CFD Simulationen von mikrofluidischen Bauelementen zur Optimierung von chemischen Reaktionen

Karl–Heinz Feller

Arbeitsgruppe Instrumentelle Analytik

FB Medizintechnik und Biotechnologie

Ernst-Abbe-Fachhochschule Jena

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outline

- **introduction**
- **development of micro fluidic chips (Lab on a Chip) for:**
  - **(I) online micro spectral investigations of kinetics studies**
  - **(II) micro biological research**
  - **(III) micro reactions studies**
- **investigation of wall roughness**
- **micro mixer optimization with DoE**
- **conclusion**

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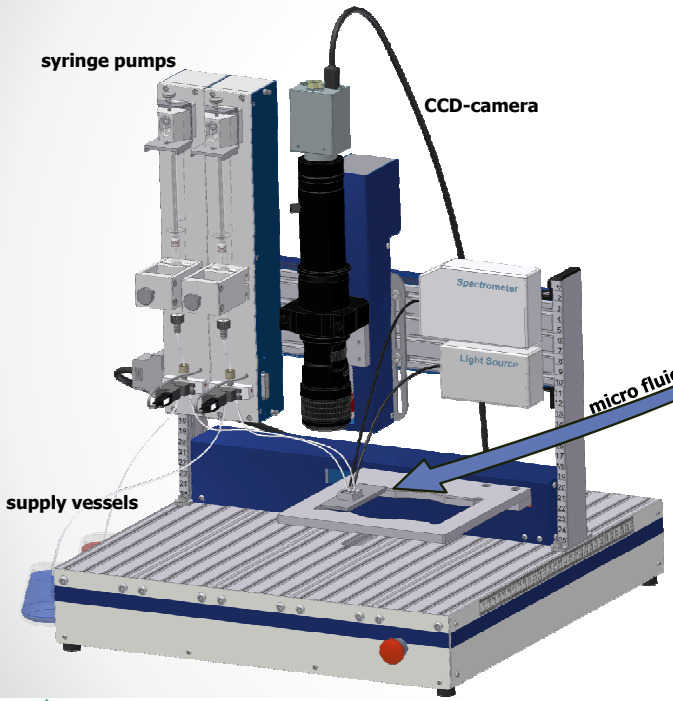
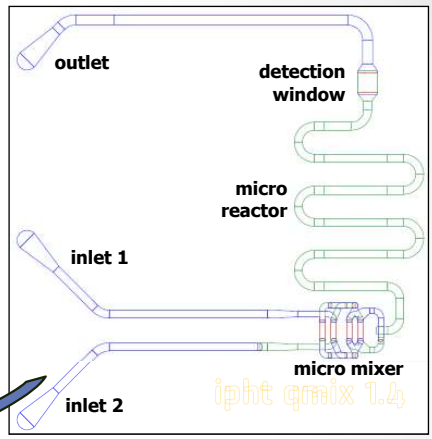
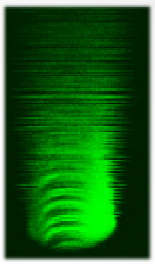
modular micro fluidic platform



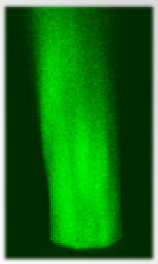


- <u>for kinetics analysis of (bio)chemical reaction</u>
- micro fluidic advantages:
  - short mixing time (ms scale)
  - small amounts
- high precision syringe pumps
- micro mixers as small as possible
- „accelerated-flow“ method
- optical measurement

pumps and chip holder



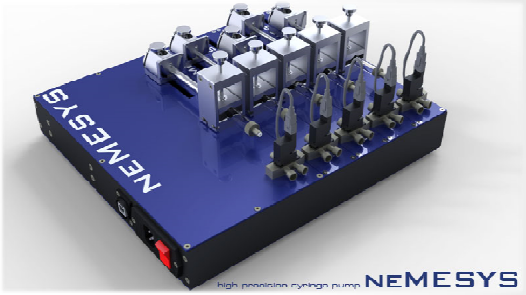
conventional pump system



NEMESYS- syringe pump

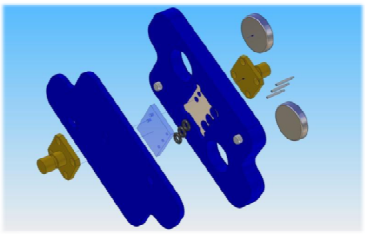
pumps:

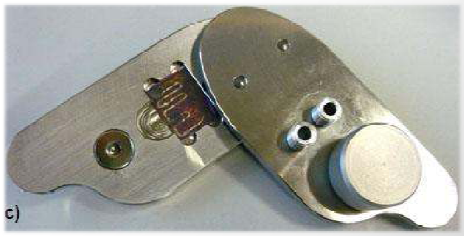
- high precision syringe pumps
- very low pulsation with volumetric flow
- modular extendibility
- pressure range up to 196 bar



chip holder:

- magnetically connected
- quick change chip system
- optical fiber connected
- O-rings as seals





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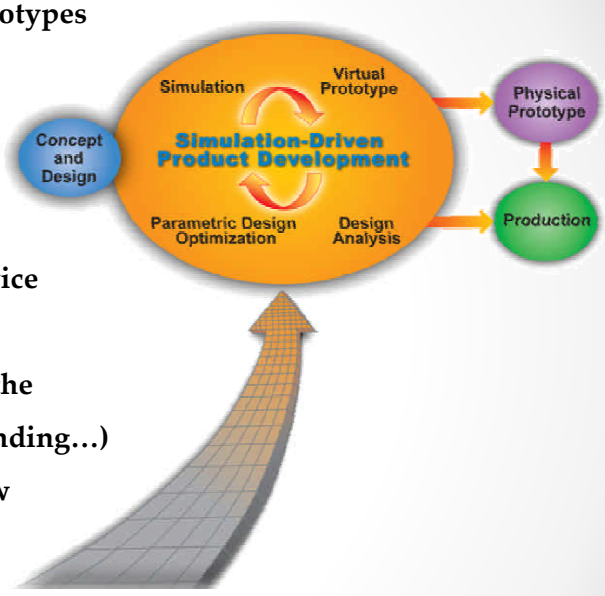
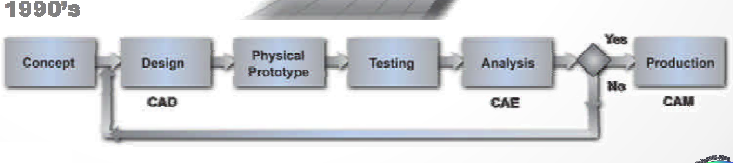
micro mixer optimization – CFD simulations

- 90´s → development by means of many prototypes
- today → simulation (orange), iterative until the optimal solution is found
- saves money and time
- numerical simulation shows the characteristic behavior inside the fluidic device
- higher understanding of the mixing process
- CFD makes optimization possible ahead of the expensive productional process (etching, bonding…)
- micro reactions need small mixers with a low pressure drop at high flow rates
- comparison:
  - CFD with experiment





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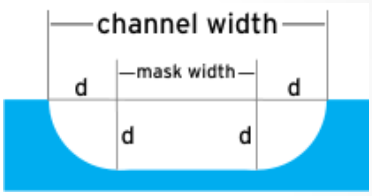
micro structures – glass and silicon substrates

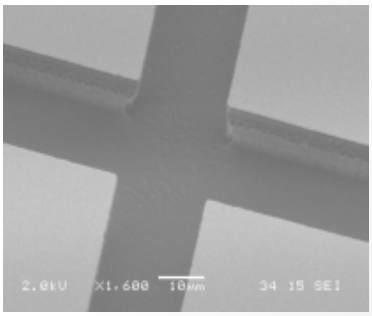
glass:

- chemical resistance
- optical transparence (point of care)
- isotropic etching of glass
- undercutting of the etching mask
- geometric limitations
- advantage for debubbling
- surface - wall roughness $R_a \approx 10nm$, optical clear



silicon:

- chemical resistance
- anisotropic etching of silicon
- good aspect ratio
- sharp edges, holes



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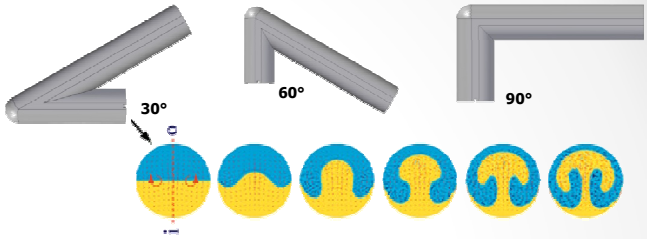
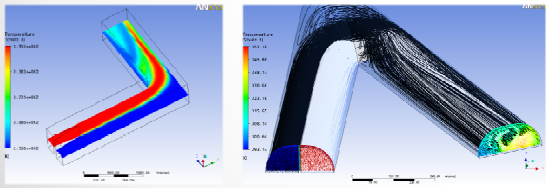
micro mixer optimization – CFD simulations

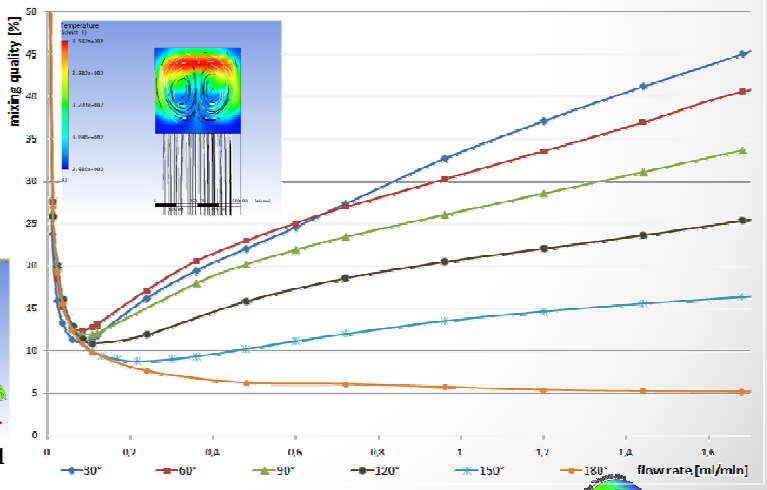
- laminar flow (0,1 - Re - 1000)
- flow rates: 0 ml/min to 2 ml/min
- pressure drop up to 2 bar
- multi layer devices (up to 3 layers)
- extension of interaction surface
- CFD software ANSYS (CFX)
- flow around bends with different angles (30° – 180°)
  → (Dean flow mixer)
- calculated 13 million cells at 30 nl



Dean flow phenomena in curved micro channels at rising flow rate



transport the inner (red) stream toward the outer wall



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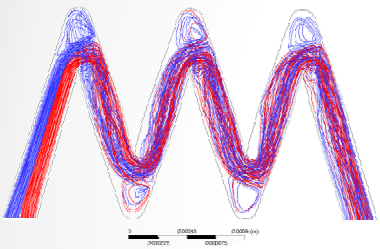
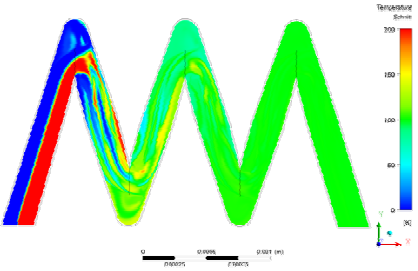
micro mixer optimization – CFD simulations

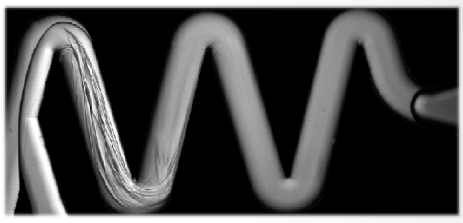
- strong increased mixing quality at typical flow rates of 2 ml/min (crossway flows)
- Dean flow mixer with 5 bends (30°) fabricated in 2 layers of glass (volume of 160 nl)
- detections windows: 2; micro reactors: 0,7µl, 1,6µl, 2,2µl, 5µl; reaction time: 20ms - 300ms



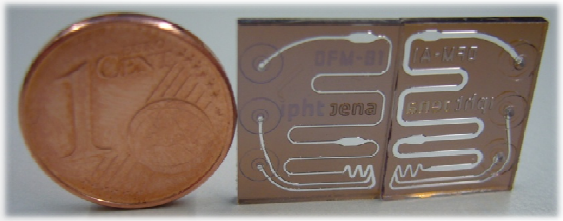
2 ml/min – Re 480 - streamlines



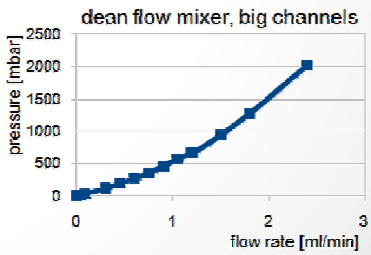
2 ml/min – Re 480 - species distribution



6 ml/min – Re 1400 – reaction product Thiocyanat



fabricated micro chips with small and big channels



lost of pressure vs. flow rate

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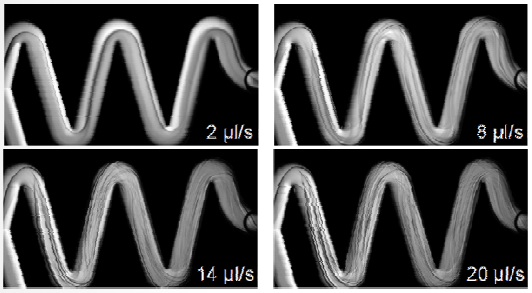
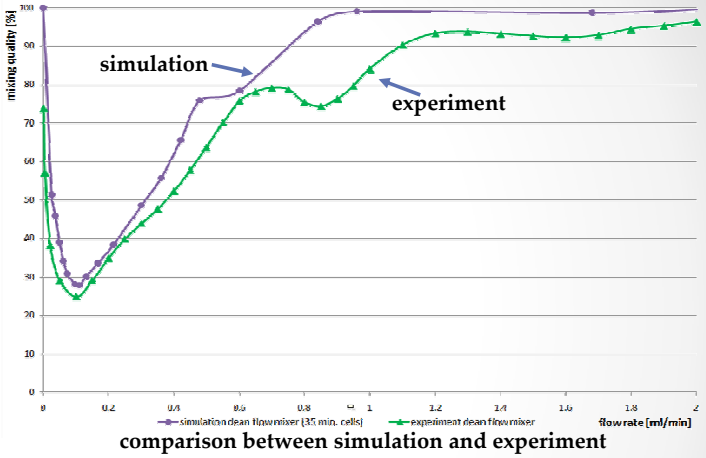
micro mixer optimization – CFD simulations

- problem: mixing quality depends very strong on flow rate
- usable for higher flow rates
- only partly suitable for kinetic investigation

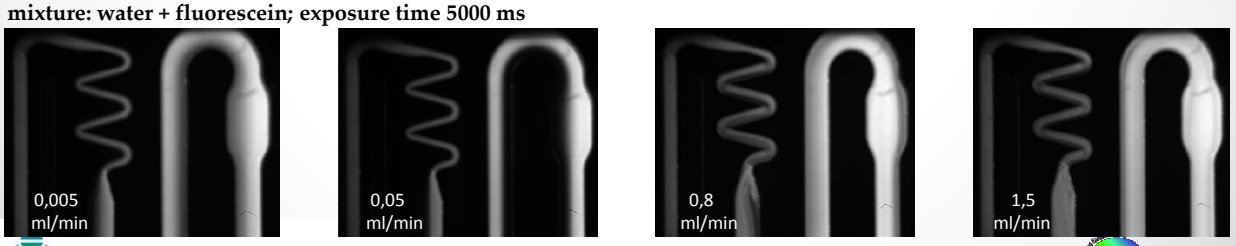


0,12 ml/min → 2,4 ml/min – reaction product Thiocyanat



comparison between simulation and experiment

mixture: water + fluorescein; exposure time 5000 ms



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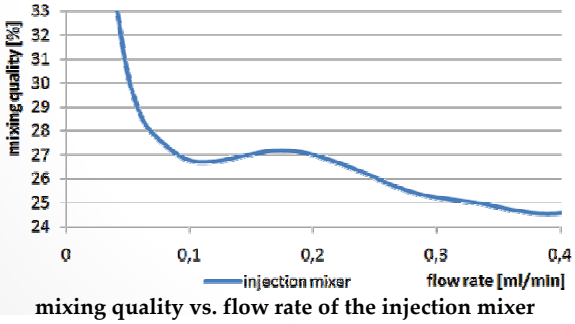
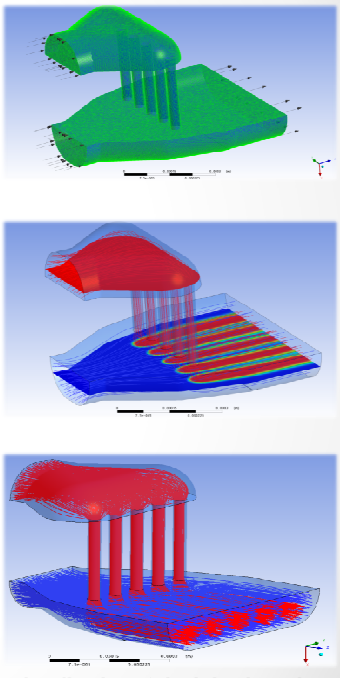
micro mixer optimization – CFD simulations

structure 1: injection of fluids

- vertical injection of a fluid stream (red) in an available second fluid stream (blue)
- mixing quality dependence on:
  - number and diameter of injection tubes
  - flow rates at the inlets
- creates multi lamination especially at low flow rates
- 3 layers necessary (glass-silicon-glass)
- optimum of mix. quality adjustable (here 0,18 ml/min)



mixing quality vs. flow rate of the injection mixer



visualisation of the injection mixer

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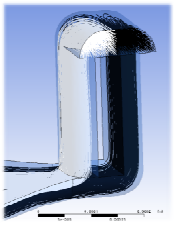
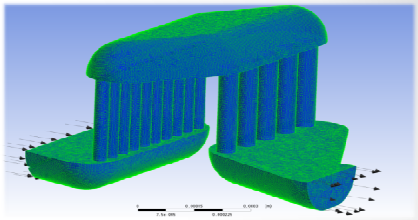
micro mixer optimization – CFD simulations

structure 2: rotation of fluids

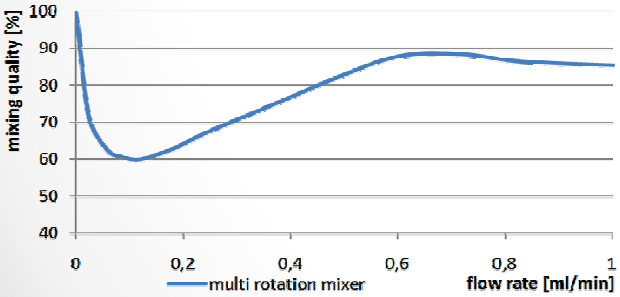
- rotation turns diffusion interface
- parallel build up allows multi lamination
- low pressure drop over mixer module
- enlarged interface for diffusion
- 3 layers necessary (glass-silicon-glass)
- optimum of mix. quality adjustable (here 0,6 ml/min)



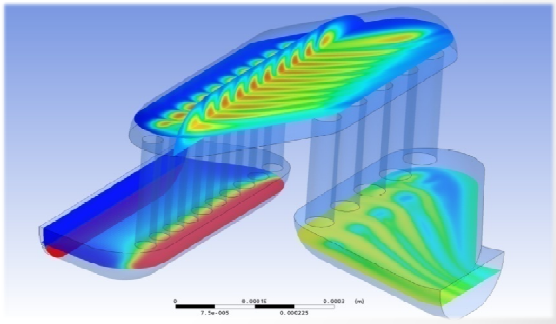
rotation



meshed multi rotation mixer



mixing quality vs. flow rate of multi rotation mixer



visualization multi rotation mixer

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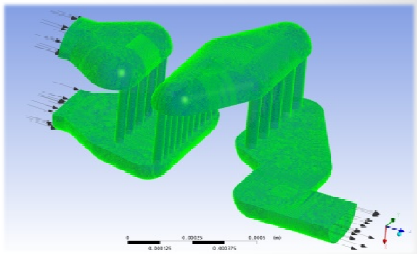
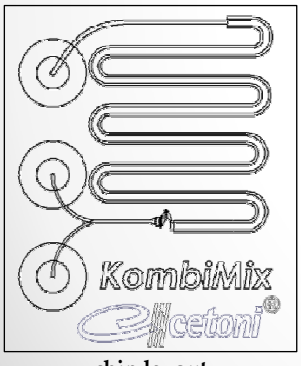
micro mixer optimization – CFD simulations

combination of structure 1+2: KombiMix

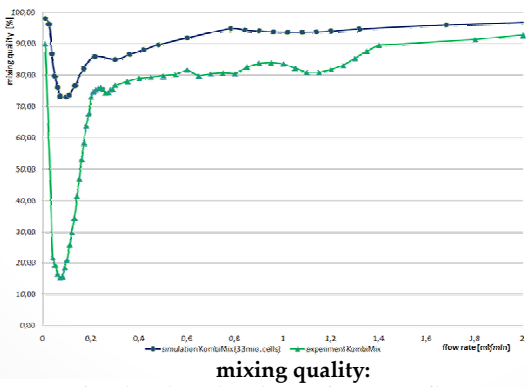
- optimized single modules serial linked
- total volume of the mixer: 60 nl
- usable at 0,2 ml/min
- pressure drop (mixer): 0,6 bar at 2 ml/min
- fluid chip with 2 detection windows: 0,6 µl → 12 µl
- reaction time: 10 ms → 4000 ms



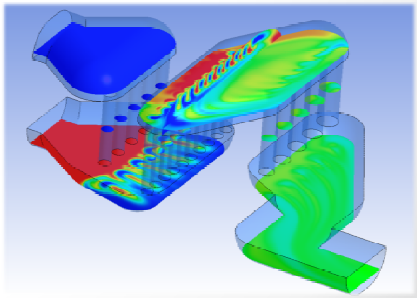
meshed KombiMix (35 million cells)
with boundary conditions



chip layout



mixing quality:
simulated and real experiment vs. flow rate



visualization KombiMix

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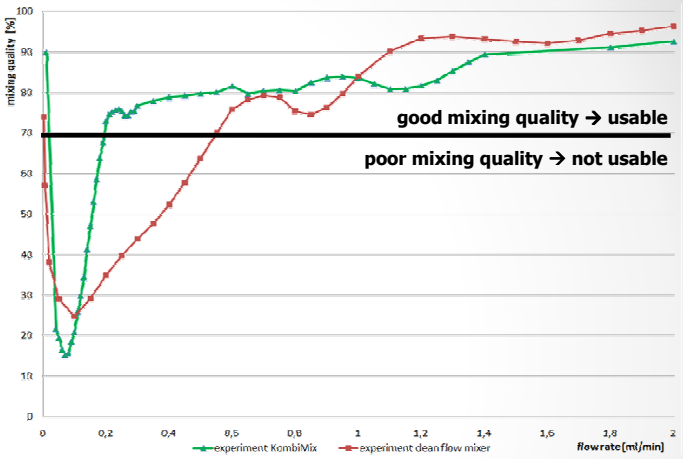
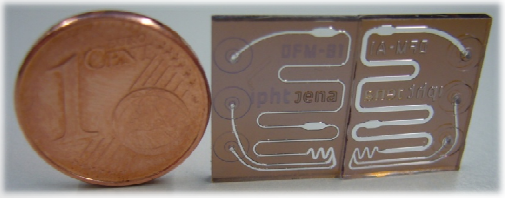
comparison of fluidic chips (kinetic distribution)

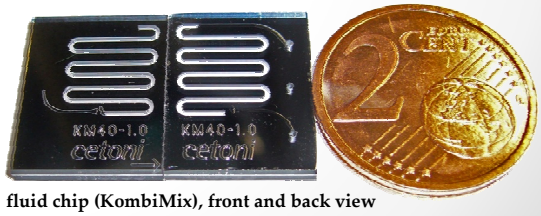
	Dean Flow mixer	KombiMix mixer
mixer volume	160 nl	60 nl
flow rates (max. 2 bar)	0,6 – 2 ml/min	0,2 – 3,5 ml/min
reaction volume	0,7 – 5 µl	0,6 – 12 µl
reaction time	20 – 300 ms	10 – 4000 ms
detection windows	2 positions	everywhere at the channel
structured Layer	2 glass	2 glass + 1 silicon



comparison of the used micro mixers



fluid chips (Dean flow mixer) with small and big channels



fluid chip (KombiMix), front and back view

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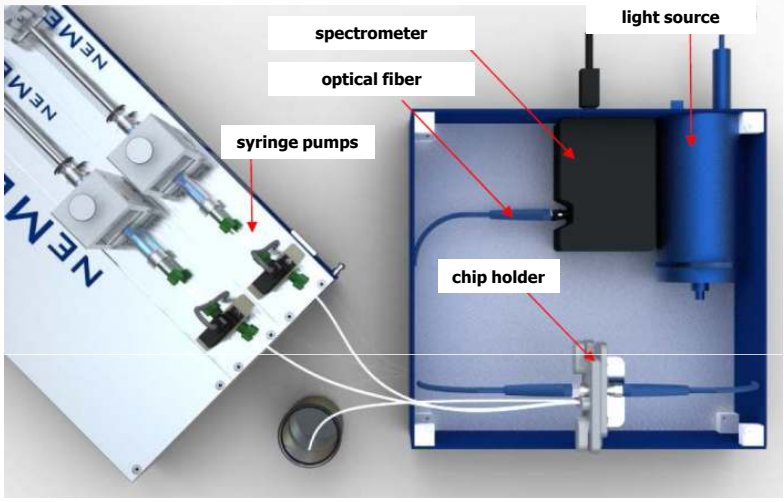
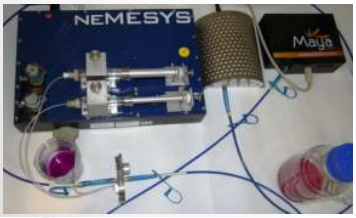
modular micro fluidic platform





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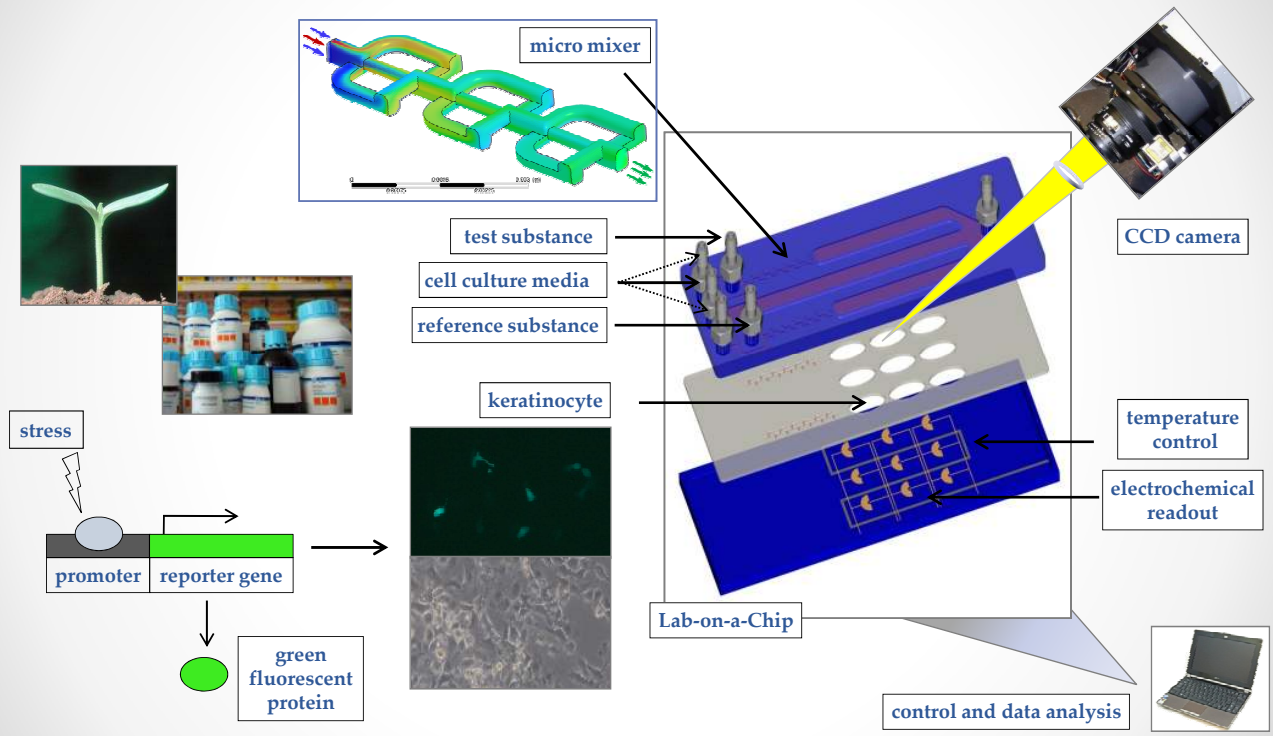
Setup of the Lab-on-a-Chip



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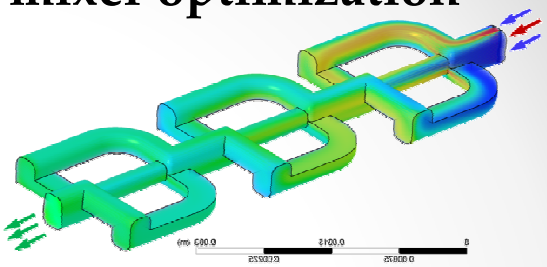
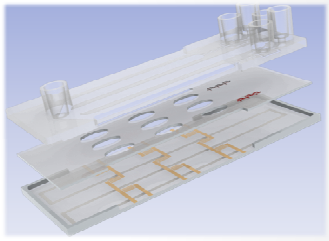
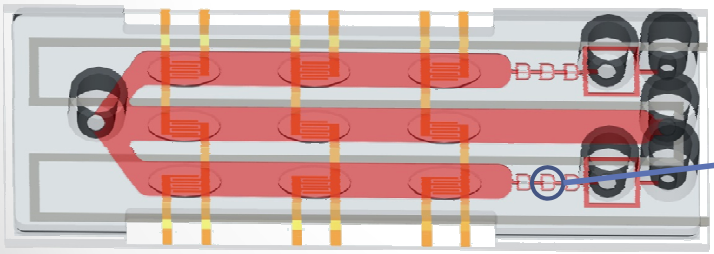
CFD simulations - micro mixer optimization

Tornado Mixer:

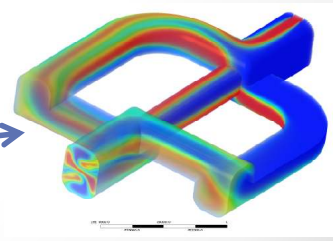
- optimized for:
  - mass production
  - low cost micro structuring
  - ultra low flow rates (1 µl/min)
- combination of splitting, rotating and twisting modules
- only 2 micro structured layers (2,8 µl)
- chip material COC (Topas)
  - micro milling (prototypes)
  - injection moulding (final design)







top view at the "cell on a chip" layout



visualization of mixing quality

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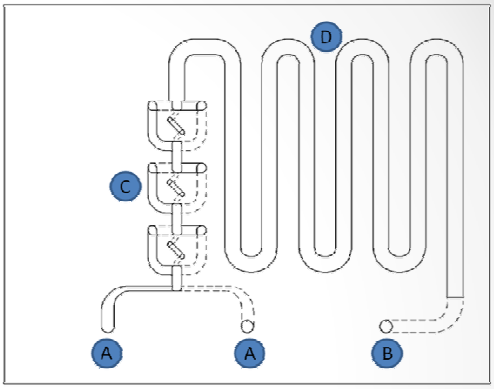
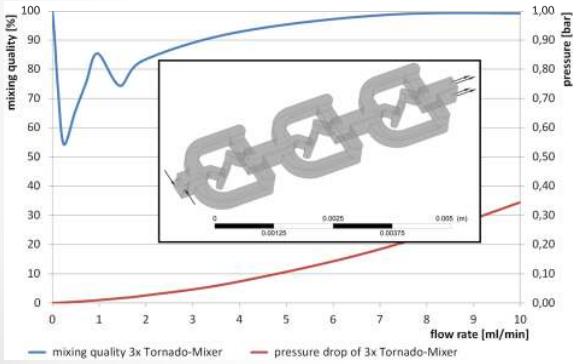
chip design for micro reaction studies

Tornado Mixer (advanced):

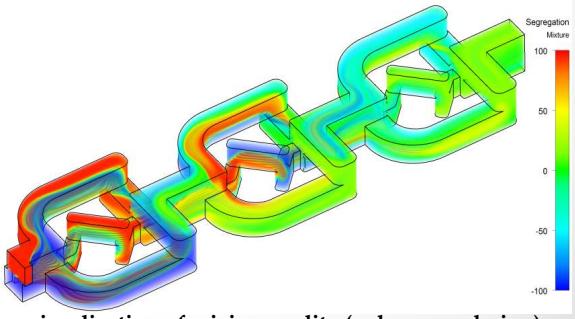
- optimized for:
  - mass production; micro structuring
  - high flow rates (50 ml/min)
- combination of splitting, rotation and twisting
- total volume of the mixer: 1,7 µl
- only 4 bar at 60 ml/min



microfluidic chip layouts with inlets (A), outlet (B), micro mixer (C) and a micro reactor (D)



Flow rate vs. mixing quality for Tornado-Mixer incl. CAD model of the micro mixer



visualization of mixing quality (volume rendering)

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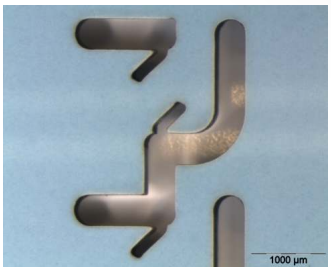
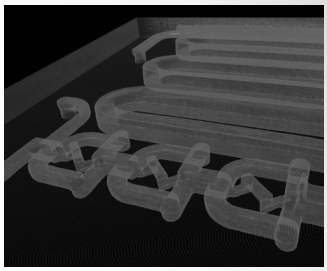
chip design for micro reaction studies

Tornado Mixer (advanced):

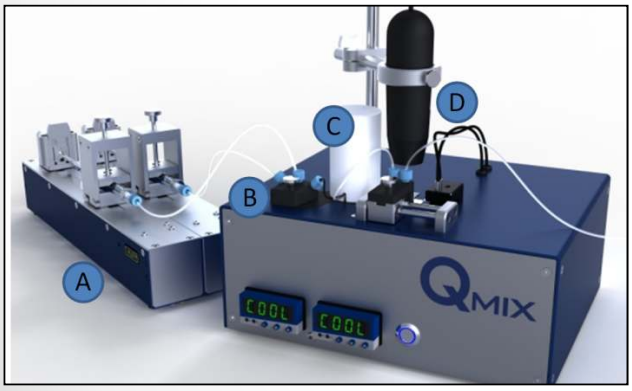
- only 2 layers micro structured necessary
- made of LTCC (ceramic)
- micro punching (Stanzen)and laser micromachining for ablating
- low cost chemical resistance fluid chip



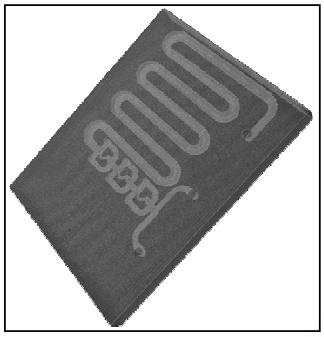
green LTCC tape made by laser cutting



detail view of the micro mixer (MicroCT)



analytical workbench with precision syringe pumps (A), chip system incl. Tornado-Mixer (B), adjustable residence zone (C) and optical readout (D) (camera and mini-spectrometer) to analysis of micro reactions



MicroCT images of the hole fabricated reaction chip

chip holding system with micro reaction chip inside

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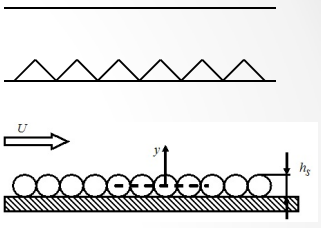
outline

- introduction
- **development of micro fluidic chips (Lab on a Chip) for:**
  - (I) online micro spectral investigations of kinetics studies
  - (II) micro biological research
  - (III) micro reactions studies
- **investigation of wall roughness**
- micro mixer optimization with DoE
- conclusion

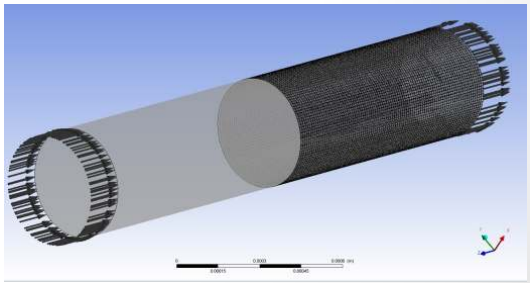
Investigation of wall roughness – CFD simulations

Tube:

- **compare of flow behavior:**
  - **(a) smooth surface**
  - **(b) CAD designed wall roughness (R_a at 3 µm)**
    wall roughness through 10 thousand of pyramids (10µm)
  - **(c) simulated wall roughness (Pre-processing, SST Model)**
    Sandgrain, R_a at 3 µm



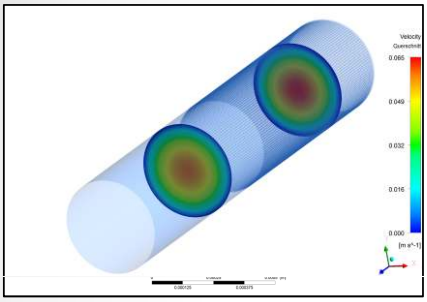
- **(b) hybrid mesh with 3 µm (refinement up to 0,2 µm)**
  - **75,7 mio. tetras**
  - **11,9 mio. hexas**
  - **0,7 mio. pyramids**
- **(c) hybrid mesh with 3 µm (refinement up to 0,5 µm)**
  - **11,6 mio. prisms (15 inflation layers)**
  - **4,7 mio. tetras**
  - **5,3 mio. hexas**
  - **0,3 mio. pyramids**

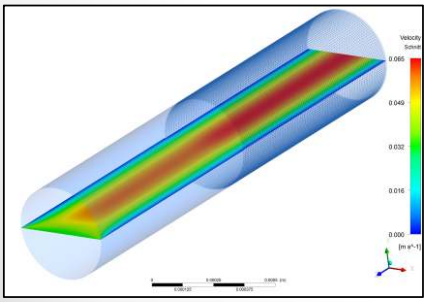


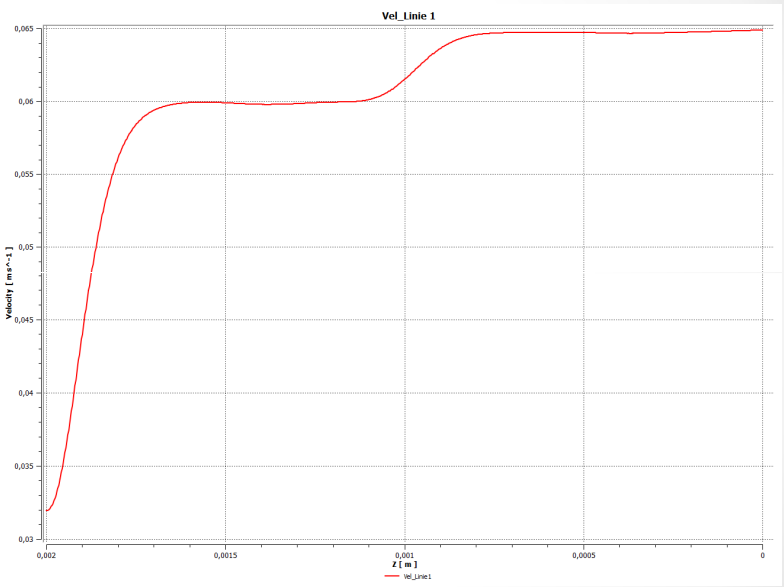
Tube with CAD designed wall roughness (pyramids)

Investigation of wall roughness – CFD simulations

First Results:

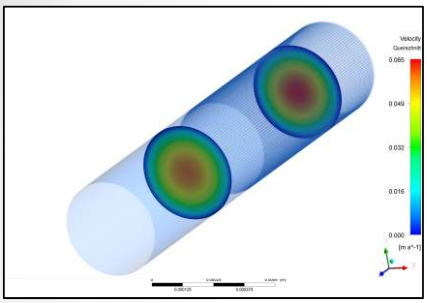


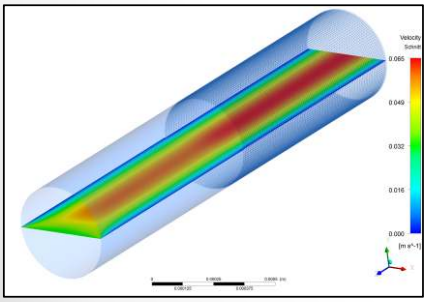


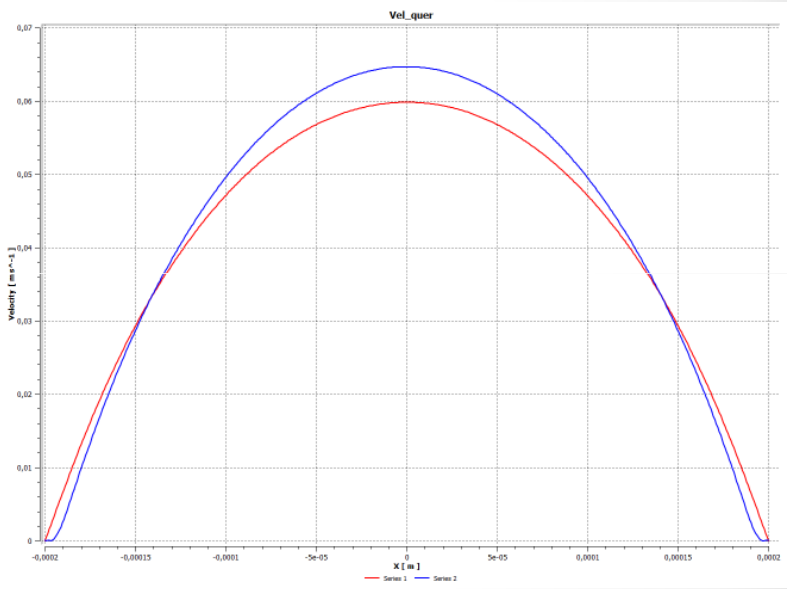


Investigation of wall roughness – CFD simulations

First Results:







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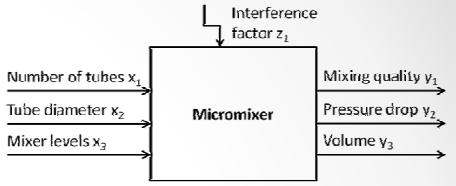
micro mixer optimization with DoE

Design of Experiment (DoE):

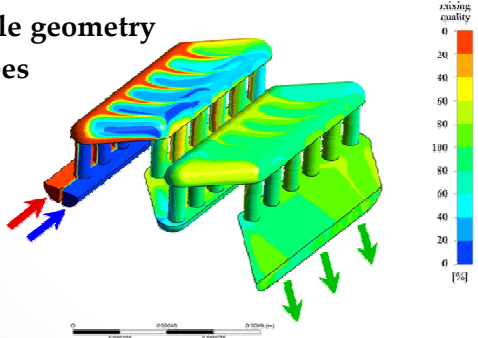
- **optimization with a minimum of CFD runs (54 → 18)**
- **investigation of the impact of each parameter**
- **to achieve:**
  - **small inner volume**
  - **small pressure drop**
  - **high mixing quality at low dependency on flow rate**



block diagram with design variables (x) and objective functions (dependent variables, y) on the micromixer system

Multirotation mixer:

- **very good adjustable geometry**
  - **number of tubes**
  - **tube diameter**
  - **mixer levels**
- **fabrication:**
  - **metal foils**
  - **glass**



Multirotation mixer with indicated mixing quality with 4 mixer levels and 6 tubes 80 µm in diameter

experimental design for micromixer optimization

Run	Design variables		
	Tube diameter	*Amount of tubes per level*	*Mixer levels*
1	70	6	2
2	70	8	3
3	70	10	4
4	70	12	2
5	70	14	3
6	70	16	4
7	80	6	4
8	80	8	2
9	80	10	3
10	80	12	4
11	80	14	2
12	80	16	3
13	90	6	3
14	90	8	4
15	90	10	2
16	90	12	3
17	90	14	4
18	90	16	2

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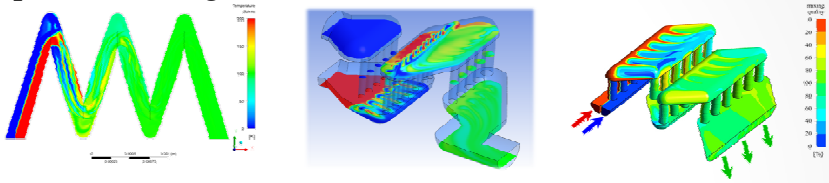
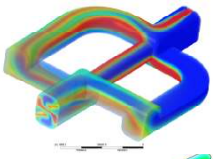
conclusion

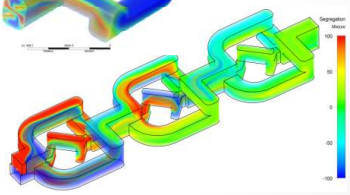
- optimization of micro fluidic chips for:
  - (I) online micro spectral investigations of kinetics studies (variable flow rate)



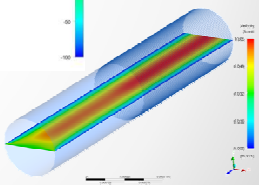
    - three chip systems: Dean Flow Mixer, KombiMix, Multirotation Mixer
  - (II) micro biological research (low flow rates)



    - one chip system: Tornado Mixer
  - (III) micro reactions studies (high flow rates)



    - one chip system: advanced Tornado Mixer



- investigation of wall roughness
- targeted multi component optimization by using design of experiments
- CFD simulations as a strong tool for optimization and understand of internal flow

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Danke für Ihre Aufmerksamkeit!!!