The German CFD Network on Nuclear Reactor Safety Research:

"Development and Application of CFD Modelling to Phenomena in the Primary Circuit of Pressurized Water Reactors"

Results & Perspectives

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Inhalt

- Motivation and Objectives
- Structure of the German CFD Network
- Partner & Organizations
- Results:
  - Model development
  - Validation
  - Experiments
- Communication
- Perspectives
- Summary and Future Directives

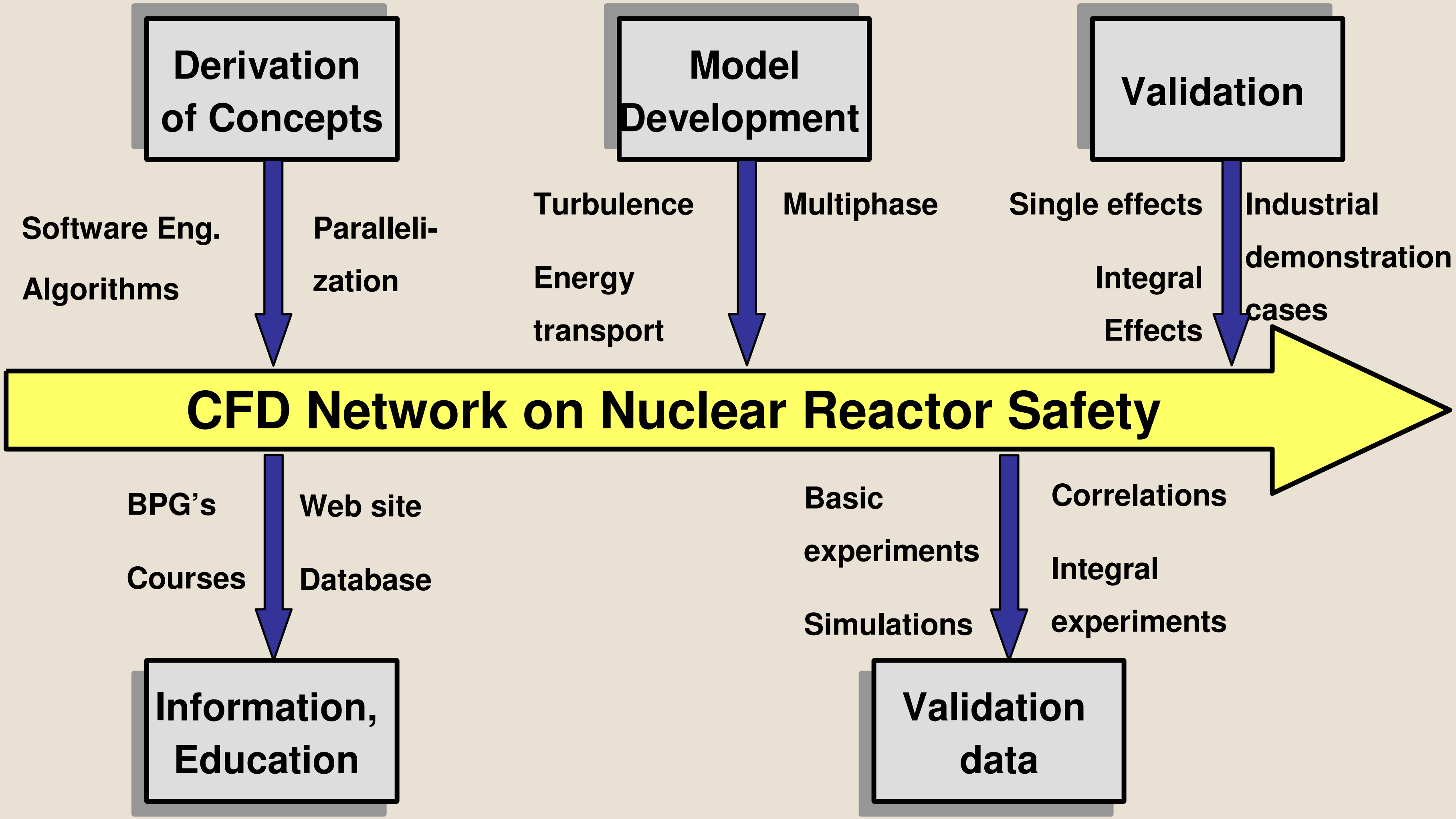
Motivation

- Requirements:
  - Quantification of safety margins
  - Evaluation of measures for increase of power output
- Further development of simulation techniques
  - Multidimensional phenomena & applications
  - Two-phase flows
  - Phase interaction (mass, momentum, energy)
  - Validation
  - Code coupling
    → Lumped parameter codes/1d codes (e.g. ATHLET, RELAP) & CFD codes
    → Neutron kinetic codes & CFD codes
- Maximize the Efficiency of model development
  - Organize a collaborative project group of research institutions and software developers

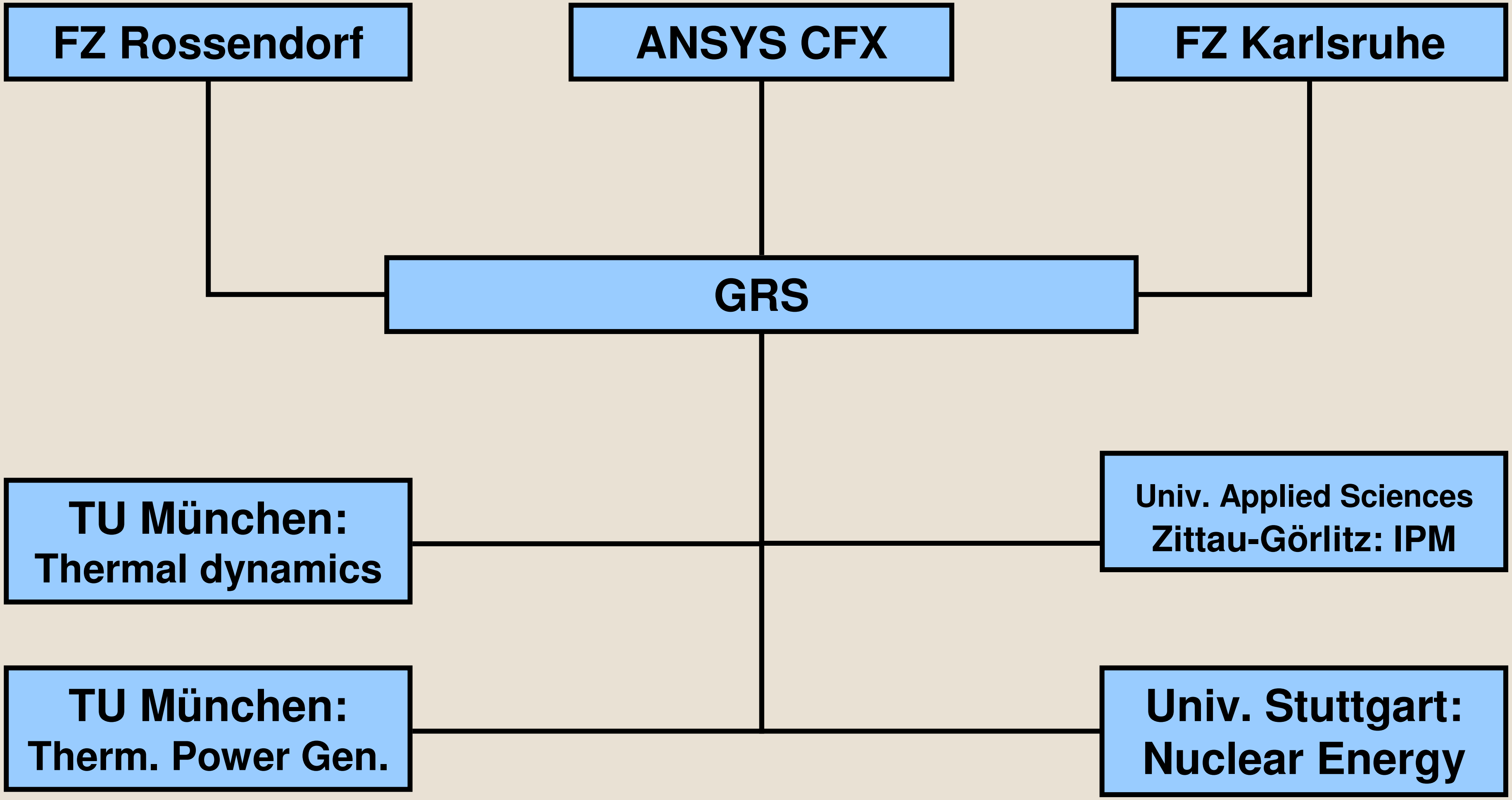
Objectives

- Investigation of 3-dimensional flows in the primary circuit and in the containment of pressurized water reactors in a coordinated action
- Development & validation of two-phase flow models
- Coordination of new CFD related validation experiments
- Validation, provision & maintenance of a CFD code
- Development of Best Practice Guidelines (BPG) and check lists for model application
- Coupling of the CFD code with ATHLET

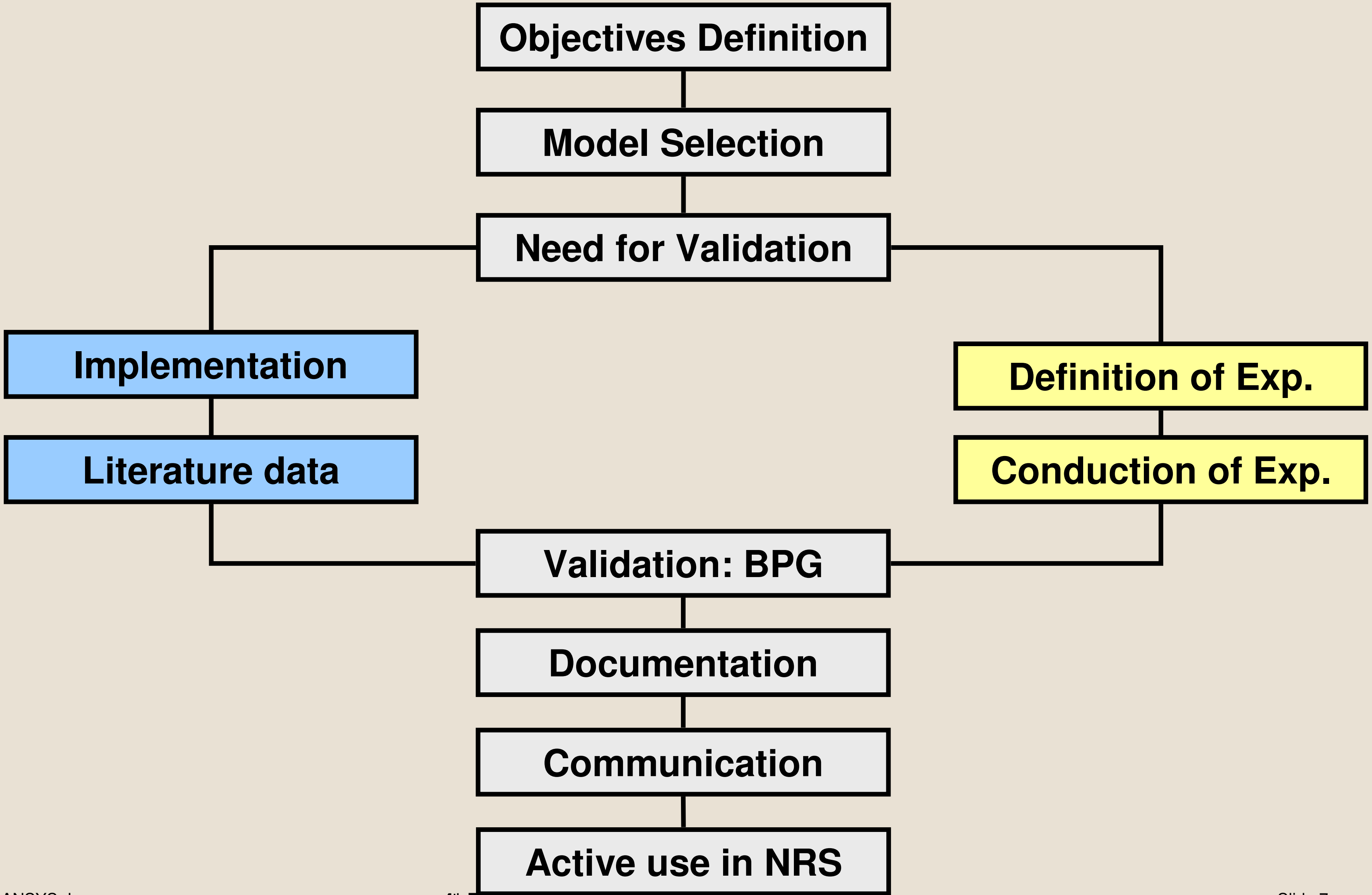
Areas of Model Development



Partners & Organisations



Work Plan



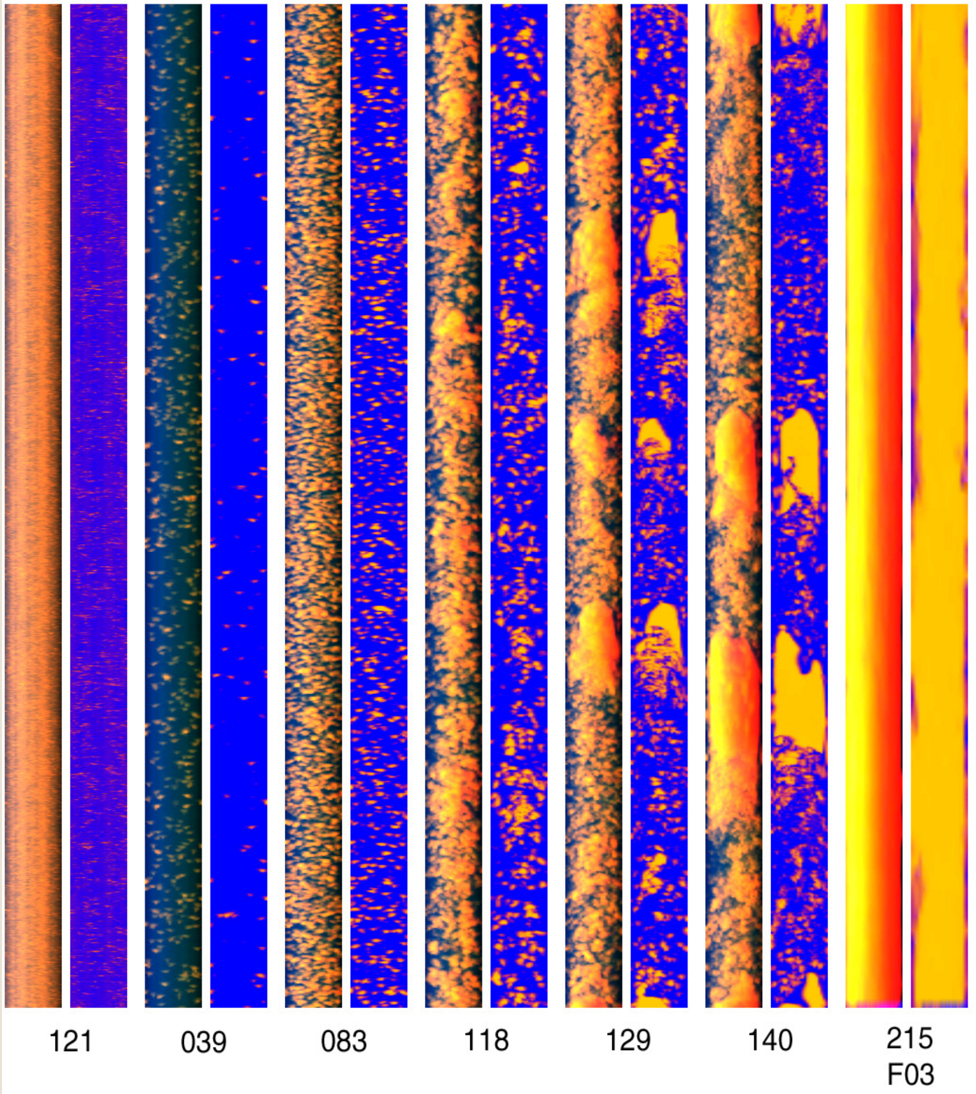
Objectives Definition
Model Selection
Need for Validation
Implementation
Literature data
Definition of Exp.
Conduction of Exp.
Validation: BPG
Documentation
Communication
Active use in NRS

Objectives Definition – Validation Test Cases

- Two-phase flows with lower void fraction
  - Vertically upward
  - Vertically downward
  - Horizontal, con-current
  - Horizontal counter-current
- Two-phase flows with higher void fraction
  - Vertically upward
  - Vertically downward
  - Horizontal, con-current
  - Horizontal counter-current
- Free Surface Flows
  - Horizontal con-current
  - Horizontal counter-current
  - Impinging Jets (Downcomer)
  - Free Jets (ECC)
- Flows with phase change
  - Condensation
  - Evaporation
  - Flashing
  - Boiling

Vertical Pipe Flows

- Experiments
  - FZR
  - MTLoop & TOPFLOW Facility
- Modeling & Validation
  - FZR
  - ANSYS CFX
- Target variables
  - Volume fraction
  - Gas velocity
  - Water velocity
  - Bubble size distributions



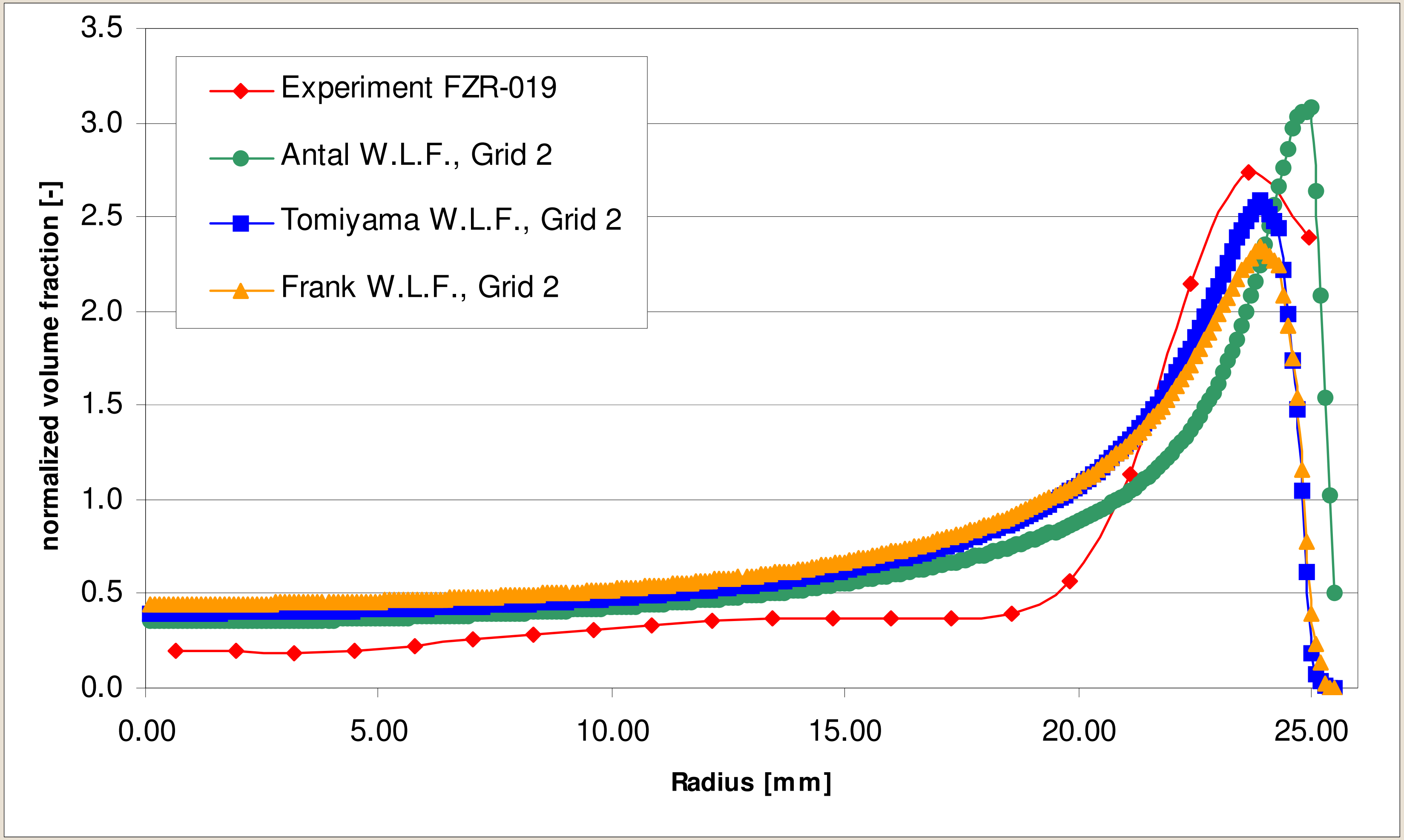
Investigation on MT-Loop & TOPFLOW Test Matrices

Testcases predicted with CFX-5.7.1/CFX-10.0:

Leerrohrgeschwindigkeit Gas J_G in m/s

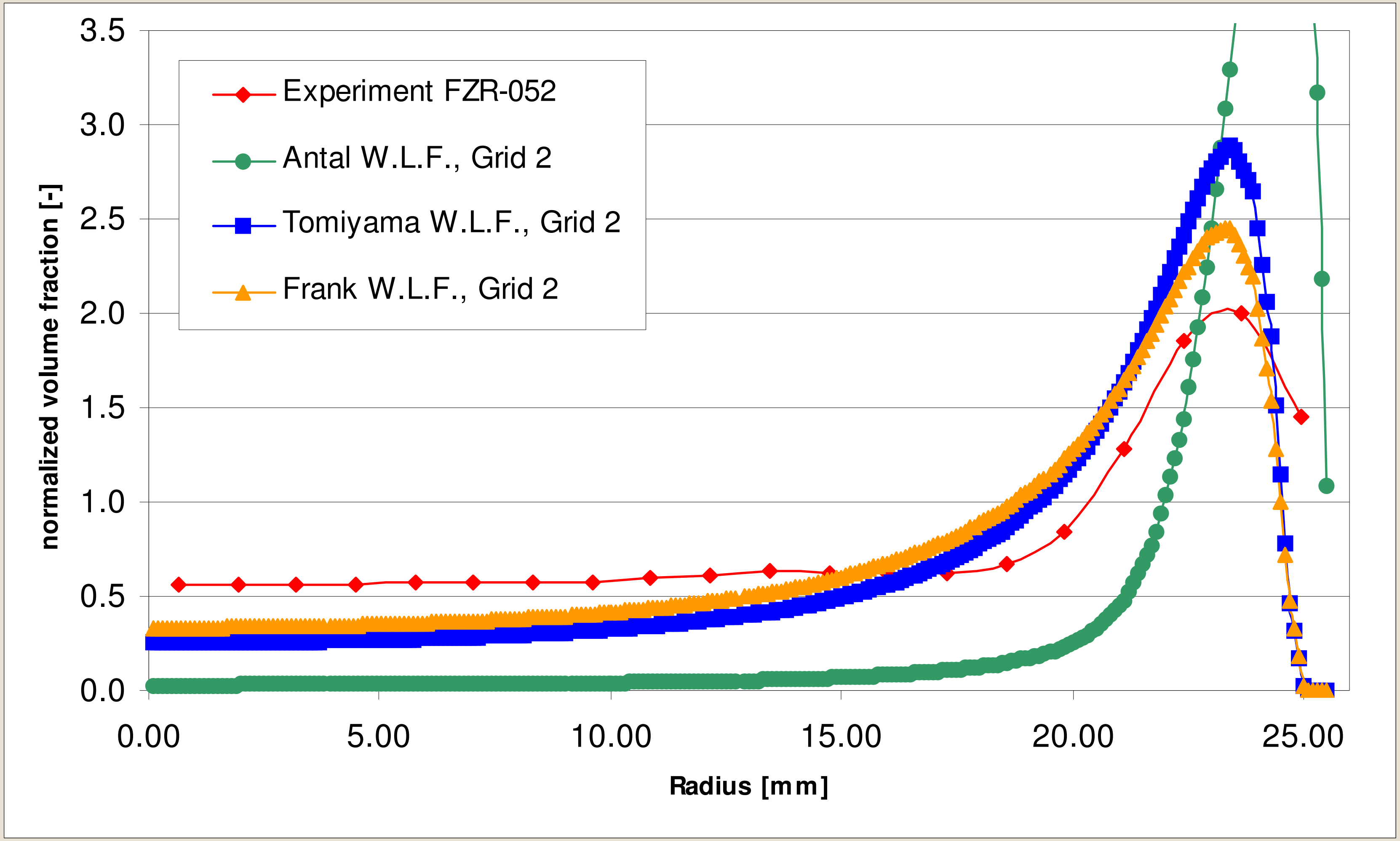
Leerrohrgeschwindigkeit Wasser J_W in m/s	0,0025	0,0040	0,0062	0,0096	0,0151	0,0235	0,0368	0,0574	0,0898	0,140	0,219	0,342	0,534	0,835	1,305	2,038	3,185	4,975	7,772	12,14
4,047	011	022	033	044	055	066	077	088	099	110	121	132	143	154	165	176	187	198	209	220
2,554	010	021	032	043	054	065	076	087	098	109	120	131	142	153	164	175	186	197	208	219
1,611	009	020	031	042	053	064	075	086	097	108	119	130	141	152	163	174	185	196	207	218
1,017	008	019	030	041	052	063	074	085	096	107	118	129	140	151	162	173	184	195	206	217
0,641	007	018	029	040	051	062	073	084	095	106	117	128	139	150	161	172	183	194	205	216
0,405	006	017	028	039	050	061	072	083	094	105	116	127	138	149	160	171	182	193	204	215
0,255	005	016	027	038	049	060	071	082	093	104	115	126	137	148	159	170	181	192	203	214
0,161	004	015	026	037	048	059	070	081	092	103	114	125	136	147	158	169	180	191	202	213
0,102	003	014	025	036	047	058	069	080	091	102	113	124	135	146	157	168	179	190	201	212
0,0641	002	013	024	035	046	057	068	079	090	101	112	123	134	145	156	167	178	189	200	211
0,0405	001	012	023	034	045	056	067	078	089	100	111	122	133	144	155	166	177	188	199	210

FZR-019

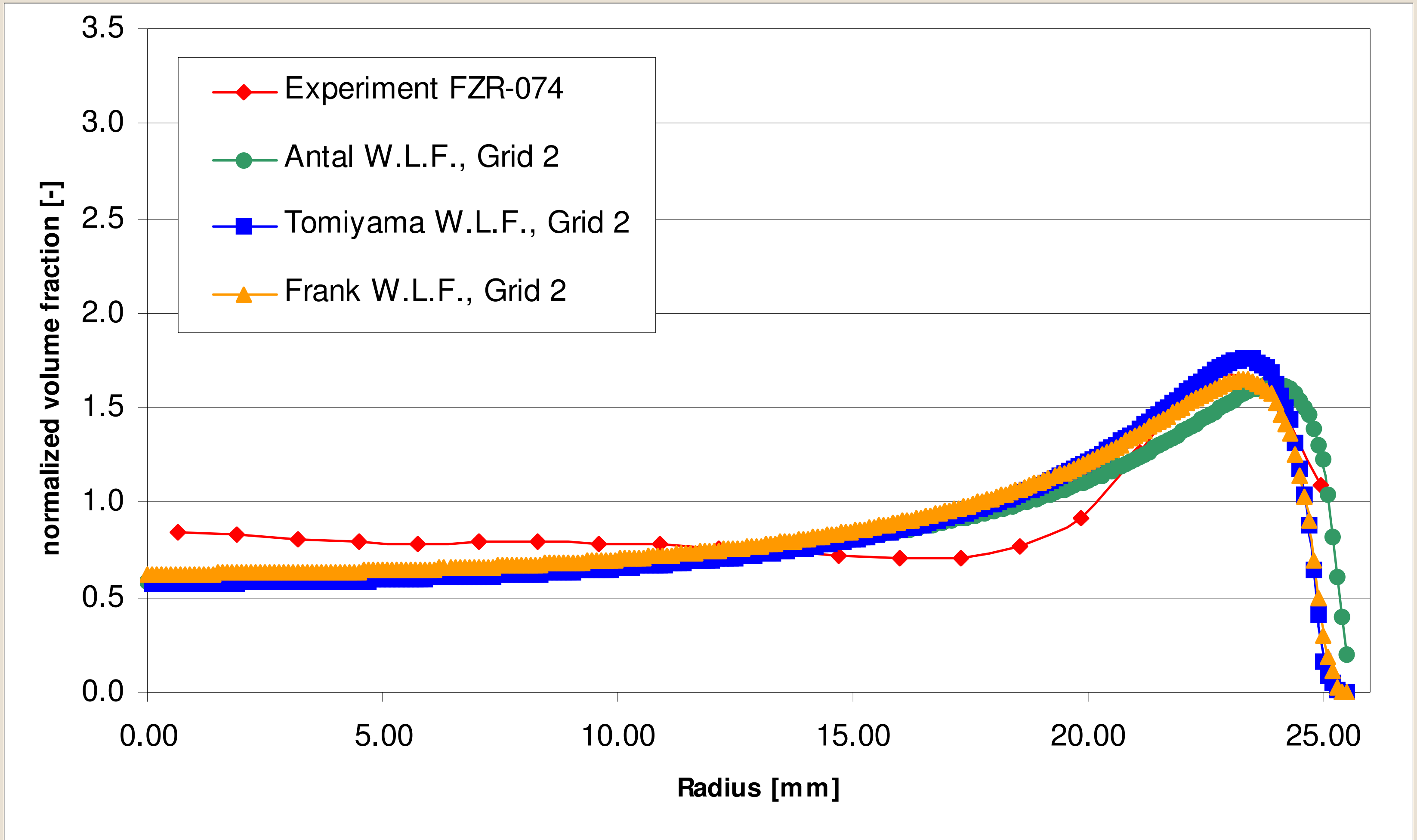


normalized volume fraction [-]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
5.00
10.00
15.00
20.00
25.00
Radius [mm]
Experiment FZR-019
Antal W.L.F., Grid 2
Tomiyama W.L.F., Grid 2
Frank W.L.F., Grid 2

FZR-052

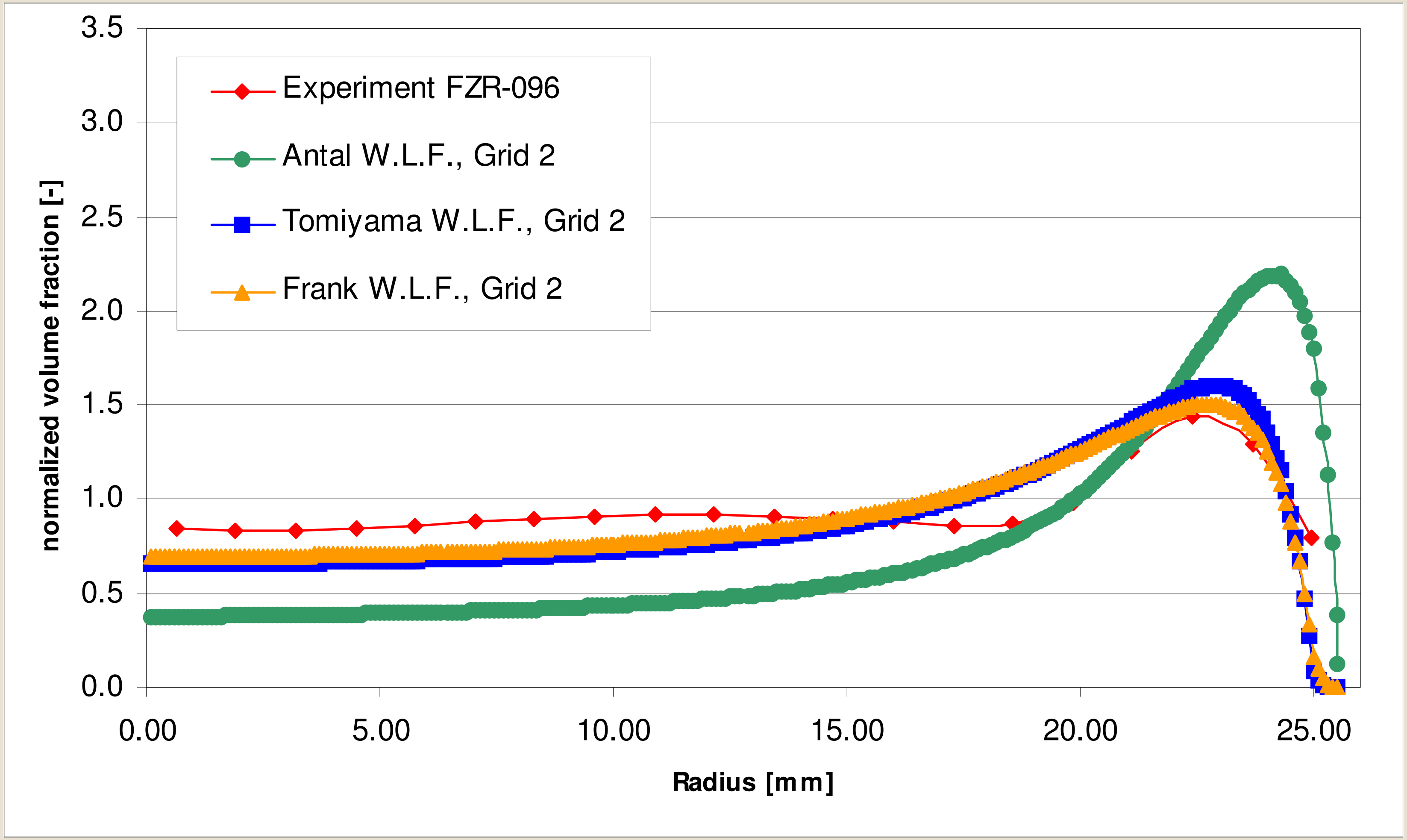

Experiment FZR-052
Antal W.L.F., Grid 2
Tomiyama W.L.F., Grid 2
Frank W.L.F., Grid 2
normalized volume fraction [-]
Radius [mm]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.00
5.00
10.00
15.00
20.00
25.00

FZR-074



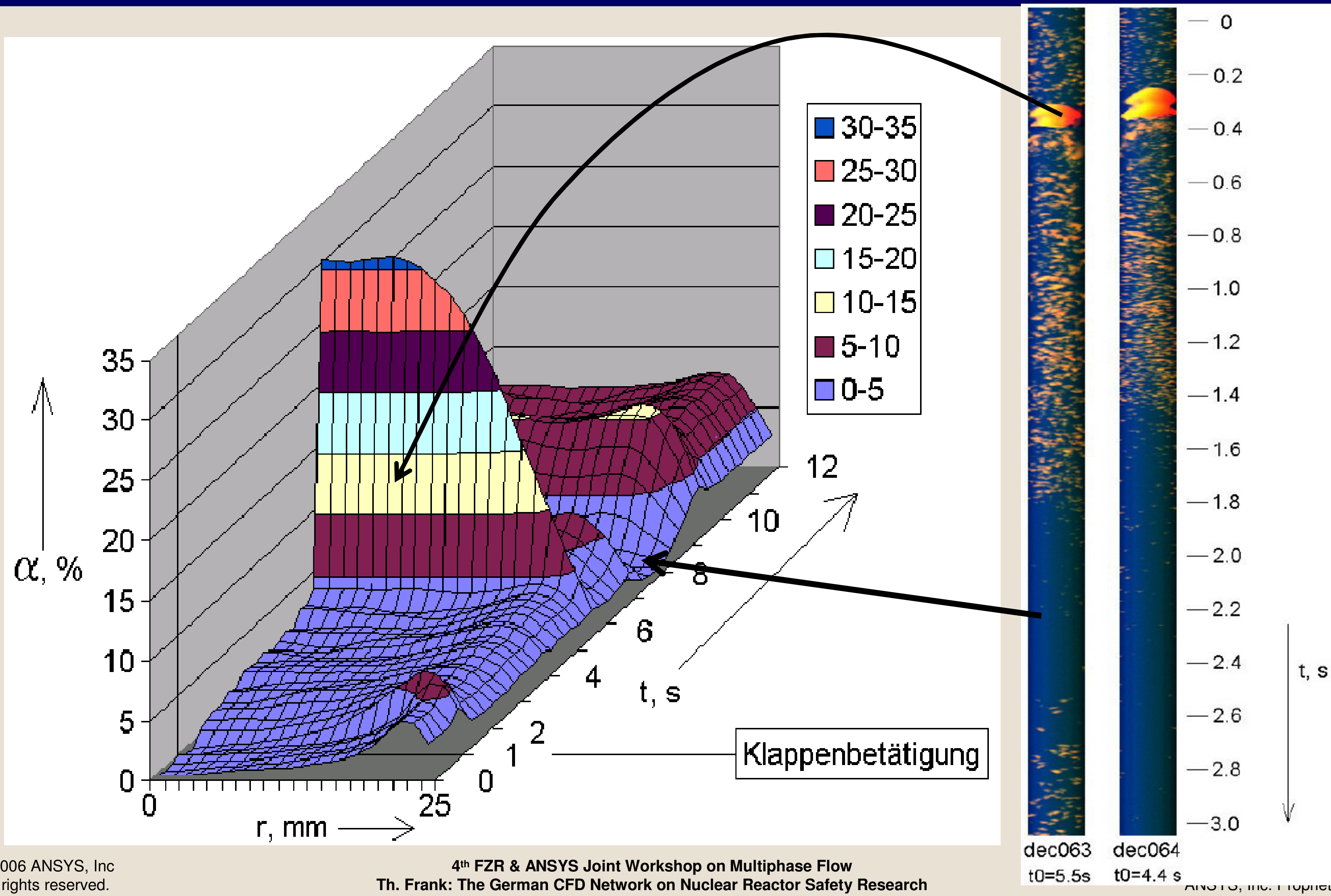
Experiment FZR-074
Antal W.L.F., Grid 2
Tomiyama W.L.F., Grid 2
Frank W.L.F., Grid 2
normalized volume fraction [-]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
5.00
10.00
15.00
20.00
25.00
Radius [mm]

FZR-096



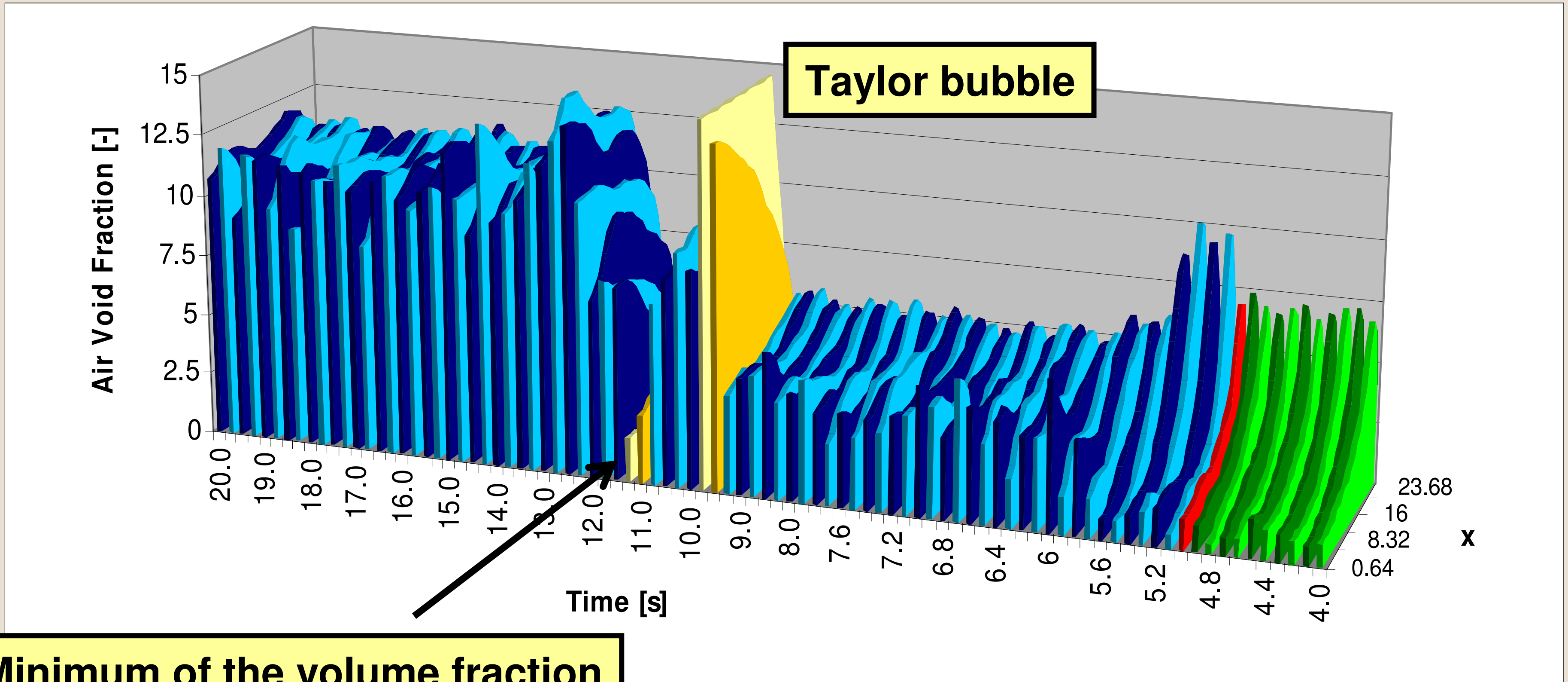
Experiment FZR-096
Antal W.L.F., Grid 2
Tomiyama W.L.F., Grid 2
Frank W.L.F., Grid 2
normalized volume fraction [-]
Radius [mm]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.00
5.00
10.00
15.00
20.00
25.00

Transient Vertical Pipe Flows



Transient Vertical Pipe Flows

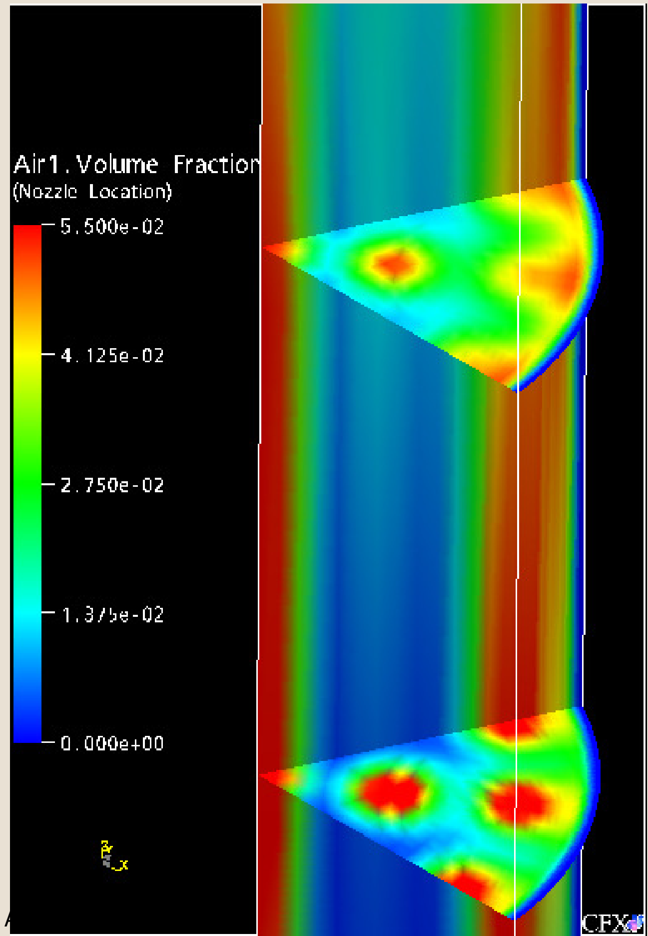
- Reduction in water mass flow rate at T *= 5 s*
- Transient radial volume fraction distribution of bubbly phase

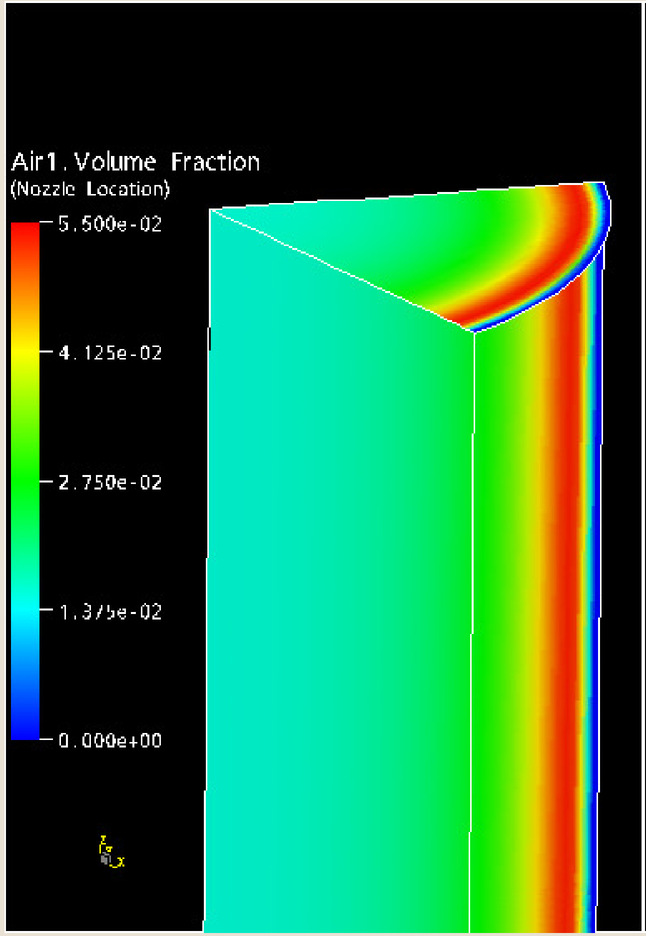


Minimum of the volume fraction

Transient Vertical Pipe Flows

- Gas superficial velocity 1.02 m/s
- Inlet boundary conditions

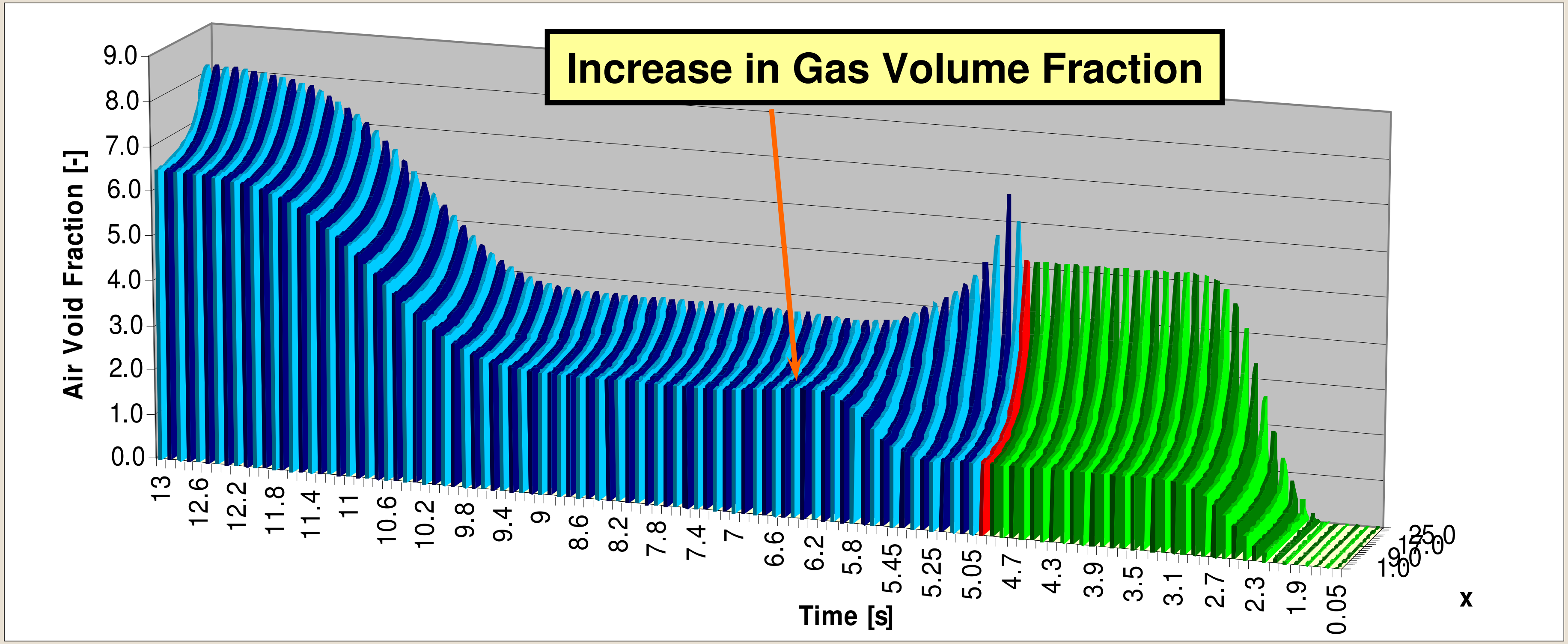




- Measurement cross section @ *t = 4.5 s*

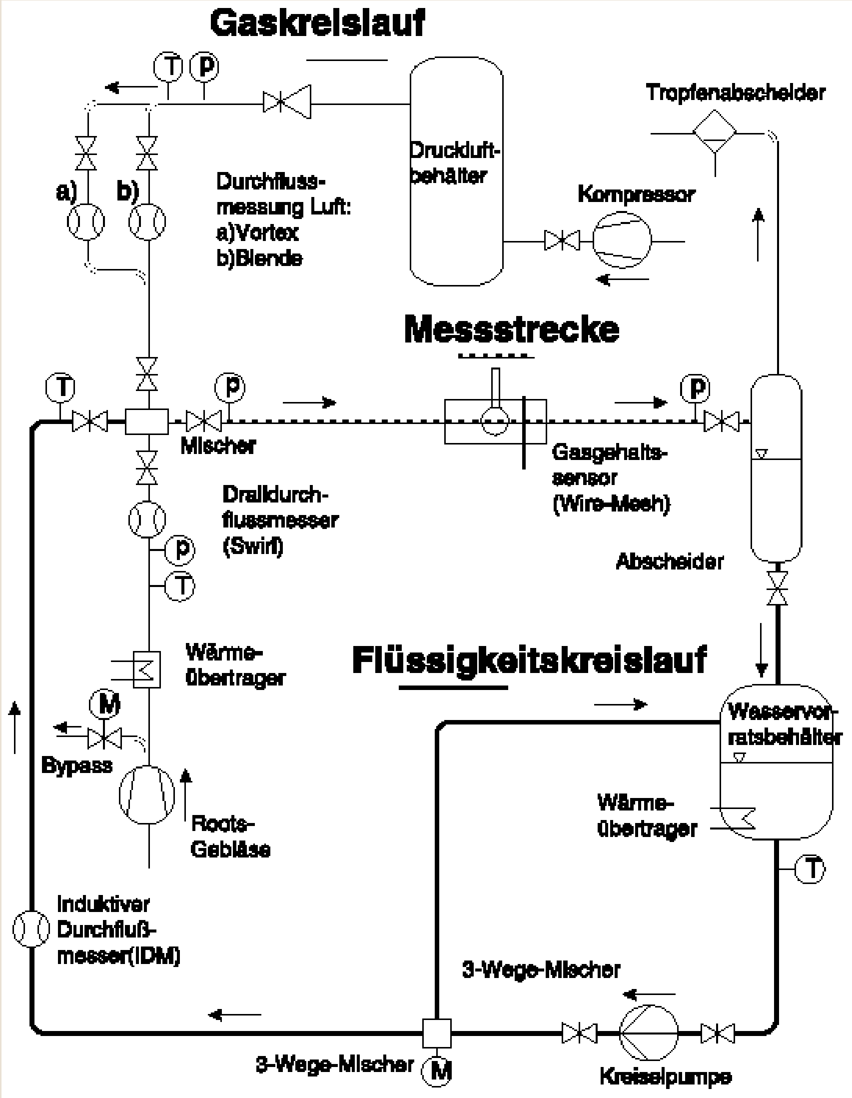
Transient Vertical Pipe Flows

- CFD Prediction
- Qualitative agreement in system behavior
- Transition between volume fraction profiles
- Taylor bubble not observed in CFD (pressure-sparger interaction?)



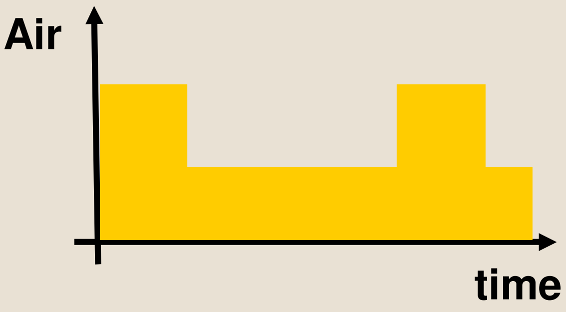
Horizontal Pipe & Channel Flows

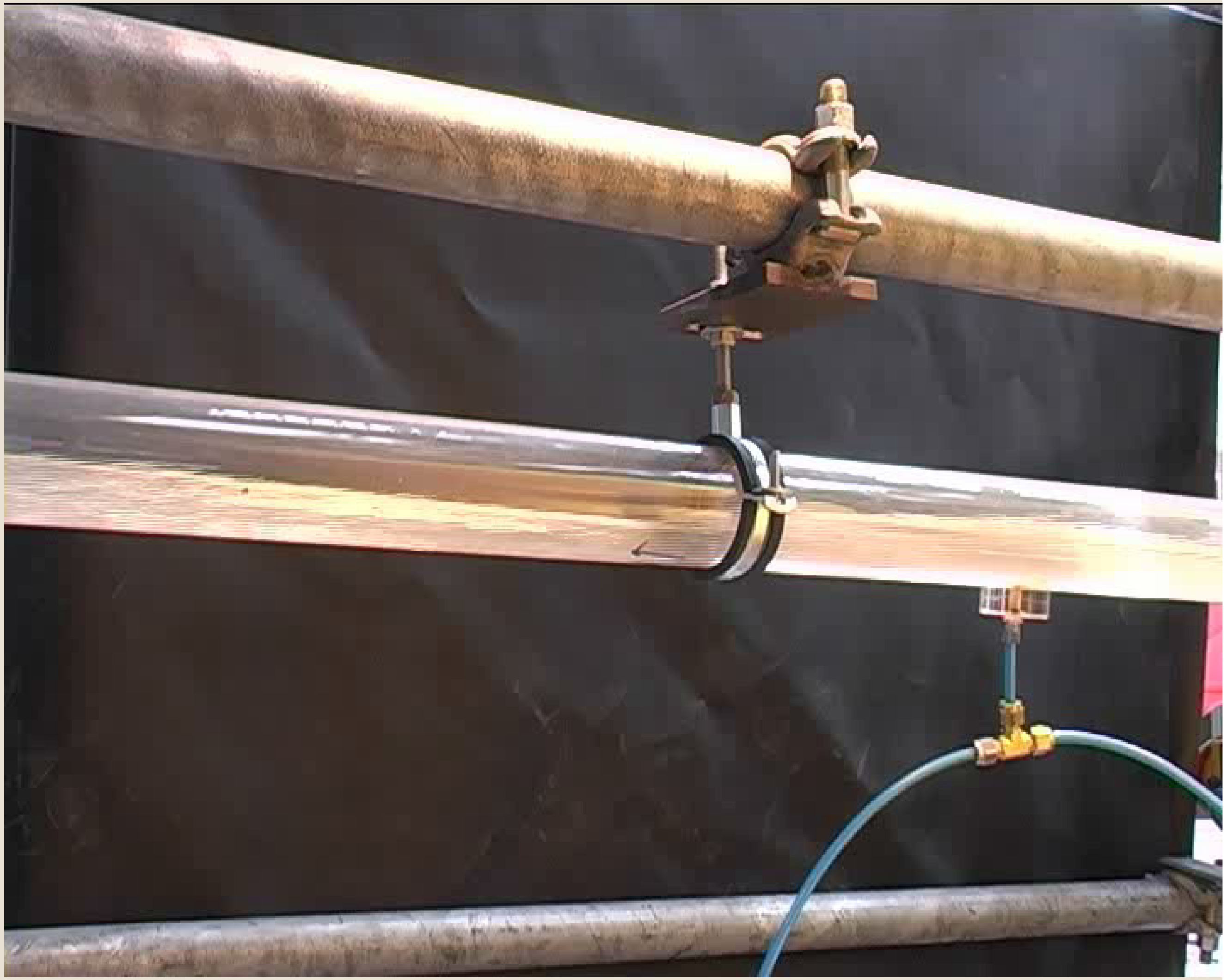
- Experiments
  - TU München (Thermal dynamics)
  - FZR
- Modeling & Validation
  - TU München (Thermal dynamics)
  - FZR
  - CFX
- Target Variables
  - Volume fraction
  - Gas velocities
  - Water velocities



Experimental Test Facilities @ TU Munich

- Regular slug flow with defined inlet BC´s

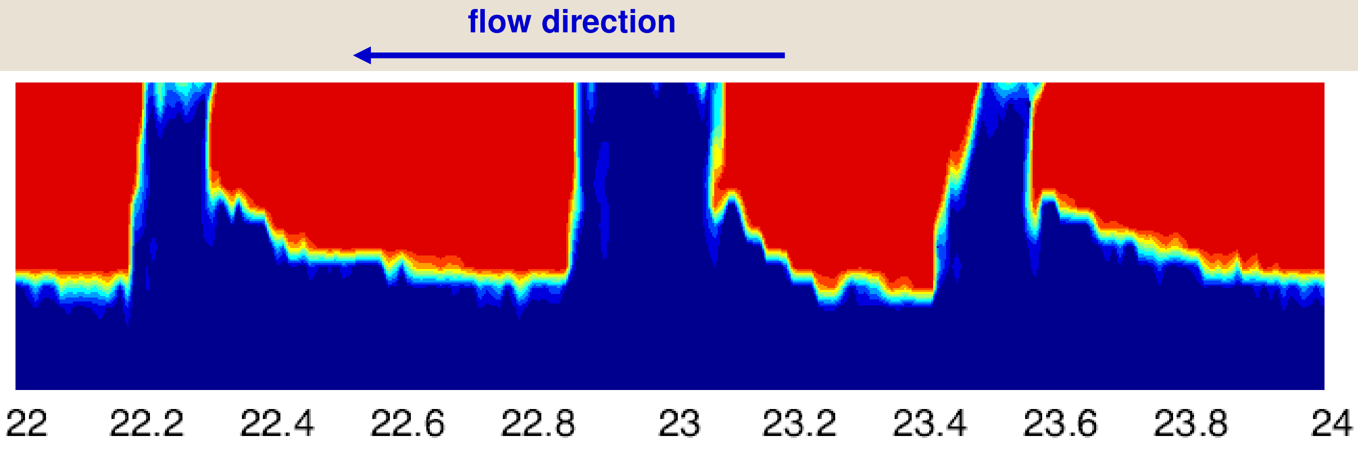




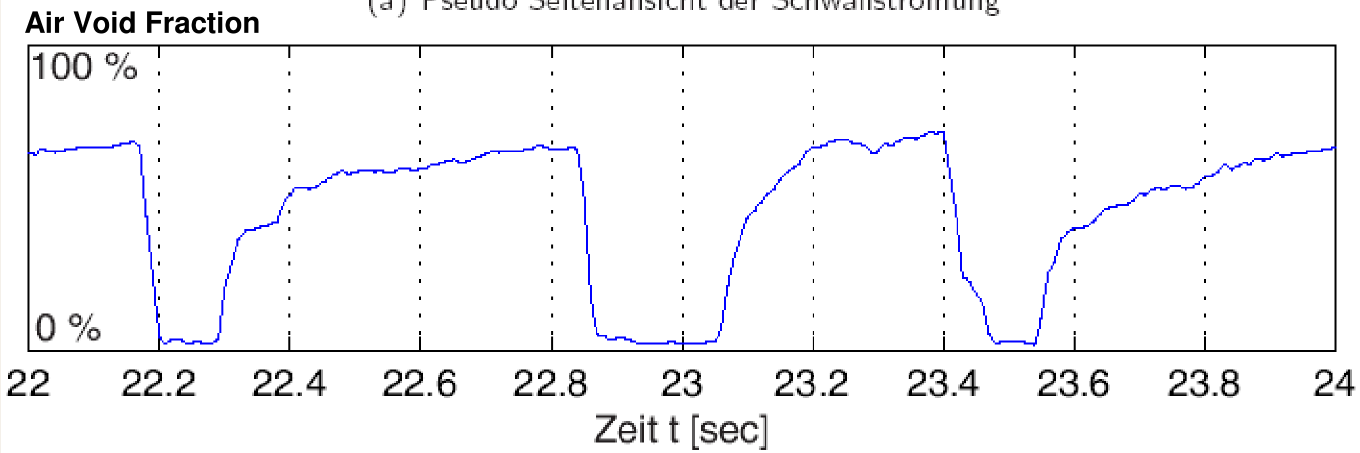
By courtesy of
Edurne Carpintiero, TD, TUM

Transient Slug Flow: Test case conditions

- $\dot{M}_L = 2.363\ kg/s$
- $\dot{M}_G = 2.9\ g/s$
- $j_G = j_L = 1$ m/s
- air void fraction $r_G = 0.5$
- air/water inlet pressure: p=1.055 bar
- slug front velocity: 2.7 m/s
- mean slug length: 1.8m (gas: 1.45m water: 0.35m)
- slug frequency: 1.5 Hz
- pressure loss: ~700 Pa/m



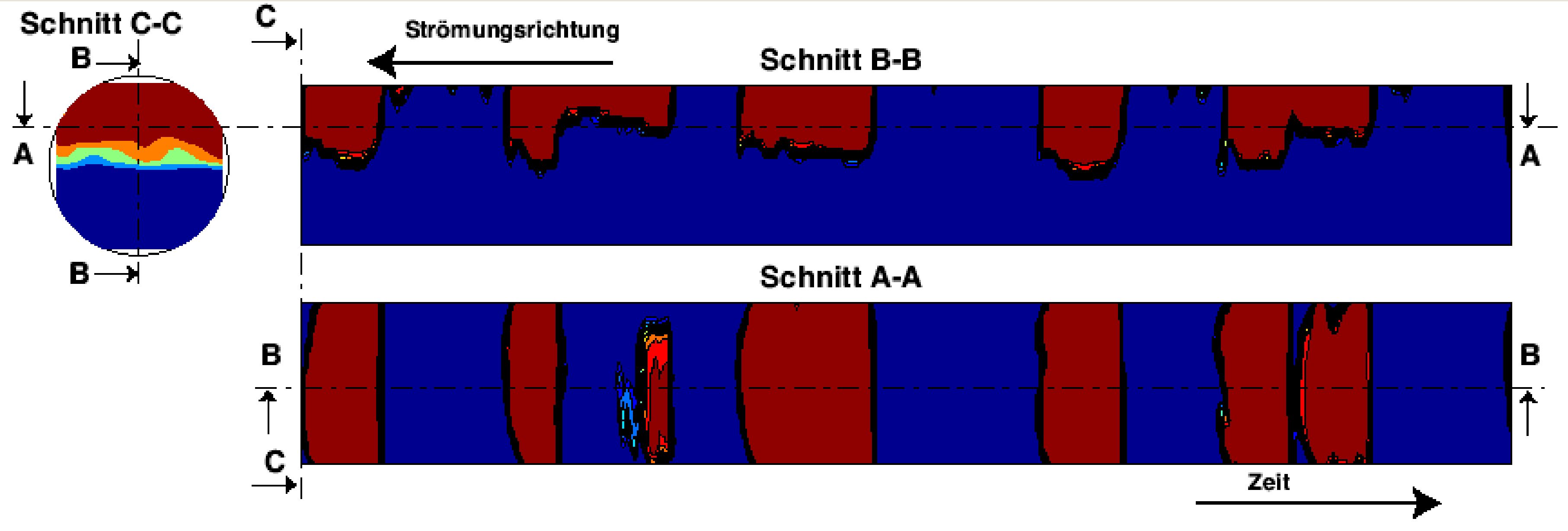
(a) Pseudo Seitenansicht der Schwallströmung



By courtesy of Thomas Lex, TD, TUM

Transient Air Volume Fraction Measurements with Wire Mesh Sensors

- this measurements correspond to j_G=j_L=1 m/s and an air and water volume fraction of 0.5



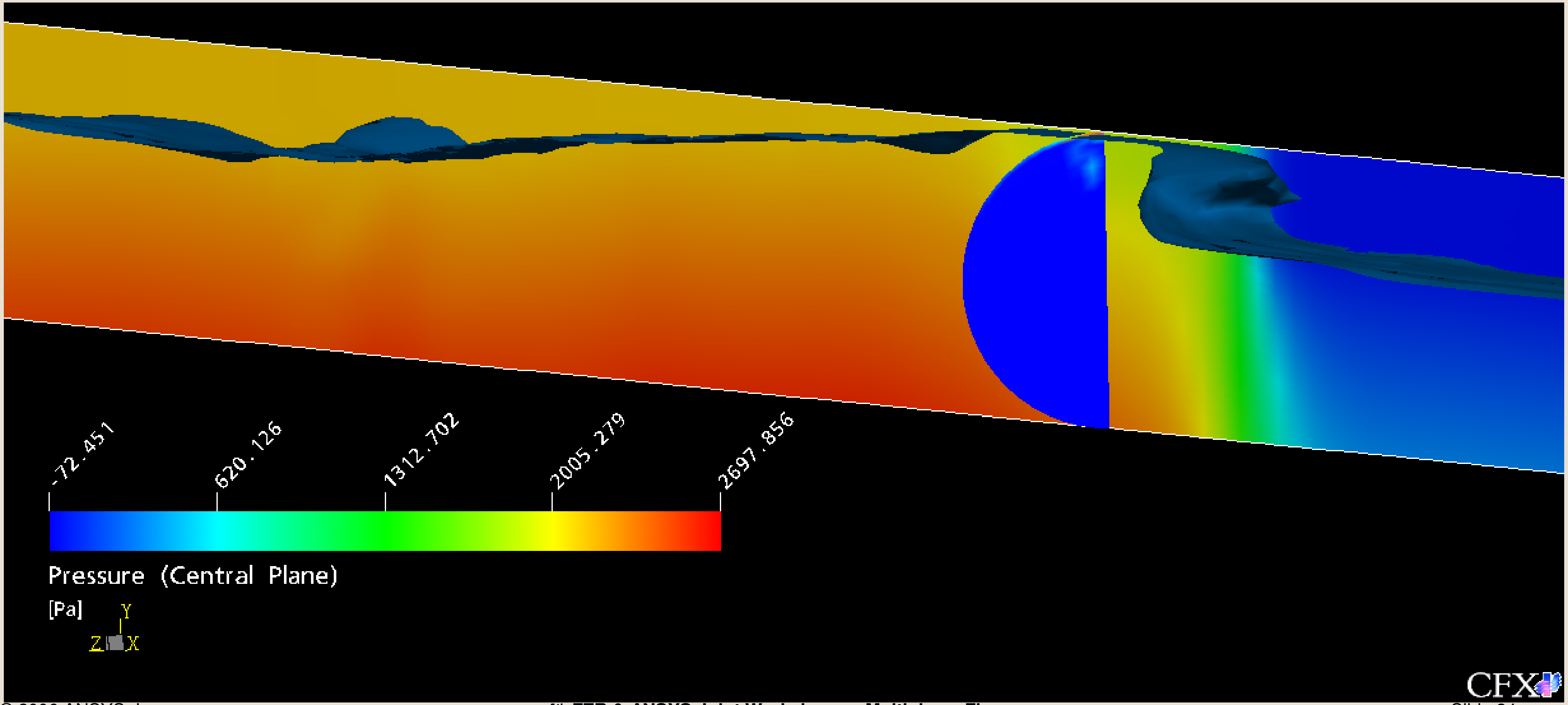
Experiments by Thomas Lex, TD, TUM

Slug Flow Simulations

No.	Pipe length	Spatial mesh resolution		No. of grid cells	Test case conditions
		Grid cells in pipe cross-section	Grid cells in axial direction		
1	1.0m / 4.0 m	249	250	73.500	Periodic BC's; Sinusoidal agitated free surface (initialization); Prescribed pressure loss of 800 Pa/m
2	8.0m	249	500	147.000	Massflow BC's; Sinusoidal agitated free surface at inlet
3	8.0m	249	500	147.000	as 2), but without surface agitation
4	8.0m	249	500	147.000	Massflow BC's; Phases homogeneously mixed at inlet; No agitation
5	8.0m	249	500	147.000	Massflow BC's; Phases homogeneously mixed at inlet; Transient change in air void fraction between 0.5 and 0.7

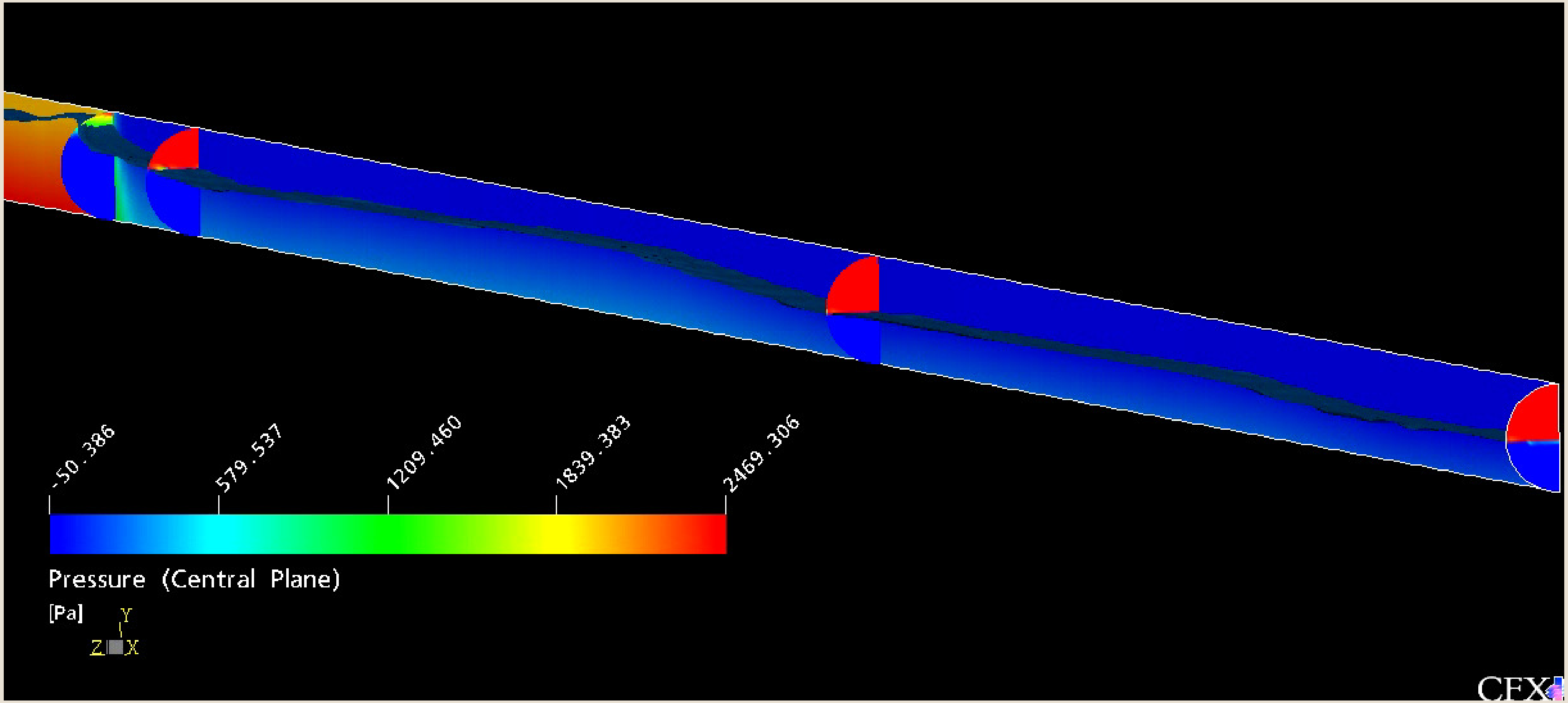
Slug Flow Simulation - Mass Flow Boundary Condition

- Sinusoidal free surface perturbation (initialization and inlet BC's)
- Transient simulation of 7.0s real time
- Slug formation after ~4.0s at x~4.0m
- Stable slug propagation; slug front/tail are continuously changing



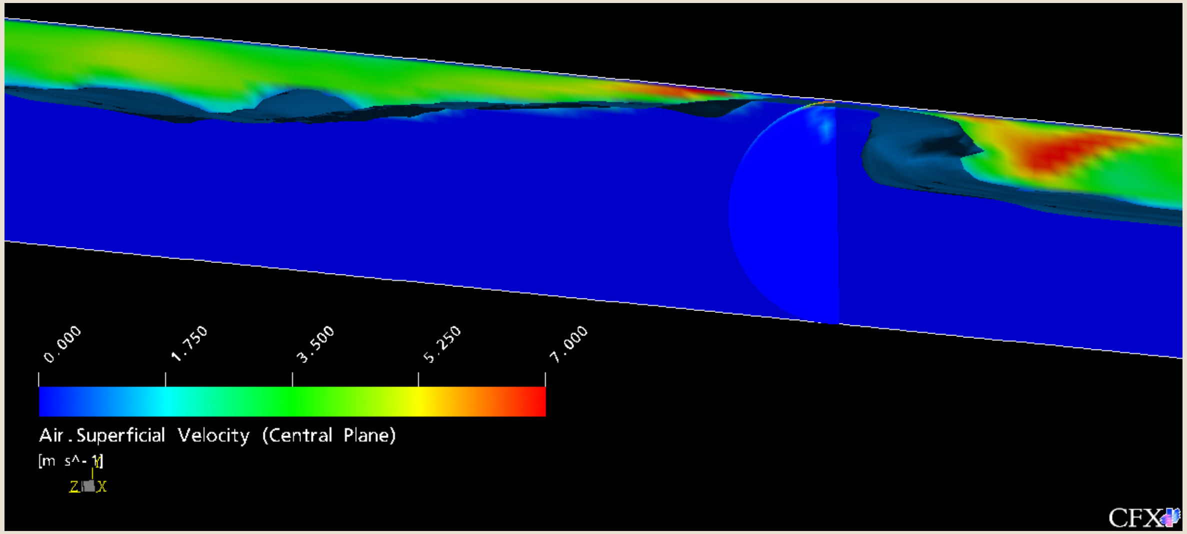
Slug Flow Simulation - Mass Flow BC's (cont.)

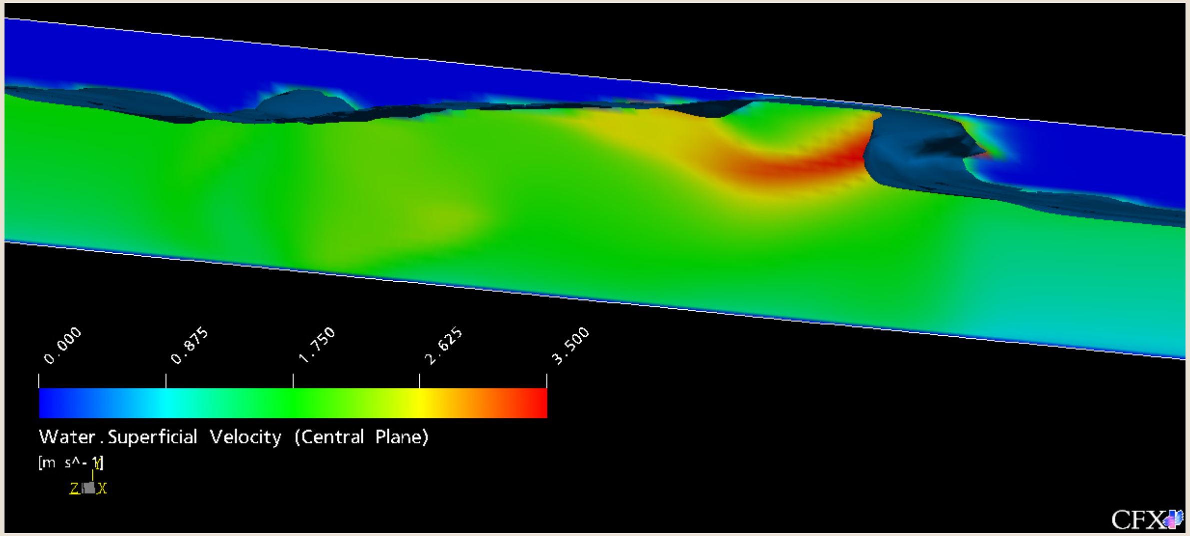
- Detail of slug flow formation and propagation (T = 3.4s,…,4.7s)
- Strong pressure gradients at slug front



Slug Flow Simulation - Mass Flow BC's (cont.)

- Superficial velocity distribution in and around a propagating slug





Slug Flow Simulation - Mass Flow BC's (cont.)

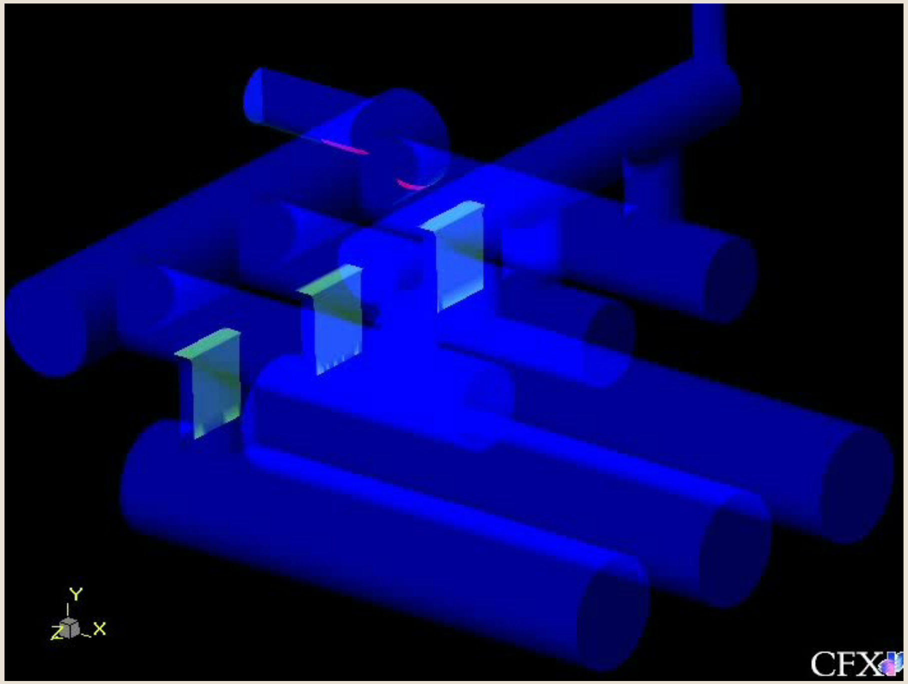
First comparison with experimental data:

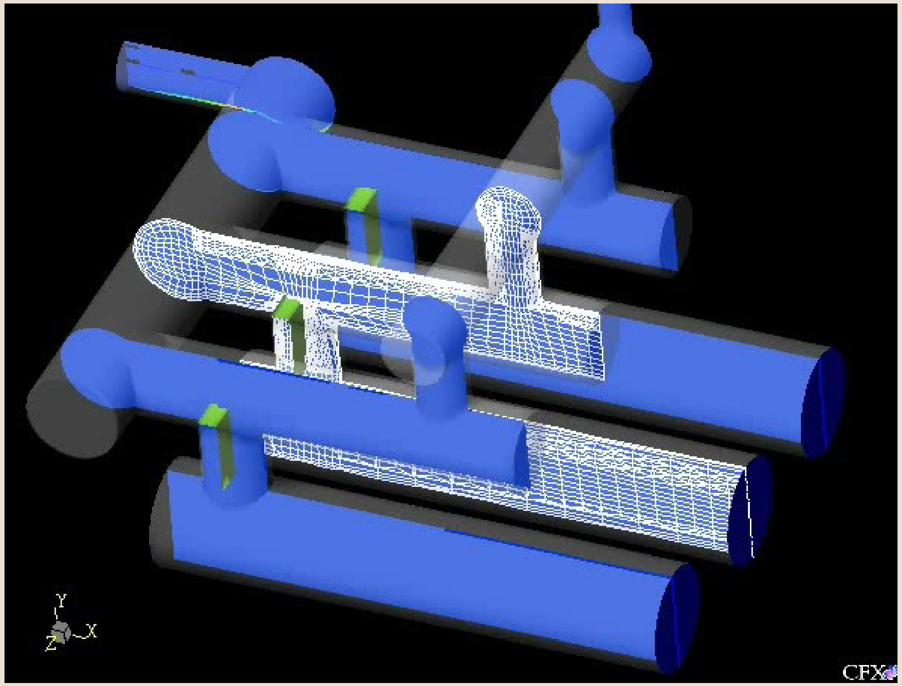
- Start of slug formation at ~4.0m from the inlet
- Difficult to reproduce experimental setup in CFD
  - Inlet BC's (e.g. phase mixing, inlet turbulence properties)
  - Pressure outlet conditions (pipes & tanks downstream of test section)
- Quantitative comparison difficult for strong transient flow
  - Small number of computed slugs
  - Slug length affected by limited pipe length and/or inlet conditions

	numerical simulation	experiment
slug period	~2.7m	~1.8m
slug transition velocity	~3.0 m/s	~2.7 m/s
pressure loss	~2000 - 2800 Pa on the last 4m, 2 slugs → ~500 - 700 Pa/m (strong transient)	~700 Pa/m

Application to Oil & Gas Technology: Slug Catcher Operation

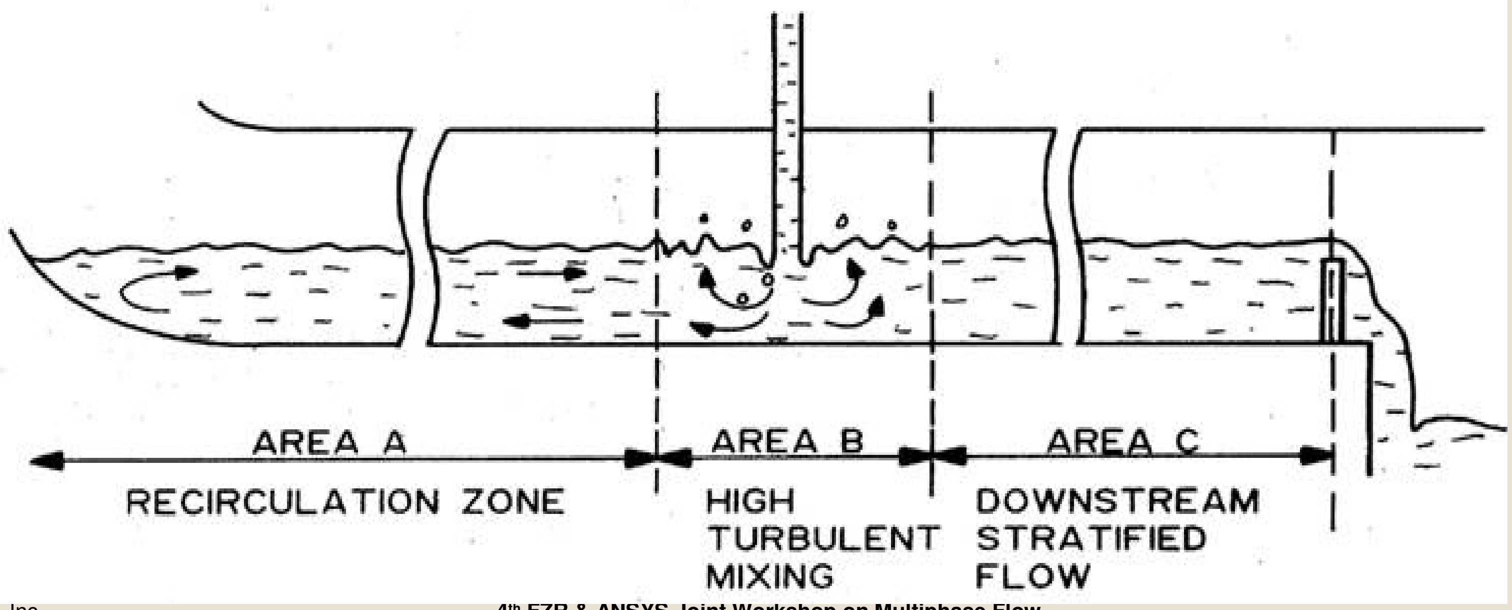
- No liquid carry-over to gas outlet
  - first separation finger (nearest symmetry plane) partially fills with liquid
  - other fingers receive less liquid



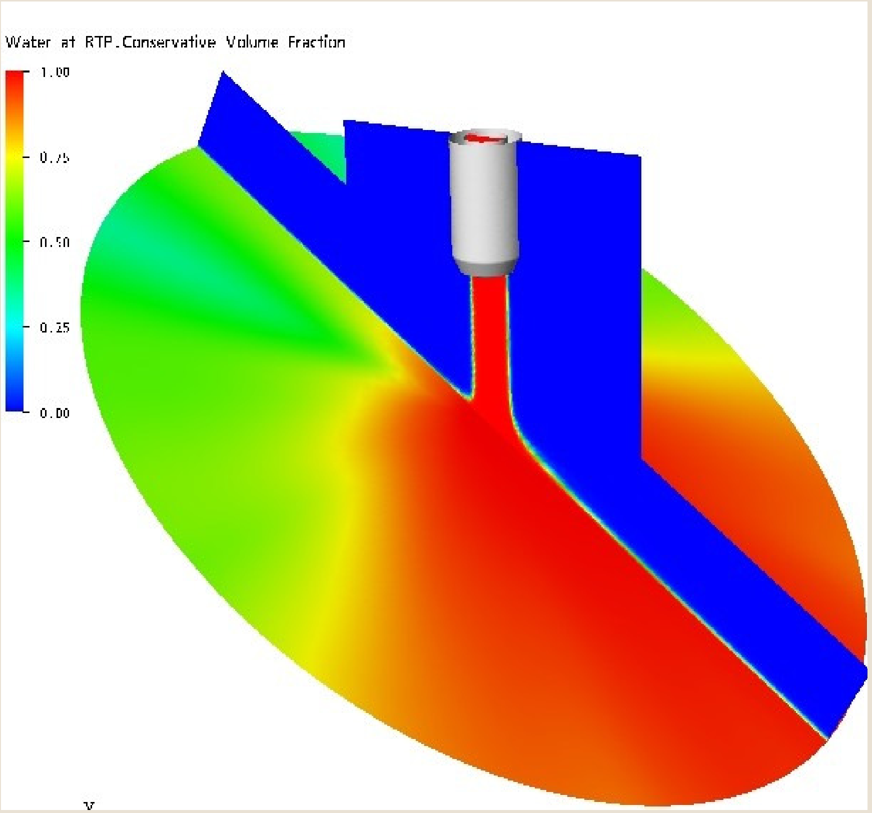


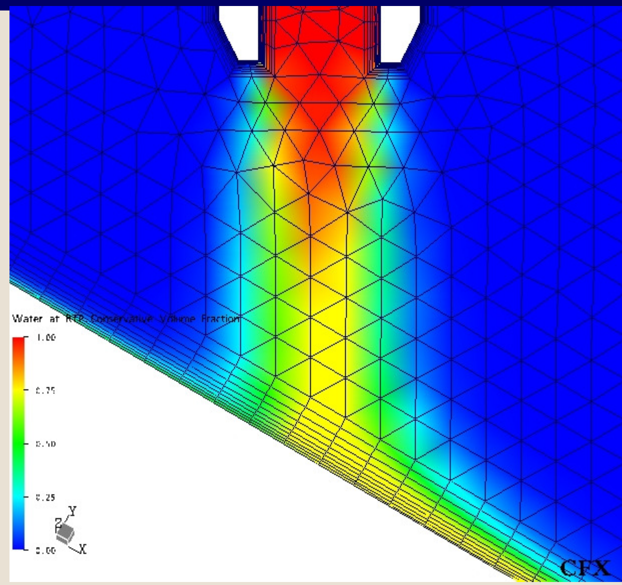
Free Surface Flows

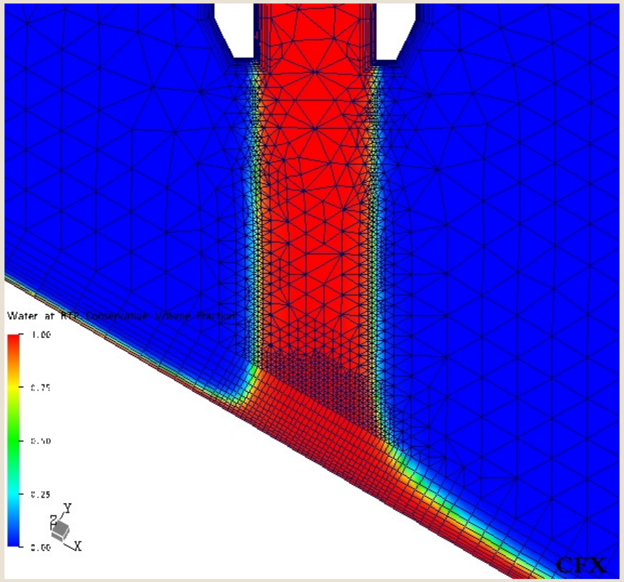
- ECC Injection:
  - Impinging jets
  - Free jet
  - Stratified flow
  - Turbulent mixing
- Experiments:
  - Kvicinsky & Avellan, EPFL
- Simulations:
  - CFX-5
  - SST-Modell
  - Free surface model



Impinging Jet on Inclined Plate

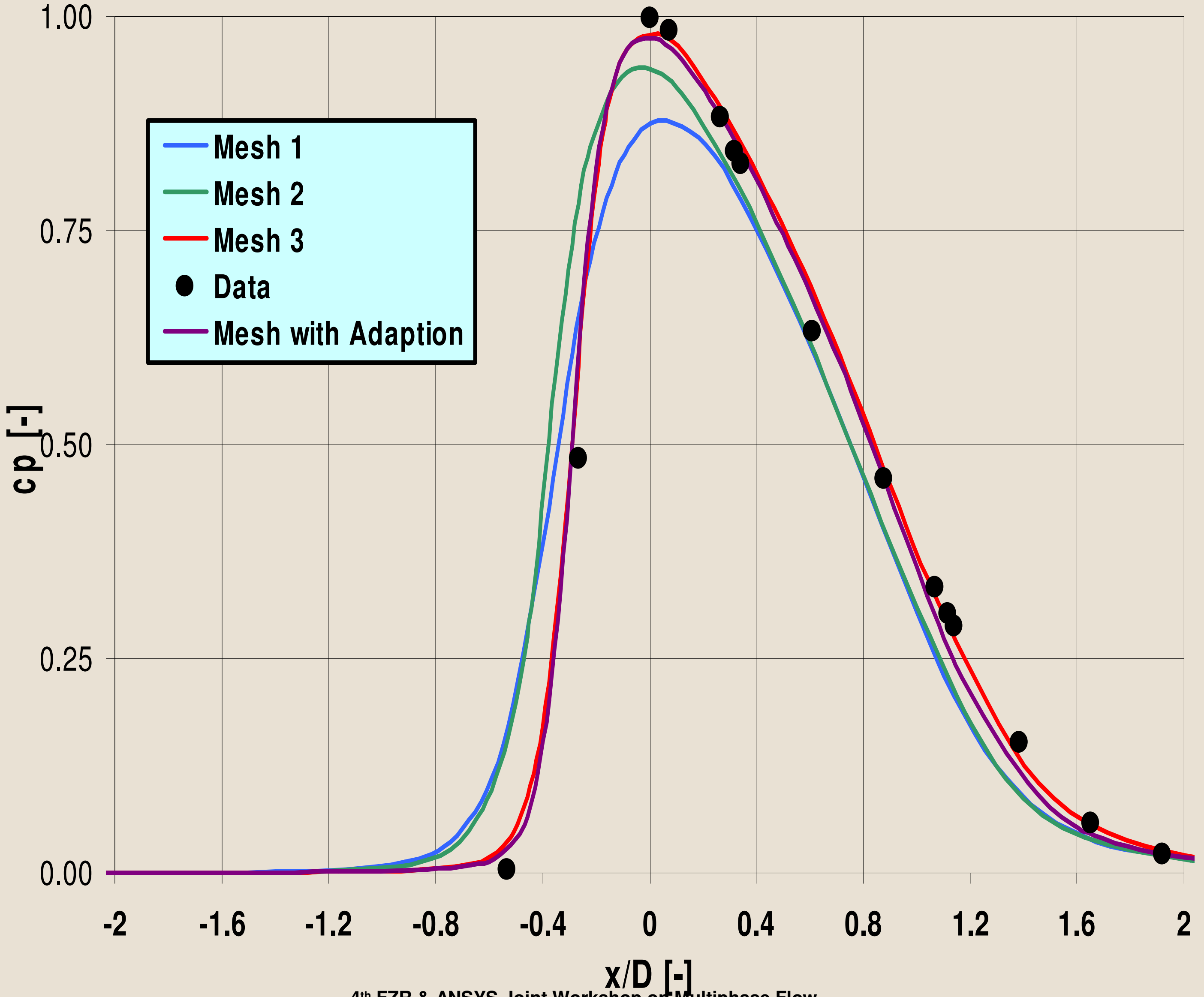




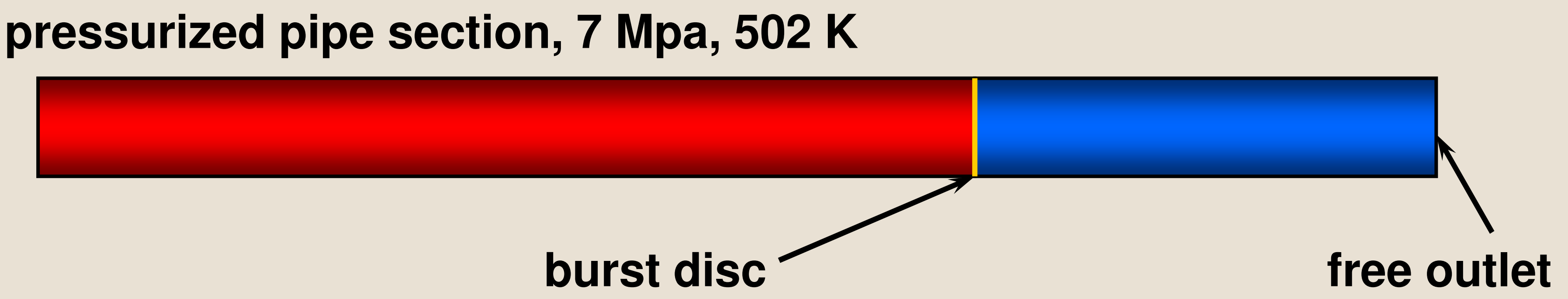


- Water volume fraction
- Automatic grid refinement

Impinging Jet on Inclined Plate



Setup of the Edwards Test



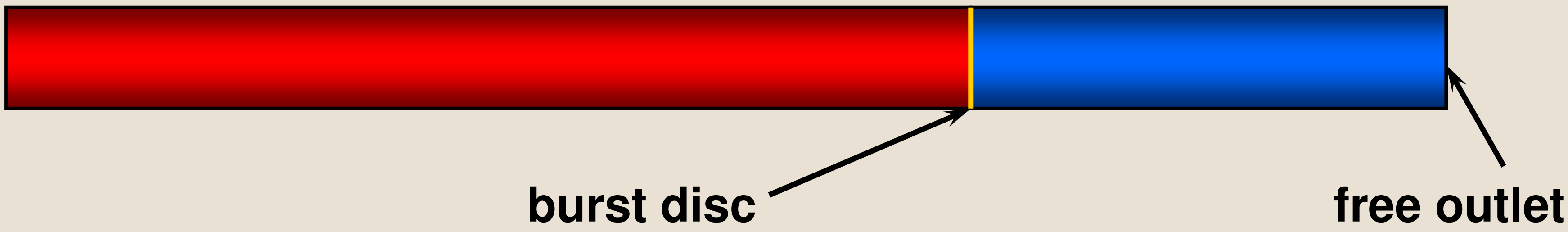
- Pressurized pipe section initially filled with water

  $p = 7$ MPa
  $T_{Water} = 502$ K
  $L_{Pipe} = 4.096$ m
  $D_{Pipe} = 0.0732$ m

- Pressurized pipe closed with a burst disc (glass), broken at t=0.0s

Setup of the Edwards Test

pressurized pipe section, 7 Mpa, 502 K



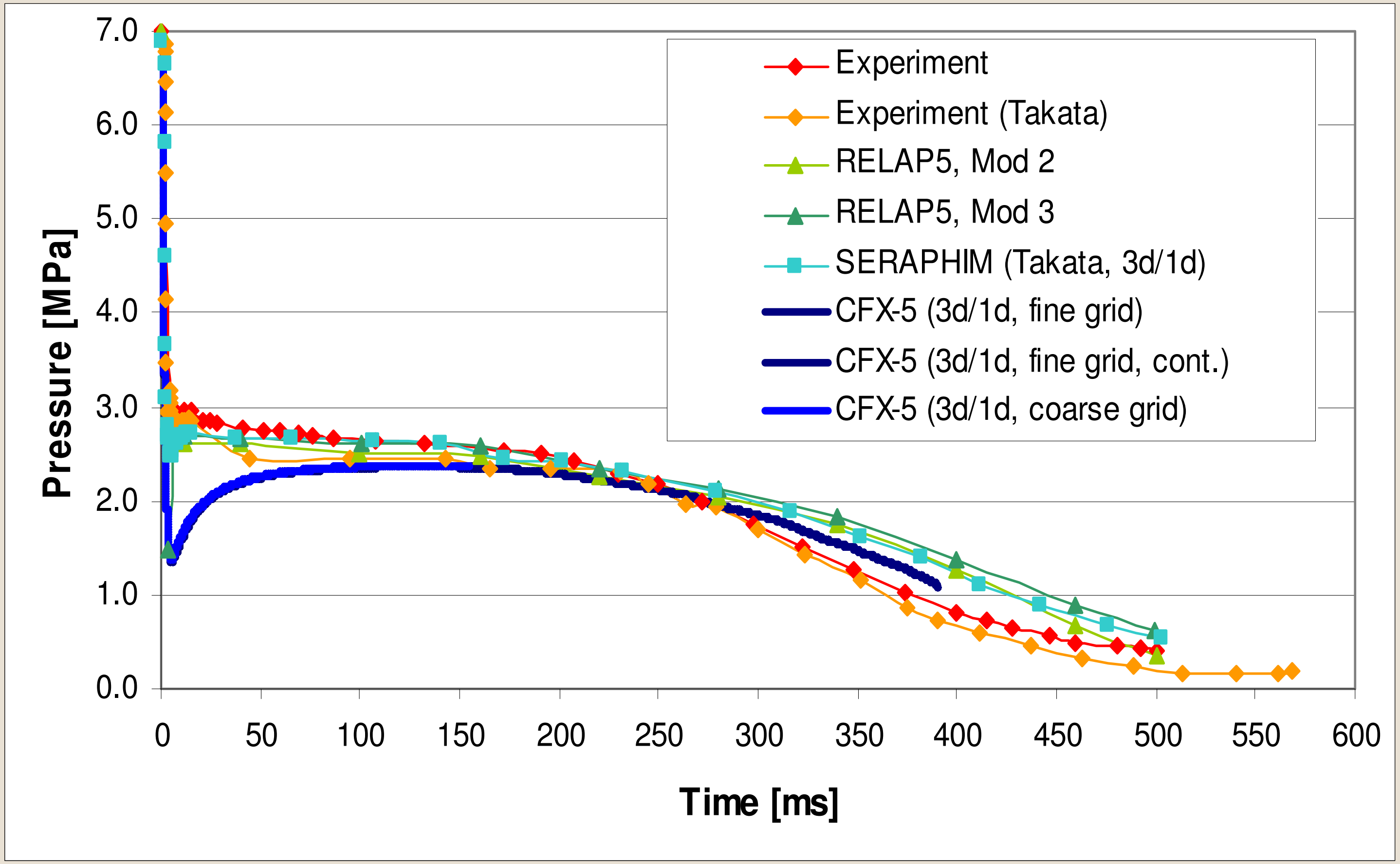
- Data of Edwards & Brien (1970), Takata & Yamaguchi (2003)
- Water-vapor flow
- Two-fluid model for bubbly flow
  - Thermal phase change model (bulk boiling) → Flashing
  - Momentum transfer → Grace drag
  - Heat transfer

→ Prediction of transient change of pressure, volume fraction, temperature

Pressure transient

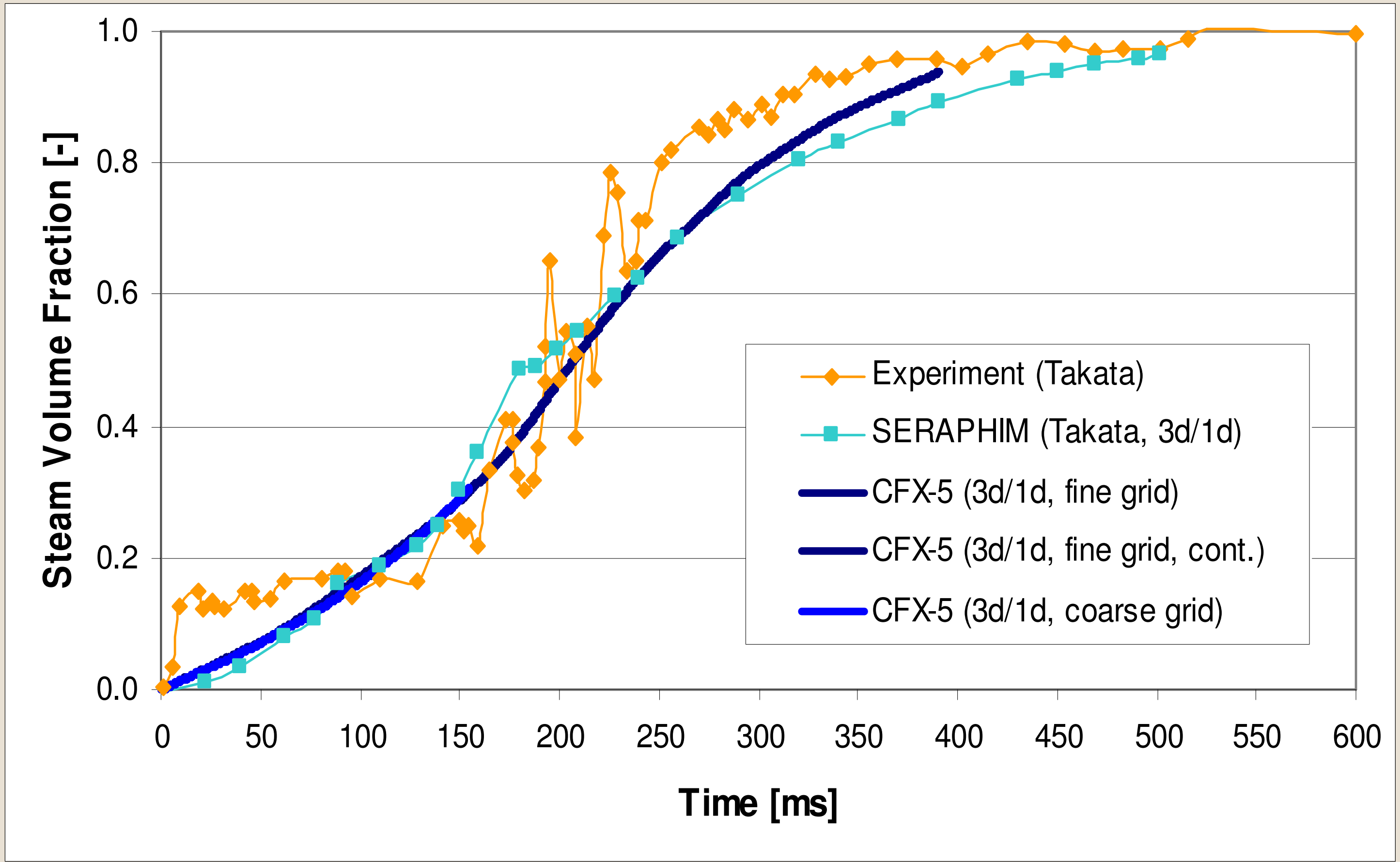
fine grid simulation; T=0.0s-0.392s

- comparison of pressure over time at the measurement location at x=1.469 m from the left pipe wall



Steam volume fraction transient
fine grid simulation; T=0.0s-0.392s

- comparison of volume fraction over time at the measurement location at x=1.469 m from the left pipe wall



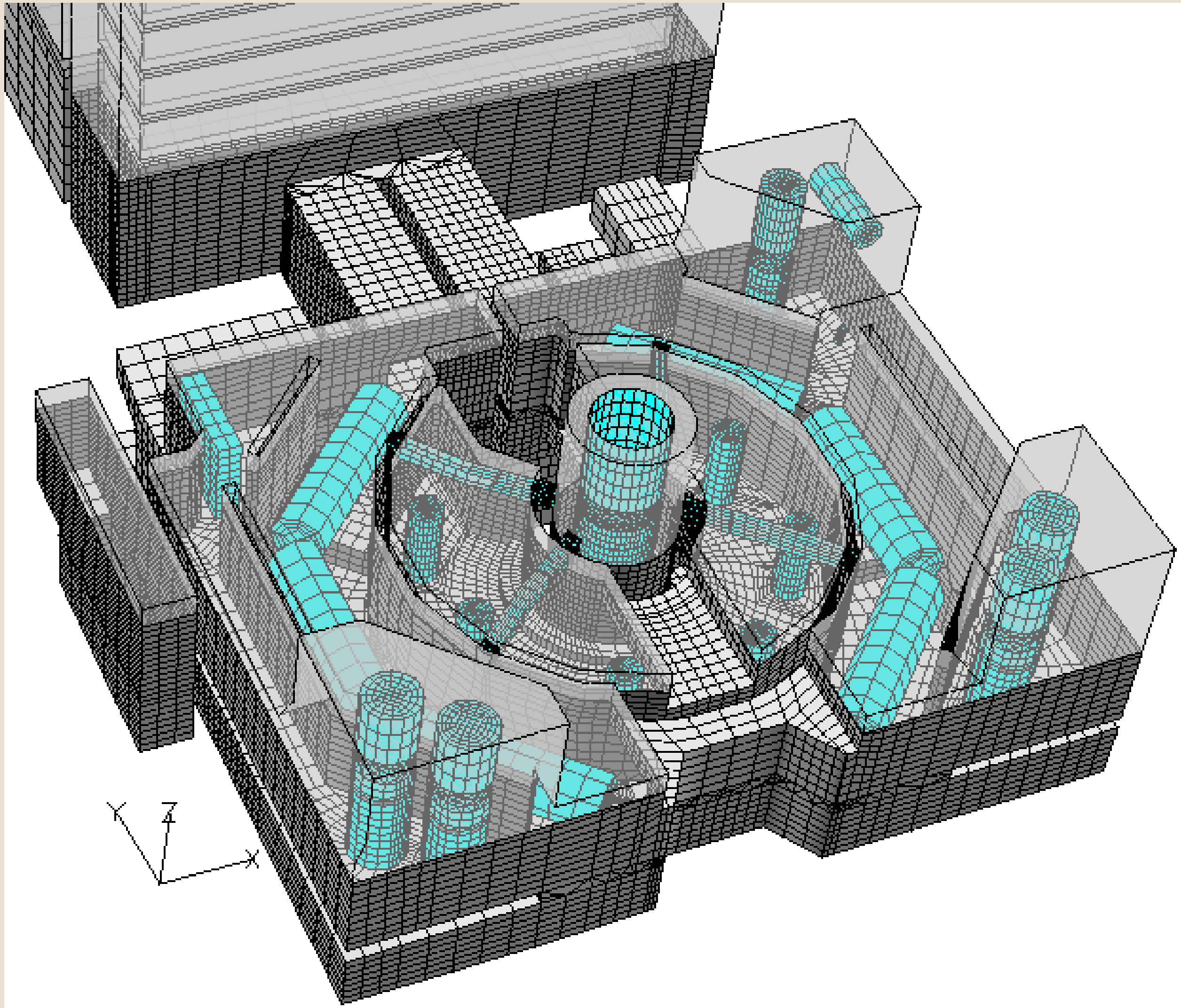
Further Projects

- GRS
  - Investigation on UPTF test cases (ECC)
  - Containment flows, e.g. ISP 47 Step 2
- ANSYS & FZR
  - MUSIG-Models
  - Condensation models for free surface flows
  - Numerics improvements
  - Wall boiling by heat flux partitioning model

- University of Applied Sciences Zittau-Görlitz
  - Flow with insulation material; clogging and sedimentation
  - Experiments & simulations
- TU München, Thermal Power Technology
  - Condensation at free water jets
- University Stuttgart, Nuclear Power Engineering
  - Stratified counter-current flow (ECC in hot leg)

Containment Analysis
VVER 440-213 (PAKS)

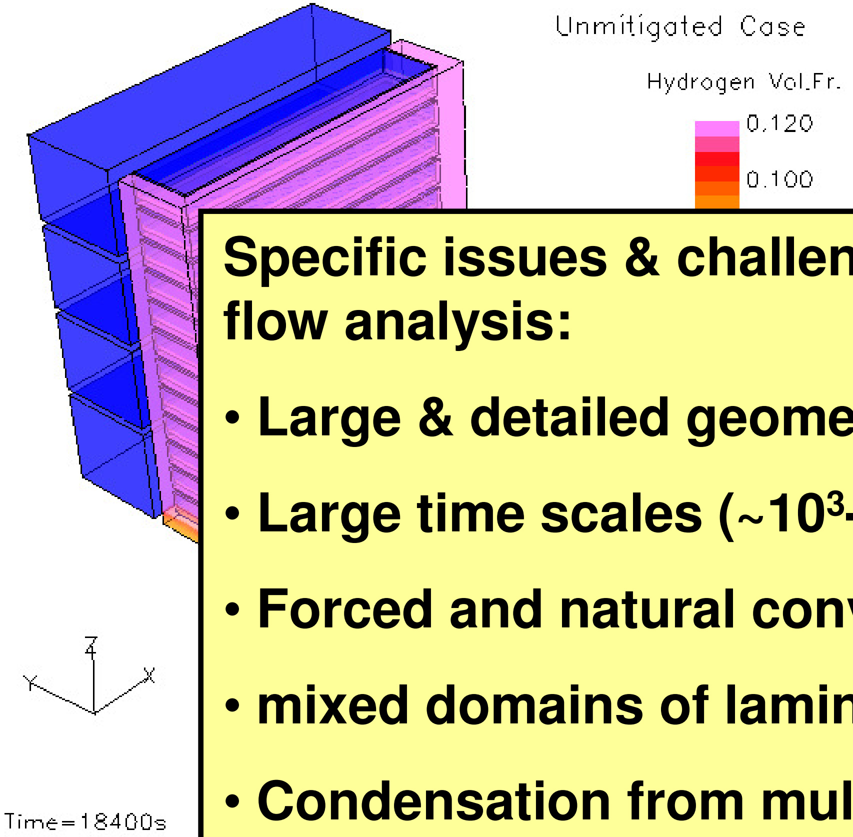
- LBLOCA with H_2 release
- 20 passive autocatalytic recombiners (PAR)
- bulk and wall condensation
- pressure peak suppression system
- 25 days on 8 processors (AMD)

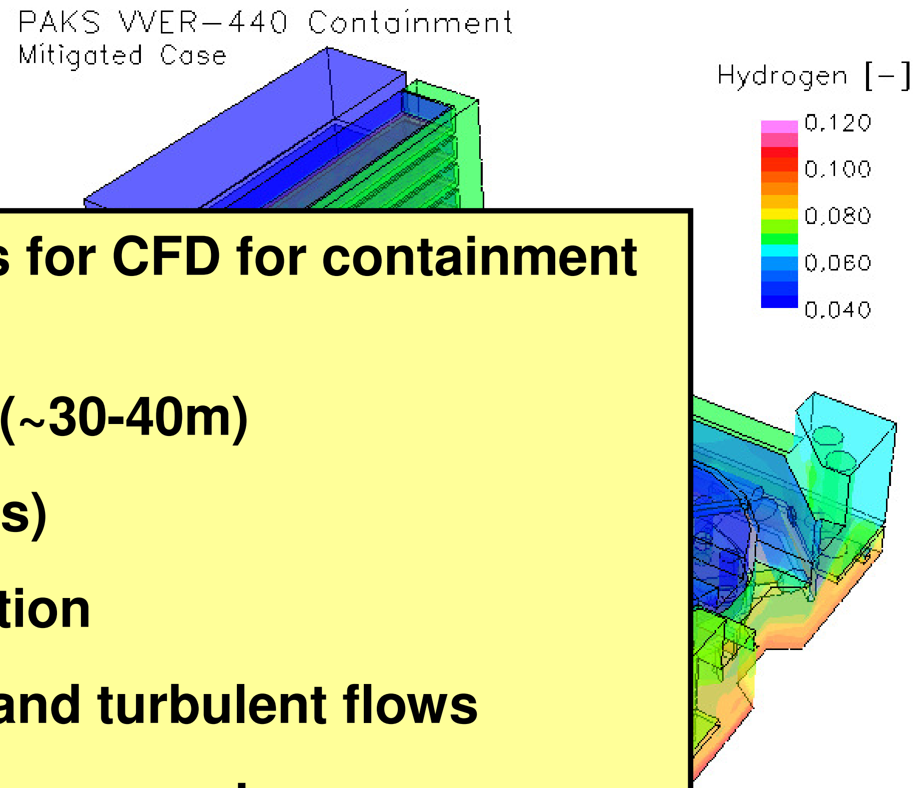


Courtesy of M. Heitsch, GRS

Containment Analysis
VVER 440-213 (PAKS)

Effect of H_2 passive autocatalytic recombiners:





Specific issues & challenges for CFD for containment flow analysis:

- **Large & detailed geometry (~30-40m)**
- **Large time scales (~10^3-10^4s)**
- **Forced and natural convection**
- **mixed domains of laminar and turbulent flows**
- **Condensation from multi-component gases (condensible & non-condensible)**

Heitsch, GRS

Communication

- http://domino.grs.de/cfd/cfd.nsf
- Contact: Martina Scheuerer, GRS
- Documents
  - Meeting protocols
  - Work plan definitions, collection of important publications
  - Validation test reports
- Measurement data
- Test case results
- CFD Network attracted further interest from
  - Nuclear Reactor Safety:
    → OECD, FISA, NURESIM, North-Net, CEA, EdF, Vattenfall, IRSN, NRG, TÜVs, Univ. Pisa
  - Process Technology:
    → Linde, BASF, Siemens

Perspective

- Project time frame 2006 – 2009
  - Funding of project partners: FZR, GRS, ANSYS
  - Cooperation with universities (driven by PhD program, 6 PhD‘s)
- Main topics of interest:
  - Flows with high volume fraction
  - Flows with phase change
  - Coupling of CFD with 1d/lumped parameter codes
  - Coupling of CFD with neutron kinetics code
  - Containment flows
- Networking with international partners:
  - NORTHNET Initiative
  - Cooperation with NRG, IRSN, PSI, ETHZ, …
  - Approach funding for further initiatives from EC

Summary

- Motivation and major objectives
- Structure of the CFD Network on NRS
- Organisation → Work plan defintion
- Results
  - Extensive validation of MPF models for vertical pipe flows
  - Horizontal pipe & channel flows
  - Free surface flows
- Active colaboration of all partners
- National and international interest

Thank You!