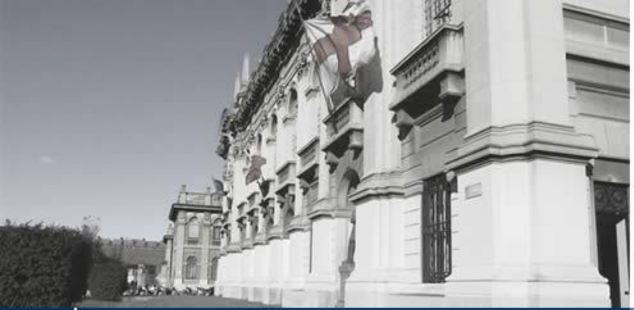


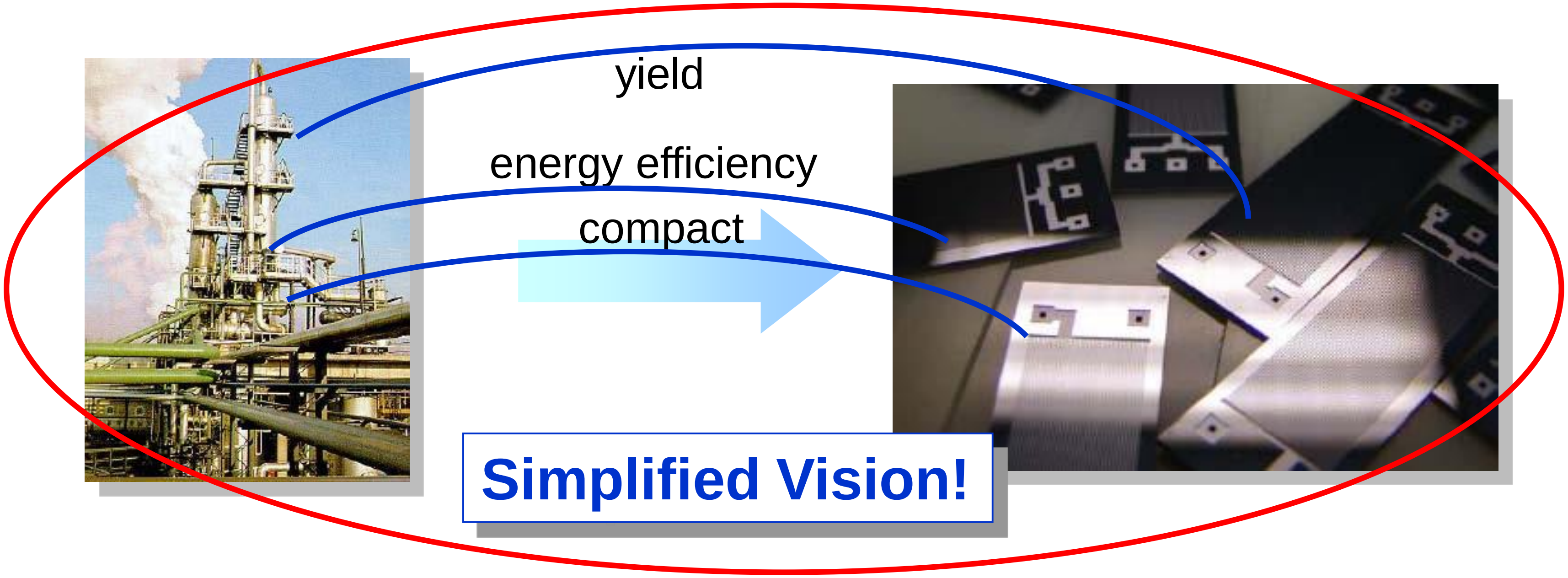
School of Industrial and Information Engineering
Course 096125 (095857)
Introduction to Green and Sustainable Chemistry

POLITECNICO DI MILANO

Microchemical and Microphysical Systems.

Prof. Attilio Citterio
Dipartimento CMIC "Giulio Natta"
https://iscamapweb.chem.polimi.it/citterio/it/education/course-topics/

Micro-chemical Systems and Processes: Opportunity and Limits.



Miniature reaction and other unit operations, show ***specific advantages*** over conventional chemical systems.

ENABLING TECHNOLOGIES

Microfabrication
↓
Microfluidics
↓
Micro process engineering

Green / sustainable chemistry
↓
Process intensification

Small-scale conti-flow processing

Novel means of chemical process engineering

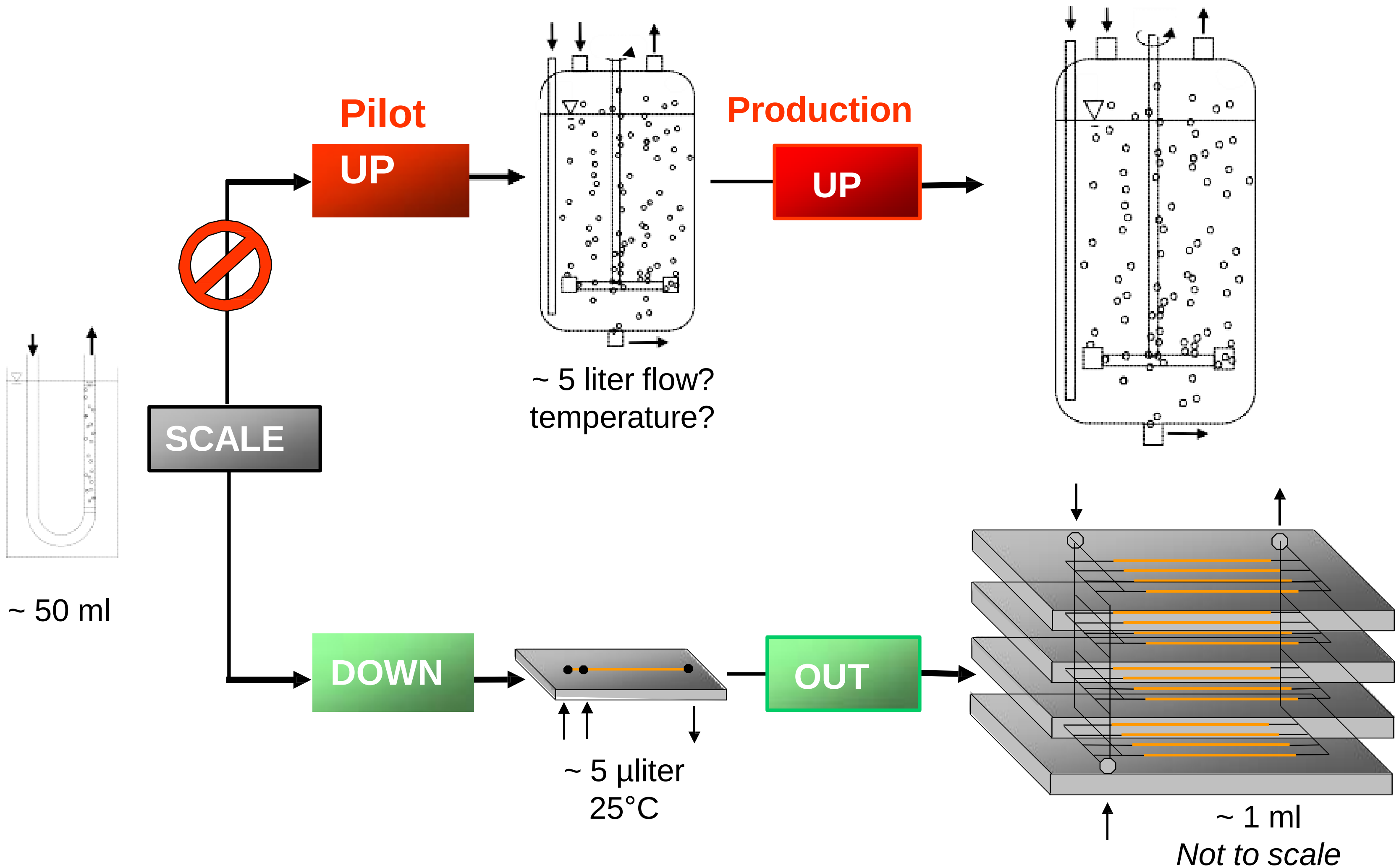
Catalyst & materials science

Mathematical Modelling & simulation

Chemistry & Chemical engineering

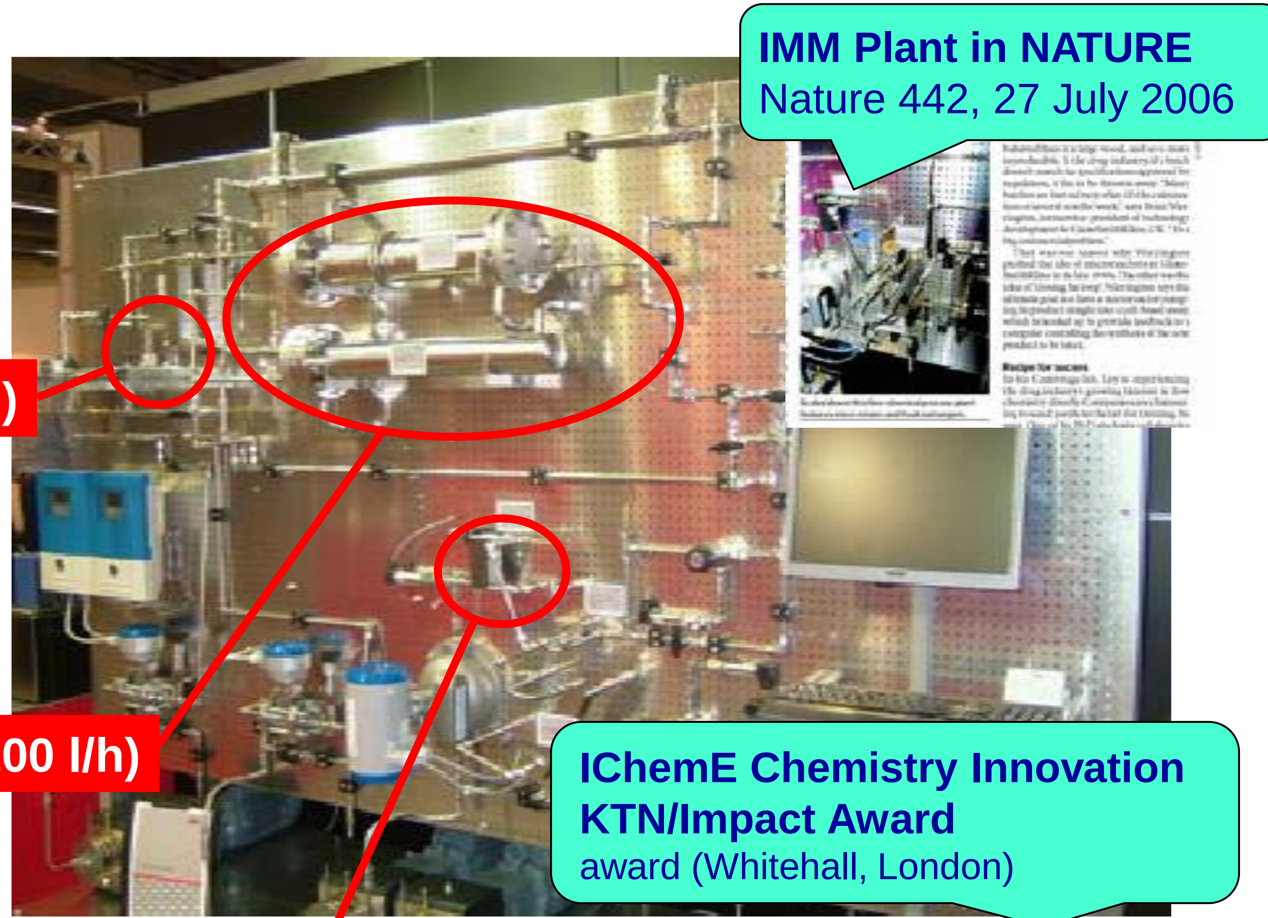
FUNDAMENTAL SCIENCES

Microchemical Systems – Scale Down and Out.



MIT

Fine-Chemical Microreactors Production Plant.



Fine-chemical plant with 10 microstructured production devices: launch at ACHEMA, May 15, 2006

“Miniature version of the regular thing.”

- Same functionality per volume as macro
- Miniature size is distinguishing factor
- Portability often important
- Often highly integrated
- Microscale platforms for nanoscale structures/materials.
- New technologies and electronic controls.
- Application of microfluids.

What is Microfluidics?

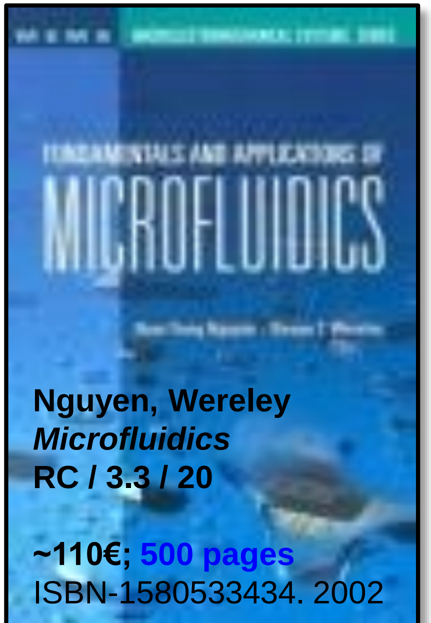
Microfluidics enables precise control, manipulation and analysis of fluids in the microliter to picoliter range. Microfluidic devices are fabricated using techniques developed in the semiconductor industry and are often referred to as microfluidic chips. Today the main application areas for microfluidics include:

- Research and development chemistry
- DNA analysis and genomics
- Microreactors
- Cell based systems
- Microarrays
- Clinical diagnostics
- Liquid chromatography
- Bio-defence sensors

The benefits of using microfluidic devices for laboratory applications include:

- Reduction in sample volume and reagent usage
- Improved resolution of separations
- Ability to run reaction and analysis processes faster
- Ability to run processes in parallel
- Improved control of mixing and heating of fluids
- Rapid mass transfer as a result of high surface area to volume ratios
- Improved integration of process steps, for example reactions and separations
- Development of new and improved detection methods
- Simpler and cheaper disposable devices
- Access to a wide range of fluidic geometries.

Microfluidic Literature.



Nguyen, Wereley
Microfluidics
RC / 3.3 / 20

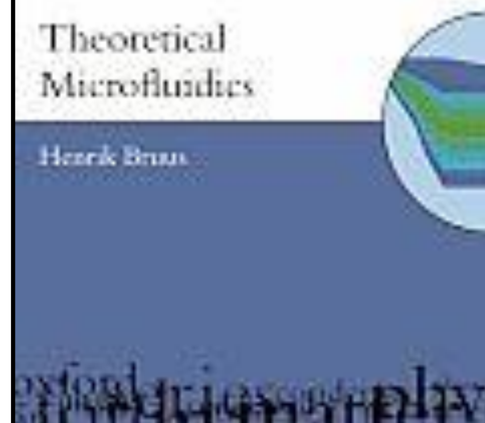
~110€; **500 pages**
ISBN-1580533434. 2002

EH / 9.0 / 31

~80€; **260 pages**
ISBN-3527307338, 2004

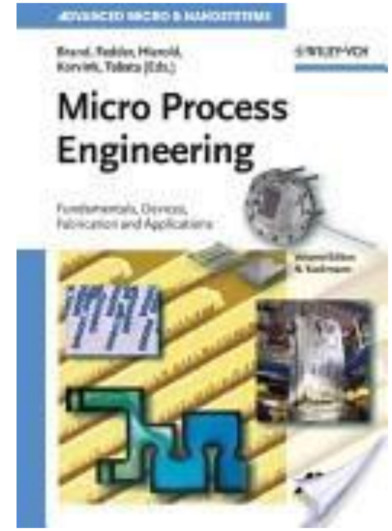
Henrik Bruus: "Theoretical Microfluidics« (Oxford Master Series in Physics)

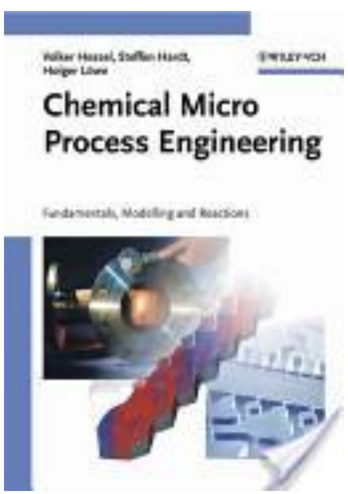
~40€; **346 pages;**
ISBN-10:0199235090. 2007

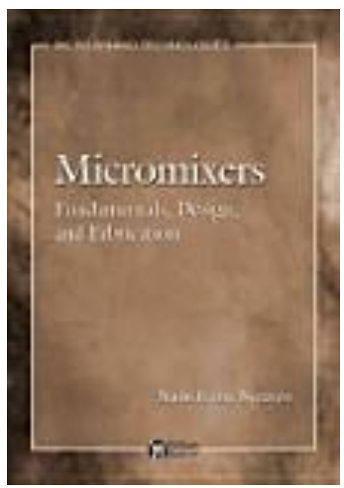


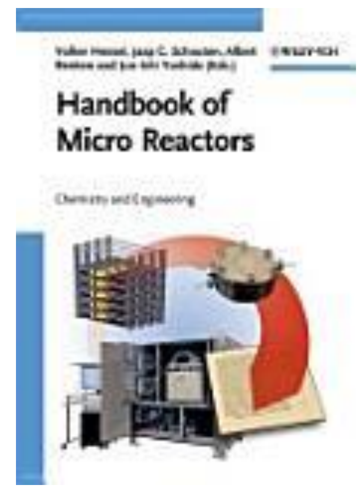
Microchemical Journal

Microreactors Literature.

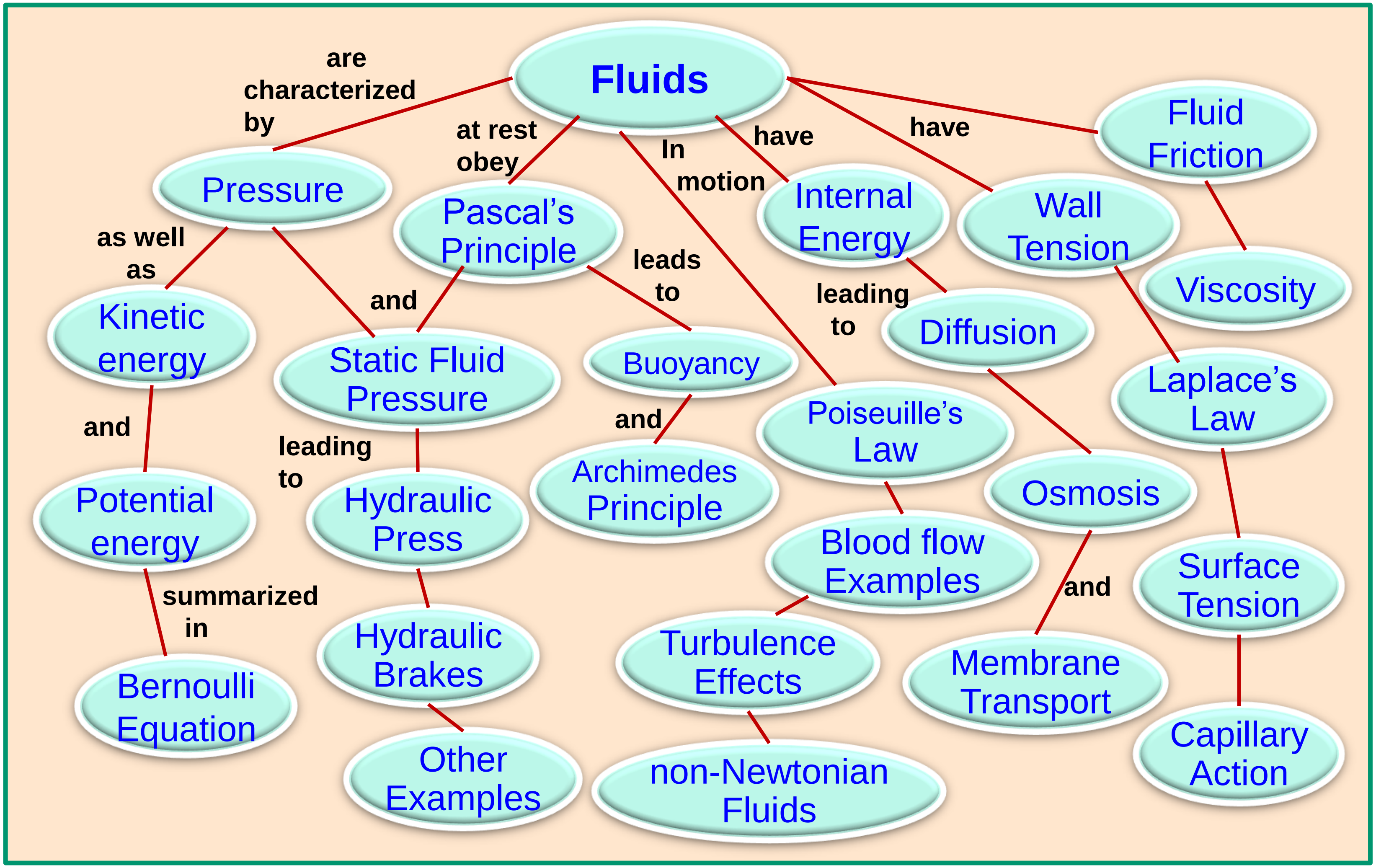






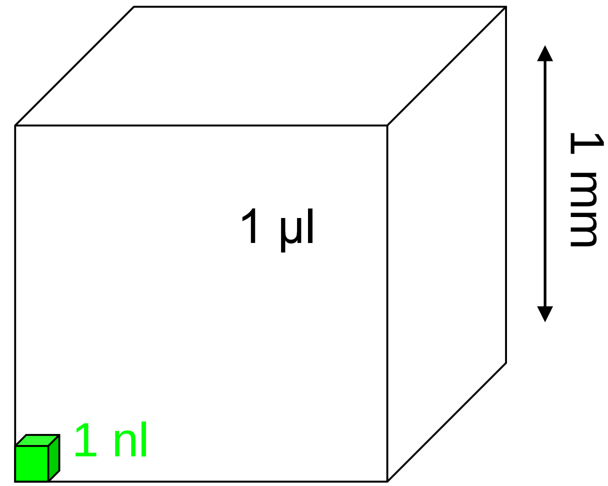


Literature – Internet.



About Microfluidics.

- „Micro“ means at least one of the following features:
  - **small volumes (µl; nl; pl; fl)**
  - small size
  - low energy consumption
  - effects of the micro-domain
    - Laminar flow
  - …



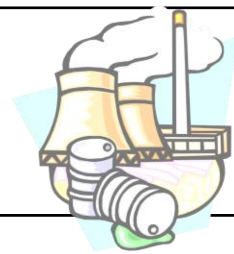
1 nl

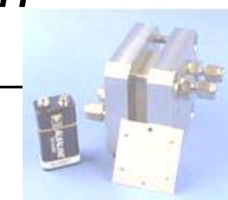
1 fl

Science Magazine 2 July 1999.

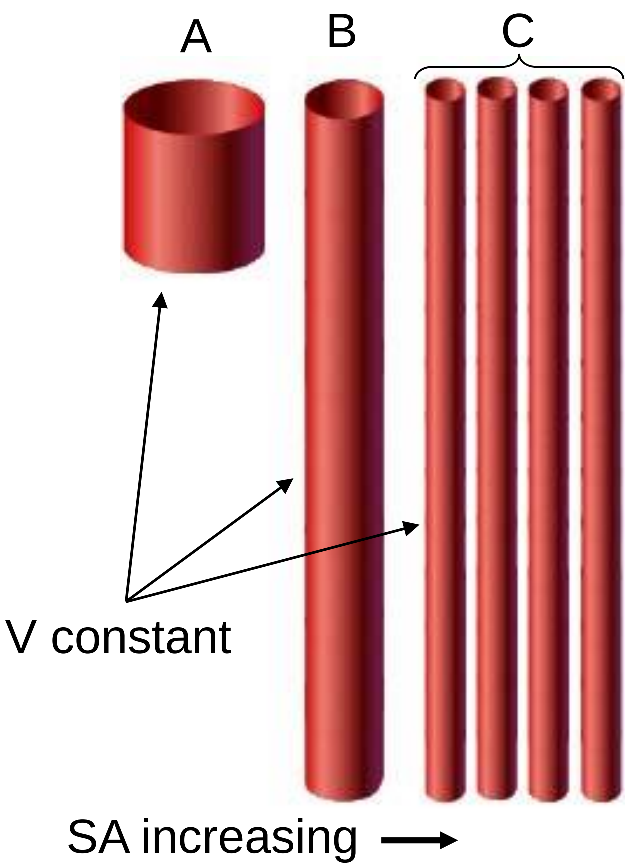
- 1 fl – 1 µl: 10 orders of magnitude
- still far away from molecular level.

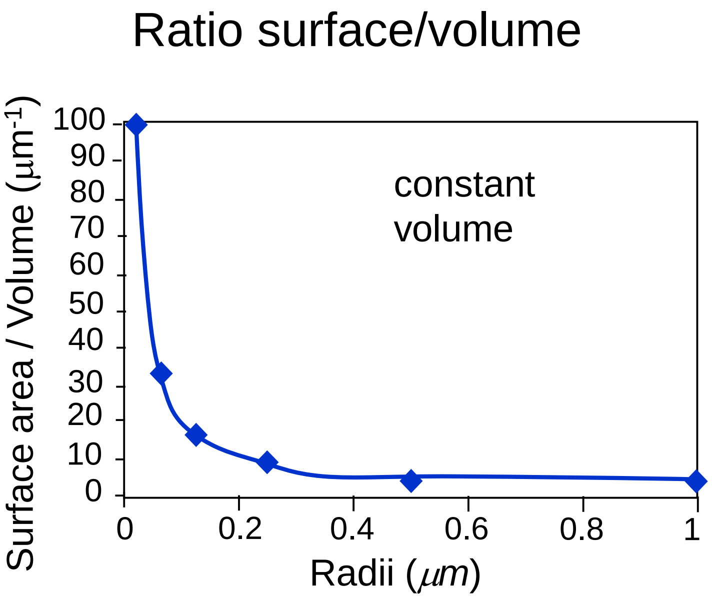
	Industry	Laboratory	Micro-system
Volume	30 m^3	10^{-3} m^3	3 10^{-11} m^3
Scale-down	1	1:3 10^{-5}	1: 10^{-12}
Diameter	2 m	2 cm	20 μm
$\frac{\text{Surface}}{\text{Volume}}$	$2\,\frac{m^2}{m^3}$	$200\,\frac{m^2}{m^3}$	$200\,000\,\frac{m^2}{m^3}$





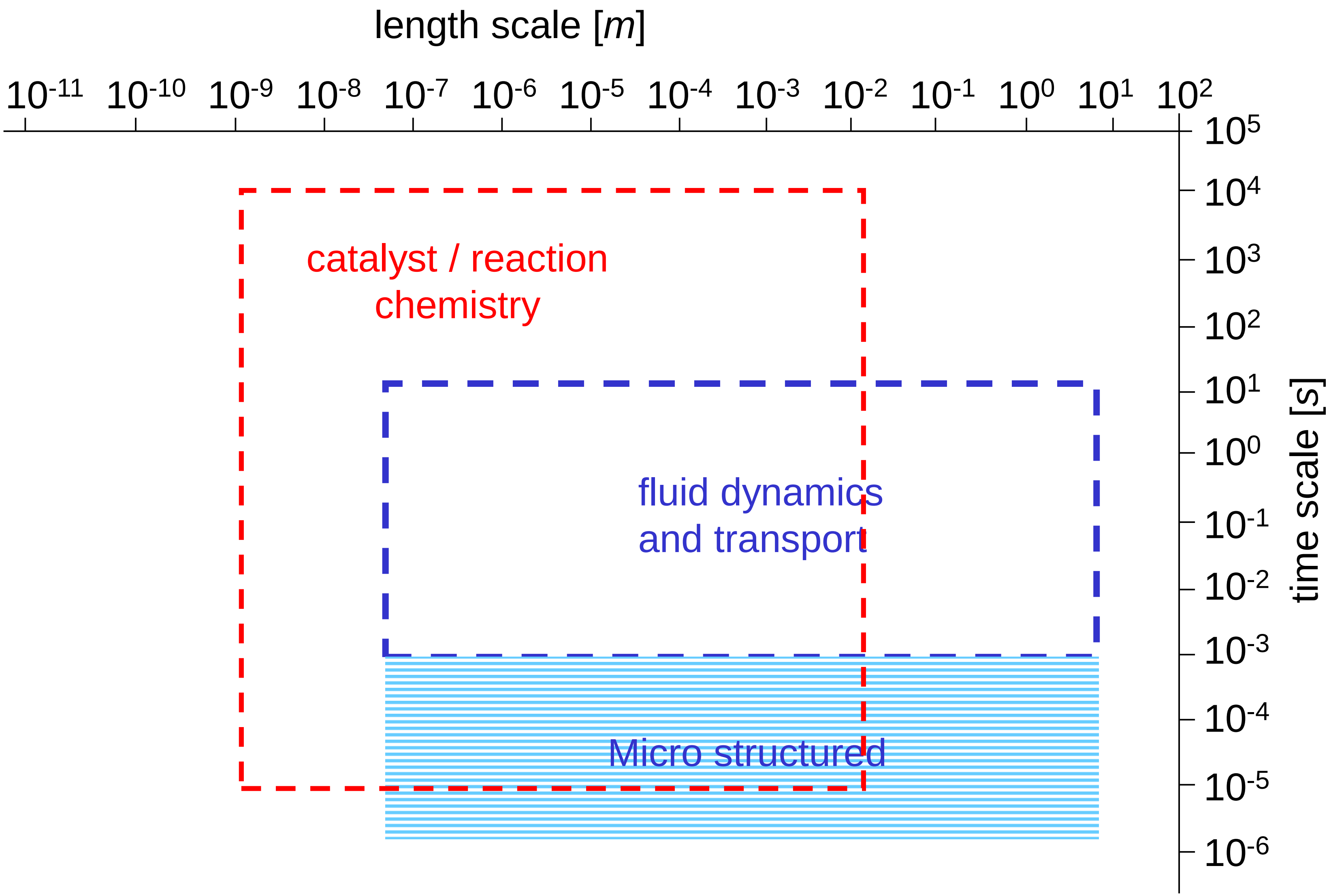
Key Benefit: Intensified Surface Phenomena by Higher Surface Area-to-Volume Ratios.



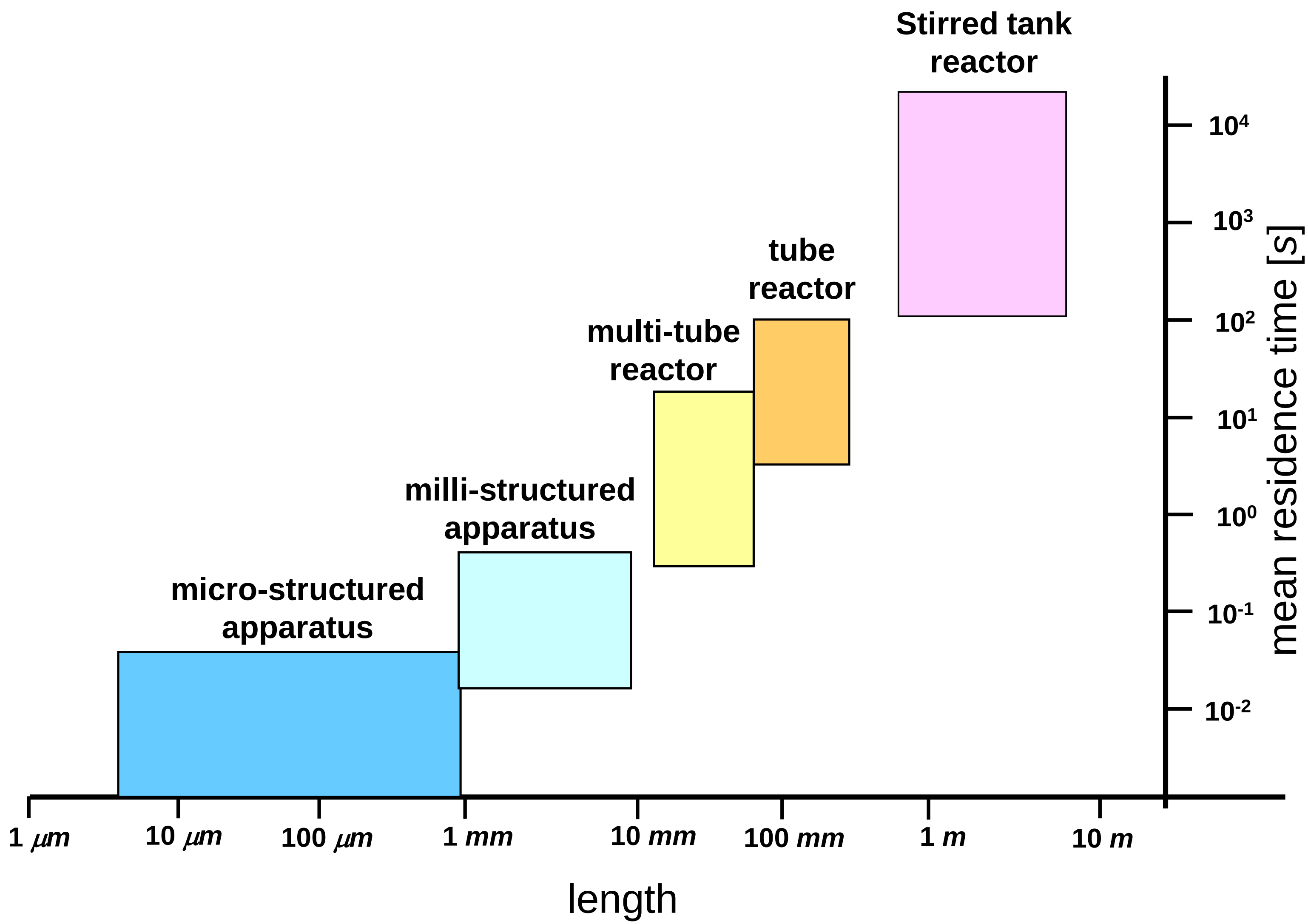


- ***intensified mass transport toward the smaller dimensions***
- ***Intensified heat transport toward the smaller dimensions***
- ***Intensified mixing***
- ***Explosion-Safety improvement***

Length & Time Scale of Chem. & Physical Processes.



Temporal Scale and Typical Length of Chemical Reactors.



Micro-structured Components are Available.

Micro mixers
Mixing from few ml/h
up to 30 l/h

IMM:

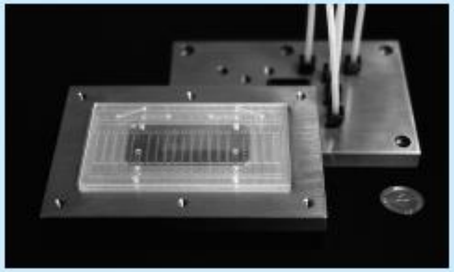
Interdigital micromixer

Micro heat exchangers
Maximum value of 700 W/m2K
at an air flow rate of 75 l/min

Heatric:

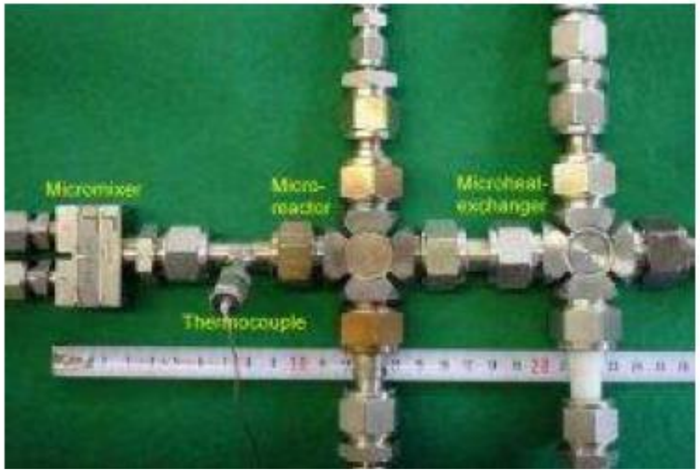
Cross Flow Heat Exchanger

Micro reactors
combinaison of μHE and μmixers



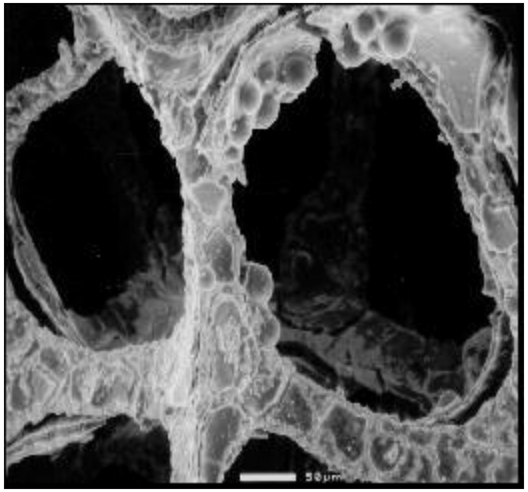
Mikroglas:

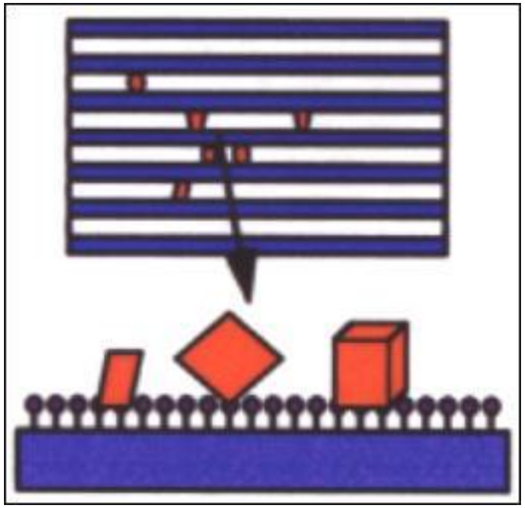
Microreact or

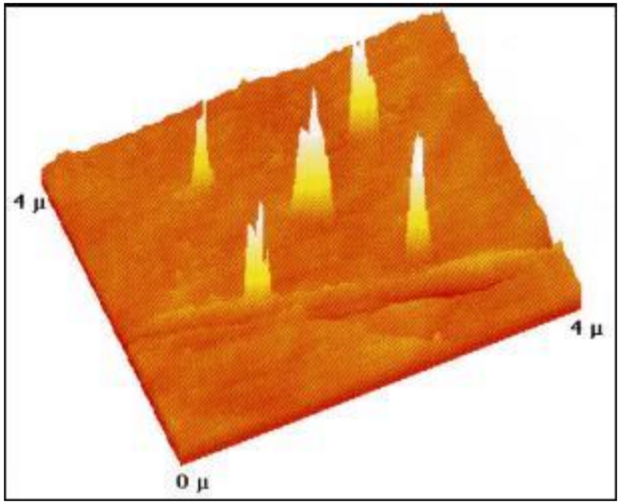


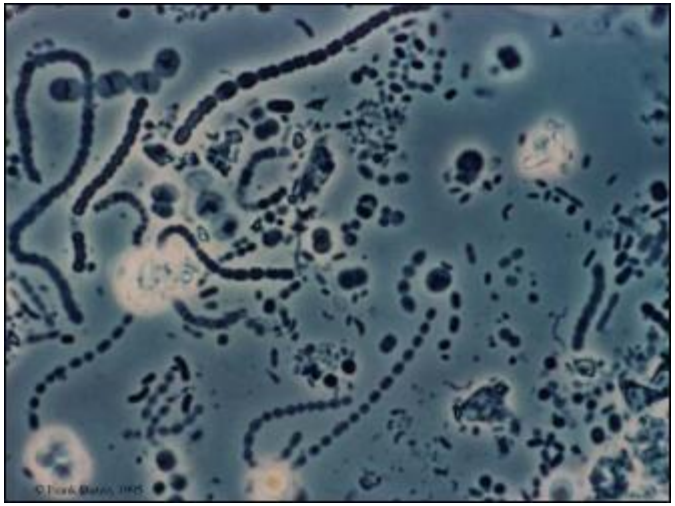
MICRO CHEMICAL AND THERMAL SYSTEMS CONSIDERED AS A “PLATFORM” FOR NANOTECH.

- Engineered structures with improved heat and mass transport
- Self-assembling surfaces
- Nano-fabricated structures
- Biological enzymes as highly functional catalysts



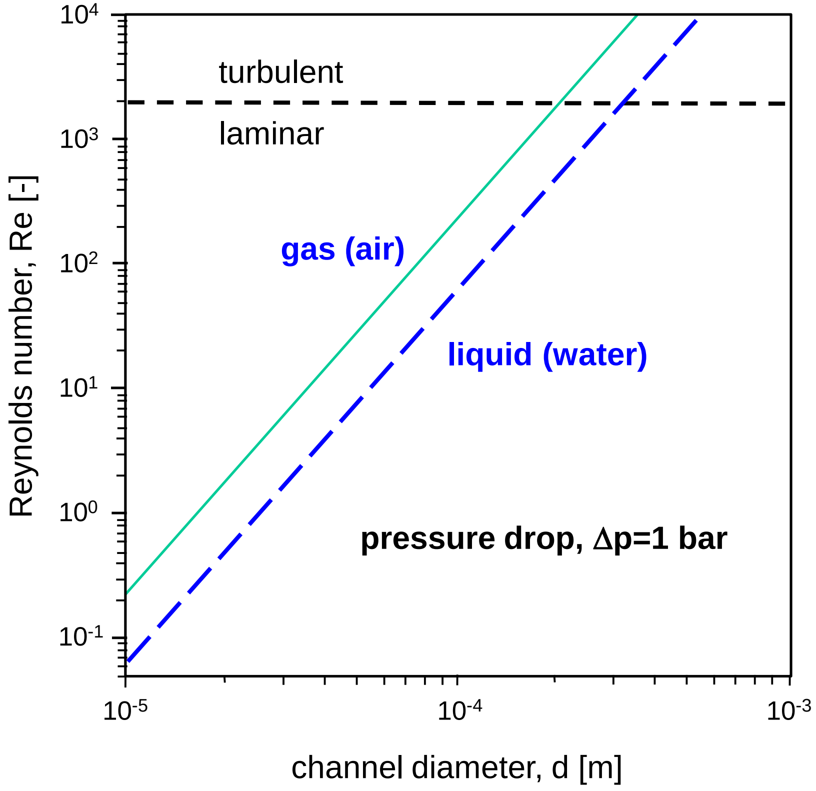


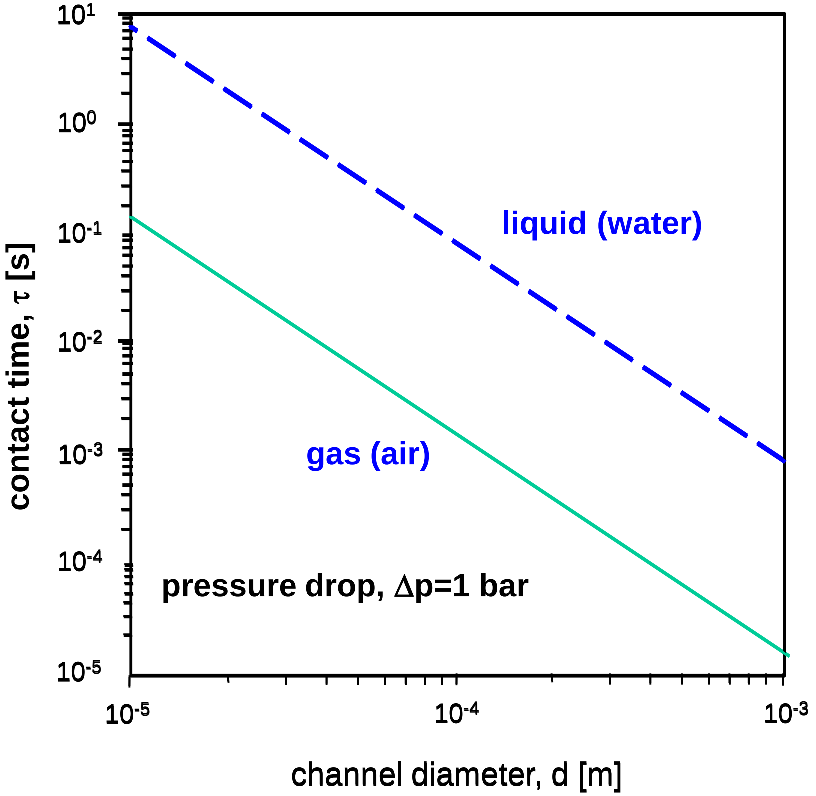




Micro-structured Multichannel Reactor.

Flow conditions for typical fluids, Volume: $V_R = 5\ cm^3$; $L = 5\ cm$



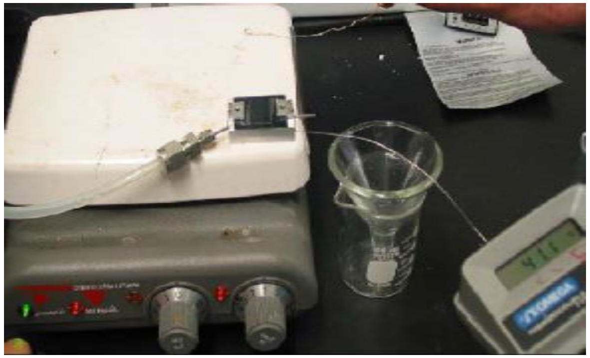


Surface to Volume: Effective Transport.

Example: overall heat transfer coefficient.

Type Hx	*U* ($W \cdot m^{-2} \cdot K^{-1}$)
Tubular	150-1200
Spiral	700-2500
Laminar	1000-4000

Micro-channel: 3800-6800 $W \cdot m^{-2} \cdot K^{-1}$



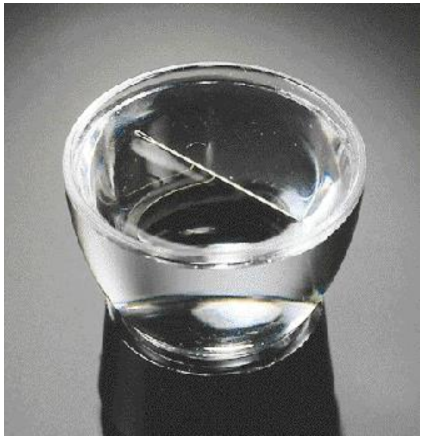
(500×500 μm^2×1.5 *cm* channels)

Properties of Micro Devices.

- **Behavior of fluids at this scale**
  - **Wall effects dominate**
- **Surfaces and interfaces**
  - **Fouling**
  - **Multi-phase flow**
  - **Surface energy, tension, wettability**
  - **Dynamics -- start-up**
- **Equipment**
  - **Basic state measurements - *P*, *T*, phase, quality, composition**
  - **Density, thermal conductivity, electrical conductivity**
  - **Controls -- need to be integrated**
  - **Fluid flow and distribution**
  - **System homogeneity**

About Microfluidics (2).

- „Micro" means at least one of the following features
  - small volumes (*μL*; *nL*; *pL*; *fL*)
  - small size
  - low energy consumption
  - **effects of the micro-domain**
    - Laminar flow
    - Surface tension



Cohesive forces bind molecules each other.

Adhesive forces bind molecules to surface.

Surface Tension γ :

$$\gamma = \frac{dw}{dS}$$

Compound :	$n\text{-}C_6H_{14}$	H_2O	Hg
γ ($mN \cdot m^{-1}$):	18.4	72.8	425.4

(work to be made to increase the surface of a unit quantity)

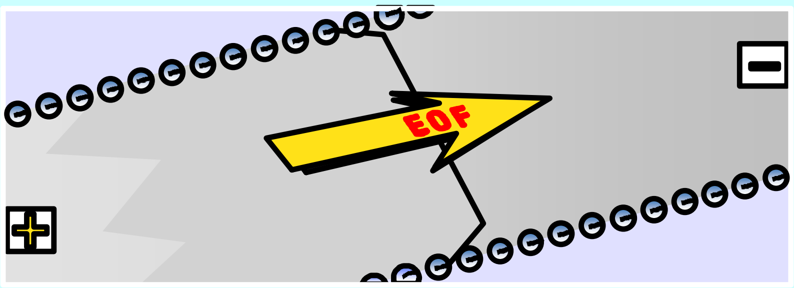
About Microfluidics (3).

- „Micro“ means at least one of the following features
  - small volumes (μl; nl; pl; fl)
  - small size
  - low energy consumption
  - **effects of the micro-domain**
    - Laminar flow
    - Surface tension
    - electrical surface charges
    - diffusion

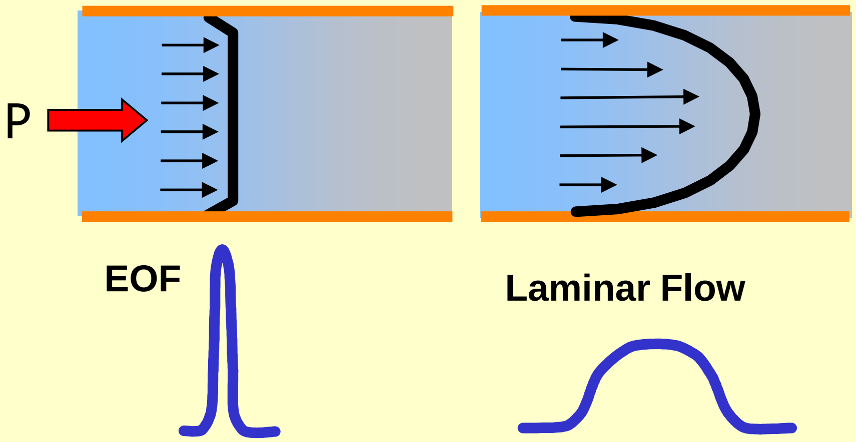
$$Re = \frac{u\rho L}{\eta}$$

Reynolds Number < 2300

velocity u, density ρ, traveled length L, and viscosity η of the fluid



Electrosmotic Flow



Pressure driven flow

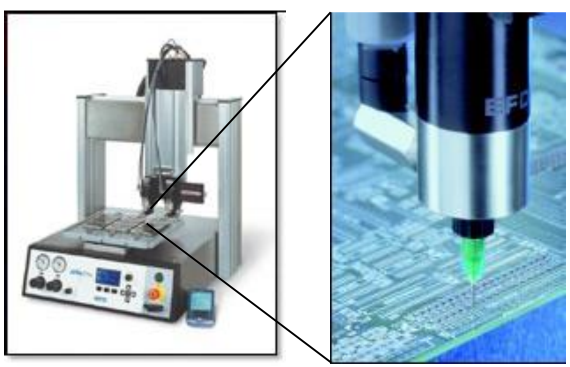
Market for Microfluidics.

Printing

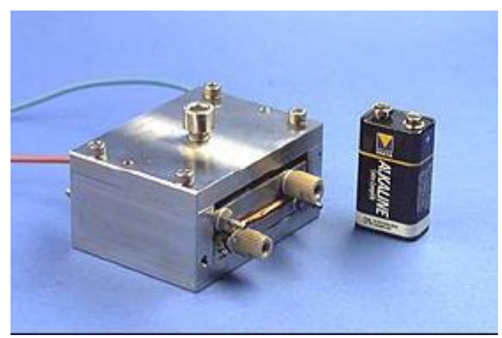
Industrial Automation

Flow sensors for air conditioning (HSG-IMIT)
50.000 units in 2005

Industrial dispenser



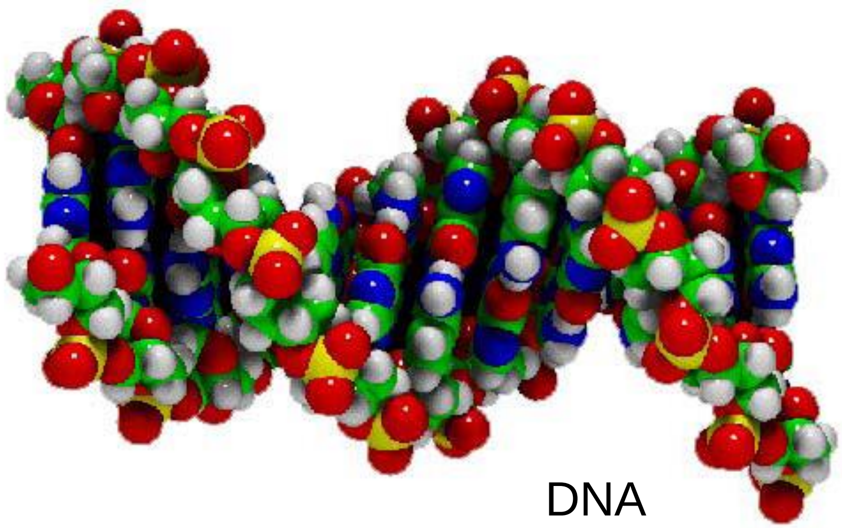
Chem Process Engineering/ Power systems



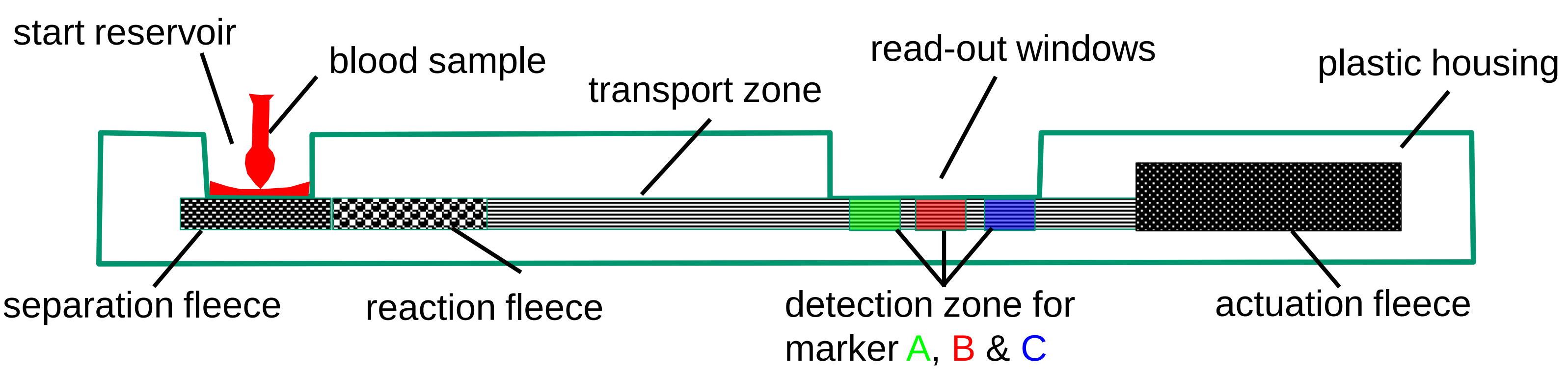
Market for Microfluidics (2).

Life Sciences!!!!

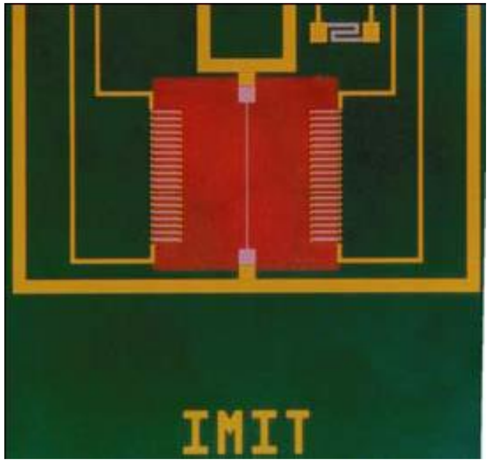
- Capillary Electrophoresis
- Lab on chip
- Drug delivery
- Clinical analysis



DNA



Flow Sensors.

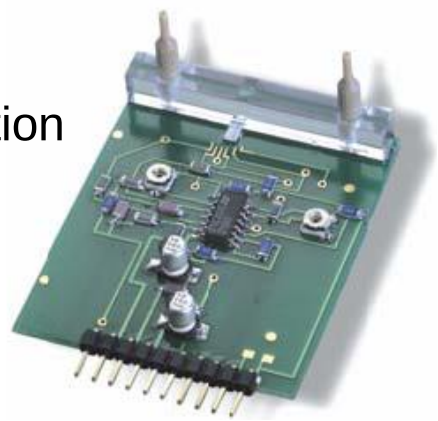


<u>Working principle:</u>

- Thermal principles
- Heaters & temperature sensors
  - Anemometer
  - Calorimeter
  - Time of flight

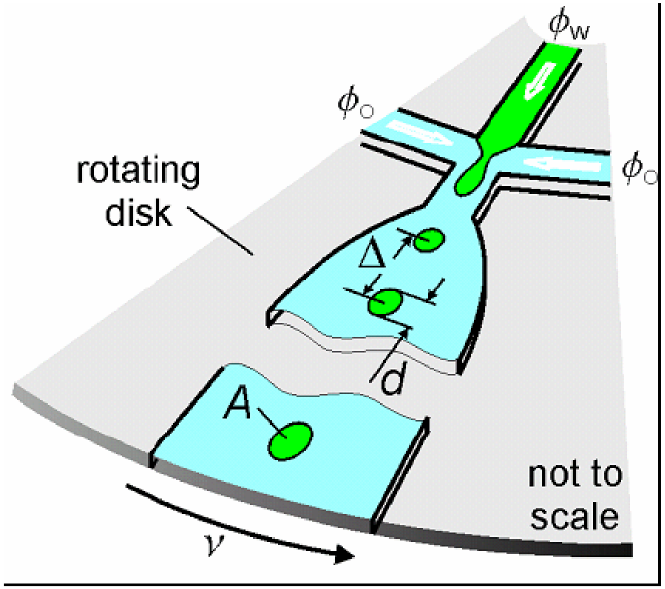
<u>Specifications:</u>

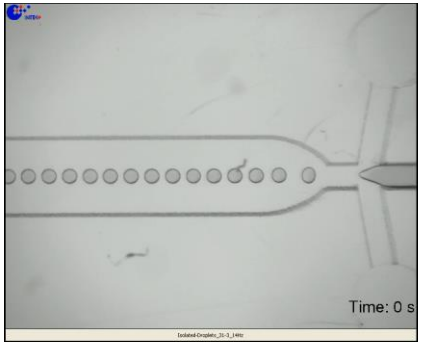
- Range: 15 *μm/s* – 1500 *μm/s*
- Power: < 15 *mW*
- Response time: < 1 *ms*
- Application specific configuration possible by adaption of flow channels

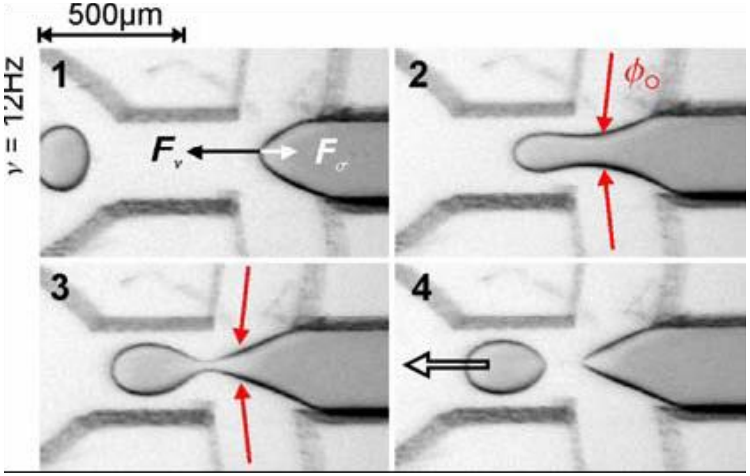


Lab-on-a-Chip: *Emulsion-Disk.*

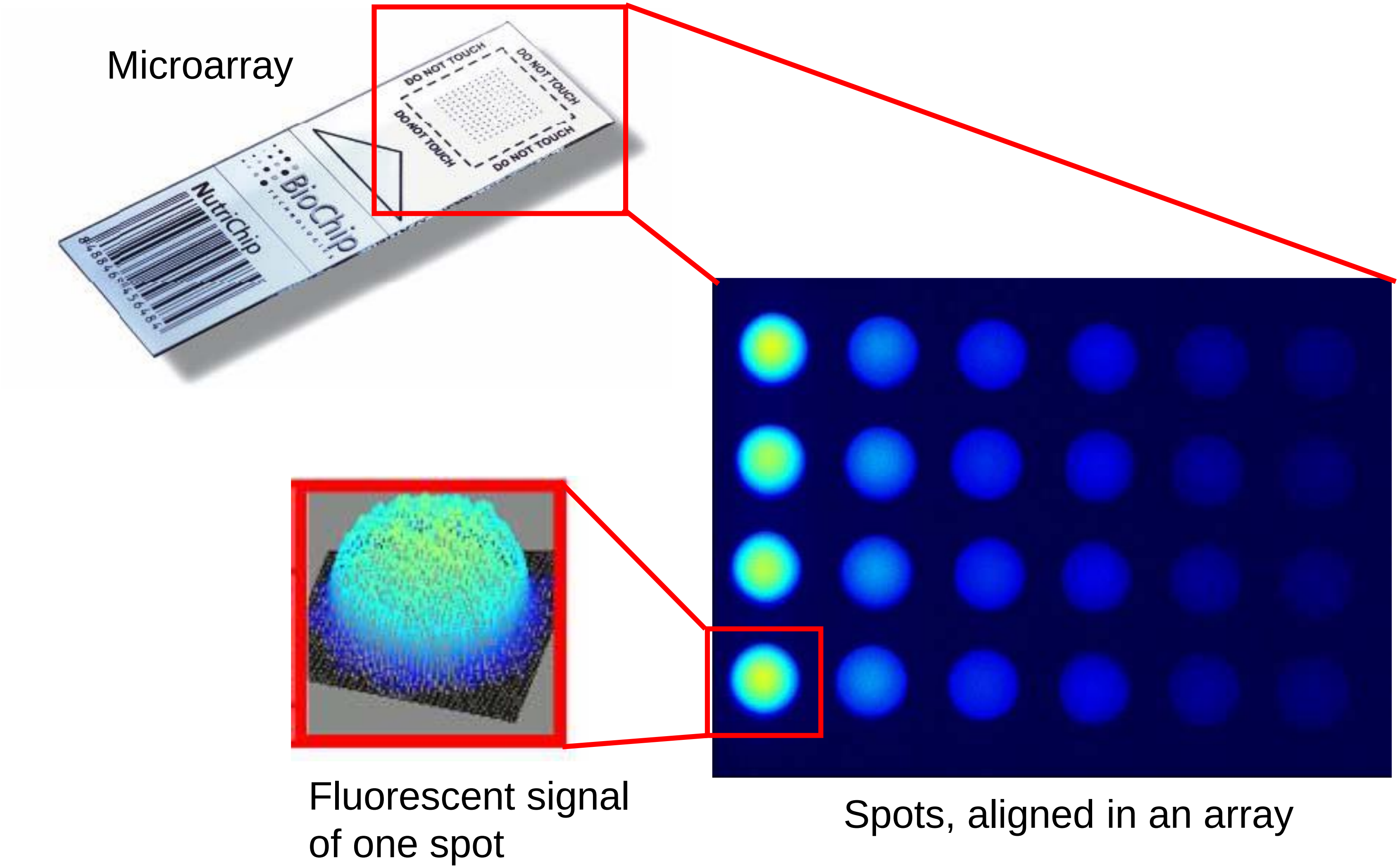
- Controlled droplet generation on rotating disk
- Water-plug is focused by two oil flows Φ_0
- Production of water-droplets in oil (W/O emulsion)
  - Volume: **5…22 *nL***
  - Rate: 0…300 *drops / s*
- High Reproducibility
  - Droplet diameter: **CV < 2%**







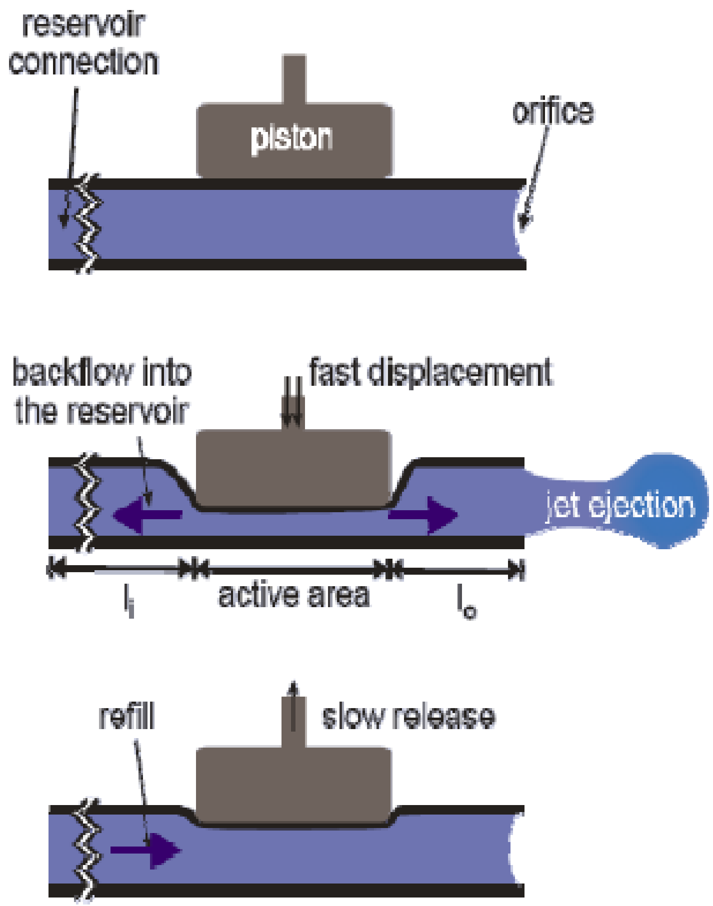
DNA Microarray Printing.



PipeJet Principle.

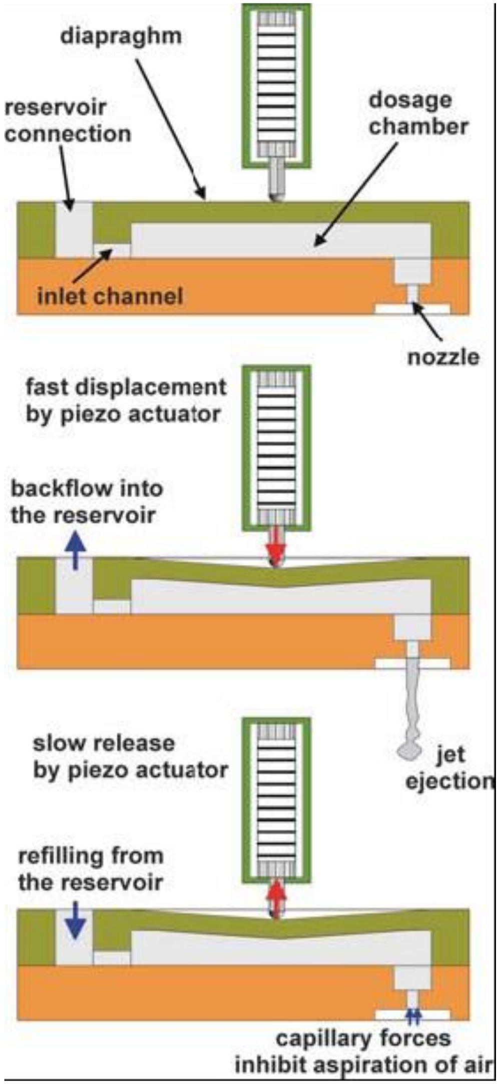
- **Dispensing by direct volume deflection**
  - Polymer tube
  - Piezo-actuated piston
  - Fast displacement for jet ejection
  - Short plateau
  - Slow release for capillary refill

- **Unique strength of concept**
  - Contact-free delivery of fluid
  - Simplest possible fluidic geometry
  - Easiest packaging (mechanical clamping).

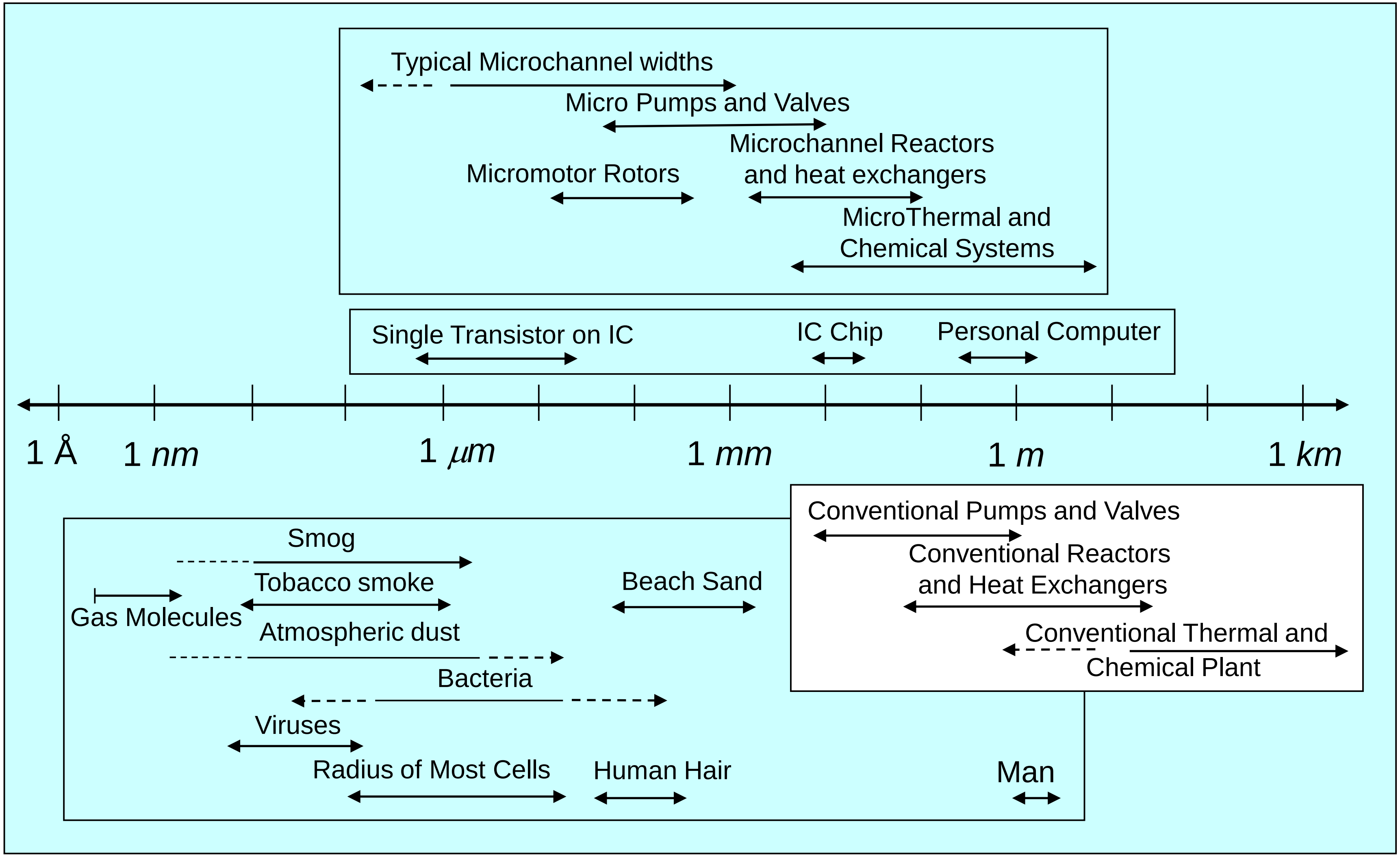


nL & pL Dosage: NanoJet.

- Dosage volume: 5 *nL* to 1.000 *nL*
- Dosage rate: 1.000 *nL/s*
- Viscosity range: 1 – 100 *mPas*
- Precision: better 5 %

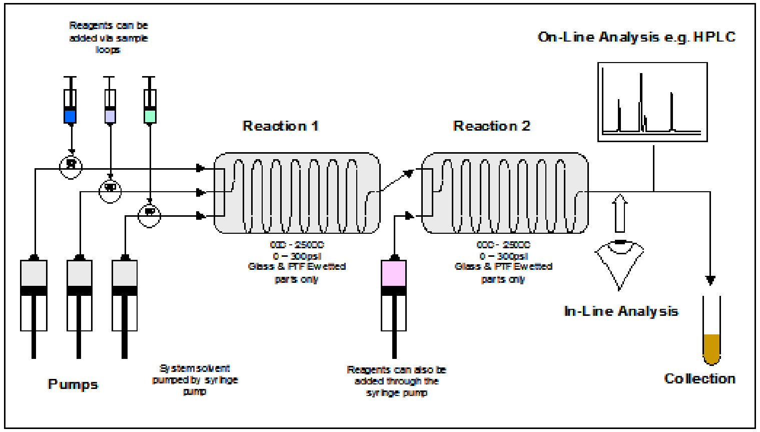


A New Class of Process Technology.



Features of a Continuous Microreactor System.

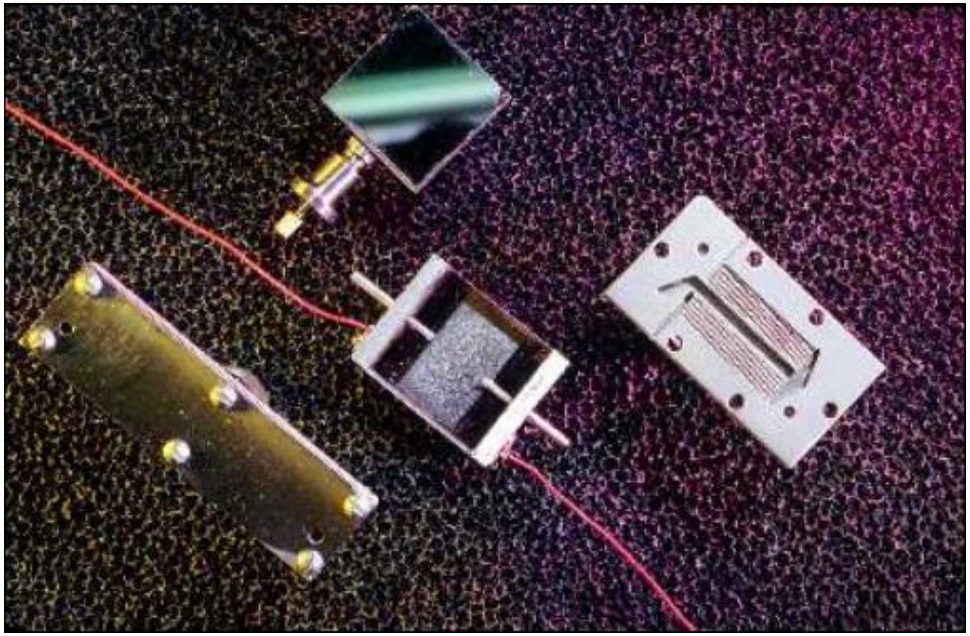
1. Precise control of temperature – easily set and changed - **no temperature gradients**
2. Precise control of time - easily set and changed – **quick hot reactions for consistent particle size**
3. Precise control of feeds/stoichiometry – **rapidly investigate stoichiometry by changing feed rates**
4. Consistent and rapid mixing – **ensures nucleation not precipitation**
5. No scale limitations – **small scale for optimisation; or “leave tap running” to make kilograms per day (100 *g/h* readily achievable)**
6. Reproducible – **same temperature, same mixing, same reaction time, every time**
7. Immediate aqueous work up – **simple work up available if required**



Tice, J.D. et al. Langmuir 2003 19, 9127-8133

Micro Chemical Equipments and Systems.

- Microreactors
- Micro-channels
- Micro heat exchangers,
- Micromixers
- Separation Units and
- Micro analytical devices



Miniaturization:

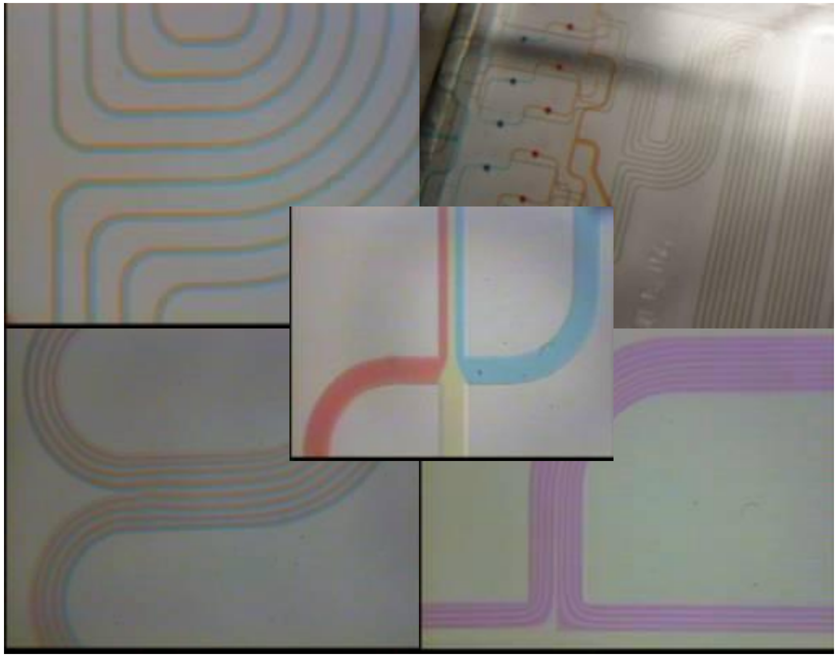
- High capacity
- Light systems
- Mass manufacture
- Costly but versatile

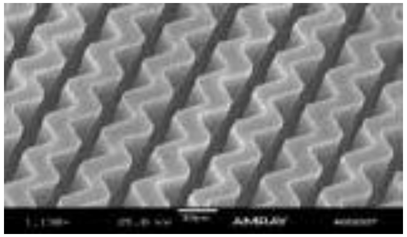
MEMS, Mesoscopic Machine
Micro/Nano Systems
Microcats

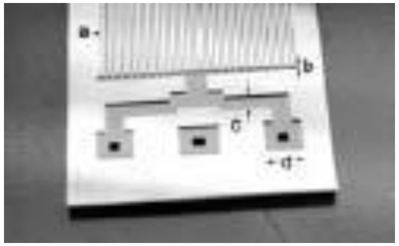
Micro-Reactors.

- New reactor types which offer high capacity and high productivity.

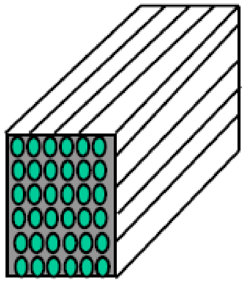
- Microreactors are more versatile and less dependent on chemical-engineering operators
  - Provide useful amount of products
  - Are easy to use.







Micro-structured Multichannel Reactors.

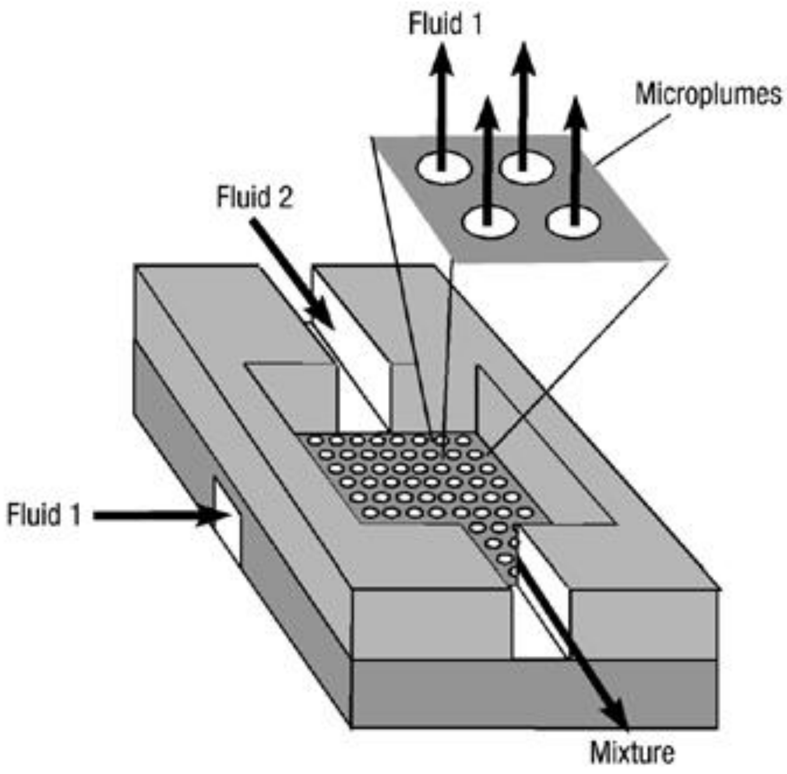


Volume: V_R = 5 *cm^3*

Pressure drop: Δp = 1 *bar*

length:	L=	5.	*cm*
diameter:	d=	100.	*μm*
Number of channels:	N=	12,740.	
Specific surface:	a=	40,000.	*m^2/m^3*
Flow velocity:	u=	0.63	*m/s* (water)
		35.	*m/s* (air)
Mass flow:	Q_m=	225.	*kg/h* (water)
		15.	*kg/h* (air)

Injection of Multiple Microjets



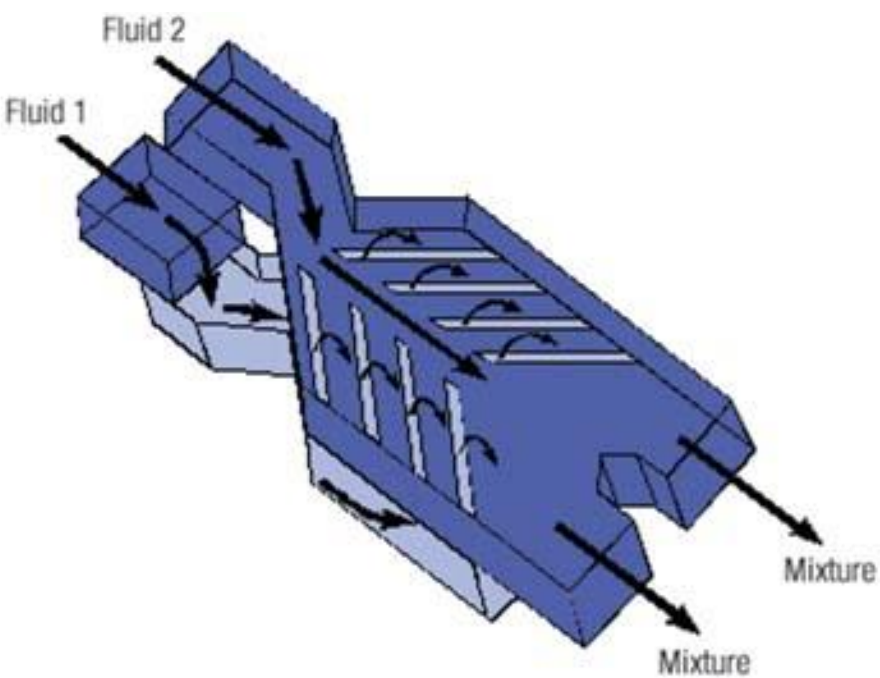
Schematic of a micromixer with injection of multiple microjets into a mixing chamber

1. The central element of the mixer is a sievelike structure with a large number of regular holes.
2. During operations, the mixing are is filled with one liquid, and the other liquid is injected into the mixing volume through a multitude of microholes.
3. Numerous microjets are generated and increase the contact surface between the two liquids.
4. The holes are positioned in rows 10-100 µm apart, which results in short diffusional paths between the jets.
5. Typical flowrates are in the µL/s, the hole diameter is 10 µm, and the height of the mixing chamber some 100 µm

Source: Quak Foo Lee

Micromixers.

Multiple Flow Splitting and Recombination

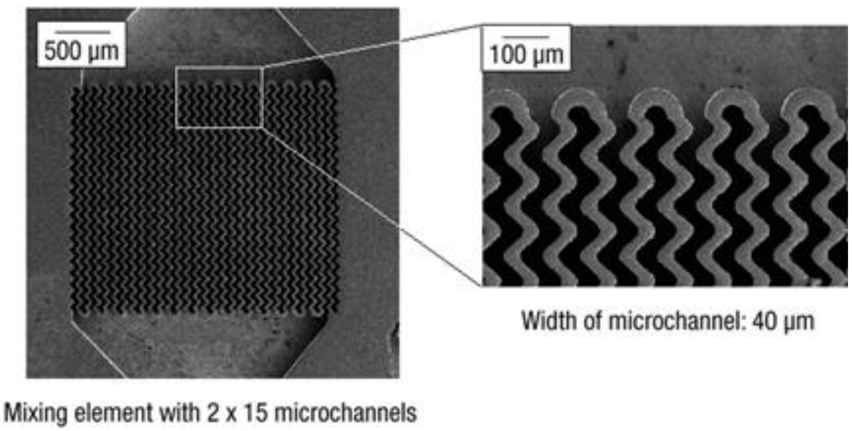


Mixing units of a static micromixer with multiple slit-shaped injection openings

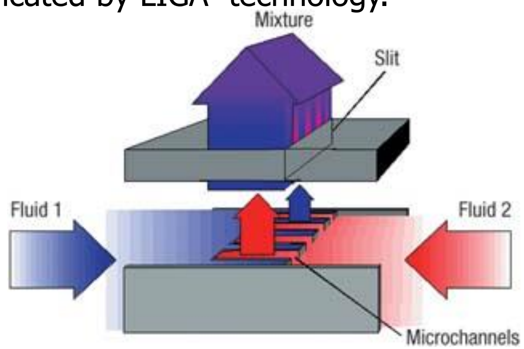
1. Application: industrial chemical sensor
2. Flow range: 0.01 – 0.1 µL/s
3. Highly viscous flow with a Re < 1
4. The whole system consists of a silicon/glass sandwich connected by anodic bonding.
5. One channel structure is etched into glass and the other into silicon.
6. In the region where the channels overlap, they are separated by a structured plate defined by an etchstop layer.
7. Max. width = 300 µm
   max. depth = 30 µm
8. The thickness of the structured plate for separating the channels in the glass and the silicon wafer is 5 µm and the slit width 15 µm.

Source: Quak Foo Lee

Multilamination of Fluid Layers



Scanning electron micrographs of a mixing element based on multilamination of thin fluid layers. The device consists of 2 × 15 interdigitated microchannels with corrugated walls, fabricated by LIGA technology.



Multilamination of streams in channels with corrugated walls, leading to fast mixing by diffusion.

1. The fluid to be mixed are introduced into the mixing elements in counter-flow and stream into an interdigitated channels with corrugated walls.
2. Typical channel widths = 25 or 40 µm
3. The channel configuration leads to a periodical arrangement of flow lamellae of the two fluids.
4. The lamellar flow leaves the device perpendicular to the direction of the feed flows and, because of the thinness of the lamellae, fast mixing takes place by diffusion.
5. The corrugated channel walls increase the contact surface of the lamellar streams and improve the mechanical stability of the separating walls.

Source: Quak Foo Lee

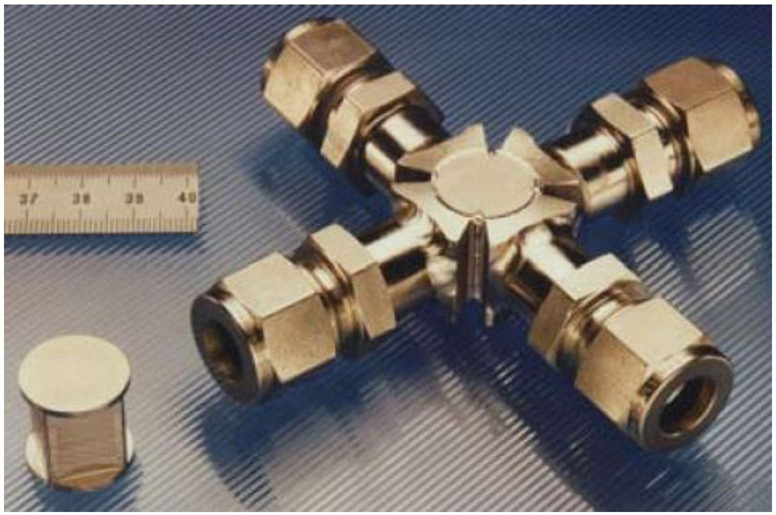
Gasoline Vaporizer.

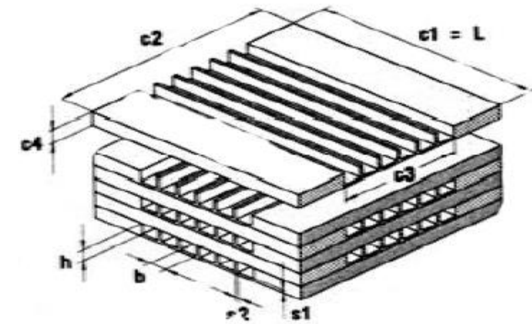
1999 - R&D Award Winner

- 50 kW_e capacity: Four cells each of microchannel reactors and heat exchangers
- Volume: 0.3 *L*
- Processes/combusts 1400 SLPM

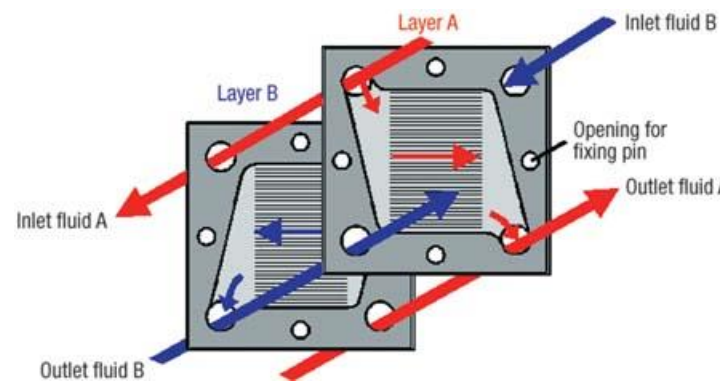
Micro Heat Exchangers.

Cross-Flow Heat Exchange in Stacked Plate Devices





Channel diameter: ~50 – 500 *μm*
Channel length: 20 – 100 *mm*
No of channel: 200 – 1000
Specific surface: 10^4–10^5 *m^2/m^3*

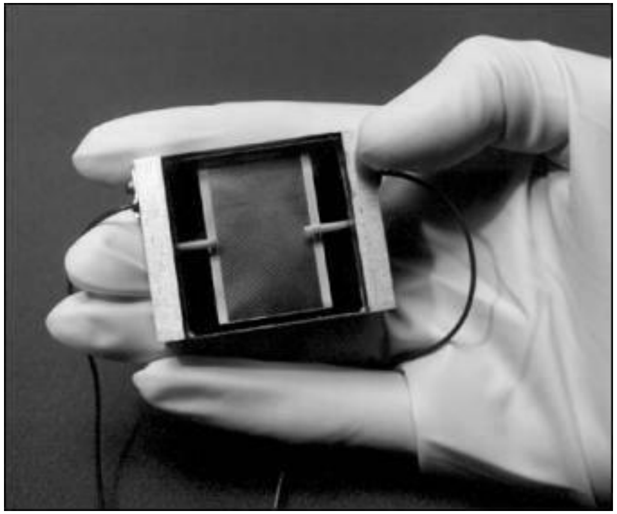


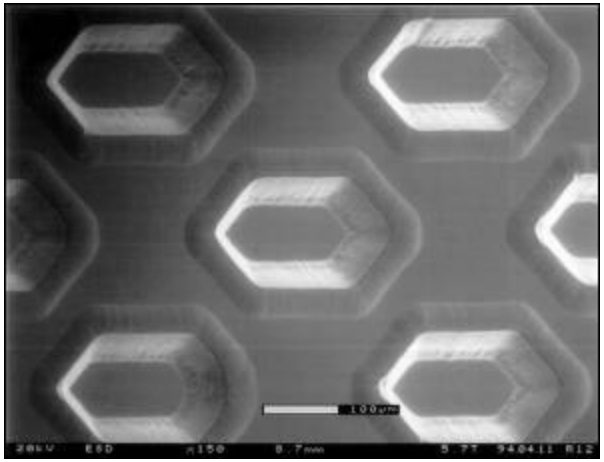
Micro heat exchanger with connections for fluid supply
(source: Forschungszentrum Karlsruhe)

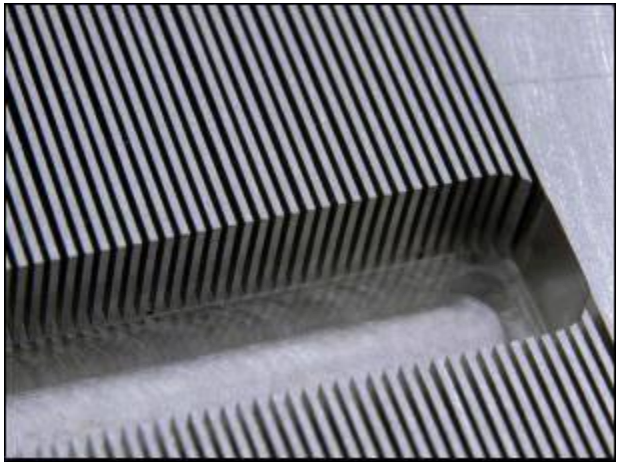
Counterflow Heat Exchange in Stacked Plate Devices

Advantage: Rapid Heat and Mass Transport Microchannel Heat Exchangers.

- Heat fluxes: 100+ watts/cm^2
- Low pressure drops: 1-2 psia
- High convective heat transfer coefficients
  - Liquid phase: 10,000 - 15,000 W·m^{-2}·K^{-1}
  - Evaporating phase: 30,000 - 35,000 W·m^{-2}·K^{-1}



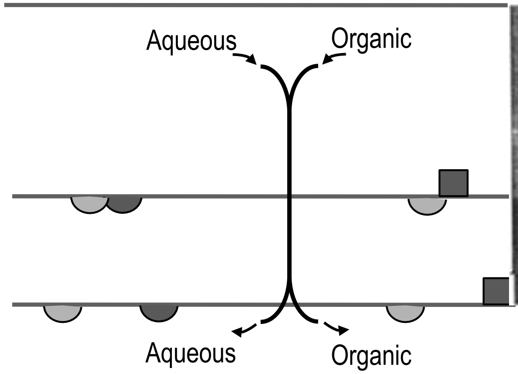


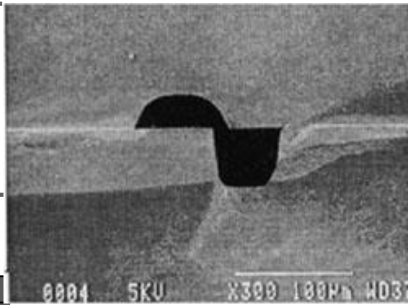


Microseparators.

Exchange between Immiscible Fluids

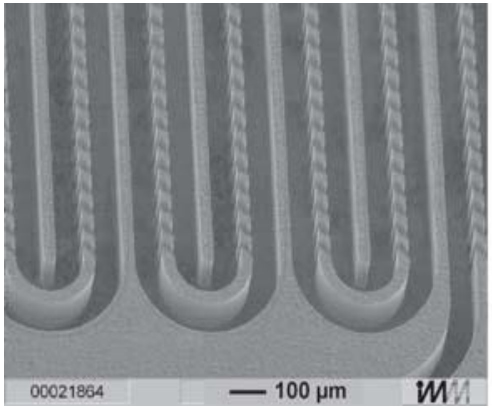
Schematic of solute exchange between immiscible fluids in partially overlapping microchannels (left) and scanning electron micrograph of the cross section of the partially overlapping microchannels (right),

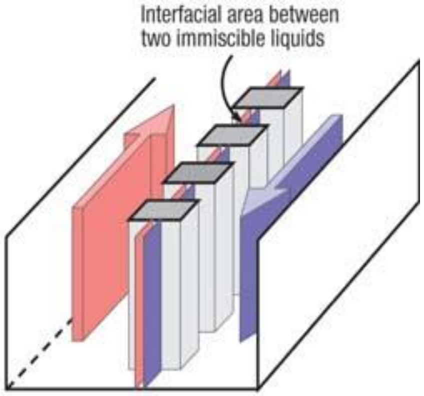




Exchange between Immiscible Fluids

Scanning electron micrograph (left) and schematic (right) of an extraction unit with adjacent channels for two fluids with slits, oblique to the flow direction, for exchange between the two phases.

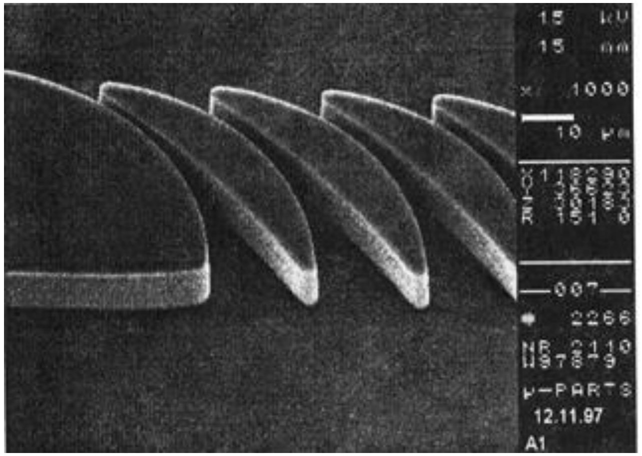




Microseparators.

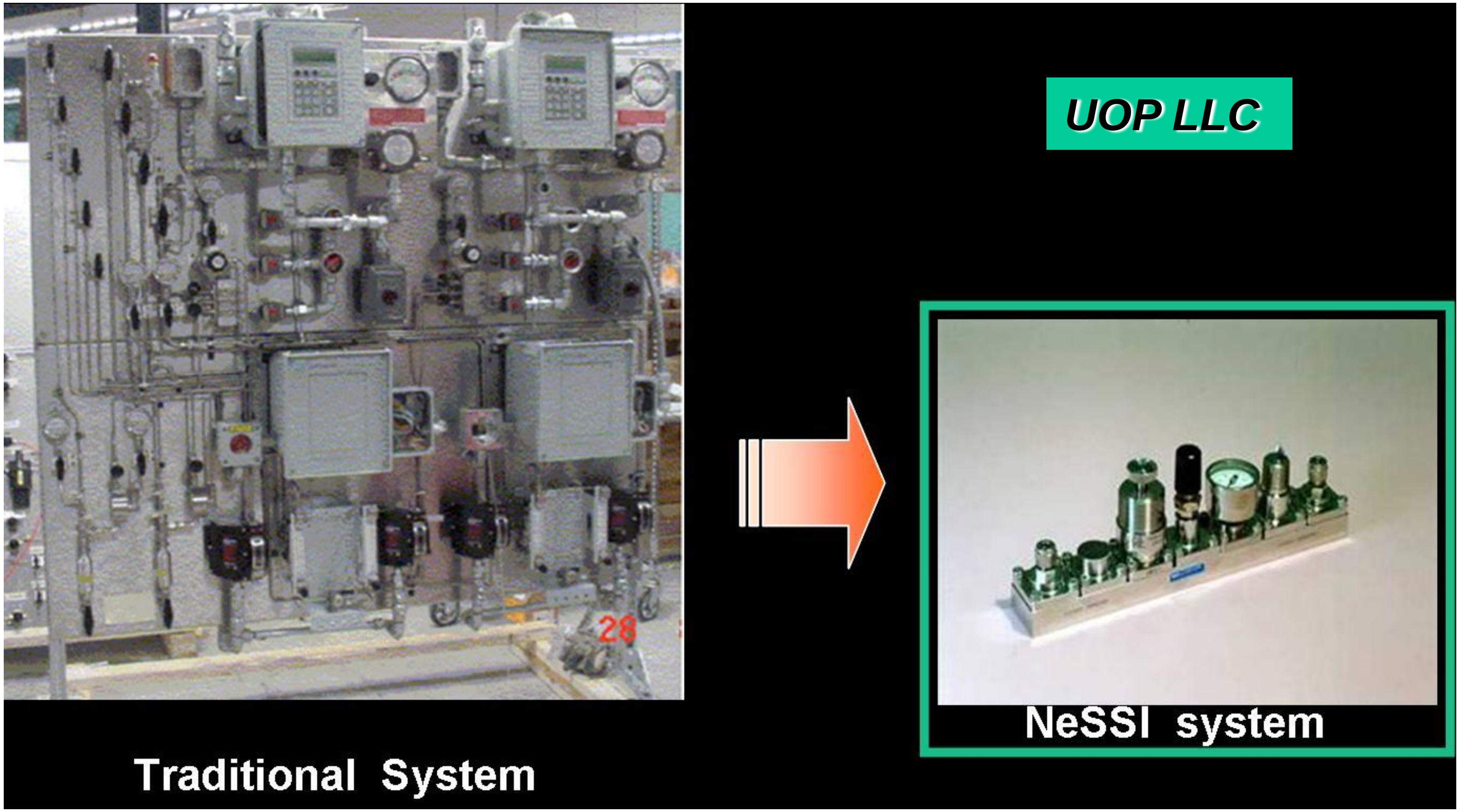
Filtration, Diffusion, and Aerodynamic Separation

Scanning electron micrograph of a cross-flow filter consisting of lamellae arranged at an angle of attack to the flow direction

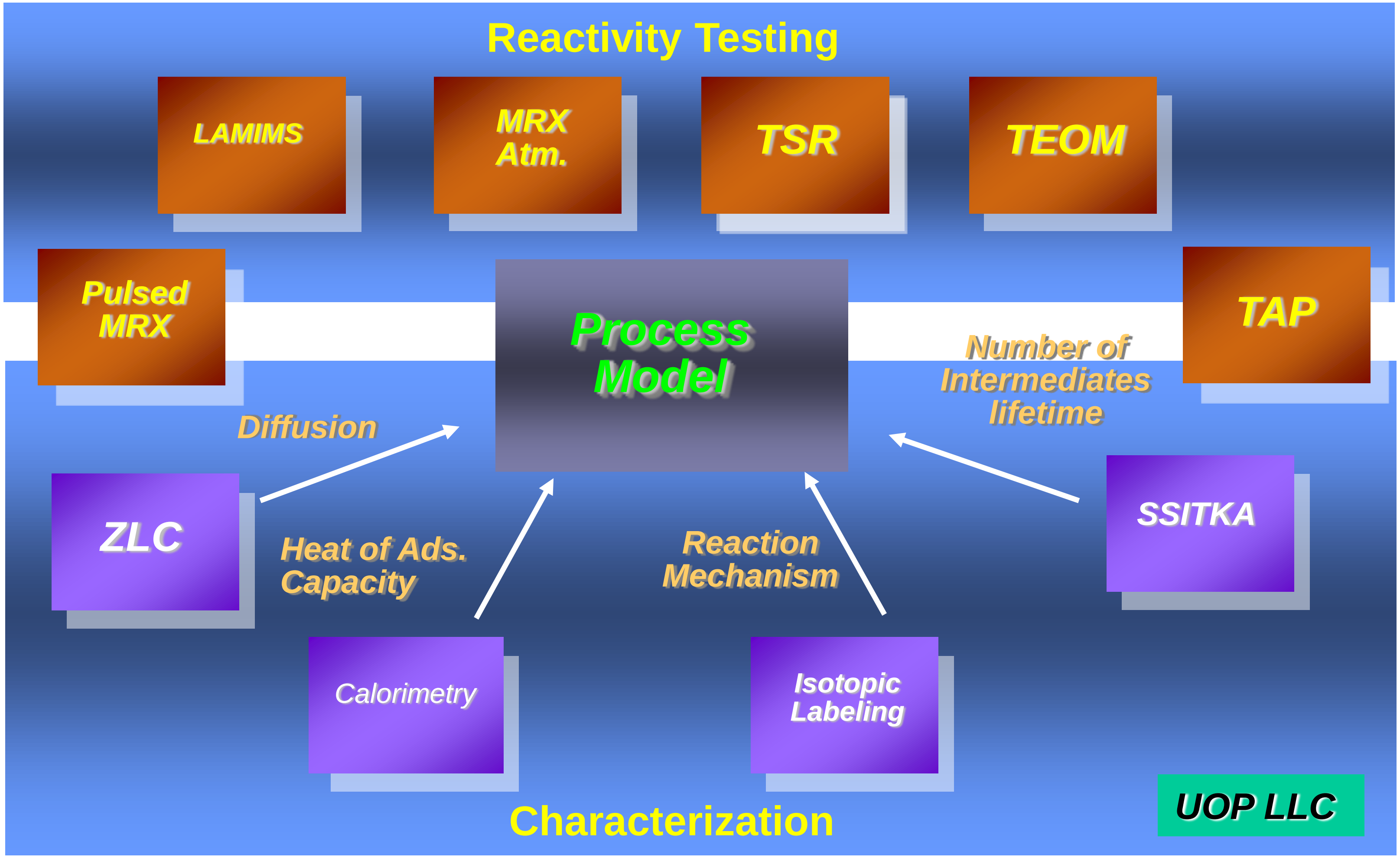


- In the macroscopic range, filtration and sieve structures are often carefully designed with regard to the shape and position of the openings.
- In the microscopic range usually porous materials with irregular pattern are applied.
- Microfabrication methods allow the production of completely isoporous microfilters (pore dimensions in the micrometer range) from a wide variety of materials, whereby the size, shape, and position of each pore can be designed.
- Special configurations for cross-flow filters for concentrating suspended particles/cells.
- In the case of membrane units, microfabricated devices are useful as carrier structures with integrated inlets and outlets for fluids.

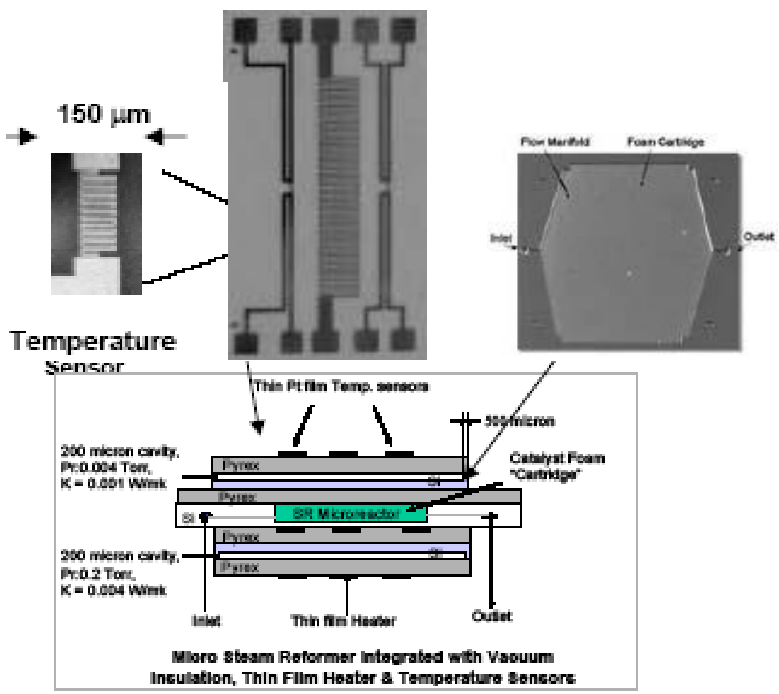
Miniaturization of Analytical Systems.

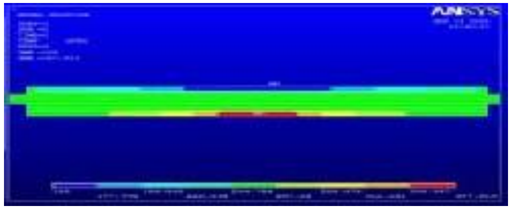


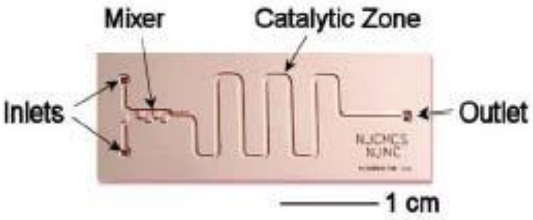
Mechanism Tools.

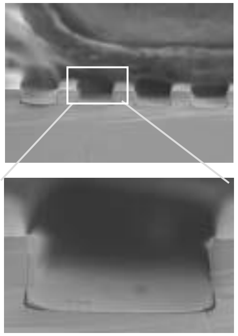


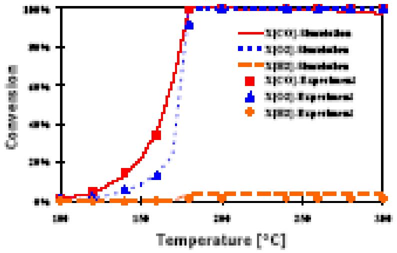
CPM – H_2 Production.

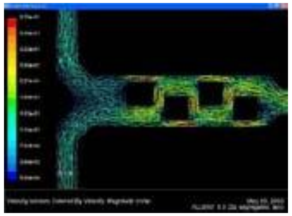




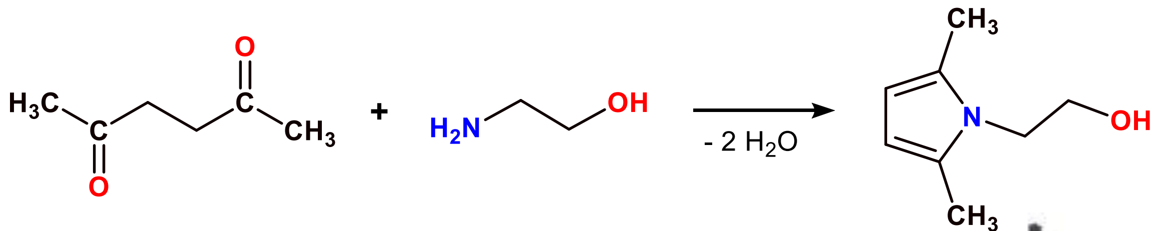


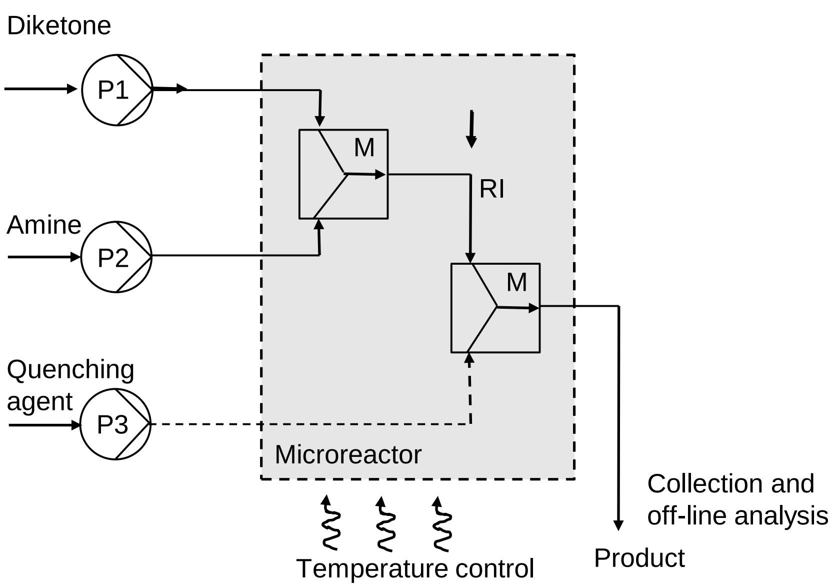


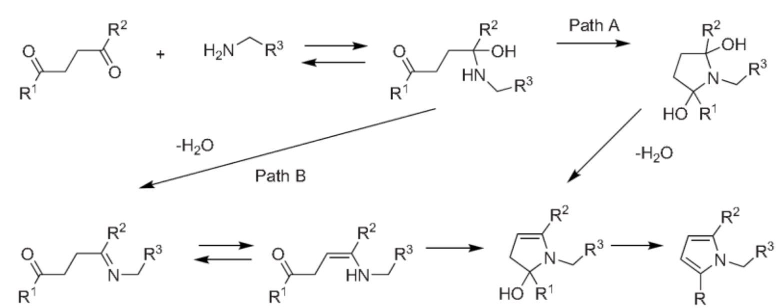




Paal-Knorr Synthesis via Microreactors.

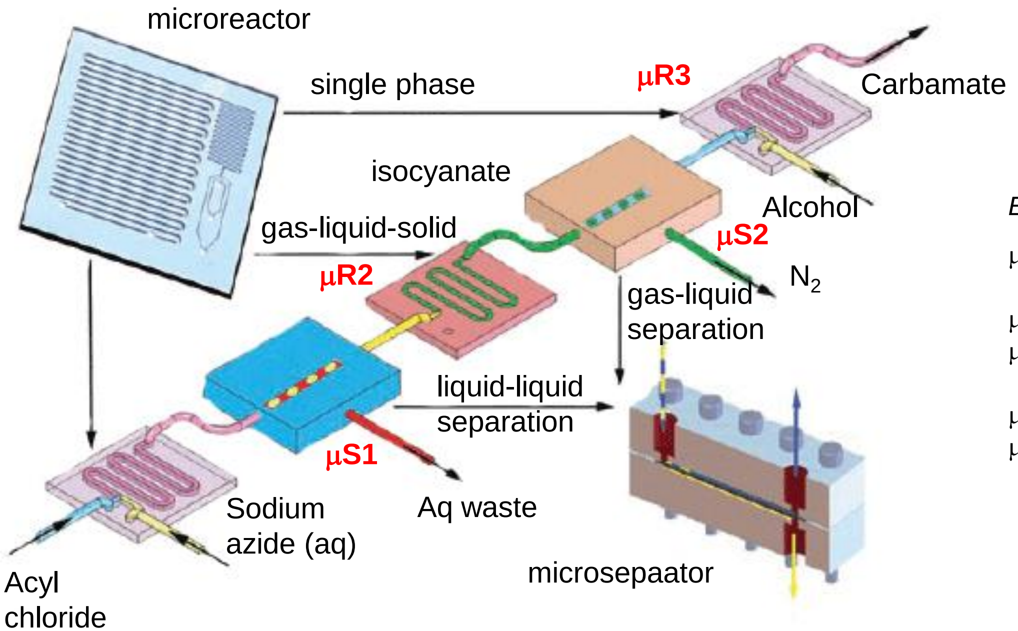






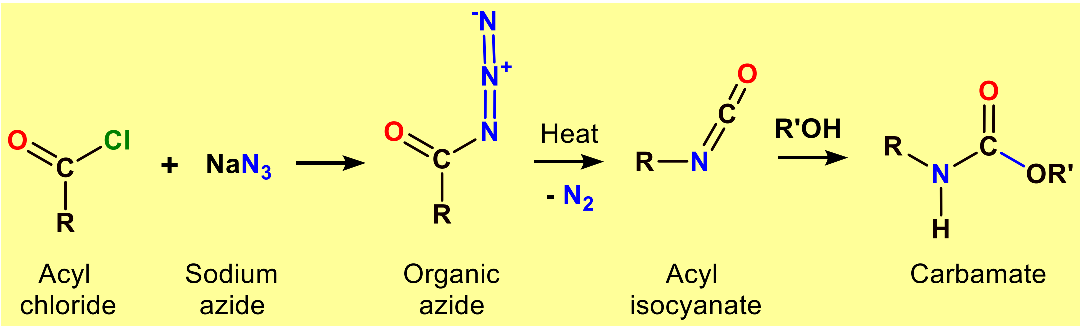
FutureChemistry's FlowSyn on
Micronit Microfluidics microreactors

Miniaturization of Chemical Reaction: Synthesis of Carbamates.



Experimental setup for carbamate synthesis.

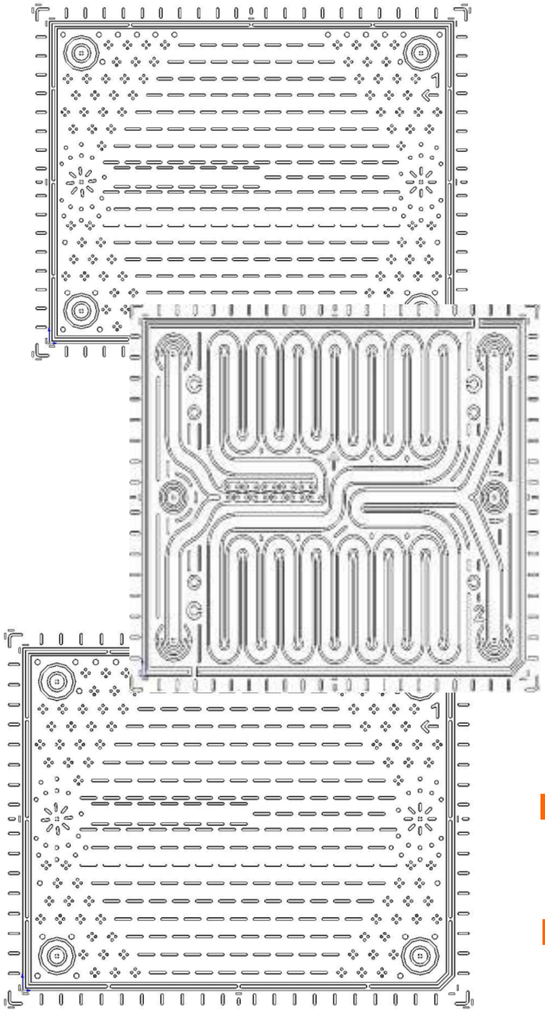
μR_1, micro-reactor for conversion of acyl chloride to organic azide;
μS_1, quantitative separation of organic and aqueous streams;
μR_2, microreactor loaded with solid acid catalyst for conversion of organic azide to isocyanate;
μS_2, quantitative separation of gaseos N_2 from the liquid;
μR_3, microreactor for reaction of isocianate and alcohol to carbamate.



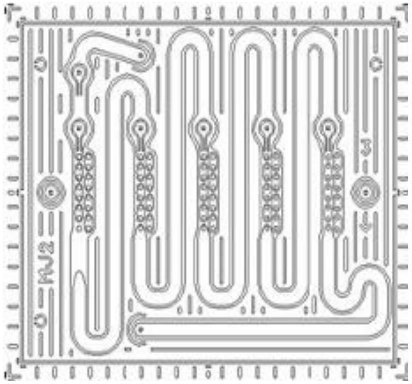
Hemantkumar R. Sahoo, Jason G. Kralj, and Klavs F. Jensen, Angew. Chem., 2007, 46, 5704-5708.

Sintesi di carbammati via azidi

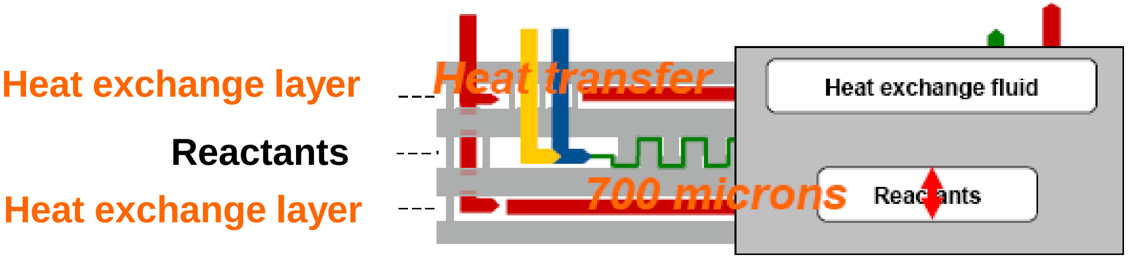
Corning Glass Microreactors.



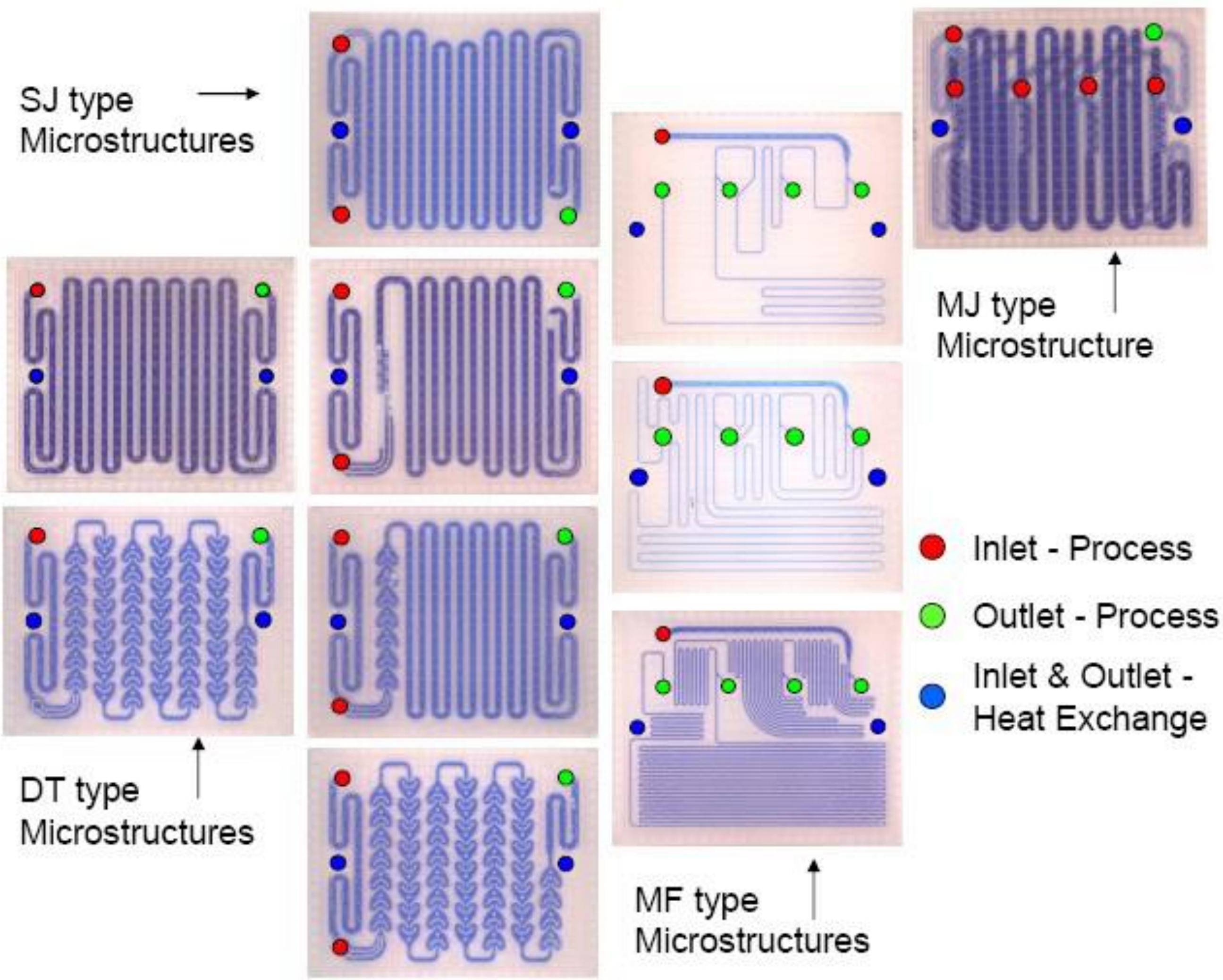
Mixing
300 micron



Pressure drop
1 millimeter

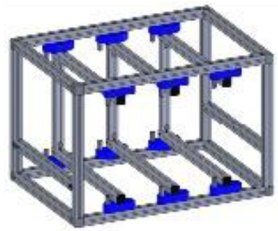


Fluidic Modules: Concept and Library.



Engineered Reactor Components.

Interfaces



Frames

Standard Fittings

Connectors

Tubing

Sensors

O-ring seals

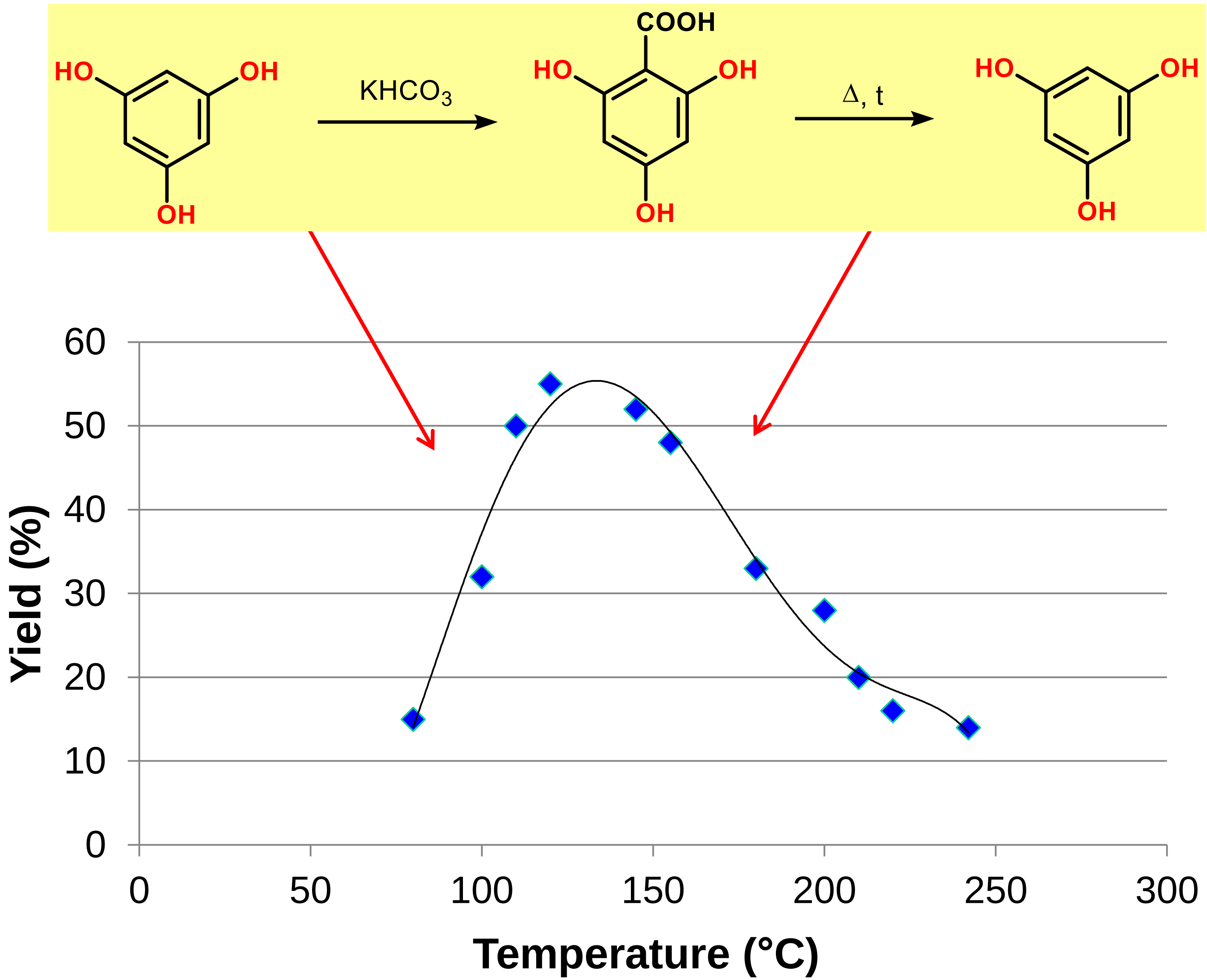
Fluidic Modules

Labelling

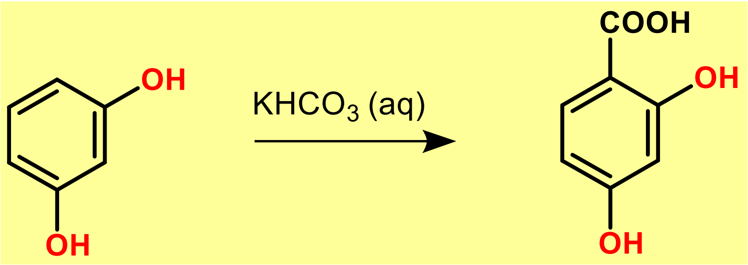
Add-on (insulation…)

Instrumentation (Pressure relief valve…)

Phloroglucinol-Type Kolbe Schmitt - Synthesis in Microreactors.

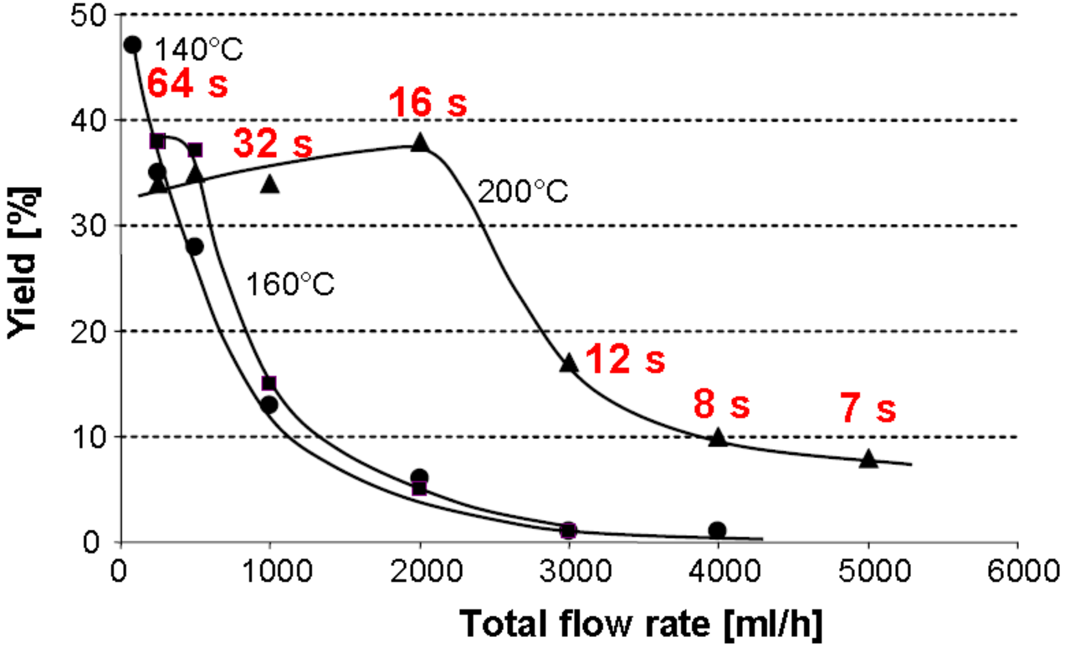


Kolbe Schmitt-Synthesis: High P,T-Processing.



V. Hessel, C. Hofmann, P. Löb, J. Löhndorf, H. Löwe, A. Ziogas
Org.Proc. Res. Dev. **9**, 4(2005) 479-489

High p,T



- **Pressure: 40-70 bar**
- **Temperature: 100-220°C**
- **Reaction time: 4 –390 s**

⇨ **Reduction of reaction time by ~2000**

⇨ **Increase in space-time yield by factor 440**

⇨ **Increase in productivity by factor 4**

Modelling Study on Styrene Solution Polymerization.

Thermal phenomenon convection/conduction

Kinetics constant depend on temperature

Heat released by polymerization

Reaction, convection and diffusion of chemicals

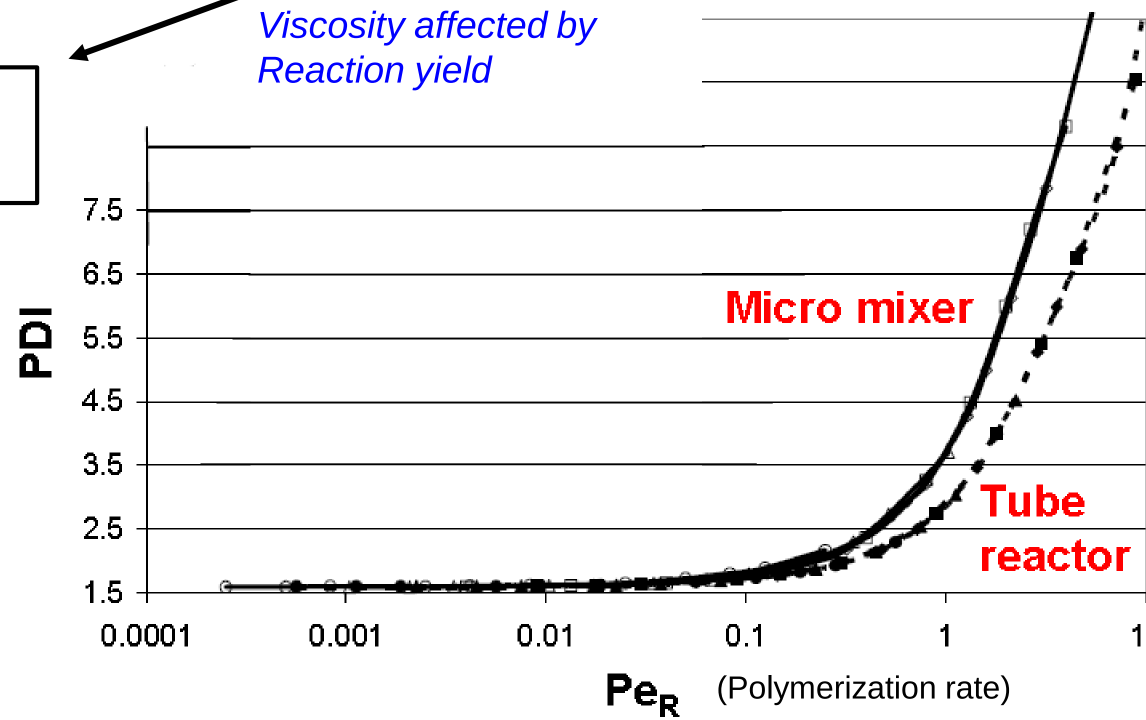
Convection

Viscosity affected by Reaction temperature

Convection

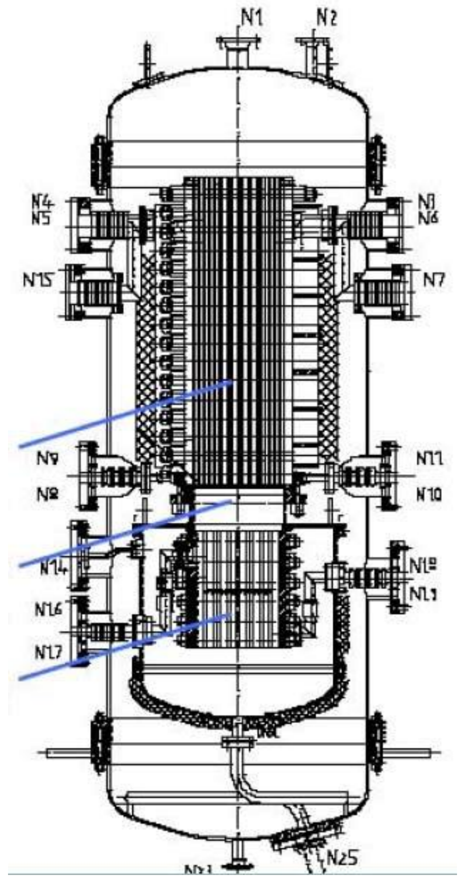
Viscosity affected by Reaction yield

Hydrodynamics Navier-Stokes equations



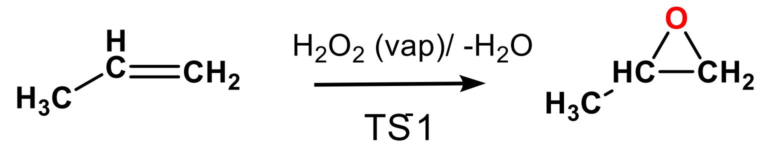
V. Hessel, C. Serra, H. Löwe, G.Hadziioannou, Chem. Ing. Techn.77, 11 (2005) 39-59,

Microstructured Epoxidation Reactor.



Degussa

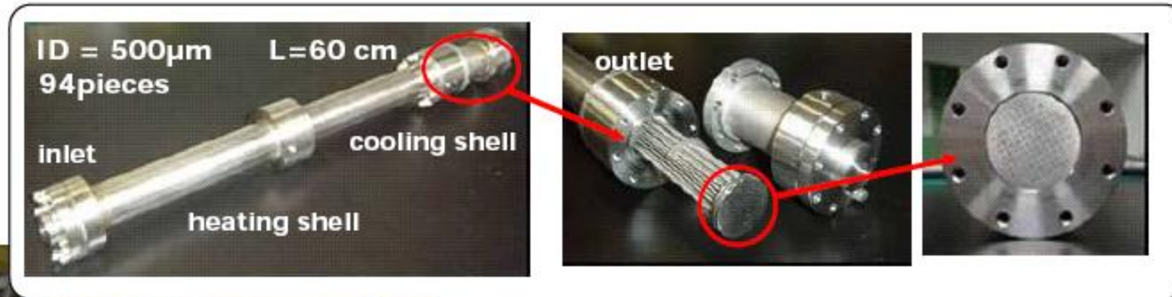
Model Synthesis:



Features:

- Modular (unit operations, capacity)
- Multi-purpose (catalyst and reaction)
- Reaction under pressure
- Reactions in the explosive regime

Radical Polymerization Reactor.



Plant running at industrial site of Idemitsu Kosan

Dr. Takeshi Iwasaki (MCPT)
Proceedings IMRET 8, Atlanta, April 2005.

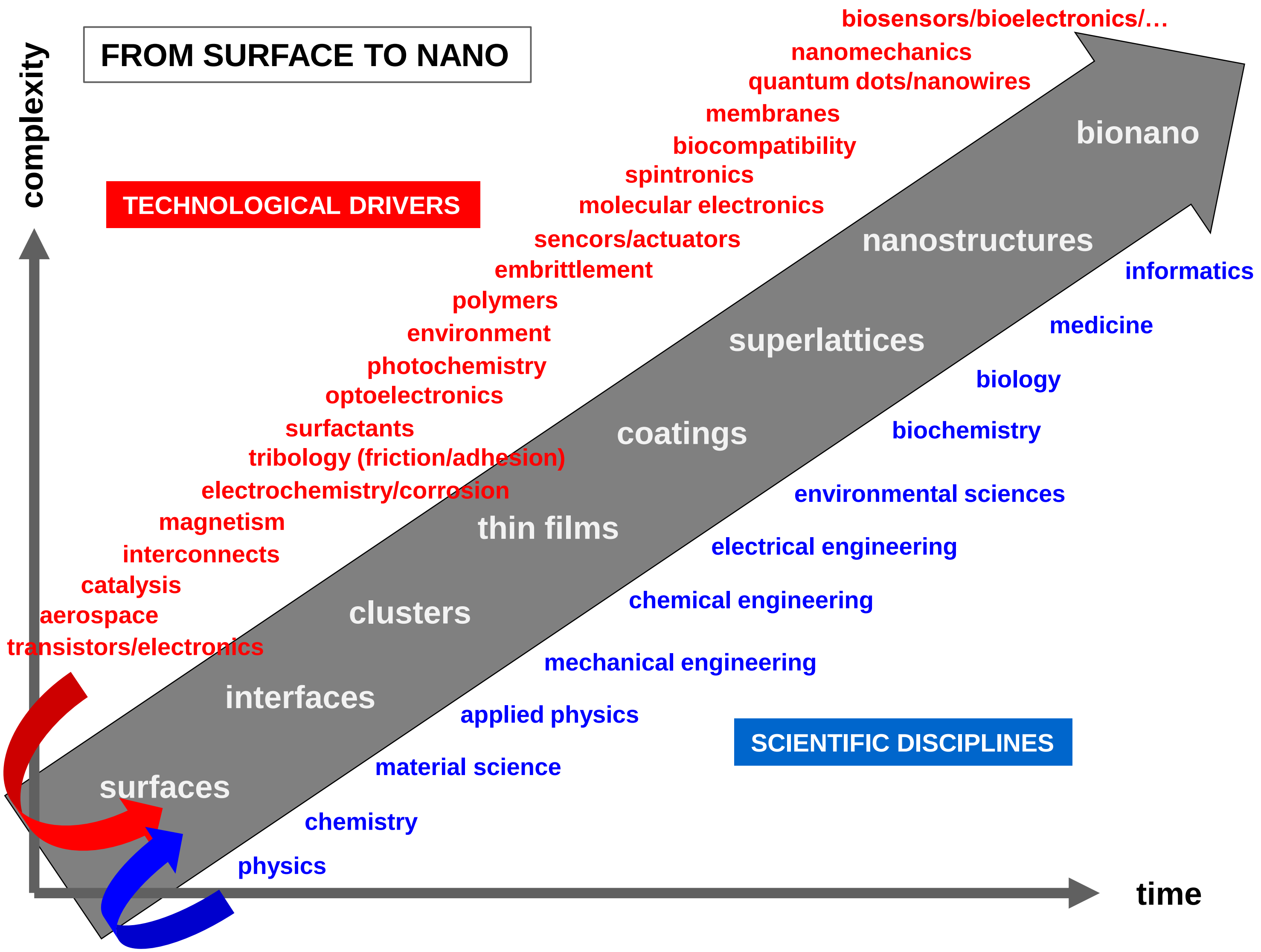
Where to Apply Microchemical Technology?

- Direct routes from hazardous systems
- Routes at increased concentration or even solvent-free
- Routes at elevated temperature and/or pressure
- Routes mixing the reactants ‘all at once’
- Routes using unstable intermediates
- Routes in the explosive or thermal runaway regime
- Routes omitting the need of catalysts and auxiliary agents

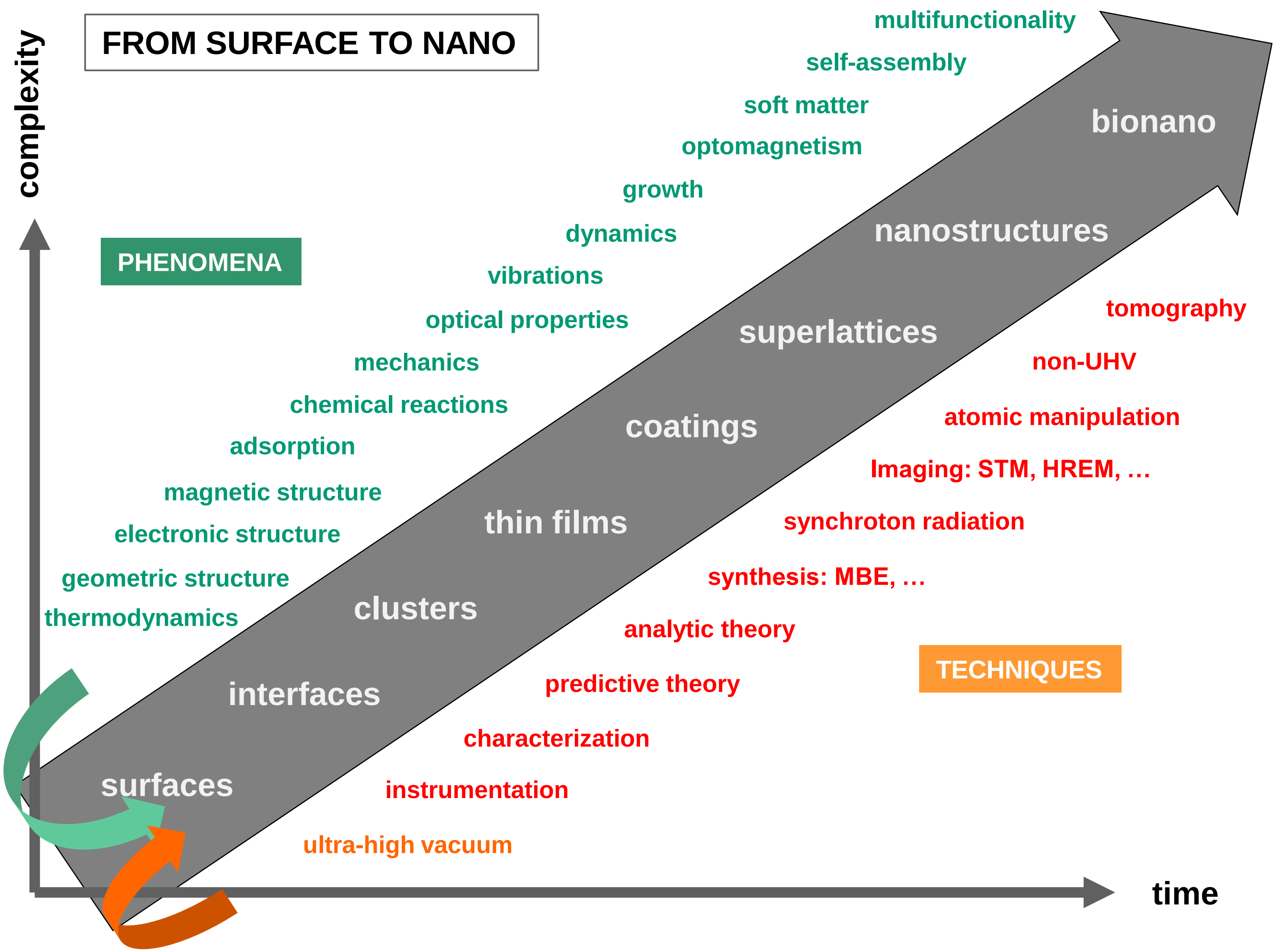
DEVELOPMENT OF REACTORS TO ENABLE CHEMISTRY RATHER THAN SUBDUING CHEMISTRY AROUND THE REACTOR

V. Hessel, P. Löb, H. Löwe, Curr. Org. Chem. 9, 8 (2005) 765-787
Jähnisch, K.; Hessel, V. et al.; Angew. Chem. Intern. Ed. 43, 4 (2004) 406-446

Scientific and Technological Drivers in Surface-Nano Applications.



Phenomena and Techniques in Surface-Nano Applications.



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11. Jun Yue, Jaap C. Schouten, T. Alexander Nijhuis, Integration of Microreactors with Spectroscopic Detection for Online Reaction Monitoring and Catalyst Characterization, Industrial & Engineering Chemistry Research, 2012, 51, 45, 14583
12. Li-Hua Du, Xi-Ping Luo, Lipase-catalyzed regioselective acylation of sugar in microreactors, RSC Advances, 2012, 2, 7, 2663