Thermal-hydraulics of Nuclear Reactors

ADVANCED MODELLING & SIMULATION – AMS –

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JULY 2018

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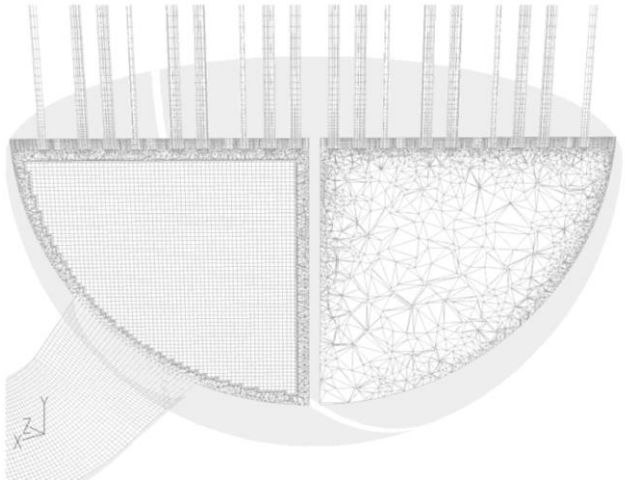
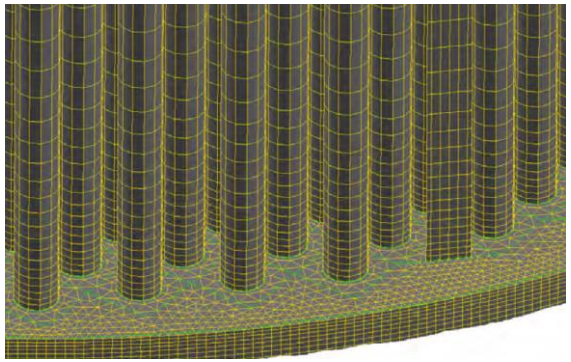
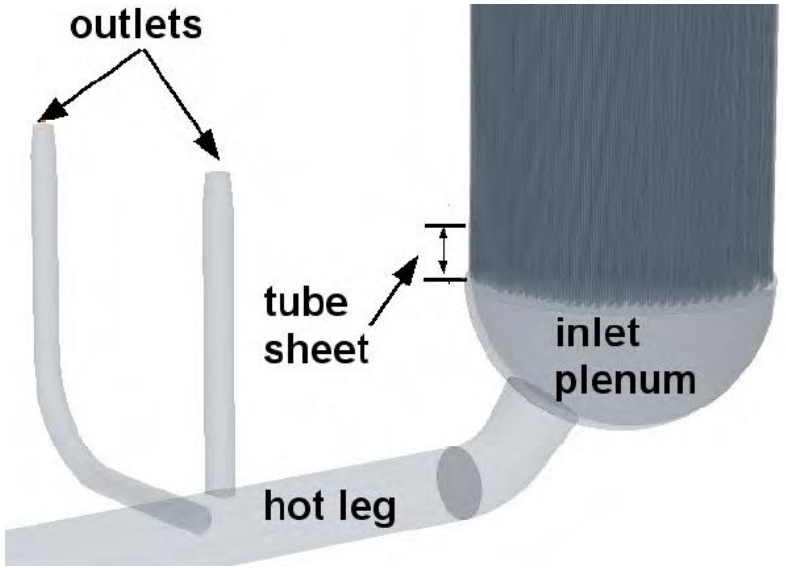
Flow in Steam Generators: Fluent grid







- **Courtesy: NRC (Chris Boyd, FLUENT)**

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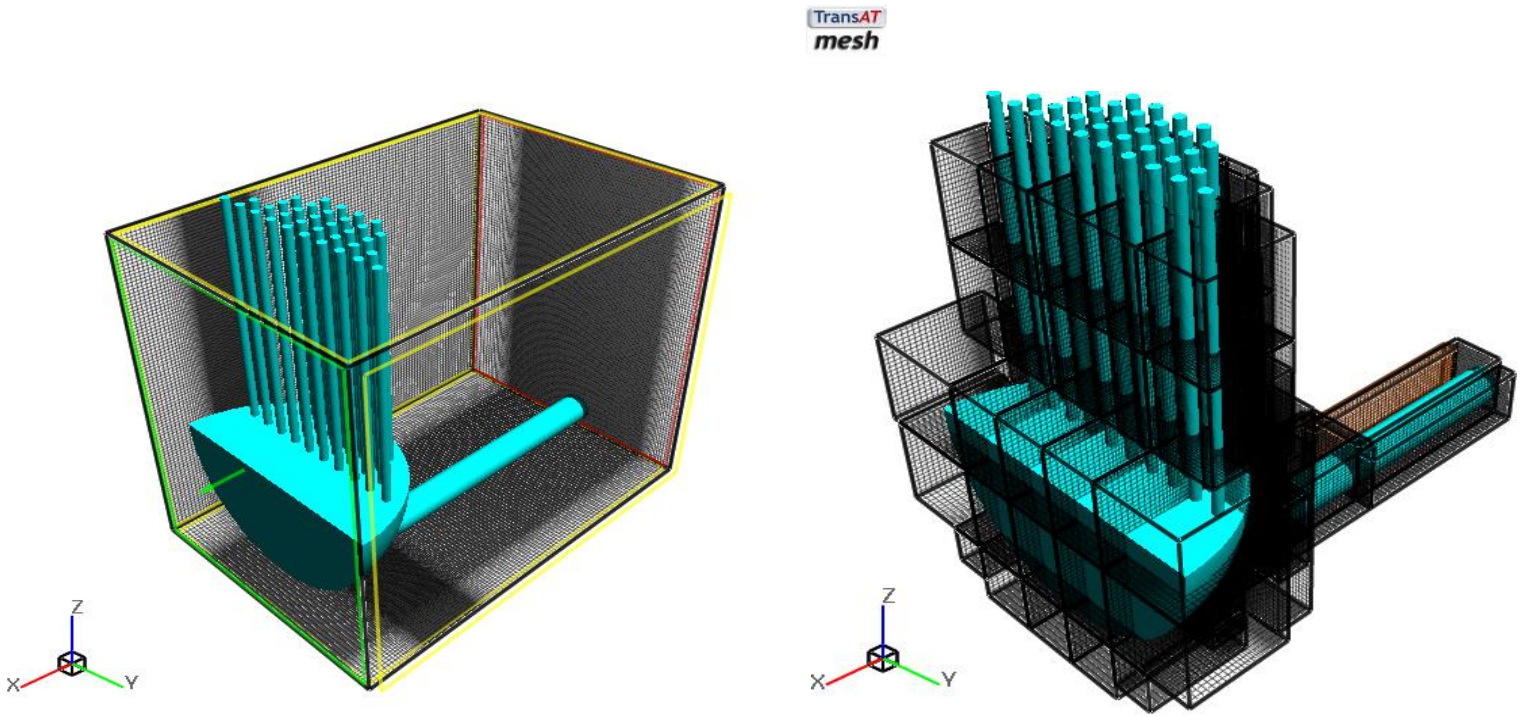
Flow in Steam Generators: TransAT grid



- **ASCOMP (TransAT)**

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Fluent & TransAT solutions

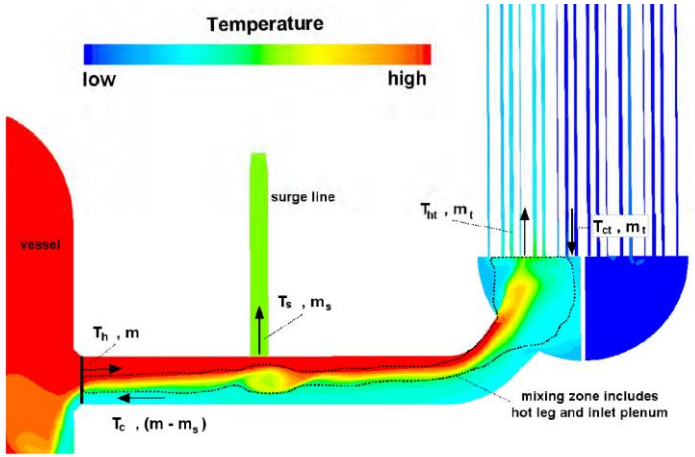
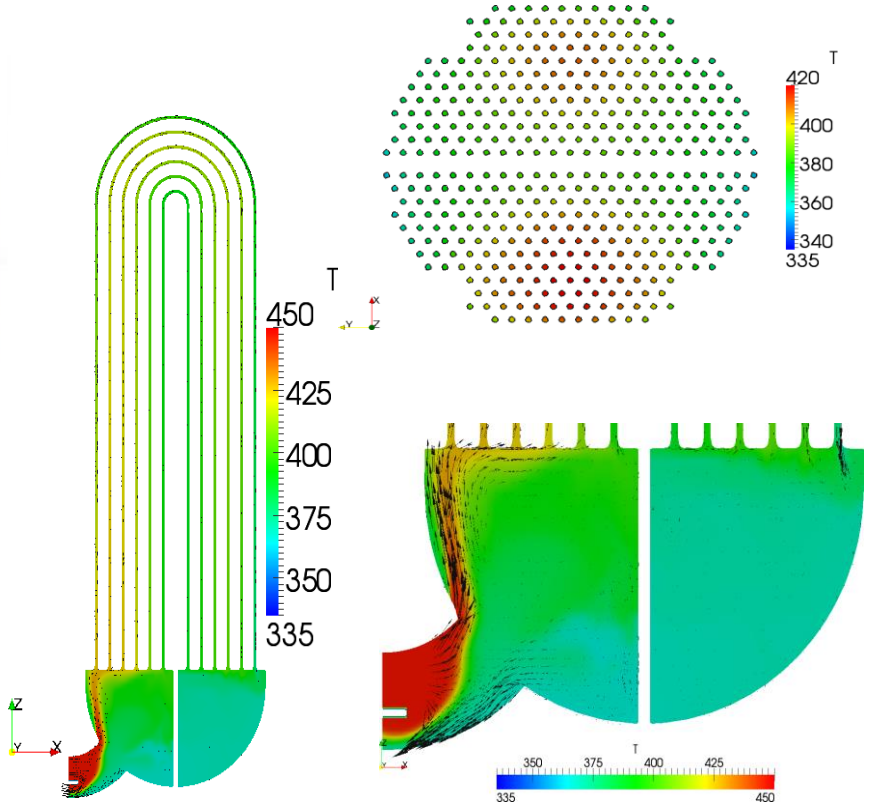


Figure 13. CFD Predictions Indicating Expanded Mixing Region

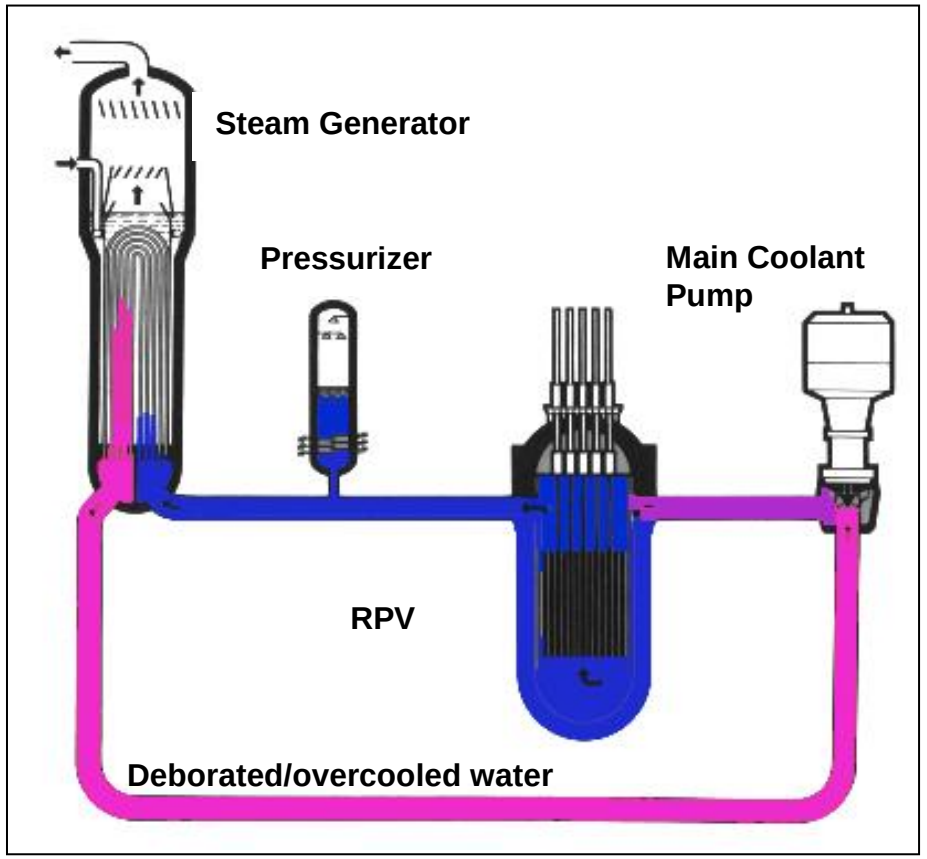
- **NRC (Fluent)**



- **ASCOMP (TransAT)**

Boron mixing in PWR primary circuit

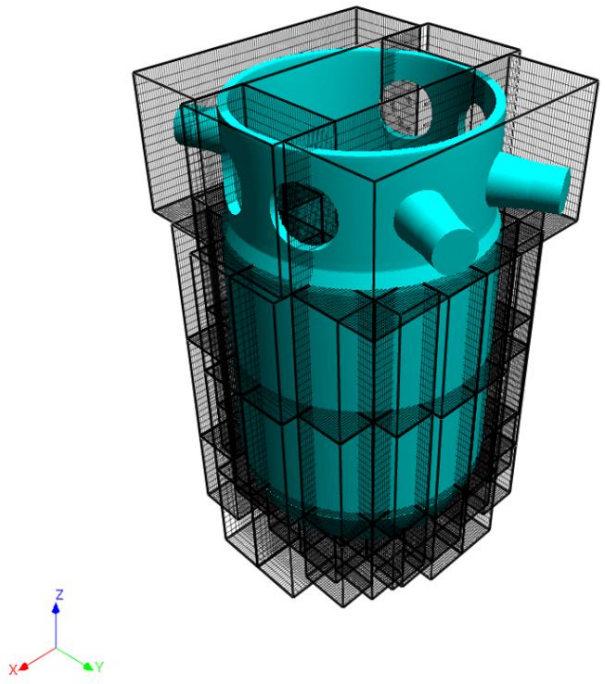
- PWR is equipped with 2 or more loops (German KONVOI: 4)
- Boron dissolved in the coolant acts as neutron absorber
- Hypothetical accidents with creation of lower borated slugs in single loops
- Importance of mixing of coolant with different boron content



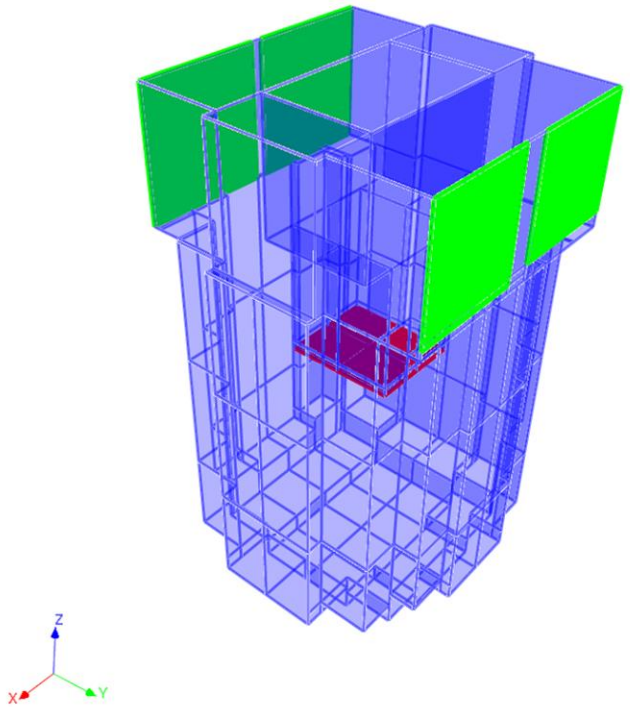
— **Primary circuit of a PWR**

ROCOM tests (SIEMENS Germany)

Boron dilution: 1D-3D Coupling (Cathare-transat)



- The flow is simulated with TransAT.
- The fluid domain is shown in blue - everything else is solid (“inverted” view).
- IST mesh is created by using multiple blocks with a total of **700k** cells.



- The inlet boundaries, indicated by green surfaces, have velocity = 2.91m/s
- The outlet/coupling boundary is indicated by a red surface, with no prescribed conditions.

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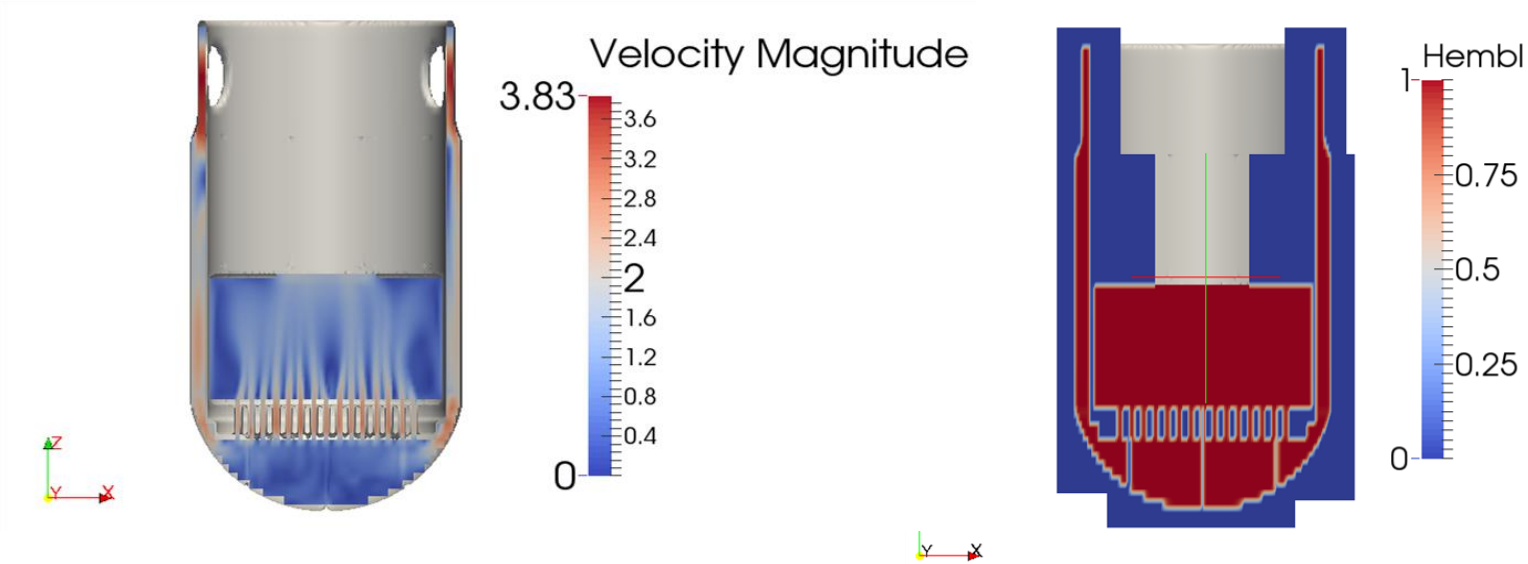
Boron dilution: 1D-3D Coupling (cathare-transat)



- Planes are perpendicular to the Y direction
- Fluid goes deep into the lower plenum, and then rises up through the support plate.
- Sharp interface is implemented, which creates gaps between adjacent objects. The unexpected gaps in the lower plenum will affect the fluid field.

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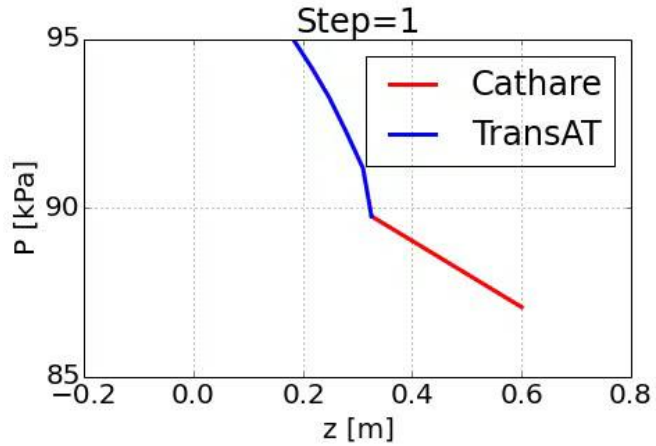
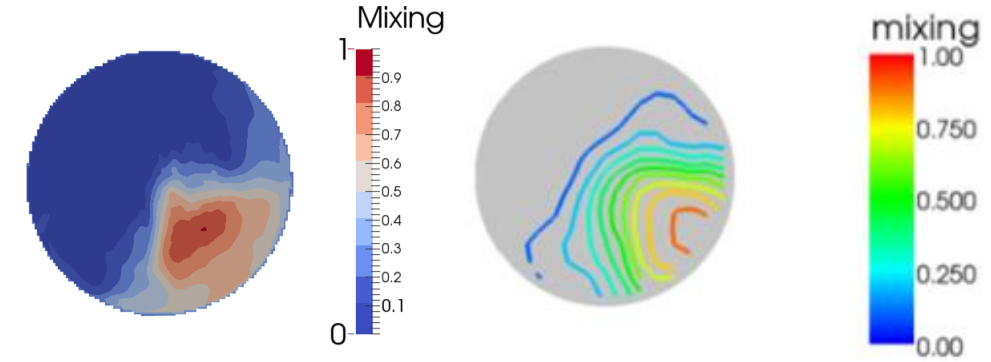
Boron dilution: 1D-3D Coupling (cathare-transat)





- With a larger time step, there are no significant pressure oscillations in CATHARE.
- At the coupling interface, pressure values from both sides match well.

- The maximum mixing scalar is very well captured by the coupled solution.
- The concentration spreading is only slightly underestimated compared to the data.

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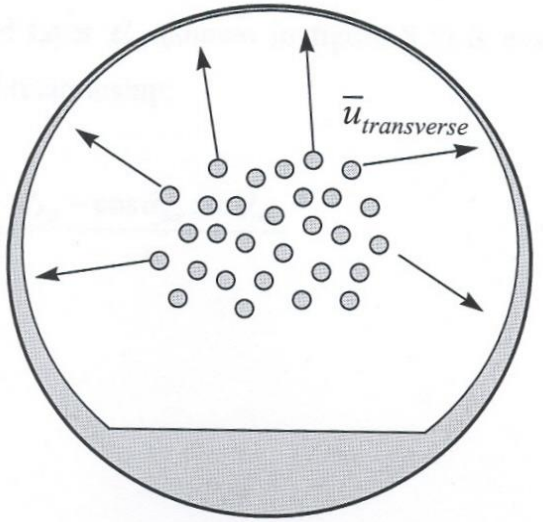
Droplet entrainment: The practical context

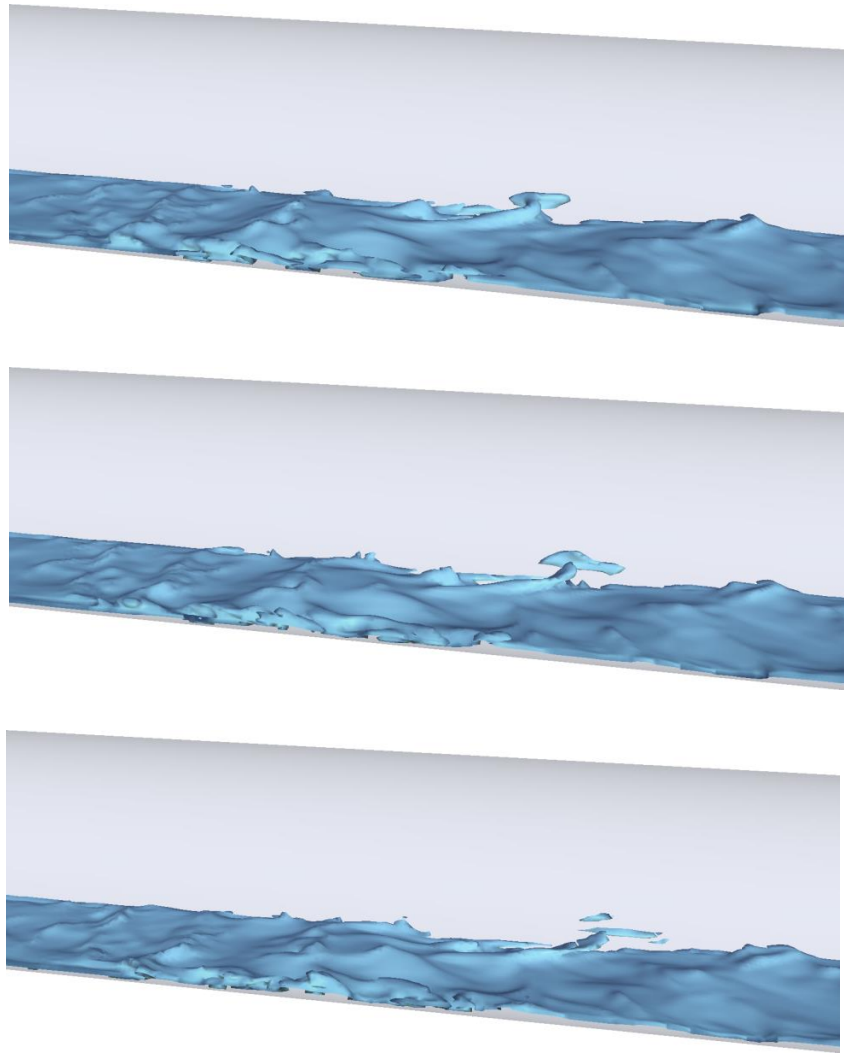
Air-water flow

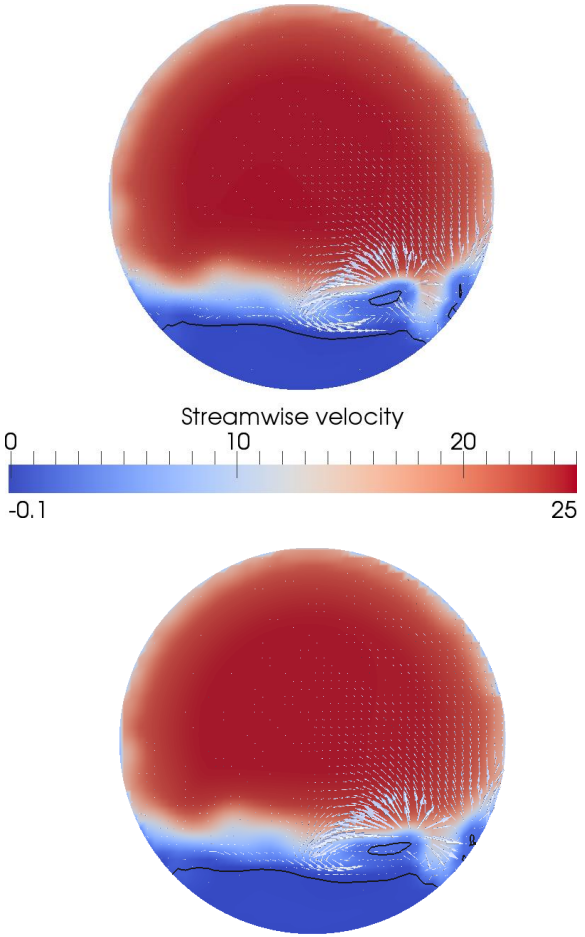
Wetting mechanism



Courtesy: Badie & Hewitt © Imperial College London

LEIS of droplet entrainment in a pipe





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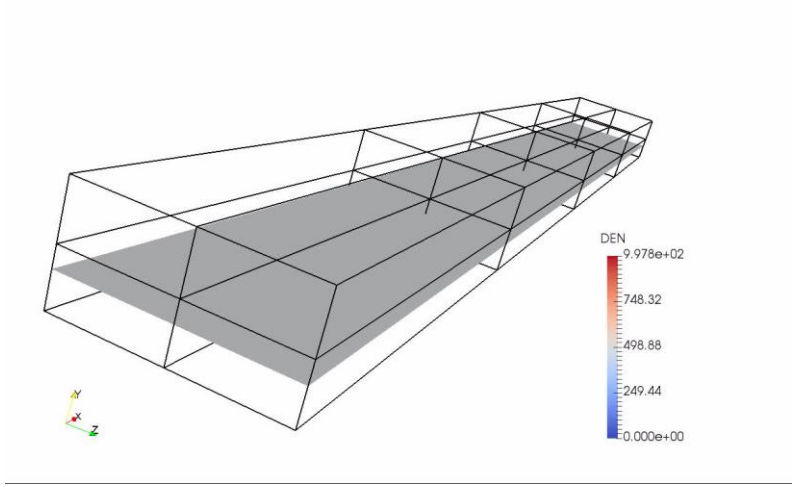
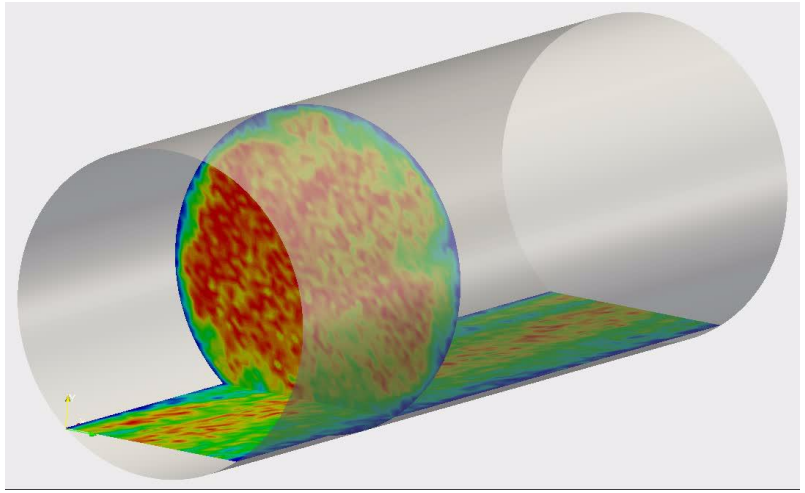
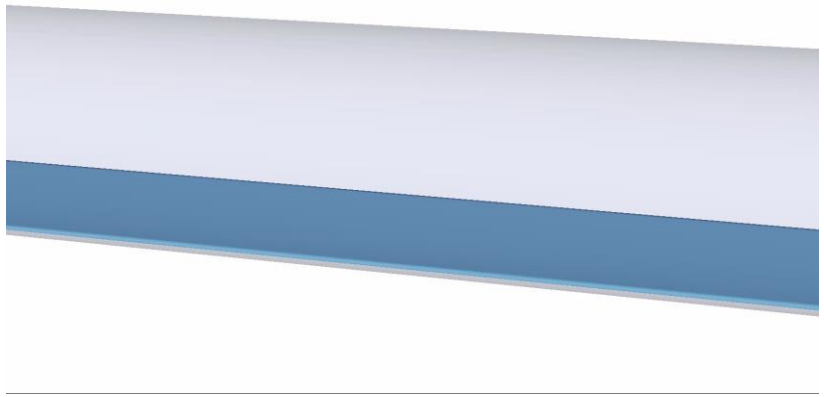
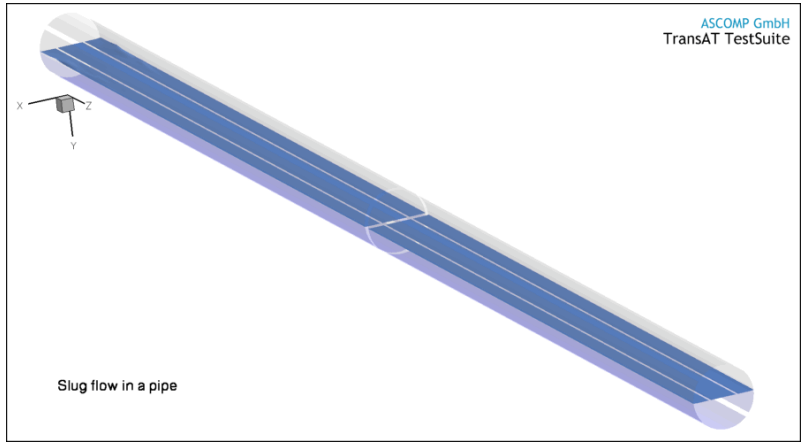
Free-surface horizontal flows







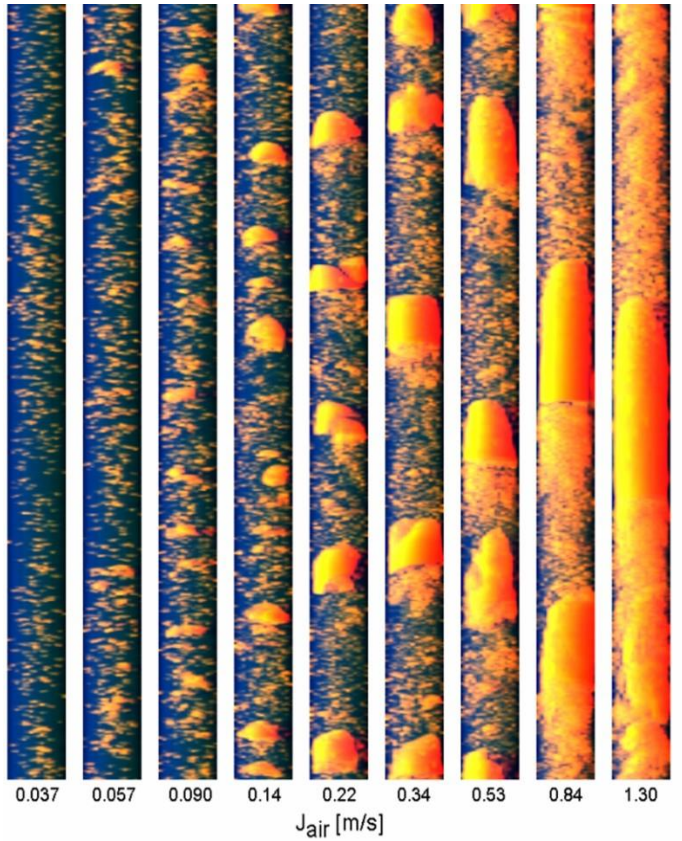


Vertical Flow: The Issues

— Flow regime map definition (e.g. slug speeds & size, etc.)
— Phase distribution
— Pressure drop and thermal transients
— Large diameter risers.

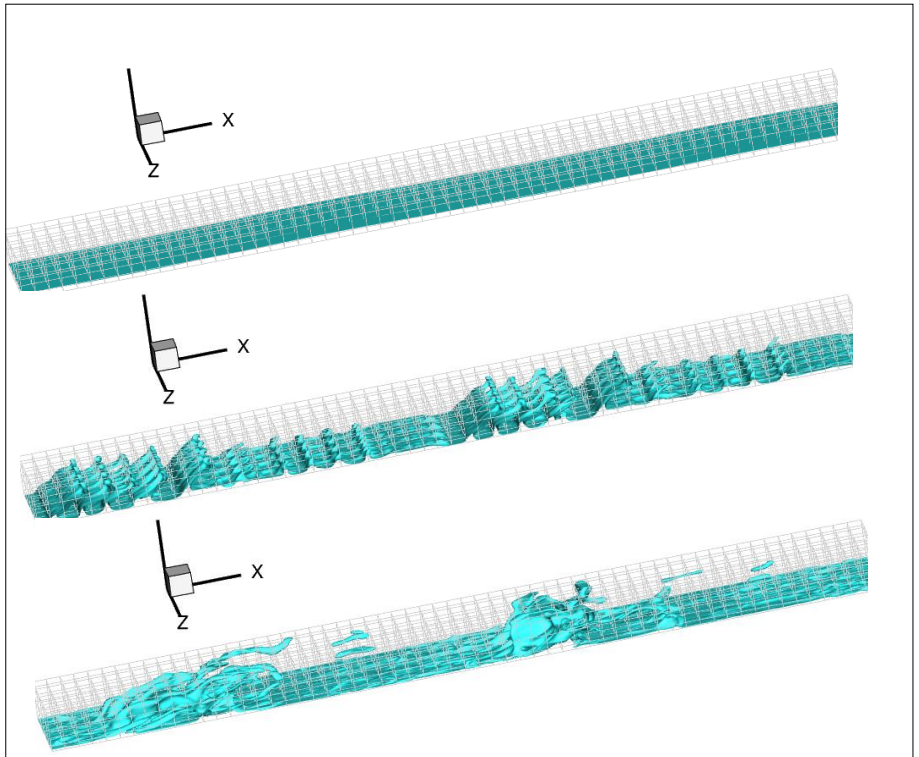
Why CMFD?

— Can simulate various flow regimes.
— Advanced models (ITM) are needed for certain flow patterns (e.g. slugging), and
— Can help identify flow regimes for large-diameter risers, as
— Shown in examples of next slide.

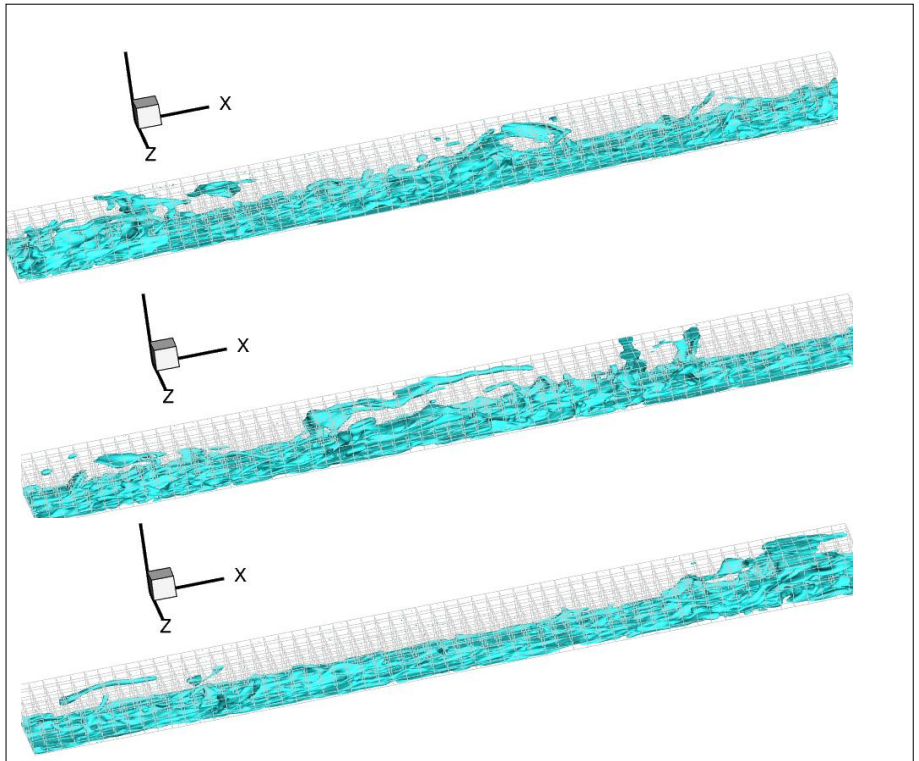


Flow Regime Prediction

Annular Flow (full domain)



- J_g = 20 m/s, J_l = 1.5 m/s. Comp. domain spans one full wavelength
- LEIS: Total number of grid points is 10 million cells distributed over 960 cores.



- Ligament formation, droplet detachment, formation of large disturbance wave clearly visible in these simulations
- Flow for full domain still developing.

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Condensation of steam jets from a sparger in a pool (KEPCO Korea)

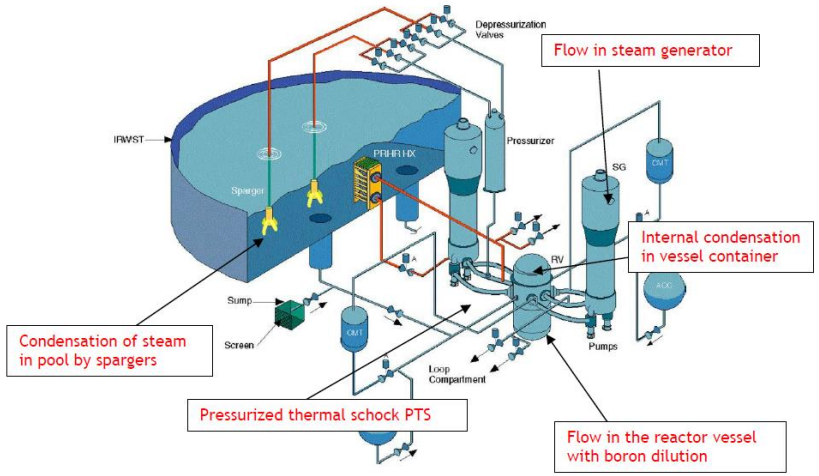
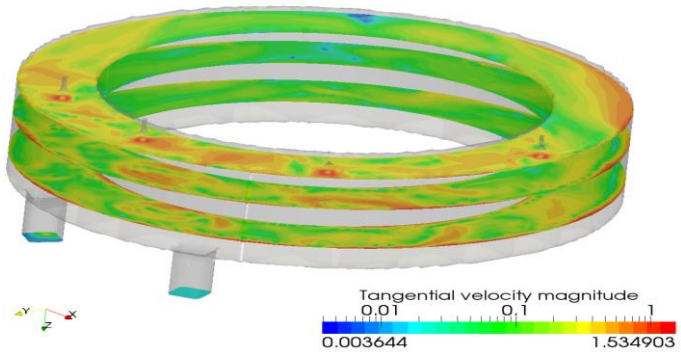
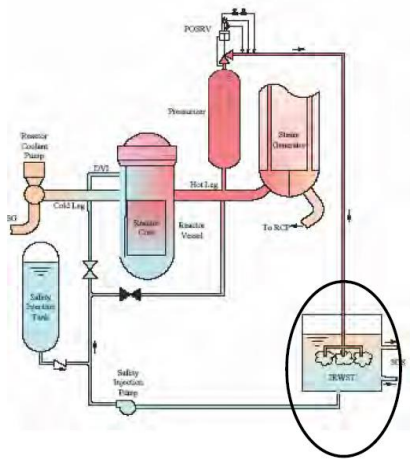
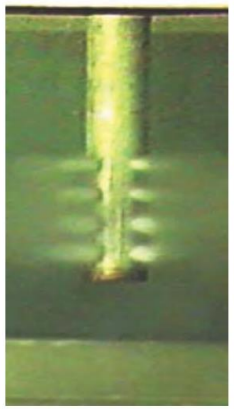


Figure 1: AP1000 RCS and passive core cooling system (Schulz, 2006)







Condensation of steam jets from a sparger in a pool (KEPCO Korea)

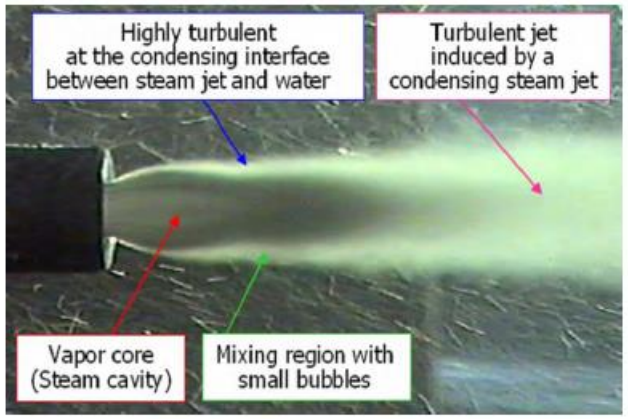
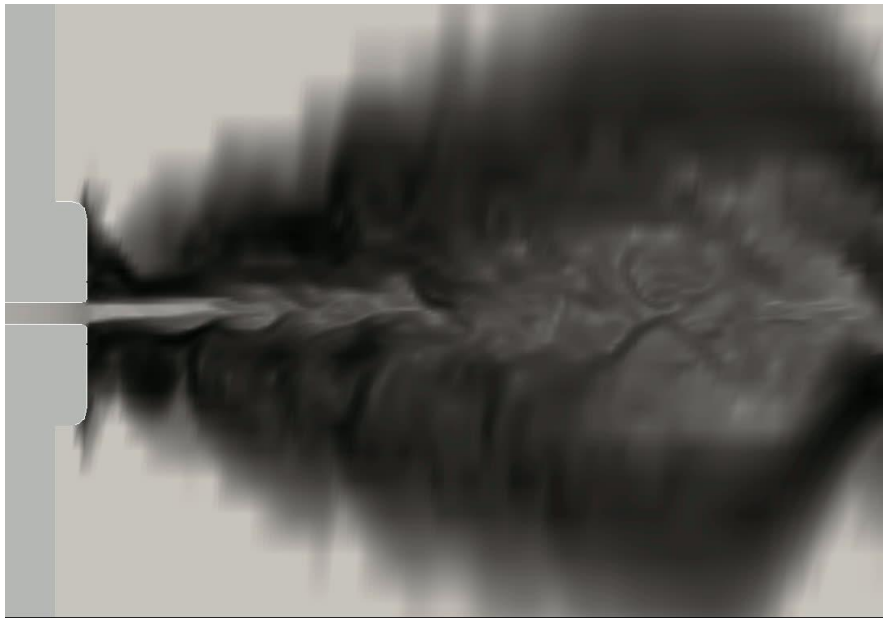
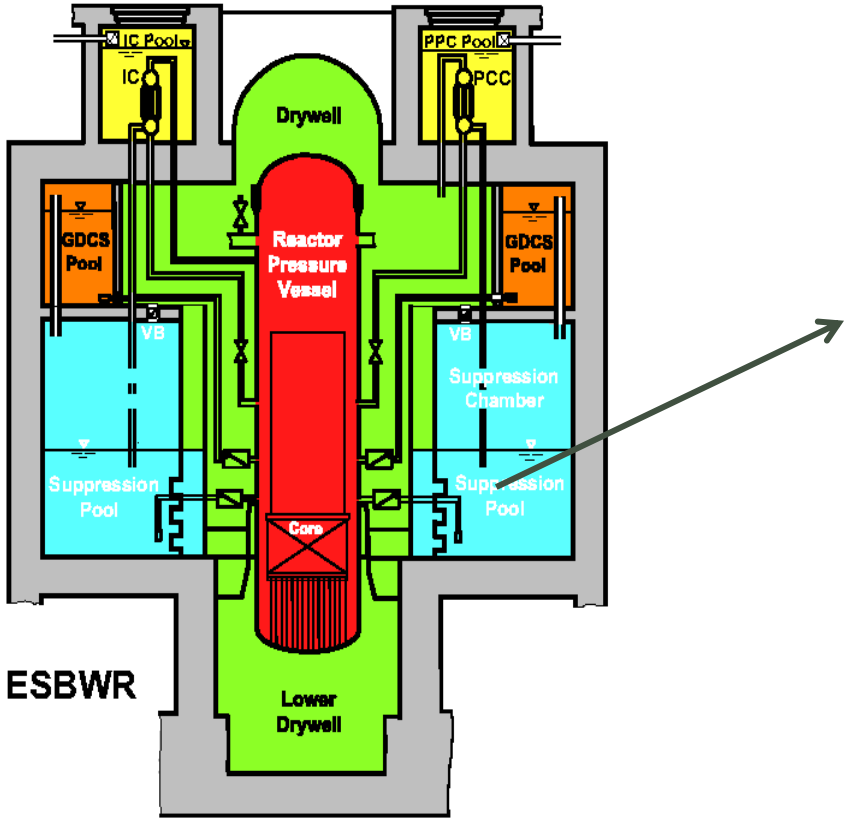
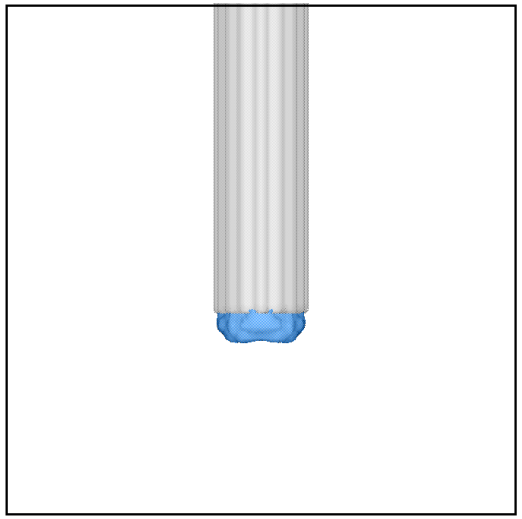


Image of condensing jet from Song et al. (2012)



RPV de-pressurisation





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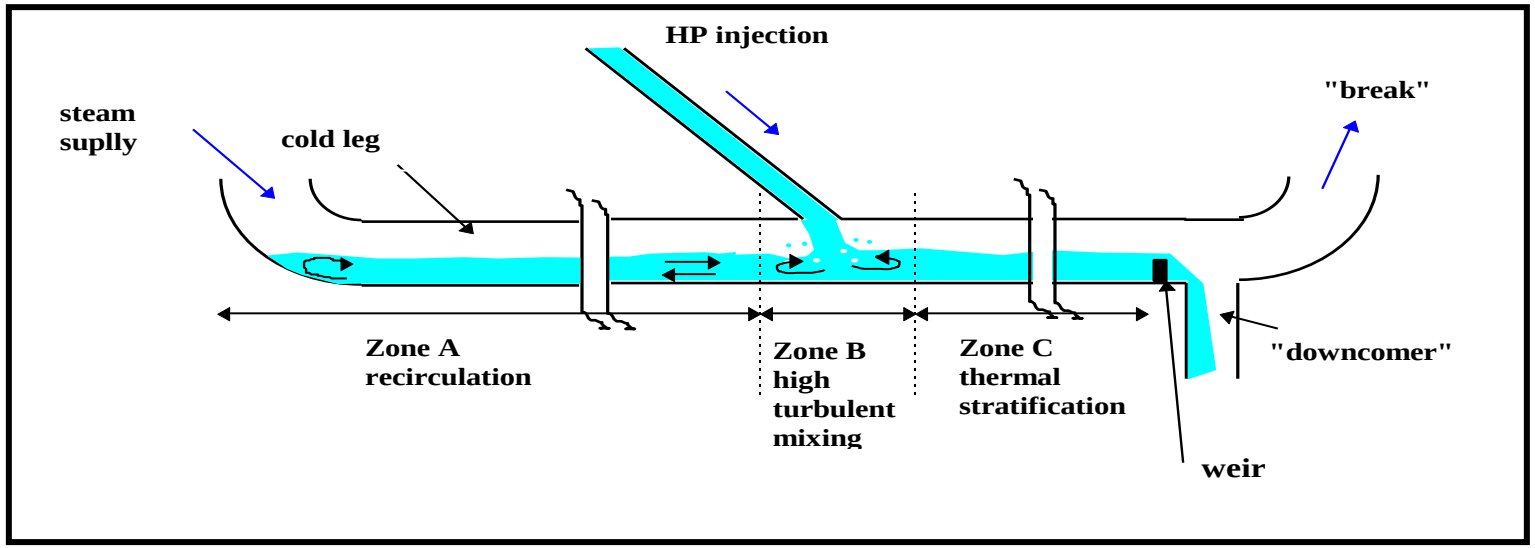
PTS: COSI Exp. (AREVA)



- **Courtesy from Yadigaroglu and Bestion, ICAPP07**

- During a hypothetical SB-LOCA, cold water is injected into the cold leg to limit the RPV lifetime (Emergency Core Cooling, ECC).
- The injected water mixes with the hot fluid in the cold leg and flows towards the downcomer leading to excessive thermal stresses on the RPV walls.

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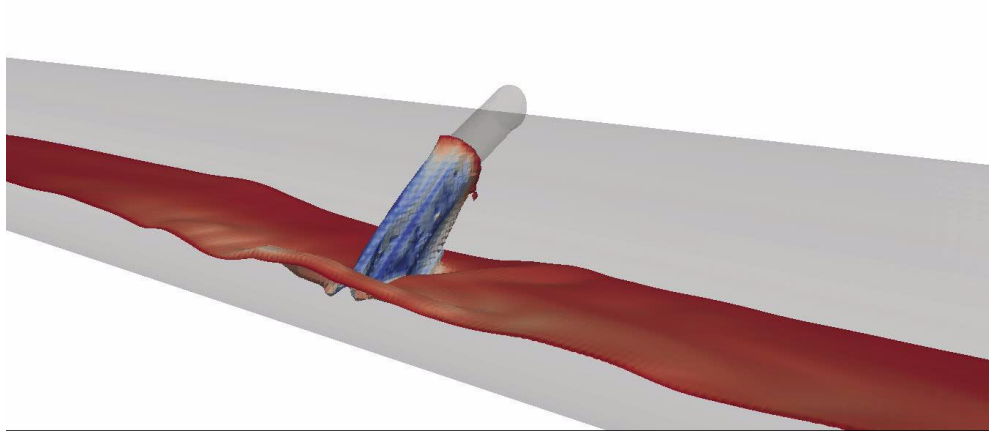
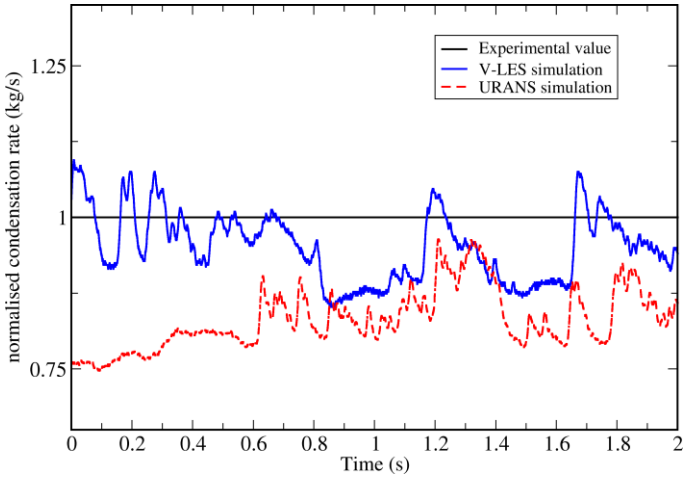
Rate of condensation

- ECC injection of cold water (296 K) in saturated water
- Steam at saturation temperature (485 K)
- Pressure 20 bars
- Simulation with TransAT level-set technique
- RANS vs. V-LES models for turbulence
- Interfacial condensation model (Labois & Lakehal, 2010)





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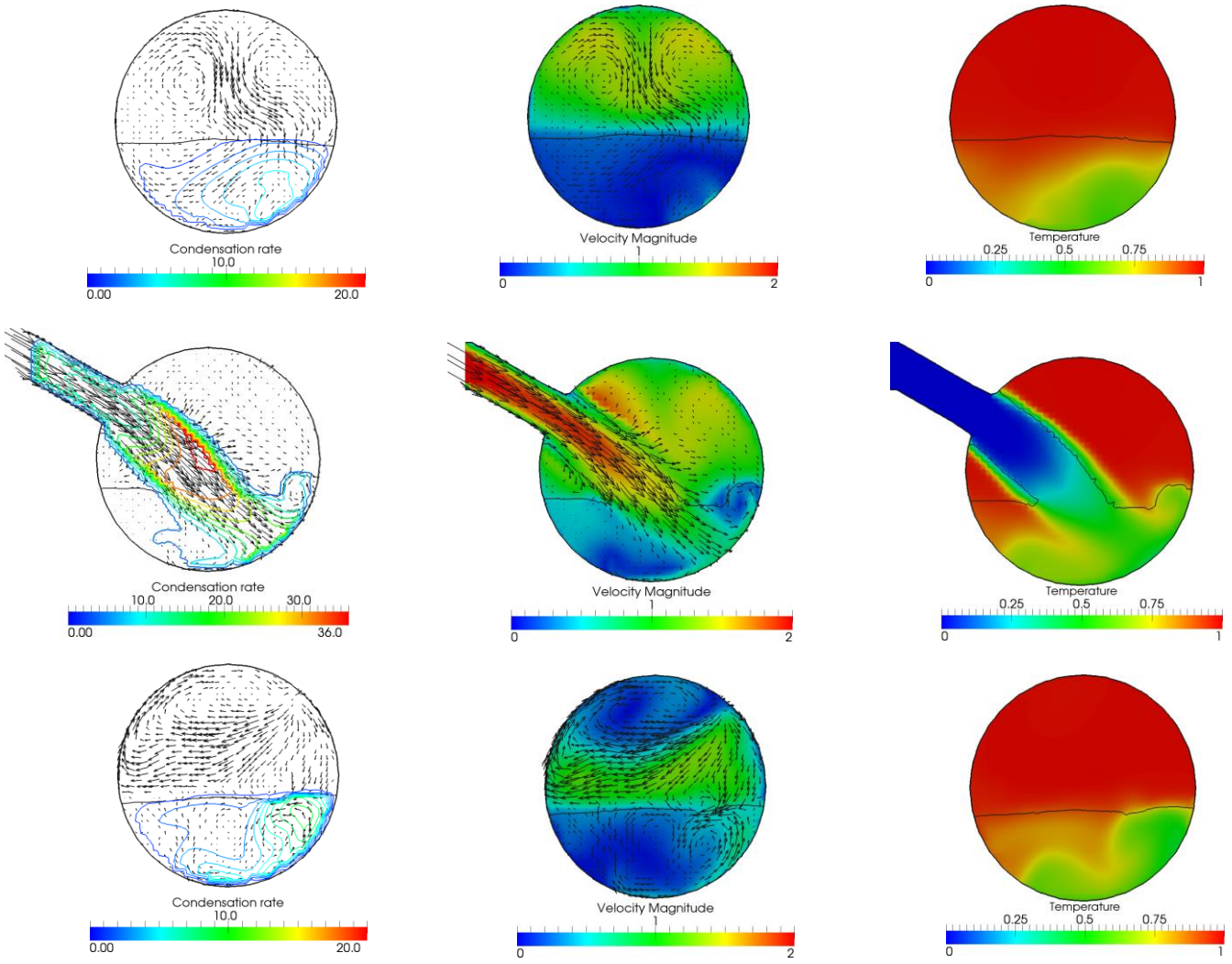
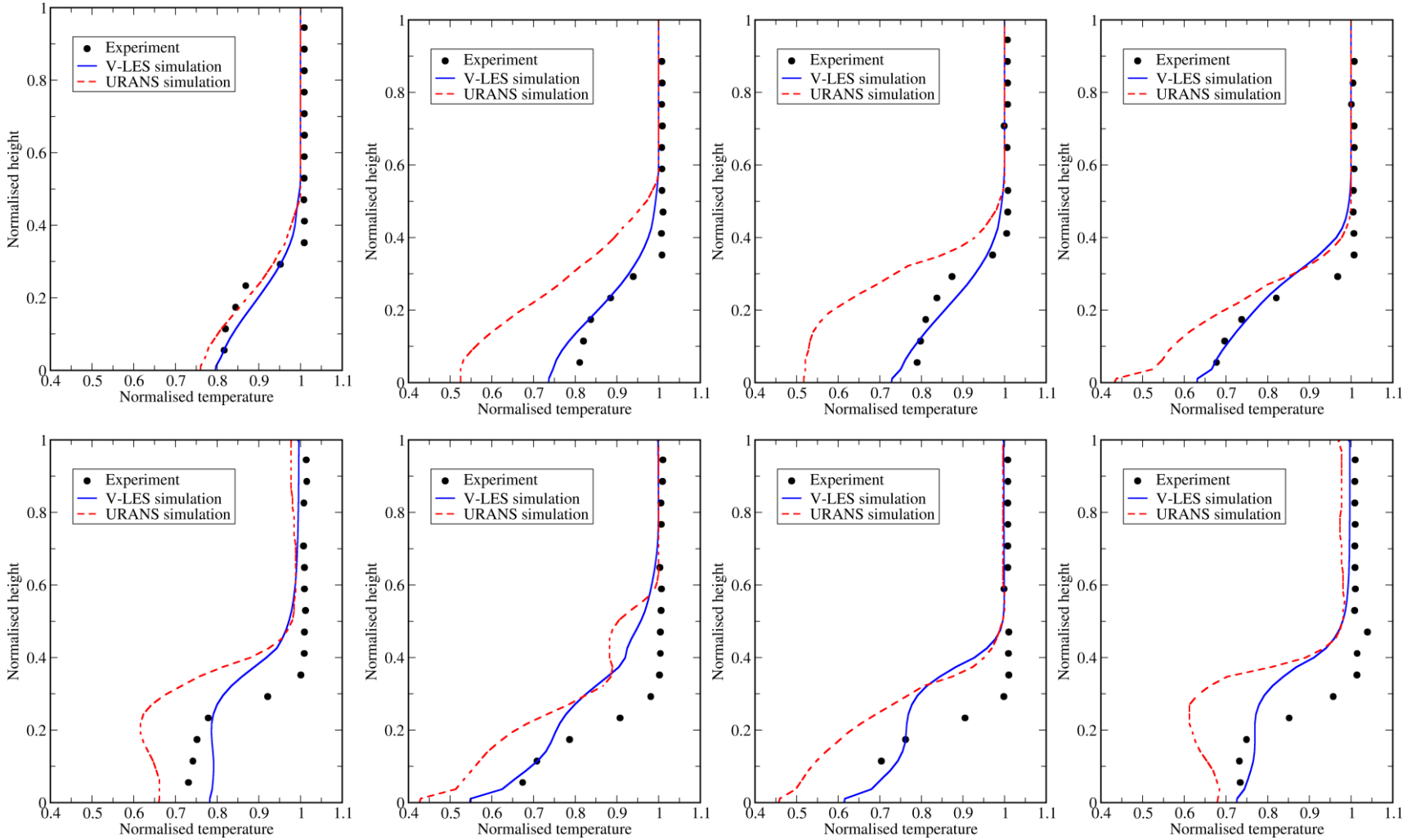
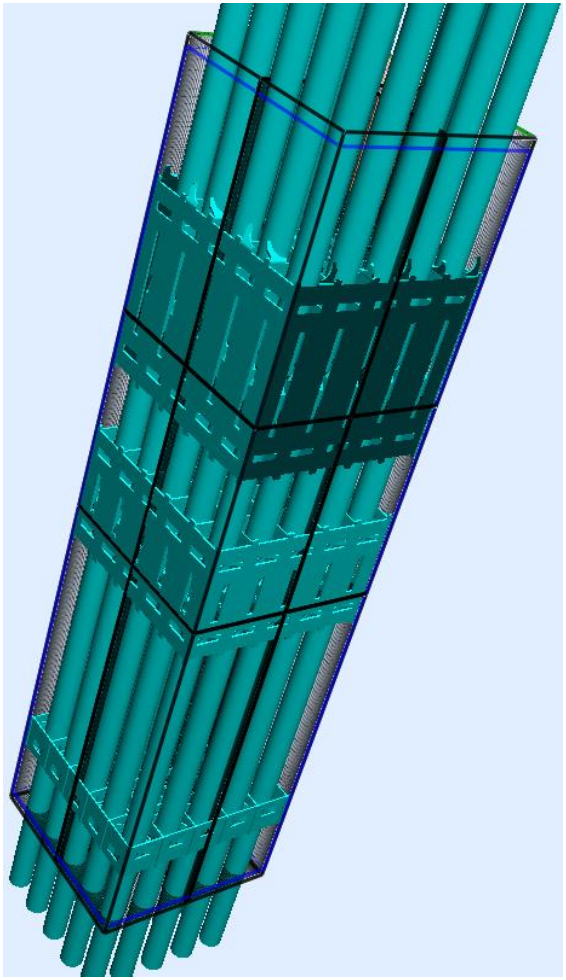
Cross-section interface & temperature

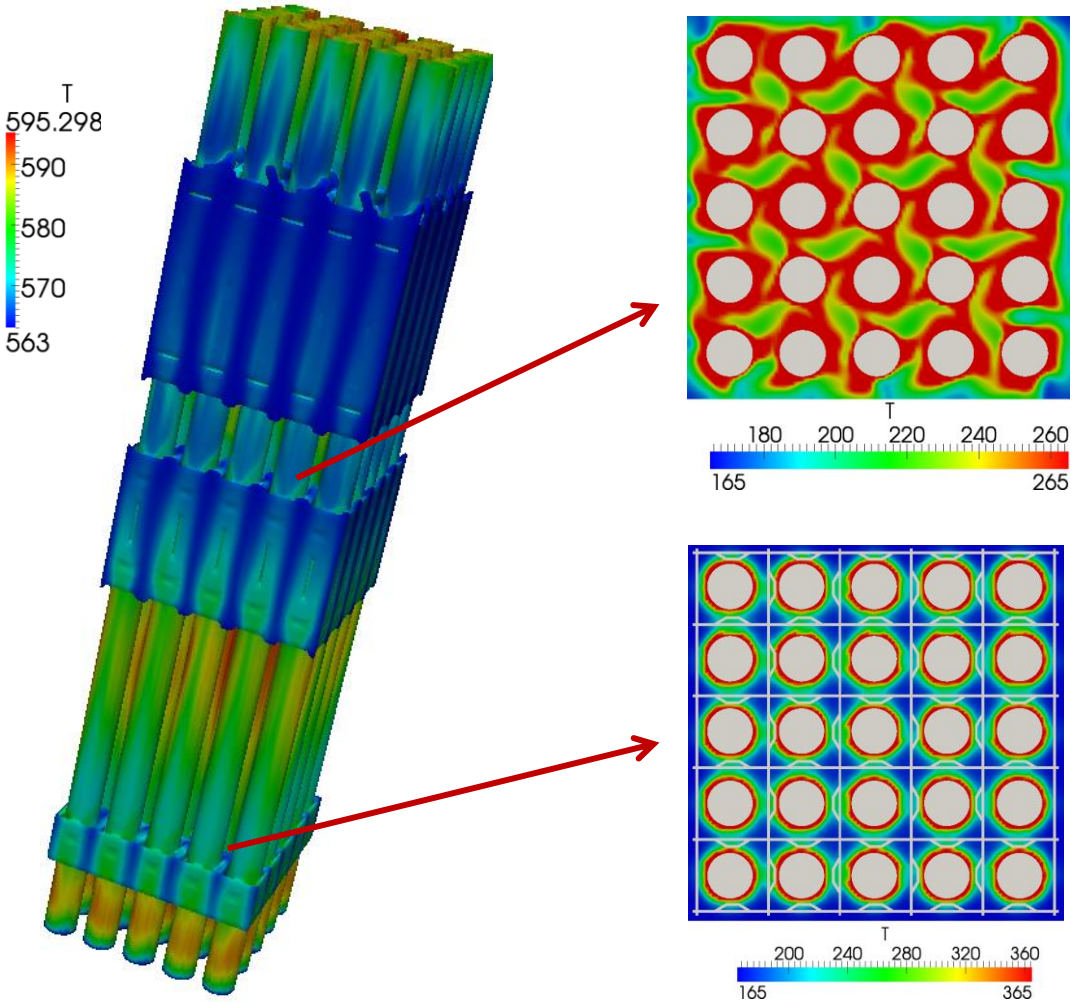


Temperature average results



The OECD PSBT 5x5 Benchmark 20





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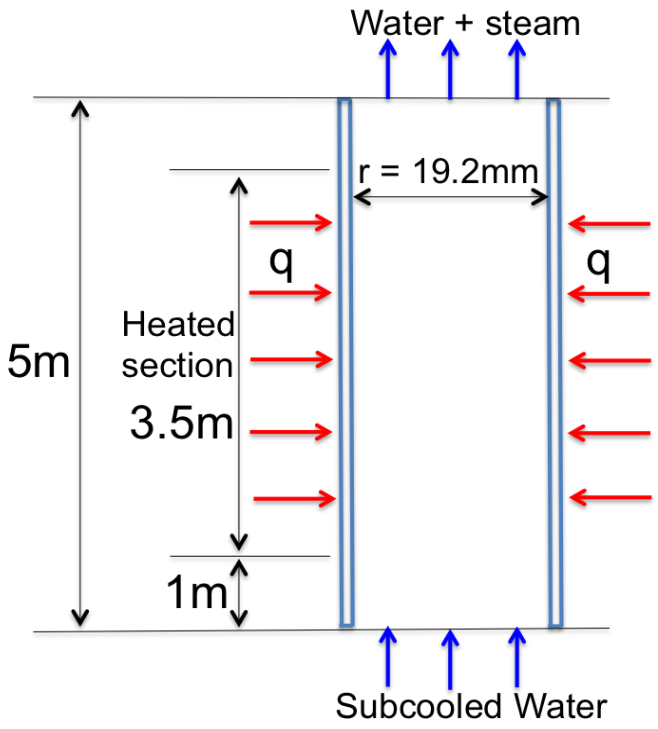
Bubbly-flow boiling: Debora test case (CEA)

DEBORA EXPERIMENTS OF MANON ET AL (2000, 2001)



Pipe Length: 5m
Pipe Diameter: 19.2 mm

Case	mass flux	T_{inlet}	T_{sat}	Bubble dia
No.	$kg/m^2/s$	°C	°C	mm
1	1006.8	52.97	94.136	0.2
2	1007.4	58.39	94.136	0.58
3	999.5	63.43	94.136	0.65
4	1005	67.89	94.136	3.2
5	1004.8	70.14	94.136	4.0
6	1004.8	72.65	94.136	5.1
7	994.9	73.7	94.136	6.2

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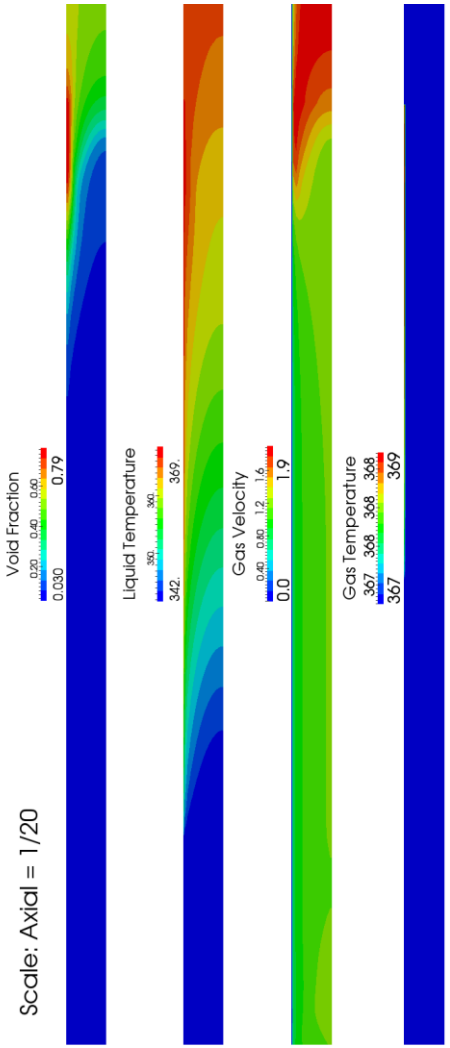
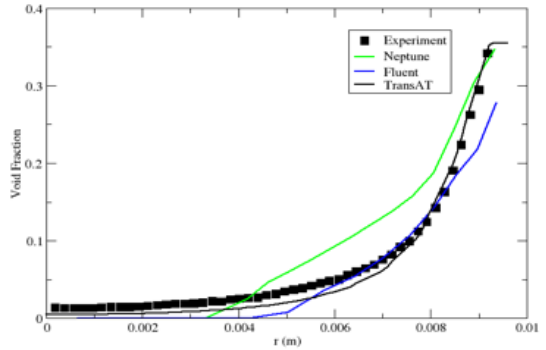
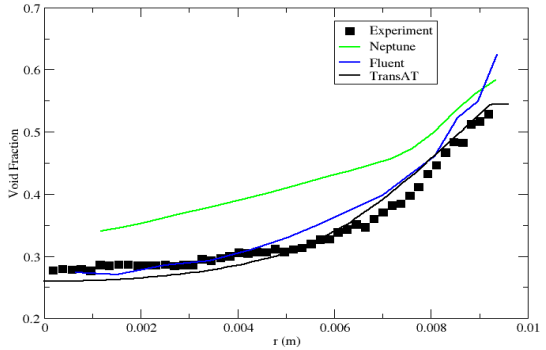
Bubbly-flow boiling: Debora test case (CEA)

- Iso-contours of transport quantities, including liquid and vapour temperature.
- 2D Axisymmetric simulations TransAT.

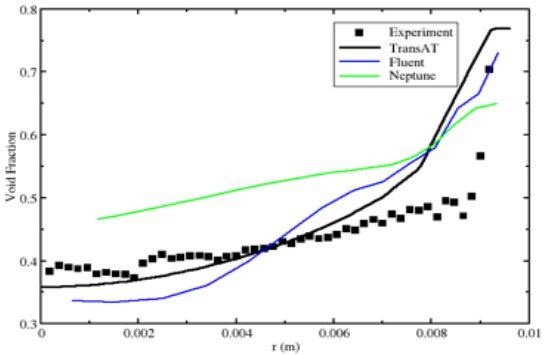




Void Fraction for Case 2 & 3:
Tin = 58.4 C and 63.4 C



Void Fraction for Case 4 & 5:
Tin = 67.9 C and 70.14 C



Void Fraction for Case 6 & 7:
Tin = 72.6 C and 73.7 C

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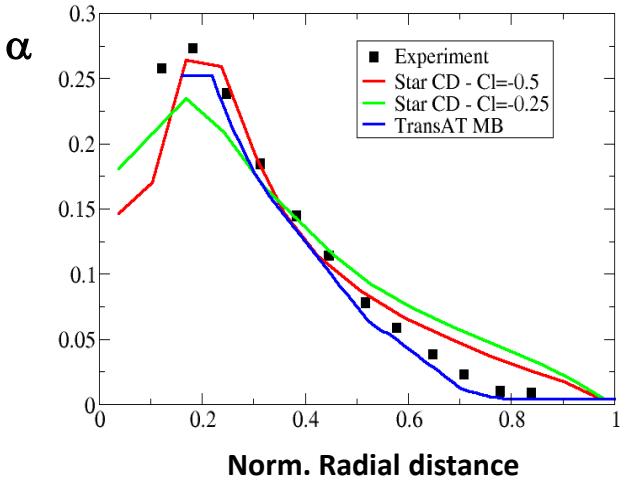
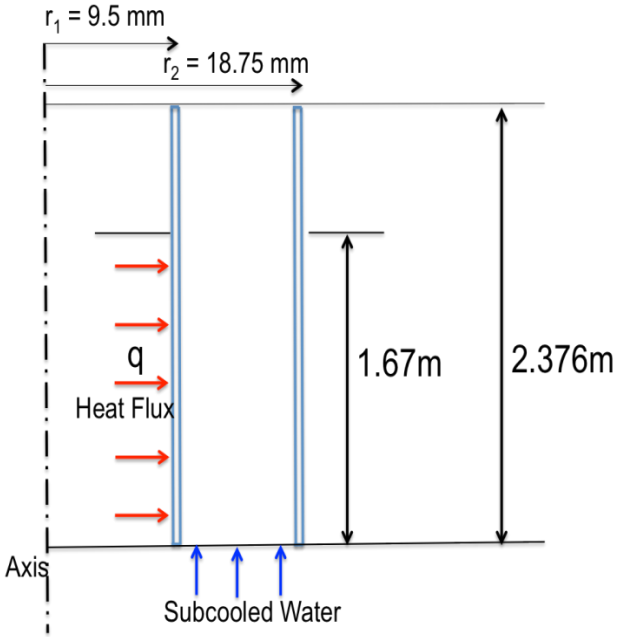
Bubbly-flow boiling: Lee et al. & Tu & Yeoh (KAERI)

EXPERIMENTS OF LEE, PARK & LEE (2002) AND TU & YEOH (2003)





- Pipe Length: 2.376m
- q=152.3 kW/m^2
- G_l=474 kg/(m^{2}s)
- P=0.14 Mpa
- ΔT_{sub}=11.5 K.

Heat flux	**mass flux**	**T_{inlet}**	**T_{sat}**
MW/ m²	kg/m²/s	K	K
0.1523	474	371.5	383

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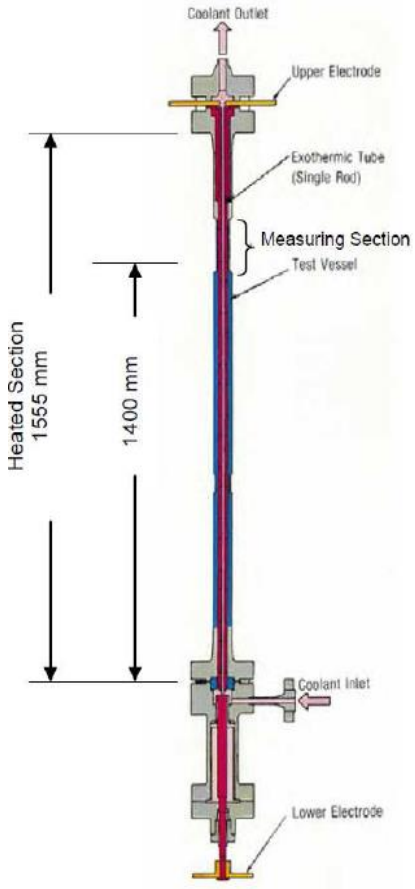
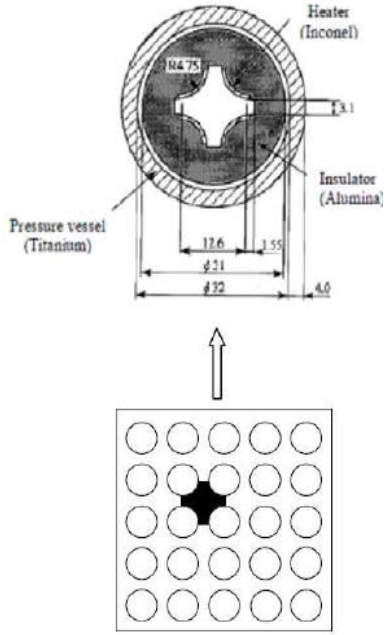
NUPEC PWR Test Facility



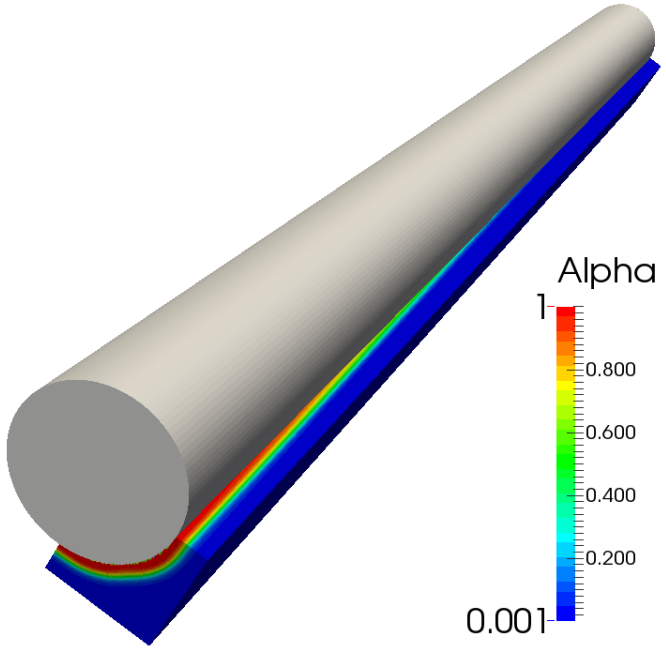


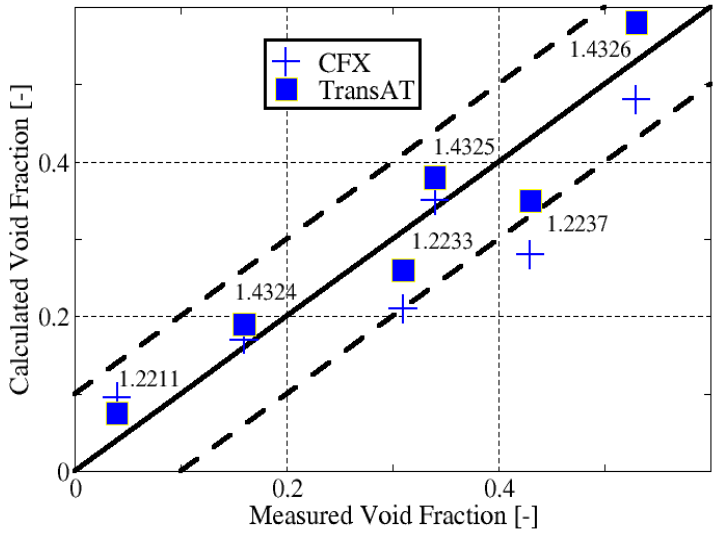
Testcase	Pressure [MPa]	Inlet Temp [°C]	Power [kW]	Mass Flux [kg $m^{-2}s^{-1}$]
1.2211	15	295.4	90	11
1.2223	15	319.6	70	11
1.2237	15	329.6	60	11
1.4411	10	238.9	60	5
1.4325	10	253.8	60	2
1.4326	10	268.8	60	5

Cell Size (in mm)	No. of Cells	No. of Processors	Wall Clock Time (in days)
5.31	9216	1	0.33
2.655	73728	8	0.75
1.328	1280000	108	1.5
0.885	2880000	128	4

NUPEC PWR Test Facility

- Iso-contours of vapour void fraction.
- Calculated vs. measured space-averaged void fraction.
- Comparison with CFX results





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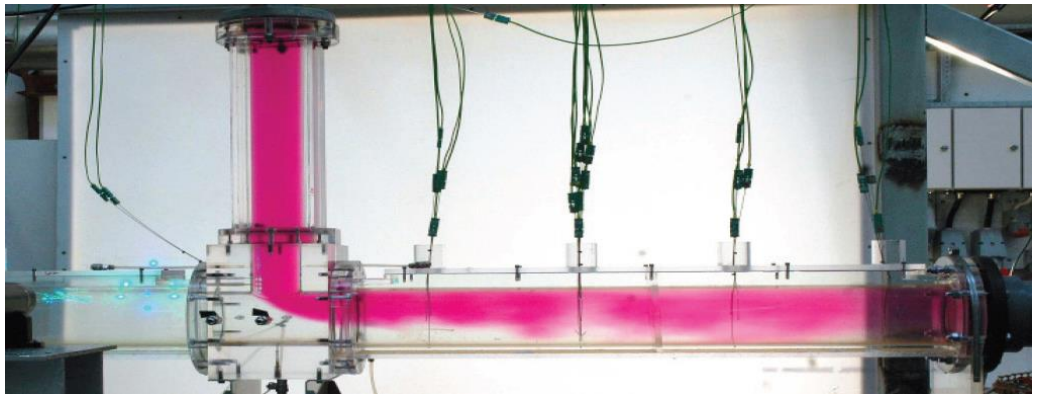
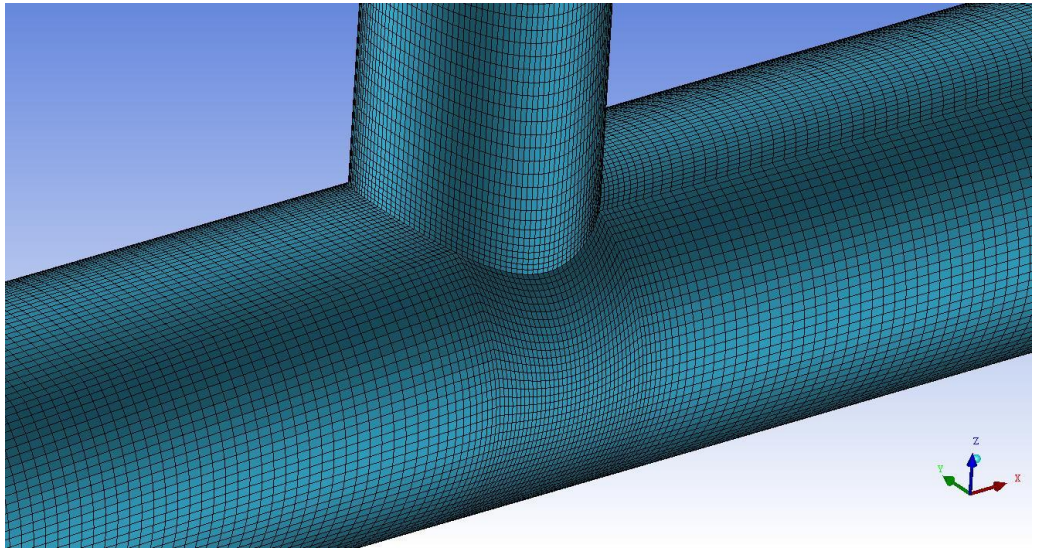
LES of Thermal stipping in a T-junction

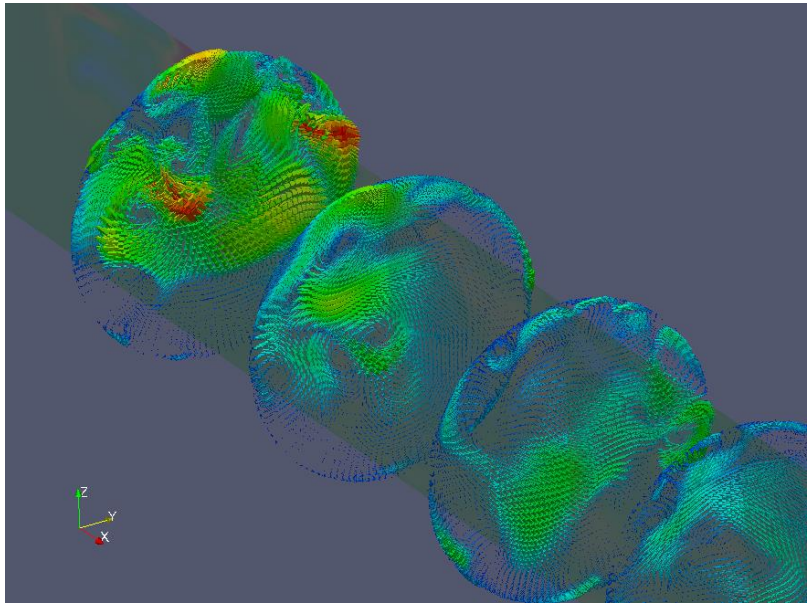
- Flow visualization test in the Vattenfall T-junction test facility (Älvkarleby Labs., Vattenfall R&D).
- Re = 1.9E5; ΔT= 15 Deg.
- BFC grid (3 million cells)
- LES with WALE SGS model

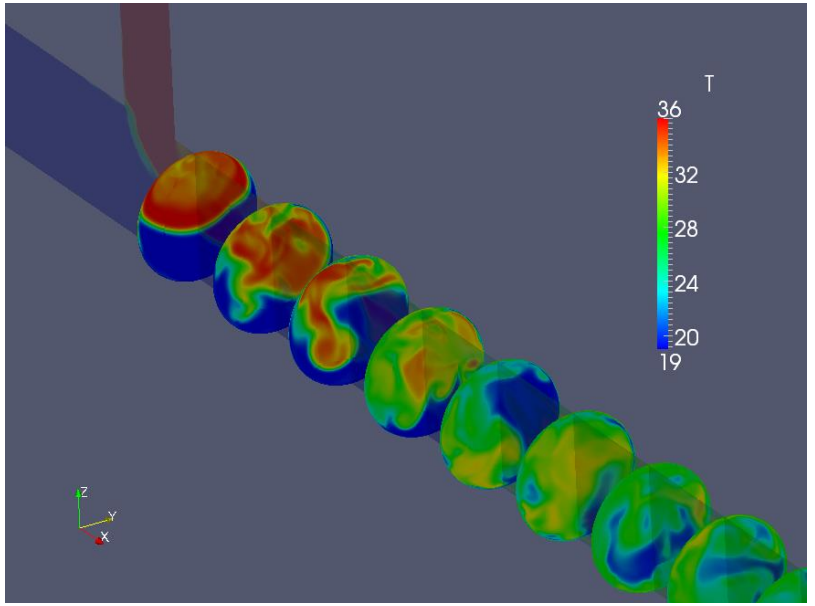


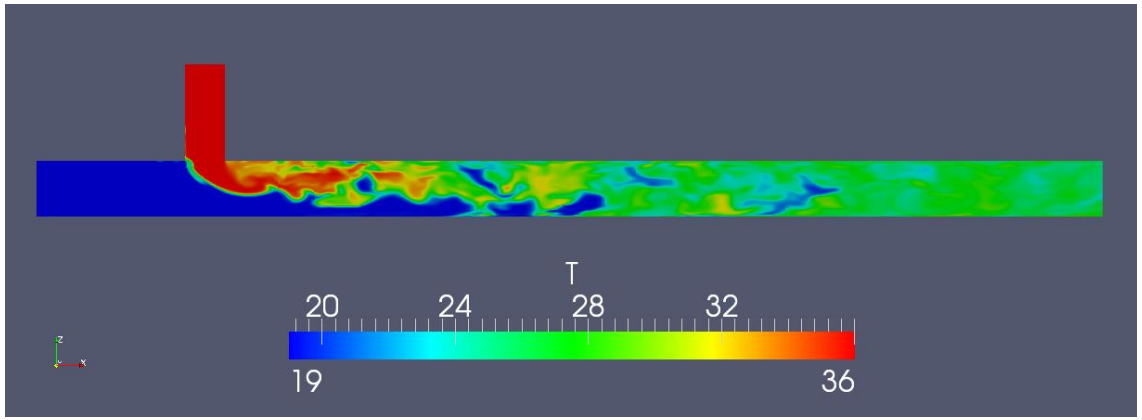


AFRY

Instantaneous results







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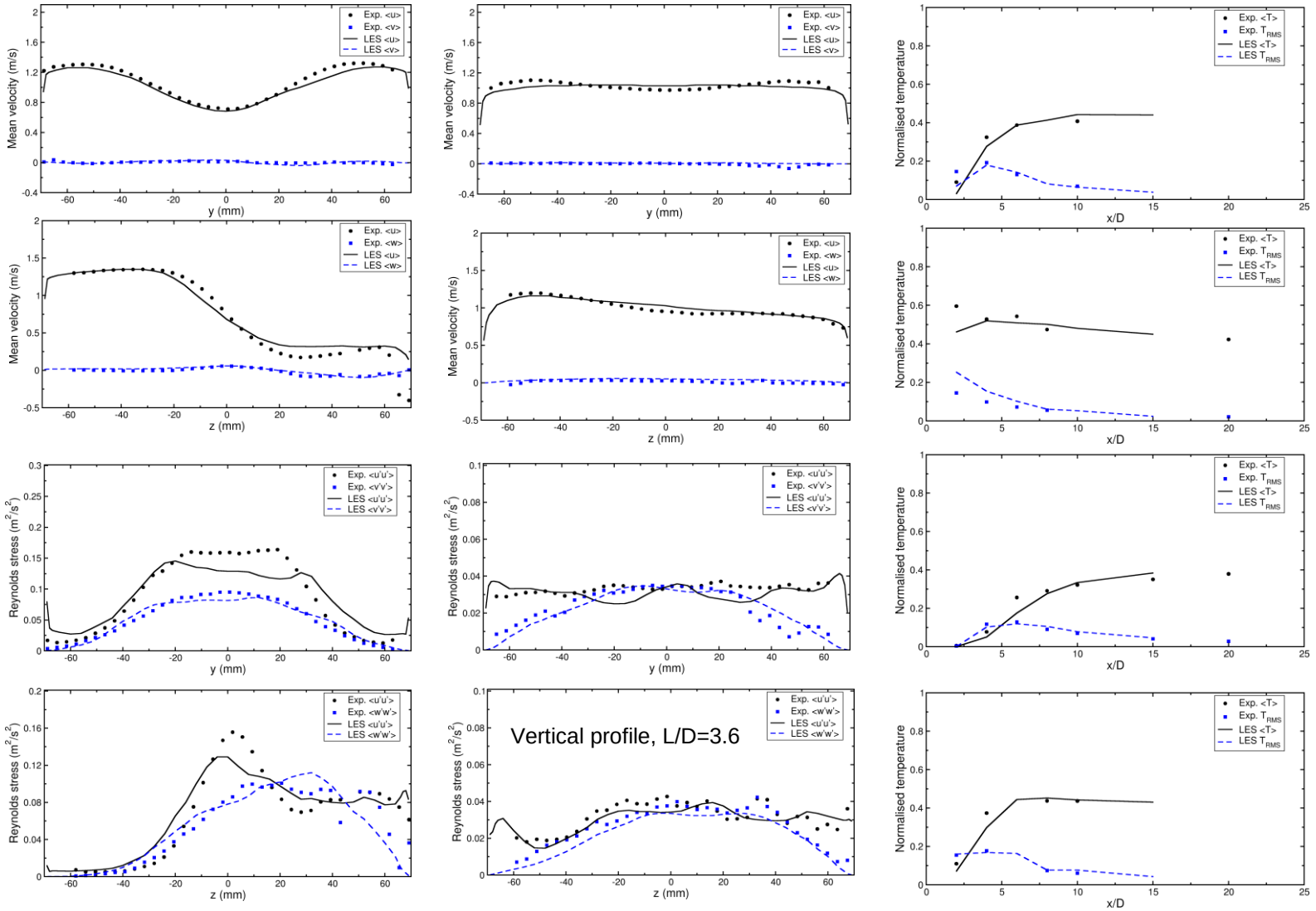
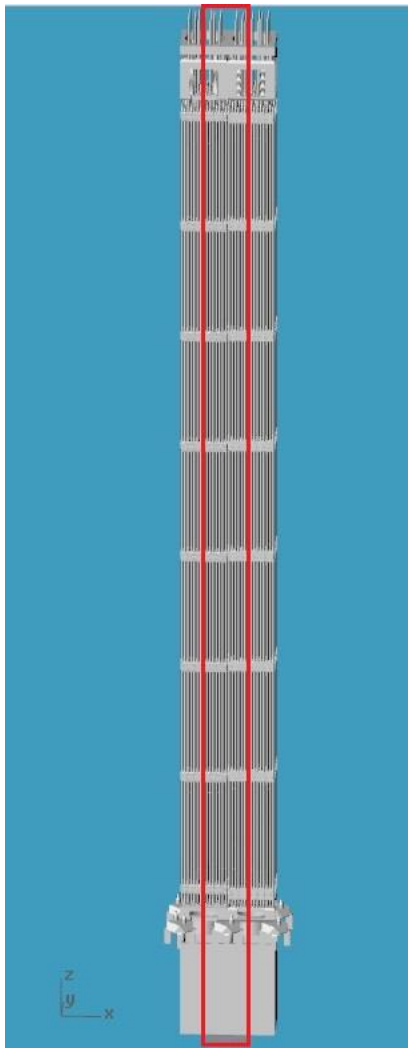
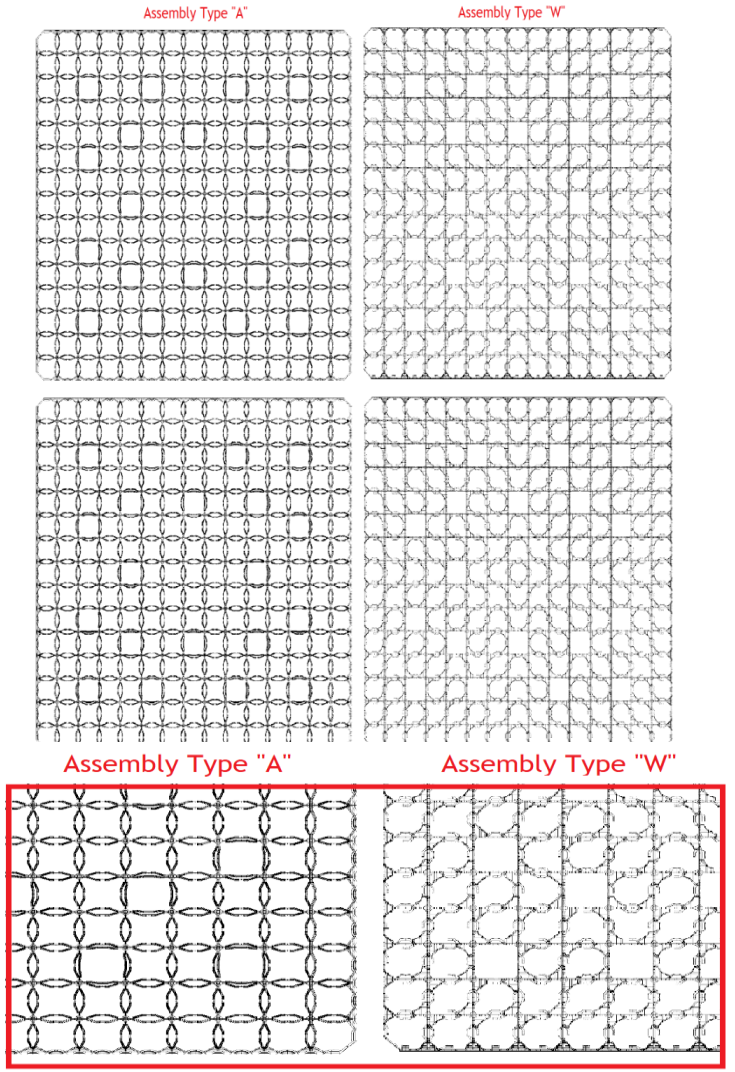
Time average results (mean & r.m.s variables)



Grand-challenge problem

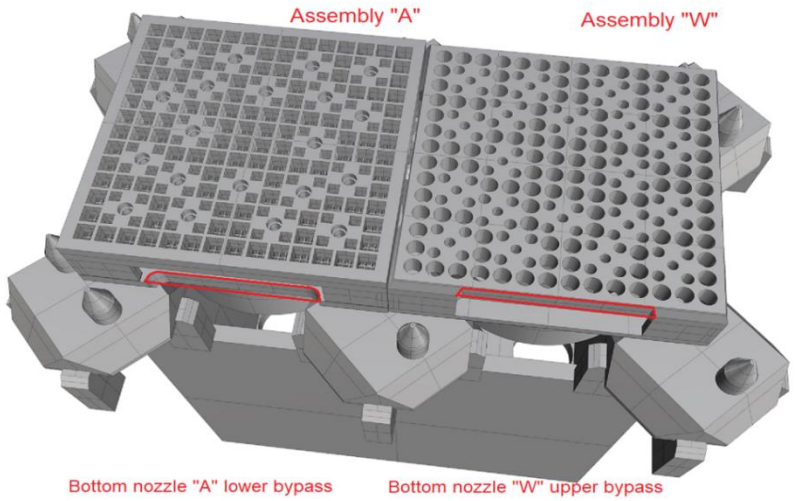
Convective boiling flow in two types of assemblies

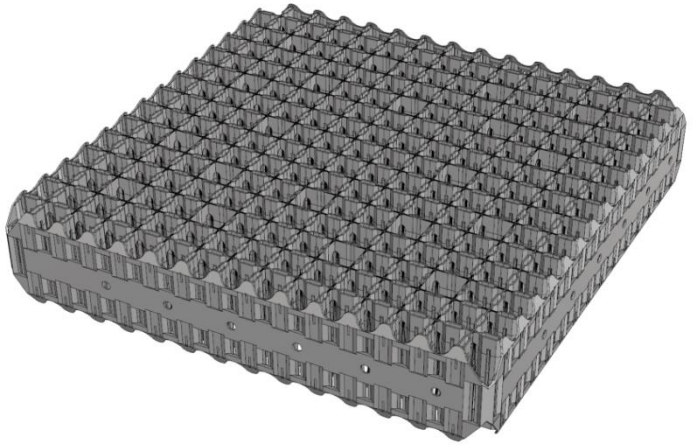


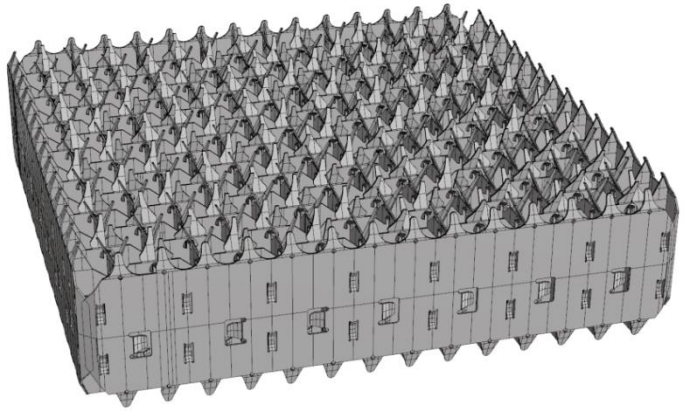


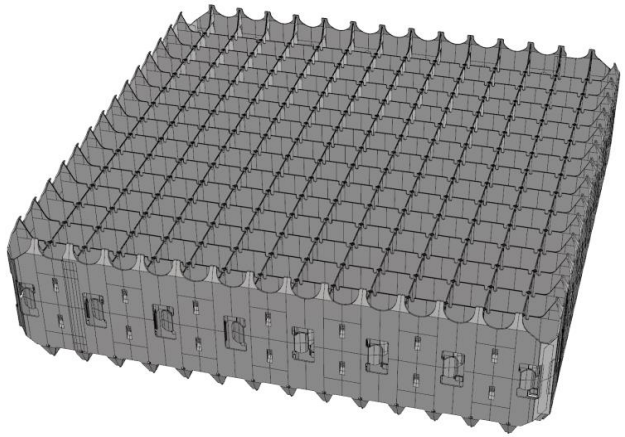
Two assembly types and the min simulation domain (in red)

AFRY

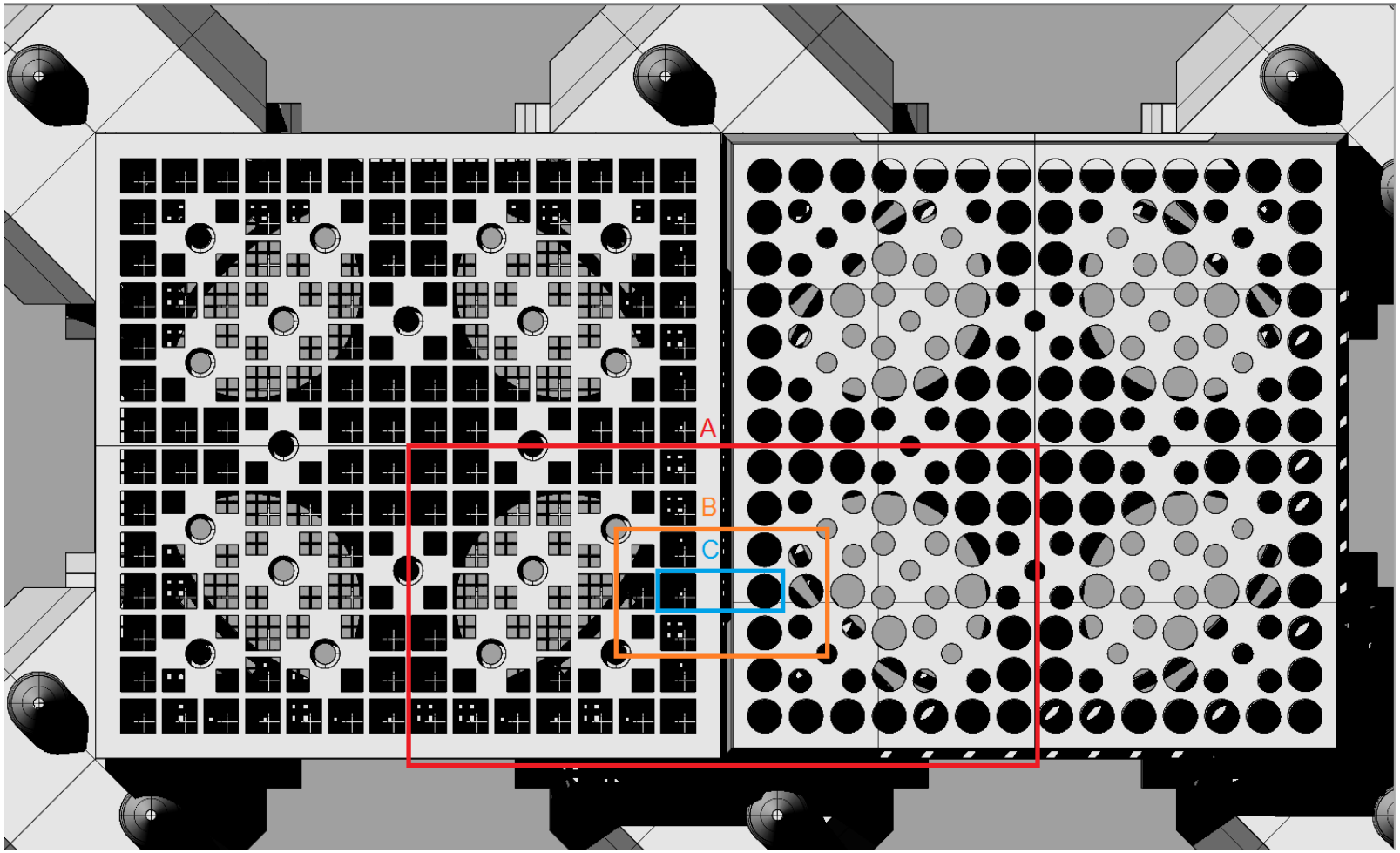

Assembly "A"
Assembly "W"
Bottom nozzle "A" lower bypass
Bottom nozzle "W" upper bypass







- Bottom nozzle

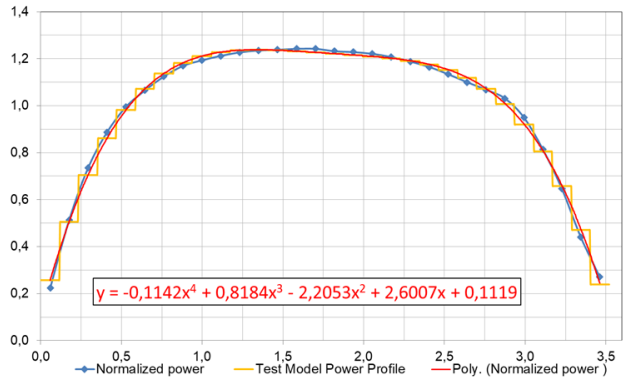


Parameter	Value
Reactor Power [MWth]	3002
Average Linear Power [W/cm]	235.04
Coolant Inlet Temperature [K]	564.65
Coolant Outlet Average Temperature [K]	599.35
System Pressure [bar]	154
Core mass flow rate [kg/s]	15980
Core volumetric flow rate [m^3/s]	21.502
Total core total bypass, mass flow rate [kg/s]	749.46 (=4.69% of core mass flow rate)
Bypass through thimble tubes, m. flow rate [kg/s]	263.67 (=1.65% of core mass flow rate)

H	367,1	371,4	395,9	0,0	403,4	382,5	373,6	376,6
G	371,4	378,1	389,9	411,5	402,6	406,6	384,3	379,2
F	395,9	389,9	396,3	417,5	422,8	0,0	403,6	383,5
E	0,0	411,5	417,5	0,0	423,7	414,3	389,5	382,8
D	403,4	402,6	422,8	423,7	404,2	408,6	385,5	379,2
C	382,5	406,6	0,0	414,3	408,6	0,0	392,6	374,0
B	373,6	384,3	403,6	389,5	385,5	392,6	368,1	364,9
A	373,6	379,2	383,5	382,8	379,2	374,0	364,9	358,7
	8	7	6	5	4	3	2	1
	Assembly A							

H	376,6	373,6	382,5	403,4	0,0	395,9	371,4	367,1
G	379,2	384,3	406,6	402,6	411,5	389,9	378,1	371,4
F	383,5	403,6	0,0	422,8	417,5	396,3	389,9	395,9
E	382,8	389,5	414,3	423,7	0,0	417,5	411,5	0,0
D	379,2	385,5	408,6	404,2	423,7	422,8	402,6	403,4
C	374,0	392,6	0,0	408,6	414,3	0,0	406,6	382,5
B	364,9	368,1	392,6	385,5	389,5	403,6	384,3	373,6
A	358,7	364,9	374,0	379,2	382,8	383,5	379,2	373,6
	1	2	3	4	5	6	7	8
	Assembly W							

Quarter average assembly power distribution [W/cm] for both assembly



Axial power distribution and fitted shape function

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#	Region	Axial Coordinate [mm]			Sub. Seg. [mm]	Δx= Δy [mm]	AR	Segment # Δz_seg [mm] Cells
		z_{start}	z_{end}	Δz				
1	Domain extention and Bott. plate	-50	385	385	435	0.25	10	
2	Bottom nozzle lower part	385	554	604	169	0.25	10	1
3	Bottom nozzle filter and bottom spacers	554	742	792	188	0.25	1	
4	Rods	742	1120	1170	378	0.25	10	1170 4.362E+08
5	Guide tube hole	1120	1212	1262	92	0.25	1	2
6	2nd spacers	1212	1306	1356	94	0.25	1	
7	Rods	1306	1673	1723	367	0.25	10	553 3.366E+08
8	Rods	1673	1746	1796	73	0.25	10	3
9	3rd Spacers and sleeves	1746	1839	1889	93	0.25	1	
10	Rods	1839	2207	2257	368	0.25	10	534 2.142E+08
11	Rods	2207	2280	2330	73	0.25	10	4
12	4th Spacers and sleeves	2280	2373	2423	93	0.25	1	
13	Rods	2373	2740	2790	367	0.25	10	533 2.144E+08
14	Rods	2740	2813	2863	73	0.25	10	5
15	5th Spacers and sleeves	2813	2907	2957	94	0.25	1	
16	Rods	2907	3275	3325	368	0.25	10	535 2.147E+08
17	Rods	3275	3346	3396	71	0.25	10	6
18	6th Spacers and sleeves	3346	3441	3491	95	0.25	1	
19	Rods	3441	3808	3858	367	0.25	10	533 2.144E+08
20	Rods	3808	3879	3929	71	0.25	10	7
21	7th Spacers and sleeves	3879	3972	4022	93	0.25	1	
22	Rods	3972	4335	4385	363	0.25	10	527 2.136E+08
24	Rods	4335	4403	4453	68	0.25	10	8
25	8th Spacers and sleeves	4403	4512	4562	109	0.25	1	
26	Region above rods up to guide tubes end plug	4512	4570	4620	58	0.25	1	665
27	Top nozzle and upper plate	4570	4753	4803	183	0.25	10	
28	Upper plate and domain extention	4753	5000	5000	247	0.25	10	3.329E+08
				Total	5050	-	-	2.177E+09
				Total fine meshing	859	0.25	1	1.278E+09
				Total coarser meshing	4191	0.25	10	8.993E+08

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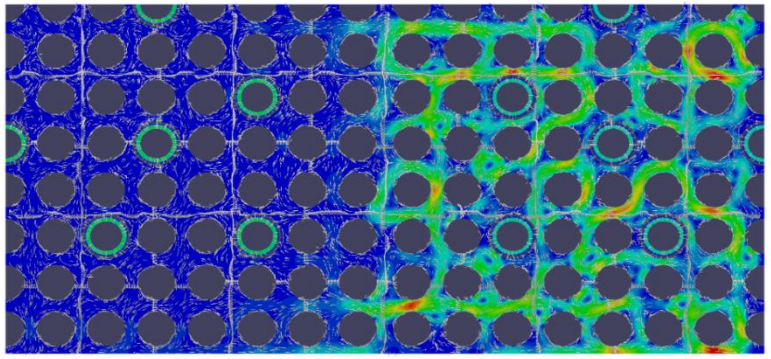
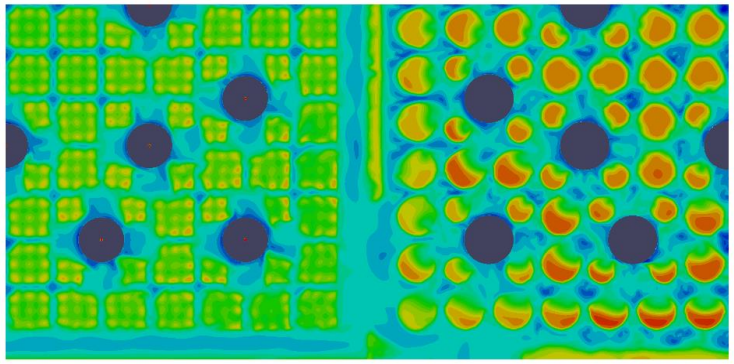
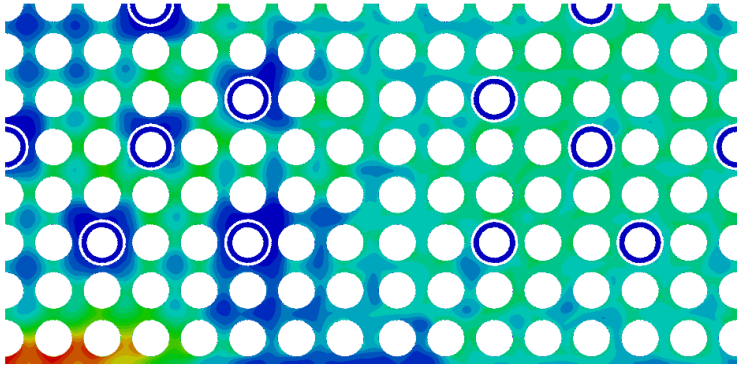
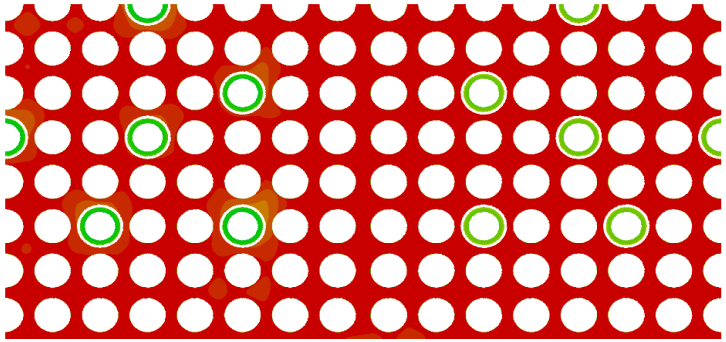
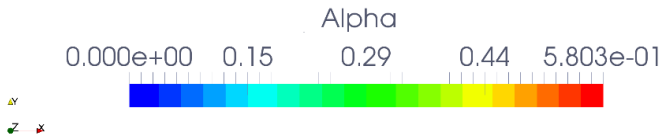
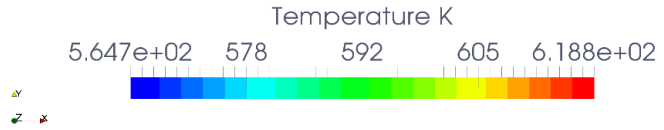









Alpha
0.000e+00
0.15
0.29
0.44
5.803e-01


Temperature K
5.647e+02
578
592
605
6.188e+02

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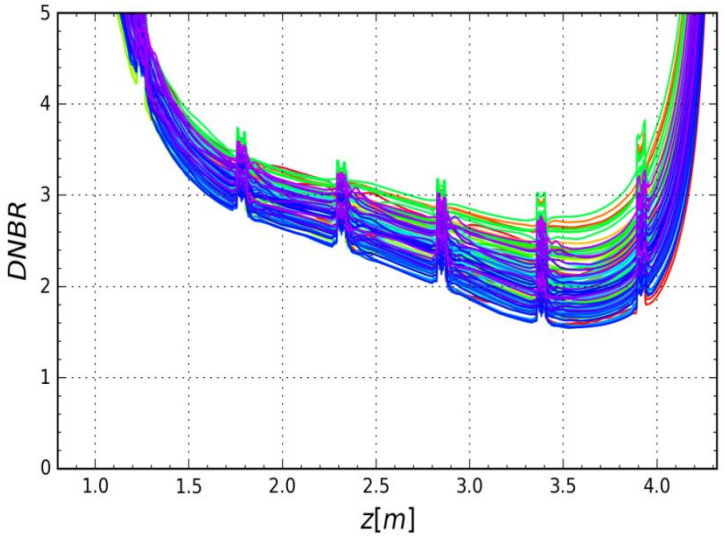
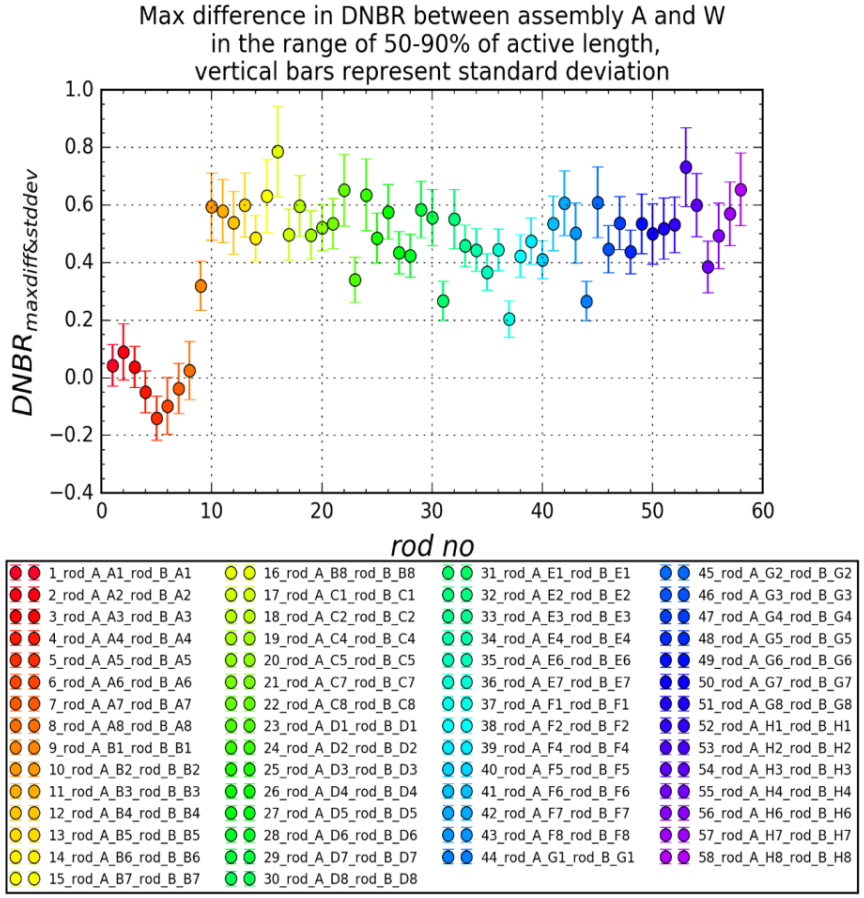
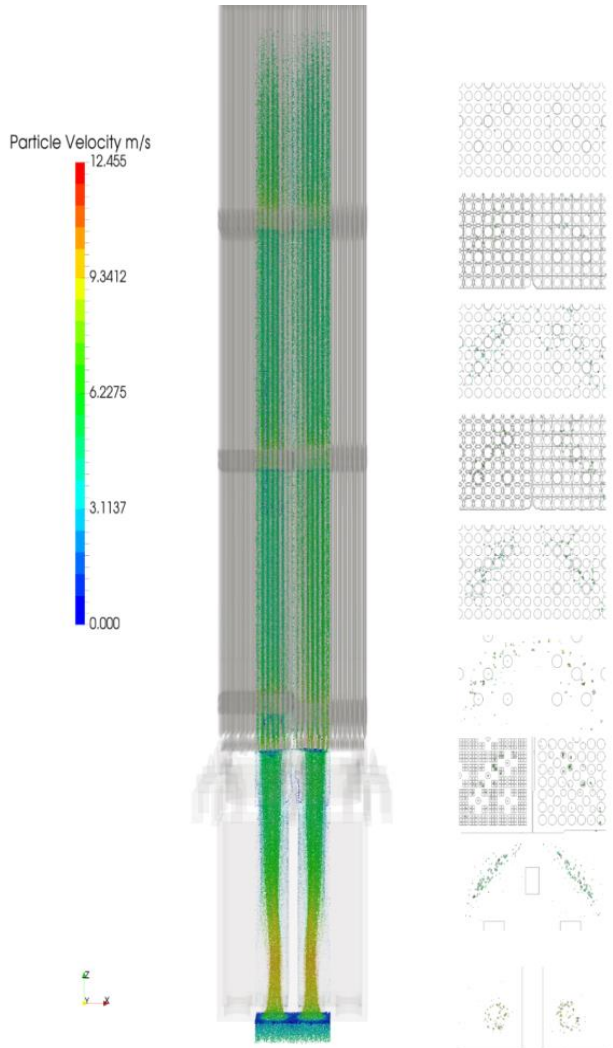

DNBR
z[m]
_rod_A_A1 _rod_A_A2 _rod_A_A3 _rod_A_A4 _rod_A_A5 _rod_A_A6 _rod_A_A7 _rod_A_A8 _rod_A_B1 _rod_A_B2 _rod_A_B3 _rod_A_B4 _rod_A_B5 _rod_A_B6 _rod_A_B7 _rod_A_B8 _rod_A_C1 _rod_A_C2 _rod_A_C4 _rod_A_C5 _rod_A_C7 _rod_A_C8 _rod_A_D1 _rod_A_D2 _rod_A_D3 _rod_A_D4 _rod_A_D5 _rod_A_D6 _rod_A_D7 _rod_A_D8 _rod_A_E1 _rod_A_E2 _rod_A_E3 _rod_A_E4 _rod_A_E6 _rod_A_E7 _rod_A_F1 _rod_A_F2 _rod_A_F4 _rod_A_F5 _rod_A_F6 _rod_A_F7 _rod_A_F8 _rod_A_G1 _rod_A_G2 _rod_A_G3 _rod_A_G4 _rod_A_G5 _rod_A_G6 _rod_A_G7 _rod_A_G8 _rod_A_H1 _rod_A_H2 _rod_A_H3 _rod_A_H4 _rod_A_H6 _rod_A_H7 _rod_A_H8 _rod_B_A1 _rod_B_A2 _rod_B_A3 _rod_B_A4 _rod_B_A5 _rod_B_A6 _rod_B_A7 _rod_B_A8 _rod_B_B1 _rod_B_B2 _rod_B_B3 _rod_B_B4 _rod_B_B5 _rod_B_B6 _rod_B_B7 _rod_B_B8 _rod_B_C1 _rod_B_C2 _rod_B_C4 _rod_B_C5 _rod_B_C7 _rod_B_C8 _rod_B_D1 _rod_B_D2 _rod_B_D3 _rod_B_D4 _rod_B_D5 _rod_B_D6 _rod_B_D7 _rod_B_D8 _rod_B_E1 _rod_B_E2 _rod_B_E3 _rod_B_E4 _rod_B_E6 _rod_B_E7 _rod_B_F1 _rod_B_F2 _rod_B_F4 _rod_B_F5 _rod_B_F6 _rod_B_F7 _rod_B_F8 _rod_B_G1 _rod_B_G2 _rod_B_G3 _rod_B_G4 _rod_B_G5 _rod_B_G6 _rod_B_G7 _rod_B_G8 _rod_B_H1 _rod_B_H2 _rod_B_H3 _rod_B_H4 _rod_B_H6 _rod_B_H7 _rod_B_H8

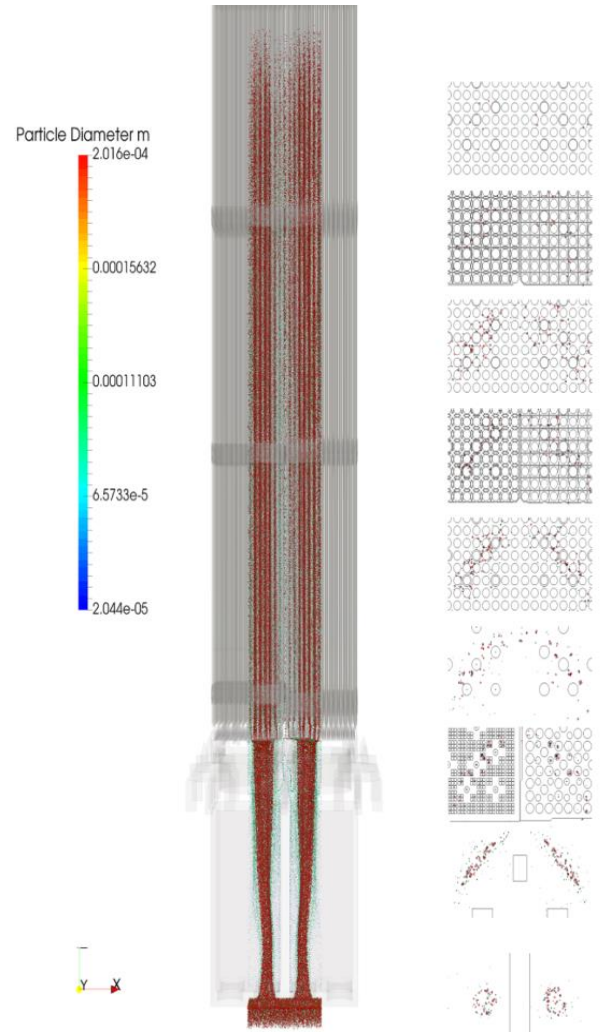

Max difference in DNBR between assembly A and W
in the range of 50-90% of active length,
vertical bars represent standard deviation
DNBR maxdiff&stddev
rod no
1_rod_A_A1_rod_B_A1 2_rod_A_A2_rod_B_A2 3_rod_A_A3_rod_B_A3 4_rod_A_A4_rod_B_A4 5_rod_A_A5_rod_B_A5 6_rod_A_A6_rod_B_A6 7_rod_A_A7_rod_B_A7 8_rod_A_A8_rod_B_A8 9_rod_A_B1_rod_B_B1 10_rod_A_B2_rod_B_B2 11_rod_A_B3_rod_B_B3 12_rod_A_B4_rod_B_B4 13_rod_A_B5_rod_B_B5 14_rod_A_B6_rod_B_B6 15_rod_A_B7_rod_B_B7 16_rod_A_B8_rod_B_B8 17_rod_A_C1_rod_B_C1 18_rod_A_C2_rod_B_C2 19_rod_A_C4_rod_B_C4 20_rod_A_C5_rod_B_C5 21_rod_A_C7_rod_B_C7 22_rod_A_C8_rod_B_C8 23_rod_A_D1_rod_B_D1 24_rod_A_D2_rod_B_D2 25_rod_A_D3_rod_B_D3 26_rod_A_D4_rod_B_D4 27_rod_A_D5_rod_B_D5 28_rod_A_D6_rod_B_D6 29_rod_A_D7_rod_B_D7 30_rod_A_D8_rod_B_D8 31_rod_A_E1_rod_B_E1 32_rod_A_E2_rod_B_E2 33_rod_A_E3_rod_B_E3 34_rod_A_E4_rod_B_E4 35_rod_A_E6_rod_B_E6 36_rod_A_E7_rod_B_E7 37_rod_A_F1_rod_B_F1 38_rod_A_F2_rod_B_F2 39_rod_A_F4_rod_B_F4 40_rod_A_F5_rod_B_F5 41_rod_A_F6_rod_B_F6 42_rod_A_F7_rod_B_F7 43_rod_A_F8_rod_B_F8 44_rod_A_G1_rod_B_G1 45_rod_A_G2_rod_B_G2 46_rod_A_G3_rod_B_G3 47_rod_A_G4_rod_B_G4 48_rod_A_G5_rod_B_G5 49_rod_A_G6_rod_B_G6 50_rod_A_G7_rod_B_G7 51_rod_A_G8_rod_B_G8 52_rod_A_H1_rod_B_H1 53_rod_A_H2_rod_B_H2 54_rod_A_H3_rod_B_H3 55_rod_A_H4_rod_B_H4 56_rod_A_H6_rod_B_H6 57_rod_A_H7_rod_B_H7 58_rod_A_H8_rod_B_H8



Time: 0.401 s

Particle scale factor 10.

Particle distribution at Z = 0.06, 0.45, 0.6, 0.618, 1.1, 1.25, 1.6, 1.8, 2.2 m. Scale factor 20.



Time: 0.401 s

Particle scale factor 10.

Particle distribution at Z = 0.06, 0.45, 0.6, 0.618, 1.1, 1.25, 1.6, 1.8, 2.2 m. Scale factor 20.

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