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# On-microchip multiphase chemistry—a review of microreactor design principles and reagent contacting modes

George N. Doku,<sup>a</sup> Willem Verboom,<sup>b</sup> David N. Reinhoudt<sup>b</sup> and Albert van den Berg<sup>a,\*</sup><sup>a</sup>Laboratory of (Micro)Biomedical and Environmental Technology, MESA<sup>+</sup> Research Institute, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands<sup>b</sup>Laboratory of Supramolecular Chemistry and Technology, MESA<sup>+</sup> Research Institute, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

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## 1. Introduction

Miniaturized chemical reactors, typically on-chip micro-channel reactors have become important for analytical and environmental monitoring,<sup>1–4</sup> as measuring devices for on-line process optimisation,<sup>5</sup> as catalyst screening tools,<sup>6</sup> for the production of micro fuel cells,<sup>7</sup> and especially for microorganic synthesis/production in the pharmaceutical industry where the test-rig stage in the development of a drug does not require the production of large quantities of the chemical.<sup>8–12</sup> The most striking advantages of such microsystems are the high portability, reduced reagent consumption, minimization of waste production, remote (on-site) applications and efficient heat dissipation owing to the high surface-area-to-volume ratios. Quite a number of the reactions executed in such systems have involved reagent phases which are immiscible with one another; these include aqueous-organic liquid,<sup>13–16</sup> gas-liquid,<sup>17–37</sup> gas-liquid-solid,<sup>26–47</sup> and gas-gas-solid<sup>48–51</sup> systems. In such

systems, there exists the complexity of forcing a reactant of one phase to mix, diffuse and react with that of another, making the flow dynamics, the methods of promoting phase contacting and mixing critical.<sup>16–37</sup> The chemical kinetics would not only depend on the concentrations of the reacting species, but also on the mass transfer between the different phases. Whereas the design and operation of liquid-liquid and gas-liquid immiscible microreactor systems have depended mainly on the method of dispersion/phase contacting, gas-liquid-solid and gas-gas-solid systems have depended not only on the phase contacting, but also on the solid integration principles employed. In this paper, we present an overview of the critical issues in the development of on-chip multiphase chemistry systems. The microreactor design ideas employable, the methods of phase contacting and the consequent effects on the reaction yields are discussed.

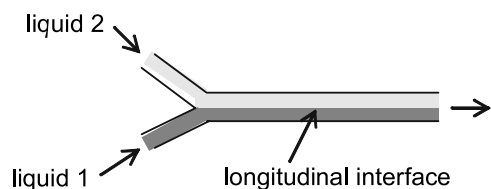
## 2. Immiscible aqueous-organic liquid systems

In immiscible organic-aqueous systems, the two different liquids could be pumped from individual supply channels to assume a parallel (longitudinal) contact-flow in a common

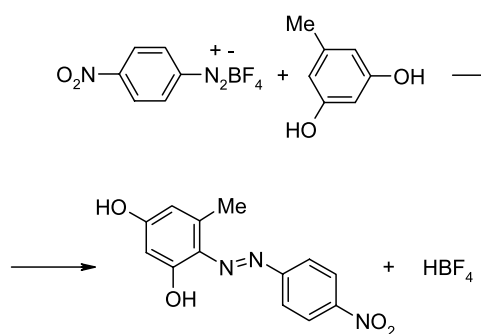
**Keywords:** Lab-on-chip microreactors; Multiphase reactions; Immiscible liquid-liquid; Gas-liquid; Gas-liquid-solid; Gas-gas-solid; Review.

\* Corresponding author. Tel.: +31 53 4892691; fax: +31 53 4892575; e-mail: a.vandenberg@el.utwente.nl

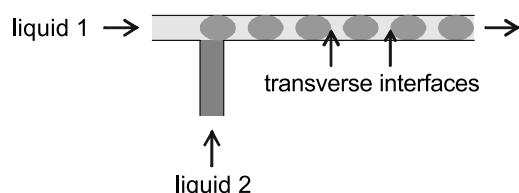
reactor channel (Fig. 1), where the phase contacting, diffusion-based dispersion and reaction occur at the longitudinal interface established.<sup>13,14</sup> Using a 250  $\mu\text{m}$  wide, 100  $\mu\text{m}$  deep and 3 cm long microchannel reactor, and a linear flow rate of 1.3  $\text{cm s}^{-1}$  (a residence time of 2.3 s), Kitamori et al.<sup>15</sup> reported a specific interfacial contact area of 80  $\text{cm}^{-1}$  and a close-to-100% conversion efficiency for the reaction between aqueous 4-nitrobenzene diazonium tetrafluoroborate ( $10^{-4}$  M) and ethyl acetate-dissolved 5-methylresorcinol ( $10^{-3}$  M), under continuous flow conditions (Scheme 1). An undesirable insoluble precipitate side product (a bisazo product), which is normally produced from the main reaction product in conventional macrosystems, was not observed for the microsystem. This was said to be due to the large specific interfacial area and short molecular diffusion distance in the microsystem, which removed the main product from the aqueous phase to the organic phase, thus preventing the undesirable side reaction. Another configuration involves multiple-pulse (segmented) injections of one liquid into a main flow of the other, where diffusion and reaction occur at the multiple transverse interfaces established (Fig. 2).<sup>16</sup> Mixing in immiscible liquid systems and, in particular, fluid mobilization in electro-osmotic flow-based systems are improved by changing the lipophilic properties of the non-



**Figure 1.** Cocurrent mobilization of two immiscible liquids, and established longitudinal contact interface in a microchannel.



**Scheme 1.**

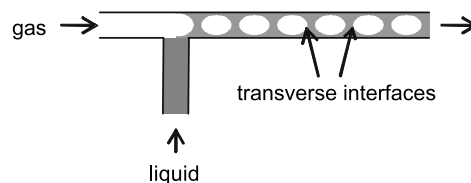


**Figure 2.** Segmented-pulse injection of one liquid into the main flow of another immiscible liquid, and established transverse contact interfaces in a microchannel.

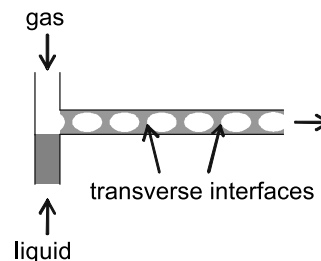
polar species in processes such as the addition of ion pairs (e.g., quaternary ammonium salts), the formation of micelles or, optimally, the formation of oil-in-water micro-emulsions, using appropriate surfactants.<sup>16</sup> This is, however, possible where surfactant and any co-surfactant additives would not interfere with the chemistry to be carried out. Whichever of the above techniques are used, however, the two liquid phases could be driven into a temporary hold-up reservoir equipped with some sort of turbulence-generating mechanism to improve upon the dispersion and mass transfer.

### 3. Gas–liquid systems

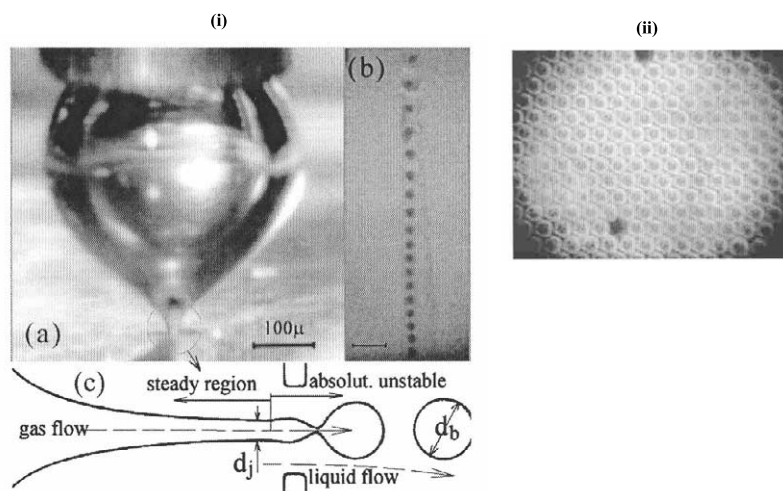
Gas–liquid microreactor systems require an efficient method of dispersing the gas in the liquid to increase the interfacial contact area whilst maintaining the dispersed regime along the whole microchannel reactor within a desired time frame. These reactors have mainly been hollow microchannels equipped with gas–liquid in-feeding mechanisms. Both the gas and liquid streams could be made to flow-in cocurrently, but, whilst the gas flows continuously, the liquid flow is pulsed, which results in a single-line segmented gas–liquid distribution in the channel (Fig. 3).<sup>17</sup> The gas and liquid streams could be fed at high speeds in a direct counterflow configuration using a ‘T’ mixer, where the gas and liquid streams collide head-on and generate a single-line, segmented bubble-train into a perpendicular microreactor side channel (Fig. 4).<sup>18</sup> In another configuration described by Gañán-Calvo et al.<sup>19–21</sup> for the generation of monosized microbubbles dispersed in a liquid for biomedical applications, the gas was continuously supplied through a capillary tube to form a large bubble in the vicinity of a small orifice through which a surrounding coflowing liquid stream is forced to produce a steady gas ligament which is focused through the orifice (Fig. 5). After passing through the orifice the gas ligament generated, at a constant frequency, a single-line, same-sized microbubble



**Figure 3.** Cocurrent continuous mobilization of gas and pulse injection of liquid stream, leading to single-line gas microbubble train in a microchannel.



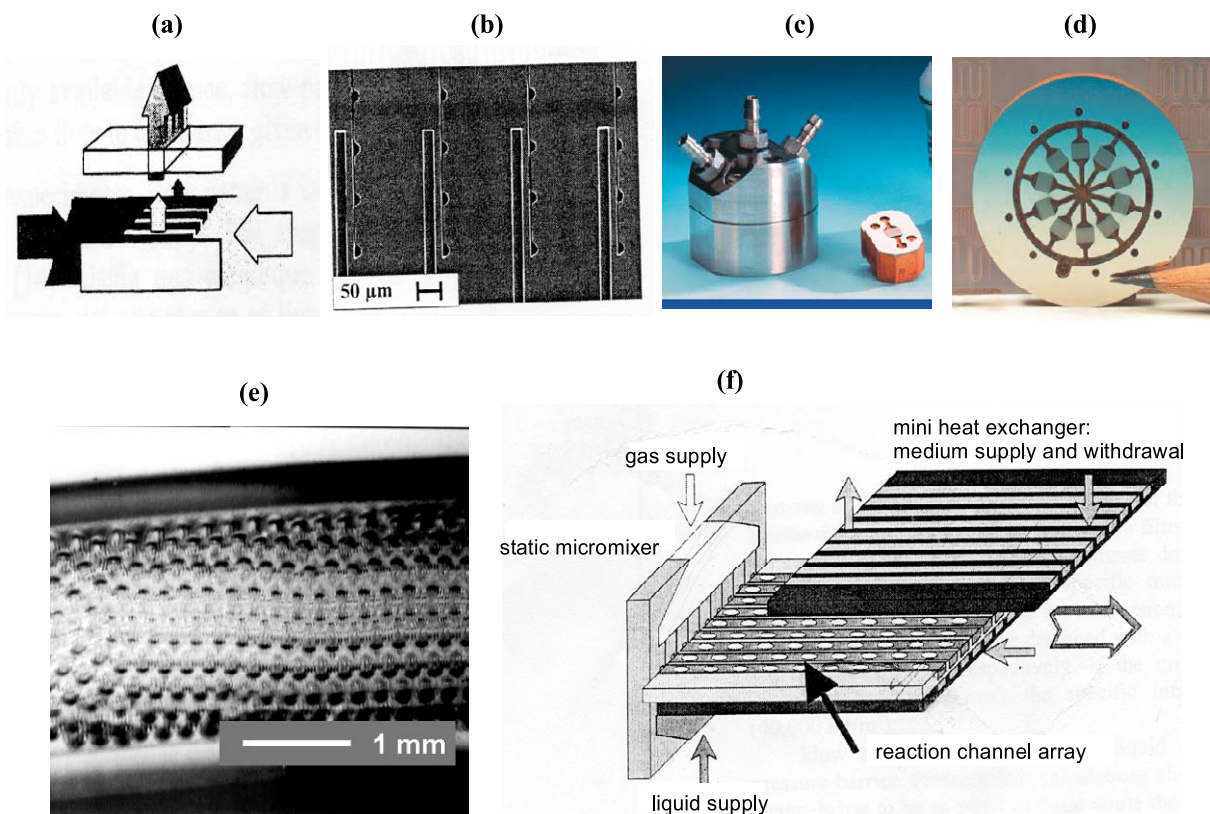
**Figure 4.** Counterflow mobilization of gas and liquid streams, leading to single-line gas microbubble train in a microchannel.



**Figure 5.** (i) (a) Cusplike bubble, attached to a capillary gas-feeding tube, from the cusp of which a gas ligament issues through the orifice placed in front of the capillary. (b) Stream of gas bubbles issuing from the orifice. (c) Sketch of the region about the exit orifice, showing the steady and absolutely unstable regions of the gas ligament. (ii) A 'mesocrystal foam' or lattice formed when microbubbles rise and settle (reproduced with permission from Ref. 19, pages 274501–1 and 274501–3).

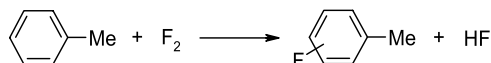
train. By controlling the relative gas and liquid flow rates, the orifice diameter (30–500  $\mu\text{m}$ ) and liquid viscosities, the authors reported microbubble sizes ranging between 5 and 120  $\mu\text{m}$ . Recent advances in gas–liquid premixers called (static) micromixers have been reported,<sup>22–26</sup> which have been employed for gas–liquid contacting by coupling them to microchannel reactors of internal diameters below 600  $\mu\text{m}$ . Some of these micromixers are based on the

principle of gas–liquid stream interdigitation (multilamination)<sup>22–26</sup> which, although it generates a uniform ordered array of bubbles, normally supplies only a single-line segmented microbubble train per reactor microchannel, due to the bubble size constraints (Fig. 6). Using the sulphite oxidation and carbon dioxide-sodium hydroxide reaction models, specific interfacial areas as large as 9000–50,000  $\text{m}^2/\text{m}^3$ , with decreasing channel dimensions and



**Figure 6.** Static micromixer components/configuration: (a) Liga static micromixer, with arrows showing gas and liquid inflows; (b) inside design of the mixer; (c) complete unit of mixer; (d) multiple mixer configuration in one unit device; (e) uniform, ordered array of microbubbles coming out of the micromixer; (f) a micromixer coupled to a multichannel reactor (reproduced with permission from ref 23, page 1077–78, and Ref. 26, page 118).

bubble sizes down to 50  $\mu\text{m}$ , have been reported,<sup>25</sup> and direct fluorination of toluene gave up to 20% yield of monofluorinated products, calculated from the consumption of toluene,<sup>24,26</sup> for the microbubble columns (Scheme 2).



Scheme 2.

Additives such as surfactants and glycerol, which increase the dispersion stability by influencing the surface tension and liquid-phase viscosity, respectively, were found to prevent coalescence of these bubbles. Gas–liquid dispersions in microfluidic structures could, however, also be stabilized by integrating the mixing and reaction channels in one microdevice, thus making chemical additives unnecessary. The characteristics of such two-phase gas–liquid flows, that is, void fractions, pressure drops and flow regimes (patterns) ranging from dispersed bubbly to churn, stratified, slug (elongated bubbles) and annular flow patterns (where channel walls are wetted by a thin liquid film surrounding a gas core), have been extensively studied and reported<sup>27–36</sup> for miniaturized channels of internal diameter up to 1.5 mm, and which depend on the relative in-feed rates of the gas and the liquid. The flow regimes have been found to change from microbubble columns to slugs and then to subsequent annular flow patterns (Fig. 7) as the flow conditions were

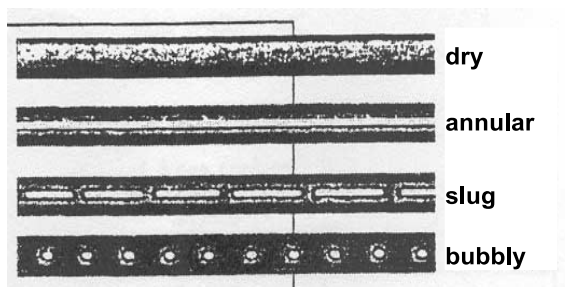


Figure 7. Microbubble columns, slugs and annular flow patterns, obtained as a function of relative gas and liquid volume flow rates (reproduced with permission from Ref. 25, page 178).

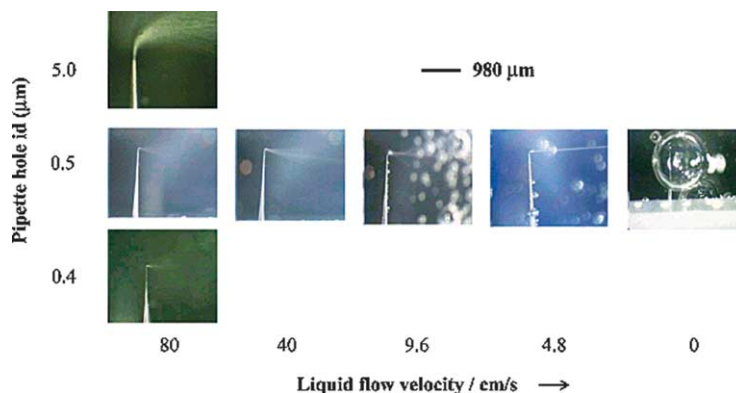


Figure 8. Pictures of a micropipet tip mounted horizontally and 2 mm deep in the channel perpendicular to liquid flow direction, and microbubble stream configurations captured with a low-magnification microscope/low-speed camera system for different pipet hole sizes (0.4, 0.5, and 5.0  $\mu\text{m}$  i.d.) at a liquid velocity of 80 cm/s; and for different liquid velocities (40, 9.6, 4.8, and 0 cm/s) for the 0.5  $\mu\text{m}$  i.d. pipet. The channel in each case is 2 mm deep, 4 mm wide, and 6 cm long. (Reproduced with permission from Ref. 40, page 3724).

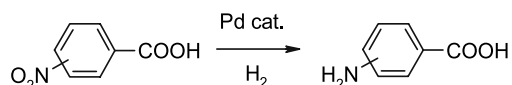
changed from both high-gas and liquid flows to relatively higher gas volume flow rates, by monitoring gas pressure barriers. The turbulent and laminar behavior of two-phase gas–liquid flows in miniaturized channels have also been studied and reported,<sup>38</sup> which depend on the Reynold's number.<sup>39</sup> Falling film microreactors,<sup>24,25,37</sup> characterized by a thin liquid film trickling down the walls of a vertically oriented reaction channel by gravity and contacted by an upward-moving gas occupying the middle of the channel, have also been reported, that gave specific interfacial areas greater than 15,000  $\text{m}^2/\text{m}^3$ , and a 25% monofluorinated toluene.<sup>24–26</sup> The bubbles generated by the micromixers, however, have sizes of the order of the channel diameters employed and would not break up into minute bubbles to enhance further dispersion in the channel. A recent development has demonstrated the use of in-channel integrated micropipette tips, prior to the reactor chamber, for online gas introduction and generation of multiple-line bubble trains (microbubble beams) in a microchannel (Fig. 8).<sup>40</sup> The micropipettes are erected perpendicularly to the main liquid flow and the energy of the moving liquid breaks the gas into minute-bubble sprays in the channel. The bubble sizes reported were far smaller, the bubble quantities were larger and yielded gas–liquid specific interfacial contact areas as large as  $40 \times 10^4 \text{ m}^2/\text{m}^3 \pm 10\%$  (greater than achieved with single-line bubble columns reported in the literature), corresponding to bubbles as small as 5  $\mu\text{m}$  in diameter. The most important operational conditions for this effective microbubble generation were small pipette internal diameter (0.3–1.0  $\mu\text{m}$ ), high liquid speed, reverse pipette-liquid hydrophilicity and liquid hydrophobicity. A multiple-micropipette configuration, rather than one large pipette hole, was reported as the recommended means of increasing the gas quantity requirements. If operated in conjunction with liquid recycling for the purpose of further gas enrichment, such a principle would go a long way to improve upon gas–liquid microreactor performances.

#### 4. Gas–liquid–solid systems

In gas–liquid–solid systems, besides the method of dispersing the gas in the liquid and the maintenance of the dispersed regime along the whole reactor within a desired

time frame, the method for incorporating the solid to provide a large total solid surface area and a large net gas–liquid–solid interfacial contact area, while reducing pressure drops across the reactor channels, is also crucial for the reactor success. Only a few gas–liquid–solid microchannel reactor systems have been reported in the literature, with the solid being a catalyst in most cases, and these have relied on the microbubble train, slug and annular flow gas–liquid dispersion principles described above,<sup>17–37</sup> but in conjunction with monolithic,<sup>17,23–26,40–44</sup> packed-bed<sup>22,45,46</sup> or fixed-bed<sup>45,46</sup> solid integration principles. The mass-transfer characteristics in such multiphase flow channel systems have been well studied and reported.<sup>22,25,43,48–56</sup>

Monolithic microreactors are those with the solid/catalyst immobilized on hollow channel surfaces as thin porous membranes,<sup>17,41,42</sup> by sputtering or surface chemistries and wash-coats, and which normally require higher in-channel pressures to aid gas diffusion through thin liquid films on the channel walls to the solid/catalyst surface. An earlier conventional monolithic device described by Hatziantoniou et al.<sup>17</sup> for the hydrogenation of nitrobenzoic acid consisted of 427 parallel channels (each 1.5 mm wide and ~20 cm long), created in a material made of a mixture of glass, silica, alumina and minor amounts of other oxides reinforced by asbestos. The catalyst was integrated by impregnating the channel surfaces with a PdCl<sub>2</sub> solution for 2 h, drying at 450 °C for 1 h under nitrogen and then reducing the Pd salt with hydrogen at 450 °C for 3 h, resulting in a 2.5% Pd catalyst. The gas and liquid streams were fed cocurrently, but, whilst the gas flow was continuous, the liquid was pulsed using a displacement pump, resulting in a single-line segmented bubble train flow in the channel.<sup>17,23–26,43</sup> Yields of over 40% were reported for the hydrogenation of the nitrobenzoic acid<sup>17</sup>, depending on the reagent concentration, the gas–liquid feed rates, and the temperature and pressure employed (Scheme 3). The reproducibility was found to be satisfactory, the catalyst deactivation with time was negligible, and mean reaction rates in the range of 0.74–6.16 mol of H<sub>2</sub>/s kg of catalyst were reported, depending on the operational conditions mentioned above. The reactor effectiveness was theoretically calculated to be 8.1–11.5%. Studies into smaller microchannel monolithic systems have produced gas–solid specific interfacial contact areas ranging from 9000 to 50,000 m<sup>2</sup>/m<sup>3</sup>, with decreasing channel dimensions and bubble widths down to 50 μm, and have been reported for the microbubble train/slug configurations,<sup>24–26</sup> with the annular flow configurations giving even higher specific interfacial areas.<sup>24–26</sup> The chemical conversion efficiencies achieved with these microchannel systems have been found to be higher than the efficiencies achieved with many other contacting mechanisms for the traditional trickle- and packed-bed reactors described in the literature.<sup>24,25</sup> Conventional bubble columns, for example, are characterized by specific interfacial areas in the range of only 50–600 m<sup>2</sup>/m<sup>3</sup>,



Scheme 3.

and even the special-type reactors designated for intensive gas–liquid contacting such as the impinging jets only yield specific areas of 2700 m<sup>2</sup>/m<sup>3</sup>, which are far smaller compared with the microbubble column technique.<sup>25</sup> As a further step in the development of microsynthesis systems, a mini-industrial system which employs a simple on-chip, single-line monolithic microreactor etched in silicon for the routine heterogeneous and high-pressure hydrogenation of organic substrates, has been developed by us,<sup>44</sup> which is based on in situ-generated microbubble slug or annular dispersion regimes, a Pd/Al<sub>2</sub>O<sub>3</sub> catalyst and off-line electrospray-TOF-MS detection. In this system, the liquid is distributed in a main flow channel whilst a side-intersecting channel feeds the gas. The channel width (up to 200 μm) and depth (down to 5 μm), the gas-inlet angle, and the liquid velocity and gas in-flow pressure are parameters optimized for the generation of the microbubble slug and annular flow regimes and the maximization of the gas–solid interfacial contact area (m<sup>2</sup>/m<sup>3</sup>), whilst the inside-reactor pressure (reaction pressure), the temperature and residence time (allowed reaction time) were optimized to maximize the product yield. The catalyst deactivation, versus time and number of reaction runs, and reproducibility of the yield, were studied.

Most of the reported on-chip gas–liquid–solid microreactors are packed-bed microhydrogenation reactors<sup>22,45,46</sup> (channel widths 500–625 μm; Fig. 9) etched in silicon, and employing metal catalysts supported on granular porous particles (25–75 μm). This is possibly because the packed-bed principle presents the largest possible solid-catalyst surface for reaction, whilst hydrogenation reactions represent one of the typical and ubiquitous industrial processes; nearly 20% of all the reaction steps in a typical

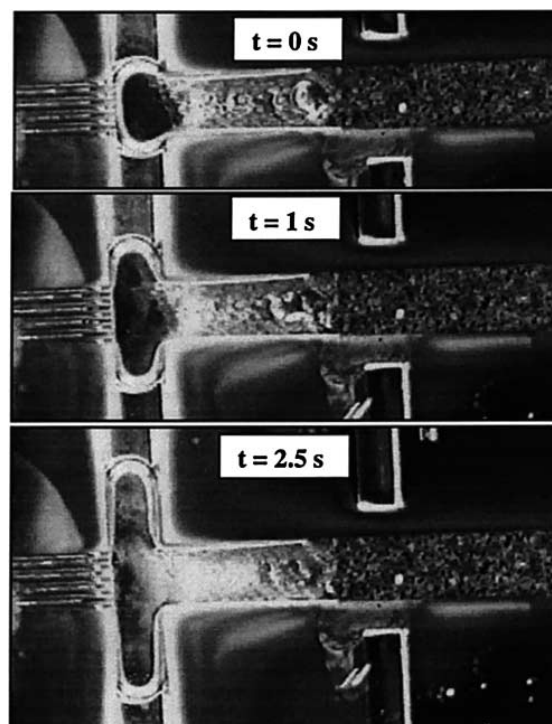
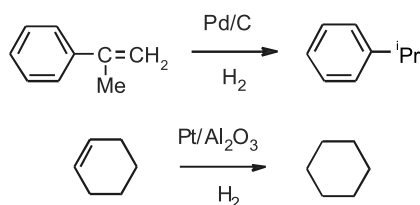


Figure 9. Packed-bed microchannel reactor, with interleaved gas–liquid supply and distribution system (reproduced with permission from Ref. 22, page 2559).

fine chemical synthesis are catalytic hydrogenation,<sup>24</sup> making it a good choice of study with respect to microreactor systems. The metal catalysts supported on granular porous particles are standard catalyst powders which are readily available and information on their chemical kinetics is already well known.<sup>22,45–47</sup> Proper scaling of the reactor and catalyst dimensions is, however, required to maintain an acceptable pressure drop; the catalyst particle sizes employed in the above systems range between 25 and 75  $\mu\text{m}$ . In these systems, the gas and liquid streams were fed continuously and concurrently by a series of interleaved (multilaminated<sup>22–26</sup>) inlet microchannels (25  $\mu\text{m}$  wide for the gas and 50  $\mu\text{m}$  wide for the liquid), and a series of rectangular posts (40  $\mu\text{m}$  wide with 25  $\mu\text{m}$  inter-post gaps) etched in the silicon at the outlet of the reactor served as filters to retain the catalyst particles, but the particles eventually packed at the end of the reactor and generated high-pressure drops across the channels.

Conversions of higher than 10% were reported for the hydrogenation of  $\alpha$ -methylstyrene to cumene over a Pd/C catalyst, and the gas–liquid hydrogenation of cyclohexene over 1 wt% Pt/Al<sub>2</sub>O<sub>3</sub> (Scheme 4), depending on the feed composition and flow rates.



Scheme 4.

To circumvent the problem of pressure drop, whilst still achieving the large catalyst surface areas required, a fixed-bed reactor principle that avoids packing variations associated with catalyst size distribution was suggested<sup>45,46</sup> (Fig. 10) for future applications, which permit reactions on the channel walls as well as in the inner volume of the reactor. This involves the erection of microposts, in a

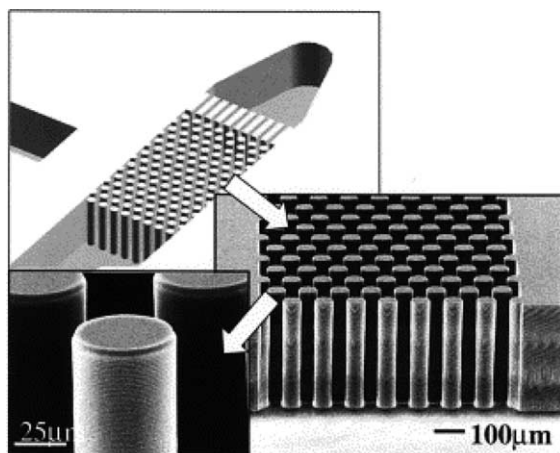


Figure 10. In-channel microposts on microreactor channel bed, produced by deep reactive ion etching into silicon, for surface-catalyst immobilization (reproduced with permission from Ref. 45, page 299).

staggered configuration, on the channel bed across the whole length and breadth of the reactor channel by deep reactive ion etching into silicon for surface solid-catalyst immobilization. The posts can be made porous and modified to have different organic groups. A suitable gas–liquid feeding and distribution procedure that would be suitable for such an in-channel micropost design has yet to be established; the single-line bubble train gas–liquid distribution may not be suitable for such a micropost, fixed-bed microreactor principle, because the large gas bubble that enters the reactor would not break-up into smaller bubbles to disperse in the system.

## 5. Gas–gas–solid systems

Gas–gas–solid microreactor systems<sup>57–60</sup> are also based on the monolithic, packed-bed or fixed-bed solid integration principles, whilst the gas–gas mixing is almost completely achieved at a simple T junction<sup>57,58</sup> (Fig. 11), due to the inherently large radial diffusion rates of the gases in such small-volume systems. In the work by Kursawe et al.,<sup>57</sup> monolithic microchannel reactors made up of stacks of aluminum wafers were catalytically activated by anodic oxidation, followed by calcination in air, then soaking with toluene after a vacuum treatment and impregnating the porous alumina with Ru(acac)<sub>3</sub> dissolved in toluene for several hours at slightly elevated temperatures, and, finally, followed by calcination in air. 15 Wafers containing a total of 450 Al/Al<sub>2</sub>O<sub>3</sub>/Ru microchannels were assembled by a mechanical packing process and were used for the difficult partial hydrogenation of benzene to cyclohexene in a gas–gas phase reaction, which yielded a 20% selectivity at 13% total conversion degree after 15 h on stream (Scheme 5). Dietzsch et al.,<sup>58</sup> by using a similar system but with Pd–Zn microchannels, coupled with a channel surface regeneration procedure involving oxidation and reduction cycles in order to use one microchannel for repeated catalytic runs to improve the yield, as well as adding traces of carbon monoxide to the reactor feed to improve on the selectivity, obtained a 99.9% conversion and 98% selectivity in the

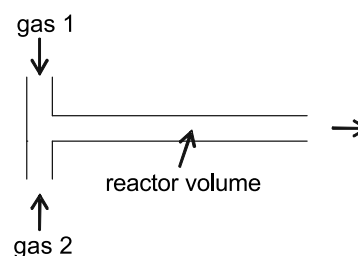
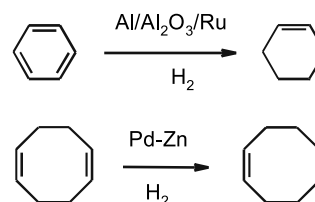


Figure 11. T-mixing of two gases in a gas–gas reactor system.



Scheme 5.

gas-phase hydrogenation of 1,5-cyclooctadiene to cyclooctene, depending on a high hydrogen/cyclooctadiene in-feed ratio (Scheme 5).

## 6. Conclusions/outlook

Clearly, the most difficult multiphase system to develop is the gas–liquid–solid system, with the solid being a catalyst in most cases. The most advanced solid-catalyst integration principle for such a system is the fixed-bed reactor principle<sup>45,46</sup> that involves the erection of microposts, in a staggered configuration, on the channel bed across the whole length and breadth of the reactor channel by deep reactive ion etching into silicon for surface solid-catalyst immobilization. It would circumvent most of the major problems associated with these microreactor systems, which include the problem of pressure drop, the achievement of large catalyst surface areas, and the maximization of heat transfer in exothermic systems. It would also permit reactions on the channel walls as well as in the inner volume of the reactor and the consequent maximization of the product yield. As pointed out earlier, a gas–liquid feeding and distribution procedure that would be suitable for such an in-channel micropost design has yet to be established and that is the challenge for future developments.

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## Biographical sketch



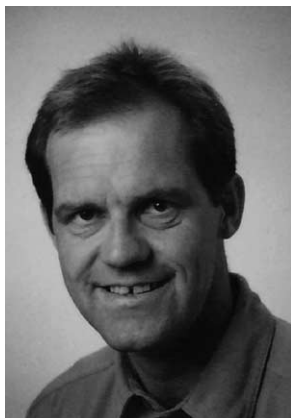
**George N. Doku** (1964) received his masters degree in analytical chemistry from the University of Cape Coast (Ghana). In the period 1992–1995, he was a lecturer at this university and a chemical consultant. He received his PhD under the supervision of Prof. Dr. S. J. Haswell with a thesis entitled 'analytical and synthetic reactions in micro-reactor systems' at the University of Hull (UK) in 1999. After working as a post-doc in Hull, he joined the group of Prof. Dr. Ir. A. van den Berg in the Mesa<sup>+</sup> Institute for Nanotechnology at the University of Twente (2001–2004). His present main interest is the design and application of micro reactor systems. He is the author of four basic chemistry books and quite a number of (popular) scientific publications.



**Willem Verboom** was born in 1954 in Goes, The Netherlands. He studied chemistry at Utrecht University, where he also received his PhD with Prof. Dr. H.J.T. Bos with a thesis entitled 'thermal and photochemical rearrangements of  $\gamma$ -oxo- $\alpha,\beta$ -unsaturated carboxamides and esters'. Subsequently, he joined the group of Prof. Dr. Ir. D.N. Reinhoudt at the University of Twente, where he now is an associate professor in organic chemistry. Over the years, the research interests moved from heterocyclic chemistry to supramolecular chemistry. His present research topics involve the functionalization and application of suitable molecular building blocks, in particular calixarenes and cavitands, for the development of specific receptors and larger (non-)covalent assemblies and recently, chemistry in microchips. He is the (co-)author of about 275 scientific publications. He served as a board member of the International Society of Heterocyclic Chemistry in the period 1992–1995. He was a member of the editorial board of the Dutch journal 'Recl. Trav. Chim. Pays-Bas' (1992–1996). Already for a long time he is a member of the refereeing panel of different journals of the Royal Chemical Society (UK). Currently, he is secretary of the 'Design and Synthesis' study group of the Council for Chemical Sciences of the Netherlands Organization for Scientific Research (CW-NWO) (since 2001)



**David N. Reinhoudt** was born in 1942 in The Netherlands. He studied Chemical Technology at the Delft University of Technology and graduated (summa cum laude) in chemistry in 1969 with Professor H.C. Beijerman. In the period 1970–1975 he worked at Shell where he started the crown ether research program. In 1975, he was appointed as a part-time professor (extraordinarius) at the University of Twente followed by the appointment as a full professor in 1978. The major part of his research deals with supramolecular chemistry and technology. Nanotechnology, molecular recognition, and non-covalent combinatorial synthesis are the major fields. Application of supramolecular chemistry, for example, in 'lab-on-a-chip', in the field of electronic or optical sensor systems, catalysis, and molecular materials. Professor Reinhoudt is the scientific director of the MESA<sup>+</sup> Research Institute. Since 2002, he is the chairman of the Board of NanoNed, the Dutch Network for Nanotechnology. He is a member of the Royal Dutch Academy of Sciences, Fellow of the American Association for the Advancement of Science, and Fellow of the Institute of Physics. He is the author of more than 800 scientific publications, patents, review articles, and books. He has been honored with the Izatt-Christensen award (1995), the Simon Stevin Mastership (1998) and Knight of the Order of the Dutch Lion (2002).



**Albert van den Berg** received his Masters degree in applied physics from the University of Twente, The Netherlands in 1983. In 1988, he finished his thesis at the same university on the topic of chemically modified ISFETs. From 1988 to 1990, he was at the Swiss Center for Microelectronics and Microtechnology (CSEM) in Neuchâtel, Switzerland, project manager in the chemical sensor department. From 1990 to 1993, he did research on miniaturized chemical sensors and sensor systems at the IMT, University of Neuchâtel, Switzerland. From 1993 until 1999, he was research coordinator Micro Total Analysis Systems ( $\mu$ TAS) at MESA, University of Twente, later extended to Miniaturized Chemical Systems (MiCS). In 1998, he was appointed as full professor in the Lab-on-a-Chip group. Albert van den Berg is and has been member of numerous scientific committees ( $\mu$ TAS, MEMS, Micromachine Summit, Transducers, Nanotech) and served as editor of the section  $\mu$ TAS of Sensors and Actuators B. In 2002 he received the 'Simon Stevin Master' award from the Dutch Technical Science foundation. He has published over 100 peer reviewed papers and edited several books on Labs-on-a-Chip. His current research interests focus on analysis systems and sensors, microreactors, micro- and nanofluidics and Lab-in-a-Cell.