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New non-traditional multiphase catalytic reactors based on monolithic structures

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Abstract

Also in multiphase applications, monolithic catalytic reactors have a large potential. In many respects they outperform the conventional reactors such as slurry and trickle bed reactors. Monoliths can play a role in process intensification because they allow exceptionally large rates and selectivities. They can also be used in multifunctional reactors. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Monolithic catalysts; Multiphase reactions; Multifunctional reactor

1. Introduction

In the last decades of the 20th century, a clear trend has been set in chemical industry towards sustainable technology. Routes to accomplish this include at the chemical side the opening of alternative, more efficient and less polluting production routes, often based on new, highly selective (bio)catalysts and at the engineering side the integrated approach to improved or new processes. Process intensification currently draws a lot of attention and it has become clear that multifunctional and structured reactors will play a key role [1]. These two approaches meet where catalysts are applied in a structured way. A monolith is a good example: the borders between catalyst and reactor vanish [2,3]. Also other structured reactors deserve attention, but for the 'message' it suffices to limit the discussion to monolithic reactors. The monolithic catalyst is well known from the automotive application as exhaust gas converter, and probably it is the most popular catalytic reactor worldwide. Without exaggeration, it can be seen as one of the major contributions in the last decades of science and technology to the quality of the environment.

Various types of monolithic catalysts can be distinguished (Fig. 1). They can be produced by extrusion of support material (often cordierite is used), of a paste containing catalyst particles (e.g. zeolites) or a precursor for the final product (e.g. polymers for carbon monoliths).

Alternatively catalysts, supports or their precursors can be coated onto a monolithic support structure ('washcoating'). The corners in the channels are generally coated more resulting in a rounded shape. Zeolites can be coated by growing them directly on the support during the synthesis [4]. Even the extruded monolith can partially be converted into zeolites [5,6].

All major catalyst support materials, ceramic and polymeric, have been extruded as monolithic structure [3,7], while as support mostly ceramic materials are used. Metallic support structures are only used

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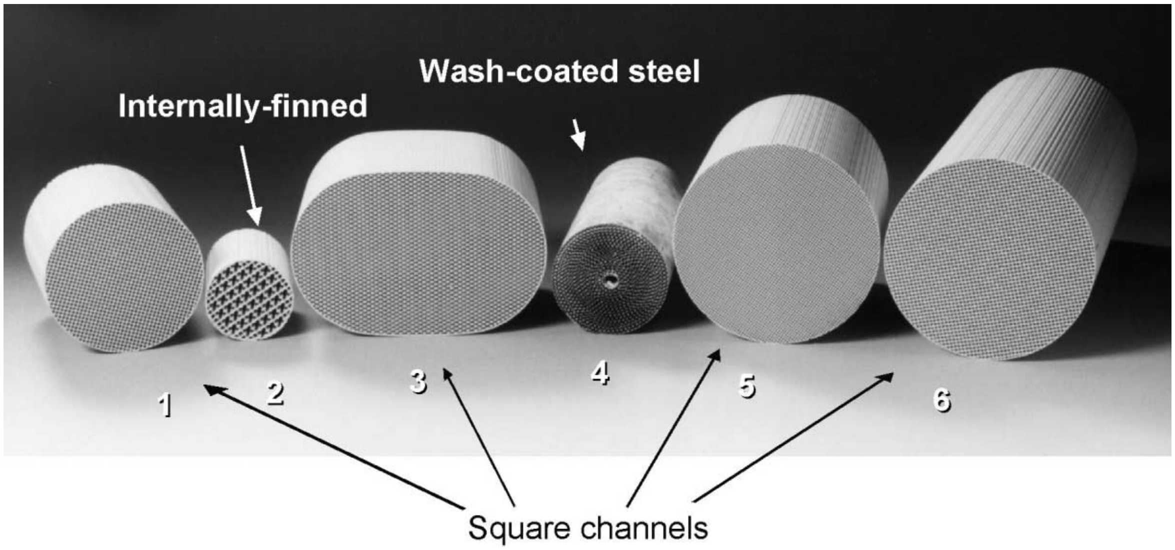

Fig. 1. Monolithic structures of various shapes. Square channel cordierite structures (1, 3, 5, 6), internally finned channels (2), washcoated steel monolith (4).

for automotive applications [8]. The choice for a certain catalyst type will strongly depend on the balance between maximizing the catalyst inventory and catalyst effectiveness. For slow reactions a high catalyst loading is desired and the pure catalyst-type monolith is desired, while for fast reactions or if diffusion is slow a thin coating with a maximum geometric area is preferred.

Monoliths are at present mainly used as three-way catalysts in cars [9–11], as selective catalytic reduction catalysts in power stations [12,13] and for ozone destruction in airplanes. What causes this popularity? The catalyst consists of one piece, so no attrition due to moving particles in a vibrating case occurs. The large open frontal area and straight channels result in an extremely low pressure drop essential for end-of-pipe solutions like exhaust pipes and stack gases. The straight channels prevent the accumulation of dust in demanding applications like coal-fired power stations. Although for these applications numerous hurdles have been taken, the reaction system is relatively simple: a single fluid (gas) phase has to be treated. More demanding applications of monoliths are now being investigated, fast reactions at high temperatures such as steam reforming, partial oxidation of hydrocarbons to syngas and oxidative dehydrogenation [14]. These examples are limited to single-phase applications. In the following it will be shown that also in multiphase processes, monoliths are often preferred reactors.

Monoliths are industrially produced in large numbers by extrusion. This leads to the attractive situation that although they are sophisticated structures, they are commercially available at reasonable costs. Of course, monoliths have disadvantages. They share with packed bed reactors the requirement of a sufficient catalyst stability. With respect to mass- and heat-transfer characteristics, the major limitations are the laminar flow through the channels, no interconnectivity between the channels and a poor radial heat conductivity. The latter two properties are much better for the foam-type monoliths, but with a trade-off in a higher pressure drop. In principle, a laminar flow velocity profile is associated with low mass transfer and a large residence time distribution. Fortunately, for gases due to the small channel size and high diffusivity, this radial transport in the channels is sufficiently fast. Typical time scales for diffusion are given in Table 1. In liquid phases the diffusivity is three orders of magnitude smaller and this is one of the reasons that monoliths do not enjoy such a popularity in liquid phase operations. In this paper it will be shown that this is based on a misconception.

Table 1
Diffusion time scales in catalytic reactors ($\tau_D = \ell^2/2D$)

	D (m^2/s)	ℓ_D			
		1 mm	0.1 mm	10 μm	1 μm
Gas	$\sim10^{-5}$	50 ms	0.5 ms	5 μs	50 ns
Liquid	$\sim10^{-9}$	500 s	5 s	50 ms	0.5 ms
Liquid in catalyst pore	$\sim10^{-10}$	5000 s	50 s	0.5 s	5 ms
In zeolite pore	$\sim10^{-11}$	50 ks	500 s	5 s	50 ms

2. Multiphase reactions and reactors

Various types of reactors are being used commercially for multiphase applications, the major ones being the slurry reactor, bubble column and the trickle bed reactor. Fig. 2 gives a schematic of the slurry, the bubble column and the trickle flow reactor. Each reactor has its own advantages and disadvantages. Slurry catalysts are small (typically 50 μm), while trickle bed particles are larger (millimeter scale) in view of the allowable pressure drop over the bed. The particle size is a crucial parameter. In general it can be stated that larger particles are less efficient and, even more important, are less selective in those reactions where the desired product is subject to an undesired following reaction (A → B → C with B as the desired product). Major disadvantages of the slurry reactor are the separation of product and catalyst and catalyst attrition. Filtration of fine and often highly pyrophoric particles makes this an often inconvenient reactor type. The trickle bed reactor is much more convenient but large particle sizes are unavoidable. Moreover, local hot spots may develop and cause runaways. An important limitation of trickle bed reactors is that in practice, they are nearly always operated co-currently to avoid liquid entrainment by the gas ('flooding'). Some important commercial applications, however, would benefit from a counter-current operation, especially for equilibrium limited reactions and in case

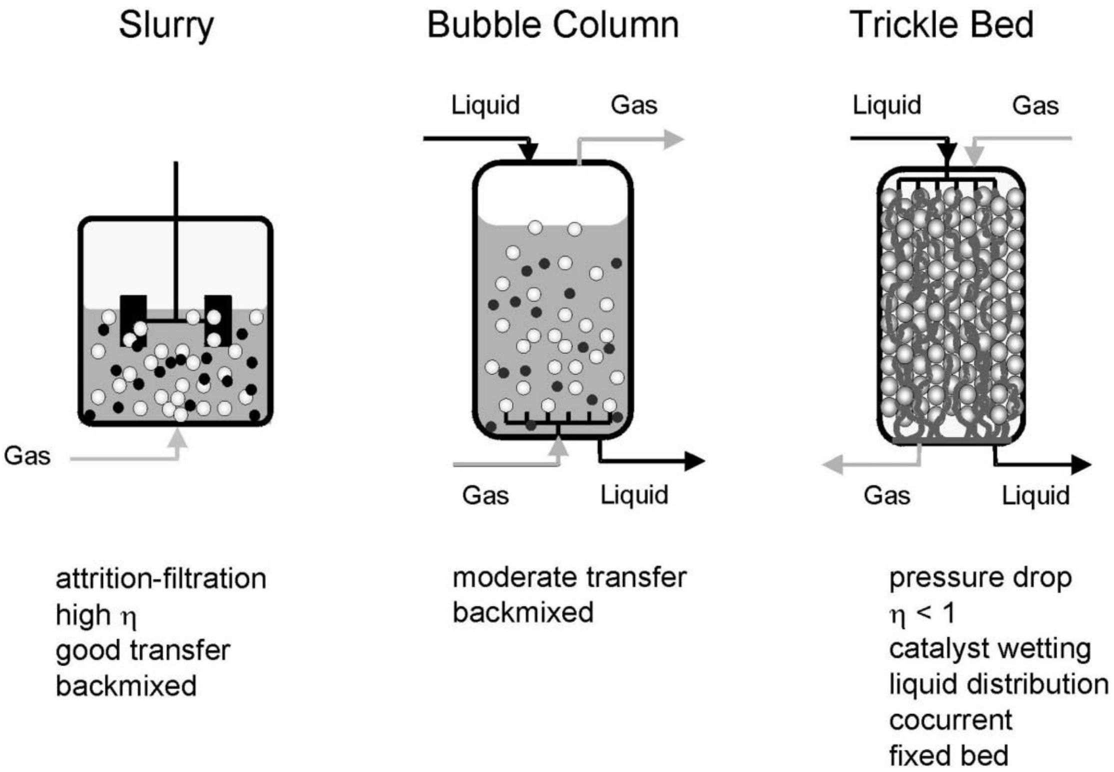

Fig. 2. Schematic representations of three practical gas–liquid–solid reactor systems.

of strong product inhibition [15]. Examples are hydrotreating processes like hydrodesulfurization (HDS), hydrodenitrogenation (HDN), hydrocracking, and organic synthesis like esterifications and acylations. Only for large particles or low flow rates this operation mode could be achieved in a packed bed (Synsat process, [16]). Deep desulfiding is a good example of a reaction where the concentration profile in counter-current operation is more optimal from a reaction kinetics point of view. Also more active catalysts (e.g. noble metals) can be used in the last part of the reactor ('catalyst profiling') that are more susceptible to H_2S poisoning and, as a consequence, are not suitable for co-current operation. Overall counter-current operation leads to deeper desulfurization with smaller catalyst units or to larger throughputs [17].

3. Hydrodynamics and mass transfer

For co-current gas–liquid flow, several flow regimes can occur. The preferred one usually is the so-called Taylor or slug flow. This type consists of gas bubbles and liquid slugs flowing consecutively through the small monolith channels. The gas bubble fills up the whole space of the channel and only a thin liquid film separates the gas from the catalyst (Fig. 3). For two reasons, the rate of mass transfer is large. First,

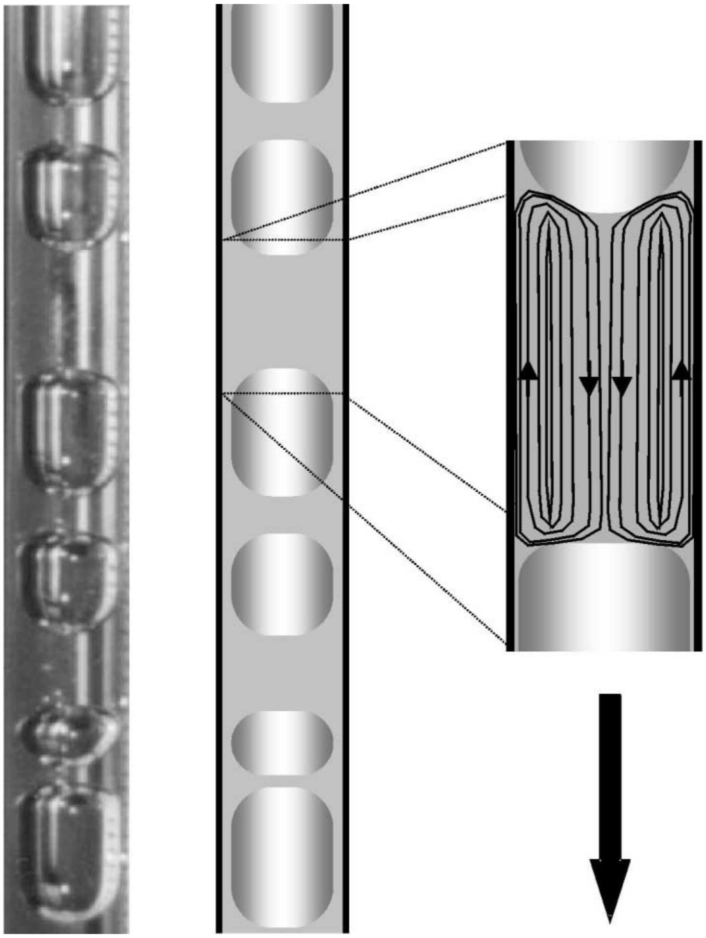

Fig. 3. Taylor flow through a single tube. Left: picture of air–water flow, middle: schematic representation of the gas and liquid slugs, right: CFD velocity pattern in a liquid slug showing the liquid recirculation.

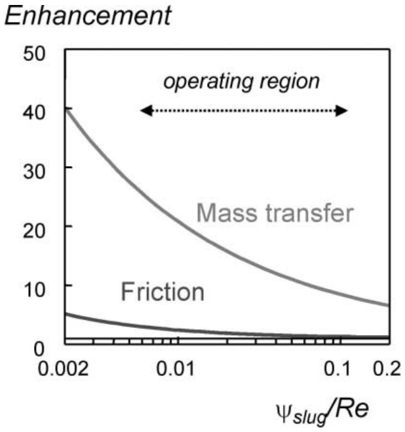

Fig. 4. Relative increase of friction and mass transfer due to gas–liquid Taylor flow compared to developed laminar flow in small tubes. ψ represents the dimensionless length of a liquid slug, *Re* the Reynolds number based on the liquid.

the liquid layer between bubble and catalyst coating is thin, increasing mass transfer. Secondly, the liquid slugs show an internal recirculation during their travel through a channel. Because of this, radial transfer of mass is increased. Moreover, the gas bubbles push the liquid slugs forward as a piston and a type of plug flow is created. Compare this with single-phase liquid flow through the channels. Because of the low channel diameter the flow will be laminar and, as a consequence, the radial transport will be extremely slow, leading to a very poor reactor: rates are slow and the reactor exhibits strong non-plug flow behavior. For multiphase operation under slug flow conditions the mass transfer increase is an order of magnitude larger than for single-phase liquid flow, whereas the increase in friction, that is pressure drop, is much less (Fig. 4). A fortunate finding is that Taylor flow conditions are easily realized under practical conditions. These results even suggest to induce Taylor flow in single-phase liquid phase reactions over monoliths by adding an inert gas component. Mass transfer is usually expressed as the factor $k_l a$, the mass transfer coefficient times the exposed surface area per unit volume a. Values of $k_l a$ depend strongly on the gas and liquid properties, but for many systems values $>0.5\,\mathrm{s}^{-1}$ are found, and possibly values even much larger than $1\,\mathrm{s}^{-1}$ apply. This is one order of magnitude higher than in order reactor types.

Ideally, in contrast to packed beds, scale-up of monolithic reactors is very simple. When we know the behavior of one channel, we should be able to predict the whole reactor. Is this really true? Compared to a packed bed, a monolithic reactor differs in radial transport. When the initial distribution of liquid in the radial direction is non-ideal, going down through the reactor, this unfavorable distribution does not change. In a packed bed reactor this happens to a certain degree. Therefore in scale-up the reactor inlet system has to be designed well so that the distribution of the liquid in the top of the reactor is ideal. We found that if a bubble emulsion on top of the monolith is present a satisfactory distribution seems to be guaranteed, similar as found for trickle bed reactor operation. We carried out a large experimental program and defined the conditions where this happens to be the case. It appeared that the flow rate has to be above a specified minimal value. Stacking of monolith pieces on top of each other or with some spacing in between, to allow some radial mixing, does not seem to have a negative impact on the flow characteristics.

So, the flow rates have to be sufficiently high in order to guarantee a good distribution of liquid over the cross-section of the reactor. One might wonder if upflow of gas and liquid is not to be preferred because lower flow rates might be applied. This appeared not to be the case. Again, high flow rates are needed to establish a good gas–liquid flow distribution. Currently, research is in progress to design systems that allow low flow rates.

From an extensive study, it appeared that in structured reactors, counter-current operation is possible at industrially relevant conditions. The breakthrough was the design of optimal monolithic structures and dedicated inlet and outlet systems. For example, good results were obtained by cutting the monolith under an angle of 70° as most optimal value, or by a special outlet construction, guiding away the liquid from the exit (Fig. 5).

Mass transfer was studied experimentally in various ways. Non-reactive studies involved the uptake or release of oxygen by the liquid for the measurement of gas–liquid transfer, while in reactive studies the overall gas–solid or liquid–solid transfer could be determined. Satisfactory reactions for this purpose appeared to be the hydrogenation of α-methylstyrene, the oxidation of formic acid and some (immobilized) enzyme catalyzed reactions. As an example of the performance, a monolith in the hydrogenation of α-methylstyrene was

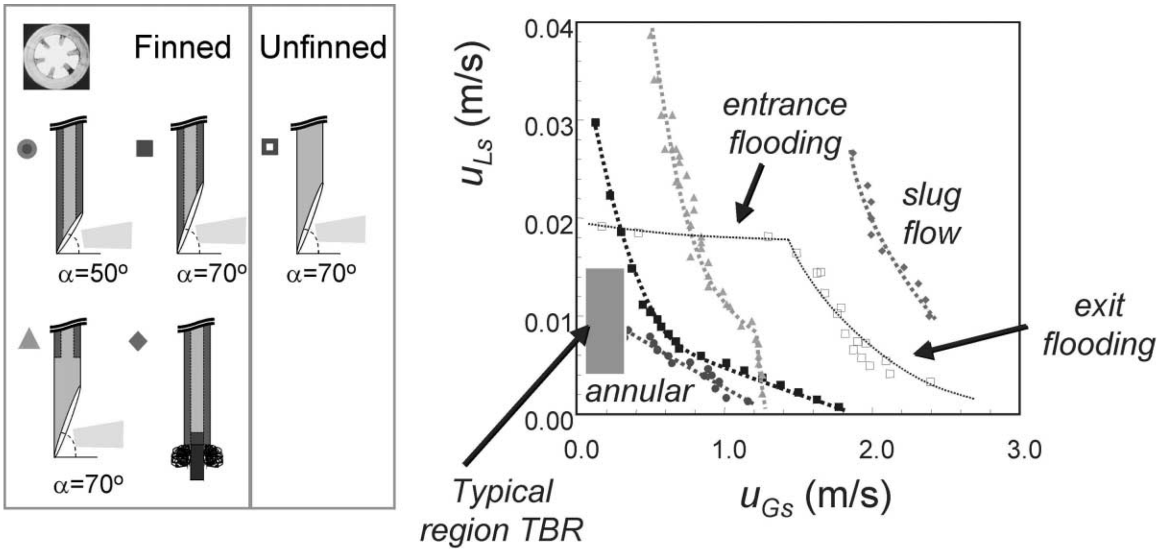

Fig. 5. Flow map for counter-current gas–liquid flow (*n*-decane/air) through finned channels with different outlet geometries. Indicated are the flooding limits for single tubes. Finned tubes mainly only exhibit outlet flooding, the unfinned tube also inlet flooding. The unfinned tube has a larger hydraulic diameter due to the absence of the fins and hence a wider flooding-free region. Injecting the gas via a capillary and guiding away the liquid through quartz wool plugs even enlarges this region for the finned channel. This graph illustrates that current operating region for trickle bed reactors (HDS) is well covered by the finned monoliths.

compared with a trickle bed reactor under identical reaction conditions in co-current mode. Both catalysts were prepared by deposition precipitation resulting in an egg-shell type of Ni catalyst. Observed reaction rates on different bases are compared in Table 2.

Per unit reactor volume the washcoated 400 cpsi monolith yielded a more than four times higher hydrogenation rate. For a reaction that is mass transfer controlled, this stresses the better mass transfer in the monolith. Overall, the Ni was used 40 times more efficiently in the monolith than in the trickle bed reactor, even in spite of the use of an egg-shell catalyst in both cases. Probably the Ni containing layer in the extrudates is still too thick compared with that in the washcoat layer and not all of it is being used. This demonstrates the attractiveness of using monoliths in very fast catalyzed gas–liquid–solid reactions.

A better fundamental understanding of the effect of the Taylor flow through the channels and the effect on the mass transfer is still needed in order to answer questions like is there an optimum bubble/slug length, what is the optimal frequency, and can this be controlled?

4. Catalyst preparation

Monolithic catalysts can be prepared and classified in various ways. The optimal morphology and structure will depend on the specific application. The

Table 2

Activities for both a monolithic and trickle bed reactor for the mass transfer limited hydrogenation of α-methylstyrene over an egg-shell nickel catalyst (373 K, 10 bar H_2)

Activity per	Units	Monolith (400 cpsi)	Trickle bed	Ratio
Reactor volume	$\mathrm{mol/m^3_{reactor}\,s}$	21.0	4.6	4.6
Nickel amount	$\mathrm{mol/g_{nickel}\,s}$	3.4×10^{-3}	8.4×10^{-5}	40

ceramic monoliths as used in catalytic converters are produced by extrusion. Analogous systems are produced from corrugated metal sheets. The ceramic type is by far the most used. Catalysts are put on the surface by coating techniques. Usually, the active catalyst phase is a nanosized material and in order to produce satisfactory catalytic monoliths a so-called washcoat is applied, allowing various near-conventional catalyst preparation techniques. In a sense, the monolithic structure is the backbone of the catalyst support. Another way of preparation is the direct extrusion of the support or the active material. Examples of the former are silica and alumina washcoated monoliths. Examples of the latter are monoliths produced by extrusion of mixtures containing zeolites or catalyst particles. An advantage of the latter is that the catalyst loading of the reactor can be high.

Slurry-type catalysts are often carbon supported noble metals. Monoliths, however, are hardly known in the carbon form. Vergunst and co-workers [18] developed a technique to coat ceramic monolithic structures with a carbon layer by dipcoating with a partly polymerized polyfurfurylalcohol liquid and further polymerization at the channel walls. Carbonization led to a regular coating of the cordierite with carbon. Noble metals could be applied to this carbon coating by surface activation and ion exchange. A Pt on carbon coated monolith proved to give a good performance in the selective hydrogenation of cinnamaldehyde to cinnamylalcohol, at least as good as a slurry catalyst, but without the inconvenience of slurry reactors.

The ceramic monolith that is being used as a support structure for a catalyst is macroporous. This facilitates the anchoring of washcoat layers. Also the macroporous structure can be used to enlarge the surface area of essentially nonporous catalytic materials. Even a thin support layer can be coated first on the ceramic structure followed by catalyst coating. This was successfully applied in our group with the strongly acidic polymeric catalyst Nafion and with BEA zeolite. They were applied in several acid catalyzed reactions, like alkylation, acylation, etherification and esterification.

It is not surprising that impregnation of a washcoated monolith must be performed with caution. In fact similar phenomena occur with a monolith as with a particle, only the dimensions of a monolith and a particle differ considerably. Both in particles and in monolith washcoats capillary phenomena can take place during the drying phase. This causes liquid transport out of the particle or monolith (!) to the external surface, resulting in uneven distributions of the active phase. Although the radial length scale of the washcoat is small, even an egg-shell distribution in the washcoat layer can occur, analogous to particles.

The activated monolithic catalysts turned out to have the expected pleasant property of simple handling. They can easily be stored in a liquid phase and transferred simply to a reaction vessel. The adhering liquid prevents sufficiently the reaction of an activated catalyst with ambient air. In this way catalysts can be stored on the shelf and used whenever needed. This is comparable to the protection of activated fat hardening catalysts by impregnation with fats.

5. Reactors

It is useful to start with a summary of the major basic concerns for gas–liquid–solid catalyzed reactions:

- catalyst quality (diffusion length, loading, profiles),
- catalyst separation and handling,
- heat supply and removal,
- hydrodynamics (regimes, controllability, predictability),
- safety and environmental (run-aways, hazardous materials, selectivity),
- transport resistances (rate and selectivity).

Monoliths can be used both for co- and counter-current operation in gas–liquid reactions. They can combine the advantages of the slurry and trickle bed reactor and eliminate their disadvantages [19]:

- The catalyst can be coated as a thin layer on the channel walls, and can be described as a “frozen slurry reactor”.
- Larger channel geometries (e.g. in the internally finned monolith channels) allow counter-current operation of gas and liquid.
- The catalyst inventory can be increased by using thicker coatings or using a monolith extruded from the catalyst support, e.g. an all-silica-monolith.
- The high cell density of the monoliths creates a high geometric surface area. Using a packed bed, unrealistically small particles would be needed to achieve this.

- The monolith reactor has a negligible pressure drop.
- Scale-up is in principle straightforward.
- Monolith reactors are intrinsically safer. The monolith channels have no radial communication in terms of mass transport and the development of runaway by local hot spots in a trickle bed reactor cannot occur. Moreover, when the feed of liquid or gas is stopped, the channels are quickly emptied.

Of course, monoliths have disadvantages. They are at this moment more expensive than particle catalysts. In fixed bed operation, they will have to exhibit a sufficiently long lifetime. In quickly (irreversibly) deactivating reactions, they will not be used. Of extreme importance is that the inlet distribution should be secured. In co-current flow, both gas and liquid have to be contacted evenly with the catalyst at the monolith walls.

From the above, it should be evident that monolithic reactors (and other structured reactors) in many respects are superior to classical reactors. Indeed, for several reactions, monolithic catalysts have been reported, although except for one case only at the bench or pilot scale. The interesting points are to demonstrate that the 'theoretically' outlined advantages are indeed present. They in fact boil down to compared to classical reactors, a larger reactor productivity, a better selectivity control and a higher efficiency. The first implies also a better catalyst utilization. Obvious is the fact the catalyst is fixed in a reactor and pressure drops are low.

Satterfield [20] already demonstrated that in co-current mode hydrotreating using monoliths led to deeper removal of sulfur and nitrogen compounds. The hydrogenation step in the anthraquinone process of AKZO-Nobel is an industrial realization of a monolithic reactor and includes a lot of pioneering work from the Anderson group [21–24]. More examples of the use of monoliths can be found in [1].

In our own group in cooperation with a chemical industry, we have studied the selective hydrogenation of pyrolysis gasoline, a by-product of the naphta cracking which can be upgraded to gasoline by selectively removing gum forming dienes and styrene-like molecules, leaving intact the internal alkenes. This study [25,26] demonstrated the plug-flow behavior needed for such a selective conversion and the efficient use of the active phase, which was at least a factor 3–4 better than in a trickle bed operation. The hydrogenation of α-methylstyrene, mentioned above, is an even more appealing example of a better active phase utilization and exemplifies the good mass transfer properties.

Recently, a patent concerning the hydrogenation of dinitrotoluene to toluenediamine over a monolith was issued [27]. In this process the important claims comprise a fast and efficient continuous production, a safe operation, a good reaction selectivity, and the elimination of the use of a solvent.

The batchwise hydrogenation of benzaldehyde indicated that the selectivity to benzylalcohol was at least as good as for a similar slurry catalyst. More reactions that are being studied in our group comprise not only other selective hydrogenations and oxidations, but also purely liquid phase reactions, biocatalyzed reactions and even four-phase reactions, indicating the application potential of monoliths.

An attractive property of monolithic reactors is their flexibility of application in multiphase reactions (Fig. 6). These can be classified according to operation in (semi)batch or continuous mode, and as plug flow or stirred tank reactor, or according to the contacting mode as co-, counter- and cross-current. In view of the relatively high flow rates and fast responses in the monolith, transient operations also belong to the possibilities.

The co-current monolith reactor, with its plug flow characteristics, can in principle be used in downflow, upflow and horizontal flow mode, provided a good gas–liquid distribution is secured [28]. The latter mode might solve a major problem in practical applications of monoliths: because for hydrodynamic reasons high flow rates are needed, the reactor length tends to be very large. Research with respect to this type of reactor is in progress.

The best studied mode is co-current downflow. It can be envisaged in two ways, either with a controlled flow of gas or a free recirculation due to entrainment by the liquid (Fig. 6). This reactor is an alternative to the bubble column reactor, often used in biotechnological applications. Since high reactor types are being used and large gas flow rates are required, the energy input to introduce and compress the gas for injection at the bottom is relatively high. In the downflow monolith reactor, this gas injection is automatically achieved. The co-current reactor type can easily be used as a stirred reactor type by a large recirculation flow without extremely large energy input due to the low pressure drop. Highly exothermal reactions can be applied by external heat exchange. If a CSTR-type reactor is not desired, the horizontal reactor with interstage cooling is an attractive alternative.

For slower reactions the monolithic catalyst can be mounted as a stirrer on a rotating shaft, alternatingly being contacted with the liquid phase and the gas phase. By sectioning the reactor, co-, cross- and counter-current flow can be achieved (Fig. 6). Monolithic stirrers can also be applied in purely liquid phase reactions. Recently, the monolithic stirrer has been demonstrated for hydroformylation. Due to the low friction, about 70–80% of the advected liquid flows through the monolith and a good contact with the catalyst is guaranteed [29].

The application of monolithic catalysts is not restricted to a gas and one liquid phase. More liquid phases can be used when they are immiscible and contain reactants in different phases. A second liquid phase can also be added deliberately to enhance

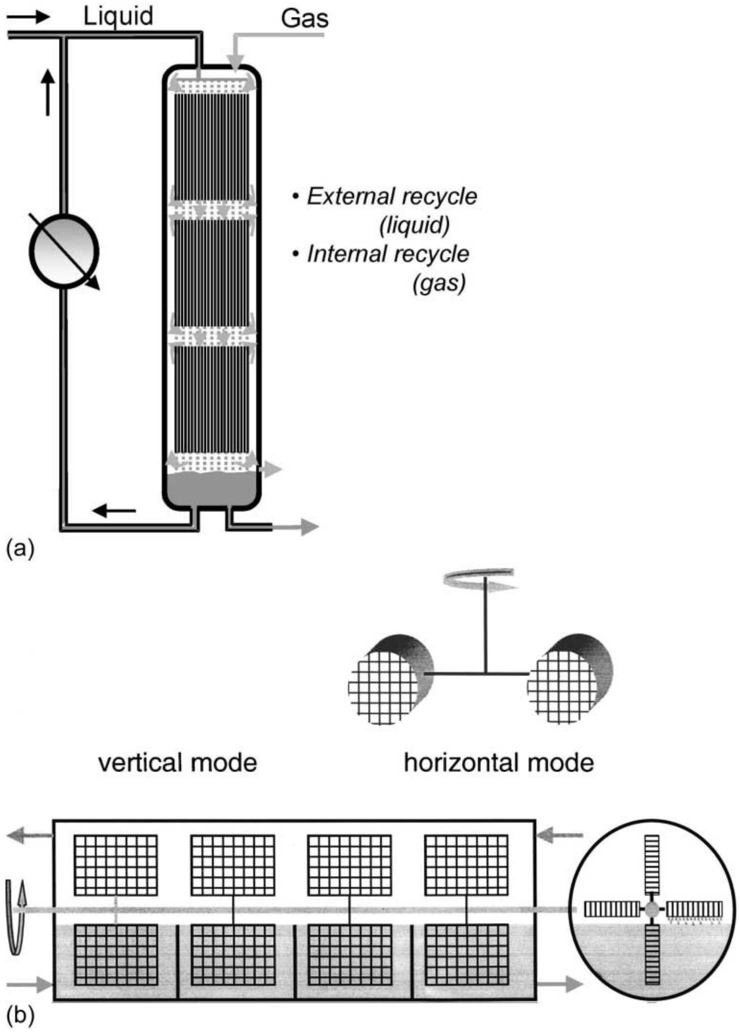

Fig. 6. Various examples of multiphase reactor configurations for monolith applications: (a) co-current Taylor flow reactor, (b) horizontal and vertical monolithic stirrer reactors, (c) moving bed applications.

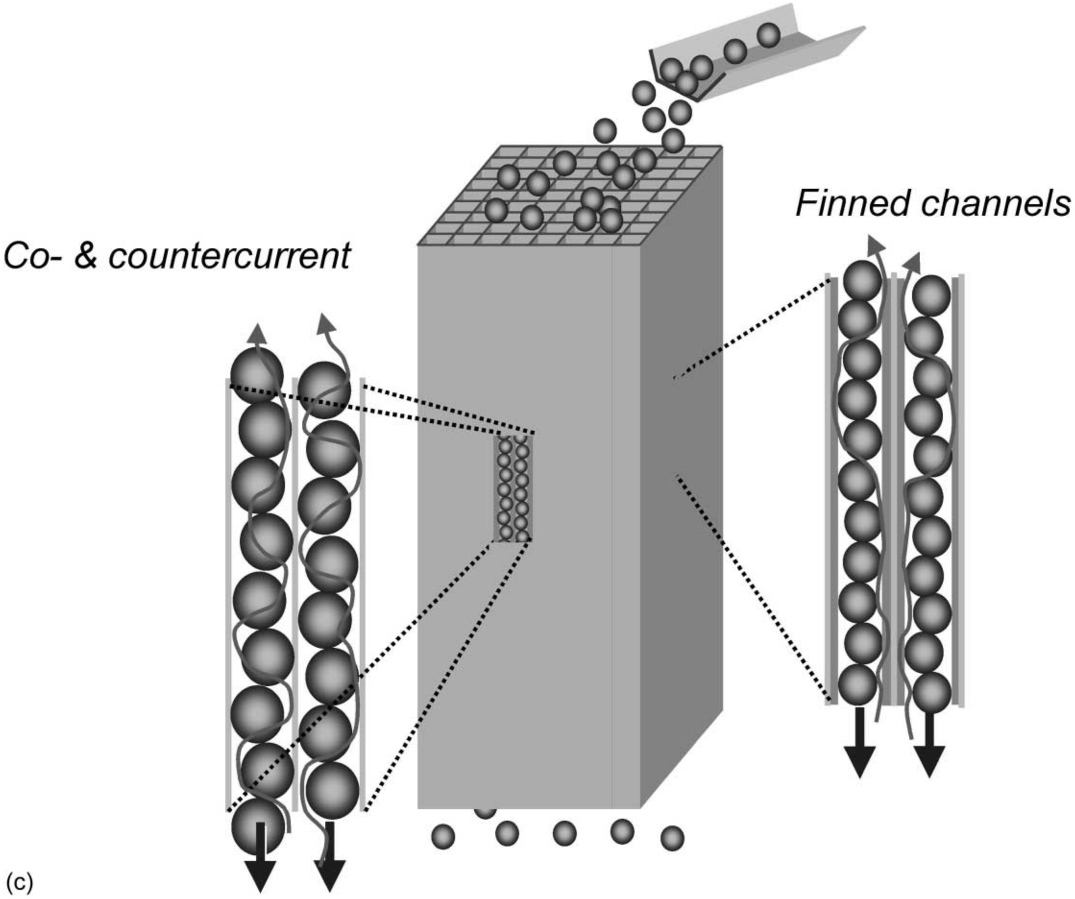

Fig. 6 (*Continued*).

selectivity or to extract a product. A good example is the following. The selectivity of the (commercial) slurry phase hydrogenation of benzene to cyclohexene over Ru black is tremendously enhanced by adding a water salt solution to the slurry phase. This will surround the Ru particles and modify the adsorption properties of the reacting components [30]. In a monolith, this might be well achieved too, with a better control of the catalyst wetting.

So, apart from GLS-type also LLS- and GLLS-type catalytic reactions are possible using monoliths. The attractive property is to bring reactants efficiently in contact with the solid catalyst. But there is more. They can be applied in stripping, extraction, evaporation, drying and distillation, in co- as well as in counter-current modes. Monoliths are then used as low-pressure drop and low-energy consuming contacting devices. The combination with catalysis is then obvious to arrive at a multifunctional reactor system in which reaction and controlled reactant addition or product removal is achieved. These applications are not restricted to gaseous or liquid phases, but also solid phases. The straight channels are ideal for fixed or moving bed applications (Fig. 6). The former to combine an optimized catalyst inventory and liquid hold-up, while still having a relatively low flow resistance of a single pellet string reactor. Moreover, existing catalysts can be applied. The use of finned channels gives even more freedom. This could be considered as a ‘structured trickle bed reactor’ where longer residence times can be achieved than in a straight channel monolith. Blocks of monoliths filled with particles may find application in catalytic distillation or three levels of porosity reactors [31], replacing the catalyst 'bales' [2].

Channels filled with a single particle string have much better solid flow characteristics than a packed bed, so application of monoliths as moving bed reactor internal is seducing. This opens a wide range of applications, covering moving bed adsorption processes, moving bed applications for deactivating catalysts (reforming, hydrodemetallization, dehydrogenation), solids trickle flow reactors, and regenerative processes where a moving catalyst is alternatingly subjected to different atmospheres and transport reaction intermediates and/or heat (FCC, butane to maleic anhydride oxidation). The channel structure also works as a flow straightener, providing better plug flow characteristics in large diameter entrained flow reactors, which suffer from backmixing of catalyst at the reactor wall.

Other applications of monoliths comprise combinatorial catalysis. A monolith is in principle a large set of parallel reactor tubes ('a large-scale microreactor') and suited for testing a large number of catalysts simultaneously.

In summary, monoliths are a versatile and powerful tool for catalysis engineering.

6. Conclusions

Monolithic and other structured catalysts have a large potential in contributing to a sustainable chemical process industry. In catalytic processes they exhibit favorable properties with respect to practical convenience, high rates, high selectivity and low energy consumption. From an engineering point of view, also the easy scale-up and the potential of high safety are appealing. This is not limited to single-phase processes but they are also well placed for multiphase processing.

Monoliths exhibit a large flexibility in operation. They are well suited for optimal semi-batch, batch, continuous and transient processing. Catalytic conversion can be combined with in situ separation, catalytic reactions can be combined, heat integration is possible, and all lead to process intensification. On the short term, catalytic monoliths will be applied to replace trickle bed reactor and slurry phase operations in view of the better overall conversion and selectivity performance. Monoliths allow the efficient use of the small sized catalyst particles, e.g. zeolites, and have a substantial flexibility with respect to catalyst inventory in a reactor. Multifunctional reactor operation like reactive stripping or distillation are challenging applications which are not too far away.

In the laboratory, monolithic structures provide a tool for downscaling catalyst testing units, contributing to microreactor technology and combinatorial catalysis. Research is still needed to provide the enabling tools for realizing many of these ideas. Catalyst preparation and extrusion should be developed further for specific applications, optimizing the structure and active phase distribution. Hydrodynamics and transport processes have to be described better to design processes.

In conclusion, it is expected that monoliths will be increasingly applied in chemical and biochemical conversion processes, from bulk to fine and specialty chemical production processes, in catalytic and non-catalytic clean-up processes and in a wealth of other applications such as drying and heat exchange.

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