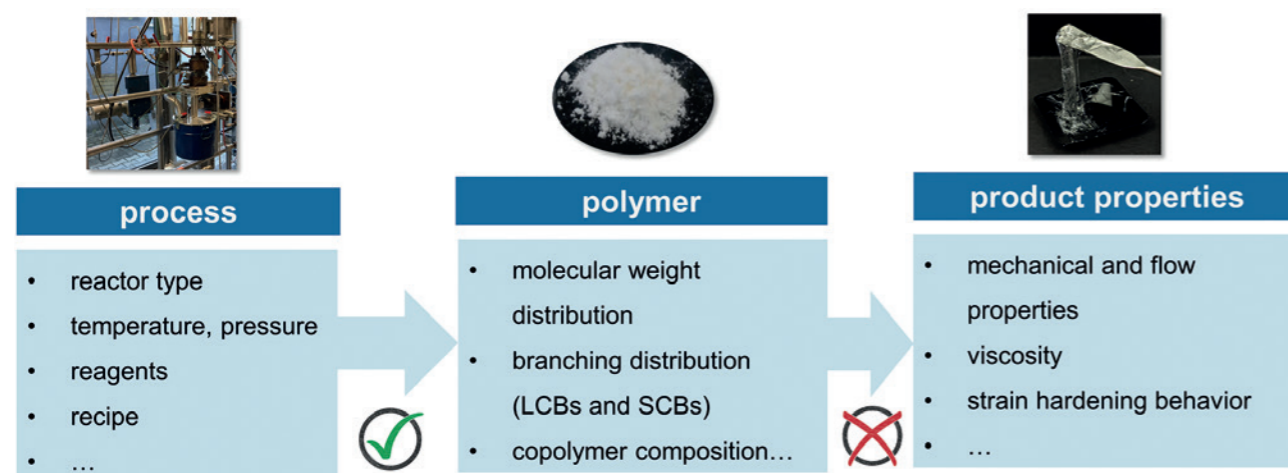


Figure 6.8: Realized and targeted levels of description in industrial process modeling for polymerizations.

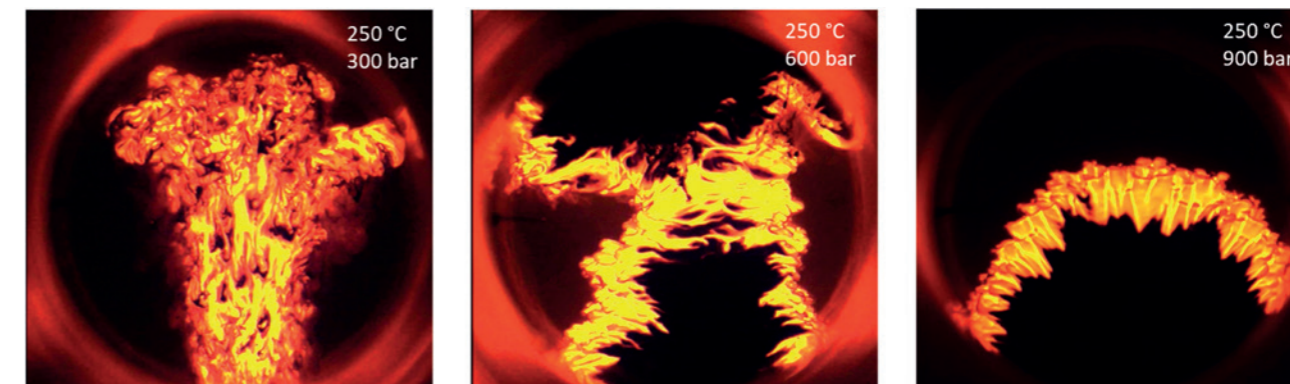


Figure 6.9: Visualized deflagrations of a high-pressure polymerization mixture on laboratory scale.

tion based on which a virtual size exclusion chromatograph can be created. For further mechanical application properties, however, such a detailed level of description has yet not been attained and one must resort to short-cut methods and more empirical approaches [7]. Nevertheless, it will probably only be a matter of time until the success achieved elsewhere will stimulate similar developments based on first principles in these areas, too.

Polymerization technology on a large scale should not be viewed just as a technique to selectively tune the properties of polymers, though. The reaction process is highly exothermic, making it necessary to find a good and robust compromise between operating the process at maximum efficiency on the one hand but safely on the other. In the worst case,

when the reaction mixture exhibits no upper explosion limit, as with high pressure ethene mixtures, this can entail deflagration scenarios.

Figure 6.9 illustrates such situations that were triggered intentionally and captured by video for laboratory scale investigations. CFD calculations of highly resolved temperature fields inside reactors can help to identify and avoid local hot spot runaway while simulations of flame front propagation extend our understanding of decomposition processes that can significantly endanger equipment [8]. Such examples demonstrate that reaction engineering is an indispensable tool in driving process developments in a safe, efficient and sustainable direction.

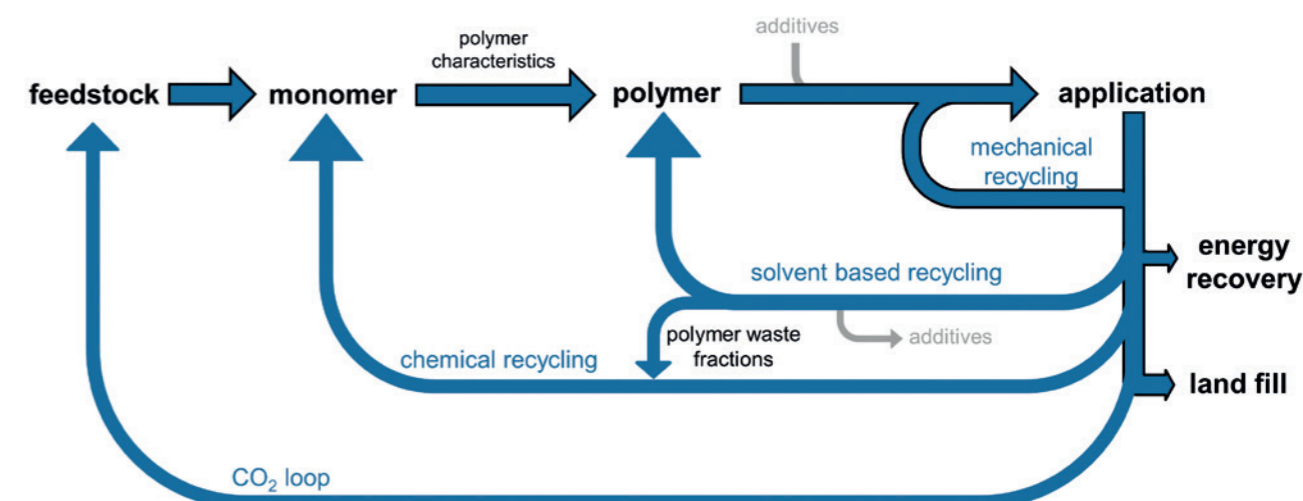


Figure 6.10: Potential flows of material closing the loop in circularity for polymers.

Sustainability and responsibility are important criteria. This particularly applies to polymer production due to the enormous production scales and the still growing demand, which must factor in the future societal need for sustainability [9]. Closing the loop in terms of a circular economy will be a challenging target in the near future and the energy needed to close the loop will be the critical parameter. At first glance, material reutilization would be the most direct recycling pathway with the lowest energy demand. However, for a significant portion of plastic waste this might be

unsuitable (see also Case Study 2). Figure 6.10 provides a schematic of potential production and recycling routes. The overarching challenge for large-scale polymer production in the short term is to develop polymer product designs that satisfy the needs of both the application envisaged and the circular economy.

An initial attempt to achieve a completely closed carbon loop for polymers may be found in [10].

REFERENCES:

- [1] Handbook of polymer reaction engineering, Wiley-VCH, Weinheim, 2004.
- [2] W. H. Ray, Journal of Macromolecular Science, Part C 1972, 8, 1.
- [3] H. Tobita, A. E. Hamielec in Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2000, S. 1–50.
- [4] P. Lorenzini, M. Pons, J. Villermaux, Chem. Eng. Sci. 1992, 47, 3969.
- [5] K. M. Zentel, J. Degenkolb, M. Busch, Macromol. Theory Simul. 2021, 30, 2000047.
- [6] K. M. Zentel, P. S. Eselem Bungu, J. Degenkolb, H. Pasch, M. Busch, RSC advances 2021, 11, 33114.
- [7] S. Lazzari, A. Lischewski, Y. Orlov, P. Deglmann, A. Daiss, E. Schreiner, H. Vale in Advances in chemical engineering, volume 56 (Hrsg.: D. Moscatelli, M. Sponchioni), Elsevier Academic Press, Cambridge, MA, San Diego, CA, Oxford, London, 2020, S. 187–227.
- [8] A. Hilfer, J. Degenkolb, M. Busch, Chemie Ingenieur Technik 2019, 91, 657.
- [9] A. K. Mohanty, F. Wu, R. Mincheva, M. Hakkarainen, J.-M. Raquez, D. F. Mielewski, R. Narayan, A. N. Netravali, M. Misra, Nat Rev Methods Primers 2022, 2.
- [10] <https://www.on-running.com/de-ch/explore/sustainability/cleancloud>

CASE STUDY 6: CONTINUOUS SYNTHESIS OF PHARMACEUTICAL ACTIVE INGREDIENTS EXPLOITING NATURAL PRODUCT EXTRACTS

Background

Active pharmaceutical ingredients are predominantly produced in batch-wise operated chemical synthesis steps. Typically, the feed constituents are small molecules provided in high purities. On the other hand, a large number of plants contain numerous attractive and already highly functionalized molecules, which can serve as alternative starting materials. Drawbacks of this approach are that after extraction these potential reactants are mixed with a number of other components and that their concentrations are relatively low.

There are presently intensive activities in three different areas to extend the usage of plants as a feedstock source to produce valuable drugs:

- A) Development of efficient technologies to selectively extract target molecules, combined with simultaneous co-extractions of precursor molecules, which have so far been treated as waste.
- B) Development of efficient separation processes for purifying the final product and potentially valuable precursors and intermediates.
- C) Application of reaction engineering principles to optimize the reactions transforming eligible co-extracted precursors into the target molecule (semisynthetic approach). Additionally, there is a recognizable trend to try to exploit more productive continuous operation modes.

An example illustrating these trends is the manufacture of the sesquiterpene endoperoxide artemisinin (see Fig. 6.11). Artemisinin is currently the key active pharmaceutical ingredient in the most effective antimalarial drugs [1]. It is a secondary metabolite of the herb sweet wormwood (*Artemisia Annua* L.). For the discovery and investigation of the antimalarial activity of artemisinin, Tu Youyou was awarded the Nobel Prize for Medicine in 2015. An ever-increasing demand for artemisinin is expected in the future, due to other promising possible applications [2, 3].

Soon after the isolation of artemisinin, much research was devoted to developing a total synthesis. In 1983 a first successful, if albeit with low yield, synthesis was reported, which started from iso-pulegol and comprised 11 steps [4]. Subsequently, terpene-based chemical routes were also realized [5, 6]. More recently, strains of *Saccharomyces cerevisiae* (baker's yeast) were developed to utilize a biological synthesis, which can produce artemisinic acid, a closely related precursor of artemisinin, with high yield [7]. To prepare semi-synthetic artemisinin, a process based on performing a diastereoselective hydrogenation and photooxidation reactions was subsequently developed and commercialized [8, 9].

Despite the extensive effort invested, extraction from *Artemisia Annua* L. nevertheless remains the most important route for economically generating the large amounts of artemisinin needed to treat the high prevalence of malaria.

To improve the efficiency and the yield of artemisinin extraction, comprehensive efforts have been made to identify suitable new solvents, to devise and apply efficient operating procedures and to optimize the operating conditions [e.g. 10, 11]. Since the complex biosynthesis of artemisinin in *Artemisia Annua* L. is now well understood [12], the potential of co-extracting artemisinic acid and dihydroartemisinic acid (DHAA) as biosynthetic precursors for artemisinin has been recognized [13]. Currently these valuable ingredients in the extracts are still discarded.

A general challenge in treating plant extracts remains

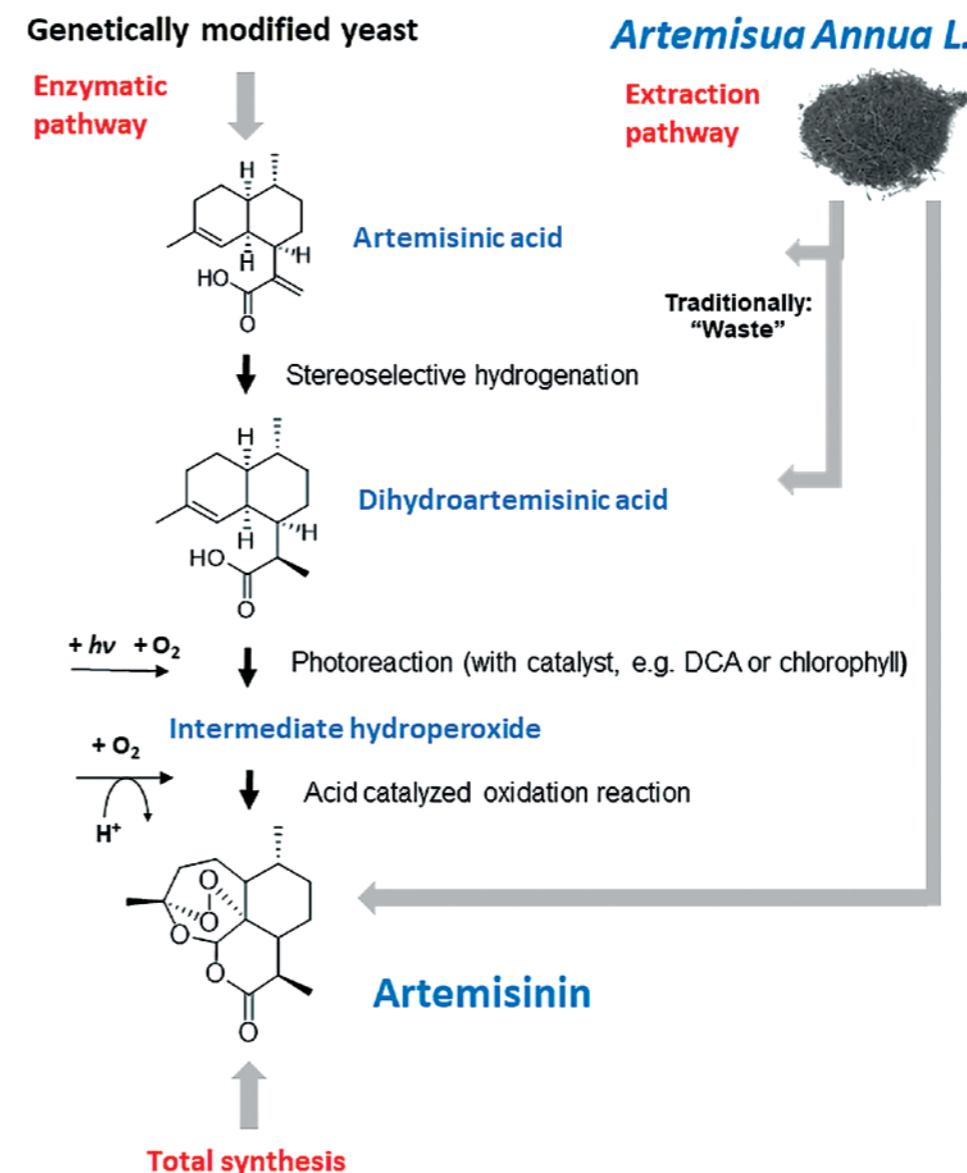


Figure 6.11: Pathways to provide artemisinin.

the removal of the numerous other co-extracted components, in order to yield the pure target molecules. Considering the whole process chain, there is a need to identify the best locations and techniques to introduce selective separation processes. In order to produce pharmaceutically interesting target molecules, crystallization and preparative chromatography are, and will remain, the most powerful tools available. They can often be combined effectively. The ability to switch various reaction modules and to combine them expediently with purification steps has allowed the production of artemisinin and its derivatives used in drugs as demonstrated in [14].

Contribution of Chemical Reaction Engineering

Reaction engineering can contribute to organic synthesis by providing increasingly automated approaches [15]. They are supported by advanced real-time process analytics, to observe and control multistep synthesis in continuous flow [16]. This has already led to successful and impressive examples of the continuous production of active pharmaceutical ingredients in flexible plug-and-play flow chemistry modules [17].

In an extension to the case study considered here, crude extracts of *Artemisia Annu* L. were processed in a continuously operated photoreactor with light, oxygen and acid. The results confirmed the potential for enhanced production of artemisinin from DHAA [13, 18]. It was shown that efficient irradiation with visible light can generate artemisinin with high yields in a flow set-up with short residence times. Furthermore, as a substitute for the typically expensive chemical photocatalysts (such as 9,10-dicyanoanthracene, DCA), successful results were reported with chlorophyll A, which can be also co-extracted from the plant. It was demonstrated that for the amounts of chlorophyll A thus accessible, similar photooxidation results can be achieved as with DCA. To help optimize a suitable reactor, a detailed kinetic model was developed capable of quantifying and predicting the photooxygenation of DHAA to an intermediate hydroperoxide, which is formed in the essential initial step of the partial synthesis route to artemisinin [19].

Beyond the specific example described here, it is expected that the large available pool of natural products combined with multi-step continuous synthesis and efficient purification will in the future open up new routes for producing active pharmaceutical ingredients.

REFERENCES

- [1] Youyou Tu, From *Artemisia annua* L. to Artemisinins. The discovery and development of artemisinins and antimalarial agents, 1st Edition, 2017, Hardcover ISBN: 9780128116555, eBook ISBN: 9780128116562
- [2] Kolesar, J.M., Seeberger, P.H., Editorial: Anticancer potential of *Artemisia annua*, *Frontiers in oncology*, 2022, 12, 853406
- [3] Zhou Y., Gilmore K., Ramirez S., Settels E., Gammeltoft K. A., Pham L.V., Fahnøe U., Feng S., Ofersgaard A., Trimpert J., Bukh J., Osterrieder K., Gottwein J.M., Seeberger P.H., In vitro efficacy of artemisinin-based treatments against SARS-CoV2, *Scientific Reports, Nature Portfolio*, 2021, 11:14571.
- [4] Schmid G., Hofheinz W., Total synthesis of qinghaosu, *Journal of the American Chemical Society*, 1983, 105.3, 624–625.
- [5] Avery M.A., Jennings-White C., Chong W.K.M., The Total synthesis of (+)-artemisinin and (+)-9-desmethylartemisinin, *Tetrahedron Letters*, 1987, 28.40, 4629–4632.
- [6] Yadav, B J.S., Thirupathiah B., P. Srihari. P., A concise stereoselective total synthesis of (+)-artemisinin, *Tetrahedron* 66.11 2010, 66.11, 2005–2009.
- [7] Paddon C.J., Westfall P.J., Pitera D.J., Benjamin K., Fisher K., McPhee D., Leavell M.D., Tai A., Main A., Eng D., Polichuk D.R., Teoh K.H., Reed D.W., Treynor T., Lenihan J., Fleck M., Bajad S., Dang G., Dengrove D., Diola D., Dorin G., Ellens K.W., Fickes S., Galazzo J., Gaucher S.P., Geistlinger T., Henry R., Hepp M., Horning T., Iqbal T., Jiang H., Kizer L., Lieu B., Melis D., Moss N., Regentin R., Secrest S., Tsuruta H., Vazquez R., Westblade L.F., Xu L., Yu M., Zhang Y., Zhao L., Lievens J., Covello P.S., Keasling J.D., Reiling K.K., Renninger N.S., Newman J.D., High-level semi-synthetic production of the potent antimalarial artemisinin, *Nature*, 2013, 496.7446, 528–532.
- [8] Turconi J., Griollet F., Guével R., Oddon G., Villa R., Geatti A., Hvala M., Rossen K., Göller R., Burgard A, Semisynthetic artemisinin, the chemical path to industrial production, *Org. Process Res. Dev*, 2014, 18.3, 417–422.
- [9] Burgard A., Gieshoff T., Peschl A., Hörstermann D., Keleschovsky K., Villa R., Michelis S., Feth M.P., Optimisation of the photochemical oxidation step in the industrial synthesis of artemisinin, *Chemical Engineering Journal*, 2016, 294, 83–96.
- [10] Lapkin A.A., Peters M., Greiner G., Chemat S., Leonhard K., Liauw M.A., Leitner W., Screening of new solvents for artemisinin extraction process using ab initio methodology, *Green Chemistry*, 2010, 12.2, 241–251.
- [11] Zhang Y., Prawang P., Li C., Meng X., Zhao Yu., Wang H., Suojiang Zhang S., Ultrasonic assisted extraction of artemisinin from *Artemisia Annu* L. using monoether-based solvents, *Green Chemistry*, 2018, 20.3, 713–723.
- [12] Brown G.D., The biosynthesis of artemisinin (Qinghaosu) and the phytochemistry of *Artemisia annua* L. (Qinghao), *Molecules*, 2010, 15.11, 7603–7698.
- [13] Kopetzki D., Lévesque F., Seeberger P.H., A Continuous-flow process for the synthesis of artemisinin, *Chem. Eur. J.*, 2013, 19, 5450–5456.
- [14] Gilmore K., Kopetzki D., Lee J.W., Horváth Z., McQuade D.T., Seidel-Morgenstern A., Seeberger P.H., Continuous synthesis of artemisinin-derived medicines, *Chem. Comm.*, 2014, 50, 12652–12655.
- [15] Sourav Chatterjee, Mara Guidi, Peter H. Seeberger, Kerry Gilmore, Automated radial synthesis of organic molecules, *Nature*, 2020, 579, 379–384.
- [16] Sagmeister P., Lebl R., Castillo I., Rehl K., Kruijs J., Sipek M., Horn M., Sacher S., Cantillo D., Williams J.D., Kappe C.O., Advanced real-time process analytics for multistep synthesis in continuous flow, *Angew. Chem. Int. Ed.*, 2021, 60, 8139–8148.
- [17] Rogers L., Briggs N., Achermann R., Adamo A., Azad M., Brancazio D., Capellades G., Hammersmith G., Hart T., Imbrogno J., Kelly L.P., Liang G., Neurohr C., Rapp K., Russell M.G., Salz C., Thomas D.A., Weimann L., Jamison T.F., Myerson A.S., Jensen K.F., Continuous production of five active pharmaceutical ingredients in flexible plug-and-play modules: a demonstration campaign, *Org. Process Res. Dev.*, 2020, 24.10, 2183–2196.
- [18] Triemer S., Gilmore K., Vu T.G., Seeberger P.H., Seidel-Morgenstern A., Literally green chemical synthesis of artemisinin from plant extracts, *Angewandte Chemie International Edition*, 2018, 57, 5525–5528.
- [19] Triemer S., Schulze M., Wriedt B., Schenkendorf R., Ziegenbalg D., Krewer U., Seidel-Morgenstern A., Kinetic analysis of the partial synthesis of artemisinin: Photooxygenation to the intermediate hydroperoxide, *Journal of Flow Chemistry*, 2021, 11:641–659.

7 Outlook

The future of a globally integrated world changes with each new idea, hopefully progressing towards a prosperous, peaceful and sustainable society. The key challenge lies in the duality of tackling climate change still providing adequate water, food and energy supply to the world population, but also enabling the development of new technologies, markets and products. All aspects of this challenge involve transformations in raw materials and their conversion as well as in the supply and storage of energy. These are all core competencies of chemistry. Thus, the rapid changes in society and industry will foster innovation, which in turn will shape the chemical industry of tomorrow. Consequently, chemical engineering toolboxes will be an indispensable part of the race to find timely, reliable interim and final solutions on the way to a sustainable world.

Chemical reaction engineering will make significant contributions to key issues. A future economy needs to move beyond finite fossil resources and limit its emissions to non-persistent and environmentally acceptable chemical compounds. The troika of **circularity, sustainability** and a **secure material and energy supply** will drive manifold activities in the coming years as the axioms of research and development (see Figure 7.1). The simultaneous consideration of these three aspects reveals the tensions, but also development potential, where contradictory influences necessitate novel concepts that are highly pareto-efficient.

Products will be derived from **fully-interconnected but decentralized material cycles** requiring a new type or redesign of **highly integrated production sites with modular multifunctional plants**. Fossil feedstocks will be replaced by integration of **recycling, bio-derived raw materials** and **carbon capture and utilization (CCU)** concepts. Most important, raw material security will be achieved by departing from classical routes and developing **tolerant synthesis pathways and processes** while increasingly merging the energy and chemical sectors. It will also involve the flexibility to substitute raw materials, in order to circumvent shortages or high prices, by using **advanced materials** with good availability. Meeting these goals means to intensify activities in emerging areas of reaction engineering, such as **multiscality, diversification** as well as **digitalization**.

Digitalization has already had a massive impact on all parts of the economy, especially in manufacturing, including the chemical industry. This is not just significant for better customer service or the management of supply chains, but also for the optimization and development of novel processes. The collection and management of relevant data provide comprehensive information about chemical processes. The recording of data and its assembly to a useful piece of information can be implemented in two ways: either in new processes or in a retrospective analysis based on existing information from the past. A vast scope and high quality are fundamental for what is called **big data**. The large-

est impact can be expected on the development of the next generation of production processes from scratch, making intense use of digital technologies and linking plants with one another along the value chain.

Already, in the early stage of process development, **data-driven design of experiments** provides a purposeful selection of lab experiments. The experiments are conducted in an environment, where the lab has a **digital twin** and thus all experimental steps are traceable and documented. This facilitates the subsequent scale-up of the process, either via classical methods or with an **automated or fully-integrated scale-up** guided by the digital twin.

Not only novel processes benefit from digitalization, but also established industrial-scale processes can be explored, examined and optimized by applying **blackbox and greybox modeling**. These tools can be used to improve existing processes with **advanced process control systems**, rendering even amortized plants more efficient and sustainable.

The ability to scale-up from a digital twin strongly depends on the understanding of the **multiple scales in chemical processes**, which is where the multiscality of chemical processes comes into play. **Hierarchical structures on different scales** are decisive features in reaction systems to manage heat and mass transfer processes. In thermocatalytic heterogeneous catalysis, structuring can take place on **micro, meso- and macroscales**, represented by the primary structures of the active material, the assembly within a catalyst pellet and the arrangement of the catalyst bed inside a reactor, respectively. All scales are of equal interest during design and optimization of chemical reactors, and an **understanding of transport trajectories** reveals the associated characteristic time constants for mass and energy transport.

Data processing and analysis is a key challenge to meet the high demands imposed by multiscale systems. Developments in the field of **intelligent algorithms** will help to identify and assess the uncertainties in **multiscale modeling**. This also includes the evaluation of certain phenomena at different scales for the sensitivity of the overall process. Thus, modeling and simulation try to account for all scales, using **surrogate models and shortcut methods** in order to limit the time and power of computation necessary. A promising possibility is offered by advanced combinations of classical simulation approaches and intelligent algorithms,

which, for example, provide a new form of parameter fitting in the form of **physically informed neural networks**.

The necessary insights will be provided by advanced analytical techniques analyzing the reaction system *in situ* and *operando*. The so-called **operando spectroscopy** provides a detailed glimpse into reactors and can be combined to benefit from multiple spectroscopic methods. Reaction engineering may also exploit new techniques offered by **synchrotron measurements**. However, reaction engineering equipment and the infrastructure of beamlines needs further tuning to enhance the synergies from **interdisciplinary work** associated with synchrotron measurements. New spectroscopic techniques and the collaboration in interdisciplinary teams offer a huge potential for the **analysis of 2D and 3D concentration fields**.

Another way to examine reaction systems is the use of **dynamic methods**. Different techniques are under constant development, with the common denominator being that a reaction system is forced by an input signal and the corresponding response of the system is then analyzed. In particular, a **combination of spectroscopic methods with dynamic methods** is a promising approach, since their amalgamation makes it possible to observe the change of the system and simultaneously identify the **time constants** from the system's response. In this manner, the global **dynamic material balance** can be investigated, including the storage of reactants at the active sites and on the catalyst support. These methods are also of interest for process development, even for the design of a steady-state process, because the information acquired can also be used to **optimize the transport trajectories** in novel processes.

The shifting raw material situation and the goals of sustainability and circularity will foster a **diversification of reaction engineering**. The discipline is characterized by methodical approaches, which make it possible, as development progresses, to enrich innovations with an increasing number of concepts. Process developments will thus benefit directly from newly invented techniques that can be assembled from the library of methodological building blocks.

The future axioms of reaction engineering will facilitate the direct usage of solar energy, promoting the importance of **photochemical and electrochemical reactions**. In particular, the likely merging of the energy and chemical sectors makes

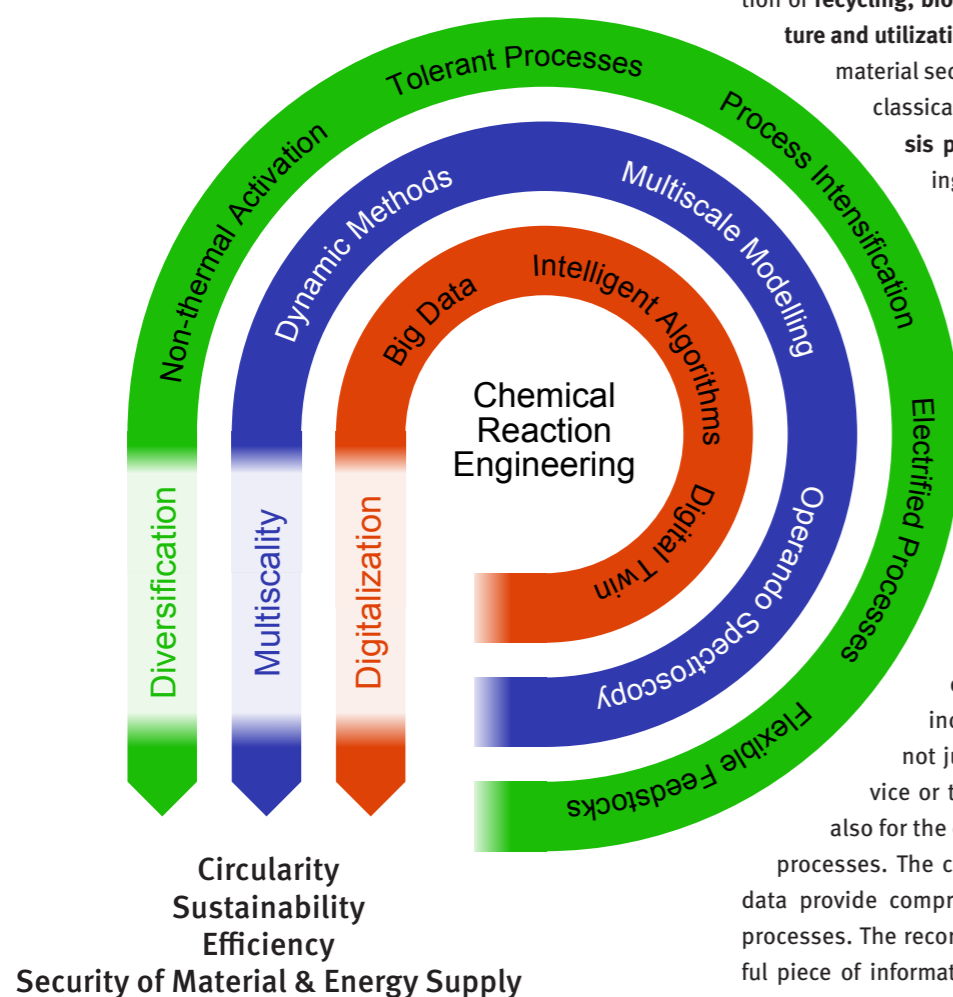


Figure 7.1: Chemical reaction engineering is driving the development towards circularity and sustainability as well as a secure material and energy supply.

the use of photons and electrons as reaction partners seem attractive. These systems require new methods to account for the transport trajectories of electrons and photons. The methodology of construction also needs to be modified, resulting in **new reactor concepts** and scale-up strategies. Additionally, because of the special trajectories of these additional ‘reactants’, photo- and electrochemical processes will open up fresh options for process intensification.

The exploration of novel process concepts will be based on the direct implementation of **process intensification**. The exploration of reaction systems takes place on a knowledge base using an **agile knowledge management**. The design starts and proceeds in a **multidisciplinary environment**, where experts from different disciplines contribute the expertise needed to derive an intensified process. The **evolutionary development** of the novel processes avoids the dead-ends of incremental research initiatives. In this transformation, material science will play a key role providing unique process options with **bi- and multifunctional materials**. Not just conventional systems, but also electrochemical and photochemical systems will benefit from advanced materials in various forms. The special design criteria will benefit from **advanced materials** as well as from advanced processing, e.g. via **additive manufacturing**, which enables new concepts specially tailored for the trajectories of molecules, electrons or photons.

The diversification exhibits different facets of reaction engineering in the combination of concepts from different reaction engineering disciplines. Enzymes, light collectors, electrodes and catalysts offer new degrees of freedom in the **development of hybrid systems**. Especially the intensification of multiphase systems will be stimulated by the combination of different concepts of transformation processes.

Diversification of processes in the **circular economy will give rise to new platform chemicals** during the synthesis of chemicals as well as during recycling. The new idea of **flexible feedstocks** will be a key element on the road to a sustainable economy. Furthermore, it is to be expected that **Power-to-X technologies** will strengthen sector coupling and lead to a **merging of the chemical and energy sectors**, providing the necessary flexibility to ensure raw material security and simultaneously guarantee sustainability along the value chain. The primary material availability will be assured by **carbon capture and utilization** as well as **bio-derived chemicals** – however, the predominant source of feedstocks will be **secondary raw materials** within the framework of the circular economy. It is to be anticipated that material flows will change with the economic cycle and thus not only flexible feedstocks but also correspondingly **flexible storage and processing facilities** will be required.

Looking at the revolutionary changes in society as a whole that await us during the course of the forthcoming material and energy transitions, there is a need for enormous creative potential, which must be met by well-trained specialists. It can be assumed that in the years up to 2050 a transformation comparable to the Industrial Revolution will occur. Contemporary education is thus a challenge, where training content must keep pace with technical developments.

Innovation will increasingly take place at the interface between disciplines. Close cooperation between material scientists, biotechnologists and chemists as well as process, reaction and polymer engineers is required. Future education should emphasize the synergy between the experiment and the model as well as the importance of holistic thinking, to enable the next generation of engineers to master the challenges they will encounter.

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