EUROPEAN PROCESS INTENSIFICATION CENTER

- TECHNOLOGY REPORT UPDATE-

TECHNOLOGY: MICROMIXERS

DATE OF UPDATE: 17.06.11

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1. Technology

1.1 Most important developments since the last update/report

- **Focus on convection-based microstructured mixers (with large flow rate)**

  During the last ten years or so a slight shift in focus has occurred in the choice of mixing mechanism – from diffusion-type to convection (recirculation)-type micromixers. Consequently more and more mixing concepts originally developed for static mixers are utlilised – not seldom by mere miniaturization of the physical objects behind (such as baffles). This allows to achieve higher flow rates, as convection-type generally have larger internal characteristic dimensions (cross-sections). This gives the innovative tools a more 'conservative firnish' – which increased the acceptance of the technology, especially in industry. Negative and cutting experiences such as clogging are not so likely anymore in channels of mm-size.

  Also, commercial and commercially used microstructured mixers orient on this. For example, Lonza Comparny uses cyclone mixers with their typical internal vortex generation.

  The focus on convection-type mixers also means that the mixing elements extend not seldom over the whole channel range; thus, having besides the initial reactants' mixing function, the function of maintaining mixing / dispersion along the whole reaction path ('redispersion reactor') and also to ensure axial mixing for lowering the residence time distribution. Commercial micromixers from Little Things Factory or mikroglas follow that principle. This implies from the design side a system integration of mixing and reaction units; quite different from the early, consecutive mixer-reaction channel concepts.

- **Commercial modules**

  Microstructured mixers in a variety of mixing principles, materials, flow rates and pressure stability can be purchased from different companies and applied research institutes. Even specialized micromixers for precipitation are at hand. Mixing units have entered plates consisting of complete reaction systems such as provided from Corning Company. Mixers are available at very high flow rates; even in the range of 1000 l/h. This development actually started more than ten years ago, but is still considered as vital and active development in the field of micromixers.

- **Use of micromixers for RTD enhancement**

  The initial focuses of micoreactor development were concerned with achieving high mass and heat transfer. More recently, the capability to operate under narrow residence time distribution is more and more exploited. This is mainly due to an increased theoretical understanding here and more advanced analytical RTD characterization techniques (apart from, e.g., simple dye pulse injection). The promotion of axial mixing over the whole channel length is especially easy accomplished through convection mixing and its more simple mixing elements which – alike static mixers – can be repeatedly placed along a large channel length.

- **Focus on passive micromixers**

  The past ten years and early time in micromixer development showed a considerable attention towards the conceptual and design development of active micromixers such as electrokinetic and ultrasound actuated devices. Almost always these devices were used for integration into Lab-on-a-Chip systems and were devoted to a semibatch (stop-flow) operational mode.

Accordingly and also as a consequence of the higher viscous fluids involved, mixing times were in the seconds range; much unlike the often thousand times faster mixing in passive mixers due to the large energy input (high flow rates and fast contacting times).

The emerge of active micromixers has somehow stopped. In 2010/2011 only a few number of publications were devoted to this topic. This is partly due to the fact that already a lot has been developed in the past and that the scope at hand is somehow exploited. This is partly and probably more importantly due to the fact that Lab-on-a-Chip systems have not experienced the industrial uptake as prognosed in the past. The academic Lab-on-a-Chip developments also go more and more into system development and special applications rather than into single-unit development as being a strong motivation in the 90ies.

An exception constitutes mixers used for droplet and digital microfluidics. These very specific devices gain increasing interest and the number of papers and books increases here.

- **Focus on specific applications – 'establishment in reaction'**

  Initially, the focus of micromixer development was on mixer design, principle, modeling and characterisation. Meanwhile this has shifted to applications. The use of micromixers, often as the most crucial and enabling element, in fine-chemical synthesis is large; actually so large that almost all these references were excluded from the long literature list and description in this report, since this is information given already 10 years ago and "just" a continuing story. Still, it has to be mentioned here that micromixers are used in an ever increasing and large number of reaction success stories.

  Besides being used for reactions, micromixers are used in many other applications. Initially referred as 'antagonists', micromixers meanwhile are used almost as one standard tool for precipitations, e.g. to make (functional) nanoparticles for optics, electronics, and catalysis.

  Micromixers are more and more used for dispersion of immiscible liquids and even for gas-liquid mixing (although here usually specific gas-liquid contactors are advised). Typical applications are phase-transfer reactions or making of polymer particles through (monodisperse) droplets.

- **Energy dissipation**

  With the orientation towards static mixers, energy dissipation studies enter more and more into micromixer literature. Seldom as own and main topic, but among the most prime characterizations to be reported for a new micromixing devices next to mixing time and mixing efficiency.

- **Mixing characterisation**

  The analytical community has increased their interest into mixing with micromixers as a new field for analytical science with chance to develop new mixing characterization methods and to utilise new equipment (NMR, FTIR instead of the formerly used UV-Vis and chemical detection). The Villermaux-Dushman reaction is still the (dominating) method of choice and even variations in the exact composition and procedure for flow mixing characterization is the topic of several new papers. Ongoing creativity is also given for proposing entirely new concept as well as in adaptation of existing methods to allow online and inline detection.

1.2 New types and versions

(Describe new forms/versions of technology under consideration, including their characteristic features, differences and similarities)

- **Redispersion- or large-serial connected micromixers – trend to sub-structures instead of units**

  While previously constituting a small and own footprint within the total ‘area” of the whole microreactor system, it is meanwhile more common to have mixing substructures within the microchannel (as opposed to total units) which are repeatedly placed along the whole reaction path. The most prominent substructure used is mentioned in the following paragraph.

- **Herringbone-based micromixers**

  With the first mentioning of the staggered herringbone micromixer (SHM) by Stroock et al. more than ten years ago a continuous reporting on optimization of this device and principle has set on. Mostly these were modeling studies with no experimental proof. Recently, the herringbone and similar structures find more and more application in fine-chemical applications; which is remarkable as this device initially was developed for Lab-on-a-Chip applications at quite low Re numbers and respectively very low flow rates.

- **Commercial offer of pilot and production microstructured mixers-reactors as a consequence of increasing microreactor provision**

  Companies/providers such as Corning, IMM, BTS-Ehrfeld, and Alva Laval launched a distinct offer of commercial pilot and production microstructured reactors.

- **Commercial offer of mixers as parts of flow chemistry platforms**

  Companies/providers such as Thales-Nano. Syrris, and many more give meanwhile a quite manifold offer on commercial flow chemistry platforms which are fully automated and typically rely on capillary / tube reactor processing.

- **Focus on certain mixing principles and device designs**

  The development of new micromixers principles and designs in the very last years is characterized by an iteration and focusing of principles and designs initially developed in the last reporting period, but still with remarkable breakthroughs. The following types find most attraction:

  - Split-recombine micromixers – the “evergreen” with still increasing permutation with true optimization
  - Cyclone / vortex micromixers – overlooked in the past; now finding increasing interest
  - Nozzle / orifice micromixers – often put in a row; exploiting the large velocity increase after flow contraction; also: Venturi-designs
  - Microjet mixers – initially more a curiosity, now becoming established in niches as for making precipitation. Different from nozzle mixers by typically relying on jet-to-jet collision.
  - ‘Slurry micromixers’ – connected to the last type, the development focuses also on handling solids in flow

2. New applications

2.1 Commercial applications

(In Table 1 provide new applications and provide their short characteristics)

Table 1. New commercial applications of the Technology (existing and under realization)

Micromixers on their own are very seldom used (with no other microreactor unit) and for non-reaction based purposes. Thus, the list on commercial applications given already in the Microreactor-EUROPIC report partly is reported here; as long as micromixers were used. Exceptions constitute applications such as the cosmetic manufacture of Kao Corporation, listed as first example below, which only need micromixers and were the product is made only by mixing without any reaction contribution.

Pure Mixing Applications					
Sector	**Company - Process/Product name/type**	**Short characteristic of application**	**Production capacity/Plant size**	**Year of application**	**Reported effects**
Cosmetic, personal care	Kao Corporation, Toyko/Japan	Emulsified gel capsules	30-70 l/h	2010	• Droplet diameter is well correlated with the energy dissipation rate, easily controlled by adjusting the orifice diameter and flow rate • Micro-in-macro strategy: retrofit of existing equipment by a full-scale micromixer
Writing ink	Pelikan PBS-Produktionsgesellschaft mbH & Co. KG, Hannover / Germany	Highlighter fluid	Pilot: 7 L/h Production: 25–70 L/h	2009	• Reduction of volume of cleaning and rinsing agents by 90 up to 99% • Much reduced plant hold-up • 150 nm nanoparticles • Improved mixing • 48 h continuous production run

Reactions Applications, enabled or faciliated through Mixing					
Sector	**Company - Process/Product name/type**	**Short characteristic of application**	**Production capacity/Plant size**	**Year of application**	**Reported effects**
Fine chemistry	Lonza Group Ltd, Visp	Nitration of phenol	Not reported	Around 2008	• Largely increased purities (25 -> 79%) • Higher yields(32 -> 77%) • Solvent-free and almost acid-free
Fine chemistry	Lonza Group Ltd, Visp / Switzerland	Diverse processes, see first citation below, including Grignard reaction, Organolithium coupling, Alkylation, , Nitrosation Reduction (DIBAL), etc	200-600 l/h 1 – 100 t/a	2007-2010	• Up-scalability • Increased selectivities • Operational temperatures closer to ambient (than being cryo) • Reduced OPEX costs
Medicine - osteoarthritis therapy	DSM Pharma Chemicals, Linz / Austria	Naproxcinod drug - Cyclooxygenase-inhibiting Nitric Oxide-Donating (CINOD) anti-inflammatory agent	Not reported	2010	• Scalability • Cost-effectiveness • Less development efforts
Pharmaceutical chemistry	Eli Lilly & Co, Indianapolis / US	Oxidation of alcohols to aldehydes and ketones by Pd-catalysed aerobic oxidation reaction	Gram to kilogram-scale	2010	• Scalability • Safety for O_2 • Green chemistry: replacing toxic permanganate • 90% yield • Only water as by-product • Easily transport-table modular flow reactor
Pharmacy	N. V. Organon, Oss / the Netherlands	Testosterone: 4-Androstene-3,17-dione	64 $g \cdot h^{-1}$	2008	• Reduced holdup: voidance of accumulation of labile salts • Shortening of residence time minimises Pummerer rearrangement side reaction • Good mixing • 0−20 °C operation temperature instead of −70 °C • Good scalability and reliability • 1.5h h continuous production run

Some References

- www.lonza.com/group/en/products_services/Custom_Manufacturing/chemical_synthesis/microreactors/our_continuous_flow.html
- www.siegfried.ch/fileadmin/User2/Bilder/Fotogalerien/Symposium_2010/2010-09-23_SandmeyerTech_Final.pdf
- http://pubs.acs.org/cen/coverstory/87/8711cover4.html
- http://pubs.acs.org/iapps/wld/cen/results.html?line3=production+microreactor&x=30&y=18
- http://pubs.acs.org.janus.libr.tue.nl/isubscribe/journals/cen/88/i21/html/8821notw7.html
- http://pubs.acs.org.janus.libr.tue.nl/isubscribe/journals/cen/88/i51/html/8851news9.html
- http://pubs.acs.org.janus.libr.tue.nl/isubscribe/journals/cen/88/i27/html/8827sci4.html
- http://achema-content2.dechema.de/achema2009_media/Downloads/Presse/Trendberichte+AA+09/tb_6_e_
- Process+Intensification+_+Energy+Efficiency-p-1076.rtf
- http://onlinelibrary.wiley.com/doi/10.1002/ceat.200900309/abstract
- http://pubs.acs.org/doi/abs/10.1021/op700228e

2.2 Demonstration projects

(Are there any new demonstration projects known related to the technology under consideration? In which process industry sectors are those projects carried out: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? In Table 2 provide the short characteristics of those projects.)

Table 2. New demonstration projects related to the technology (existing and under realization)

A quick internet search revealed what was expected – there seem hardly to be any specific projects devoted on micromixers on their own like the former German DFG project cluster SPP 1141 “Analyse, Modellbildung und Berechnung von Strömungsmischern mit und ohne chemische Reaktionen” with a larger number of projects.

http://www.ifv.uni-hannover.de/spp-mischen/

Some project titles (in German)

- Charakterisierung und Intensivierung des Mikromischens zur Nanopartikelfällung (Leiter: Peukert, Wolfgang)
- Direkte, Large-Eddy- und Filtered-Density-Funktion- Simulation des Mikromischers (Leiter: Manhart, Michael)
- Direkte numerische Simulation, Analyse und Modellierung der Vermischung eines runden Freistrahls in einer ebenen Querströmung (Verbundprojekt "Freistrahlmischer") (Leiter: Bockhorn, Henning)
- Dreidimensionale Visualisierung von Wirbelstrukturen bei der turbulenten Vermischung mit Hilfe von PIV und LIF (Leiter: Sommerfeld, Martin)
- Experimentelle und theoretische Untersuchungen in T-förmigen Mikromischern zur Bestimmung von Stofftransportvorgängen bei der flüssig/flüssig-Mikromischung (Verbundprojekt "Vermischung in Mikroreaktoren") (Leiter: Woias, Peter)
- Mischung und Reaktionsinitiierung in druckverlustarmen statischen Mikromischern (Leiter: Sattelmayer, Thomas)
- Mischungsoptimierung von Strahlmischern mit Hilfe der Grobstruktursimulation (Leiter: Sadiki, Amsini)

… more project titles listed under

http://gepris.dfg.de/gepris/OCTOPUS/;jsessionid=A659521477705BFFCCAD183CBB4CDE68?module=gepris&task=showDetail&context=projekt&id=5471746

Besides this, micromixers are often one or even the essential part in microreactor project research. Below a list is given which was already given in the EUROPIC “Microreactor” Report. Projects with dedication to fuel processing or other gas-phase reactions, with no real connection to micromixer development were omitted.

Sector	Who is carrying out the project	Short characteristic of application investigated, including product name/type	Aimed year of application	Reported effects
Specialty chemicals, large volume chemicals	EU Large-Scale NMP Project F3 FACTORY www.f3factory.com	€30 million collaborative research programme on faster, more flexible production methods 25 companies and research institutions 1) Solvent-free polymer process 2) Innovative surfactants' process 3) Compounds for the healthcare industry (for toxicological studies in vivo, in vitro) 4) Materials from renewable resources.	Started 2010; 4 years	• Conceptual development • Plant and module development • Process development
Specialty chemicals, large volume chemicals	EU Large-Scale NMP Project COPIRIDE www.copiride.eu	€17 million collaborative research programme on developing new technologies, processes and manufacturing concepts for the "chemical plant of the future". 16 companies and research institutions 1) Two polymer reactions 2) Biodiesel production 3) Soybean oil epoxidation 4) Ammonia synthesis 5) Sugar hydrogenation	Started 2010; 3.5 years	• Conceptual development • Container design • Catalyst development • Process development
Specialty chemicals, large volume chemicals	EU Large-Scale NMP Project POLYCAT www.cordis.europa.eu	€11 million collaborative research programme on novel polymer based nano-particle catalysts with the enabling functions of micro process technology and green solvents. 19 companies and research institutions 1) Pharmaceutical processes 2) Crop protection processes	Started 2010; 4 years	• Conceptual development • Catalyst / support development
Specialty chemicals, large volume chemicals	EU Large-Scale NMP Project PILLS www.fp7pills.eu	€5.5 million collaborative research programme on process intensification of liquid/liquid reactions. 10 companies and research institutions 1) Bulk-chemical two-liquid/liquid process 2) Cyclisation reaction	Started 2009; 3 years	• Process development • Reactor engineering – micro and meso • Pilot set-up
Specialty chemicals, Pharma, consumer goods	EU Large-Scale NMP Project SYNFLOW www.synflow.eu	€11 million collaborative research programme on shifting paradigm from batch processing to highly integrated and yet flexible catalytic continuous-flow processing. 19 companies and research institutions 1) Pharma process 2) Fine-chemical process	Started 2010; 3 years	• Synthetic development • Catalyst development

		3) Consumer good process		
Specialty chemicals, Pharma, consumer goods	Novartis-MIT Center for Continuous Manufacturing http://engineering.mit.edu/research/labs_centers_programs/novartis.php	$65 dollar industry funded research programme on transforming pharmaceutical production into continuous-flow processing. 19 companies and research institutions 1) Accelerating the introduction of new drugs through efficient production processes 2) Requiring the use of smaller production facilities with lower building and capital costs 3) Minimizing waste, energy consumption, and raw material use 4) Monitoring drug quality on a continuous basis rather than through post-production, batch-based testing 5) Enhancing process reliability and flexibility to respond to market needs	Started 2009; 10 years	• Reaction rate acceleration • Automated process control • Scale-up • High pressure and high temperature processing • Diverse syntheses demonstrated; among these Heck reaction, aminolysis • Progress documented in several recent papers, e.g. given in Angew. Chem. Intern. ed.
Large volume chemicals	Research Center for Ubiquitous MEMS and Micro Engineering, the National Institute of Advanced Industrial Science and Technology (AIST), in collaboration with Mitsubishi Gas Chemical Company http://www.aist.go.jp/aist_e/latest_research/2010/20101111/20101111.html	Direct synthesis process for hydrogen peroxide production - Grant for Industrial Technology Research of the New Energy and Industrial Technology Development Organization. AIST press release of September 14, 2010	2010	• >10wt% solutions • 40% yield • 10 bar / room temperature • Safe synthesis • Direct route • low-environmental-load, low-carbon on-site process for producing highly pure hydrogen peroxide in required quantities
Large volume chemicals	Research Center for Compact Chemical Process, National Institute of Advanced Industrial Science and Technology (AIST), Environment and Energy Department of Hokkaido Industrial Research Institute http://www.aist.go.jp/aist_e/aist_today/2009_34/hot_line/hot_line_20.html	Rapid production of bioactive substance, 5-hydroxymethyl-furfural, HMF, from saccharides AIST TODAY Vol.9 No.8 p.16 (2009) AIST press release of April 20, 2009	2009	• High-pressure and high-temperature water (400°C) • 10 s reaction time • Prevention of life-style related diseases such as hypertension and diabetes • Inexpensive starting materials – saccharides such as glucose • Rapid heating to 400°C in less than 0.01 s • High yield (70 %) and high selectivity (80 %) • Highly pure aqueous solution of HMF, for use in pharmaceuticals, food additives
Functional materials	Development of Microspace and	Development of innovative chemical processes to use a	2006	• Mass production technology to produce

	Nanospace Reaction Environment Technology for Functional Materials FY2006-FY2010; FY2006 Project http://www.nedo.go.jp/english/activities/portal/gaiyou/p06035/p06035.html http://www.nedo.go.jp/kankobutsu/pamphlets/04nano/nano_e/14.pdf	concerted reaction field formed based on microreactor and nanoporosity technologies. Combining such processes with other technologies, including microwave and supercritical fluid technologies.		• Plant technology to manufacture food-related functional chemicals, etc. • Industrial use catalyst production technology using nanospaces • Organic hydroxylamine production technologies using the nitro-group partial reduction method • Microwave use concerted microreactor general purpose plant technology • Plant technology with nitrile compounds based on a revolutionary microreactor as its start point and stop point
Specialty chemicals, large volume chemicals	Dutch ACTS program from NWO (including PoAc, see below) http://www.nwo.nl/nwohome.nsf/pages/NWOA_6P69LY	Advanced Chemical Technologies for Sustainability - ACTS ACTS is a public private partnership between Dutch government, universities, research institutes and industry in the field of sustainable chemical technologies. Its mission is to initiate and support the development of innovative technologies for the sustainable production of materials and energy carriers.	2004-2013	• see below under PoAc
Specialty chemicals, large volume chemicals	Project example for Dutch ACTS program http://www.nwo.nl/nwohome.nsf/pages/NWOA_6P69LY	Direct epoxidation of propene in a microreactor Develop a clean, simple, and energy efficient process for the safe production of propene oxide in a microreactor system containing a gold-titania based catalyst.	2008-2012	Claimed: • Working in ex-regime; >10 vol% of hydrogen,oxygen, propene • Increase in yield - propene conversion of 15 % an selectivity of 80 • Microplant with integrated separation • Propene oxide production rate of 20 ml/min
Specialty chemicals, food technology, pharmacy	Dutch PoAc program from NWO (part of ACTS program) http://www.nwo.nl/nwohome.nsf/pages/NWOA_6NSHCF_Eng	PoAc: Process on a Chip Fundamental and applied research for novel production processes which forms a bridge between chemistry and micro-system technology, between fundamental science and its innovative applications. Four themes • Basic expertise • Analysis on a chip • Synthesis on a chip • Mixing and separation on a chip	2004-2013	Projects: • Enzyme-based nano-scale multistep reactors • Versatile micro-NMR • CCS ChipChemStation: on-line kinetic study of organic reactions in a chip • Massive parallelisation of multi-chamber reaction and separation microreactors • Multi-Phase Micro-reactors as basis for Process Intensification

				• Meander Reactor • Enhanced NMR by Polarization-on-a-Chip • Microreactor chips with integrated work-up functionality • Fine Chemicals Production and Separation in Micro Structured Process Systems (FiPSMiPS)
Specialty chemicals, large volume chemicals	Dutch GSPT program from STW http://www.stw.nl/Programmas/GSPT/	GSPT: Green and Smart Process Technologies Sustainability-oriented projects Three themes • Process architecture • Process intensification • Enabling technologies	>2009	Selected STW projects • Exciting chemistry in microreactors (TMF.6626) • Next generation microreactors for ultra-pure H2 production (10244) • MEMFiCS-Microwave enhanced microprocessing in large-scale fine chemical synthesis (07974)
Specialty chemicals, consumer goods	PROCESS, ENVIRONMENT & SUSTAINABILITY PROGRAMME British program from EPSRC http://www.epsrc.ac.uk/SiteCollectionDocuments/other/PES_Combine.pdf	Key themes include heat/mass transfer, thermodynamics, fluid dynamics, multiphase flow, catalysis, colloidal systems, particle technology, rheology, reactor engineering, process systems modelling & design, reliability of systems, processes and plant, mineral processing and oil/gas extraction from reservoirs	>2009	
Specialty chemicals, Pharmacy	EPSRC funding http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/I027858/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/D064635/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/G009732/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/E039278/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/E500951/1	Selected EPSRC projects: • Dual mode plasma UV micro-reactor for ozonolysis and hydrogenation green chemistry (2011) • Engineering Functional Materials for Catalytic Smart Microreactors (2007) • Integrated Synthesis and Characterisation of Organic Nanoparticles Using Microfluidic Technology for Drug Delivery Applications (2009) • Microfluidic Devices Applied to the Synthesis of [11C]methyl Labelled Molecules of Biological Interest for Positron Emission Tomography (PET) (2007) • Follow On: Plastic Microcapillary Film Development (2007)	see left	
Specialty chemicals,	EPSRC Flow	The EPSRC, in partnership with GlaxoSmithKline and Pfizer, is	2008	

Pharmacy	Chemistry program Research in flow chemistry (continuous processing) http://www.epsrc.ac.uk/funding/calls/2008/Pages/flow.aspx	announcing a call for collaborative research proposals in the area of flow chemistry (continuous processing). The aim of this call is to increase the volume of research and training in flow chemistry and to provide opportunities for technology and knowledge transfer between academia and industry.		
Specialty chemicals, Pharmacy	EPSRC funding on Flow Chemistry http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/G027986/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/F050410/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/G027765/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/G027447/1 http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/G027919/1	Selected EPSRC projects: • Reagent-Free Flow Chemistry: The Generation and Trapping of Reactive Intermediates (2009) • Chemistry in Flow: Amplification versus Extinction (2008) • Development of novel catalytic structures and thermal regimes for continuous flow reaction chemistry (2009) • Challenging Ozonolysis (2009) • In-flow Preparation and use of Diazo Compounds for Heterocycle Construction (2009)	see left	
Large volume chemicals	U.S. Environmental Protection Agency (EPA) http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/9135/report/0http://gow.epsrc.ac.uk/ViewGrant.aspx?GrantRef=EP/G027447/1	A Portable Microreactor System to Synthesize Hydrogen Peroxide	2010	Onsite H_2O_2 production at 35wt% to decontaminate the interiors of vehicles and buildings.
Functional materials	US Department of Energy (DoE) Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program http://www1.eere.energy.gov/industry/nanomanufacturing/pdfs/nanomaterial_tech_for_photovoltaic.pdf	Microreactor-Assisted Nanomaterial Deposition for Photovoltaic Thin Film Production	2010	Production of nanoscale materials relevant to photovoltaic devices. The project will involve improved synthesis, purification, surface functionalization and surface deposition, as well as integration of nanomaterials into composite devices.
Functional materials	US Department of Energy (DoE) Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program http://www1.eere.ene	Microchannel Reactor System for Catalytic Hydrogenation	2009	Aim to reduce the energy and feedstock requirements and reduce the generation of waste and byproducts, compared to conventional catalytic hydrogenation processes. Potential energy benefits are over

	rgy.gov/industry/chemicals/pdfs/microchannel.pdf			50 trillion Btu per year and 70% waste savings.
Functional materials	US Department of Energy (DoE) Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program http://www1.eere.energy.gov/industry/chemicals/pdfs/microchannel_h202_highlight.pdf	New Microchannel Reactor System Allows Safe and Efficient On-Site Hydrogen Peroxide (H202) Production	2007	• 5 wt% solutions of H_2O_2 • Potential to save 5 trillion Btu/year of steam and 3 trillion Btu/year of electricity in the production of H_2O_2 alone • 50 % reduction in waste disposal cost • 10% reduction in feedstock energy • 30% reduction in the overall production and transportation costs for the $1B annual H_2O_2 market

2.3 Potential applications discussed in literature

(Provide a short review of new potential applications of the Technology, including, wherever possible, the types/examples of products that can be manufactured with this technology)

The vast majority of all micromixer applications (>90%) is still given in the field of fine chemistry. The role of the micromixer as enabling or only process-completing tool is not always clear. Since this trend is given in literature since more than 15 years, this is not highlighted in this report (but still shortly mentioned). The result of process intensification is most often increased selectivity and yield, increased conversion rate (reduction in reaction time), and enhanced interfacial mass transfer in case of multiphase reactions.

Selected fine-chemical applications

As mentioned, the "evergreen" under the applications. Some even at industrial scale.

Micromixers have enabling function for the very fast, mixing sensitive reactions such as organometallic reactions. Otherwise – for the somewhat slower heat-transfer sensitive reactions, they serve to create reaction mixtures "at the spot" – to prevent reaction under non-defined conditions and for safety reasons.

"Generation and reactions of oxiranyllithiums by use of a flow microreactor system"
A. Nagaki, E. Takizawa, and J.-i. Yoshida

→ for more information here and in the following papers referenced, please refer to the literature list below with more bibliographic data and short abstract.

Enzyme-based reactions and analytical detection

Enzyme microreactors are an emerging field – see EUROPIC report on microreactors. It is not clear to what extent micromixers will profit here, as these reactions typically are slow and do not have specific mixing issues. Still, micromixers are needed here as process-completing devices and maybe for RTD issues, see below.

Enzyme-based reactions are common in Lap-on-a-Chip applications in biochemistry / clinical chemistry and analytical detection. Here and there micromixers have a more central role.

"An enzymatic microreactor based on chaotic micromixing for enhanced amperometric detection in a continuous glucose monitoring application"
B.-U. Moon, S. Koster, K. J. C. Wientjes, R. M. Kwapiszew¬ski, A. J. M. Schoonen, B. H. C. Westerink, E. Verpoorte

"An integrated on-chip sirtuin assay"
S. Ohla, R. Beyreiss, G. K. E. Scriba, Y. Fan, D. Belder

"Determination of free bilirubin and its binding capacity by HSA using a microfluidic chip-capillary electrophoresis
device with a multi-segment circular ferrofluid-driven micromixing injection"
H. Sun, Z. Nie, Y. S. Fung

Polymerisations and polymer (melt) processing

Micromixers have entered as standard tool into flow polymerizations; an overview is given in the following reference.

"Micromixer-assisted polymerization processes"

F. Bally, C. A. Serra, V. Hessel, G. Hadziioannou

Micromixers continue to be used here and there for more explorative, specialty polymerizations such as emulsion polymerisation.

“Feasibility of tubular microreactors for emulsion polymerization”
A. K. Yadav, J. C. de la Cal, M. J. Barandiaran

New and innovative is the idea to use micro- or millimixers to create polymer blends of advanced properties by virtue of material structuring through the laminar flow (e.g. layering).

“Forced assembly and mixing of melts via planar polymer micro-mixing”
D. Moon, K. B. Migler

Particle and material making – in general; fundamental studies

The use of micromixers for precipitation, reduction, and other chemical means to produce particles is not new and hast started about ten years ago. Still, it seems that the research has been intensified here in the very last years. It seems that material scientists have discovered micromixers as tool for their studies, while initially the studies made here came from micromixer developers. A third group of researchers use micromixers to make materials not primarily motivated by fundamental research on the materials, but to have smart materials to intensify their applications.

In the following selection works of the researcher groups 1 and 2 are given. Group-1 researchers focus on making noble metal nanoparticles, most often gold, which is used for a variety of applications in optics, electronics, and catalysis (which however is not specified most often; different from group-3 works).

“Turbulent precipitation in micromixers: CFD simulation and flow field validation”
E. Gavi, D. L. Marchisio, A. A. Barresi, M. G. Olsen, R. O. Fox

“Au/Ag/Au double shell nano-particles with narrow size distribution obtained by continuous micro segmented flow synthesis”
S. Kaluza, M. Behrens, N. Schiefenhövel, B. Kniep, R. Fischer, R. Schlögl, M. Muhler

“Au/Ag/Au double shell nano-particles with narrow size distribution obtained by continuous micro segmented flow synthesis”
A. Knauer, A. Thete, S. Li, H. Romanus, A. Csákib,W. Fritzsche, J.M. Köhler

Nucleation and growth of gold nanoparticles studied via in situ small angle X-ray scattering at millisecond time resolution”
J. Polte, R. Erler, A. F. Thunemann, S. Sokolov, T. T. Ahner, K. Rademann, F. Emmerling, R. Kraehnert

Drug nanoparticles

This is one of the prime current dedicated applications (researcher group 3).

H. H. Himstedt, Q. Yang, L. P. Dasi,X. Qian,S. R. Wickrama-singhe, M. Ulbricht
“Integrating micromixer preci-pitation and electrospray drying toward continuous production of drug nanoparticles”

“Structure evolution of curcumin nanoprecipitation” from a micromixer”
Yi He, Y. Huang, Y. Cheng

Catalysts and inorganic materials

This is one of the prime current dedicated applications (researcher group 3).

"A novel synthesis route for Cu/ZnO/Al_2O_3 *Catalysts used in methanol synthesis: combining continuous consecutive precipitation with continuous aging of the precipitate"*
S. Kaluza, M. Behrens, N. Schiefenhövel, B. Kniep, R. Fischer, R. Schlögl, M. Muhler

"Continuous hydrothermal synthesis of Fe_2O_3*, NiO, and CuO nanoparticles by superrapid heating using a T-type micro mixer at 673K and 30MPa"*
K. Suea, S.-i. Kawasaki, M. Suzuki, Y. Hakuta, Hiromichi Hayashi, K. Arai, Y. Takebayashi, S. Yoda, T. Furuya

Cosmetics and personal care

This is one of the prime dedicated applications (researcher group 3) since the very beginning of micromixer developments.

Design of micromixer for emulsification and application to conventional commercial plant for cosmetic"
K. Matsuyama, K. Mine, H. Kubo, K. Mae

Membrane applications

This is a pretty new application with only a very references and very different facets. It is unclear if such trend will be sustainable. To be checked in the next update of this report.

"Systematic analysis of micromixers to minimize biofouling on reverse osmosis membranes"
S. J. Altman, L. K. McGrath, H. D.T. Jones, A. Sanchez, R. Noek, P. Clem, A. Cook, C. K. Ho

"Magnetically activated micromixers for separation membranes"
Y. He, Y. Huang, W. Wang, Y. Cheng

3. New development and application issues

3.1 Technology development issues

(In Table 3 list and characterize the new development issues (if any), both technical and non-technical, of the technology under consideration. Also, provide your opinion on how and by whom these issues should be addressed)

Table 3. New technology development issues

Issues – seen from ‚pure-micromixer' perspective		
Issue	**Description**	**How and by whom should be addressed?**
Unification and classification	There are basically two mixing mechanisms - diffusion and convection. However, virtually several hundreds micromixers are described. Often different names are given to similar micromixers. Sometimes the real mixing mechanism is not clearly given or at least presented using confusing, own phenomenological terms. Especially commercial micromixers may lack from a clear fully-developed theoretical background. A clear classification und unification would help and clear up here. The customer and user of the technology mainly wants to know which type of micromixer suits best for his application – that question is most often not answered so that coincidence decides on the selection and thus existing micromixer offer variety turns a bit into appearing as overdone, useless choice. Academic fascination in ever new micromixer designs has to be justified by real needs.	• Initially a topic for EU project coordinators – but hardly possible in the current activities due to plant and process orientation • A joint effort seems to be needed – platforms, technology providers, and end-users. Finally the push ahs to come from the latter two groups because they would benefit most.
Comparative performance evaluation	This issue follows directly from the mentioning above. Real helpful comparisons between micromixers are missing. Often the comparison holds for one specific set of parameters and one applications, e.g. using micromixers far from their best operational point. More generalized comparisons were recently given by Falk et al. (see literature list below). More are needed to complete the picture as known for static mixers. Users in the latter field and also from batch mixing, often are irritated by the fewer degree of systematic characterization of the micromixers.	• Initially a topic for EU project coordinators – but hardly possible in the current activities due to plant and process orientation • A joint effort seems to be needed – platforms, technology providers, and end-users. Finally the push ahs to come from the latter two groups because they would benefit most.

Scale-up and production issues	A few institutes (FZK, IMM) devote to scale-up (e.g. by numbering-up) and have made some scouting studies here. Companies (Corning, BTS-Ehrfeld) offer pilot micromixer devices. However, most of the researchers in the field do not show interest in even outlining scale-up, but get their motivation through getting fundamental physical insight.	• EU project coordinators (Future Factories) • Project coordinators worldwide with similar aims • Platforms (Suschem) • Technology providers in microreactors, flow chemistry and modular plants • End-users (chemical companies)

Issues – seen from full ‚microplant‘ perspective

Issue	Description	How and by whom should be addressed?
Compact plant design as environment for micromixer devices	Micro and flow chemistry mixers and reactors are available, but a proper plant and process control environment is needed. So far a Micro-in-Macro strategy is often used, just taking the normal “macro peripherals”. There is potential for further process intensification on a plant level and actually such endeavours are made (Future Factories; 50% idea).	• EU project coordinators (Future Factories) • Project coordinators worldwide with similar aims • Platforms (Suschem) • Technology providers in microreactors, flow chemistry and modular plants • End-users (chemical companies)
PI suited process control	Referring to the same arguments as given above. Fast and faster mixing and chemistry needs faster real-time process analysis. Due to the increasing automation in flow chemistry, there is an increasing demand on proper process optimization (DoE) tools. Recently, a kind of self-optimisation by a learning-automated system was proposed (Jensen, Angew. Chem. 2010).	• EU project coordinators (New NMP call on Process Control for Process Intensification) • Project coordinators worldwide with similar aims • Leading Process Control experts (Hasebe, Marquardt, …) • Platforms (Suschem) • Technology providers in microreactors, flow chemistry and modular plants • End-users (chemical companies)
Particle and material flow synthesis	Microreactors allow intensification in mixing and heat transfer, both of which have large impact on particle size, shape, morphology, and size distribution. Meanwhile, unrivalled control is exerted – e.g. monodisperse polymer particles or specially-(disk) shaped particles. This is on the way to be transferred to industrial practice (Fuji). Issues like clogging are properly handled, although not completely solved. Recently, the particle making was complemented by the synthesis of self-assembled system (vesicles) in microreactors. While the particles are made, a real push from the application and end-user side is to be strengthened.	• Project coordinators worldwide on this topic • Leading experts in particle synthesis • Technology providers in microreactors, flow chemistry and modular plants • End-users (chemical and functional material companies)

GMP grade flow pharma manufacturing	Micromixers and –reactors have entered into fine-chemical synthesis (see Lonza, DSM, …) and there is meanwhile a considerable experience in pilot and production processing. Flow chemistry is increasingly used by pharmaceutical companies for screening of new lead molecules. But the introduction into GMP grade pharma manufacturing is much beyond the fine-chemical production use. The topic of GMP issues needs to be developed towards micromixer-/reactor-based flow chemistry processing.	• EU project coordinators (e.g. POLYCAT with dedicated pharma success) • Project coordinators worldwide with similar aims • Platforms (Suschem) • Technology providers in microreactors, flow chemistry and modular plants • Pharmaceutical end-users
Cost and sustainability (ecologic) analysis	Initially, the demonstration of microreactor effects was mainly done at the reaction engineering side – conversion, selectivity, and other parameters. Recently, process and plant related issues come more into play. Cash-flow studies are released – plant depreciation. Life-cycle analysis has emerged into process chemistry in the last decade (BASF as pioneer). In the last five years, more and more LCA analyses were made for micro process engineering. This is to be strengthened and added by (comprehensive) multi-parameter analyses. Cost and LCA analyses have to be extended to pilot and production processing. There is a need for pre-process developments judgments – ex-ante analyses in costs and LCA.	• EU project coordinators with similar aims (e.g. Future Factory projects) • Project coordinators worldwide with similar aims • Experts in cost and LCA analysis (e.g. Hungerbühler, Kralisch) • Platforms (Suschem) • Technology providers in microreactors, flow chemistry and modular plants • Pharmaceutical and chemical end-users

3.2 Challenges in developing processes based on the technology

(In Table 4 list and characterize the new challenges (if any), both technical and non-technical, in developing commercial processes based on the technology under consideration. Also, provide your opinion on how and by whom these challenges should be addressed)

Micromixers are far developed; they are not at the end, but the challenges here are considered to be much less than for microreactors in general. Some of the issues presented under 3.1 are challenges as well, but shall not be repeated here. Thus, in the following only “real challenges” are given, i.e. which have hardly been explored so far and have potential to open new gateways.

Table 4. New challenges in developing processes based on the technology

Challenge	Description	How and by whom should the challenge be addressed?
Viscous fluids mixing	Most often fluids of similar property are mixed – e.g. with the same solvent. Mixing fluids with very different property/ies is still a challenge, especially in case of very different viscosity (and density as well)	• Specialists from academy • Technology providers in microreactors, flow chemistry and modular plants • End-users: for problem definition
Suspension handling	There is some interest in handling suspensions in micromixers and microreactors, although these tools never will replace the conventional equipment over here for obvious reasons. Smart interfaces, see below, may have enabling function over here.	• Specialists from academy • Technology providers in microreactors, flow chemistry and modular plants • End-users: for problem definition
(Bio-)fouling prevention	This can be achieved by surface modification, e.g. using nanostructured surfaces. Probably an essential step to allow biotechnology applications.	• Specialists from academy • Technology providers in microreactors, flow chemistry and modular plants • End-users: for problem definition
Gas-liquid mixing	True gas-liquid contactors such as the falling film microreactor are still complex and costly devices. The use of more simple structures, truly belonging to the class of micromixers, seems to increase. However, then smart details of the mixing devices probably need much more attention, e.g. to reduce deviations in fabrication tolerances.	• Specialists from academy • Technology providers in microreactors, flow chemistry and modular plants
True integration of mixing and reaction under intensified conditons	This was claimed as the ultimate goal in the early microreactor literature and still is referred as such. Honestly, this has not been reached in an ideal way. Mixers are most often only serially connected to reactors and this is referred as “integrated” (but ideally is not). Micromixers having heating and cooling function inside the device are needed. Up to now this did not pose a large problem, because most of the reactions are heating-sensitive. The use of Novel Process Windows may shift many of these into the mixing-sensitive region and then trylu integrated systems are demanded.	• Specialists from academy; in particular on harsh and new process conditions – kinetic modelling • Technology providers in microreactors, flow chemistry and modular plants

4. New publications

4.1 Papers/books

(Provide the list of key new papers/books in Table 5)

Table 5. Key new papers/books on the technology

Authors/Title	Publication details	Remarks
Reviews, Books, Handbooks		
"Current methods for characterizing mixing and flow in microchannels" J. Aubin, M. Ferrando, V. Jiricny	Chem. Eng. Sci. 65, 6, 15 (2010) 2065-2093	Review over existing methods for the characterisation of mixing and flow in microchannels, micromixers and microreactors. The review shows that the majority of the experimental techniques used employ optical methods, which require optical access to the flow, or off-line measurements. Modern developments use confocal scanning laser microscopy and high resolution stereo micro particle image velocimetry. However, integration of microchannel devices in industrial processes will require other on-line measurements for process control. Developments are being made in the areas of non-intrusive sensors, magnetic resonance techniques, ultrasonic spectroscopy and on-line flow through measurement cells.
"Micromixer-assisted polymerization processes" F. Bally, C. A. Serra, V. Hessel, G. Hadziioannou	Chem. Eng. Sci. 66, 7, 1 (2011) 1449-1462	Uneven mixing in polymerization inevitably leads to the synthesis of polymer with undesired characteristics. Microeaction technology has enabled the development of efficient micromixers which, within typical few milliseconds, allow mixing fluids at the microscale level. Recent developments in polymerization reaction engineering include the use of such micromixers to mix either initial reactants or reactive viscous solutions in multistep processes. Thus, polymers with improved control over their molecular weights and molecular weight distributions, chemical compositions and architectures can be synthesized. Micromixers can also be used to open new operating windows in which controlled polymerization can be performed faster or under less stringent reaction conditions.
"Applications of micromixing technology" G. S. Jeong, S. Chung, C.-B. Kim, S.-H. Lee	Analyst 135 (2010) 460-473	Review on application of micromixer technologies covering: (1) chemical applications, including chemical synthesis, polymerization, and extraction; (2) biological applications, including DNA analysis, biological screening enzyme assays, protein folding; and (3) detection/analysis of chemical or biochemical content combined with NMR, FTIR, or Raman spectroscopies. In the chemical application even industrial applications were reported. The biological and biochemical applications span from enzyme assays, biological screening assays, cell lysis, and protein folding to biological analytical assays. Re number and mixing time depend on the specific application, and micromixers in

		various applications were clustered accordingly.
“Continuous mixing of fluids” M. Kraume, C. Merz, H. J. Henzler	Ullmann's Encyclopedia of Industrial Chemistry (2011)	Contents list: 1. Introduction 2. Basic Concepts - 2.1. Scales of Mixing, 2.2. Definitions of the Degree of Mixing, 2.3. Description of the Mixing Process, 2.4. Required Power Input 3. Mixing in Pipes - 3.1. Mixing Properties, 3.2. Pressure Drop 4. Jet Mixers - 4.1. Mixing Properties, 4.2. Configuration of Jet Inlets, 4.3. Pressure Drop 5. Static Mixers - 5.1. Pressure Drop, 5.2. Mixing Properties 6. Micromixers - 6.1. Classification, 6.2. Operation Ranges of Micromixers 7. Dynamic Mixers - 7.1. Mixing Properties, 7.2. Power Requirements 8. Residence Time Distribution 9. Mixing of Non-Newtonian Fluids - 9.1. Mixing Behavior, 9.2. Pressure Drop for Non-Newtonian Fluids, 9.3. Power Requirements of Dynamic Mixers 10. Selection and Comparison of Continuous Mixers - 10.1. Parameters for Energetic Comparison, 10.2. Energetic Comparison
“Single-phase fluid flow and mixing in microchannels” V. Kumar, M. Paraschivoiu, K. D. P.Nigam	Chem. Eng. Sci. 66 (2011) 1329–1373	Experimental research on microscale single-phase fluid flow was analyzed in terms of friction factor, laminar-to-turbulent transition, and the effect of roughness on fluid hydrodynamics for different cross-sectional geometries. The differences in the uncharacteristic behavior of the transport mechanisms through microchannels due to compressibility and rarefaction, relative roughness, property variations and viscous dissipation effects are discussed. Finally, progress on recent development of micromixers has been reported for different micromixer types and designs. The micromixers were quantified based on their operating ranges (Reynolds number, Peclet number, and Strouhal number) and mixing characteristics.
“Thermomagnetic convection in magnetic fluids subjected to spatially modulated magnetic fields” A. Lange, S. Odenbach	Physics Procedia 9 (2010) 171-175	A horizontal layer of magnetic fluid subjected to a vertical temperature gradient and a spatially modulated magnetic field is considered. For the case of symmetric modulation the initial state characterised by a nonzero flow field is identified. By conducting a linear stability analysis the area of stability of the initial state against small perturbations is determined. In contrast to the purely thermal driven system, the nonzero flow field of the initial state is characterised by a two vortex structure. With the possible options for the spatial modulation of magnetic fields, a new scope of research on thermomagnetic convection starts to emerge.

Microfabrication of micromixers		
“Design and fabrication of an affordable polymer micromixer for medical and biomedical applications” L. Li C. Yang, H. Shi,W.-C. Liao, H. Huang, L. J. Lee J. M. Castro, A. Y. Yi		A split-and-recombine polymer static micromixer can be fabricated at low expenditure using precision engineering and microinjection molding. Concerning the latter, parameters were varied to investigate their effects on replication quality. Experiments using two colored water solutions were conducted to evaluate the device performance.
Modelling of mixing		
“Computational analysis of an Instantaneous chemical reaction in a T-microreactor” D. Bothe, A. Lojewski, H.-J. Warnecke	AIChE J. 56, 6 (2010) 1406-1415	Extension of method for the numerical computation of convective and diffusive mixing in liquid systems with very fast irreversible chemical reaction to the case of unequal diffusivities. Circumvention of the solution of stiff differential equations and, hence, facilitation of simulation of reactive flows with quasi-instantaneous reactions. Validated by a neutralization reaction studied in a T-shaped micromixer and compared with existing experimental LIF-data. Numerical computations for different reactor dimensions reveal the fact that, in a dimensionless setting, the obtained conversion is independent of the reactor size, if the flow conditions are the same. This corresponds to an increase of space-time-yield proportional to the square of the inverse scale factor.
“Spectral characterization of static mixers. The S-shaped micromixer as a case study” F. Garofalo, A. Adrover, S. Cerbelli, M. Giona	AIChE J. 56, 2 (2010) 318-335	The steady-state performance of a planar micromixer composed of several S-shaped units is investigated. Mixing efficiency is quantified by the decay of the scalar variance downstream the device for generic feeding conditions. It is discussed how this efficiency is controlled by the spectral properties of the advection-diffusion Floquet operator, F, that maps a generic scalar profile at the inlet of a single unit into the corresponding profile at the unit outlet section. Two advantages characterize the Floquet operator approach —(i) it allows to analyze an arbitrarily long device and (ii) it provides a quantitative assessment of mixing efficiency that is independent of the feeding conditions and that depends solely on the interaction between advection and diffusion.
“The simplicity of fractal-like flow networks for effective heat and mass transport” D. Pence	Exp. Thermal and Fluid Science 34, 4 (2010) 474-486	A review is given on disk-shaped fractal-like flow networks and the status of one and twodimensional predictive models. Applications discussed include single-phase and two-phase heat sinks and heat exchangers, two-phase flow separators, desorbers, and passive micromixers. Advantages of using these fractal-like flow networks versus parallel-flow networks are outlined, in particular for microscale fractal-like branching heat exchangers.
“Numerical simulation on fluid mixing by effects of geometry in staggered oriented ridges micromixers” Z. Xua, C. Li, D. Vadillo, X.	Sensors and Actuators B 153 (2011) 284–292	Simulations of a micromixer with patterned grooves address geometric variations. The ridge height ratio and the ridge asymmetry index, the modes of fluid motion and the pressure drops are studied about their effect on mixing.

Ruan, X. Fu		
Mixer design and mixing principle optimisation		
“Mixing performance of unbalanced split and recombine micomixers with circular and rhombic sub-channels” M. A. Ansari, K.-Y. Kim	Chem. Eng. J 162, 2, 15 (2010) 760-767	Mixing performance evaluated for planar split and recombine micromixers with asymmetric sub-channels – for fluid flow and mixing in a Reynolds number range from 1 to 80. Two shapes of the split channel are investigated - circular and rhombic. For rhombic sub-channels, higher mixing is achieved when width of the major sub-channel is either three or four times as wide as the minor sub-channel unlike the case of circular sub-channels. The results show the lowest mixing performance for the case of balanced collisions of fluid streams.
“Rapid micromixer via ferrofluids” L.M. Fu, C.H. Tsai, K.P. Leong, C.Y. Wenc	Physics Procedia 9 (2010) 270-273	The performance of a micromixer based on ferrofluids is predicted numerically. A permanent magnet is used to induce transient interactive flows between a water-based ferrofluid and water. The external magnetic field causes the ferrofluid to expand significantly and uniformly toward miscible water, associated with a great number of extremely fine fingering structures on the interface in the upstream and downstream regions of the microchannel. These pronounced fingering patterns increase the mixing interfacial length dramatically. The mixing efficiency can be as high as 95% within 2.0 s and a distance of 3.0mm from the inlet of the mixing channel, when the applied peak magnetic field is 145.8 Oe.
“Simple channel geometry for enhancement of chemical reactions in microchannels” B. R. Fu, Chin Pan	Ind. Eng. Chem. Res. 49, 19 (2010) 9413–9422	Experimental and theoretical investigation of the effect of the microchannel axial cross-section shape on mixing and chemical reaction. Three microchannels with uniform, converging, and diverging axial cross-sections were used to perform a liquid-liquid acid-base reaction that produces CO_2 gas. Flow visualization demonstrated that the most intense chemical reactions (enhanced bubble formation) occurred in the diverging microchannel. The flow deceleration effect in the diverging microchannel significantly enhanced diffusive mixing in the lateral direction and, consequently, chemical reaction.
“Gas–liquid mixing in a multi-scale micromixer with arborescence structure” J. Hou, G. Qian, X. Zhou	Chem. Eng. J. 167, 2-3 (2011) 475-482	A micromixer with arborescent structure for high throughput gas–liquid mixing was evaluated by absorbing pure CO_2 into alkaline solutions, and the volumetric mass transfer coefficient, interfacial area, liquid side mass transfer coefficient and pressure drop were determined for different configurations how to contact gases and liquids and operations (gas flow rate) of the micromixer.
“Computational design of mixers and pumps for micro-fluidic systems,based on electrochemically-active conducting polymers” K. Kannappan, G. Bogle J. Travas-Sejdic, D. E. Williams	Phys. Chem. Chem. Phys. 13 (2011) 5450-5461	Theoretical description of the propagation of composition waves along a strip made of an electrochemically-active conducting polymer, upon electrochemical stimulation. The electro-neutral Nernst–Plank equations in 2-D for electromigration and diffusional transport are solved. Under some circumstances, waves reflecting back from the end of the strip are predicted. It is demonstrated theoretically how such waves, associated as they are with expansion of the polymer, could be employed to enhance mixing or induce pumping in microfluidic systems.

“Mixing efficiency and energy consumption for five generic microchannel designs” M. Kashid, A. Renken, L. Kiwi-Minsker	Chem. Eng. J. 167, 2-3 (2011) 436-443	Homogeneous mixing at relatively high throughput for a single microchannel (of 1–18 ml/min) was investigated in microchannels with different dimensions, cross sections and mixing elements (with and without structured internal surface). A method based on the Villermaux–Dushman reaction was employed and the intensity of segregation was determined. Further, simulations were carried out to investigate the mixing time and the effectiveness of different microchannels. The data obtained for mixing time was correlated in terms of specific power dissipation which can be used for a priori predictions of mixing in microchannels. The results show that a microchannel with structured internal surface shows better performance in terms of mixing efficiency which has to be paid by high energy consumption.
“Design parameter studies on cyclone type mixers” A. Kölbl, M. Kraut, A. Wenka	Chem. Eng. J. 167, 2-3 (2011) 444-454	The influence of different structural parameters on mixing in cyclone type mixers was investigated numerically and experimentally utilizing CFD and the Iodide Iodate reaction method. The desired swirl motion in the mixing chamber as well as the occurrence of zones of complete recirculation (dead zones) and a zone with the occurrence of cavitation effects were found. The length of the cyclone mixing chamber has only a minor influence on mixing. The diameter of the cyclone mixing chamber had a severe effect on mixing. A cyclone mixing chamber with a diameter of 1 mm has significantly reduced mixing quality compared to a diameter of 500 µm (‘standard design’).
“Optimization methodology of operation of orifice-shaped micromixer based on micro-jet concept” K. Matsuyama, K. Mine, H. Kubo, N. Aoki, K. Mae	Chem. Eng. J. 65, 22 (2010) 5912-5920	The relationship between the channel geometry of micromixers and the size of the formed droplets was investigated. An orifice serves for sudden contraction and expansion of the flow. Fine droplets were produced and the mean droplet diameter is predicted on the basis of the pressure drop due to convection and the energy dissipation rate in the mixer chamber irrespective of the orifice geometry. Kinetic energy is dissipated within the order of milliseconds by the formation of a jet flow and the energy dissipation rate was quantified. The mean droplet diameter is proportional to $e_{jet}^{-0.4}$ irrespective of the channel geometry of the mixer. This understanding allows to enter into an optimization methodology for the orifice-based emulsification in microchannels.
“Nucleation of Alpha lactose monohydrate induced using flow through a Venturi orifice” J.S. McLeod, A.H.J. Paterson, J.E. Bronlund, J.R. Jones	J. Crystal Growth 312, 6 (2010) 800-807	Three different sized Venturi orifices were used to determine Alpha lactose monohydrate nucleation in supersaturated solution. Different characteristics of the mixing process were studied, including cavitation, power input, Reynolds number and vortex formation. Most decisive is the impact of the number of vortices on the nucleation rate. More vortices in a given chamber decrease the diffusion distance between the molecules and finally improve nucleation.
“Slurry mixing device with microchannels for gelcasting” K. Nagato, H. Hoshino, T. Hamaguchi, M. Nakao	Microelectronic Engineering (2011) in press	A slurry mixing device uses oblique ridges on the microchannel wall with the aim of rotating the slurry through the induced chaotic mixing. When investigating the effect of various ridge angles (30, 45, and 60 degrees), it was found that the slurry was successfully mixed by ridges with a 45-degree ridge angle.

“Indentations and baffles for improving mixing rate in deep microchannel reactors” K.-I. Sotowa, A. Yamamoto, K. Nakagawa, S. Sugiyama	Chem. Eng. J. 167, 2-3 (2011) 490-495	The effect of indentations and baffles in a deep micro-channel on the mixing was investigated. Results from both theoretical and experimental investigations demonstrated these substructures induce secondary flow and thus enhance mixing. The impact of their dimensions and of the flow rate; the latter was found to have a strong impact.
“A microfluidic mixer with self-excited ‘turbulent’ fluid motion for wide viscosity ratio applications” H. M. Xia, Z. P. Wang, Y. X. Koh, K. T. May	Lab Chip 10 (2010) 1712-1716	The influence of fluid properties on mixing has been less discussed, although diverse biological and chemical liquids to be mixed have large variations. A microfluidic mixer has been designed for mixing fluids with widely different viscosities. An interconnected multi-channel network divides bulk fluid volumes into smaller ones and then chaotically reorganizes these before entering in an expansion chamber which triggers viscous flow instabilities. Experiments with glycerol and aqueous solutions show an automatic transition of the flow from a steady state to a ‘turbulent’ state, even at small Reynolds number. This works well up to a viscosity ratio of 104.
“Microdevice for the mixing of a highly viscous biosample with water/membrane protein solution using microchannel and centrifugation” L. Yuan, Y. F. Zheng	Lab. Automation 16, 1 (2011) 68-81	Mixing of a highly viscous biosample at the microliter scale is performed with monoolein and a water/ membrane protein solution in a so called microcapsule microdevice using a microchannel and centrifugation. Experimental results validate the proposed method and also determine the flow oscillation time in the microchannel.
“Flow distribution and mass transfer in a parallel micro-channel contactor integrated with constructal distributors” J. Yue, R. Boichot, L. Luo, Y. Gonthier G. Chen, Q. Yuan	AIChE J 56, 2 (2010) 298–317	Flow distribution and mass transfer characteristics during CO_2-water flow through a parallel microchannel contactor integrated with two constructal distributors have been investigated numerically and experimenttally. Each distributor comprises a dichotomic tree structure that feeds 16 microchannels. These distributors could ensure a nearly uniform gas–liquid distribution at high gas flow rates where the ideal flow pattern was slug-annular flow. On the other side, at small gas flow rates where the ideal flow pattern was slug flow, a significant flow maldistribution occurred primarily due to the lack of large pressure barrier.
Mixing and flow characterisation		
“New spectrophotometric measurement method for process control of miniaturized intensified systems” R. Barzin, S. R. Abd Shukor, A. L. Ahmad	Sensors Actuators B 146, 1 (2010) 403-409	A spectrophotometric measurement system for controlling miniaturized intensified systems is proposed which can be used for a wide range of measurement objectives such as micro total analysis systems (μTAS) or micro chemical plant systems (MCPs). An embedded PID controller in the MATLAB® environment is used as a controller which is interfaced with LabVIEW® in order to facilitate communication with the rig components. The results obtained from the experimental study showed that using a spectrophotometric measurement can dramatically reduce process time delay and measurement response time.
“Characterization of a Vertical Lamination Micromixer for IR Spectroscopy” W. Buchegger, M. Kraft, M. J.	Procedia Engineering 5 (2010) 1348-1351	A multilamination micromixer for time-resolved infrared spectroscopy is characterized for different flow rates. Measurement results prove the ultrafast mixing performance of this micromixer (< 1 ms for aqueous solutions). This device operates in a wide range of

Vellekoop		flow rates without performance drop illustrated by the linear relation between the mixing time and the flow rate. A new custom chip holder provides easy chip handling and higher pressure durability.
“Investigation of the flow field in a three-dimensional Confined Impinging Jets Reactor by means of microPIV and DNS” M. Icardi, E. Gavi, D. L. Marchisio, A. A. Barresi, M. G. Olsen, R. O. Fox, Djamel Lakehal	Chem. Eng. J. 166, 1 (2011) 294-305	The Confined Impinging Jets Reactor (CIJR) is studied for precipitation processes of micro- and nano-particles. To obtain a better understanding of the main mixing mechanisms occurring in a CIJR, the flow field was studied at four inlet flow rates ranging from Re=62 to Re = 600 (regimes with incipient turbulence). A coupled numerical-experimental approach – microPIV and DNS – show that oscillations present in the inlet flow of the device are responsible for the chaotic and turbulent effects in the reactor.
“A new adaptive procedure for using chemical probes to characterize mixing” C. Habchi, D. Della Valle, T. Lemenan, Z. Anxionnaz, P. Tochon, M. Cabassud, C. Gourdon, H. Peerhossaini	Chem. Eng. J. (2011) in press	The iodide-iodate chemical probe method is modified by a novel adaptive procedure to investigate mixing in two compact curved-duct reactors. Both reactors have rectangular cross section; the first has smooth curvature (wavy duct) and the second has sharper bends (zigzag duct). In the conventional procedure, this method is used to characterize local micro-mixing, and for all experiments (for different Reynolds numbers and injection points) the reagent initial concentrations are kept at the same values. In the new adaptive procedure, the kinetics of the second reaction are adjustted as to impose the same reactive volume for different Reynolds numbers. This allows to characterise global mixing, by enlarging the measurement volume so as to capture and take into account *all mixing scales*. Experimental results reveal that the mixing performance of the zigzag channel as assessed by this method is slightly above that of the wavy one.
“Hydrodynamic and mass transfer in inertial gas–liquid flow regimes through straight and meandering millimetric square channels” M. Roudet, K. Loubiere, C. Gourdon, M. Cabassud	Chem. Eng. Sci. (2011) in press	For meandering channels, gas–liquid mass transfer in a square millimeter-sized meandering channel was characterized for the water/air system. Compared to a straight channel, a delay in the transition from Taylor to annular-slug regimes and a rise of 10–20% in bubble lengths is observed as well as higher deformations of the bubble nose and rear due to centrifugal forces (bends). For the Taylor flow regime, the gas-liquid mass transfer coefficient kla increased with increasing gas flow rate and the meandering geometry had only small influence. On the contrary, this effect was profound for the slug-annular flow regime. Whatever the channels, the NTUI remained low, thus showing that even millimeter-sized channels allow to intensify kla.
“Effect of property variations on the mixing of laminar supercritical water streams in a T-junction” C. N. Sökmen	Int. Commun. Heat Mass Transfer 38, 1 (2011) 85-92	Change of supercritical water properties with temperature and pressure impact the mixing of streams having different temperatures in a T shaped channel which is investigated numerically. The Reynolds number of the cold stream is in the range 0.1 to 100, the inlet temperature of the hot stream varies from 300 K to 800 K. Property variations have larger impact at low Re numbers and for hot fluid inlet temperatures above the pseudo-critical temperature. This leads to non-uniform temperature distribution in the outlet section.
“Ideal micromixing performance in packed microchannels” Y. Su, G. Chen, Q. Yuan	Chem. Eng. Sci. (2011) in press	The hydrodynamics and the micromixing characteristics in the packed and non-packed microchannels were studied experimentally at low Reynolds numbers (8–300). The fluid elements were strongly stretched, folded, and sheared in the packed microchannels.

		Through varying packing length and packing position the ideal micromixing performance can be obtained. The micromixing time of the packed microchannels was about 0.1ms.
"Liquid–liquid two-phase flow and mass transfer characteristics in packed microchannels" Y. i Su, Y. Zhao, G. Chen, Q. Yuan	Chem. Eng. Sci. 65, 13 (2010) 3947-3956	The hydrodynamics are characterized for water–kerosene flows in PMMA microchannels and mass transfer is determined with the water–succinic acid–n-butanol system in stainless steel microchannels. Quartz sand packed microchannels achieve droplets with a diameter less than 10 mm. The extraction efficiency is 46–61% in the non-packed microchannel, while being 81–96% in the packed microchannel. The impact of the packing length and micro-particle size is revealed as well as the pressure drop and specific energy dissipation.
"Effect of surface properties on the flow characteristics and mass transfer performance in microchannels" Y. Zhao, Y. Su, G. Chen, Q. Yuan	Chem. Eng. Sci. 65, 5 (2010) 1563-1570	The influence of surface properties on the flow and mass transfer of two immiscible liquids (water / kerosene) are investigated in opposed and cross-flow configuration microchannels, made in PMMA and in steel, at flux ratio far < 1. Mass transfer was evaluated for water–succinic acid-n-butanol at Reynolds numbers between 11 and 275. At low Re, dispersed phase flow pattern occur in the opposed T-shaped PMMA microchannel without surface modification. At high Re, only the continuous phase flow pattern (parallel flow) is observed with and without surface modification. The fluctuation amplitude with surface modification is larger than without surface modification at the opposed T-junction. To improve the separation of oil–water and for reliable analysis, a new separation method was developed based on the principle of a siphon. Overall volumetric mean mass transfer coefficients range from 0.19 to 11.96 s-1, three orders of magnitude higher than for conventional contactors.
Residence time distribution		
"Residence-time distribution as a measure of mixing in T-junction and multilaminated / elongational flow micromixers" J. T. Adeosun, A. Lawal	Chem. Eng. Sci. 65 (2010) 1865–1874.	Numerical and experimental investigation of mixing performance in a multilaminated/ elongational flow micromixer and a standard T-junction micromixer. Tracer experiments monitored by UV–vis absorption spectroscopy gave concentration data for residence-time distribution (RTD) analysis, including its coefficient of variation (CoV). The multilamination mixer showed better performance (narrower RTD and lower CoV). Between experiments and modeling a very good agreement was found, especially in the low Reynolds number flow regime (Re<29).
"Residence time distributions in microchannels: Comparison between channels with herringbone structures and a rectangular channel" A. Cantu-Perez, S. Barrass, A. Gavriilidis	Chem. Eng. J. 160, 3 (2010) 834-844	Residence time distributions (RTD) determined numerically and experimentally for channels with and without herringbone structures. The axial dispersion exchanging mass with a stagnant zone model provides a simpler method for RTD characterisation. Experimental RTD measurements performed by monitoring the concentration of a tracer dye by means of a LED-photodiode system. For low Peclet numbers (Pe < 102) the use of herringbone structures does not have an impact on the RTD, however at high Peclet numbers (Pe > 102), channels with herringbone structures exhibit a narrower RTD than a plain channel of the same dimensions. Thus, at high Pe, inclu-

		sion of herringbones to the bottom floor of rectangular channels allows the increase in channel dimensions without adverse effect on the RTD behaviour or reaction performance.
“Residence time distribution studies in microstructured plate reactors” A. Cantu-Perez, S. Bi, S. Barras, M. Wood, A. Gavriilidis	Appl. Thermal Eng. 31, 5 (2011) 634-639	Residence time distributions (RTDs) were investigated experimentally for reactors with straight and zig-zag channels using a tracer dye. It was found that the zig-zag channel configuration gives a narrower distribution as compared to the straight channel ones. Secondary flows were thought to be present in the zig-zag channel even at small Reynolds numbers. Furthermore, as the flowrate increased, the variance of the distribution of all geometries increased. The RTD for a single rectangular cross section channel had the largest variance due to its largest hydraulic diameter. However, its variance was not far from those of microstructured reactors and this was attributed to its small aspect ratio (shallow, wide channel). The RTDs of all microstructured reactors, and in particular the zig-zag geometry, were less sensitive to flowrate increase than the RTDs of the rectangular channel.
“Characterization of viscosity dependent residence time distribution in the static micromixer Statmix6” J. M. Köhler, B. Schleiff, S. Schneider, D. Boskovic, T. Henkel, G. A. Groß	Chem. Eng. J. 160, 3 (2010) 845-851	The residence time characteristic of the static micromixer Statmix6 was determined by a pulse trace experiment applying a microphotometric setup with two flow-through detectors. The residence time distribution (RTD) shows a characteristic shift with viscosity and flowrate. The change in RTD cannot be described by reconsidering the Reynolds number only; rather an RTD tailing factor was introduced and compared with the RTD characteristic of a straight PTFE tube and a commercial interdigital micromixer at residence times (about 0.5–40 s). The tube RTD tailing factor differs considerably from the characteristic found in the static micromixer so that device design has much impact. The experimental results were interpreted by changes in the flow regime under different convection mechanism inside the microdevices.
“Analysis of a pressure-driven folding flow microreactor with nearly plug-flow characteristics” A. Vikhansky, J. M. Macinnes	AIChE J. 56, 8 (2010) 1988–1994	A pressure-driven single-phase microreactor with characteristics similar to that in an ideal plug-flow reactor is designed. The residence time distribution in a microreactor with a large number of folding flow elements is investigated. Chaotic advection both induces mixing and suppresses the axial dispersion. It is shown through modeling that chemical reactions have different sensitivity to the axial dispersion.
Special applications		(the majority of reaction applications are not considered here; but only new and innovative kinds of applications)
“Systematic analysis of micromixers to minimize biofouling on reverse osmosis membranes” S. J. Altman, L. K. McGrath, H. D.T. Jones, A. Sanchez, R. Noek, P. Clem, A. Cook, C. K. Ho	Water Research 44 (2010) 3545-3554	Corrugated membranes use UV-curable epoxy traces printed on their surface as micromixers with local creation of turbulence at the interface. This shall reduce biofouling, as demonstrated here for reverse osmosis membranes. Measured are the rate of permeate flux decline and the median bacteria concentration. The mixers do not significantly increase the pressure. Chevron designs prevented biofouling of the membranes in comparison with blank membranes.
“Turbulent precipitation in micromixers: CFD simulation	Chem. Eng. Res. Des. 88 (2010)	Nanoparticles turbulent precipitation in a micromixer is investigated in the Confined Impinging Jets Mixer

and flow field validation" E. Gavi, D. L. Marchisio, A. A. Barresi, M. G. Olsen, R. O. Fox	1182–1193	(CIJM). The CIJM micromixers can provide high mixing rates and efficiencies. Here a precipitation model based on classical precipitation theory and Computational Fluid Dynamics was developed and tested on barium sulphate precipitation. The flow field is modelled with a RANS approach, and validated through comparison with experimental data, obtained with the microscopic Particle Image Velocimetry. Model predictions on barium sulphate mean particles size were compared with experimental data and good agreement was found.
"Magnetically activated micromixers for separation membranes" H. H. Himstedt, Q. Yang, L. P. Dasi,X. Qian,S. R. Wickramasinghe, M. Ulbricht	Langmuir 27, 9 (2011) 5574–5581	Magnetically responsive micromixing membranes present a radically novel approach to reduce concentration polarization and, potentially, also fouling by colloids present in aqueous feeds. Hydrophilic polymer chains were grafted via controlled surface-initiated atom transfer radical polymerization on the surface of polyamide composite nanofiltration membranes and then end-capped with superparamagnetic iron oxide magnetite (Fe_3O_4) nanoparticles. These nanoparticles experience a magnetic force as well as a torque under an oscillating external magnetic field which induces mixing directly above the membrane surface. The membrane performance could significantly be improved (increase of flux and salt rejection).
"Integrating micromixer precipitation and electrospray drying toward continuous production of drug nanoparticles" Y. He, Y. Huang, W. Wang, Y. Cheng	Chem. Eng. J. 168, 2 (2011) 931-937	An integrated device combining micromixer precipitation and electrospray drying is used to directly produce dry drug nanoparticles. This is achieved via non-solvent precipitation in the micromixer part of the device, and the resulted nanosuspension was subsequently dried by the electrospraying. The effects of the liquid flow rate, the applied voltage, the initial drug concentration, and the mixing/precipitation duration on the size and morphology of the products were experimentally investigated. By tuning the process conditions, nanoparticles with controllable shape and size could be achieved. In addition, the possibility of using this integrated device for a continuous production process of drug nanoparticles was explored.
"A novel synthesis route for $Cu/ZnO/Al_2O_3$ Catalysts used in methanol synthesis: combining continuous consecutive precipitation with continuous aging of the precipitate" S. Kaluza, M. Behrens, N. Schiefenhövel, B. Kniep, R. Fischer, R. Schlögl, M. Muhler	ChemCatChem 3 (2011) 189 – 199	Ternary $Cu/ZnO/Al_2O_3$ catalyst are prepared in a cascade of micromixers and a tubular aging reactor. Its application, in combination with immediate spray drying, enables monitoring of the formation of the final precursor by exchange reactions between initially separated phases during the aging step. These exchange reactions were successfully simulated by consecutive precipitation by using micromixers in series. After 60 min of continuous aging, calcination, and reduction, a catalyst is produced that exhibits an almost equal mass-related activity in methanol synthesis compared to a commercial catalyst and an area-related activity that is about 50% higher.
"Au/Ag/Au double shell nanoparticles with narrow size distribution obtained by continuous micro segmented flow synthesis" A. Knauer, A. Thete, S. Li, H. Romanus, A. Csákib,W. Fritzsche, J.M. Köhler	Chem. Eng. J. 166 (2011) 1164–1169	A two-step micro continuous flow-through method for synthesizing colloidal dispersions of noble metal core/shell and multishell nanoparticles in aqueous solutions in the presence of cetyltrimethylammonium bromide is based. The synthesis is based on the reduction of the metal salts $HAuCl_4$ and $AgNO_3$ at the surface of seed particles by ascorbic acid. In the micro fluidic system, constant residence times and an effective mixing were achieved by applying the

		segmented flow principle. The size distribution was very narrow - Au/Ag core/shell nanoparticles: average diameter of 20nm with a distribution half width of 3.8 nm; Au/Ag/Au multishell nanoparticles: 46nm ± 7.4nm. The optical spectra of the particle solutions exhibited drastic changes with the deposition of each additional metal shell which might be used in future sensing applications as well as for labelling in bioanalytics or as nonlinear optical devices.
“Structure evolution of curcumin nanoprecipitation” from a micromixer” Yi He, Y. Huang, Y. Cheng	Crystal Growth & Design 10, 3 (2010) 1021-1024	Drug nanocrystal technology is used for poorly water-soluble drug delivery. Curcumin was used as model drug and in detail its nanoprecipitate structure evolution from a micromixer was studied. Curcumin initially precipitated out as amorphous nanospheres, and then went through amorphous aggregation before transforming into needle-shaped crystals. The results clearly show a nonclassical crystallization pathway for curcumin nanoprecipitation.
“An enzymatic microreactor based on chaotic micromixing for enhanced amperometric detection in a continuous glucose monitoring application” B.-U. Moon, S. Koster, K. J. C. Wientjes, R. M. Kwapiszewski, A. J. M. Schoonen, B. H. C. Westerink, E. Verpoorte	Anal. Chem. 82, 16 (2010) 6756–6763	Aiming at a continuous glucose monitoring system for diabetes-related research, glucose oxidation in a microreactor with chaotic mixing channels was investigated. Slanted or herringbone grooves were compared to channels containing no grooves. Calibration curves for glucose were determined for channels with and without grooves, using amperometric detection and a Glucose Oxidase solution for in-chip reaction.
“Forced assembly and mixing of melts via planar polymer micro-mixing” D. Moon, K. B. Migler	Polymer 51, 14 (2010) 3147-3155	The forced assembly of immiscible polymers into targeted structures is tested in a planar polymer micromixer (PPMM), in which molten polymer are guided through a series of metal mixing chambers. Via shim stacking, complex 3D mixing flows can be generated. The sample sizes is significantly less than in traditional micro-mixers (<100 mg). In this way, targeted blend structures can be made rather than the more typical domain/matrix or random co-continuous ones. Multi-layers and coaxial cylinders are formed in the first five mixing units; thereafter non-ideal flow promotes the creation of mixed domain/matrix structures.
“Generation and reactions of oxiranyllithiums by use of a flow microreactor system” A. Nagaki, E. Takizawa, and J.-i. Yoshida	Chem. Eur. J. 16 (2010) 14149 – 14158	A microreactor system consisting of micromixers and microtubes was used for the generation and reactions of aryloxiranyllithiums without decomposition due to the short residence time and efficient temperature control. The temperature used in flow at -78 or -68 C is more favourable as compared to batch processing (-100 C).The resulting α-aryloxiranyllithiums were reacted with electrophiles, finally leading to the stereoselective synthesis of tetrasubstituted epoxides.
“An integrated on-chip sirtuin assay” S. Ohla, R. Beyreiss, G. K. E. Scriba, Y. Fan, D. Belder	Electrophoresis 31 (2010) 3263–3267	A microchip-based assay to monitor the conversion of peptide substrates by human recombinant sirtuin 1 (hSIRT1) uses a microfluidic separation structure with integrated serpentine micromixerThe substrate and the deacetylated product were separated by microchip electrophoresis on the same chip. The approach was successfully utilized to screen various SIRT inhibitors.
Nucleation and growth of gold nanoparticles studied via in situ small angle X-ray scattering at millisecond time resolution”	ACS Nano 4, 2 (2010) 1076–1082	Gold nanoparticles were prepared by the mixing of flows of an aqueous tetrachloroauric acid solution and a sodium borohydride solution applying a microstructured static mixer. Online characterization was made through coupling to a conventional in-house small

J. Polte, R. Erler, A. F. Thunemann, S. Sokolov, T. T. Ahner, K. Rademann, F. Emmerling, R. Kraehnert		angle X-ray scattering (SAXS) setup. In combination with X-ray absorption near edge structure microscopy, scanning electron microscopy, and UV-vis spectroscopy a two-step mechanism was deduced; the first step being a rapid conversion of the ionic gold precursor into metallic gold nuclei, followed by particle growth *via* coalescence of smaller entities.
"Continuous hydrothermal synthesis of Fe_2O_3, NiO, and CuO nanoparticles by super-rapid heating using a T-type micro mixer at 673K and 30MPa" K. Suea, S.-i. Kawasaki, M. Suzuki, Y. Hakuta, Hiromichi Hayashi, K. Arai, Y. Takebayashi, S. Yoda, T. Furuya	Chemical Engineering Journal 166, 3 (2011) 947–953	A continuous hydrothermal synthesis of Fe_2O_3, NiO, and CuO nanoparticles was made. A T-type micro mixer was used for super fast heating of the starting solutions. In the Fe_2O_3 synthesis, the conversion became 97.9% at 0.002 s and the particle size was 4.0 to 6.7 nm. In the NiO synthesis, the conversion was 11.4% at 0.002 s and increased to 70.1% at 2 s. The particle size increased then from 15.4 to 18.7 nm. In the CuO synthesis, $Cu(NO_3)_2$ was not converted to CuO at 0.002 s. At longer residence times, the conversion, and particle size gradually increased from 25.6 to 42.5% and from 28.7 to 34.3 nm, respectively.
"Determination of free bilirubin and its binding capacity by HSA using a microfluidic chip-capillary electrophoresis device with a multi-segment circular ferrofluid-driven micromixing injection" H. Sun, Z. Nie, Y. S. Fung	Electrophoresis 31, 18 (2010) 3061–3069	A PMMA microfluidic chip-CE device with a multi-segment circular-ferrofluid-driven micromixing injector was used for the determination of free bilirubin and its binding capacity by HSA at equilibrium. Total binding capacity of HSA for bilirubin was determined. The device is capable to provide adequate margin of protection to detect an early rising level of bilirubin and impaired binding capacity prior to the onset of jaundice condition.
"Channel interlacing: A geometric concept for intensification and design of the internal structure of fluid contactors" D. Tondeur, C. Menetrieux	Chem. Eng. Sci. 66, 4 (2011) 709-720	''Interlacing''of the flow channels of two or more arborescent (dendritic) networks create a new method for multi-vascularization. Besides diffusional effects through dividing the flows into smaller channel, micro-turbulence is generated by the tortuosity of the channels. Two concepts of interlacing are introduced: "chiasma'', i.e. the permutation of the position of two neighbor channels and division into several sub-channels through separating walls. This is illustrated at a heat exchanger and a reactor-exchanger. Variation in cross-section geometries is used, e.g. triangles, to pack into hexagonal or quasi-circular spaces.
"Feasibility of tubular microreactors for emulsion polymerization" A. K. Yadav, J. C. de la Cal, M. J. Barandiaran	Macromol. React. Eng. (2011) 69–77	Tubular microreactors are used for the production of polymer dispersions. The stability of preemulsion Is decisive in achieving steady-state performance. The flow pattern was characterized, using the dispersion model because of the effect of radial molecular diffusion. Styrene emulsion polymerization in the microreactor and batch laboratory reactor showed similar kinetics and properties which indicates sufficient mixing in both cases.
Scale-out / Production		
"On the scalability of micro-structured mixing devices" A. Kolbl, M. Kraut, K. Schubert	Chem. Eng. Sci. 160, 3 (2010) 865-872	Microchannel systems for multilamination mixers can be obtained by stacking and bonding microstructured foils. So-called V-type mixers were examined by means of the Iodide Iodate reaction method. In previous work we showed that V-type mixers can be scaled by varying the number of micromachined foils and holding constant velocities of the fluids. Constant mixing qualities were obtained with mixer inlays with 6, 12 and 24 foils. No influence of the top- and the

		bottom ('boundary') foils were found even in mixer inlays with only 4 foils and 2 foils; showing even these devices are fully 'in-line' with the scaling considerations from previously examined devices. Furthermore, the arrangement of the microchannels at the interface between the microchannel system and the mixing chamber ('shape of the exit window') has a crucial impact on the mixing results: the larger the width of the exit window, the better the mixing results.
Design of micromixer for emulsification and application to conventional commercial plant for cosmetic" K. Matsuyama, K. Mine, H. Kubo, K. Mae	Chem. Eng. J. 167, 2-3 (2011) 727-733	A current commercial cosmetic manufacture process cannot achieve the desired droplet diameter which means that the characteristics of the final product cannot be achieved as well, as these strongly depend on the degree of emulsification. A micromixer (K-JET mixer) was used which has a simple orifice-based design. This mixer is known to be usable for a wide range of products, achieves good mixing, and can be easily adjusted for a wide range of throughputs. The droplet diameter was easily controlled by adjusting the orifice diameter and flow rate. A full-scale mixer suitable for a commercial plant was built and the necessary specifications for the gel capsule manufacture were specified.

4.2 Patents

(Provide the list of new patents in Table 6. Under “remarks” provide, where applicable, the names/types of products targeted by the given patent.)

Patent search was done through public available and simple-useable databases such as the following (through which the main collecting of information was done)

http://www.freepatentsonline.com

Focus was given on patents in the years 2010-2011, but some “older” patents were considered as well down to 2008. The number of patents is still quite large and this here is only a selection based on the automatic ranking in relevance by the internet platform and based on the judgment of the report author.

Table 6. New patents

Patent	**Patent holder**	**Remarks, including names/types of products targeted by the patent**
Micromixer fabrication, principle, and design		
“Active micromixer using surface acoustic wave streaming” United States Patent 7942568 Publ. Date: 05/17/2011 Filing Date: 06/17/2005	Branch, Darren W. (Albuquerque, NM, US) Meyer, Grant D. (Ithaca, NY, US) Craighead, Harold G. (Ithaca, NY, US) Sandia Corporation (Albuquerque, NM, US)	An active micromixer uses a surface acoustic wave, preferbly a Rayleigh wave, propagating on a piezoelectric substrate to induce acoustic streaming in a fluid in a microfluidic channel. The surface acoustic wave can be generated by applying an RF excitation signal to at least one interdigital transducer on the piezoelectric substrate. The active micromixer can rapidly mix quiescent fluids or laminar streams in low Reynolds number flows. The active micromixer has no moving parts (other than the SAW transducer) and is, therefore, more reliable, less damaging to sensitive fluids, and less susceptible to fouling and channel clogging than other types of active and passive micromixers. The active micromixer is adaptable to a wide range of geometries, can be easily fabricated, and can be integrated in a microfluidic system, reducing dead volume. Finally, the active micromixer has on-demand on/off mixing capability and can be operated at low power.
“Airfoil-shaped micro-mixers for reducing fouling on membrane surfaces” Publ. date: 05/13/2010	Clifford K. Ho (Albuquerque, NM, US) Susan J. Altman (Cedar Crest, NM, US) Paul G. Clem (Albuquerque, NM, US) Michael Hibbs (Albuquerque, NM, US) Adam W. Cook (Albuquerque, NM, US)	An array of airfoil-shaped micro-mixers that enhances fluid mixing within permeable membrane channels, such as used in reverse-osmosis filtration units, while minimizing additional pressure drop. The enhanced mixing reduces fouling of the membrane surfaces. The airfoil-shaped micro-mixer can also be coated with or comprised of biofouling-resistant (biocidal/germicidal) ingredients.
„Micromixer biochip“ United States Patent Application 20100246315 A1 Filed: October 7, 2009	Lee; Gwo-Bin; (Tainan City, TW) ; Yang; Sung-Yi; (Tainan City, TW) National Cheng Kung University, TW	The present invention provides a micromixer biochip, comprising: a substrate having a surface; a fluidic channel layer disposed above the surface of the substrate, including a mixing chamber and a single-opening fluidic channel, wherein one end of the single-opening fluidic channel is closed and the other end of the single-opening fluidic channel connects to the mixing chamber, and a top portion of the single-opening fluidic channel is made of a flexible material; and an air chamber layer disposed above the top portion of the fluidic channel layer, including an air pore, at least one chamber, and an air channel connecting the chamber and the air pore, wherein the number and position of the air chamber correspond to the number and position of the single-opening fluidic channel of the fluidic channel layer.
“Twin-vortex micromixer for enforced mass exchange”	Yang; Jing-Tang (Hsinchu, TW), Tung; Kai-Yang (Hsinchu, TW), Fang; Wei-Feng (Hsinchu, TW),	The present invention discloses a vortex-modulation based micromixer for enforced mass exchange. The micromixer of the present invention comprises a mixing chamber with grooves on one wall thereof and a special-shape barrier on

Filed: May 9, 2006	Huang; Ker-Jer (Hsinchu, TW) National Tsing Hua University (Hsinchu, TW)	another wall. As different fluids are injected into the mixing chamber respectively from two inlets of the micromixer, the grooves and barriers of the micromixer of the present invention create the constructive interferences to form the active-like agitation of the fluid. For every groove, the flux passed by can be increased via its high pressure gradient. Understandably, the mixing efficiency of the fluids can be greatly improved within a very short distance. At last, the outlet of the micromixer is located in the downstream of the mixing chamber and further is able to connect with other elements. The present invention is entirely a passive micromixer and no additional energy is required. The present invention can apply to a continuous chemical analysis, particularly to a lab-on-a-chip or a micro total analysis system.
“Micro mixer” Publ. date: 07/01/2010 Patent application number: 20100163114	Hidekazu Yoshizawa (Okayama-Shi, JP) Eiji Kamio (Nakago-Cho, JP) NATIONAL UNIVERSITY CORPORATION OKAYAMA UNIVERSITY	A micro mixer including a first tubular member for guiding a first fluid to be directed in a first direction; a second tubular member having a discharge portion in the downstream portion of said first tubular member for guiding a second fluid to be directed in a direction opposite to said first direction, said discharge portion having a flow passage space narrower than the flow passage space of the downstream portion of the first tubular member; a first annular space defined by the downstream portion of the first tubular member and the discharge portion of the second tubular member for guiding a mixed fluid caused by colliding the first fluid flowing in the first tubular member with the second fluid flowing in the second tubular member in a counter-flow manner to be directed in the same direction as said first direction and further for increasing the pressure of said mixed fluid; a mixing-promoting space communicating with said first annular space for lowering the pressure of the mixed fluid discharged from said first annular space to promote mixing of the mixed fluid with the aid of vortexes caused in connection with the pressure drop of the mixed fluid; and a third tubular member for guiding the mixed fluid in said mixing-promoting space into a predetermined collecting unit.
“Micromixer using integrated three-dimensional porous structure” US20080094937 Application Number US/11/863077 Publication Date 2008-04-24 Filing Date 2007-09-27	Li Wei (Shoreline, WA) Wang Hai (Seattle, WA) University of Washington	A micromixer is fabricated using a selective high intensity focused ultrasound foaming technique. The micromixer employs a 3D porous region for effective mixing. The 3D porous micromixer can achieve sufficient mixing results with a short mixing length for flows with a Reynolds number as low as 0.1. The fabrication process of the micromixer is rapid, low-cost, and biocompatible. The pore size of the micromixer can be controlled by adjusting the selective high intensity focused ultrasound foaming parameters. The micromixer has potential for use in lab-on-a-chip and micro-total-analysis devices.
“Micromixing chamber, micromixer comprising a plurality of such micromixing chambers, methods for manufacturing thereof, and methods for mixing” US Patent Application 20100067323 A1 Appl. number:12/513602 Publ. date:03/18/2010 Filing date:11/05/2007	Blom, Marko Theodoor (Enschede, NL), Mulder, Michael Christiaan (Enschede, NL), Macleod Macinnes, Jordan (Sheffield, GB) Allen, Raymond William Kenneth (Oxford, GB) MICRONIT MICROFLUIDICS B.V. (Enschede, NL)	A micromixing chamber, roughly in the form of an hourglass, having a first outer end with a tangential inflow opening and a second outer end with a tangential outflow opening. The mixing chamber in the overall flow direction first narrows more or less gradually and subsequently widens more or less abruptly. The micromixer may be made at least partially of glass, or at least partially of a plurality of glass plates. A micromixer having a plurality of such micromixing chambers connected fluidically in series is also disclosed. Methods for manufacturing such a micromixing chamber of such a micromixer, as well as method for mixing by means of such a micromixing chamber or by means of such a micromixer, are disclosed.
“Micromixer” US20080043570 Application Number US/11/864508	Arnold, Don W (Livermore, CA) Paul, Phillip H (Livermore, CA) Eksilent Technologies INC	Methods and apparatus for mixing fluids are provided. The devices and methods operate without moving parts, and generate well-mixed fluids over a broad dynamic range of flow rates. Preferred embodiments include junction-type mixers, bundled mixers, and co-axial mixers. The devices and methods are optimized to produce rapid, accurate gradients to improve associated system throughput and

Publication Date 2008-02-21 Filing Date 2007-09-28		reproducibility.
“Planar micromixer” US Patent 7344681 Appl. number:10/960324 Publ. date:03/18/2008 Filing date:10/06/2004	Fiechtner, Gregory J. (Bethesda, MD, US), Singh, Anup K. (Danville, CA, US), Wiedenman, Boyd J. (Alpharetta, GA, US) Sandia Corporation (Livermore, CA, US)	The present embodiment describes a laminar-mixing embodiment that utilizes simple, three-dimensional injection. Also described is the use of the embodiment in combination with wide and shallow sections of channel to affect rapid mixing in microanalytical systems. The shallow channel sections are constructed using all planar micromachining techniques, including those based on isotropic etching. The planar construction enables design using minimum dispersion concepts that, in turn, enable simultaneous mixing and injection into subsequent chromatography channels.
“Method for continuously and dynamically mixing at least two fluids, and micromixer” United States Patent 7287899 Appl. number: 10/517190 Publ. date: 10/30/2007 Filing date: 05/23/2003	Navarro, Christophe (Bidache, FR) Walzel, Peter (Dormagen-Allemagne, FR) Arkema France (Colombes, Cedex, FR)	The invention relates to a method for continuously and dynamically mixing at least two fluids. Said method comprises the following steps: a) the rotor (1) of a micromixer is rotatably driven, said micromixer comprising a rotor (1) which is provided with a shaft (2) encompassing blades (3) that are arranged in groups (3a-3g), a stator (4) which is provided with at least one inlet (5) for a first fluid, at least one inlet (6) for a second fluid, and an outlet (7); b) the fluids are fed into the micromixer; and c) a micromixture of the fluids is collected at the outlet (7) of the micromixer. The inventive method is particularly suitable for rapid and/or complex kinetic chemical reactions such as anionic polymerization. The invention also relates to a micromixer for carrying out said method.
Micromixers in systems and plants		
“Mixer system, reactor and reactor system” United States Patent 7829039 Appl. Number: 11/910639 Publ. date: 11/09/2010 Filing date: 03/23/2006	Schubert, Klaus (Karlsruhe, DE),Kraut, Manfred (Linkenheim-Hochstetten, DE), Bohn, Lothar (Hambruecken, DE), Wenka, Achim (Remchingen, DE) Citation:Click for automatic bibliography generation Assignee:Forschungszentrum Karlsruhe GmbH (Karlsruhe, DE)	A mixer system for mixing at least two fluids includes a plurality of micromixers that are fluidically connected in parallel. The micromixers are integrated into a guide matrix and are fluidically connected via feed lines for the fluids to be mixed
“Microchemical nanofactories” US20080108122 Filing Date 2007-08-31 Application Number US/11/897998 Publication Date 2008-05-08	Paul Brian Kevin (Corvallis, OR) Chang Chih-Hung (Corvallis, OR) Remcho Vincent Thomas (Corvallis, OR) State of Oregon	Embodiments of an apparatus, system, and method for chemical synthesis and/or analysis are disclosed. One embodiment of a disclosed apparatus comprises a laminated, microfluidic structure defining a reactor and a separator. Such apparatuses, or portions thereof, generally have dimensions ranging from about 1 micrometer to about 100 micrometers. To implement synthetic processes, disclosed embodiments of the apparatus generally include at least one unit operation, such as a mixer, a valve, a separator, a detector, and combinations thereof. Individual apparatuses may be coupled both in series and in parallel to form a system for making chemical compounds. An individual apparatus or a system also can be used in combination with known devices and processes.
Micromixer applications		
Emulsion and method of manufacturing emulsion US20080081842 Filing Date 2007-09-30 Application Number US/11/865027 Publication Date 2008-04-03	Ueyama Tomohide (Ashigara-Kami-Gun, JP) Nagasawa Hideharu (Ashigara-Kami-Gun, JP) FUJIFILM CORPORATION	An aspect of the present invention provides a method of manufacturing an emulsion by using a nonionic surfactant, an oil agent and water, wherein the following steps are conducted in a continuous flow system: an emulsification step of forming an emulsion by emulsifying the nonionic surfactant, the oil agent and the water at a phase inversion temperature at which three phases of the nonionic surfactant, the oil agent and the water coexist; and an emulsion stabilization step of passing the emulsion in a microchannel with an equivalent diameter equal to or less than 1 mm to rapidly cool or rapidly heat the emulsion from the phase inversion temperature to a temperature at which the emulsion is stabilized.

Dispenser for Beverages Including Juices US20070267441 Filing Date: 2007-07-13 Application Number US/11/777309 Publ. Date: 2007-11-22	Van Opstal Edwin Petrus Elisabeth (Victoria, AU) Rudick Arthur G (Atlanta, GA) Wilcock Mark Andrew(Victoria, AU) Zipsin Andrew (Victoria, AU) THE COCA-COLA COMPANY	A beverage dispenser for combining a number of micro-ingredients, one or more macro-ingredients, and one or more water streams. The beverage dispenser may include a micro-mixing chamber for mixing a number of the micro-ingredients and the water into a micro-ingredient stream and a macro-mixing chamber for mixing the micro-ingredient stream, the macro-ingredients, and the water into a combined stream.
“Process for production of hexafluoropropylene oxide” EP2090572A1 Filing Date: 2007-10-23 Application Number EP07830372.4 Publ. Date: 2009-08-19	Nakaya Hikeki Asano Michio Saitou Hideya DAIKIN INDUSTRIES LTD	A process for producing hexafluoropropylene oxide, which comprises passing an organic phase comprising hexafluoropropylene and an aqueous phase comprising an oxygen-containing oxidizing agent through a small space in contact with each other, thereby reacting hexafluoropropylene with the oxygen-containing oxidizing agent to obtain hexafluoropropylene oxide.
Micromixers for nanomaterial production US Patent Application 20090245017 A1 Appl. number:12/414597 Publ. date:10/01/2009 Filing date:03/30/2009	Paul, Brian Kevin (Corvallis, OR, US), Garrison, Anna Evelyn (Philomath, OR, US) State of Oregon on behalf of OR State Univ.	A micromixer device has at least one fluid inlet channel and at least one fluid outlet channel. A plurality of pathways extend between the fluid inlet channel and the fluid outlet channel. The width of at least some of the plurality of pathways varies in a substantially parabolic manner along at least one dimension of the micromixer device.
“Multicomponent packaging with static micromixer” US Patent Application 20070140042 A1 Appl. number:10/563191 Publ. date:06/21/2007 Filing date:06/04/2004	Schanz, Gerhard (Darmstadt, DE) Sendelbach, Gerhard (Darmstadt, DE) Wella AG, Darmstadt	The packaging system has two storage chambers for separately storing two components and a static micromixer for mixing them to prepare a formulation. The static micromixer is provided with plural disks (1) arranged in a stack. Each disk (1) has at least one inlet opening (2) for a feed stream, which is connected via a linking channel (3) with at least one outlet opening (4) for outflow of the feed stream into a mixing zone (5). The linking channel (3) is divided into two or more part channels (7) by microstructure units (6). Each part channel has a respective width that is smaller than a width of the mixing zone (5). A method of in-situ preparation of a formulation by mixing the components in the packaging system is also described.
“Solution-based process for making inorganic materials” United States Patent Application 2010 Publ. Date: 10/14/2010 Filing Date: 04/09/2010	Chang, Chih-hung (Corvallis, OR, US) Wang, Wei (Corvallis, OR, US) Oregon State University	Disclosed embodiments provide a solution-based process for producing useful materials, such as semiconductor materials. One disclosed embodiment comprises providing at least a first reactant and a second reactant in solution and applying the solution to a substrate. The as-deposited material is thermally annealed to form desired compounds. Thermal annealing may be conducted under vacuum; under an inert atmosphere; or under a reducing environment. The method may involve using metal and chalcogen precursor compounds. One example of a metal precursor compound is a metal halide. Examples of suitable chalcogen precursor compounds include a chalcogen powder, a chalcogen halide, a chalcogen oxide, a chalcogen urea, a chalcogen or dichalcogen comprising organic ligands, or combinations thereof. Certain disclosed embodiments concern a method for making a solar cell from I-III-VI semiconductors. 6. The method according to claim 5, further comprising: flowing the metal precursor compound and the chalcogen precursor compound to a micromixer to form the solution; and applying the solution to the substrate using a microchannel applicator.
“Extraction method using a static micromixer” US Patent Application 20070007204 A1	Schanz, Gerhard (Darmstadt, DE) Sendelbach, Gerhard (Darmstadt, DE) Wella AG, Darmstadt	A process is described for the extraction of one or more substances from a fluid starting material with an appropriate extraction agent by use of a static micromixer for mixing the starting material with the extraction agent. The static micromixer is provided with disk-shaped components, the disk (1) being provided with at least one inlet opening (2) for introducing at least one fluid stream into a linking channel (3)

Appl. number:10/563354 Publ. date:01/11/2007 Filing date:06/04/2004		disposed in the plane of the disk and at least one outlet opening (4) for removing the fluid stream into a mixing zone (5) disposed in the plane of the disk, the inlet opening (2) being connected with the outlet opening (4) in a communicating manner through a linking channel (3) disposed in the plane of the disk, and the linking channel (3) before opening into the mixing zone (5) being divided by microstructure units (6) into two or more part channels (7), and the widths of the part channels being in the millimeter to submillimeter range and being smaller than the width of the mixing zone (5).
“Components for Static Micromixers, Micromixers Constructed from such Components and Use of such Micromixers for Mixing or Dispersing or for Carrying Out Chemical Reactions” US Patent Application 20080106968 A1 Appl. number: 10/563348 Publ. date: 05/08/2008 Filing date: 06/04/2004	Schanz, Gerhard (Darmstadt, DE) Sendelbach, Gerhard (Darmstadt, DE) Wella AG, Darmstadt	Components for static micromixers, micromixers constructed from such components and processes carried out by the use of said micromixers are described. The components are in the form of a disk with at least one inlet opening (2) for introducing at least one feed stream into a linking channel (3) disposed in the plane of the disk and at least one outlet opening (4) for the outflow of the feed stream into a mixing zone (5), wherein the inlet opening (2) is connected in a communicating manner with the outlet opening (4) through the linking channel (3) disposed in the plane of the disk and wherein the linking channel (3) before opening into the mixing zone (5) is divided by microstructure units (6) into two or more part channels, the widths of the part channels being in the millimeter to submillimeter range and being smaller than the width of the mixing zone (5). The micromixers can be used for mixing, homogenizing, dispersing, emulsifying, dissolving or gassing liquids or for carrying out chemical reactions and particularly combustion reactions.
“Method of making nanoscale particles of AZO pigments in a microreactor or micromixer” US Patent 7563318 Appl. number: 12/166949 Publ. date: 07/21/2009 Filing date: 07/02/2008	Faucher, Santiago (Oakville, CA), Carlini, Rina (Oakville, CA), Moore, Emily L. (Mississauga, CA), Thompson, Christine M. (Etobicoke, CA), Gardner, Sandra J. (Oakville, CA), Gerroir, Paul J. (Oakville, CA), Allen, Geoffrey C. (Waterdown, CA) Citation:Click for automatic bibliography generation Assignee:Xerox Corporation (Norwalk, CT, US)	A process for preparing nanoscale azo pigment particles includes providing an organic pigment precursor that contains at least one functional moiety, providing a sterically bulky stabilizer compound that contains at least one functional group, and carrying out a chemical reaction to form a pigment composition in a microreactor or micromixer, whereby the functional moiety found on the pigment precursor is incorporated within the pigment and non-covalently associated with the functional group of the stabilizer, so as to allow the formation of nanoscale-sized pigment particles and the production of such in a microreactor under laminar or turbulent flow conditions without clogging.
“Production method of silver halide photographic emulsion and production apparatus thereof “ United States Patent Application 2005 Publ. Date: 07/14/2005 Filing Date: 11/24/2004	Nagasawa, Hideharu (Kanagawa, JP) Ichikawa, Yasunori (Kanagawa, JP) Shiraishi, Fumiko (Kanagawa, JP) Maeda, Hiroshi (Kanagawa, JP) Fujisawa, Mamoru (Kanagawa, JP) FUJI PHOTO FILM CO., LTD.	At least one of a nucleus forming process, a nucleus growing process, a chemical sensitizing process, and a spectral sensitizing process for producing a silver halide photographic emulsion is performed by using a microreactor. A minute region of the microreactor is used to precisely perform a reaction of nucleus formation. A condition under which host grains are allowed to react with newly supplied silver halide nuclei is made uniform to cause uniform crystal growth. A predetermined quantity of molecules for chemical sensitization is doped in a crystal lattice of a nucleus of silver halide to effect a sensitizing process. Alternatively, a spectral sensitizing process in which a single molecular layer of a spectral sensitizer is uniformly adsorbed on a silver halide nucleus grain surface is securely carried out.
“Continuous microreactor process for the production of polyester emulsions” United States Patent 7943687 Appl. number: 12/502452 Publ. date: 05/17/2011 Filing date :07/14/2009	Faucher, Santiago (Oakville, CA), Hanewich-hollatz, Mikhail (Mississauga, CA), Qiu, Shigang (Toronto, CA), Borbely, David (Oakland, CA) Xerox Corporation (Norwalk, CT, US)	A process and system for continuously making a resin emulsion suitable for use in forming toner particles includes at least one micromixer for micromixing a resin mixture and aqueous phase to continuously produce an emulsion of a high solids content. The process comprises contacting a polyester resin possessing acid groups with a component selected from the group consisting of an organic solvent and a solvent inversion agent to form a resin mixture; neutralizing the resin mixture with a neutralizing agent; and subjecting the resin mixture to micromixing.

5. New stakeholders

5.1 Suppliers and developers

(Provide the list of key suppliers/developers, including research institutes in Table 7)

The list below specifies microreactor suppliers which have own micromixer products (which is not given for all). Only a few new products were launched in the last two years. Main products are on the market already for several years. Despite the vital scientific development and the many new micromixer designs and principles proposed, this is taken up commercially only very slow. Obviously the existing micromixers satisfy also the market needs. There are reports about commercial micromixers in Japan, but this was not confirmed by this internet research. Obviously, these mixers are available, but are not heavily advertised on webpages, so that this offer seems to be semi-public.

Table 7. Supplier and developers

Institute/Company	**Country**	**Short characteristic**
BTS-Ehrfeld Mikrotechnik *www.ehrfeld.com*	Germany	From lab to production-scale mixers. Diffusive and convective mixers Steel as construction material Specialty mixers for precipitations and particle formation
Institut fuer Mikrotechnik Mainz GmbH *www.imm-mainz.de*	Germany	From lab to production-scale mixers. Diffusive and convective mixers Steel as construction material Specialty mixers for precipitations and particle formation
Mikroglas chemtech GmbH *www.mikroglas.com*	Germany	From lab to pilot-scale mixers. Diffusive and convective mixers (T-, herringbone, superfocus, interdigital, cyclone) Glas as construction material
Little Things Factory *www.imm-mainz.de*	Germany	From lab to pilot-scale mixers (MR PILOT and XXL series) Convective mixers Glas as construction material
Micronit Microfluidics *www.micronit.com*	The Netherlands	Lab mixer Convective mixer (‘folding flow’) Glass as construction material
ThinXXS *www.thinxxs.com*	Germany	One lab -scale mixer. Convective mixer. Polymer as construction material
Lionix *http://www.lionixbv.nl*	The Netherlands	Lab mixer Diffusive and convective mixer (bifurcation and planar-injection-nozzle mixer) Glass as construction material
Uniqsis *www.uniqsis.com*	United Kingdom	Lab mixer Convective mixer (static mixer) Glass as construction material
Corning Incorporated *http://www.corning.com/r_d/emerging_technologies/reactors.aspx*	USA	Mixers - part of advanced flow reactor series (lab to production scale) Convective mixers

		Glass as construction material

5.2 End users

(Describe new/potential end-users, other than those already listed in Table 1)

It is difficult to identify specific institutes and countries which are new or potential end-users. Rather it was decided to describe application fields which could profit from the development of microstructured mixers, but so far had low or no exposure. The latter can be for various reasons such as cost arguments, reliability, or just insufficient information and involvement in process intensification developments; all of which can be changed.

Field of end-user with low or no exposure	**Short characteristic**
Petrochemistry	In many large-scale processes mixing is involved. Even for gas-phase mixing the use of micro-structured mixers might be useful (safety concerns). The latter have meanwhile a capacity suitable for petrochemistry and such small footprint which should make them attractive. But there are opposing effects such as questions on reliability and real proof of principle.
Food	Food applications are full of making dispersions. Micromixers are prime dispersing devices, as e.g. demonstrated by their ability to generate monodisperse emulsions. Still, no use is made in food industry. Costs arguments are one main reason. Full-process cost analyses are needed for better understanding what should be done to raise interest in using micromixers.
Cosmetics and personal care	There is some interest and development, but even the commercial demonstration seems not to have led to large activities. The major players (e.g. Procter&Gamble, Unilever) organize “lighttower meetings” with leading experts; which demon-strates the principle interest – unlike food industry. Still the picture is scattered and especially academic contributions are largely missing.