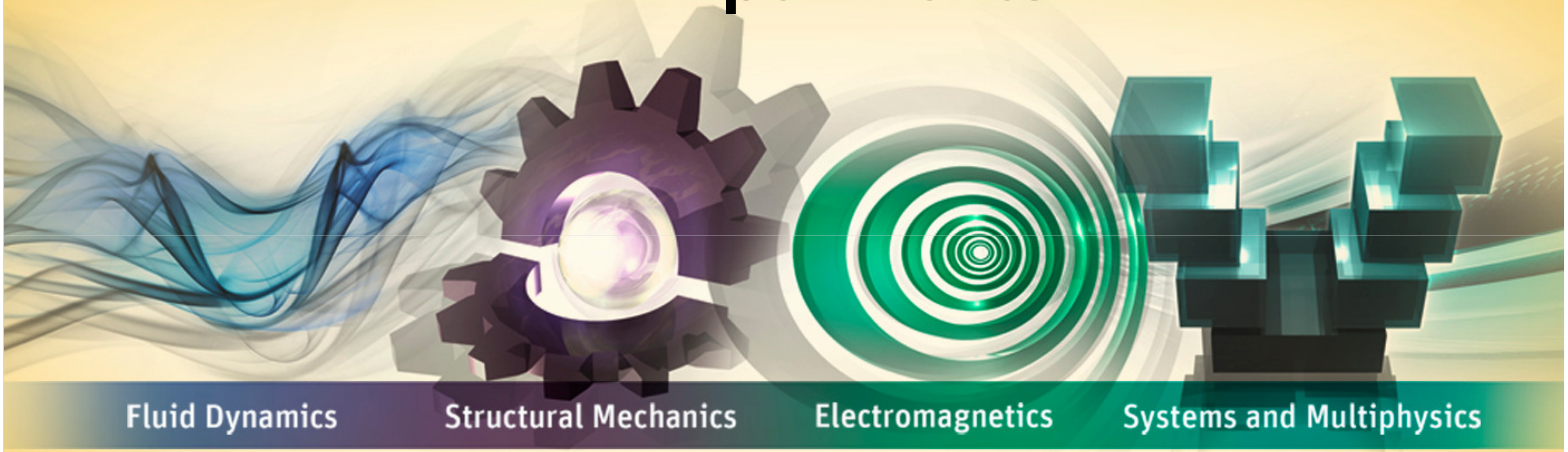
CFD-Modeling of Turbulent Flows in a 3x3 Rod Bundle and Comparison to Experiments



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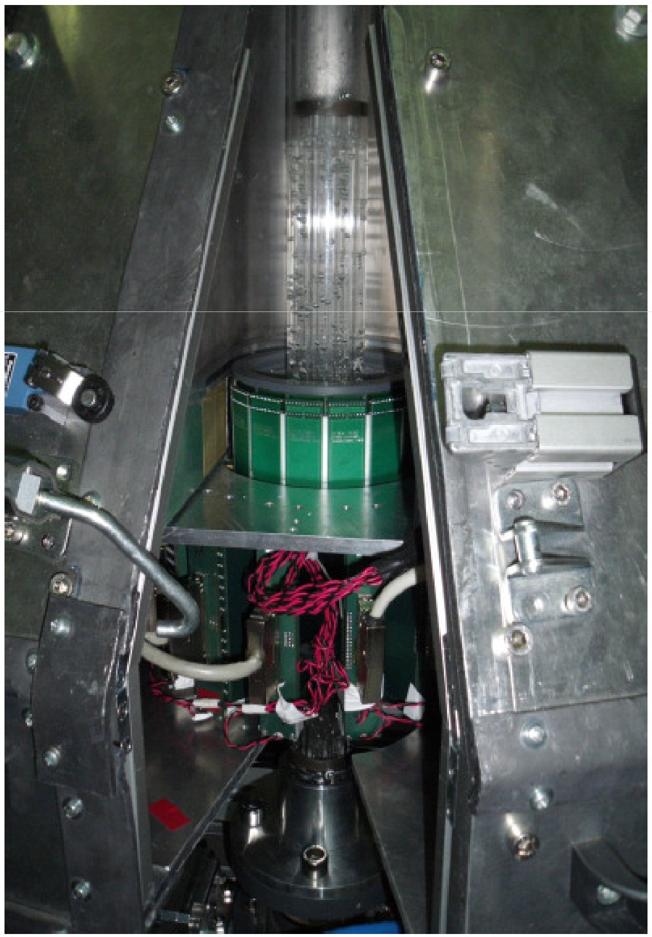
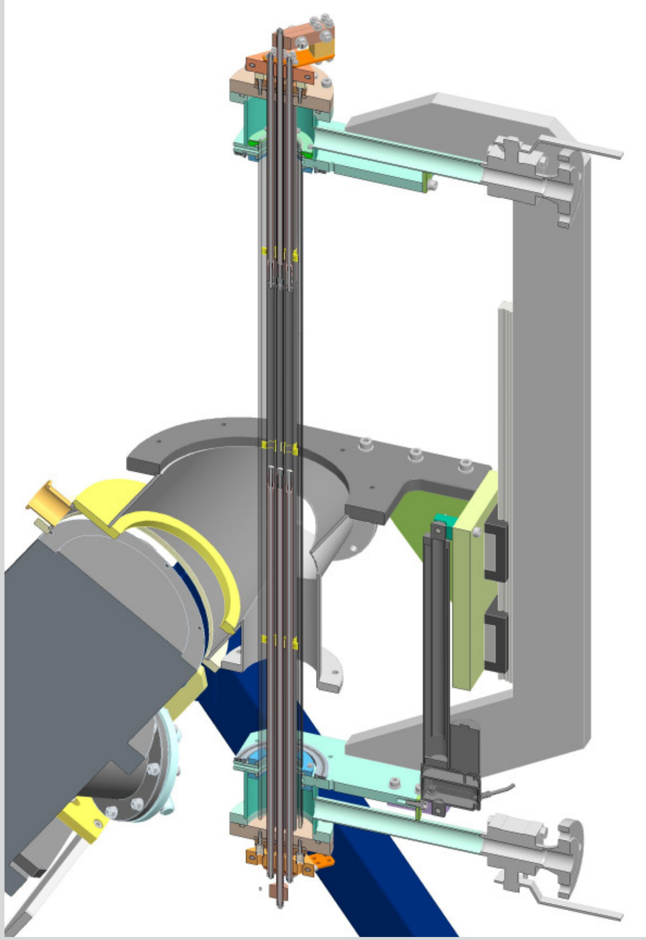
Content

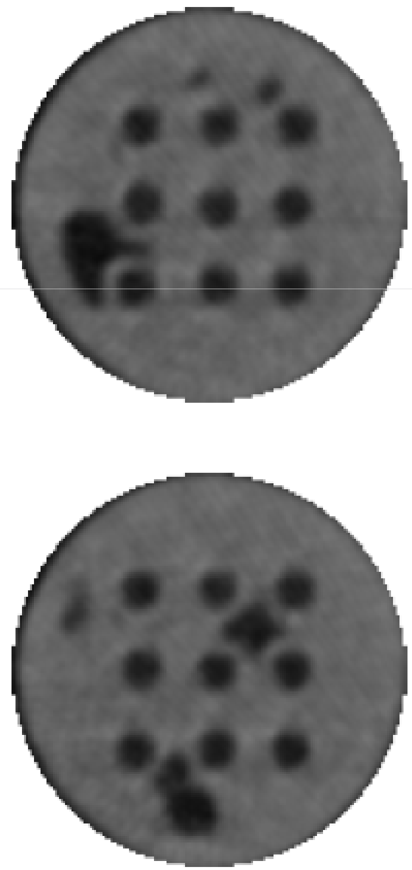
- Objective of the investigation
- CFD Approach
- Case Description
  - Experiments
  - Geometry
- Setup
  - Meshes
  - Material properties
  - Boundary conditions
- Convergence
- Qualitative Analysis: Flow Field Characteristics
  - Velocity fields and streamlines
  - Turbulence models
  - Asymmetry
  - Mirrored case
- Quantitative Analysis: Comparison to Experimental Data
  - Velocity v

Objective of the Investigation

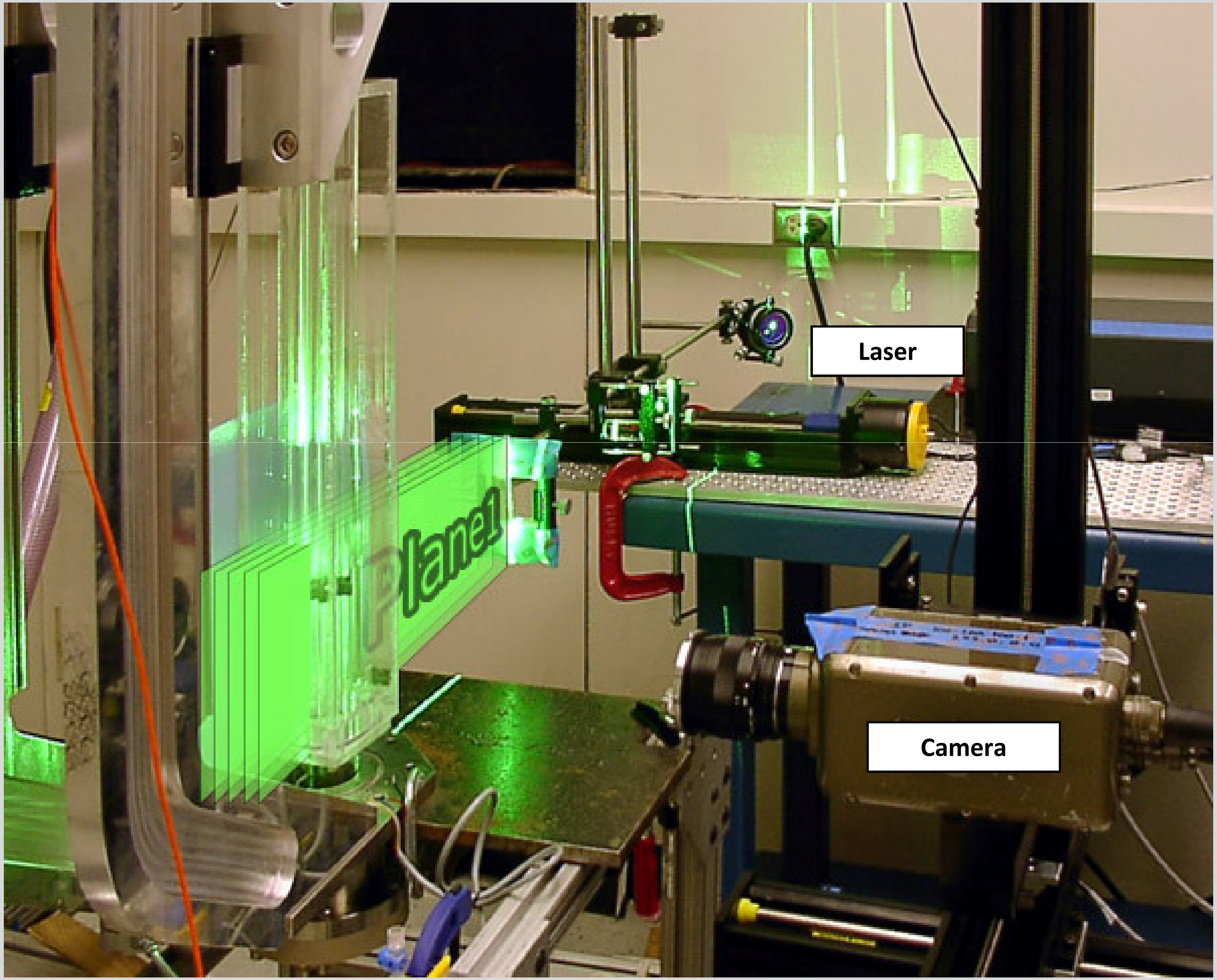
- **Investigation of flow conditions in HZDR ROFEX test section for boiling flow tomography measurements**







Texas A&M University PIV Experiments



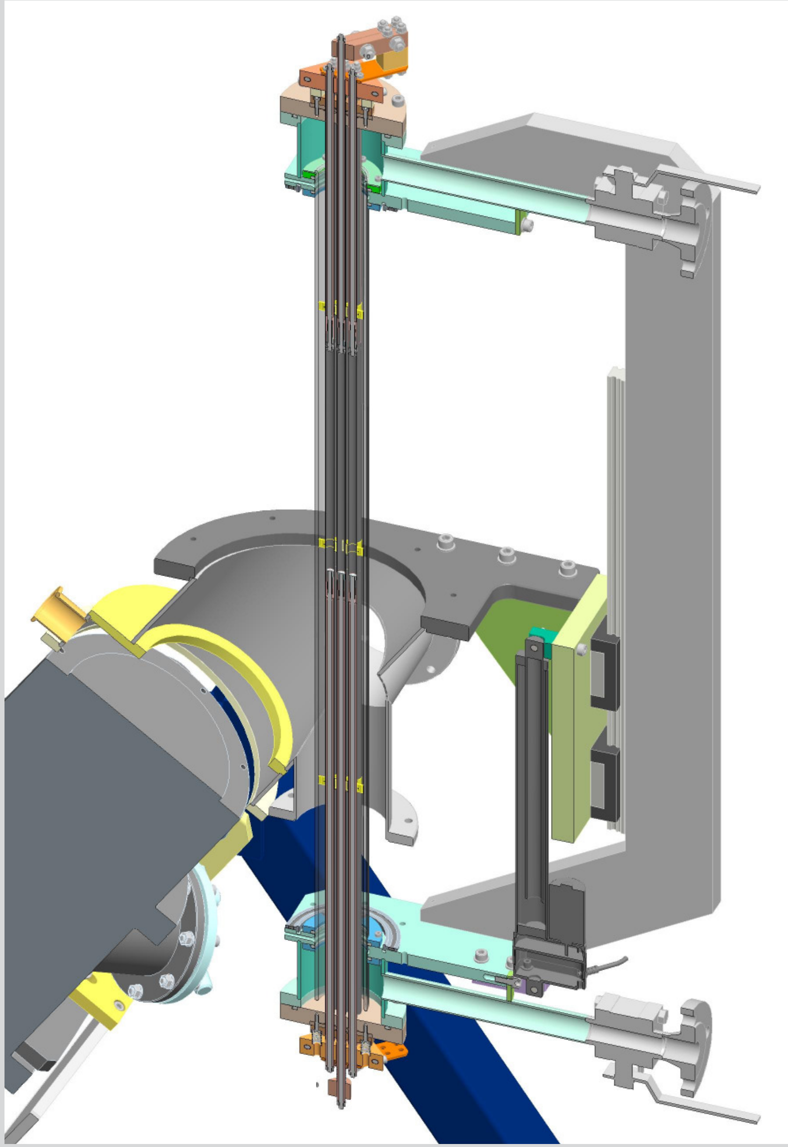
Objective of the Investigation

Answering the Questions:

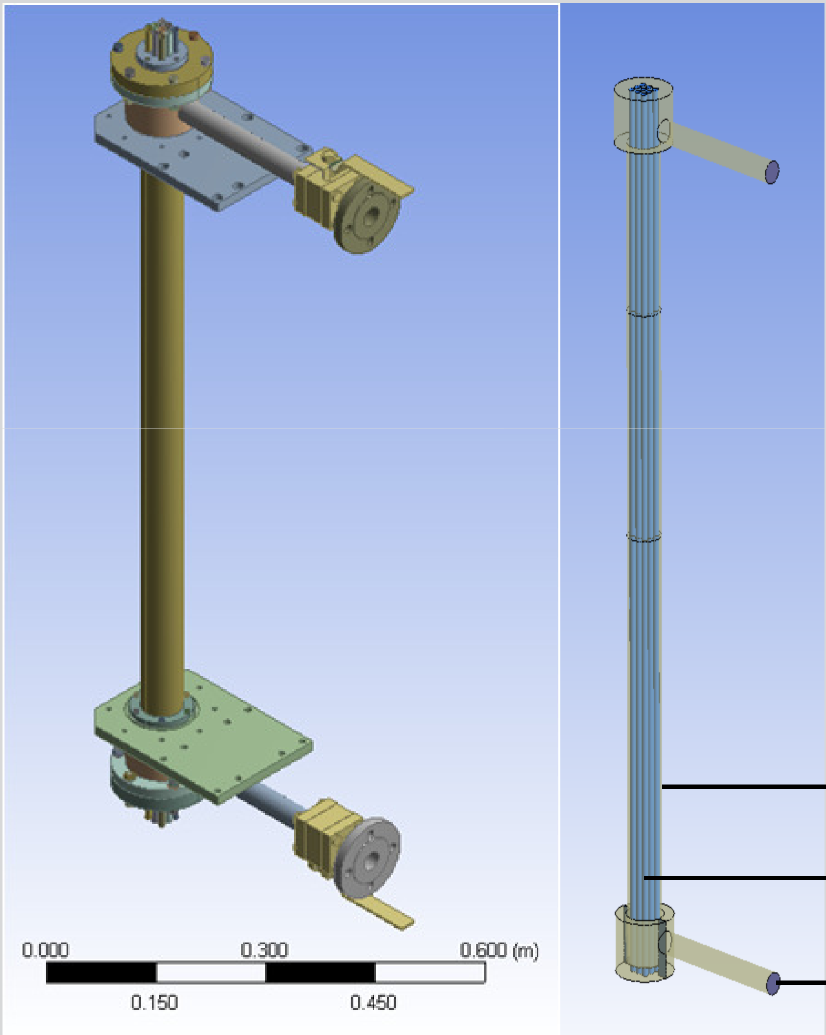
How the HZDR test facility can be used for CFD boiling model validation?

Where CFD results can be reasonably well compared to measurements?

→ **starting with single phase**



Objective of the Investigation



- Validation of single-phase flow conditions using p-cymene in a pyrex glass rod bundle
- Comparison to PIV measurements (Texas A&M University & HZDR)
- Isothermal, single-phase flow
- Expected to be transient because of previous refrigerant flow calculations

Main pipe: Ø 54.0 mm

Rods: Ø 10.2 mm

Inlet: Ø 29.7 mm

CFD Approach

Geometry

Fluid Domain

Meshes

CFD Investigations

Comparison to Experimental Data

High Quality Mesh Generation

Capturing Flow Phenomena

Mesh Independency

Convergence

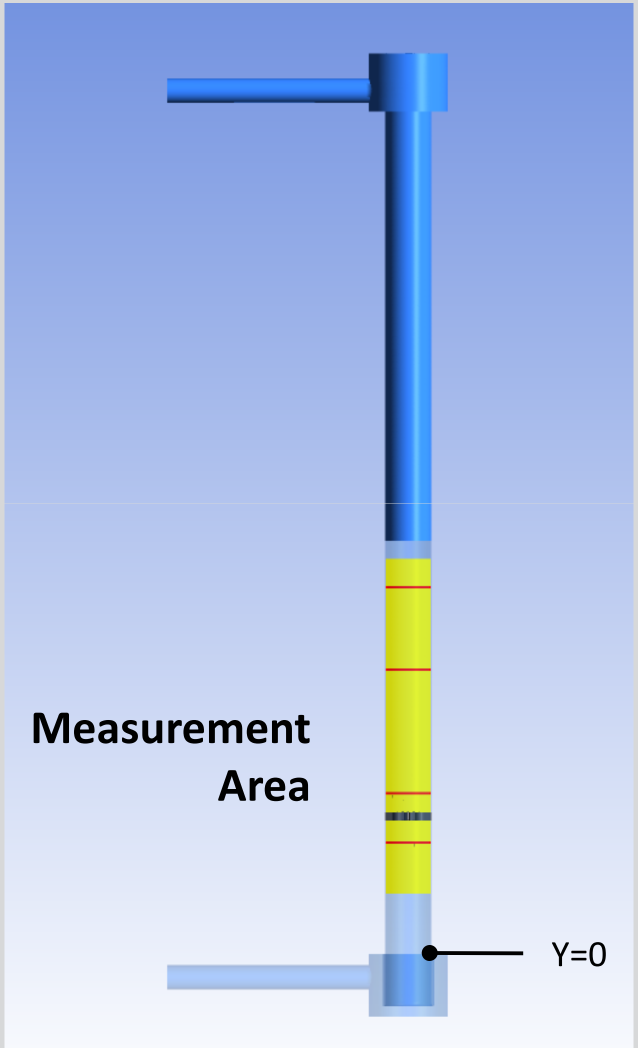
Investigation of Flow Field Characteristics

Parameters

- steady state / transient
- isotropic / anisotropic turbulence model
- mass flow rate variation
- influence of fully developed turbulent inlet flow field
- convergence criteria
- time step
- efficiency

Focus on Velocity Field as target value

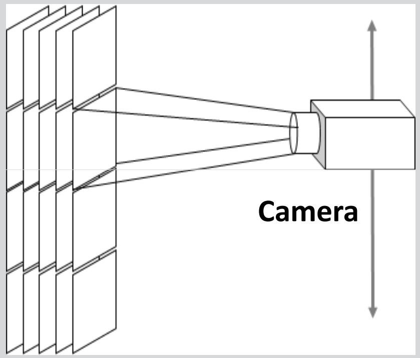
- streamlines
- velocity profiles in measurement planes
- secondary flows



PIV Experiments in Transparent Test Section

- 2-dimensional velocity data from PIV measurements (HZDR, A&M Texas University)
- 6 % error in both directions

5 4 3 2 1

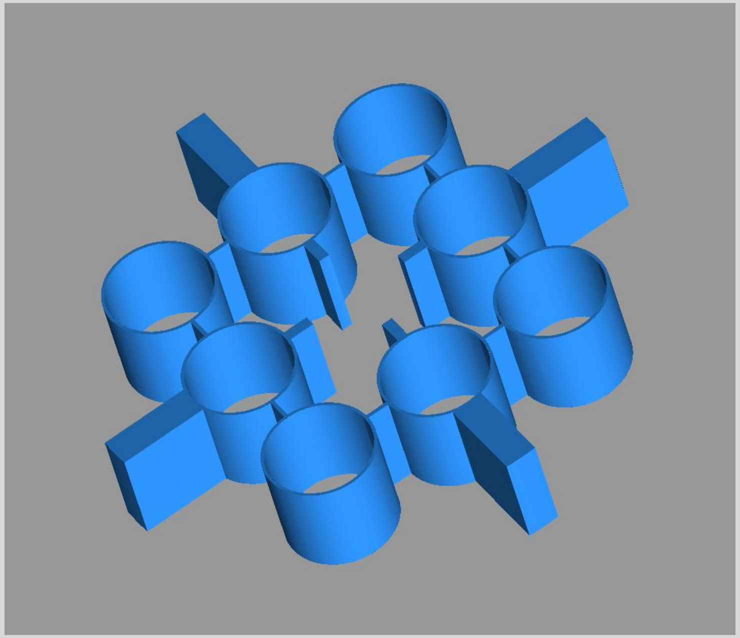


- Several inlet flow rates:

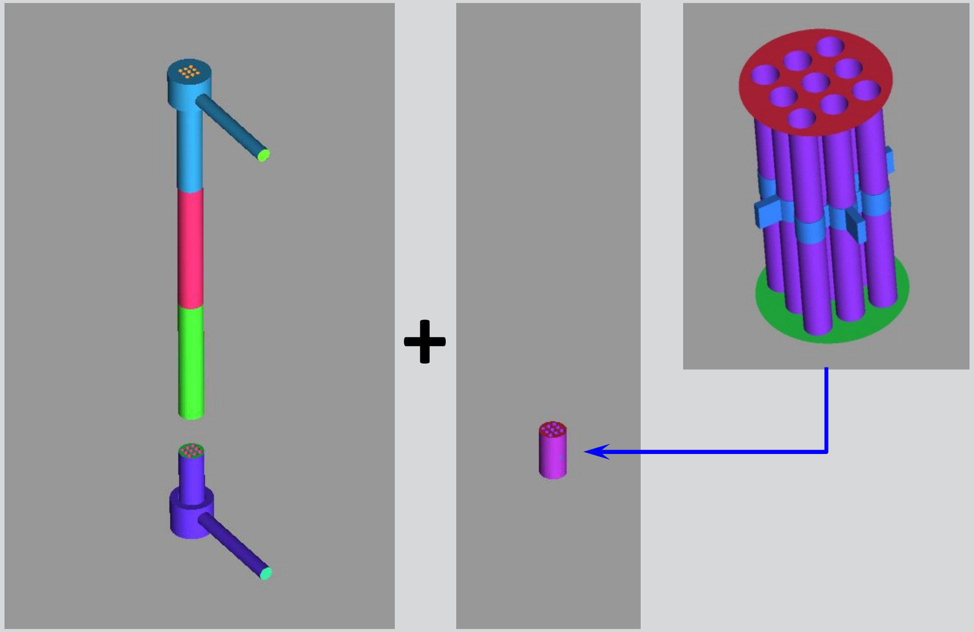
i	$\dot{V}_i$	u_i	Re_{Inlet}
1	1.20 l/s	1.732 m/s	57 510
2	1.70 l/s	2.454 m/s	81 483
3	2.14 l/s	3.089 m/s	102 568

Geometry: Grid Spacers

- **Thin metal sheet material & short length**
  → initially considered as negligible → erroneous assumption
- **One spacer in measurement area**
- **Experimental data → spacer acts more like a flow straightener**

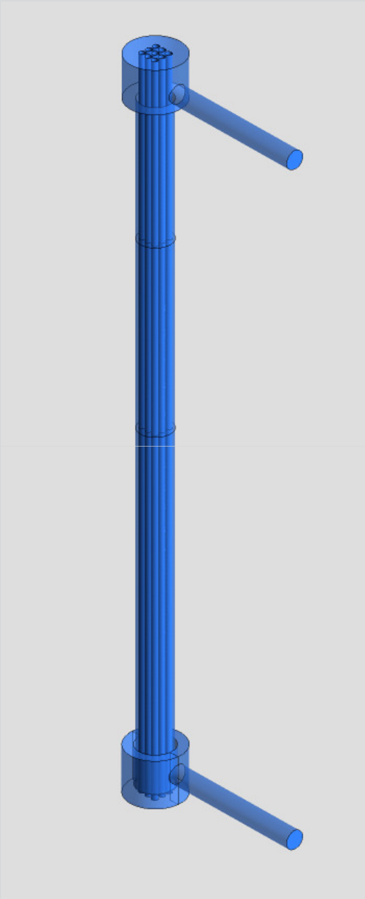


Derived from HZDR drawing 6.024:07(3)

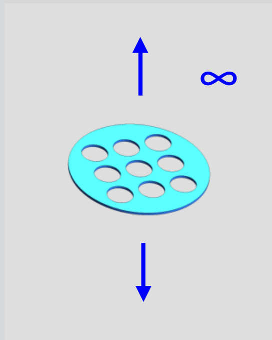


GGI connection

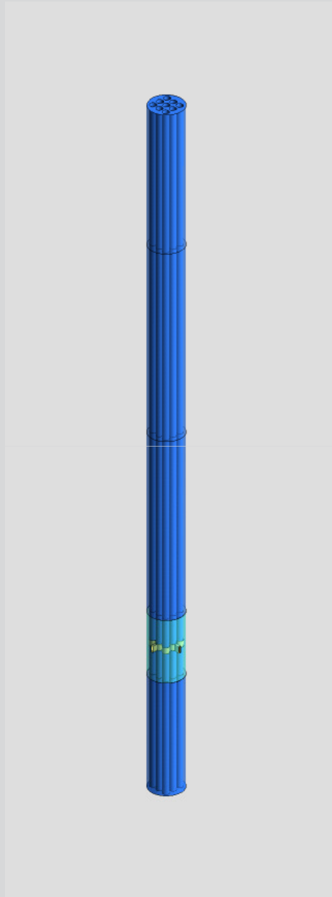
Geometry Model Configurations


Case I


Case II

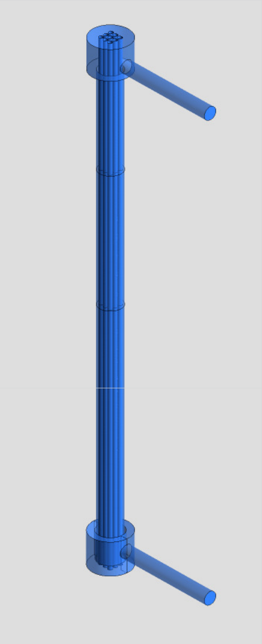


Case III


Case IV

Computational Mesh Hierarchy Case I

	Mesh01 Coarse	Mesh02 Medium
Elements (Hex)	$1.0 \cdot 10^6$	$8.0 \cdot 10^6$

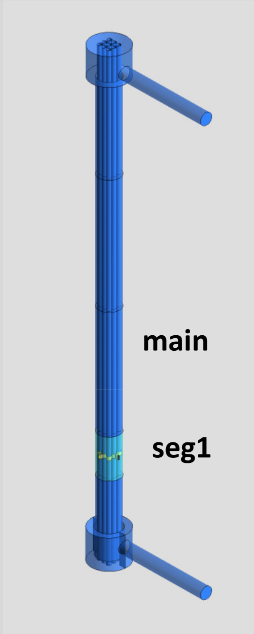


Min. Determinant	0.5
Min. Grid Angle	36
Max. Aspect Ratio	98
Max. Vol. Change	25

Computational Mesh Hierarchy Case II

	Mesh01 Coarse		Mesh02 Medium	
Elements (Hex)	main	$1.0 \cdot 10^6$	main	$8.0 \cdot 10^6$
	seg1	$0.4 \cdot 10^6$	seg1	$3.2 \cdot 10^6$
	$1.4 \cdot 10^6$		$11.2 \cdot 10^6$	

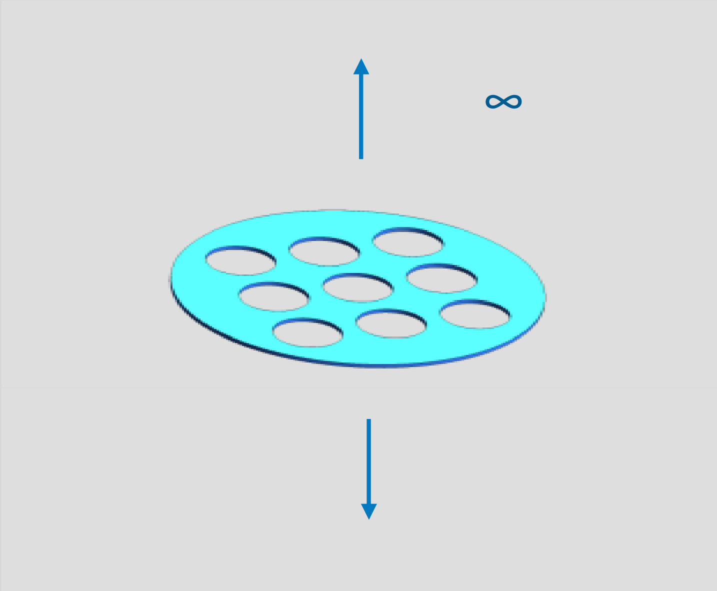
	main	seg1
Min. Determinant	0.5	0.6
Min. Grid Angle	34	35
Max. Aspect Ratio	120	94
Max. Vol. Change	30	10



Computational Mesh Hierarchy Case III

Mesh02 (slice)	
Elements (Hex)	$0.6 \cdot 10^6$

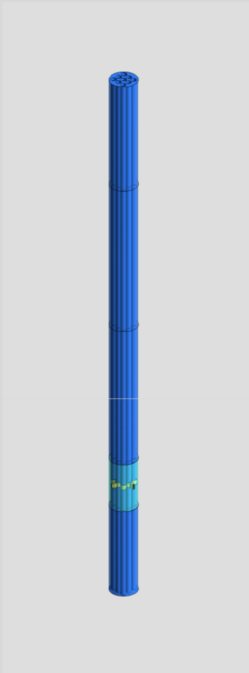
Min. Determinant	0.7
Min. Grid Angle	38
Max. Aspect Ratio	1
Max. Vol. Change	5



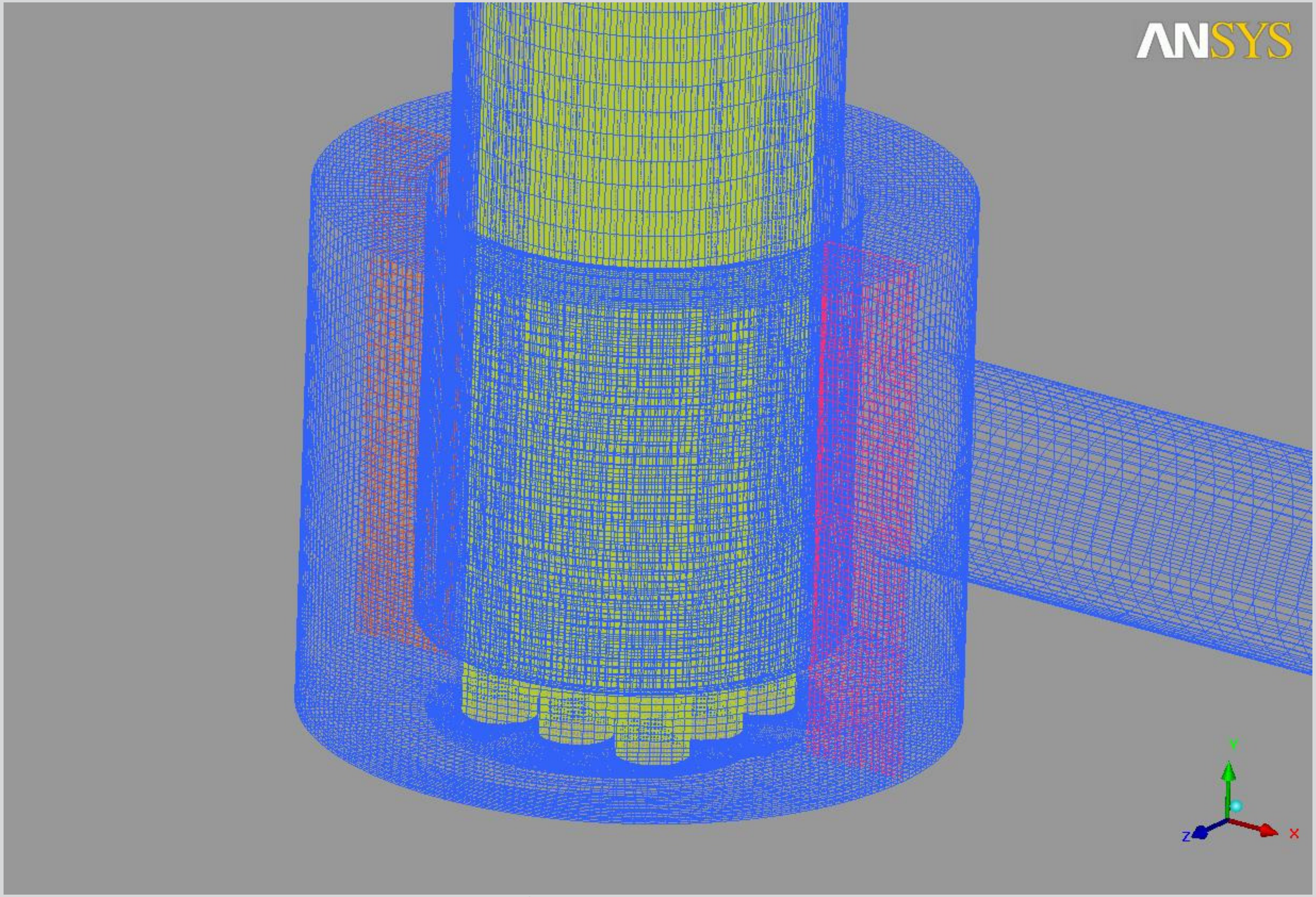
Computational Mesh Hierarchy Case IV

	Mesh01 Coarse		Mesh02 Medium	
Elements (Hex)	main	$0.6 \cdot 10^6$	main	$4.8 \cdot 10^6$
	seg1	$0.4 \cdot 10^6$	seg1	$3.2 \cdot 10^6$
	$1.0 \cdot 10^6$		$8 \cdot 10^6$	

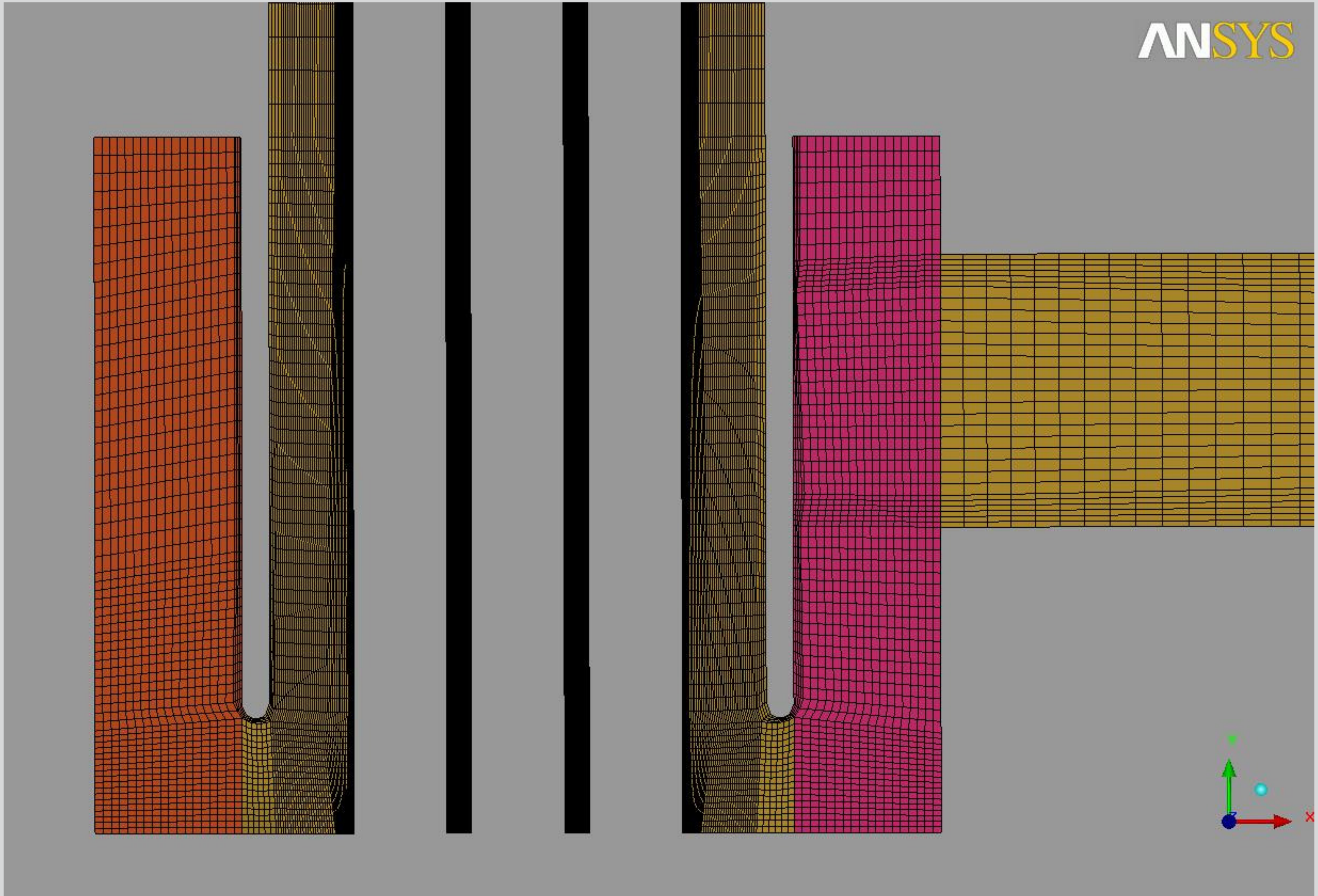
	main	seg1
Min. Determinant	0.6	0.6
Min. Grid Angle	36	35
Max. Aspect Ratio	120	94
Max. Vol. Change	7	10



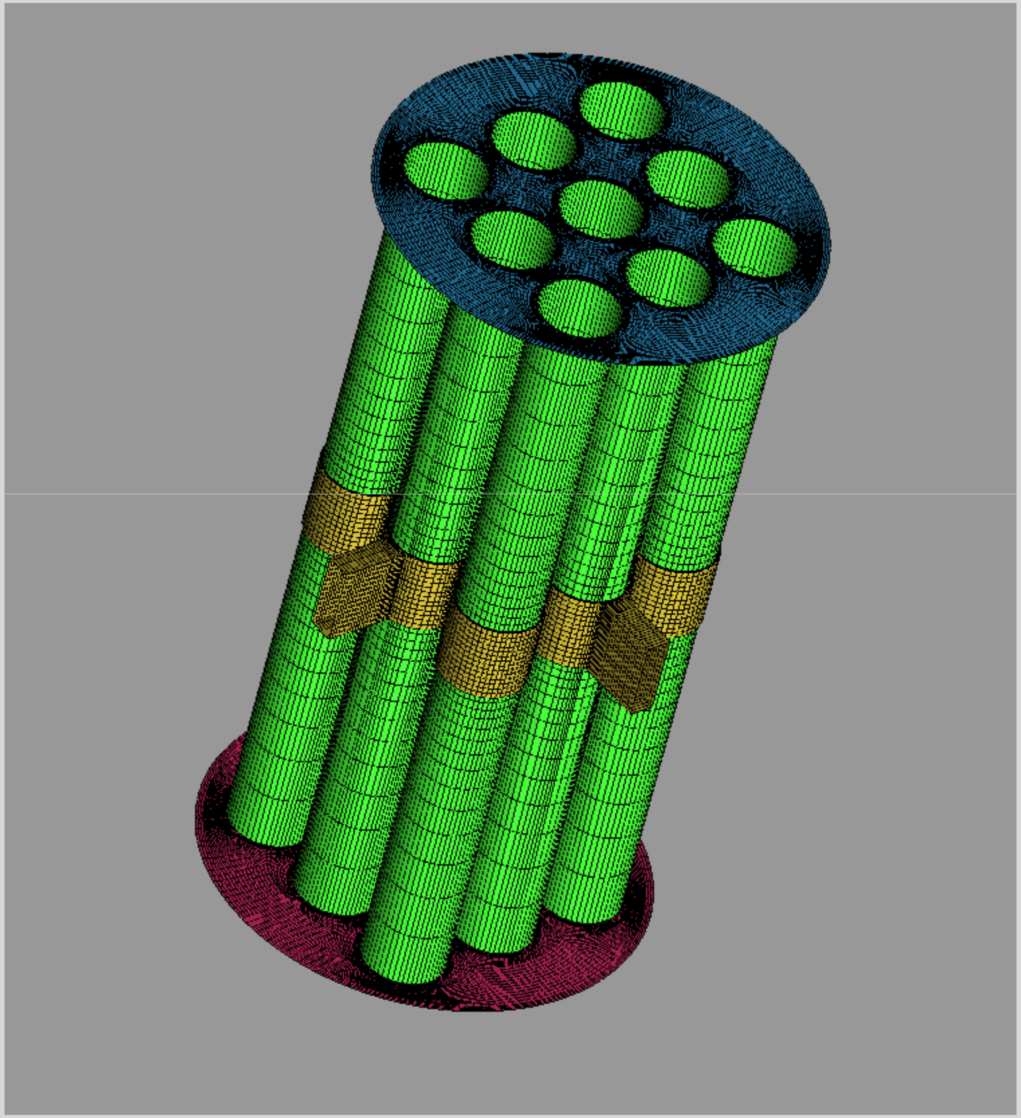
Computational Mesh



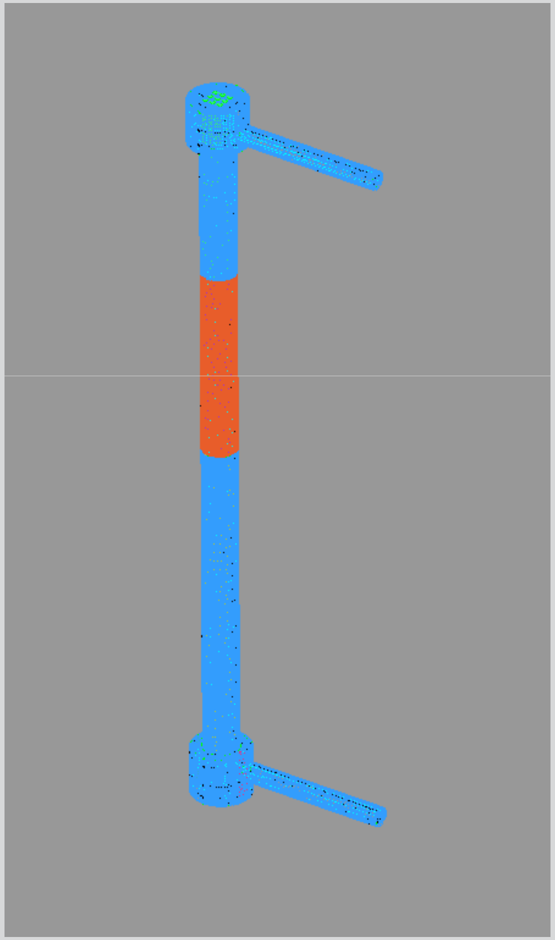
Computational Mesh - Mesh02



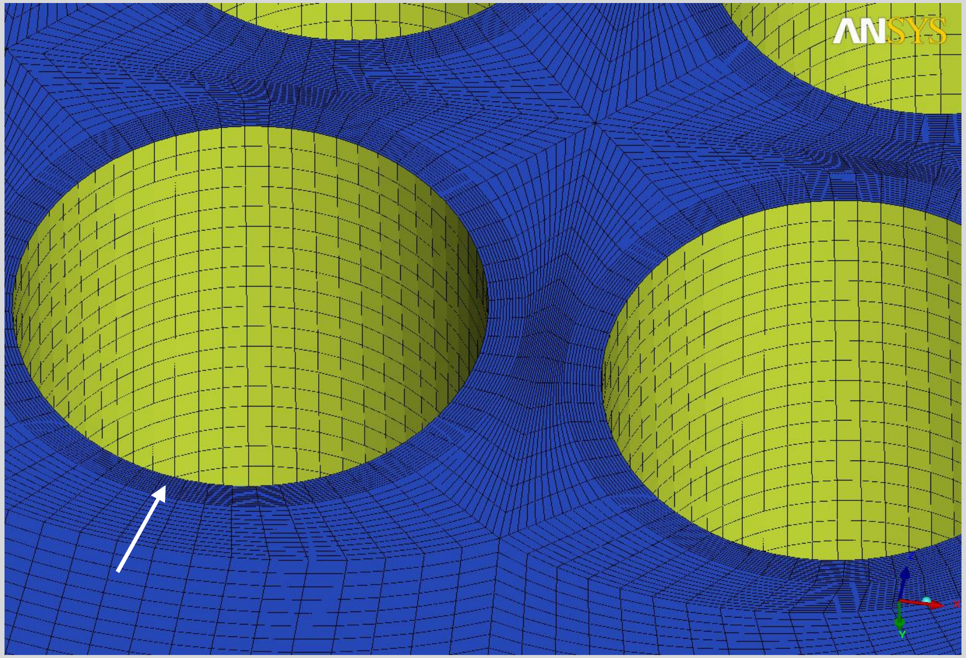
Computational Mesh – Case II and IV



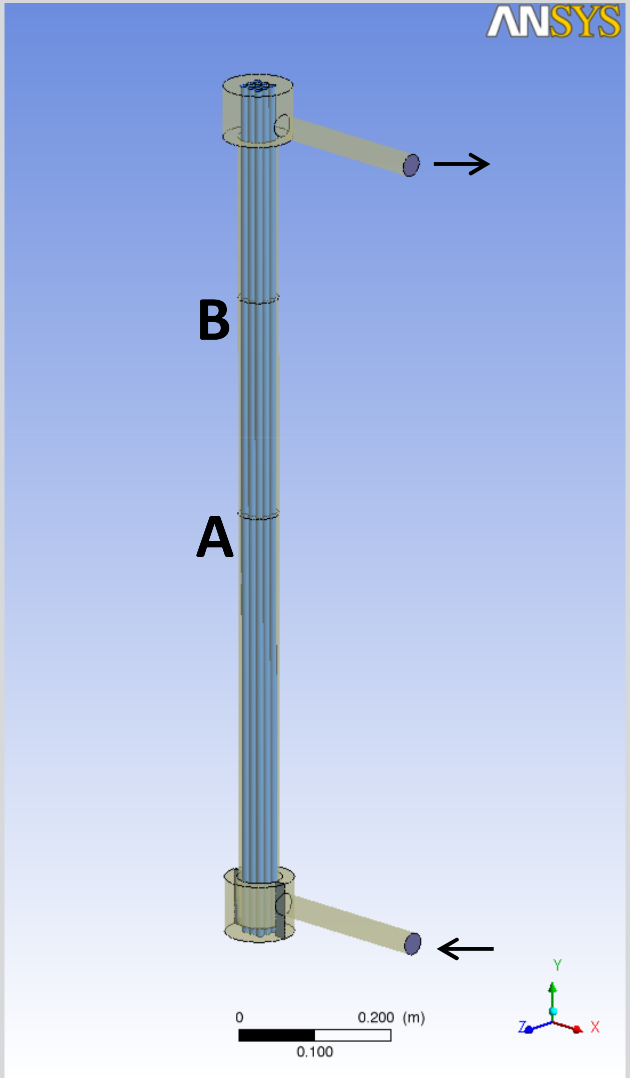
Boiling Model Demands



- **Domain is subdivided in three parts for further investigations considering heat**
- **Constant cell thickness around rods**



Boundary Conditions & Material Properties



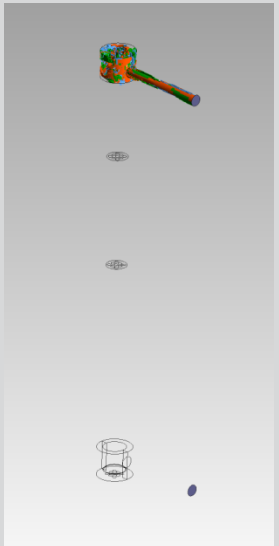
- **Inlet:** Normal Speed u_1, u_2, u_3
  Turbulence Intensity 5%
- **Domain:** Reference Pressure 1 bar
  Isothermal 28 °C
  Turbulence:
  SST, BSL RSM
- **Walls:** No Slip Wall, Smooth Wall
  for pipes, rods & dividers
- **Outlet:** Average Static Pressure
  Relative Pressure 0 bar

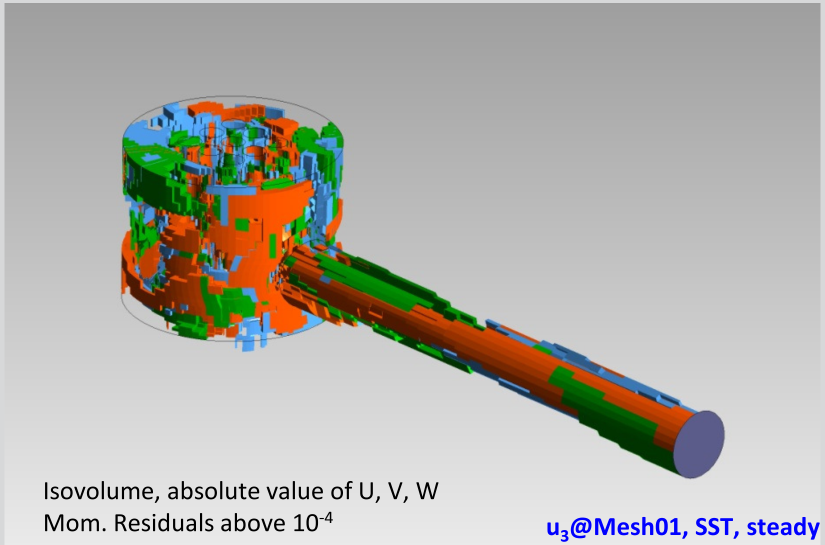
Material: P-cymene

Dynamic Viscosity	$0.761 \cdot 10^{-3}$ kg m^{-1} s^{-1}
Density	850.79 kg m^{-3}

Convergence

- **Imbalances** — **< 1%**
- **Residuals (MAX, Localization)** — **Max. Res. Criterion 10^{-4} / 10^{-2}**
- **Stability of Monitored Quantities** — **U, V, W, P (inst. / transient avg.)**



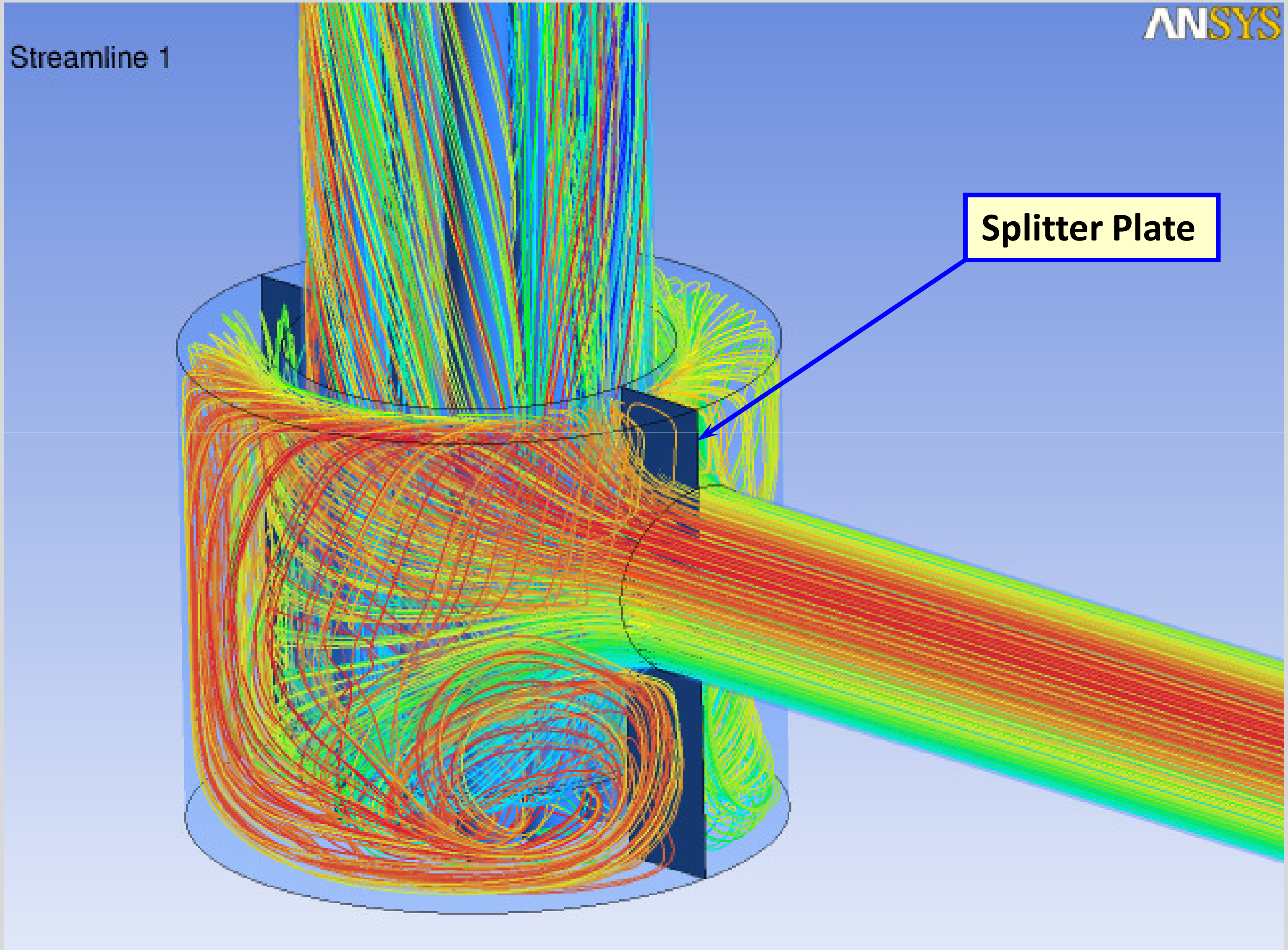


Residuals above 10^{-4} and also above 10^{-3} concentrated in outlet vessel

Qualitative Analysis:

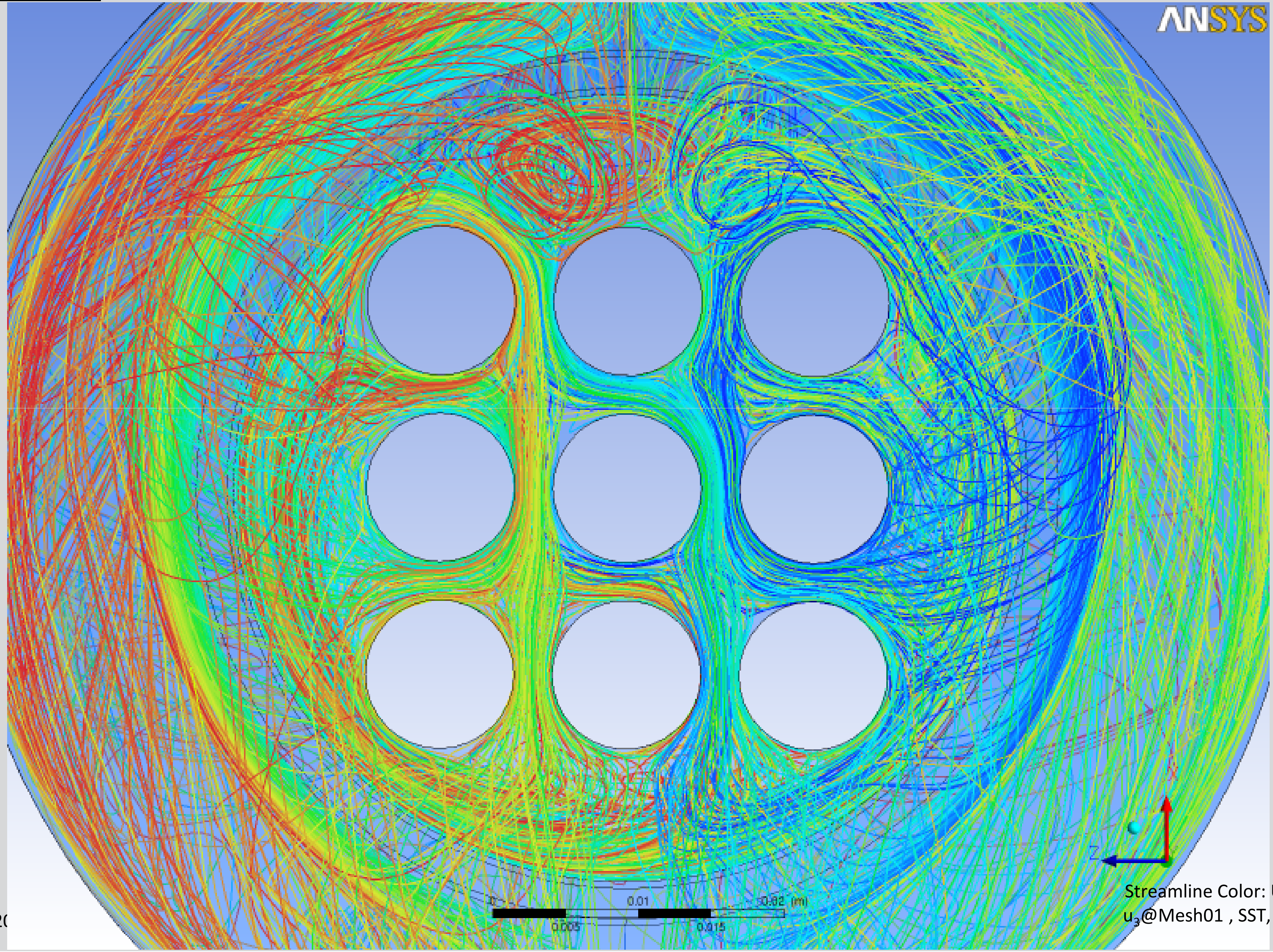
Flow Field Characteristics

Streamlines Inlet Vessel



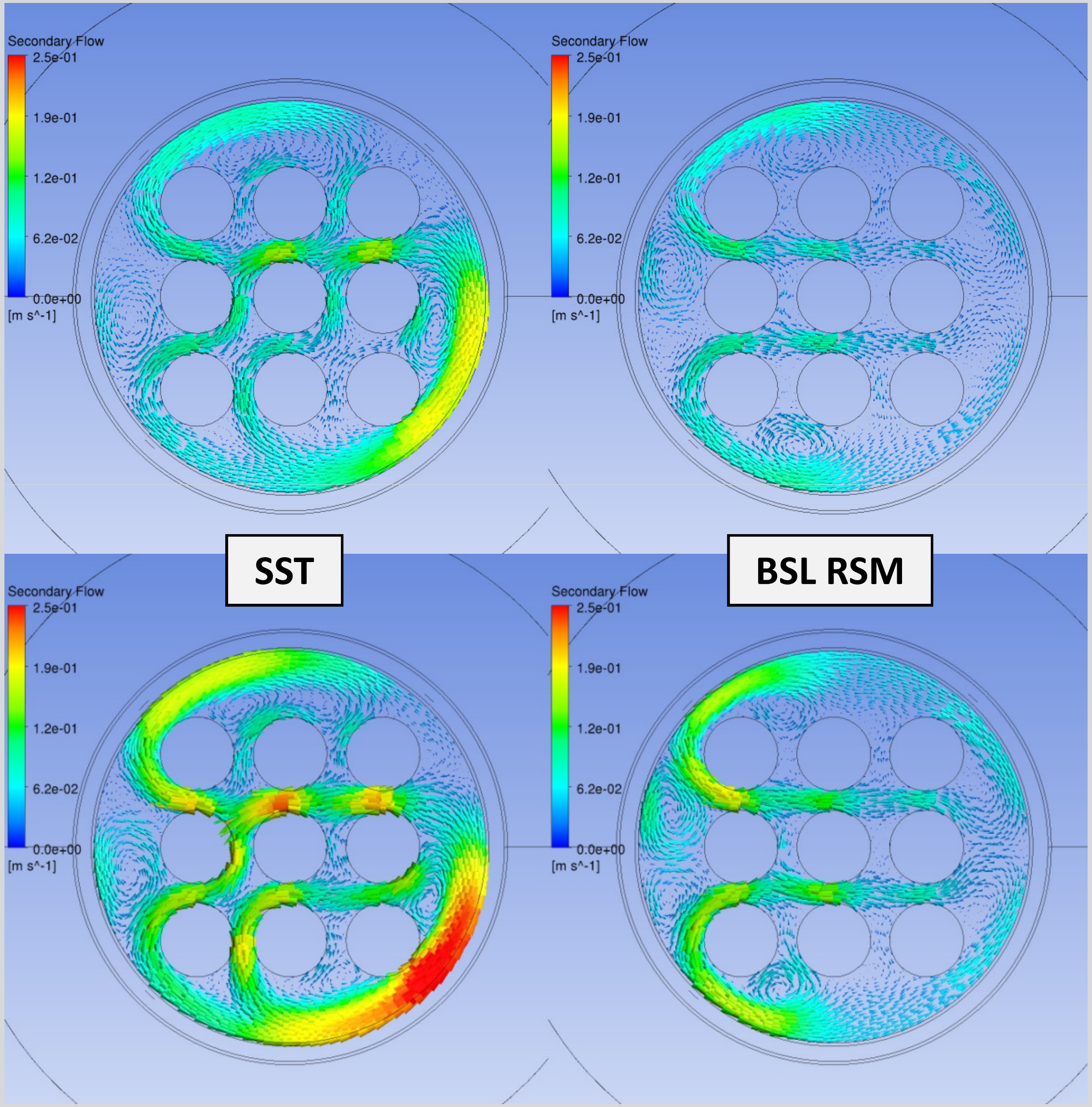
Streamline Color: Unique
u_3@Mesh01, SST, steady

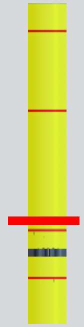
Streamlines Inlet Vessel – Bottom View

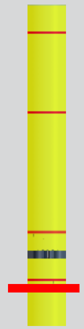


Secondary Flows w/o Spacer

u$_1$







Mesh01, transient

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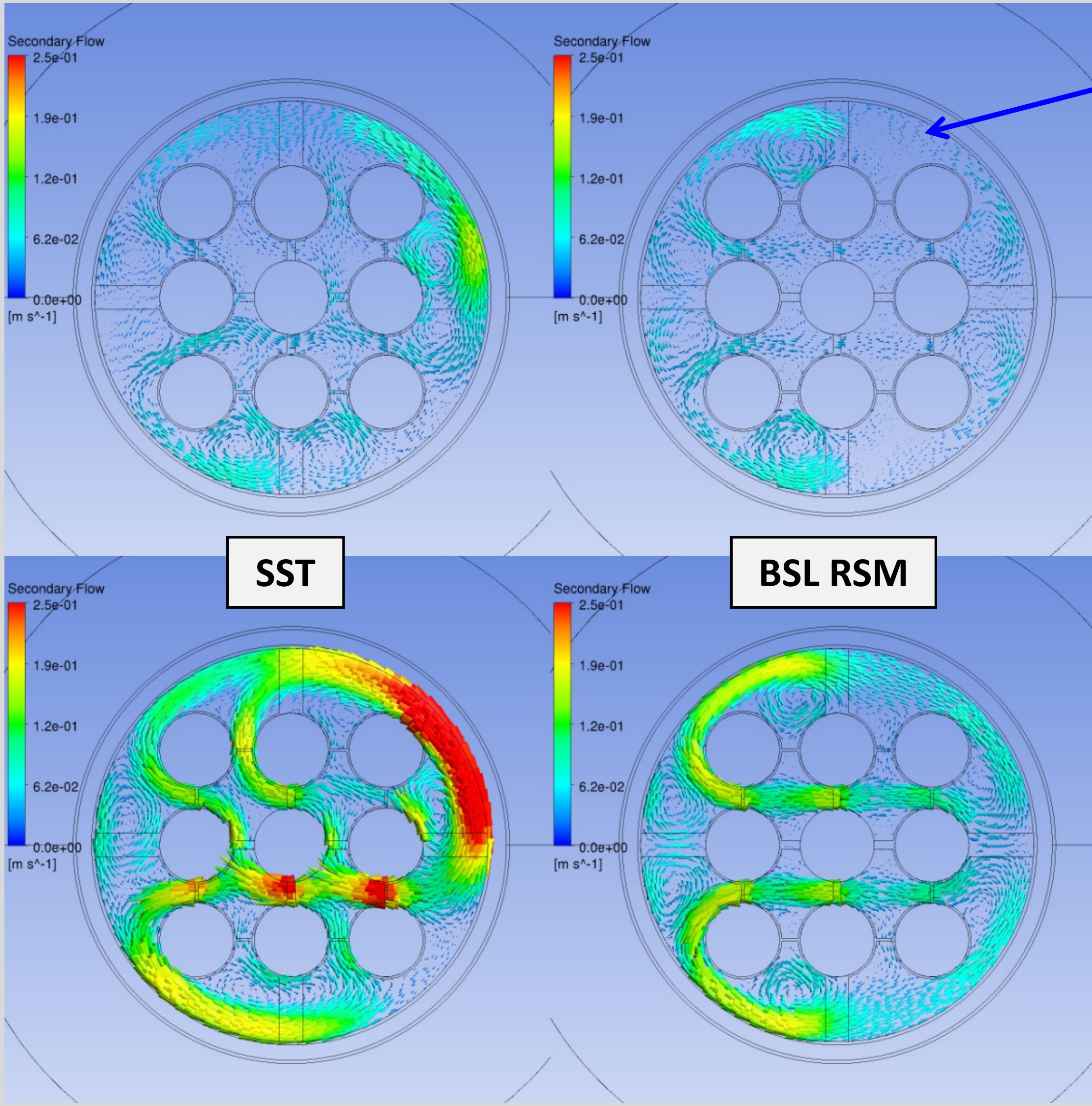
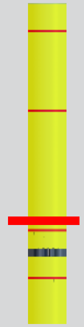
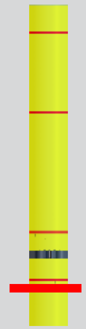
Secondary Flows with Spacer

u$_1$

Grid Spacer Effect





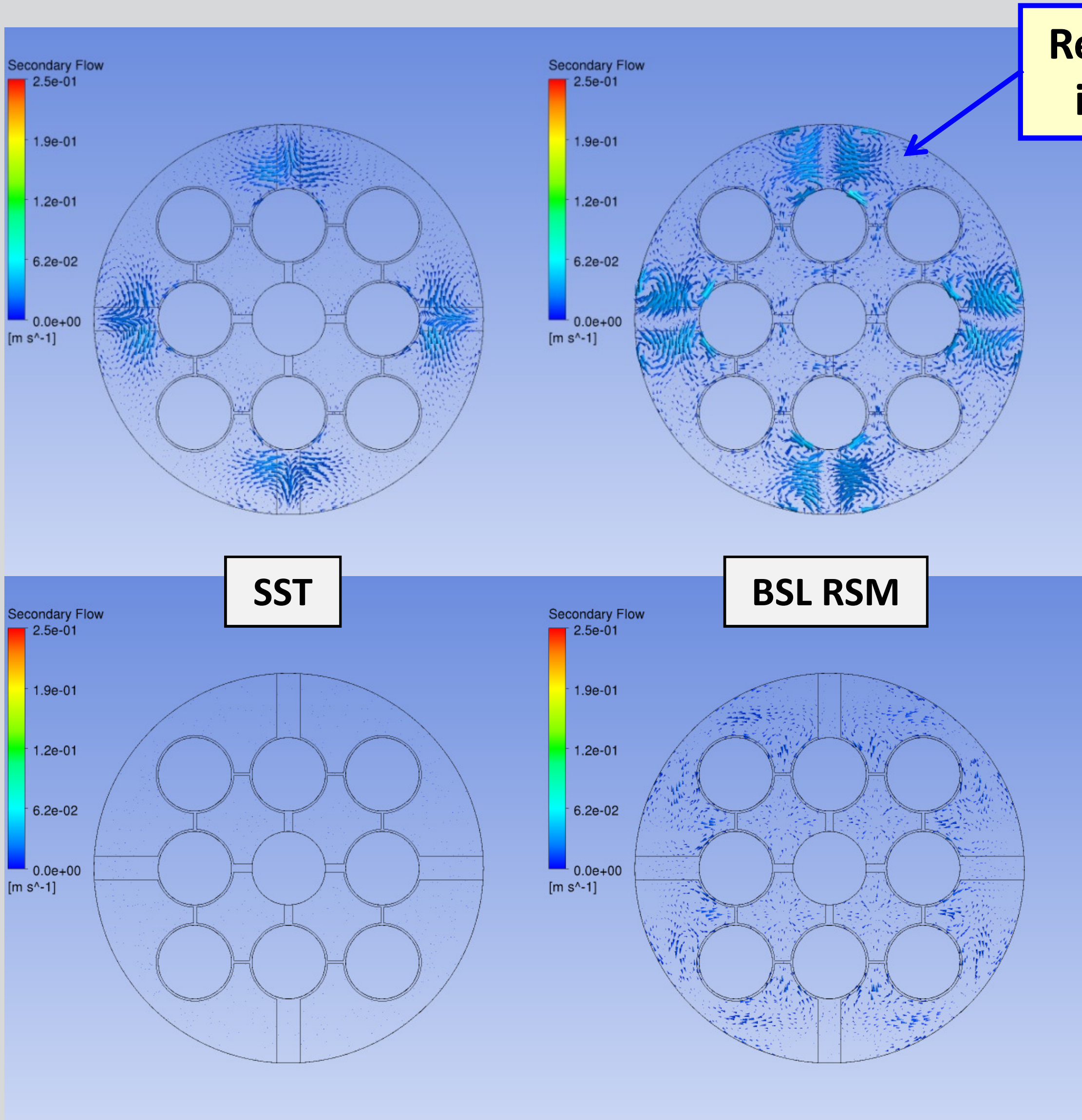


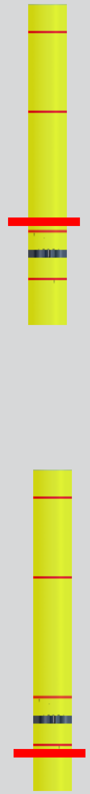
Mesh01, transient

Secondary Flows w/o Inlet Plenum

Case IV

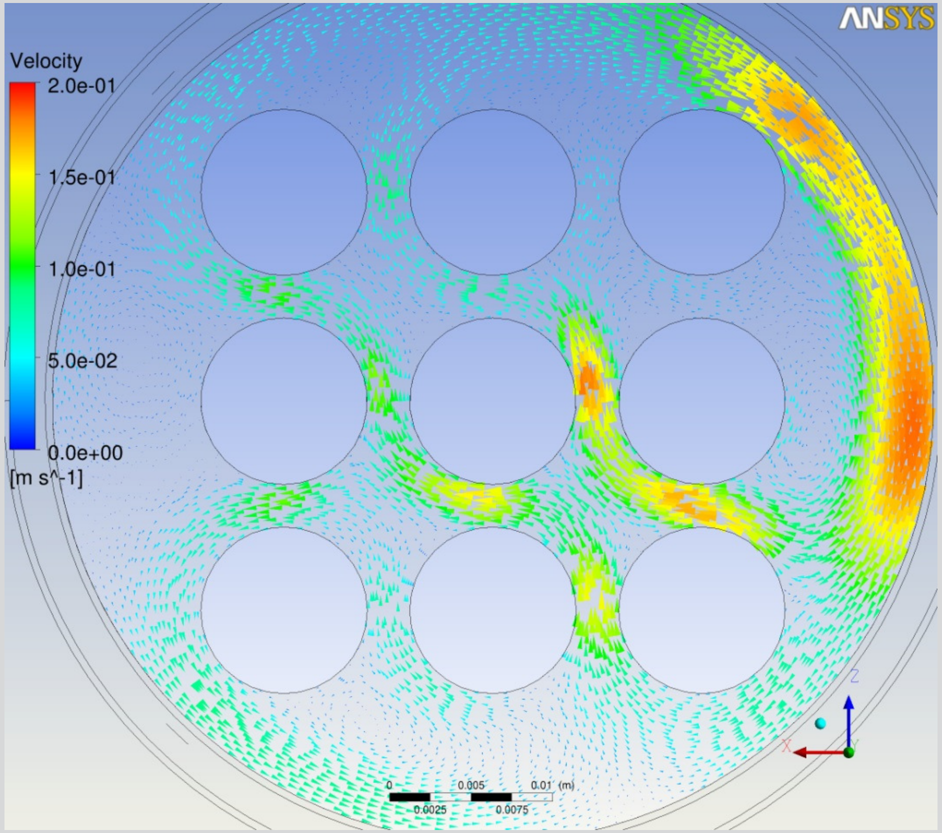
u_1





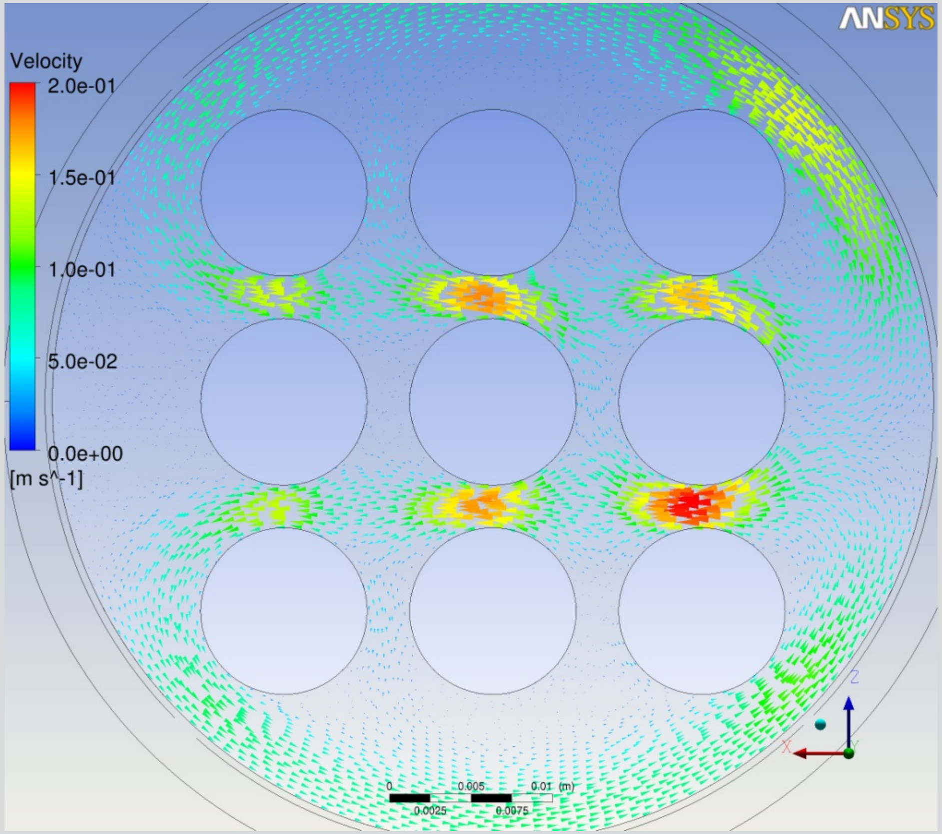
Mesh01, transient

Secondary Flow
SST Mesh Refinement



Transcient Average, SST, Mesh01

- **similar to Steady State Results, SST**



Transcient Average , SST, Mesh02

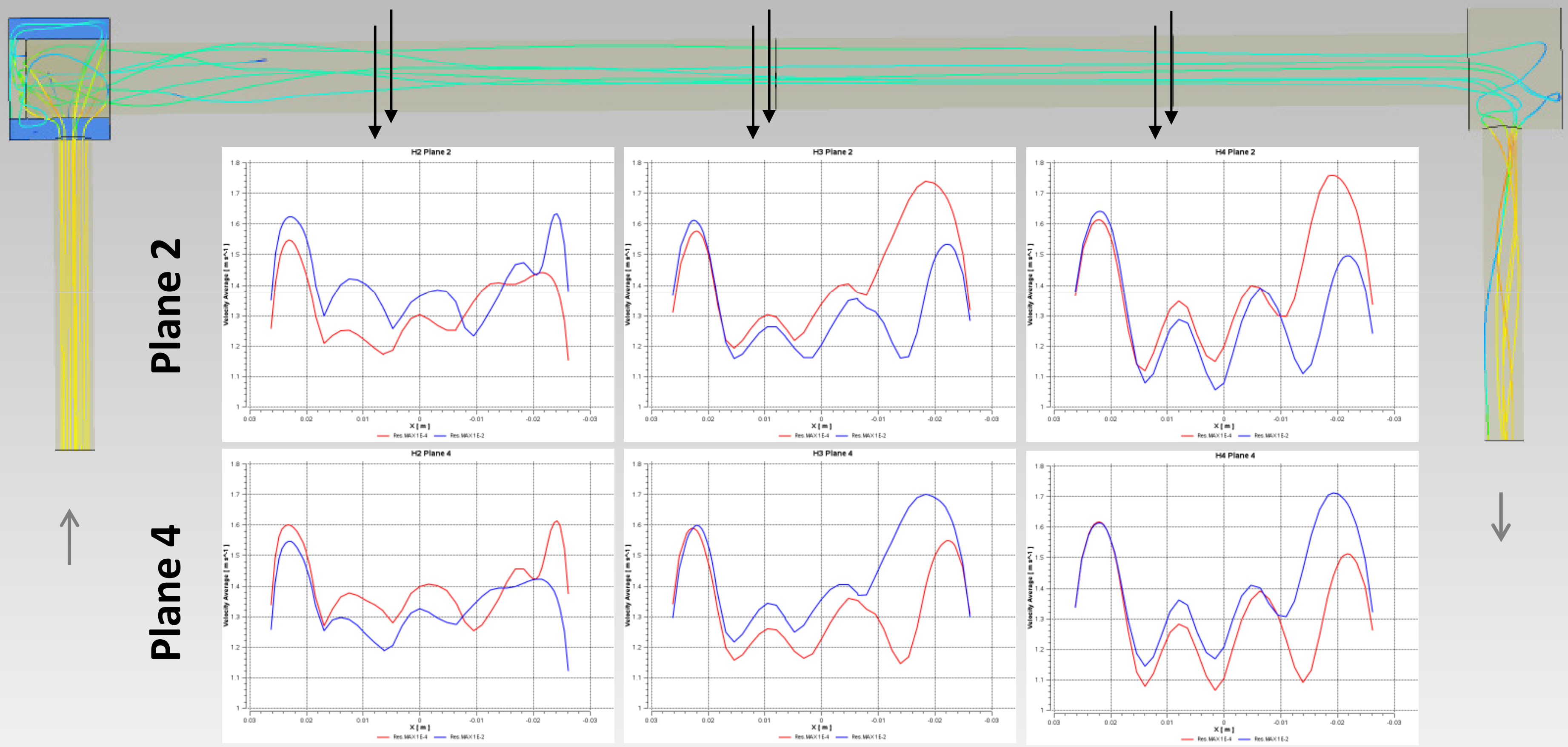
- **similar to Steady State Results, BSL RSM**

u3

Mirrored Case Appearance

Comparing Average Velocity Profiles Plane 2 and 4

Different Convergence Criteria, Velocity Range [1.0; 1.8]



Res.MAX 1E-4 Res.MAX 1E-2

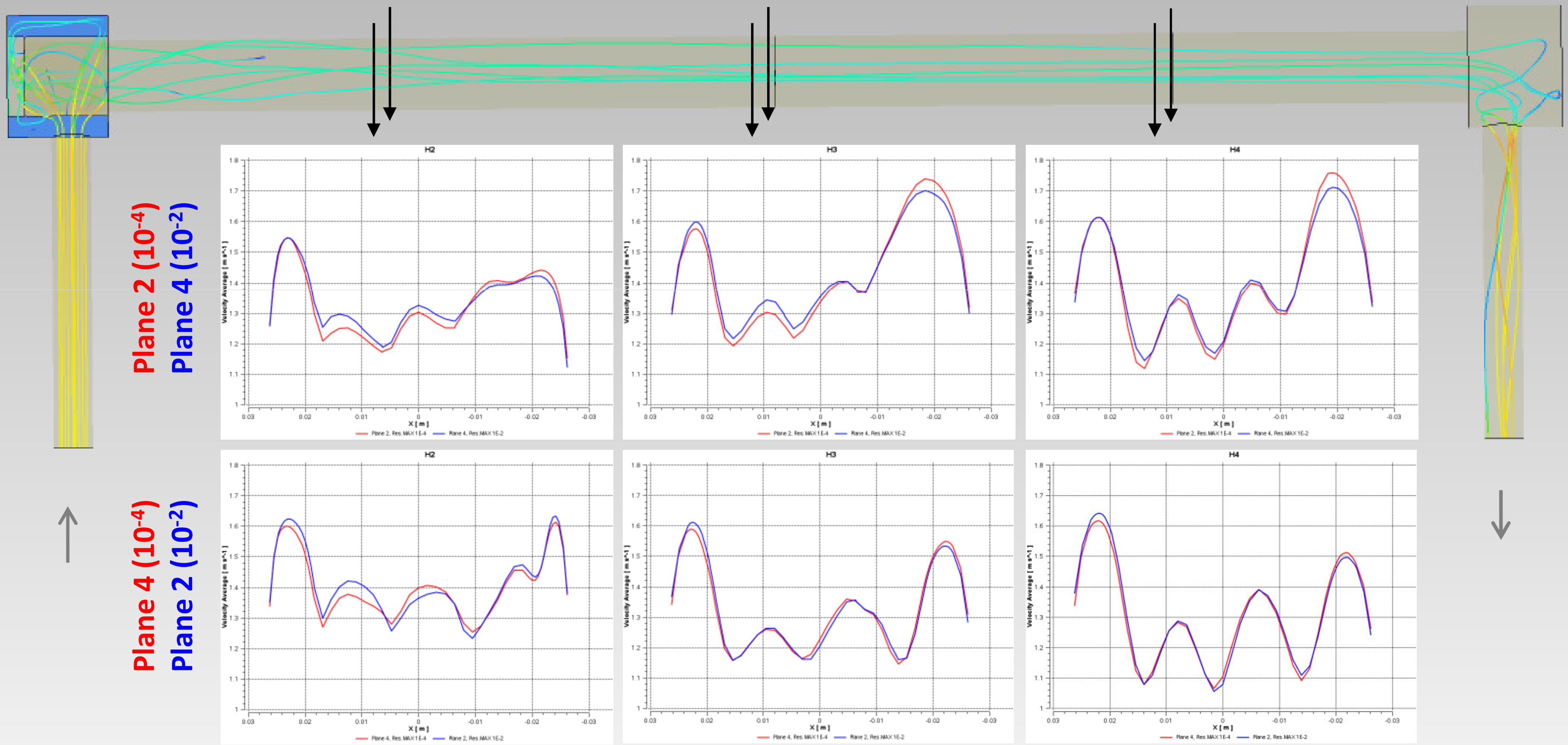
→ **Mirrored case established?**

averaging started at 1.6s, u_3@Mesh01

Mirrored Case Appearance

Comparing Average Velocity Profiles

Plane 2 and 4 switched in the 10^{-4} case



→ Mirrored case established

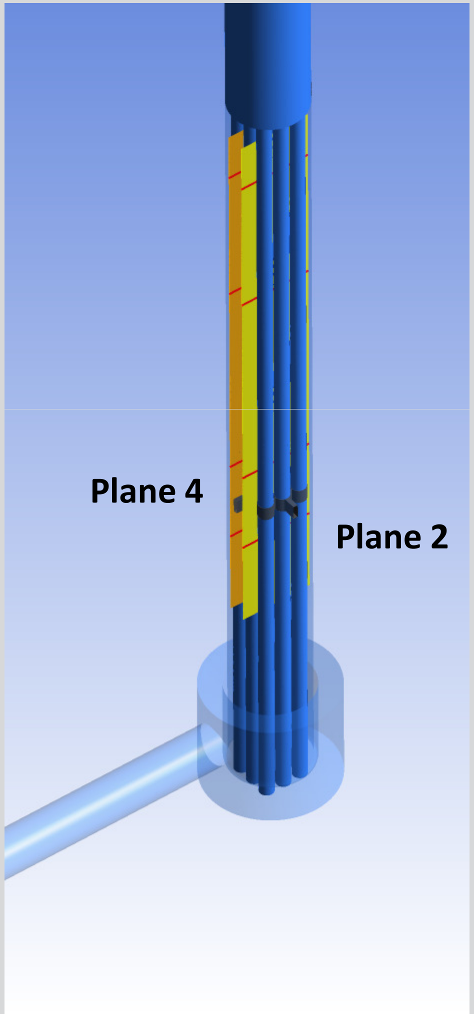
averaging started at 1.6s, u_3@Mesh01

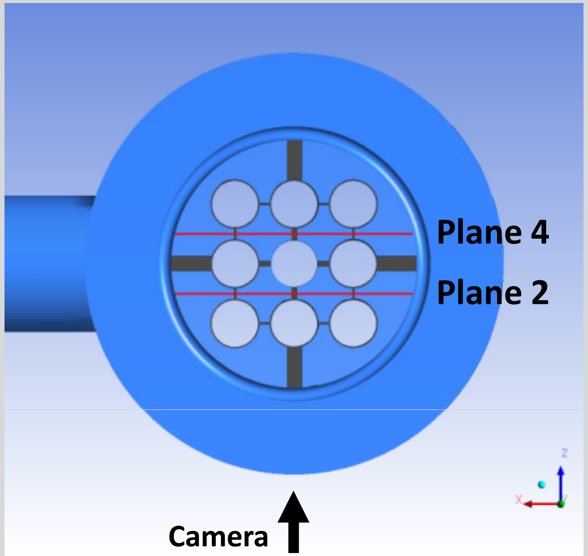
Quantitative Analysis:

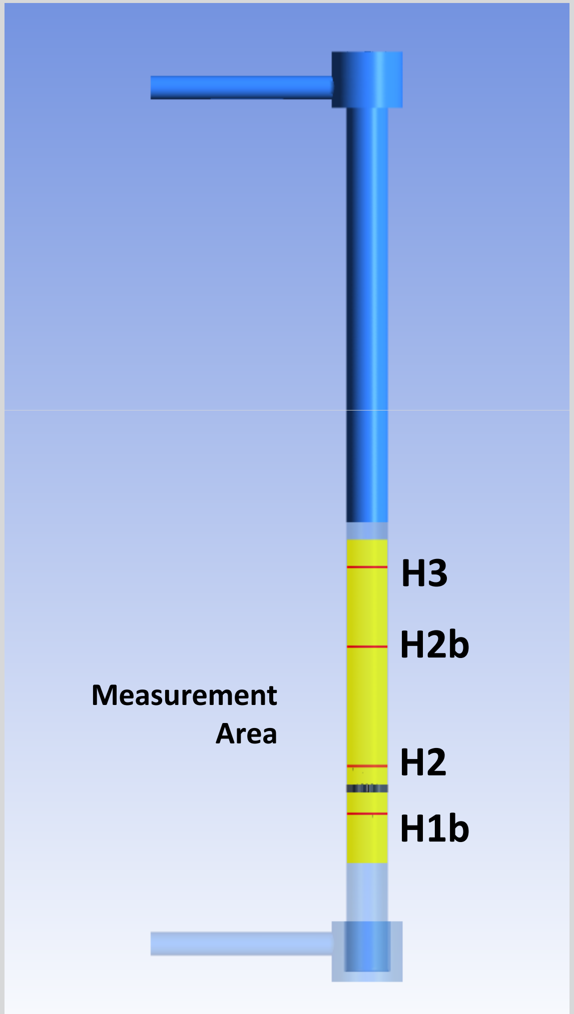
Comparison to Experimental Data

Experimental Comparison

Location of profile lines for data comparison



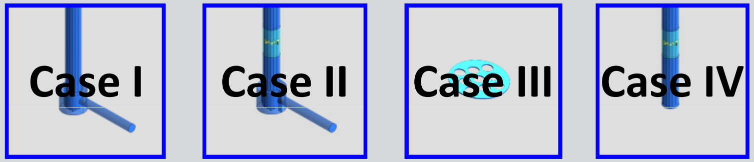




Experimental Comparison

Symbols

u_1 u_2 u_3



Legend

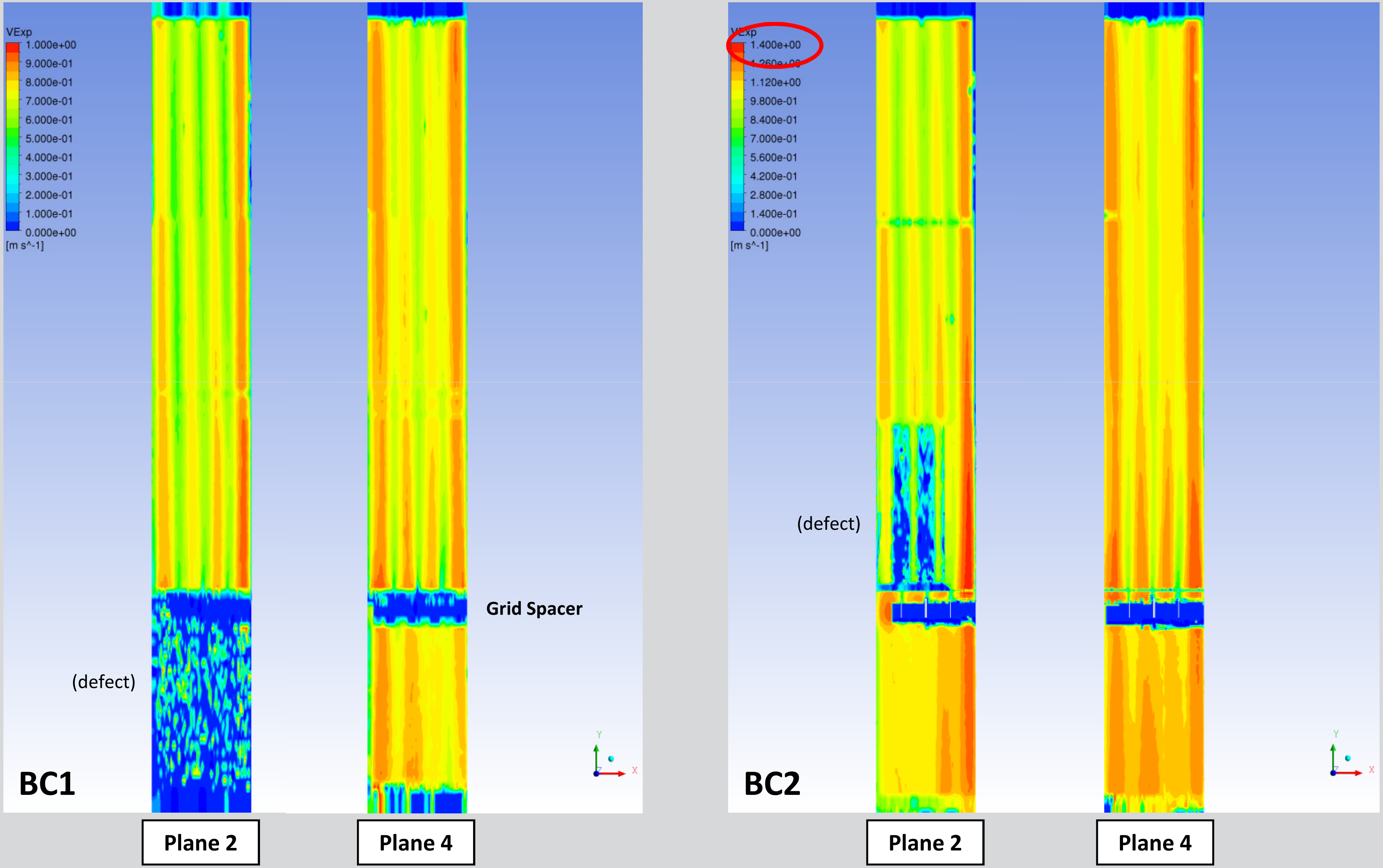
●	Experiment +/- 6%
red solid	SST Mesh01
red dashed	SST Mesh02
blue solid	BSLRSM Mesh01
blue dashed	BSLRSM Mesh02
orange solid	SST Mesh01 trans
orange dashed	SST Mesh02 trans
cyan solid	BSLRSM Mesh01 trans
cyan dashed	BSLRSM Mesh02 trans

instantaneous values considered (SST Mesh01, SST Mesh02, BSLRSM Mesh01, BSLRSM Mesh02)

average values considered (SST Mesh01 trans, SST Mesh02 trans, BSLRSM Mesh01 trans, BSLRSM Mesh02 trans)

transient SST results mirrored, velocity information changed below (SST Mesh01 trans, SST Mesh02 trans)

Experimental Velocity v



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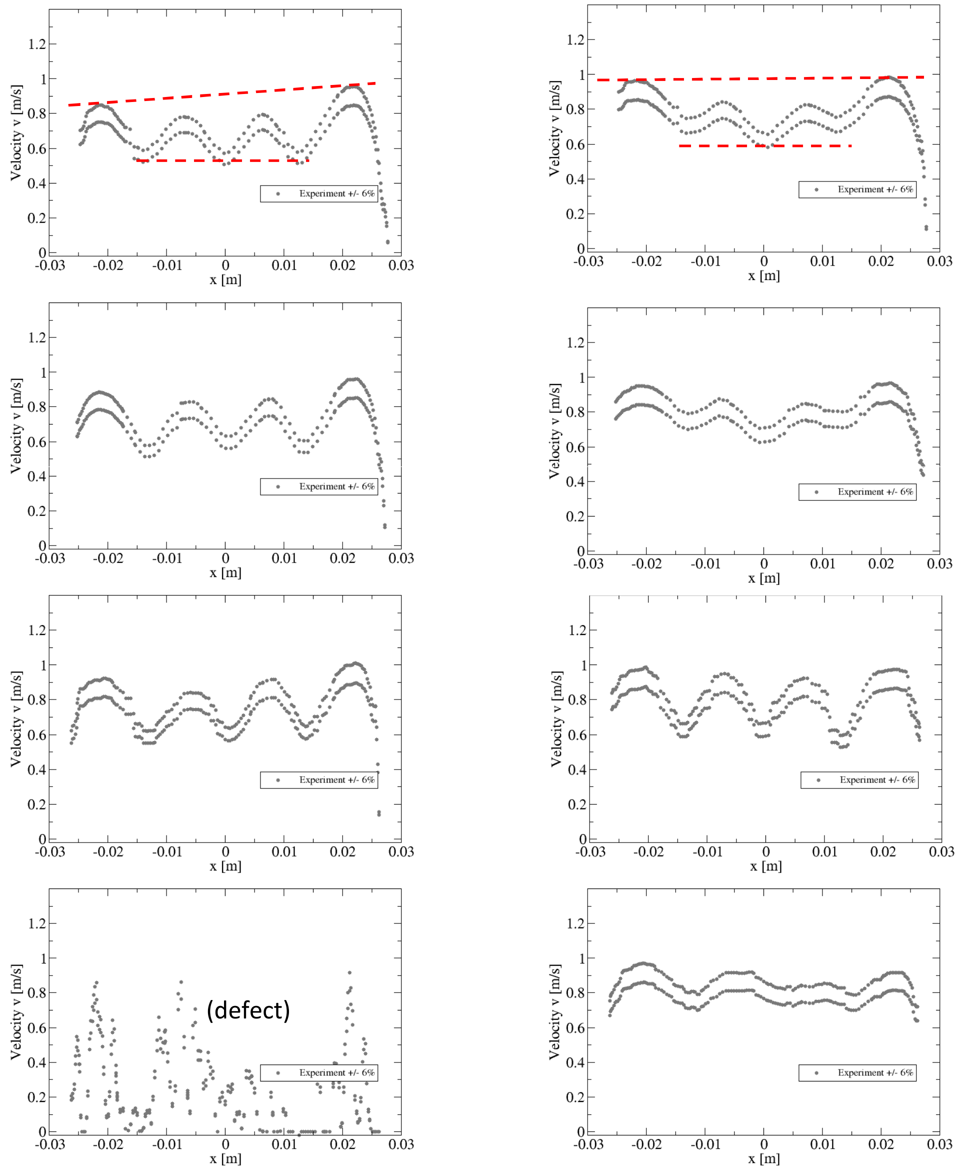
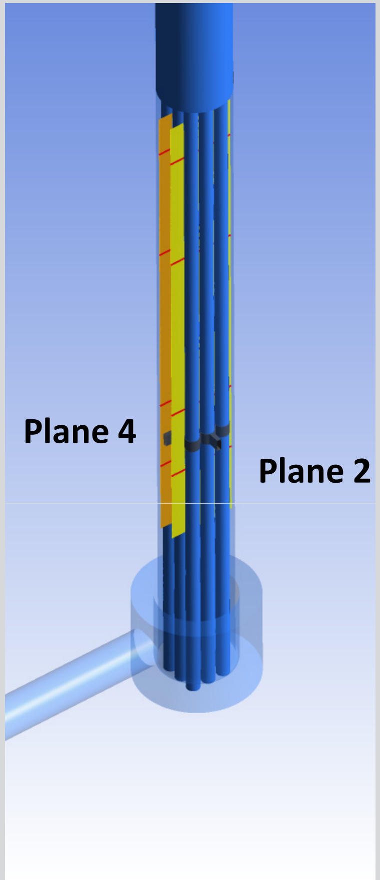
Experimental Velocity v

u_1

	Plane 2	Plane 4
H3		
H2b		
H2		
H1b		

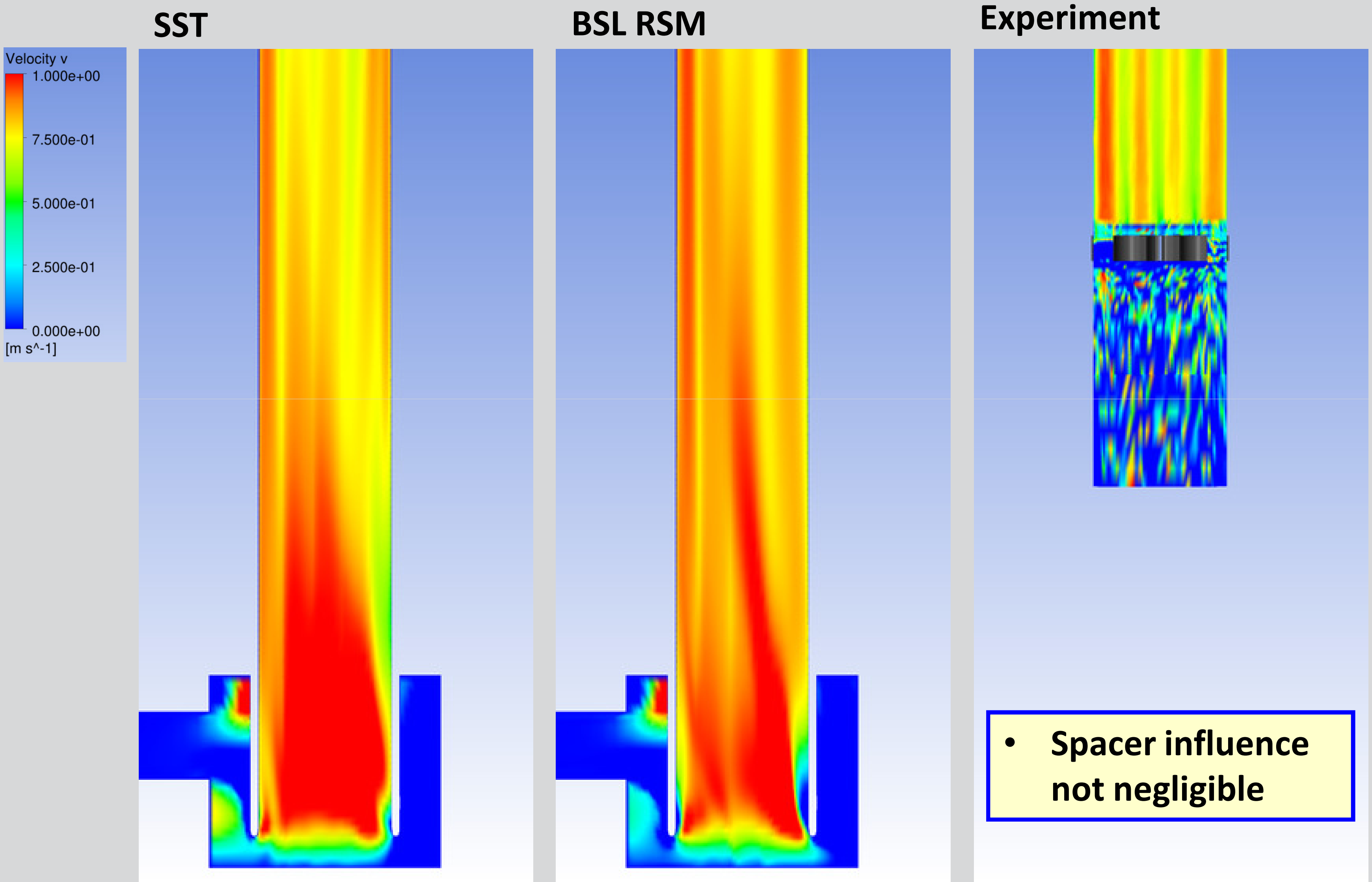




Velocity Field Plane 2

Case I

u_1



- **Spacer influence not negligible**

Plane 2, Mesh01, transient

Velocity Field Plane 4

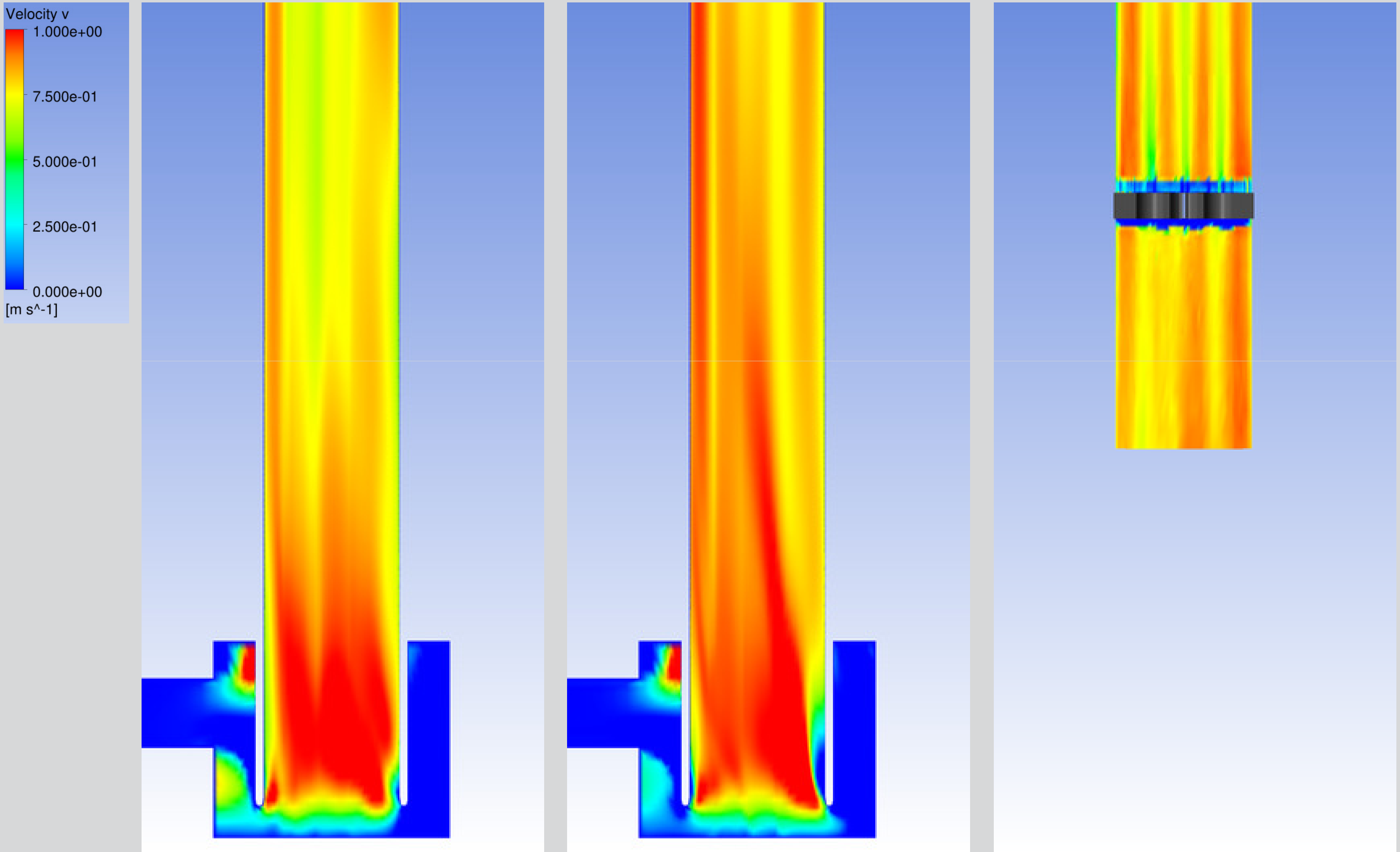
Case I

u_1

SST

BSL RSM

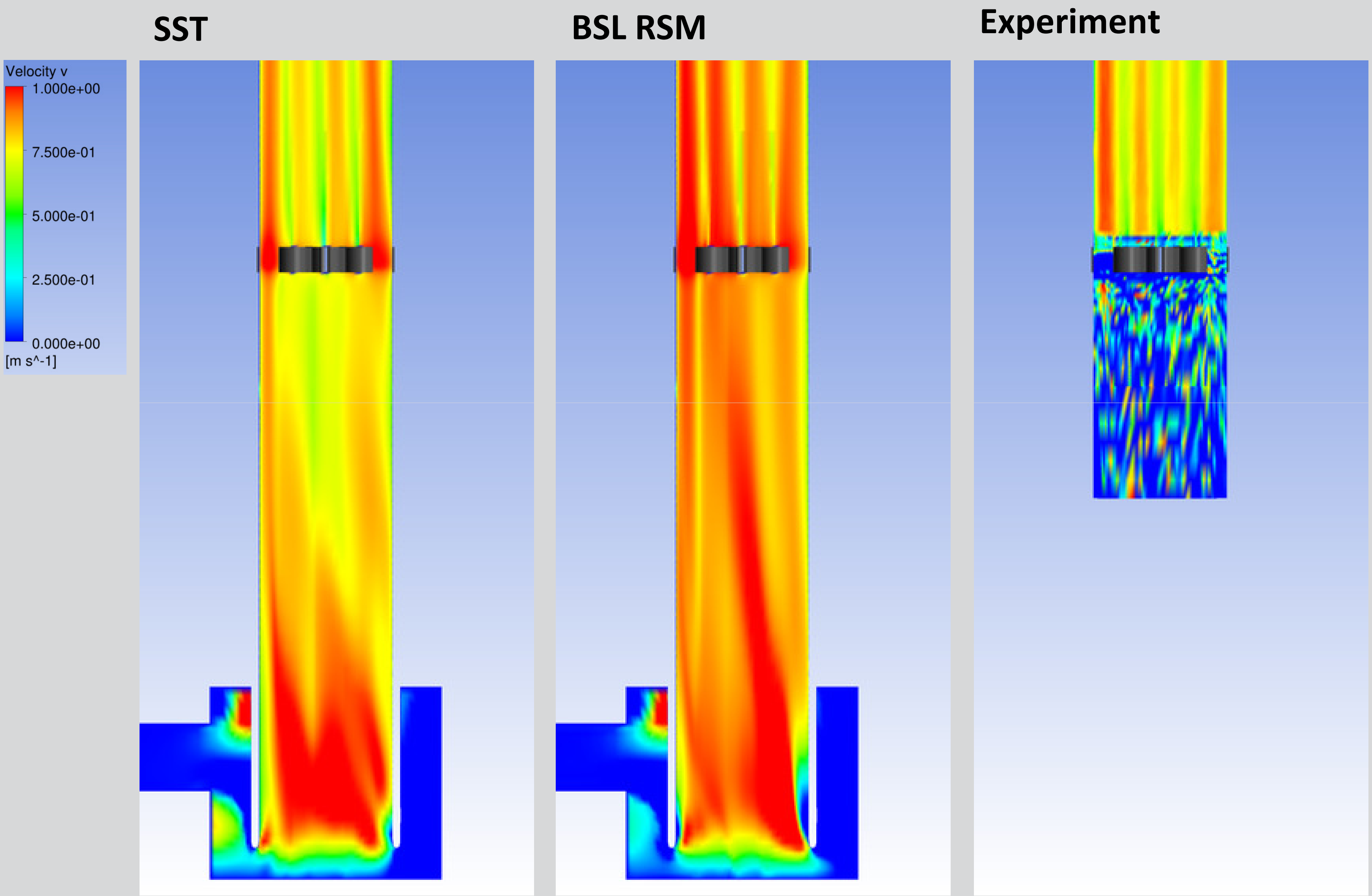
Experiment



Plane 4, Mesh01, transient

Velocity Field Plane 2

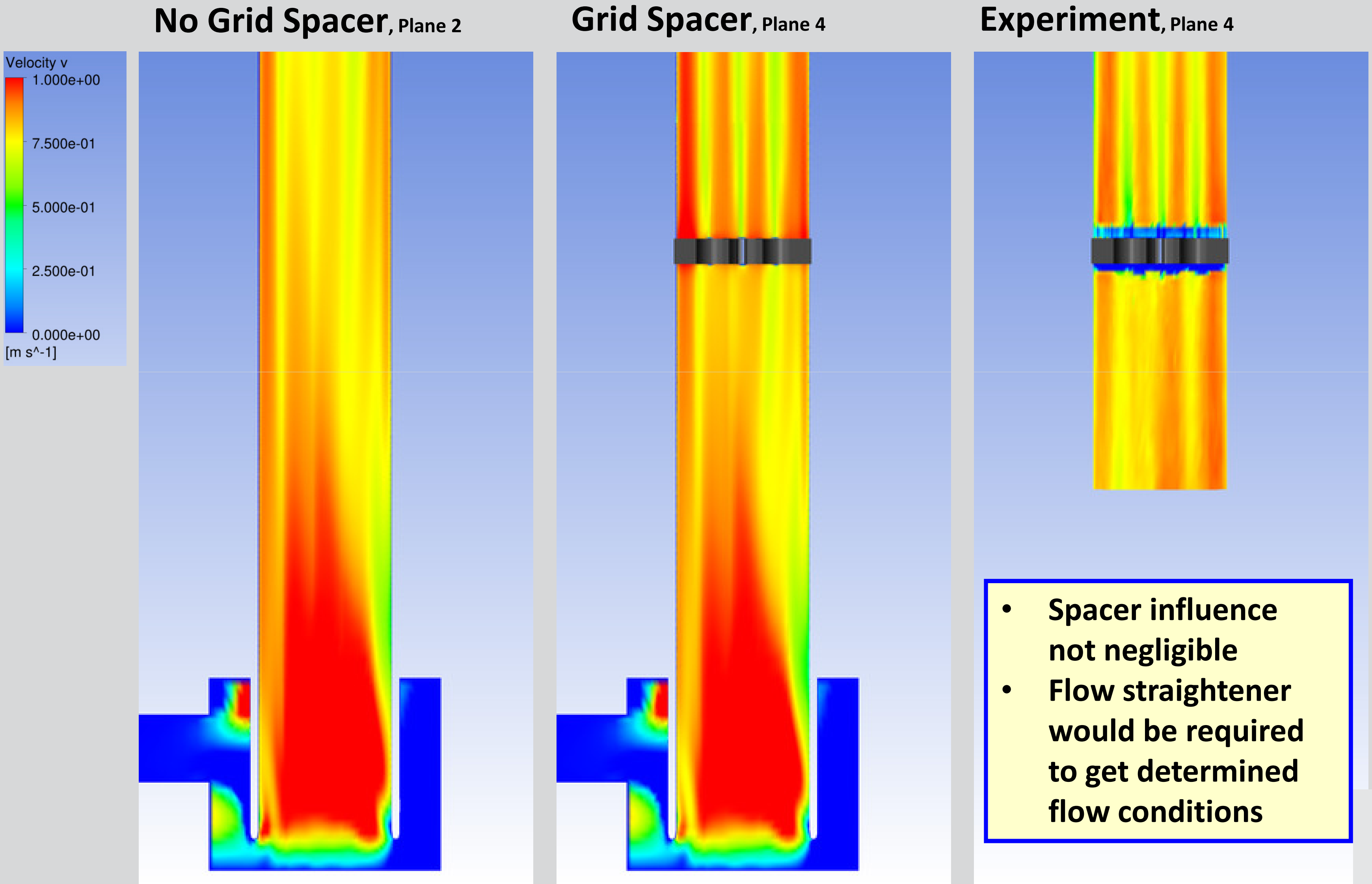
u$_1$



Plane 2, Mesh01, transient

Grid Spacer Influence, SST

u_1

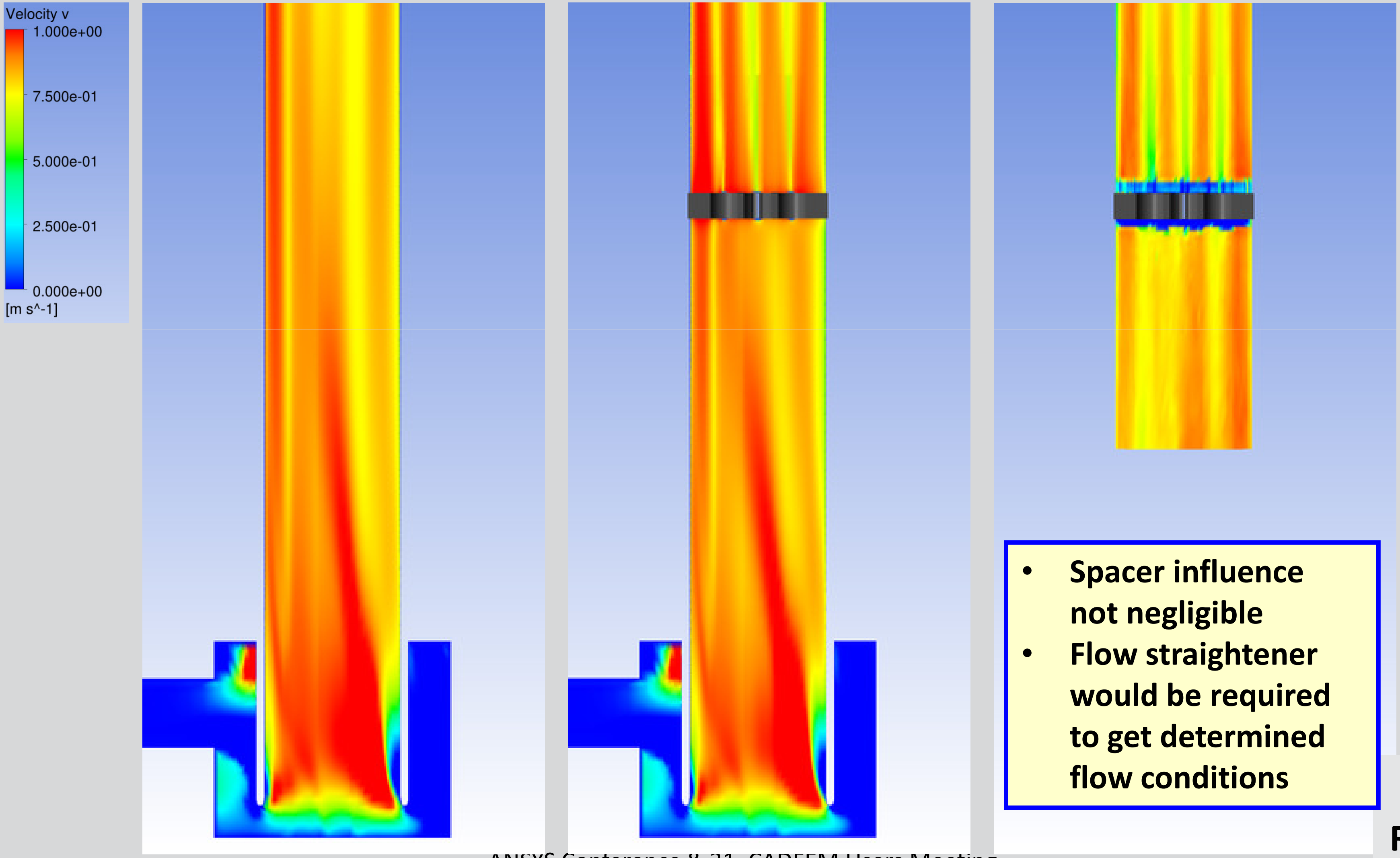


- Spacer influence not negligible
- Flow straightener would be required to get determined flow conditions

SST

Grid Spacer Influence, BSLRSM

No Grid Spacer, Plane 4 | Grid Spacer, Plane 4 | Experiment, Plane 4



- **Spacer influence not negligible**
- **Flow straightener would be required to get determined flow conditions**

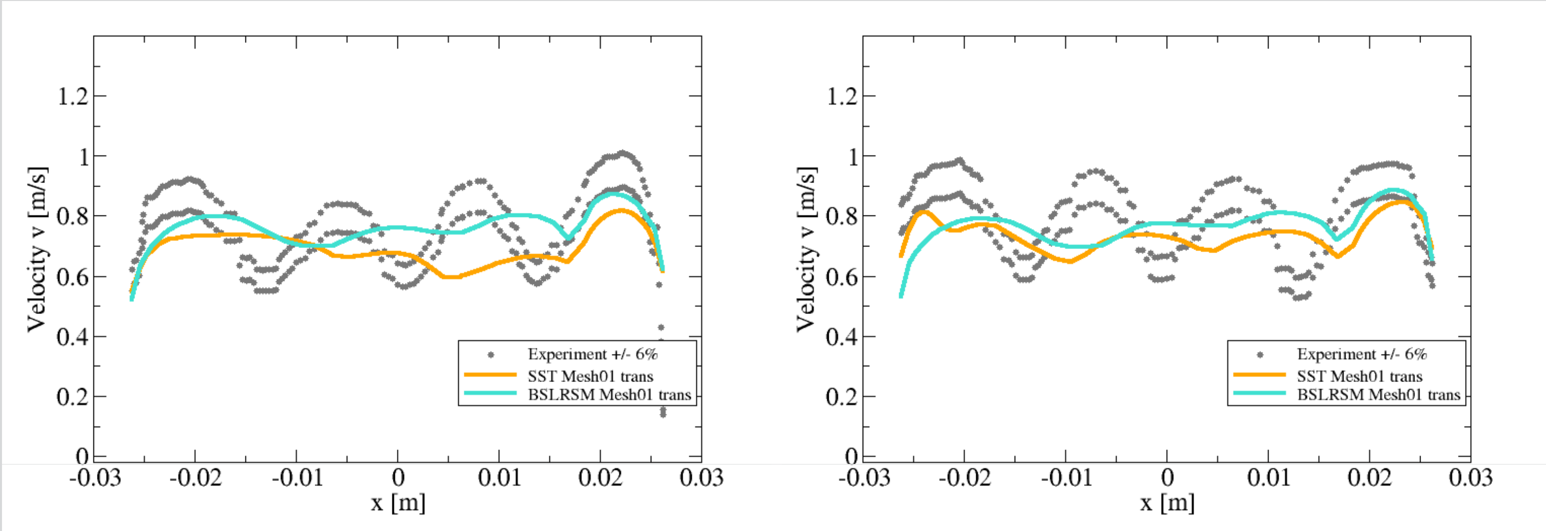
BSL RSM

Grid Spacer Influence

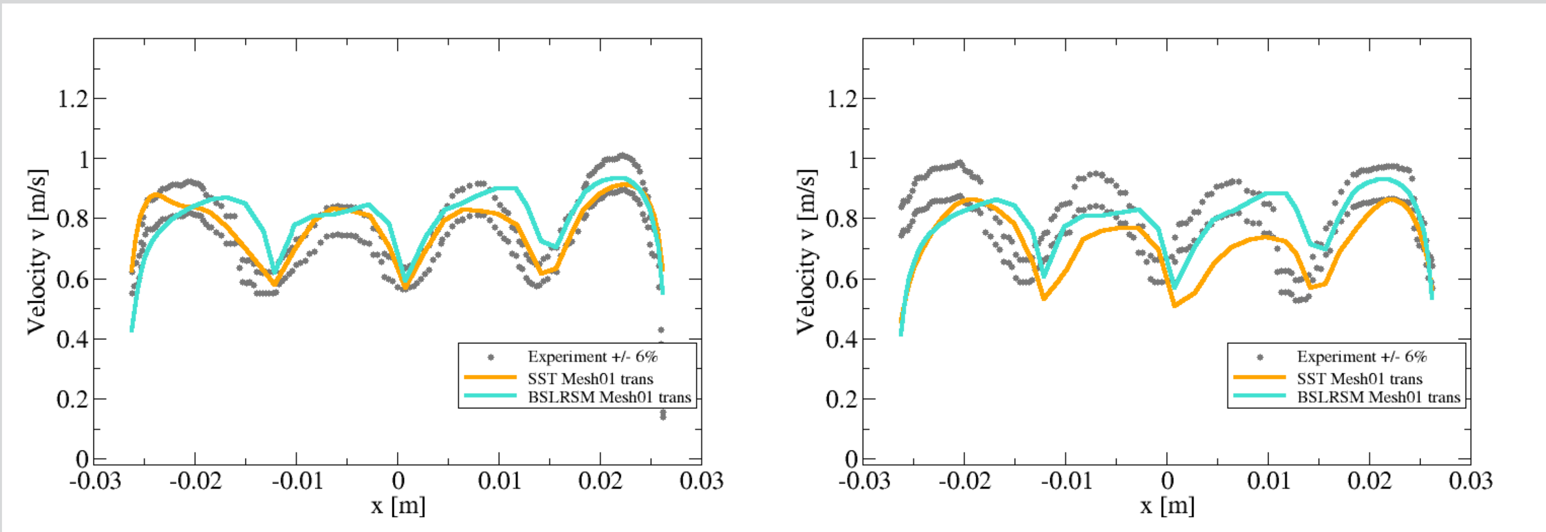
u_1

Plane 2 **Plane 4**

Case I



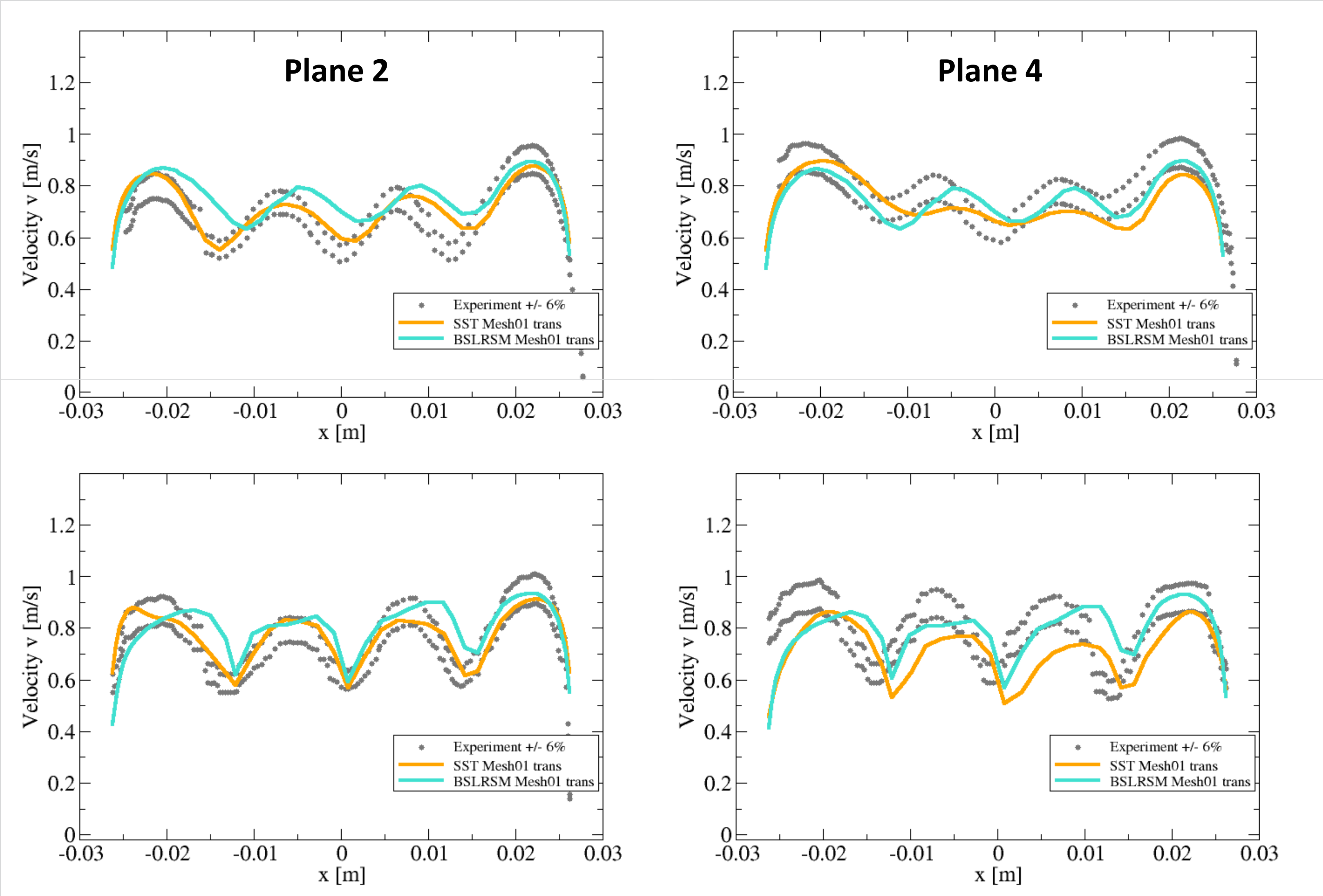
Case II

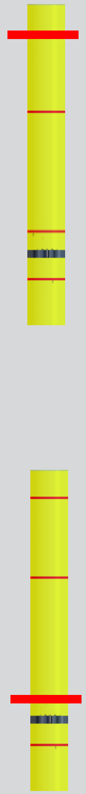


u$_1$

Turbulence Model Comparison

SST vs. BSL RSM





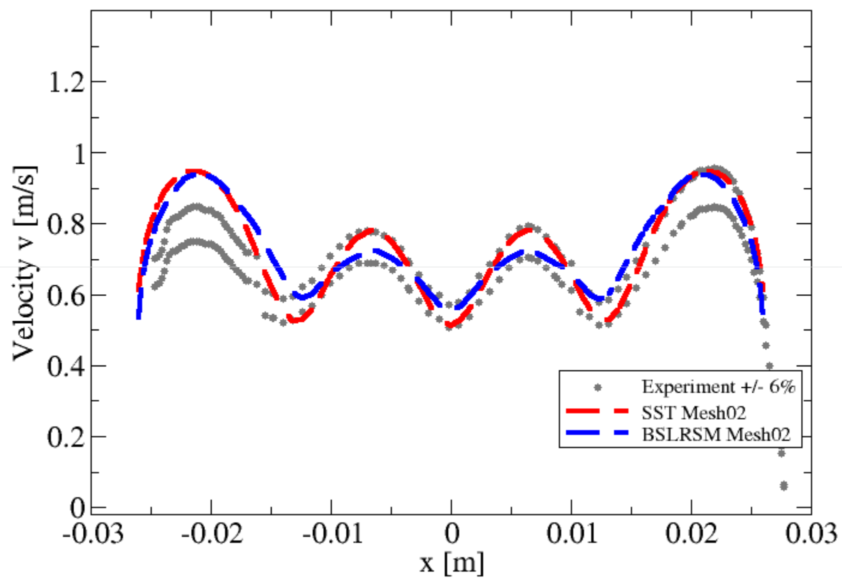
ANSYS Conference & 31. CADFEM Users Meeting,
Kongresszentrum Rosengarten, Mannheim, Deutschland, 19.-21. Juni 2013

Turbulence Model Comparison for Fully Developed Flow

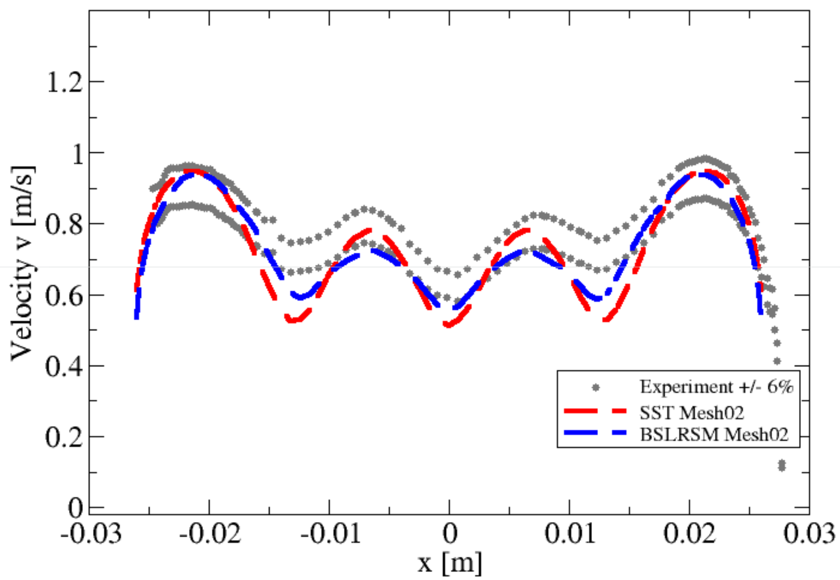
Case III u_1

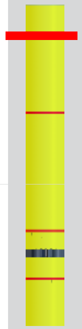
SST vs. BSL RSM

Plane 2



Plane 4





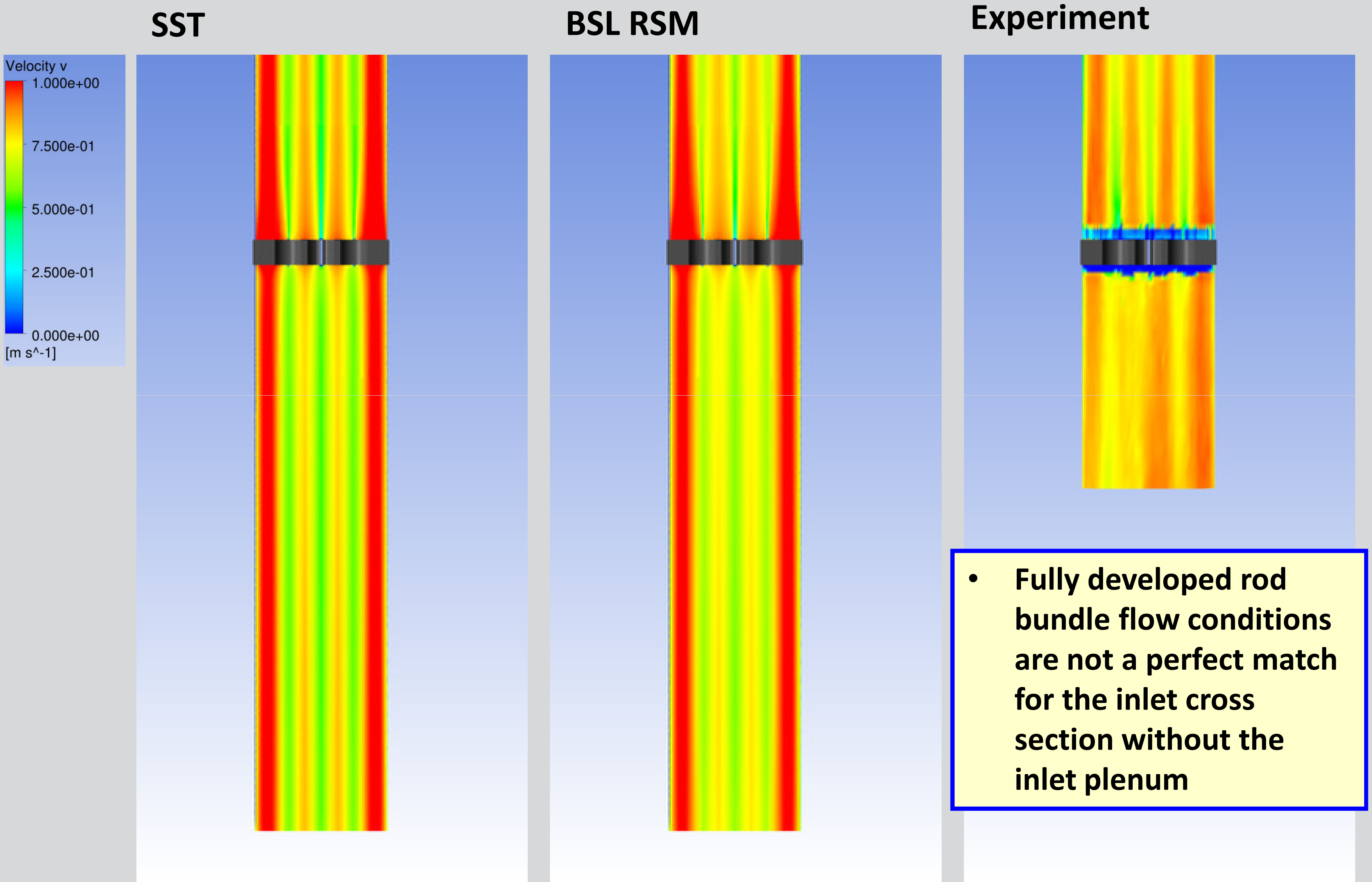
Scaling of CFD results based on comparison of fully developed flows:

$$v_{CFD,scaled} = f \cdot v_{CFD} \qquad with \qquad f = \frac{\dot{m}_{EXP}}{\dot{m}_{CFD}} \approx \frac{v_{max,\,subchannel,\,EXP}}{v_{max,\,subchannel,\,BSL\,RSM}} = \frac{0.73}{0.79} = 0.924$$

Velocity Field

Case IV

u_1



- **Fully developed rod bundle flow conditions are not a perfect match for the inlet cross section without the inlet plenum**

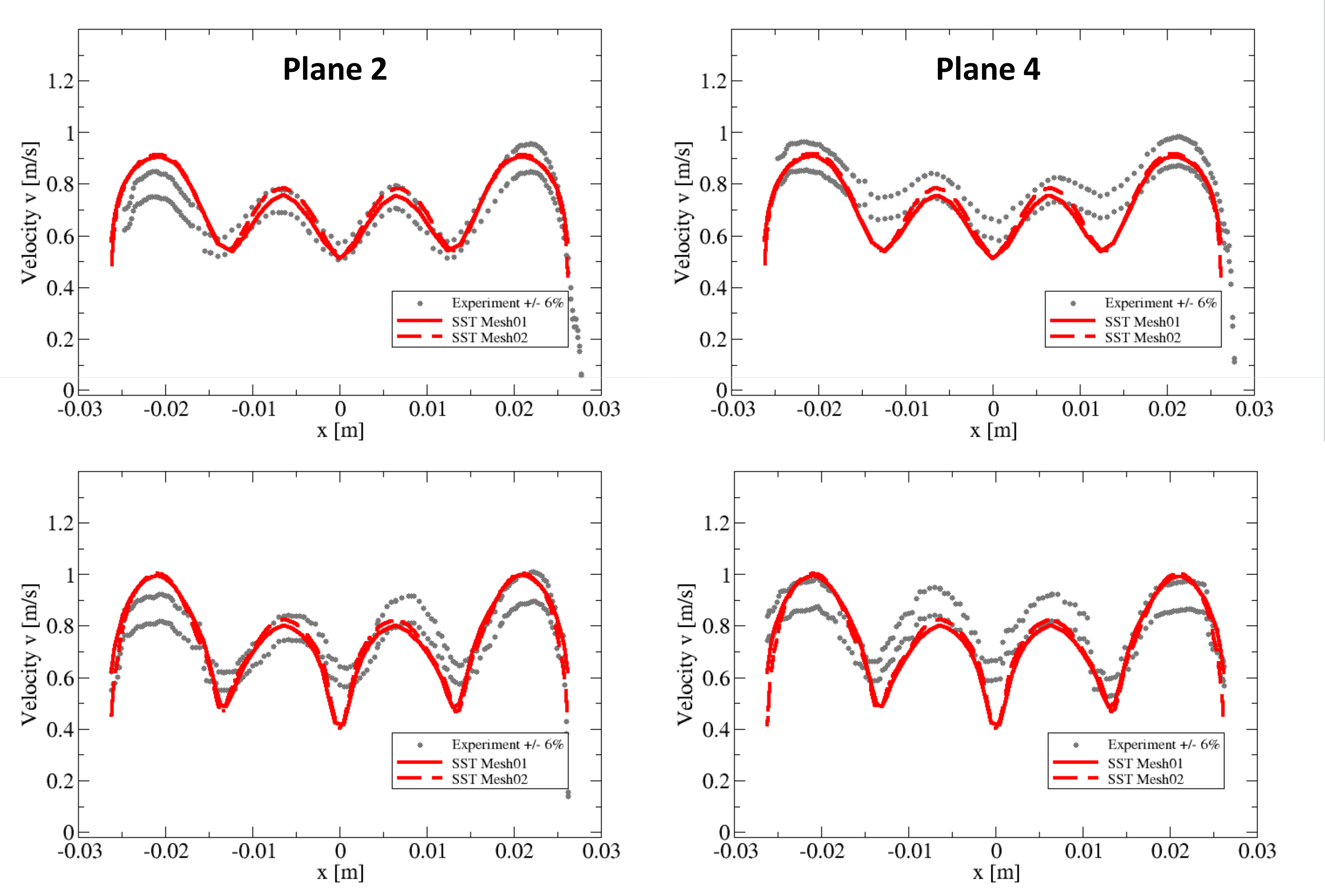
Mesh01, transient, Plane 2 and 4

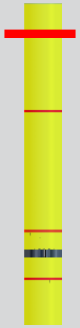
Grid Independency, SST Model

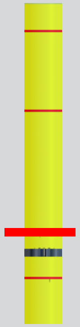
Case IV

u_1

Mesh01 vs. Mesh02, SST



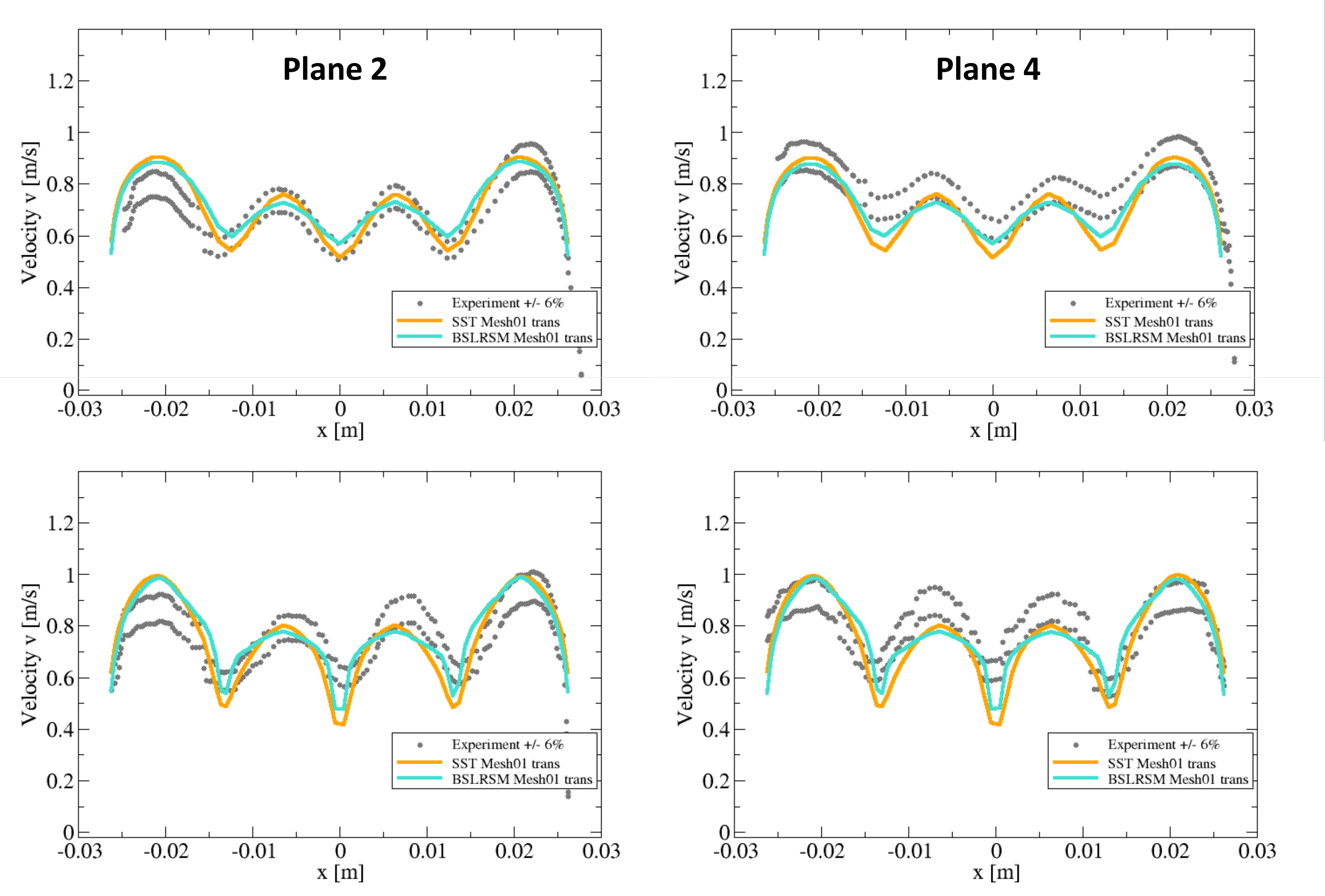


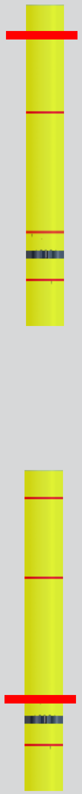


Turbulence Model: SST vs. BSLRSM

Case IV

u_1





Conclusions

- Flow in inlet plenum very unsteady, causes asymmetry and swirl, inflow conditions not well controlled in experiments

- Non negligible impact of the spacer grid
  → swirl reduction like for a flow straightener despite the short length and thin sheet metal material

- Uncertainties in experiment and measurements:
  - Flow inlet into inlet plenum with riffle hose of unclear position
  - Mass flow rates not accurately specified or controlled
  - Distance between camera position and measurement plane not accurately measured → "scaling effect" on velocities

- Geometry models I→IV: from qualitative to quantitative agreement
- Finally the Case IV results are grid independent and show reasonably good comparison to experiments, at least for higher elevation
- For boiling flow experiments more effort for reliable inflow conditions to the test section is required
  → Otherwise the use for CFD model validation would be questionable

Acknowledgements

SPONSORED BY THE

Federal Ministry of Education and Research

This research has been supported by the German Ministry of Education and Research (BMBF, Grant No. 02NUK010G) in the framework of the R&D funding concept of BMBF "Basic Research Energy 2020+", the German CFD Network on Nuclear Reactor Safety Research and the Alliance for Competence in Nuclear Technology, Germany.

Questions ?