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Microreactors. Prospects already achieved and possible misuse*

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Abstract: Microreactors as a novel concept in chemical technology enable the introduction of new reaction procedures in chemistry, pharmaceutical industry, and molecular biology. Miniaturized reaction systems offer many exceptional technical advantages for a large number of applications. The large surface-to-volume ratio of miniaturized fluid components allows for significantly enhanced process control and heat management. Moreover, the unique possibilities of microchemical systems pave the way to a distributed point-of-use and on-demand production of extremely harmful and toxic substances.

On the other side of the coin, miniaturization of complete set-ups for chemical syntheses to a suitcase or even to a shoe-box size opens several possibilities to possibly use them as tools for terrorist attacks and to facilitate the clandestine manufacture of chemical agents. Microfabrication techniques are common and allow the machining of special materials (e.g., high-alloyed steel, titanium, ceramics, or glass). Meanwhile, micromachining techniques are available anywhere in the world. Therefore, these techniques are no longer unique nor proprietary and they cannot prevent construction or distribution of microreaction systems by people with allegiance to a terrorist organization.

SCIENTIFIC ADVANCES ALREADY ACHIEVED

The use of miniaturized reactors with characteristic dimensions below (and sometimes above) 1 mm attracted great attention in chemical engineering recently. From the early concepts in the late 1980s to commonly available microreactor devices and semi-production-like setups, a worldwide research and development was done not only at universities but also by chemical industry. The development of metal microreactor components such as micro heat exchangers or micromixers and, further, the integration of these devices into an existing production line for fine chemicals were important milestones.

Microreactors offer many advantages for the performance of heat- and mass-transfer-limited reactions. Large gradients in concentration and temperature are achieved by shrinking the characteristic dimensions of a microreactor down to the micro scale. This is especially advantageous in the case of highly exothermal reactions as well as in the case of mass-transport-limited processes. Based on these technical advantages, new and unusual process regimes become technically feasible. For instance, the fluorination of toluene with elemental fluorine was carried out in a microreactor set-up comprising reaction channels and heat exchanger structures in close proximity. Due to the explosive character, this reaction could only be carried out in conventional equipment at –70 °C very carefully under lab-scale conditions. By using a specially developed microreactor, the reaction mechanism could be changed from a radical chain type (uncontrollable, unselective) to an electrophilic substitution one (safe, selective) even

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at –10 °C. The type of microreactor that was used for the synthesis was a falling-film reactor with a microstructured reaction plate, which is a means of distributing the liquid and increasing the internal surface (Fig. 1).

For a couple of years, microreactors were used for small-lot production of chemicals. Some examples describe the formation of organometallic compounds. By using matchbox-sized micromixers, a tremendous increase of yield and selectivity was observed, even by increasing the reaction temperature from below 0 °C up to 50 °C. Typical set-ups of mixer-tube reactors are given in Fig. 2.

An important further motivation to use microreactors for chemical processes arises from safety considerations. Very small hold-up of hazardous substance can significantly decrease the expenditure for safety installations. Even working with pure oxygen in the explosive envelope might be possible in a lab-scale environment. Attempts to study the extremely hazardous H_2–O_2 reaction were examined at the Forschungszentrum Karlsruhe (FZK) [1].

In most cases, explosions can be suppressed by using microchannels with a hydraulic diameter below the quenching distance [2]. The microsystem becomes inherently safe, although not necessarily

Fig. 1 Falling-film microreactor with inspection window (IMM).

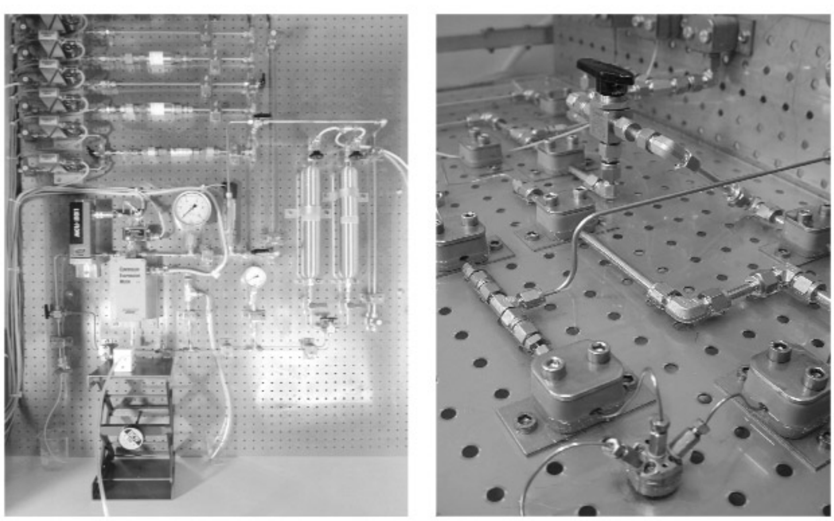

Fig. 2 Typical set-ups of mixer-tube reactors (IMM).

the complete set-up, because it acts itself as flame arrester. Even if an explosion occurs, an impact to the environment can be neglected. Reactions under high-pressure conditions such as hydrogenations with pure hydrogen seem to be possible with minor safety regulations (Fig. 3).

A high integration of microdevices is useful for the build-up of compact microplants, but it can also be interesting if a number of chemical reactions are operated in parallel (e.g., for the parallel screening of materials such as catalysts and pharmaceutical active substances). These devices cannot be considered micro in their general outer appearance. But the single reactors that carry the materials to be screened are often microstructured, so these devices may be called microstructured reactors compared to the usually much smaller microreactors. The reactor set-up for 48 single reactors is shown in Fig. 4.

A number of companies such as Cellular Process Chemistry (CPC), Mainz; mgt mikroglas, Mainz; FZK; and IMM are working presently on the design of highly integrated microdevices for the set-up of complete chemical microplants. A drawback of their product portfolio is still the lack of standardized interfaces which would correspond to industrial solutions like standardized flanges. First attempts to solve this problem are undertaken by the American Center for Process Analytical Chemistry (CPAC) consortium [3] (Fig. 5), and by the German consortium of microprocess engineering [4].

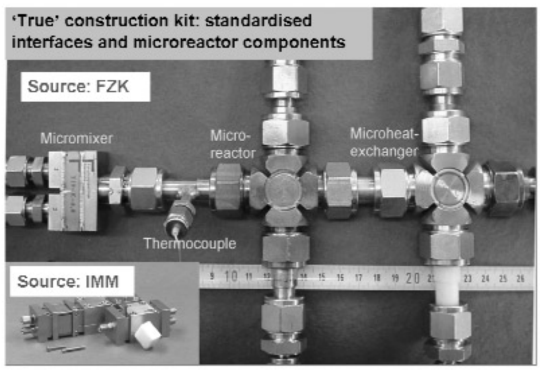

Fig. 3 Set-up of a compact plant for H_2–O_2 contacting (FZK) and standardized microreactor components (IMM).

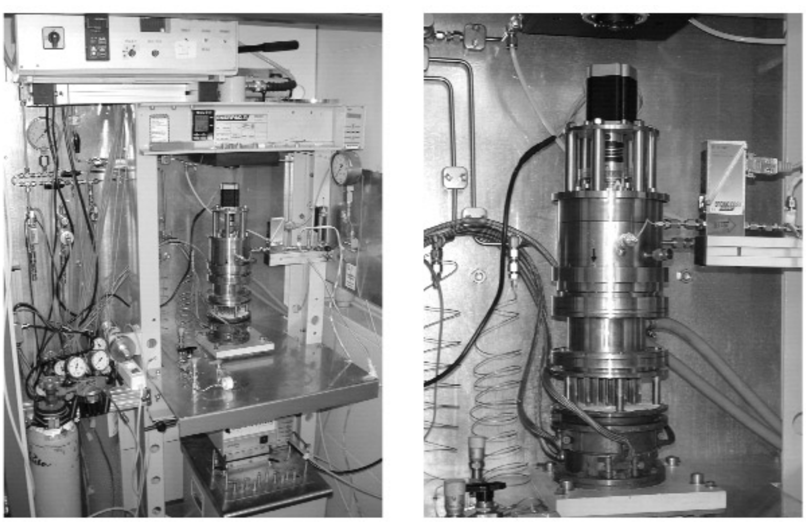

Fig. 4 Parallel reactor set-up in the laboratory (left: the hydraulic table press that seals the reactor, right: the reactor with heating bends, stepping motor, and online-connection to the GC, IMM).

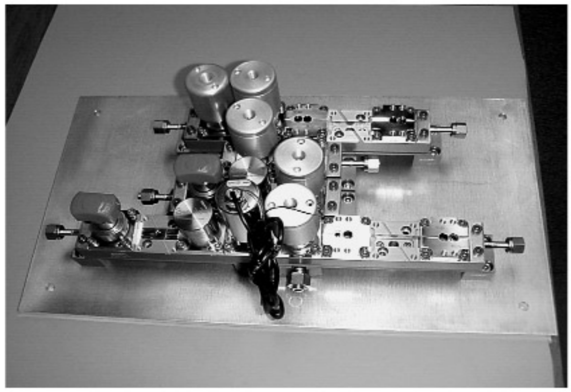

Fig. 5 Compact system set-up [3].

Another drawback to establishing complete chemical plants is the lack of separation-type unit operations for the isolation of pure products such as extraction and rectification devices. First successful results with the rectification were reported in the meanwhile [5]. Extraction in microdevices is sometimes performed by the well-known concept of mixer-settler [6], which is limited in its application to substances with fast-settling characteristics. Another more innovative extraction approach refers to the continuous, parallel guiding of two liquids without intermixing them, which is achieved by precisely defining their interface via slits (dislocation of corresponding microchannels) or microstructured membranes. However, these drawbacks are being recognized and will be dealt with in the future.

IMPACT ON CHEMICAL WEAPONS

It cannot be denied that microreactors have the potential to be used in military or terrorist applications. They can be fabricated by common technologies, of course, only by highly skilled personnel at present; but in the future, without any doubt, they can be fabricated in a regular workshop. With the knowledge of chemical fundamentals and advice found on the Internet, the fabrication of chemicals scheduled 2–3, and in some cases even scheduled 1, by the Chemical Weapons Convention (CWC) is no longer restricted to a chemical lab. Of course, there are high risks to handling highly toxic chemicals, but after the September 11th event it cannot be excluded that terrorists will not discourage a chemical weapons (CW) attack.

Besides the older chemical weapons chlorine and phosgene, methyl isocyanate becomes more and more important as a precursor for chemical weapons. This substance, widely used in chemical industry, is volatile and extremely toxic. The pilfering of this substance from a production plant cannot be noticed, but the transport is high-risk. But it is conceivable to make methyl isocyanate by catalytic dehydrogenation of *N*-methylformamide, a common and less-toxic solvent, by applying a microreactor set-up.

To prevent handling of lethal nerve gases (e.g., sarin, soman, or VX), so-called binary weapons were developed. In a last step, two primary less-toxic compounds were mixed at the point of use immediately. The same mechanism can be employed by using highly efficient micromixers, which carry out a complete mixing in less than a few milliseconds at a throughput of several litres per hour [7].

A "pocket" chemical plant, as shown in Fig. 6, cannot be monitored or detected. In this context, it has to be pointed out that the shown pocket plant was "placebo equipment" serving only for rough graphic nature without any realistic background on chemical engineering issues (Fig. 6).

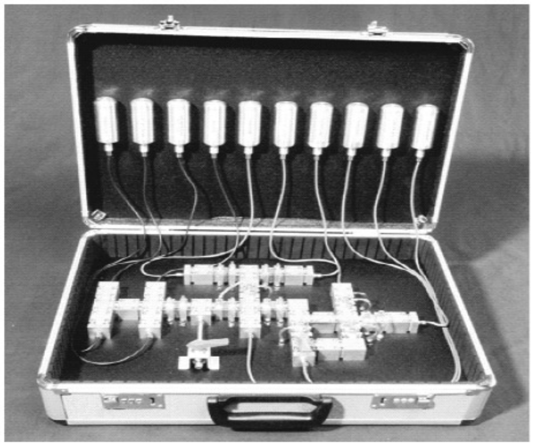

Fig. 6 Vision of a chemical suitcase plant (IMM).

SUMMARY

The situation of "microreactors", better called "microprocess engineering" is complex. We found many possibilities for applying microsystems in chemical research and even in chemical production. In the last five years, the field has become more and more attractive and a couple of start-up companies and research departments in the chemical industry were founded. The results of the research are promising, and some changes in chemical process technology are observable. From our point of view, we never expected a possible use of microreactors for fabrication of CW or for terrorist attacks, which so far has not been reported.

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