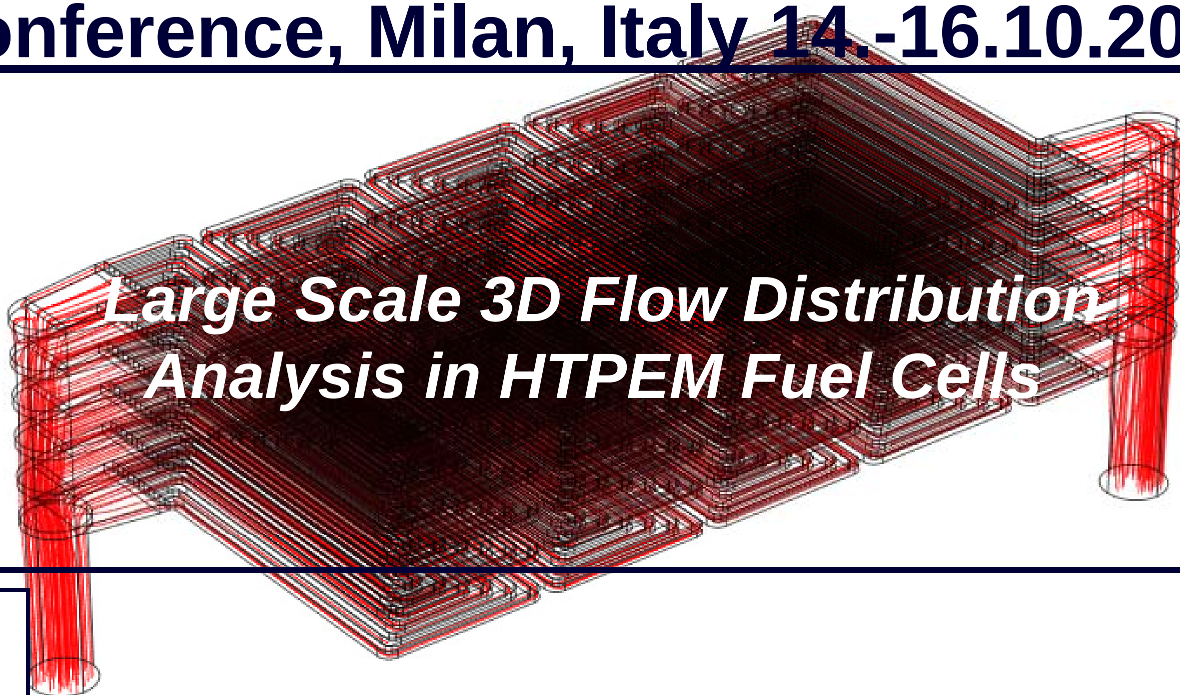
Zentrum für BrennstoffzellenTechnik

European COMSOL Conference, Milan, Italy 14.-16.10.2009



Large Scale 3D Flow Distribution Analysis in HTPEM Fuel Cells

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Outline of this talk

Introduction:

- ZBT Duisburg GmbH
- High temperature PEM (HTPEM) fuel cell
- Aim of this 3D study

Methodology:

- Computational subdomains
- Governing equations
- Solver settings, meshing and solution procedure

Experimental and theoretical results:

- PIV-measurements
- Experimental/simulation results
- Theoretical results

Summary:

- Conclusion
- Outlook

ZBT-Duisburg GmbH

ZBT Duisburg GmbH established in 2001

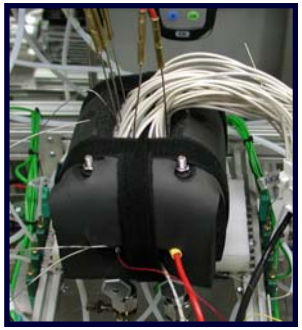
TAZ established in 2008

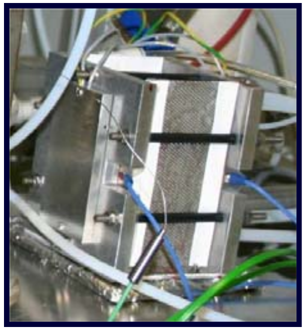
Hydrogen and fuel cell related activities in several divisions

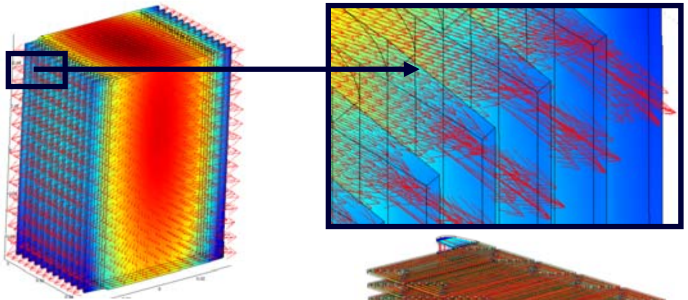
→ LTPEM and HTPEM fuel cell R&D

Focusing the HTPEM technology, e.g.:

- Bipolar-plate and component development
- Fuel cell and fuel cell stack prototype design
- Operation (short and long-term)
- System integration
- Locally resolved measurements



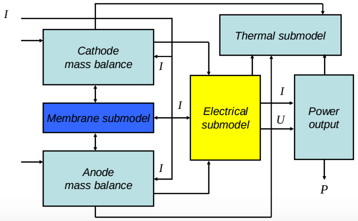


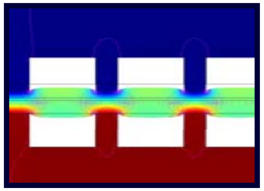


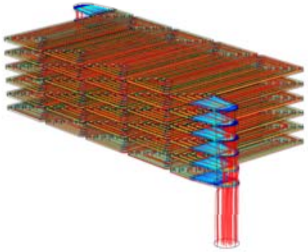
Theoretical analysis, e.g.:

- Analytical calculations
- CFD/FEM modeling and simulation
- System simulation

→ coupled to experimental investigations







High temperature PEM (HTPEM) fuel cells

→ HTPEM fuel cells electrochemically convert energy stored in a fuel and oxidant into electricity

→ Benefits against the LTPEM fuel cell technology (e.g. no humidification needed)

→ Relatively new technology (e.g. H_3PO_4 behaviour during operation not fully understood yet)

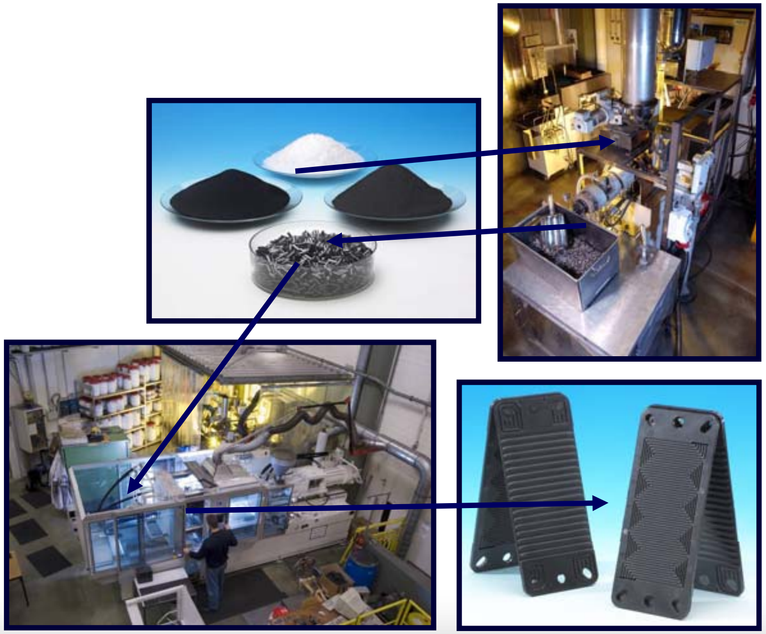
Overall goal:

- Development a complete large scale 3D HTPEM fuel cell assembly model
- Coupled CFD/FEM analysis
- 2D and 3D-studies presented at the European COMSOL conferences (2007 and 2008)

Aim of this study:

- Modeling and simulating fluid-flow behaviour
- Evaluate flow-field performance (6 different types)
- Compare results to PIV-measurements

→ Optimize flow-field layout (bipolar-plate production)?



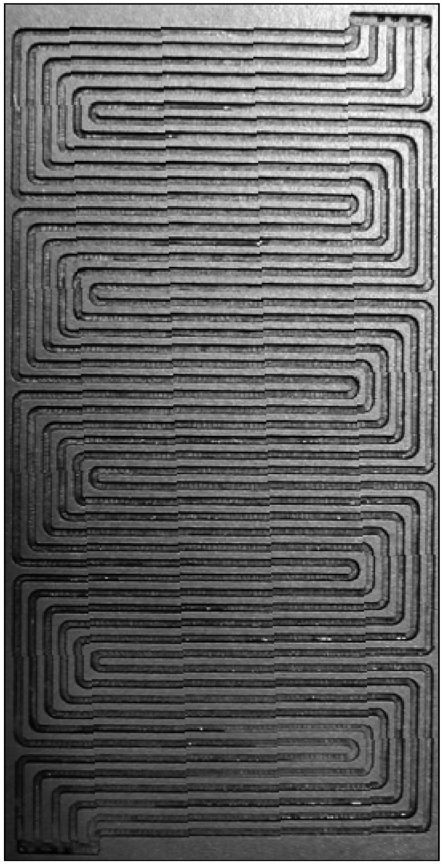
Bipolar-plate mass production at the ZBT:
e.g. injection moulding – LTPEM fuel cell applications

Computational subdomains (reference case)

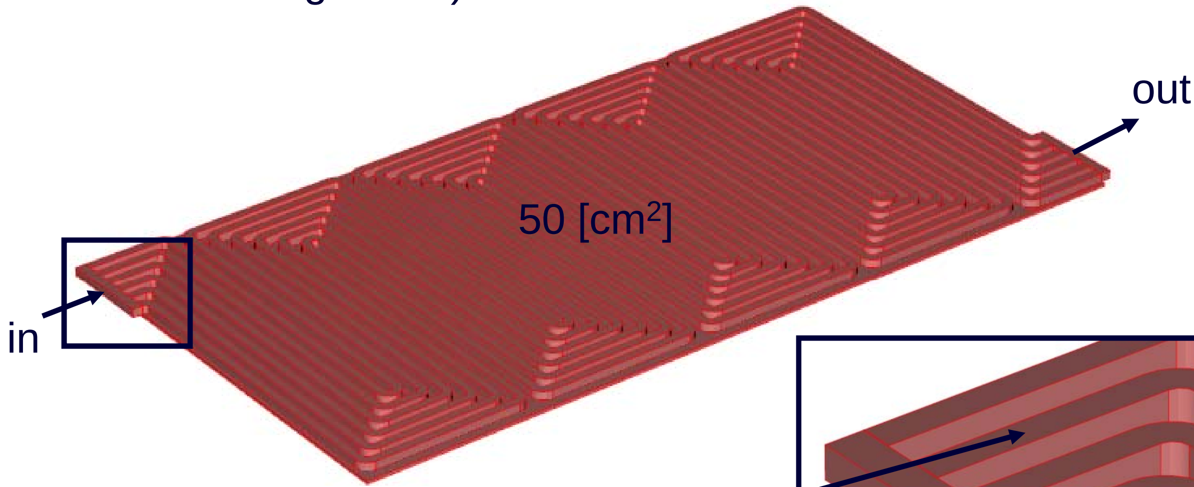
50 [cm^2] 6 channel parallel serpentine flow-field

3D model → extended to the third dimension (here z) (gas channel volume)

Geometry import (standard neutral formal '*.iges'-file)



Bipolar-plate for HTPEM fuel cell applications

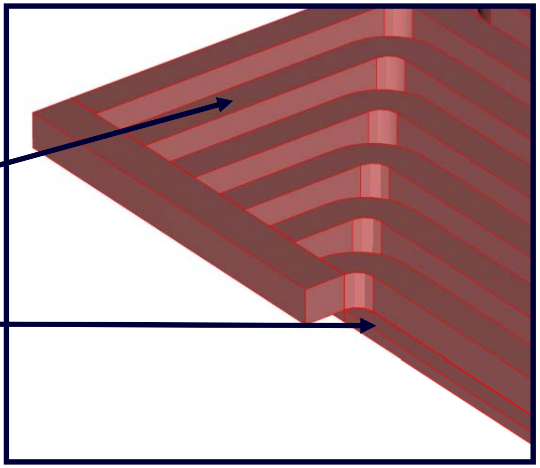


Dimensions:

Single gas channel 0.001 [m] by 0.001 (y, z)

Porous media thickness $400 \cdot 10^{-6}$ [m] (uncompressed) (z)

→ woven cloth-type material properties (E-tek (ELAT) products)



Reference case 3D model geometry

Governing equations – subdomain settings

Subdomain	*Governing equation(s)*	*Variables*
Gas channel	Navier-Stokes equations (momentum transport - laminar flow) $$\nabla \cdot u = 0$$ $$\rho \cdot u \cdot \nabla u = \nabla \cdot \left(-P \cdot I + \eta \cdot \left(\nabla u + (\nabla u)^T \right) \right) + F$$	u, v, w, P, $Pinl\_chns$ (→ weak contribution added / additional DOF)
Porous media (GDL)	Brinkman equations $$\nabla \cdot u = 0$$ $$\frac{\eta}{k_p} \cdot u = \nabla \cdot \left(-P \cdot I + \frac{1}{\varepsilon} \cdot \left(\eta \cdot \left(\nabla u + (\nabla u)^T \right) - \frac{2}{3} \cdot \eta \cdot (\nabla u) \cdot I \right) \right) + F$$ Darcy's law equation $$u = -\frac{k_p}{\eta} \cdot \nabla P$$	same as above Pd

- Physical properties of air @ 160°C used (typical HTPEM fuel cell operating temperature)
- GLS streamline diffusion (free flow) / crosswind diffusion C_k = 0.1

Governing equations – boundary conditions

Boundary	***Governing equation(s)***	***Experimental data***
Inlet	Constant laminar inflow $L_e \cdot \nabla_t \cdot \left(P \cdot I - \eta \cdot \left(\nabla_t u + (\nabla_t u)^T\right)\right) = -\vec{n} \cdot P_{0,e}$ $\nabla_t u = 0$	Volume per time unit 1000 [ml/min] (MFC)
Outlet	Pressure (no viscous stress) $\eta \cdot \left(\nabla_t u + (\nabla_t u)^T\right) \cdot \vec{n} = 0$ $P = P_{0,out}$	No back pressure (pressure loss measured)
Walls	No slip $u = 0$	n.a.
Gas channel to porous media interface	Continuity → Navier-Stokes/Brinkman $n \cdot \left(\eta_1 \cdot \left(\nabla u_1 + (\nabla u_1)^T\right) - p_1 \cdot I - \eta_2 \cdot \left(\nabla u_2 + (\nabla u_2)^T\right) + p_2 \cdot I\right) = 0$ Navier-Stokes/Darcy Pressure and velocity constraints $P, u\_chdl, v\_chdl, w\_chdl$	n.a.

Solver settings/meshing/solution procedure

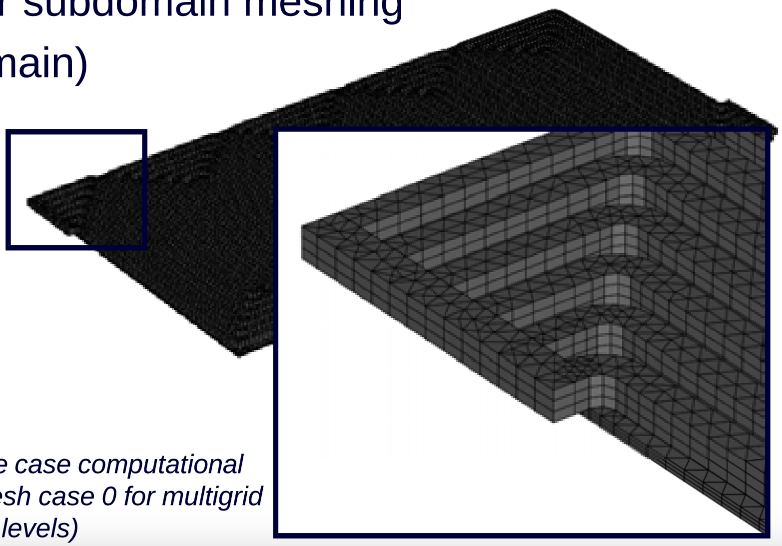
COMSOL MP 3.5a / 8 core HP workstation (Windows XP 64 bit – 64GB Ram)

1) Iterative solver or 2) Parametric iterative solver → fluid viscosity η

- BiCGStab (linear system solver)
- Preconditioner: Geometric multigrid solver (3 levels) V-cycle
- Pre-/postsmoother: Vanka (pressure update) GMRES solver
- PARDISO coarse direct solver

→ Convergence criteria $1 \cdot 10^{-6}$ [-]

- Maximum element size $0.8 \cdot 10^{-3}$ [-] (mesh case 0)
- Triangular elements on boundaries → Prism elements for subdomain meshing
- 3 elements layer (gas channel and porous media subdomain)



Reference case computational mesh (mesh case 0 for multigrid solver - 3 levels)

→ All simulations performed using the same
i) geometrical aspects
ii) HTPEM fuel cell operating conditions and material properties

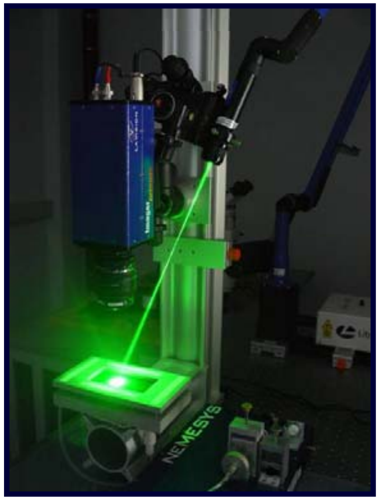
PIV-measurements (reference case)

Experimental set-up:

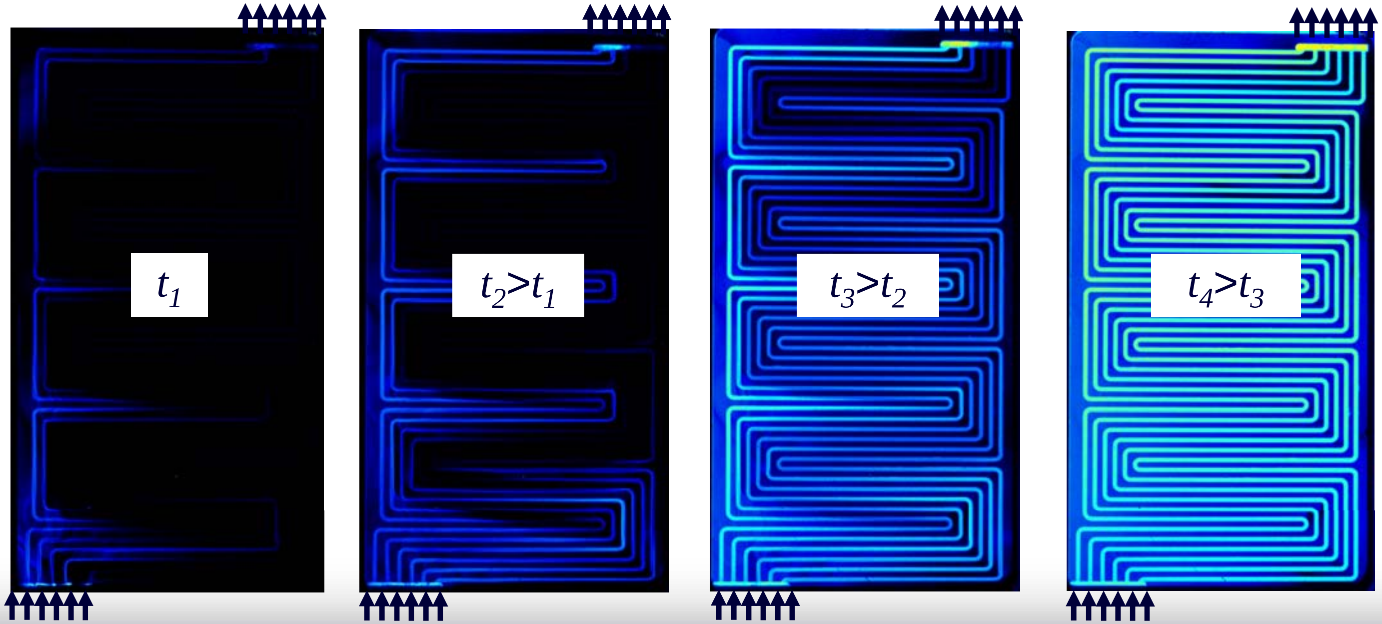
- Experimental fluid-flow data obtained by particle image velocimetry (PIV)
- 12-bit CCD camera
- Fluorescence filter
- Dual-pulse Nd:YAG laser
- Transparent HTPEM fuel cell

→ Water model conditions

→ Dimensional analysis using the Reynold's number



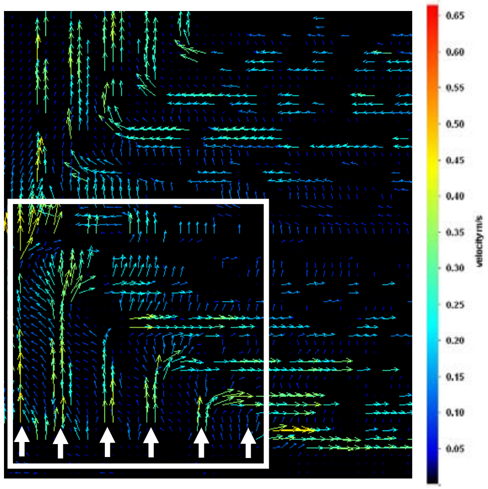
Experimental set-up



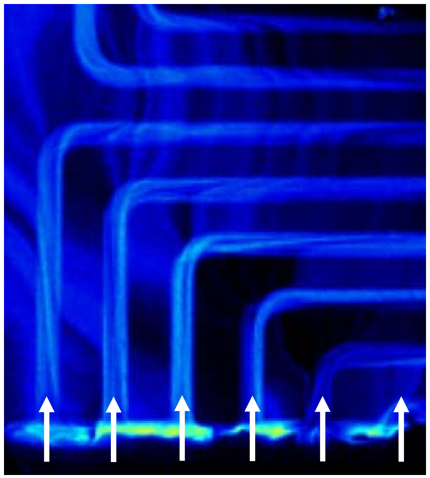
Snapshots at different times scales – PIV-measurements (x-y-plane)

Experimental/simulation results (reference case)

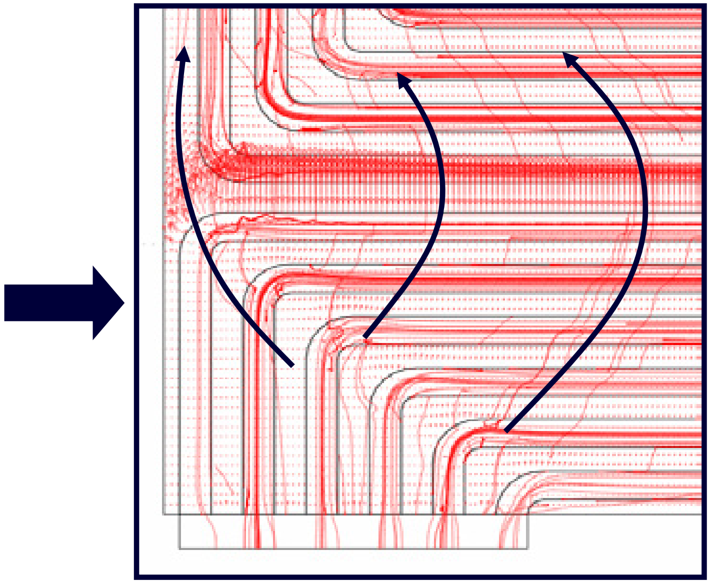
→ Quantitative comparison to CFD simulation results



Velocity vectors – PIV-measurements (x-y-plane)



Fluid bypassing between adjacent channels – PIV-measurements (x-y-plane)

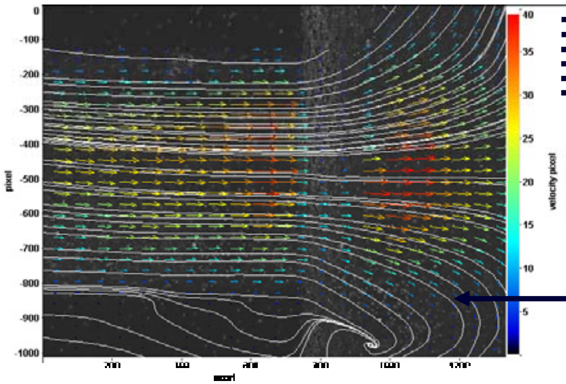


Velocity vectors and gas bypassing between adjacent channels – simulation results (arrow plot @ x-y-plane, z = $-170 \cdot 10^{-6}$ [m])

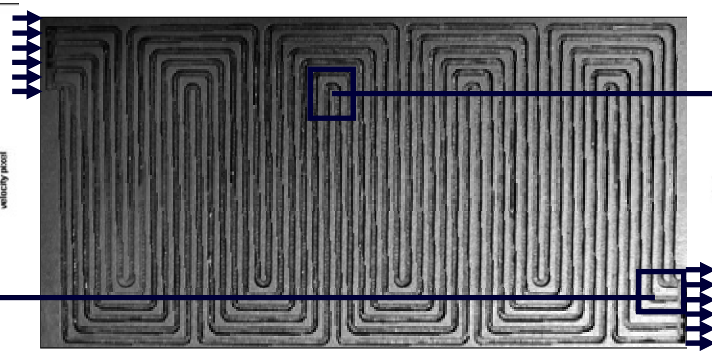
→ same shape of the bypassing flow observed in the simulations

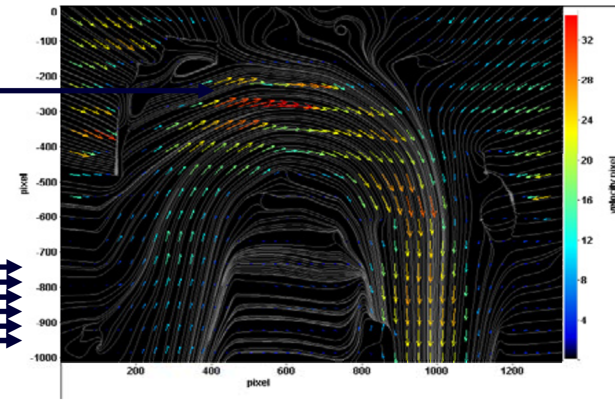
Experimental/simulation results (reference case)

→ e.g. Preliminary experimental PIV-investigations

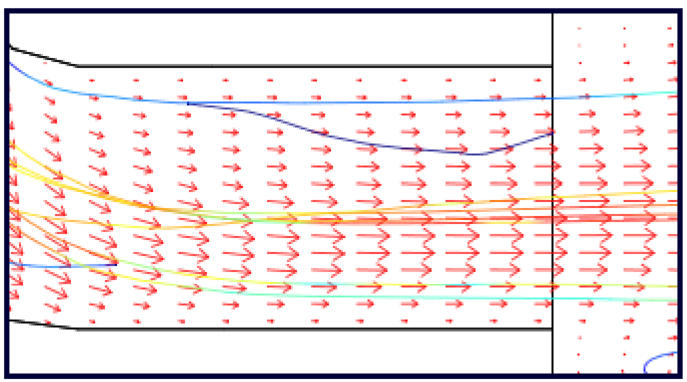


Velocity vectors within a gas channel – typical shape observed (x-y-plane)

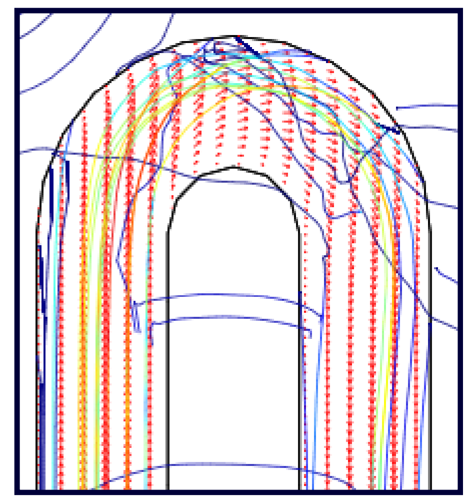




Fluid bypassing observed at the 180° bends (x-y-plane)



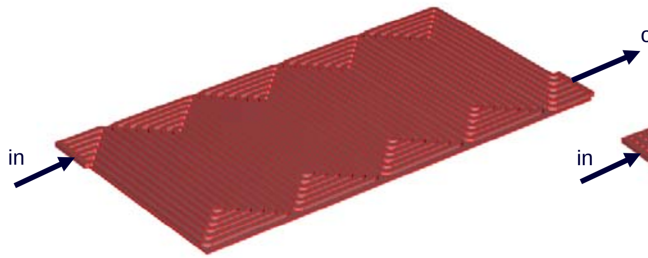
Velocity vectors and streamline plot within the gas channel (arrow plot @ x-y-plane, z = -170·10-6 [m])



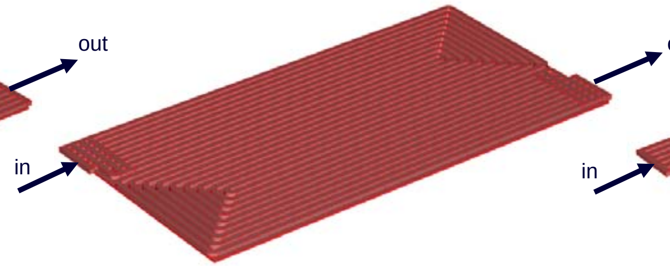
Velocity vectors and streamline plot within the gas channel close to a 180° bend (arrow plot @ x-y-plane, z = -170·10^{-6} [m])

→ quantitatively similar fluid-flow behaviour observed

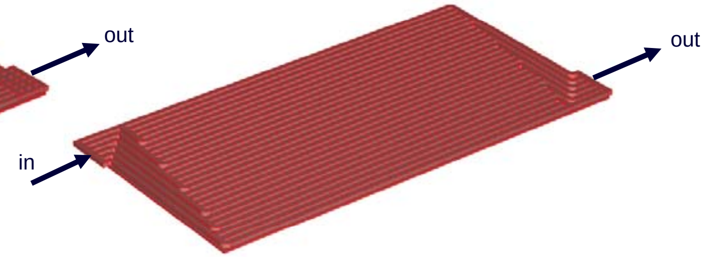
Simulation results



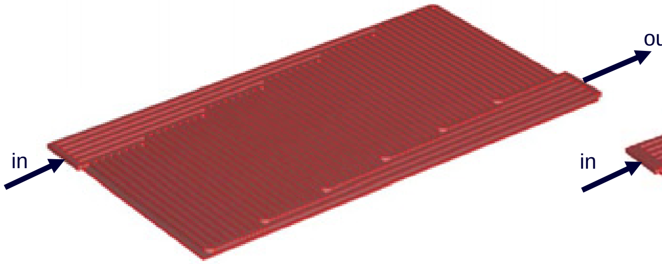
Serpentine # 1 (reference case)



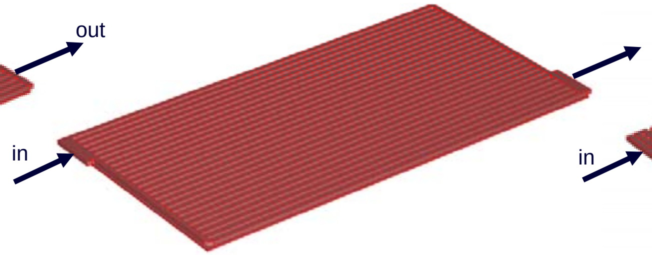
Serpentine # 2



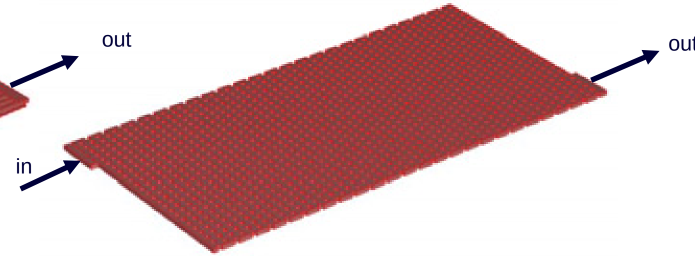
Mixed # 1



Mixed # 2



Straight

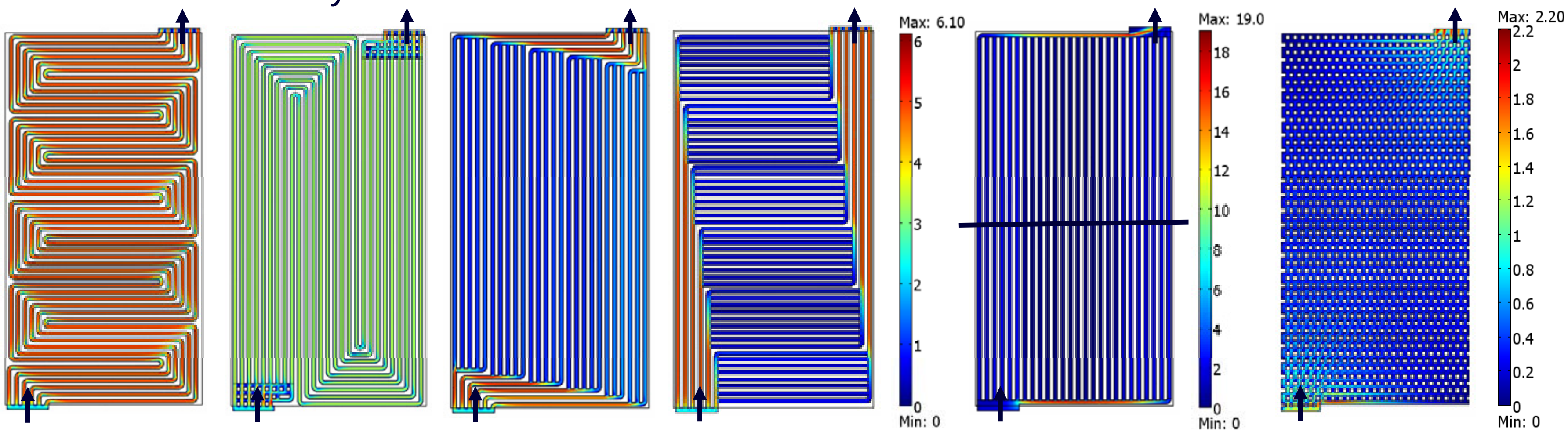


Criss-cross (pin type)

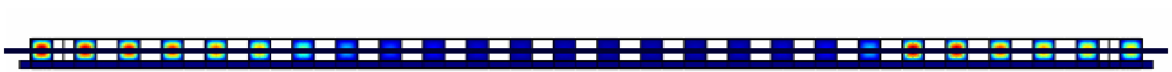
Type	***Channel/land [mm/mm]***	***Contact area [%/%]***	***Mesh elements [-]***	***DOF [-]***
Serpentine # 1	1/1	52.3/47.7	137,898	2,075,382
Serpentine # 2	1/0.9	52.6/47.4	126,972	1,914,108
Mixed # 1	1/1	50.6/49.4	121,233	1,829,532
Mixed # 2	1/1	54.1/45.9	121,257	1,828,349
Straight	1/1	50.7/49.3	113,187	1,705,113
Criss-cross (pin type)	n.a.	73.5/26.5	58,988	1,055,744

Simulation results

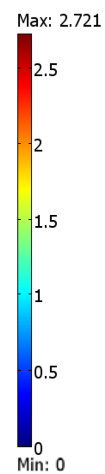
Gas channel velocity

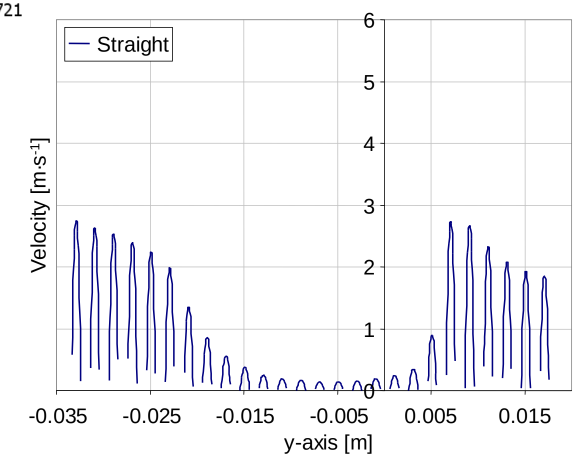


Gas channel velocity (slice plot @ x-y-plane, z = 500·10^{-6} [m]) (note: same color bar for flow-field 1-4)



Gas channel velocity (slice plot @ z-y-plane, x/xmax = ½)



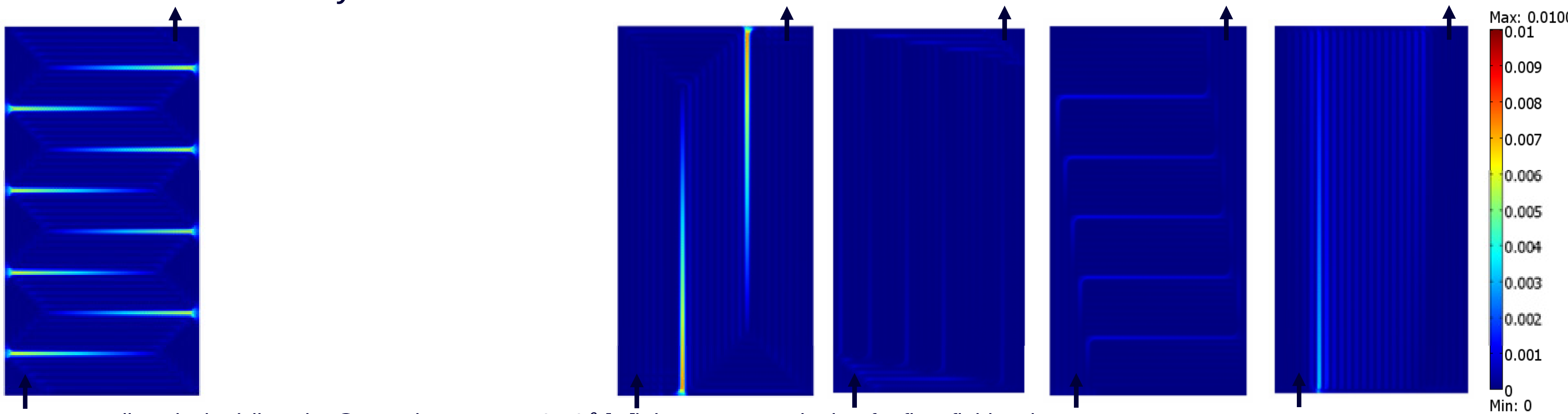


Gas channel velocity (cross-sectional plot @ x/x_{max} = ½, y = [0-y_{max}], z = 500·10^{-6} [m])

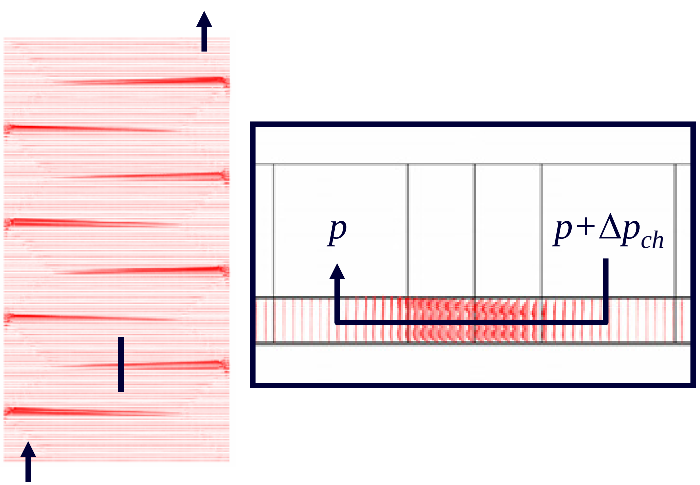
- Uniform gas channel velocity observed for both serpentine type flow-fields
- Straight flow-field shows inherent maldistribution
- Criss-cross type flow-field shows low overall velocity

Simulation results

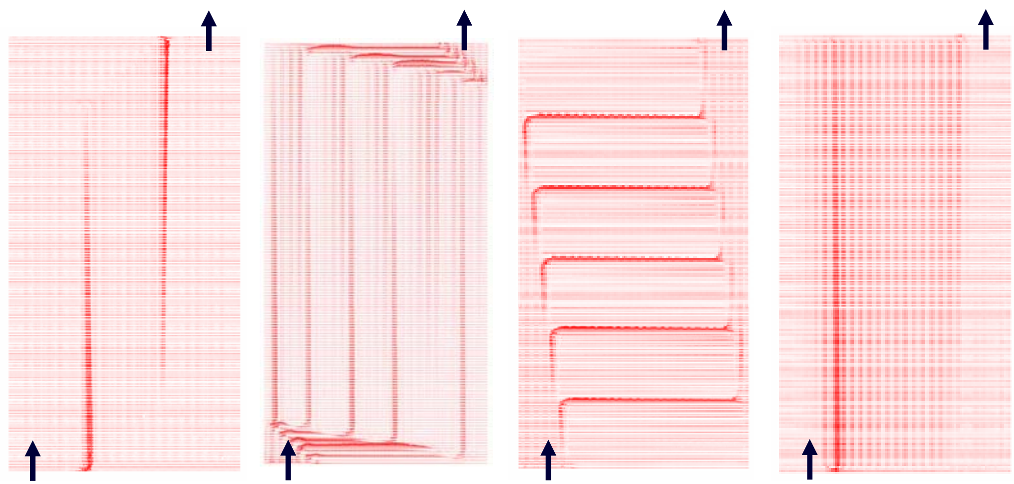
Porous media velocity → maximum located close to the 180° bends



Porous media velocity (slice plot @ x-y-plane, z = -170·10⁻⁶ [m]) (note: same color bar for flow-field 1-5)



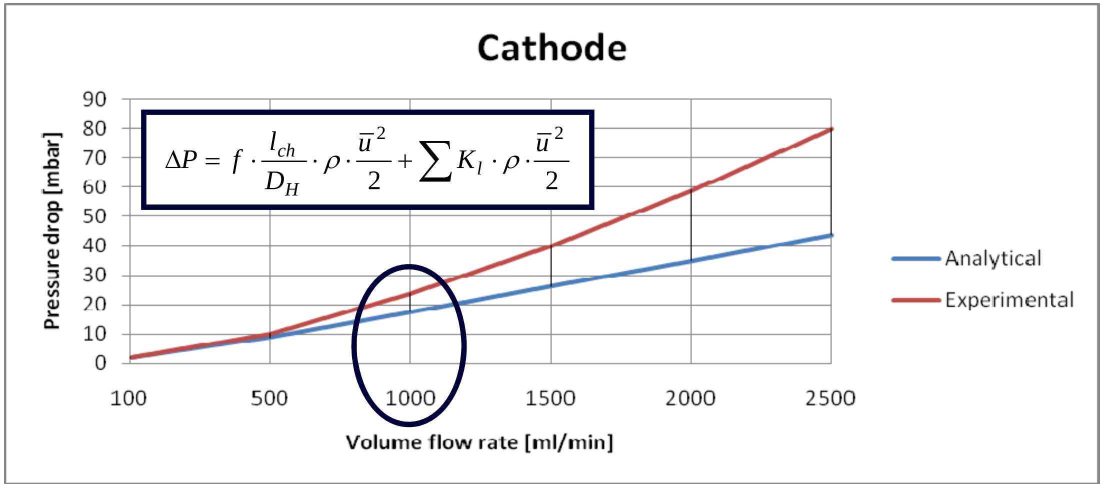
Porous media velocity vectors (arrow plot @ x-z-pane, y = -170·10⁻⁶ [m] – left, arrow plot @ x-z-pane, y/y_{max} = ½ - right)



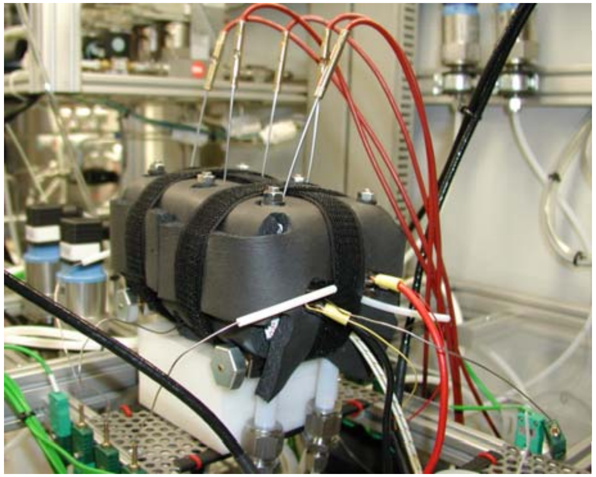
Porous media velocity vectors (arrow plot @ x, y, z = -170·10⁻⁶ [m])

Experimental/simulation results

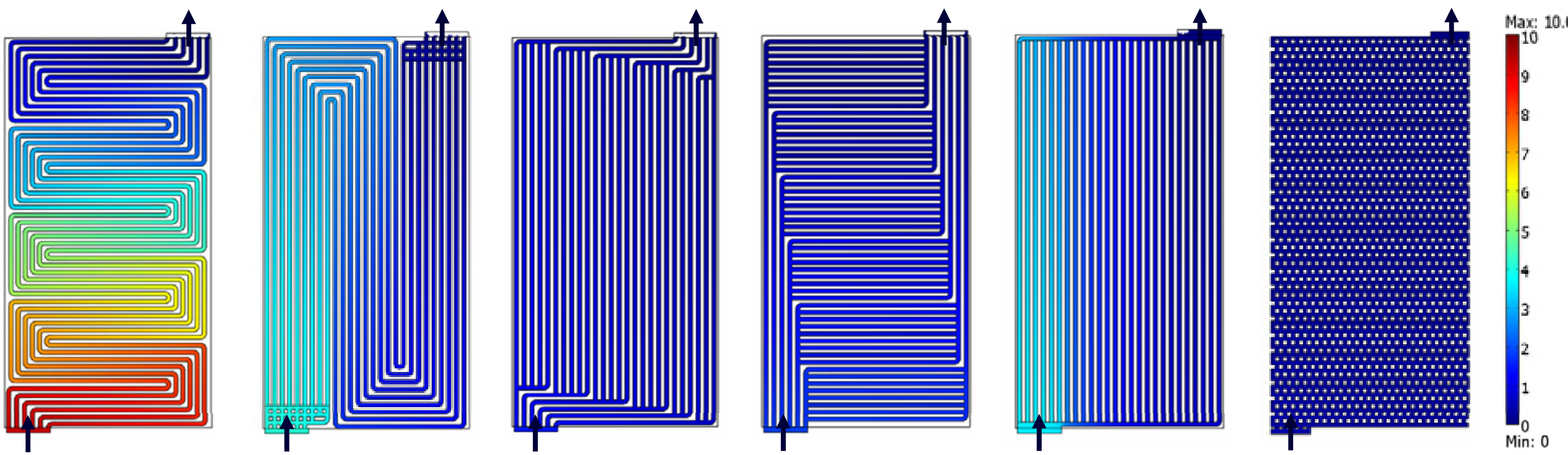
Pressure loss measured using differential pressure transmitters



Pressure loss for different flow rates – including peripheral losses) (taken from C. Agrawal – ZBT internship report)



HTEPM fuel cell operated using a LabView controlled teststand



Pressure loss (slice plot @ x-y-plane, z = $500 \cdot 10^{-6}$ [m]) (note: same color bar for flow-field 1-6)

Summary

Conclusion:

→ PIV-measurements / CFD modeling and simulation / analytical calculations

→ to be used for flow-field layout and optimization (quantitative comparison is possible)

→ Free flow, porous media flow and pressure loss compared for 6 types of flow-fields

→ Gas channel bypassing highlighted

Type	u_{ch} *[m/s]*	u_{GDL} *[m/s]*	ΔP *[mbar]*	*Re [-]*
Serpentine # 1	2.667	$4.66 \cdot 10^{-4}$	9.36	72.3
Serpentine # 2	1.778	$2.88 \cdot 10^{-4}$	4.5	46.8
Mixed # 1	0.866	$8.79 \cdot 10^{-5}$	1.48	21.1
Mixed # 2	0.799	$9.67 \cdot 10^{-5}$	1.88	23.9
Straight	0.849	$2.75 \cdot 10^{-4}$	3.58	23.7
Criss-cross (pin type)	0.232	n.a.	0.4	15.4

Outlook:

- Include multiphysics into the model (flow-field layout is more than just momentum transport!)
- Investigate for current density and temperature distribution (both theoretical/experimental)
- Analyze porous media flow and gas channel bypassing for HTPEM fuel cells
- In-, outlet positioning

Thank you very much!

Questions?