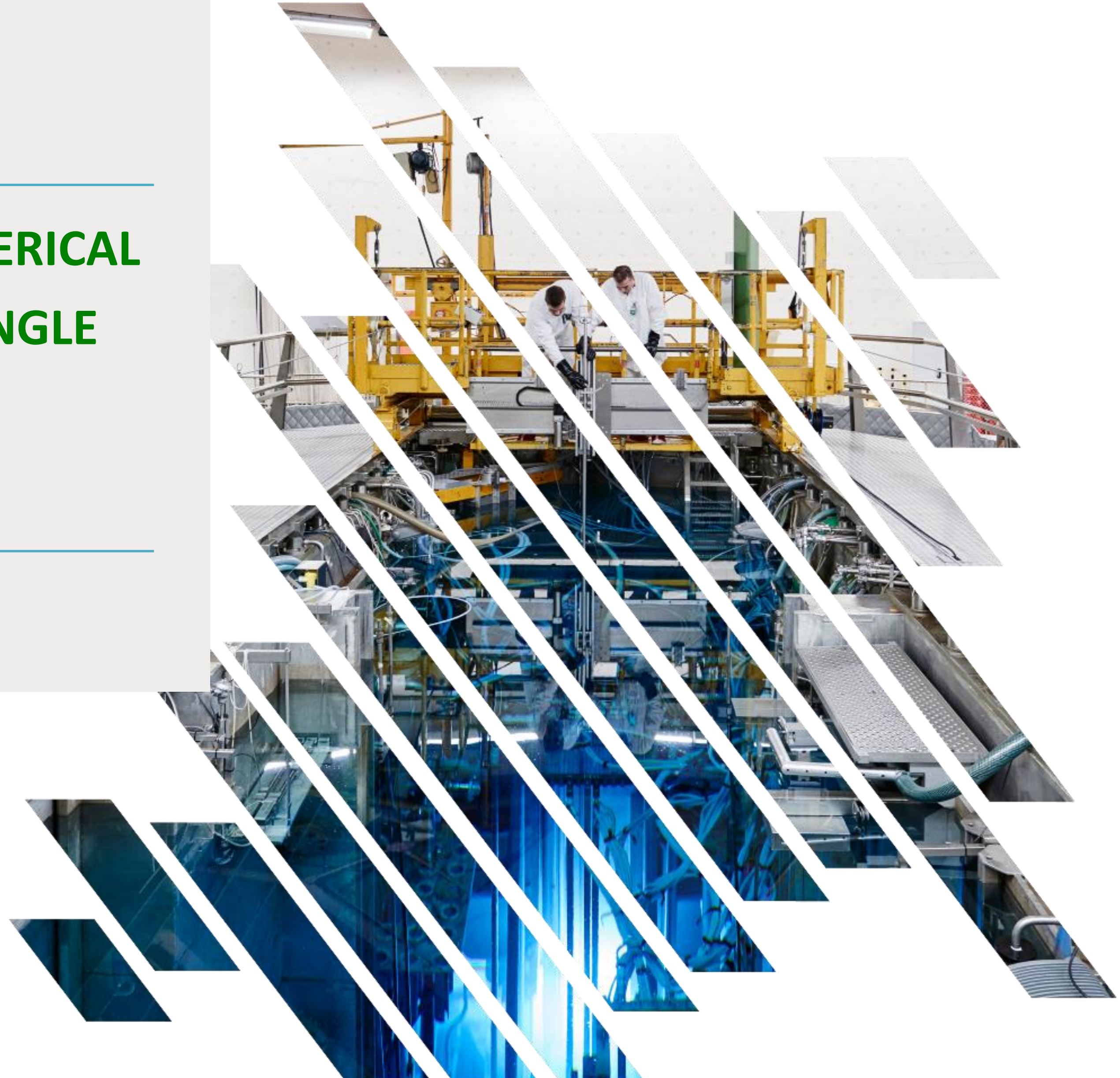
HIGH FIDELITY NUMERICAL SIMULATION OF A SINGLE PHASE PRESSURIZED THERMAL SHOCK

Seminar @ NCBJ, Poland



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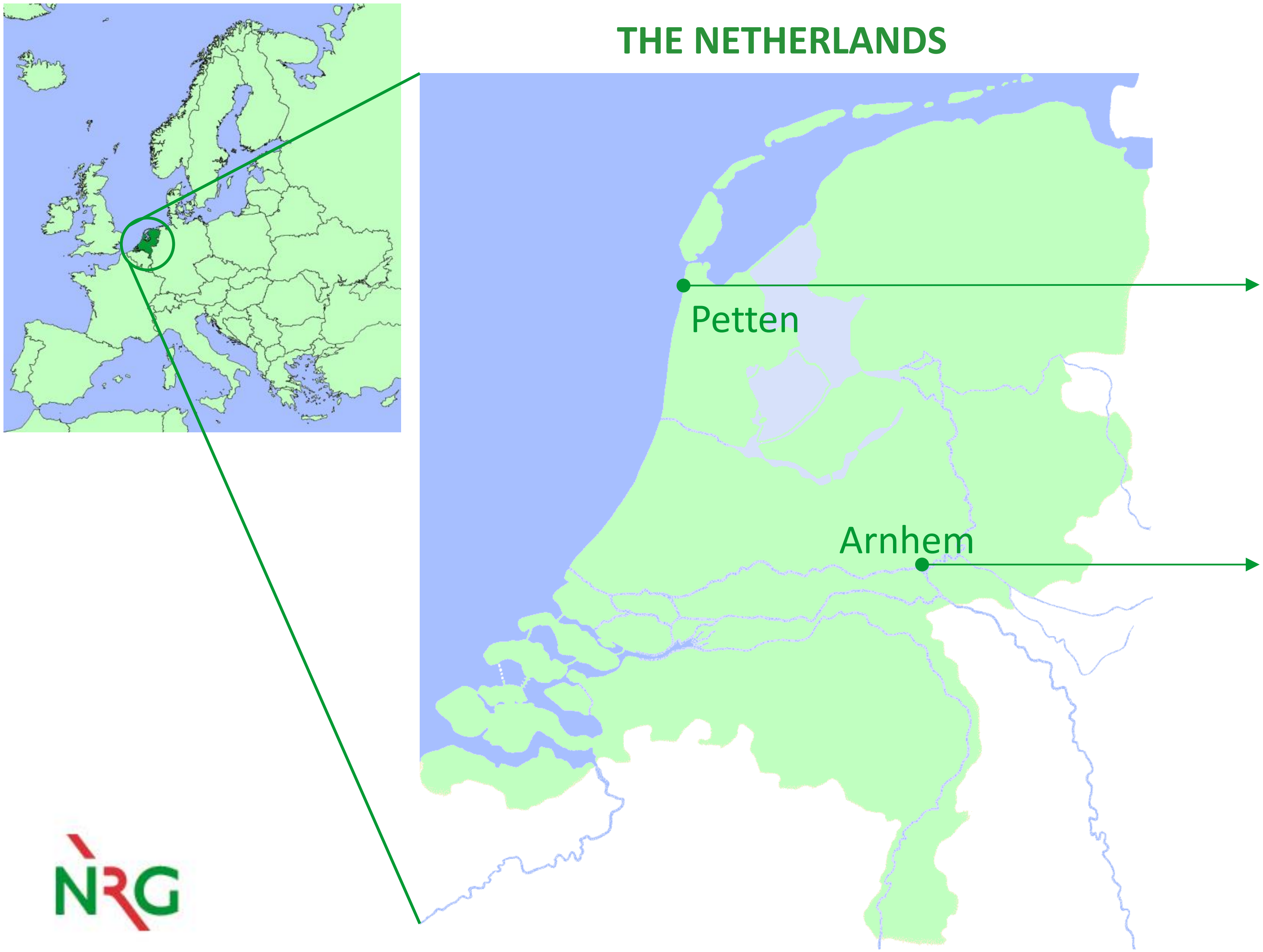
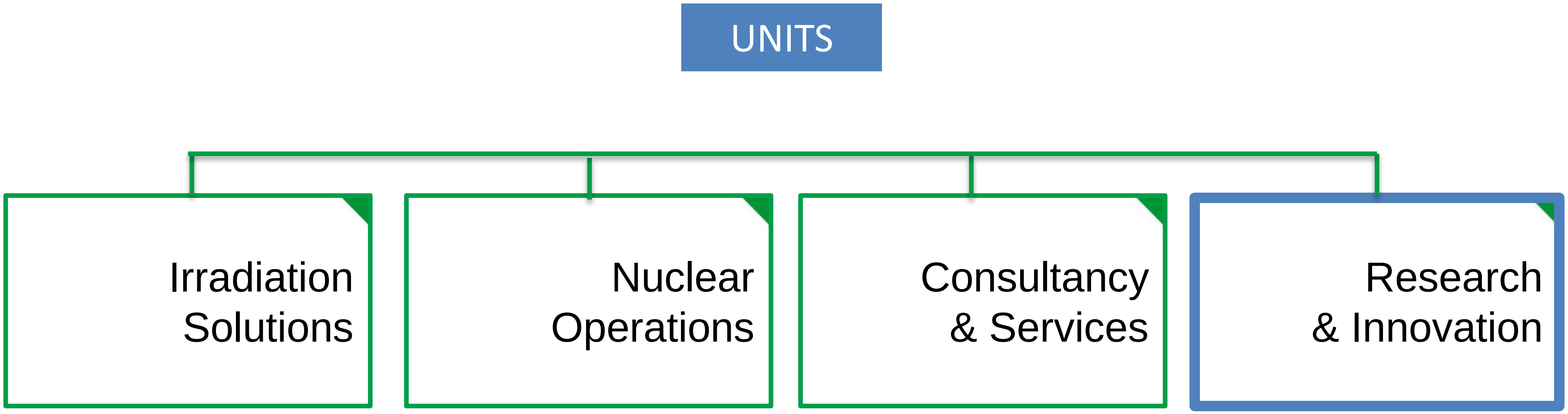
Introduction: NRG

NRG Locations



NRG Organisation



Research & Innovation

Research Program

- Reactor Operation & Safety
- Advanced Nuclear Technology
- Decommissioning
- Radiation Protection

International Cooperation

- EU framework programs (FP7 – H2020)
- OECD/NEA benchmarks
- IAEA CRPs and TWGs
- US-DOE INERI
- Bilateral collaborations

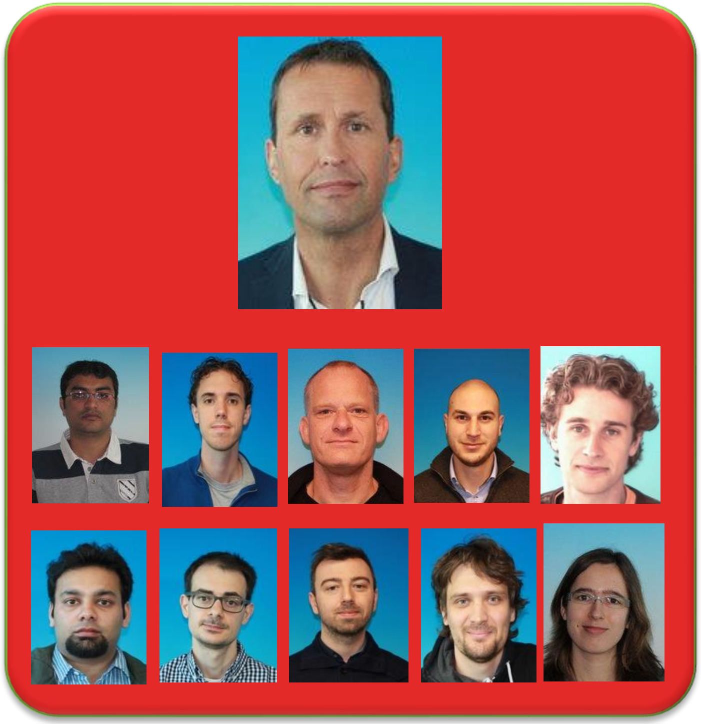
NRG-NCBJ

CFD Group

- ~11 qualified specialists
  - Total professional experience of almost 100 person-years
  - International
  - 3 master students

- Mission:
  - To provide support for safety and design improvement

- CFD Codes
  - STAR-CCM+
  - ANSYS-FLUENT, ANSYS-CFX
  - OpenFOAM
  - NEK5000
  - Code_Saturne
  - FDS

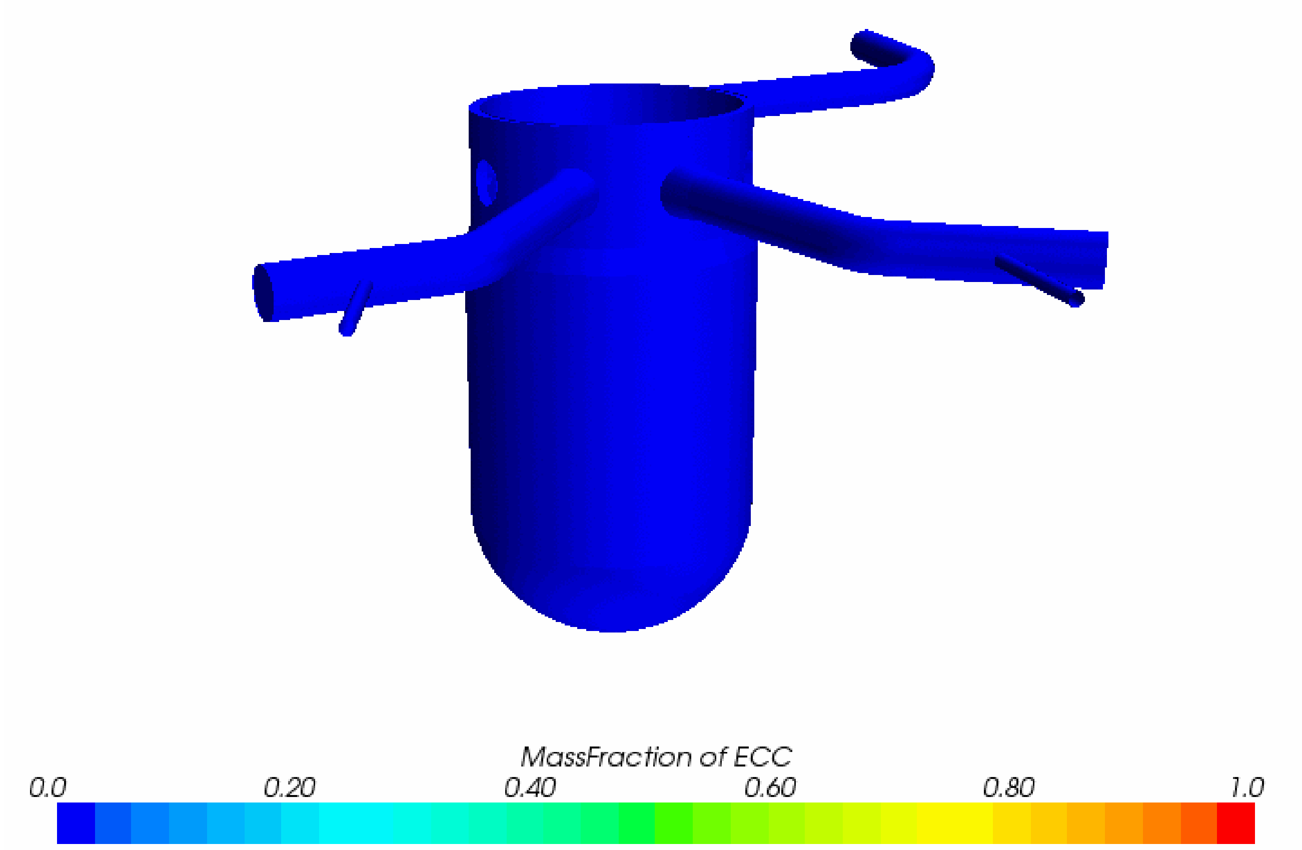


NRG

Introduction and goal

Introduction and Goal

- Main issues for *single-phase* PTS
  - Turbulent mixing of the ECC water
    - CFD grade validation exists, e.g., from ROCOM



NRG

Introduction and Goal

- Main issues for *single-phase* PTS – continued
  - Turbulent mixing of the ECC water
  - Heat transfer – RPV walls

- Both involve complex 3D phenomena
  - CFD provides more realistic representation

- CFD (pragmatic) models need to be validated for PTS using
  - Experimental data
  - High fidelity Direct Numerical Simulation (DNS) data

NRG

Introduction and Goal

The main objective is to generate a high quality DNS database

The first step is to design a <u>numerical experiment</u> in order to perform such high quality DNS computations with the spectral element code NEK5000.

Simulate a *physically meaningful* PTS benchmark configuration for the validation of CFD codes.

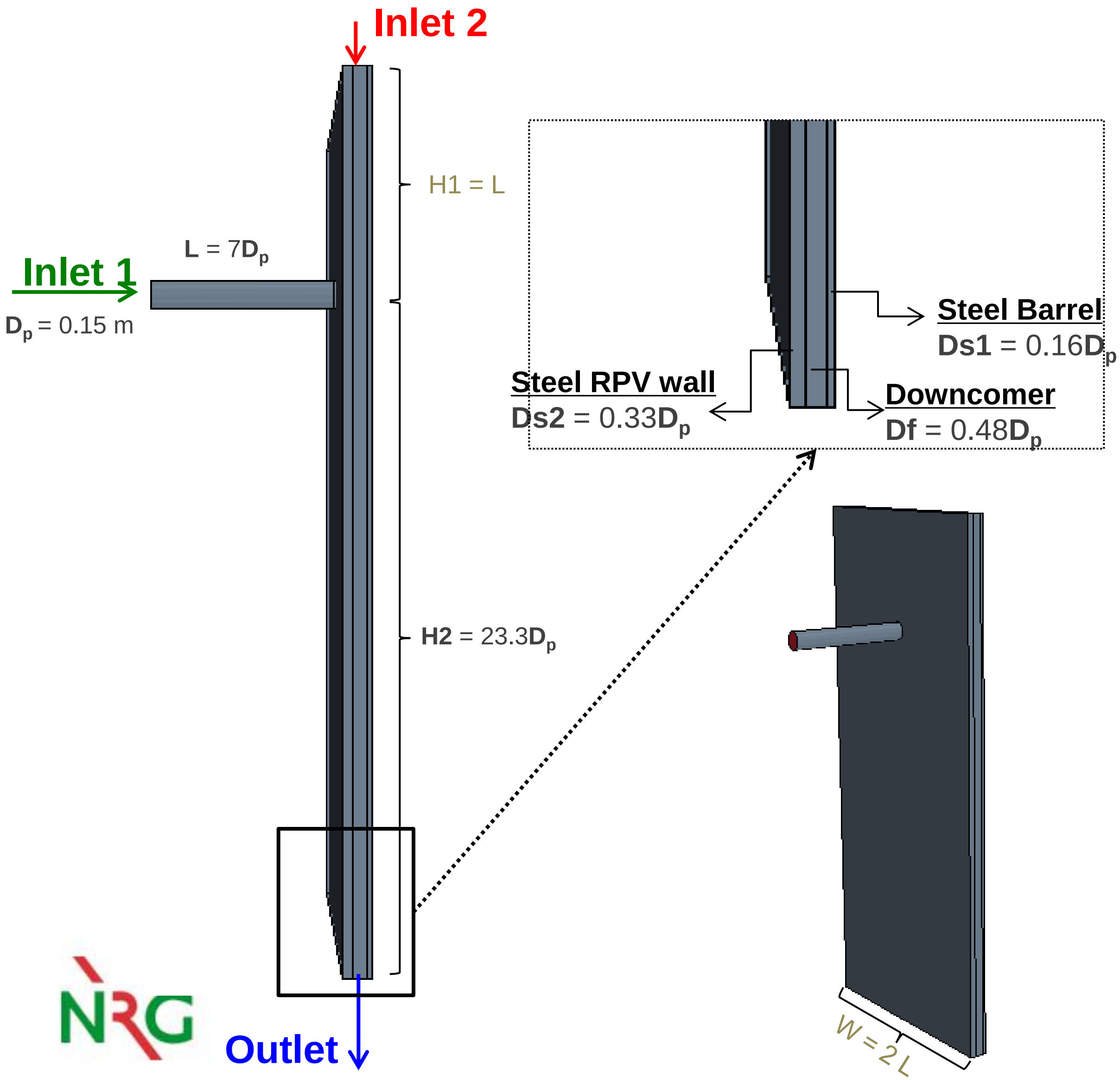
Be *simple* enough in order to:

1. isolate the phenomena of interest from the overall real scenario;
2. fulfil the foreseen computational challenges of DNS.

Conceptual design of a PTS case

Conceptual design

Parameters based on ROCOM test facility



BOUNDARY CONDITIONS

Inlet 1: U1=0.018 m/s
T1= 293 K

Inlet 2: U2=variable
T2= 353 K

Outer surfaces : Adiabatic

PART I:

Calibration and Optimization of the PTS design

Design calibration and optimization

- Calibration and optimization of the PTS case based on pre-cursor RANS analyses

- Main characteristics of the pre-cursor RANS computations
  - STAR-CCM+ v 8.06 CFD code
  - RANS: cubic non-linear k-ε model
  - Second order upwind schemes
  - Hexahedral trim mesh ~ 3.7 M (y+ < 1)
  - Prism layers next to the wall for both fluid and solid

Design calibration and optimization

Step 1 – Calibration of flow properties

Step 2 – Calibration of Inlet 2 velocity

Step 3 – Square duct shaped cold leg

Step 4 – Calibration of the sizes of the computational domain

Step 5 – Scaling of the Reynolds number

Step 6 – Mesh estimation for DNS

Step 7 – Scaling of Prandtl number to 1

Step 8 – Isothermal vs Adiabatic boundary conditions

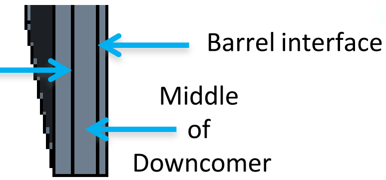
Step 1 – Calibration of flow properties

Case	U_1 [m/s]	U_2 [m/s]	Tref [K]	Pr	Re_τ
1	0.018	5% U_1	**293**	7.01	96
2	0.018	5% U_1	**313**	4.34	138
3	0.018	5% U_1	**333**	2.99	184
4	0.018	5% U_1	**353**	2.23	232

$$Pr = \frac{\nu}{\alpha} = \frac{momentum\ diffusivity}{thermal\ diffusivity}$$

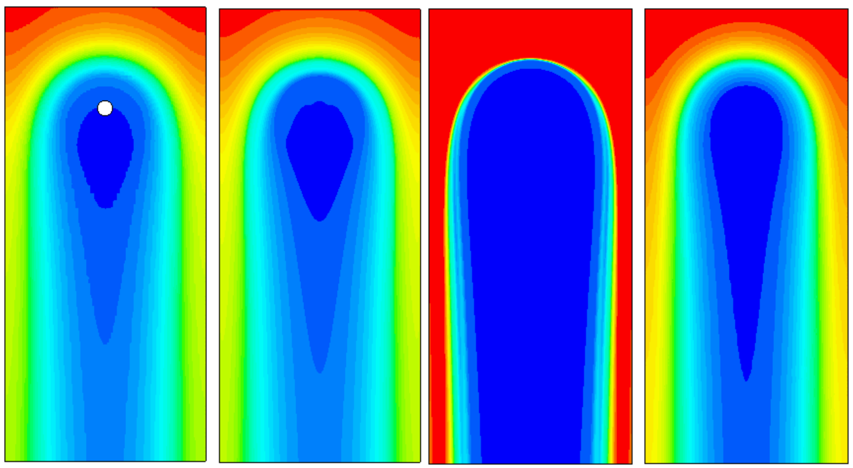
$$\frac{\eta_{batchelor}}{\eta_{kolmogorov}} = Pr^{-\frac{1}{2}} \qquad for\ Pr > 1$$

Step 1: Calibration of flow properties



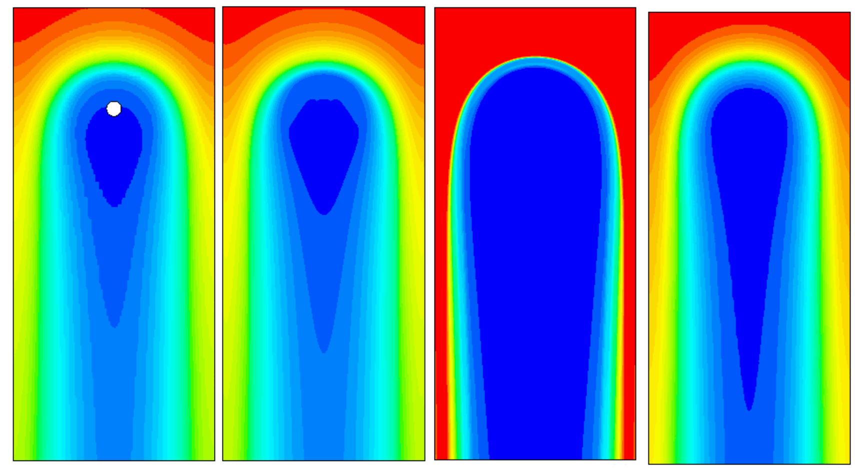
Temperature at Interfaces

Vessel Interface | Vessel Interface +~0,007Dp | Middle of Downcomer | Barrel Interface



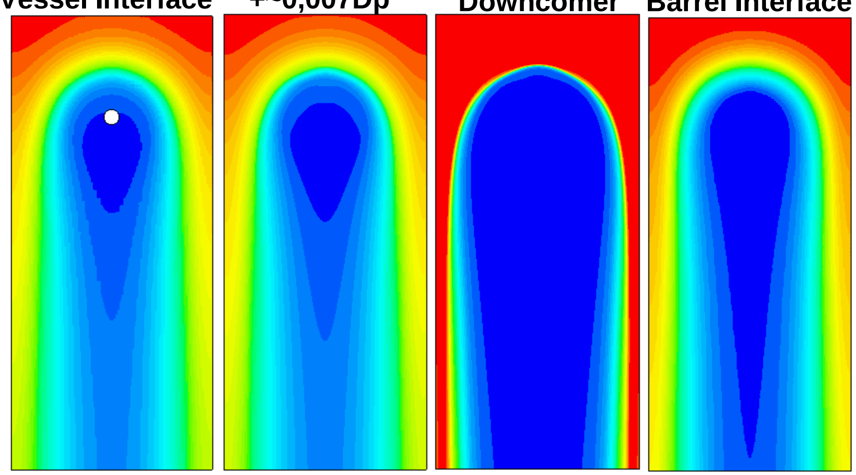
Pr = 7.01

Vessel Interface | Vessel Interface +~0,007Dp | Middle of Downcomer | Barrel Interface



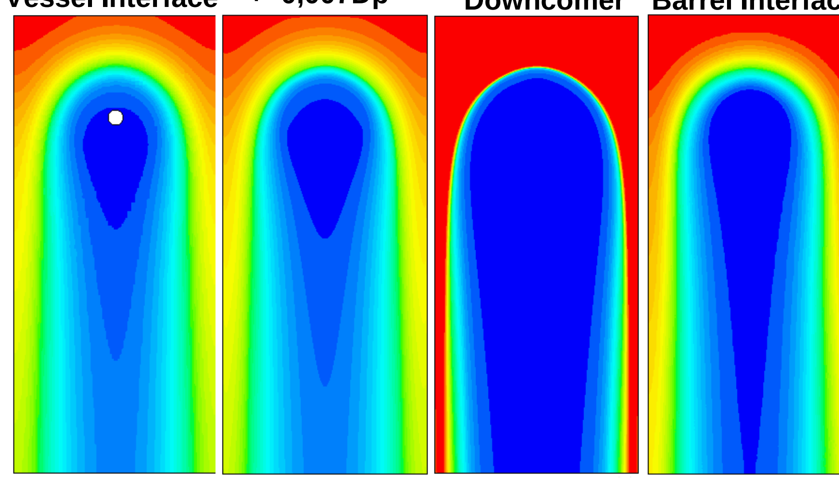
Pr = 4.34

Vessel Interface | Vessel Interface +~0,007Dp | Middle of Downcomer | Barrel Interface



Pr = 2.99

Vessel Interface | Vessel Interface +~0,007Dp | Middle of Downcomer | Barrel Interface



Pr = 2.23

NRG

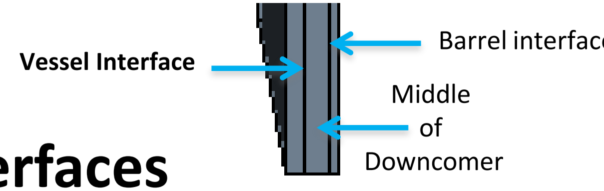
✓ Pr = 2.23 Selected

Step 2 – Calibration of Inlet 2 velocity (U2)

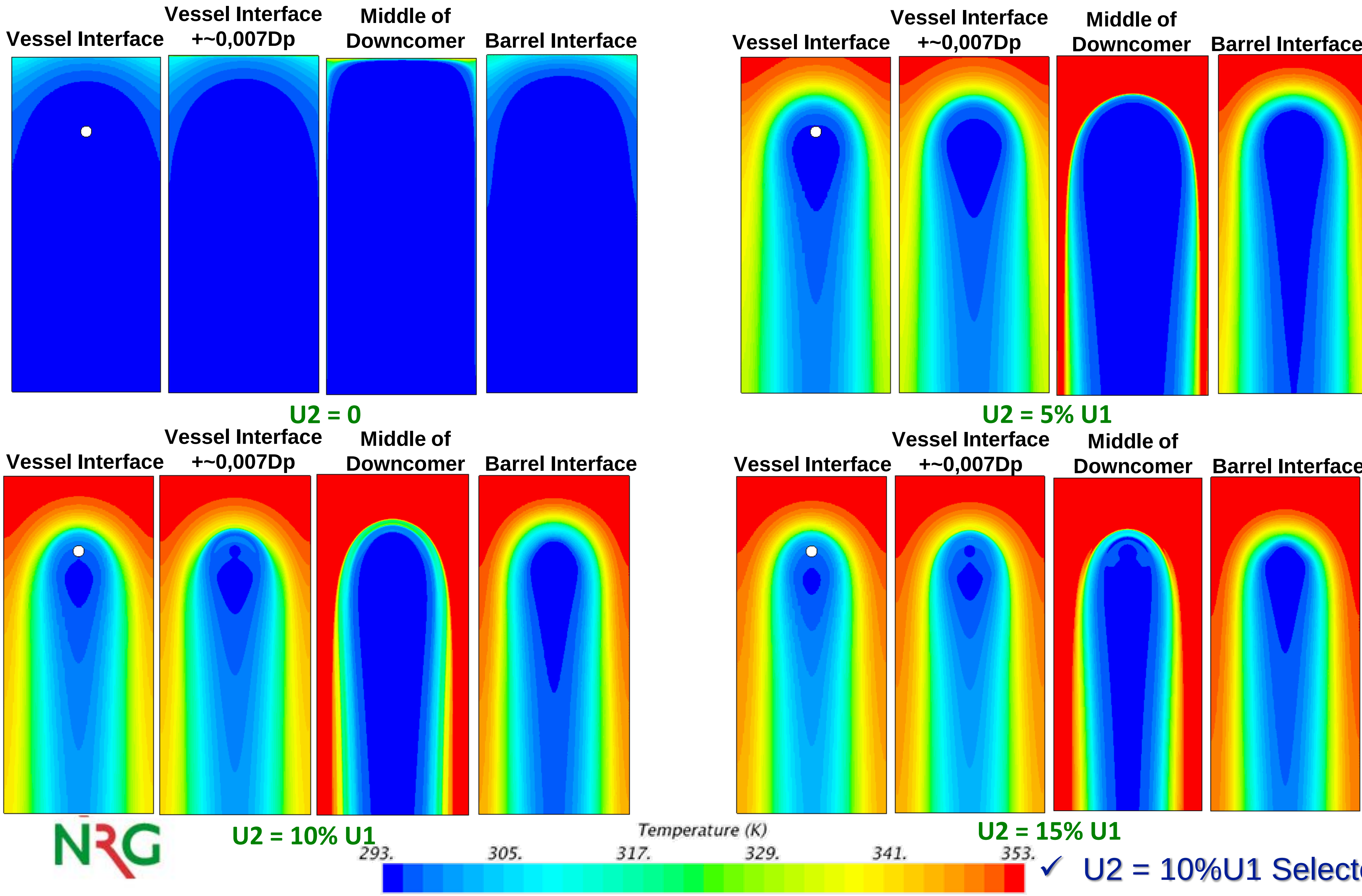
Case	U_1 [m/s]	U_2 [m/s]	Tref [K]	Pr
5	0.018	**0**	353	2.23
6	0.018	**5% U1**	353	2.23
7	0.018	**10% U1**	353	2.23
8	0.018	**15%U1**	353	2.23

- ❑ Force the impinging cold jet downward in the downcomer
- ❑ Create a certain level of thermal mixing

Step 2: Calibration of Inlet 2 velocity



Temperature at Interfaces



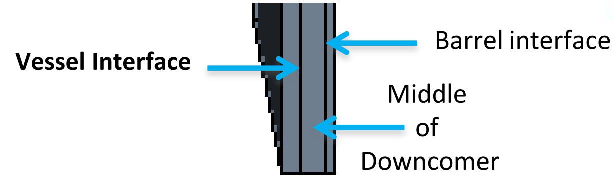
✓ U2 = 10%U1 Selected

Step 3 – Square duct shaped cold leg

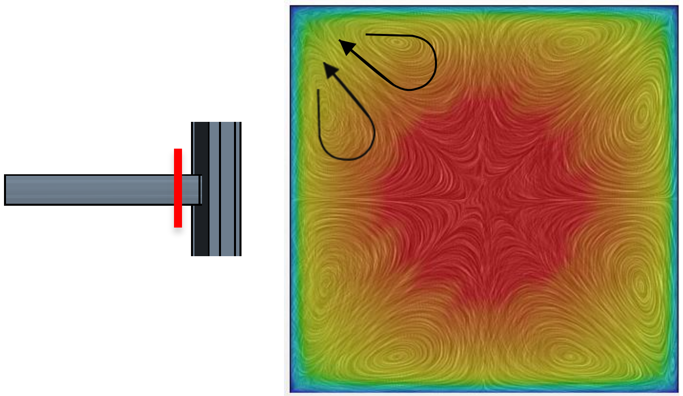
Case	U_1 [m/s]	U_2 [m/s]	Tref [K]	Pr	Cold leg
7	0.018	10% U1	353	2.23	**Circular pipe**
9	0.018	10% U1	353	2.23	**Square duct**

Minimize meshing difficulties in NEK5000

Step 3: Square duct shaped cold leg

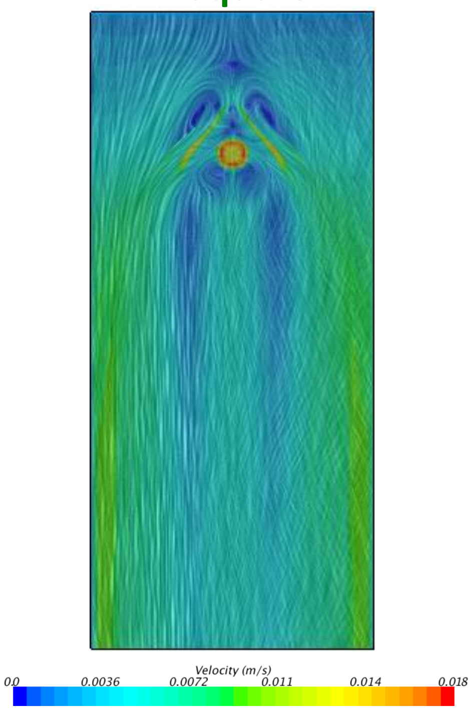


Velocity



Circular

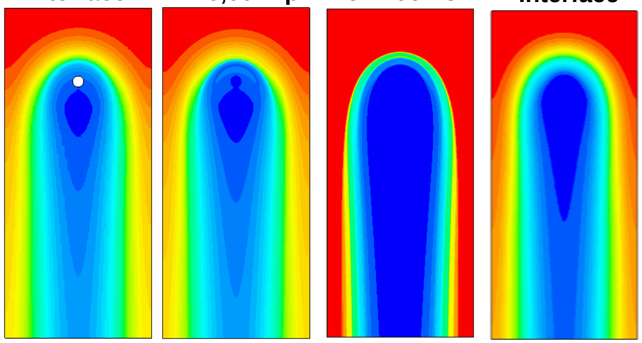
Square



Temperature

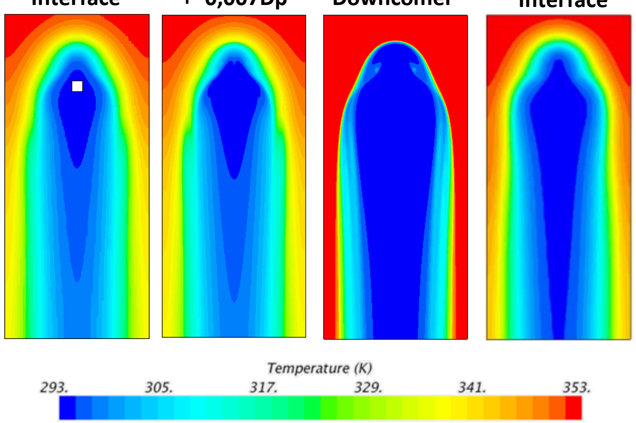
Circular

Vessel Interface | Vessel Interface +~0,007Dp | Middle of Downcomer | Barrel Interface



Square

Vessel Interface | Vessel Interface +~0,007Dp | Middle of Downcomer | Barrel Interface



Step 4 – Calibration of the sizes of the computational domain

Calibration of upper height (H1) :

$10\ D_p$

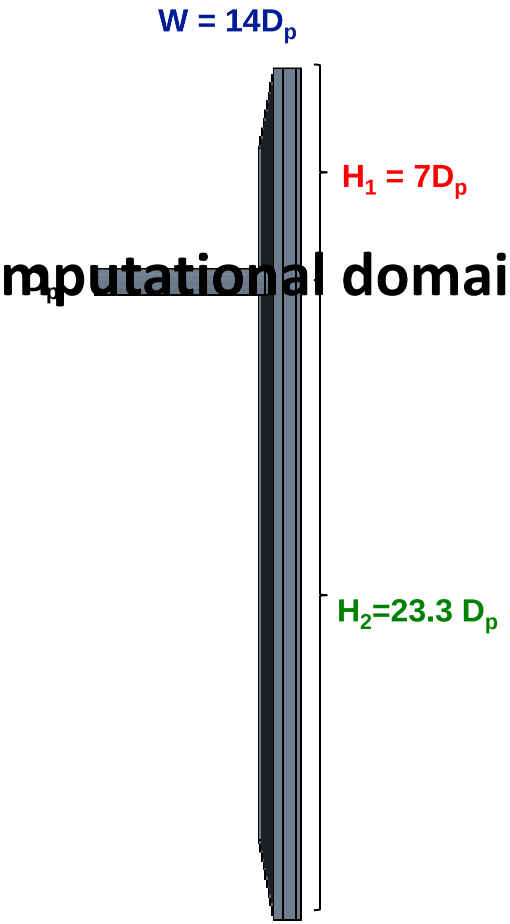
Calibration of bottom height (H2) :

$13.3\ D_p$ – $16.3\ D_p$ – $20.3\ D_p$

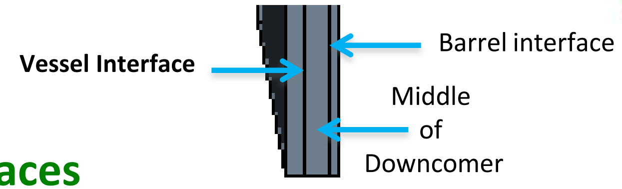
$26.3\ D_p$ – $30.3\ D_p$ – $33.3\ D_p$

Calibration of width (W) :

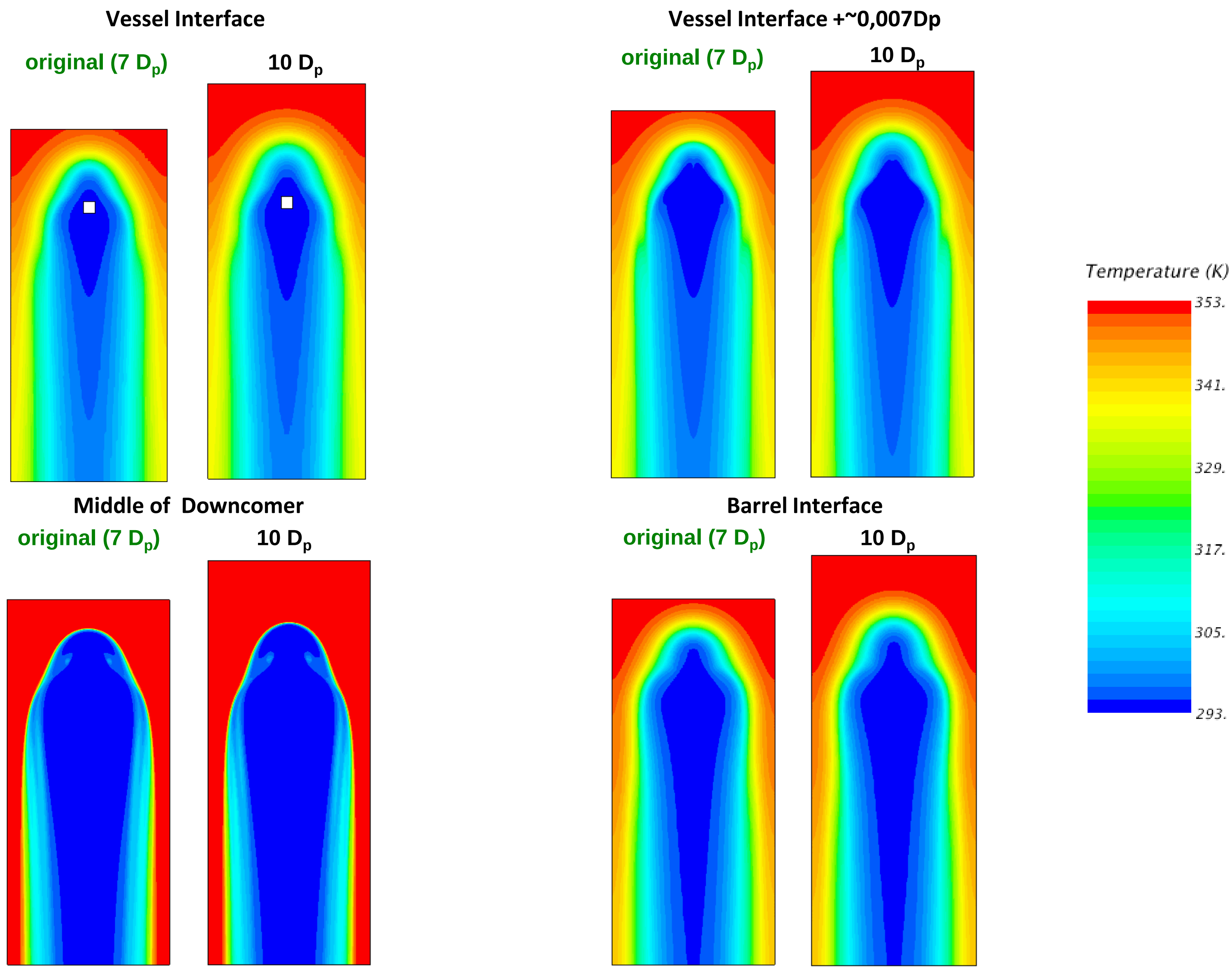
$20\ D_p$ – $26\ D_p$



Step 4 – Calibration of upper height (H1)

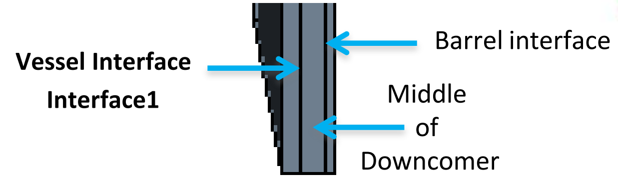


Temperature at Interfaces

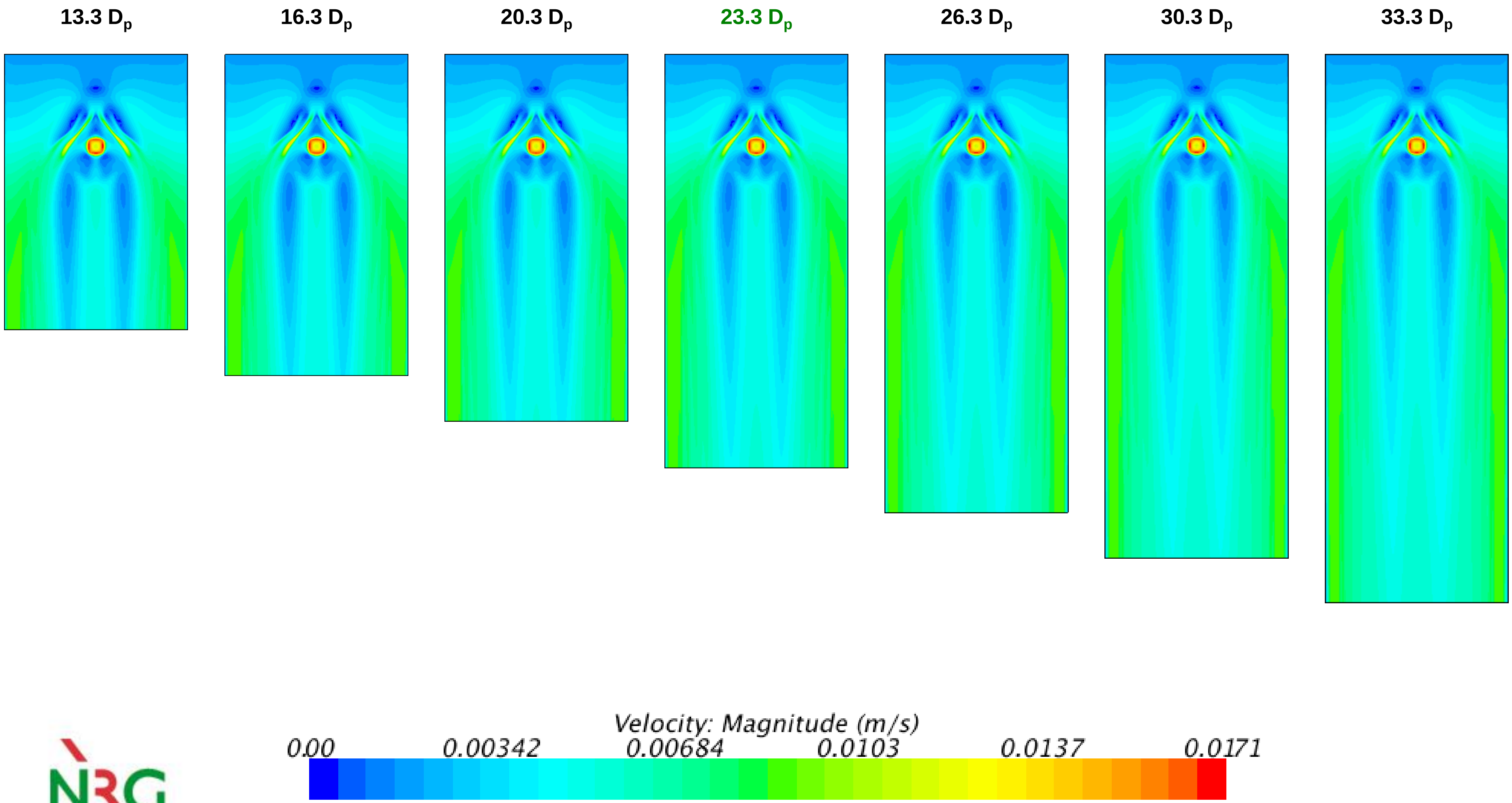


✓ **10 D_p Selected**

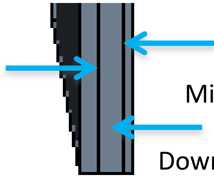
Step 4 – Calibration of bottom height (H2)



Velocity at the mid cross-section of Downcomer

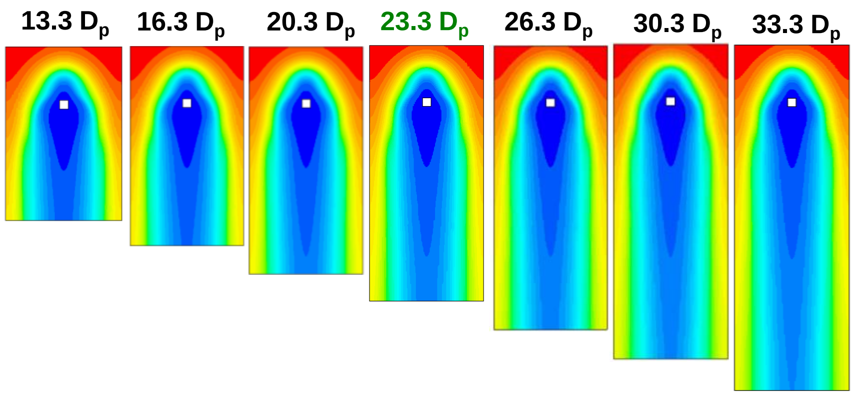


Step 4 – Calibration of bottom height (H2)

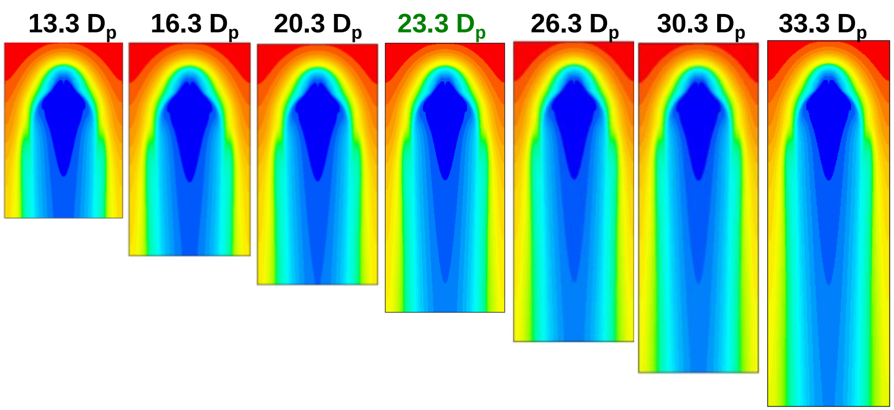


Temperature at Interfaces

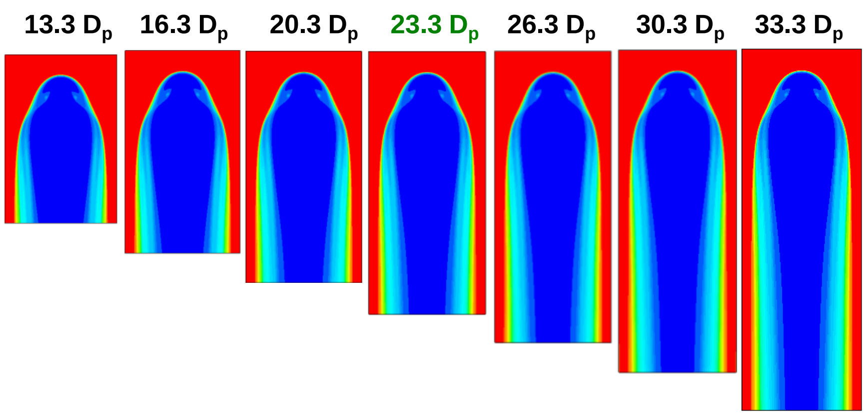
Vessel Interface



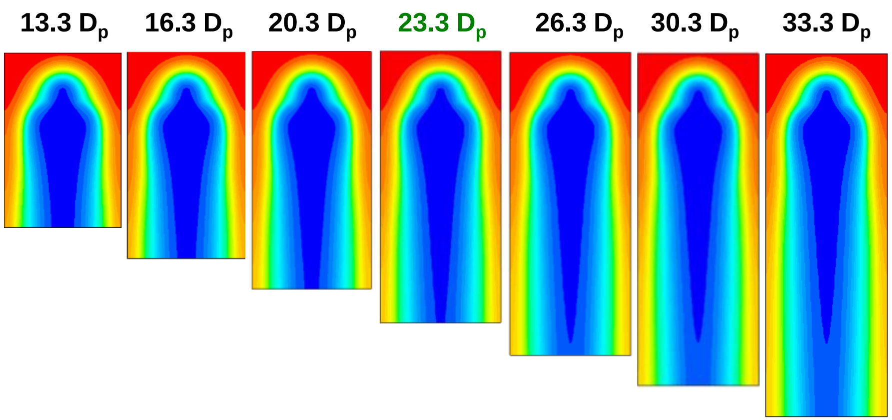
Vessel Interface +~0,007Dp

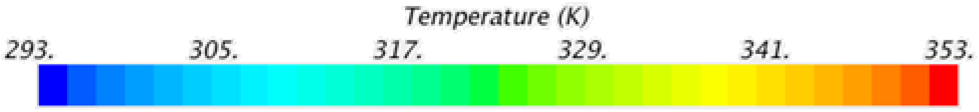


Middle of Downcomer



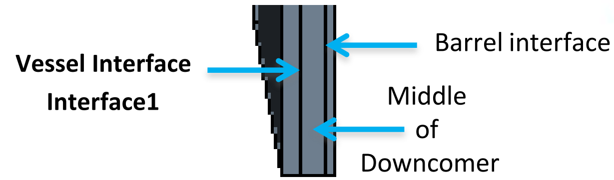
Barrel Interface



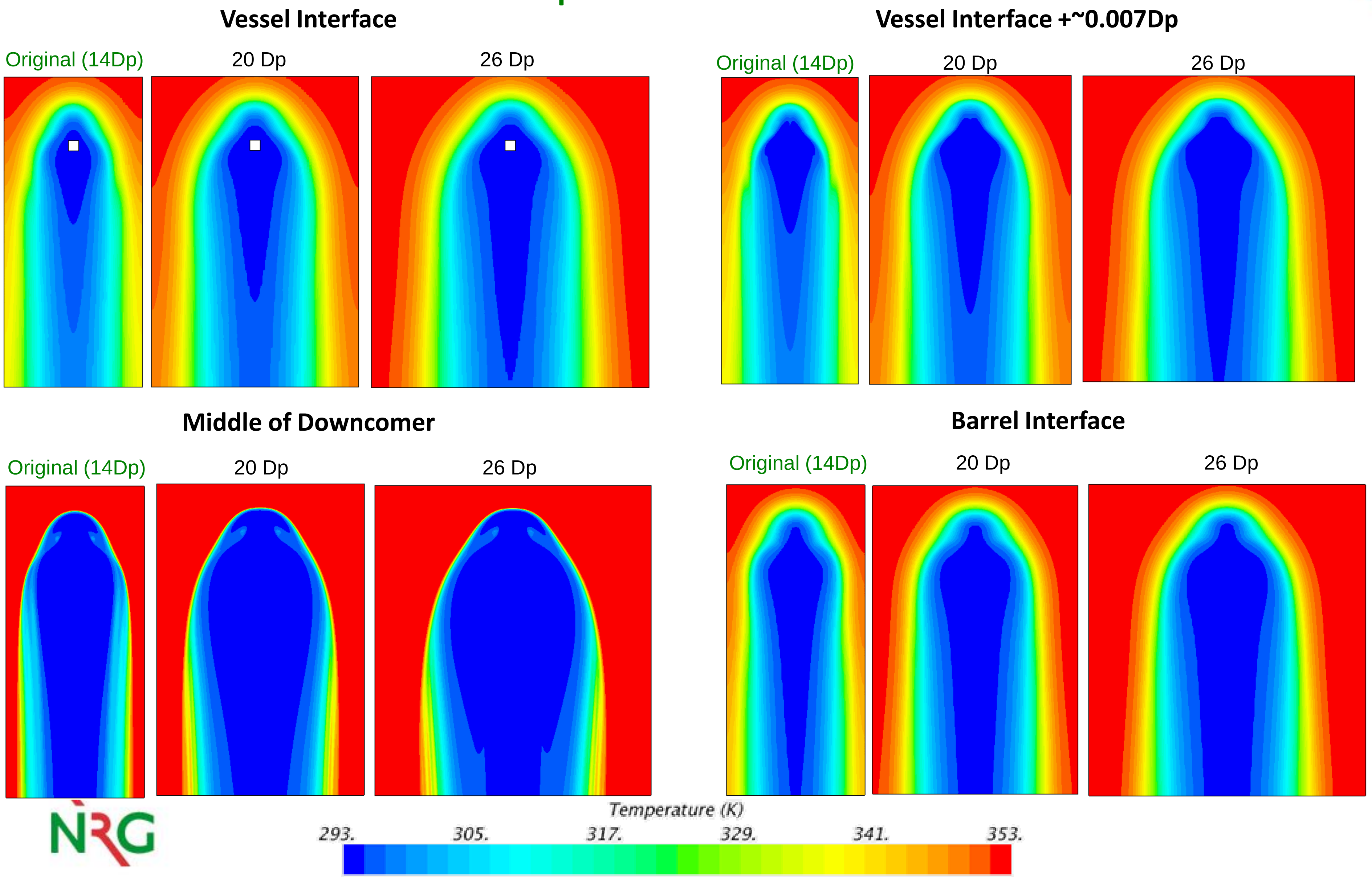


✓ Original Selected

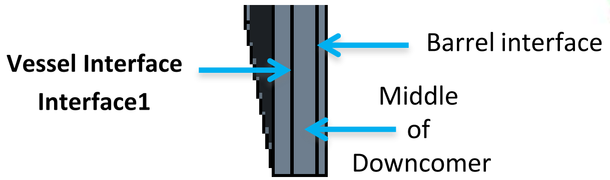
Step 4 – Calibration of width (W)



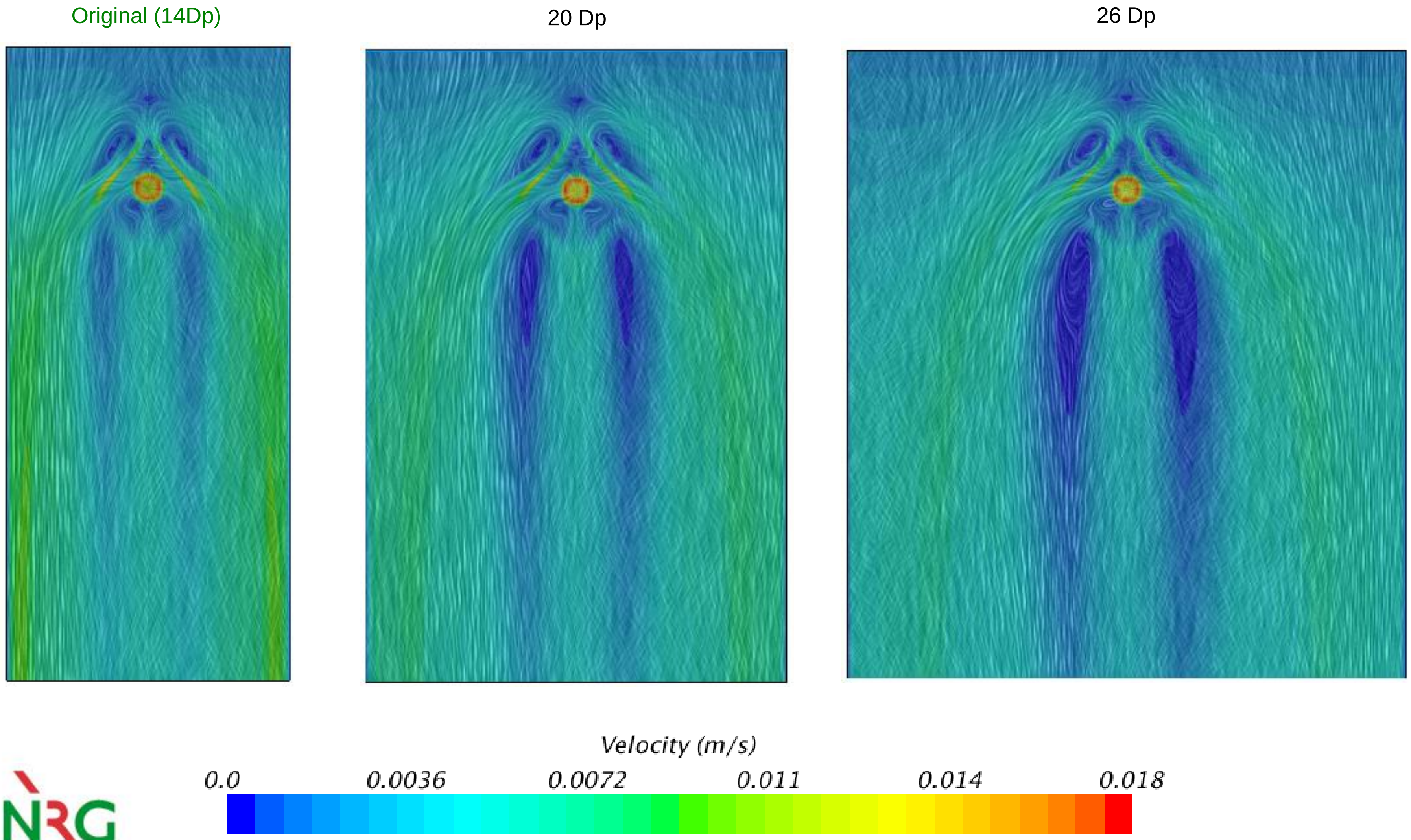
Temperature at Interfaces



Step 4 – Calibration of width (W)



Velocity at the mid cross-section of Downcomer



✓ 20 Dp Selected

Step 5 – Scaling of the Reynolds number

Case	U1 [m/s]	U2 [m/s]	Tref [K]	Pr	Re_τ
9	**0.018**	10% U1	353	2.23	**~230**
10	**0.0135**	10% U1	353	2.23	**180**

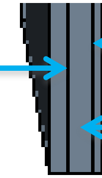
Reduce the level of turbulence

↓

✓**Increase the size of turbulence length scales**

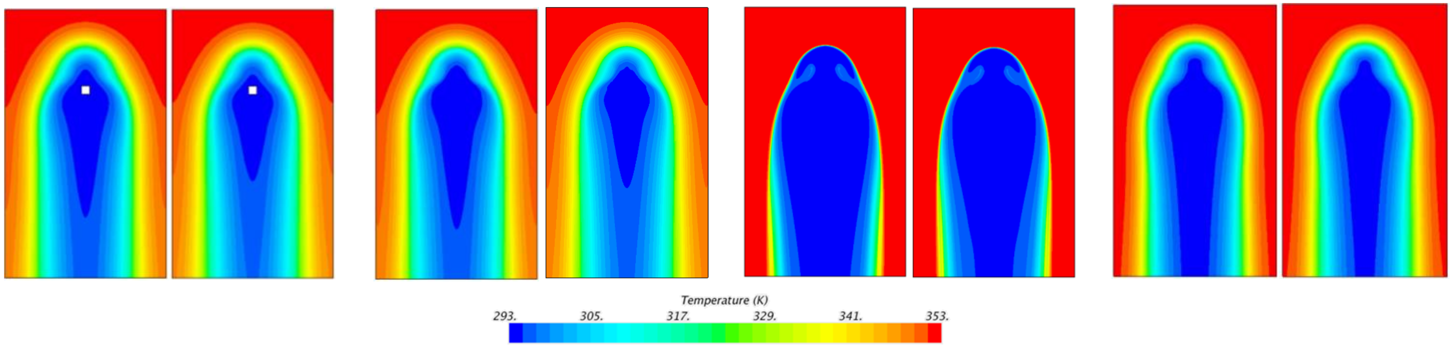
✓**Reduce the overall cost of the DNS**

Step 5 - Scaling of the Reynolds number



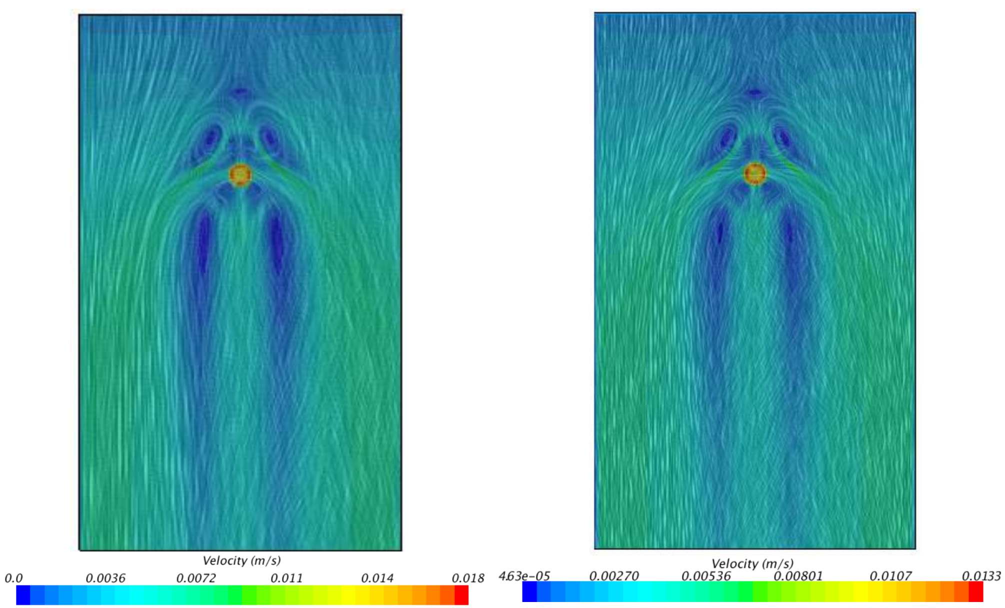
Temperature at Interfaces

Vessel Interface		Vessel Interface+~0.007Dp		Middle of Downcomer		Barrel Interface	
Re_T = ~230	Re_T = 180	Re_T = ~230	Re_T = 180	Re_T = ~230	Re_T = 180	Re_T = ~230	Re_T = 180



Velocity at the mid cross-section of Downcomer

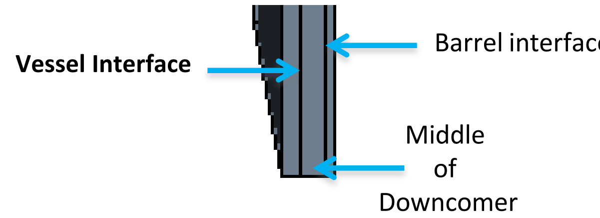
Re_T = ~230 | Re_T = 180



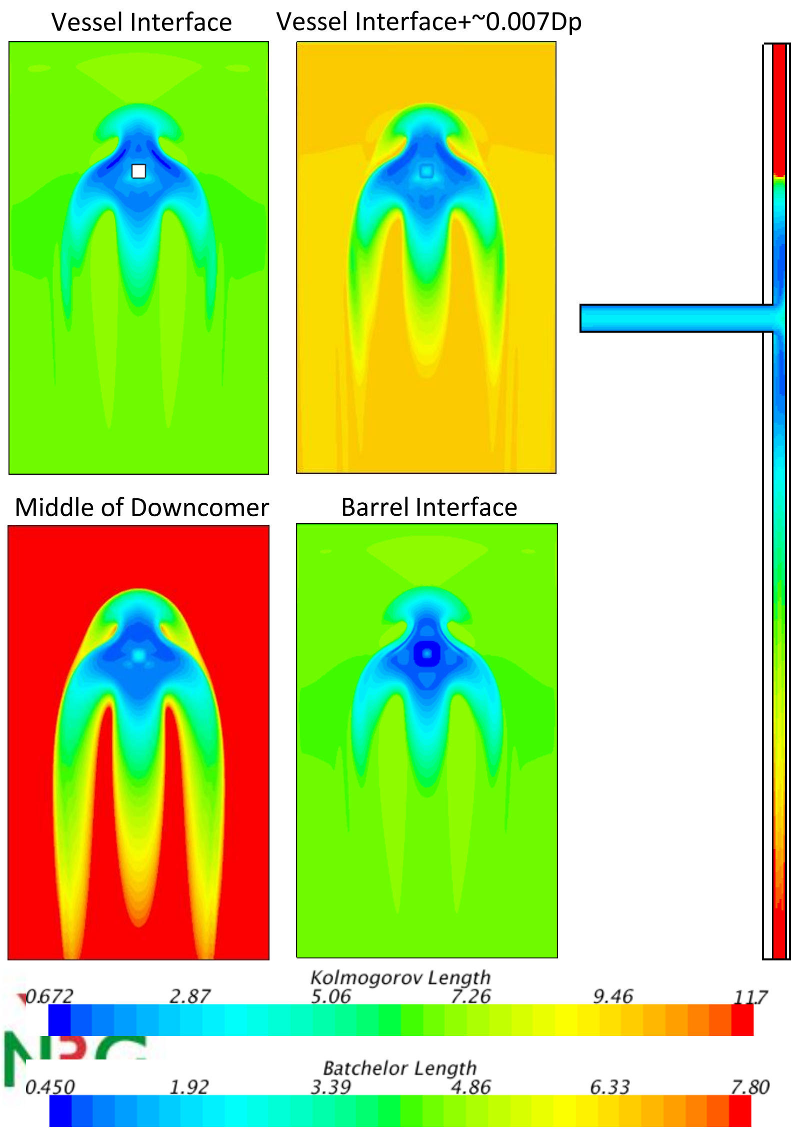
✓ **Re_T = 180 Selected**

Step 6 – Mesh Estimation for DNS

Step 6: Mesh estimation for DNS



Turbulent scales at Interfaces



Mesh estimations for DNS

1. **Quasi-uniform mesh distribution:**

   ~4 billion grid points

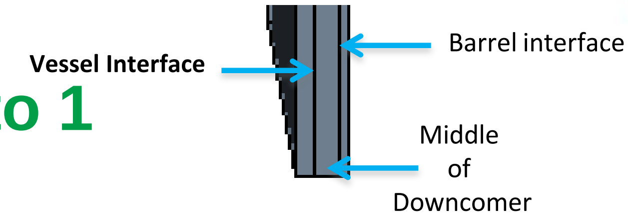
2. **Smart meshing strategy based on block structures:**

   ~1.6 billion grid points

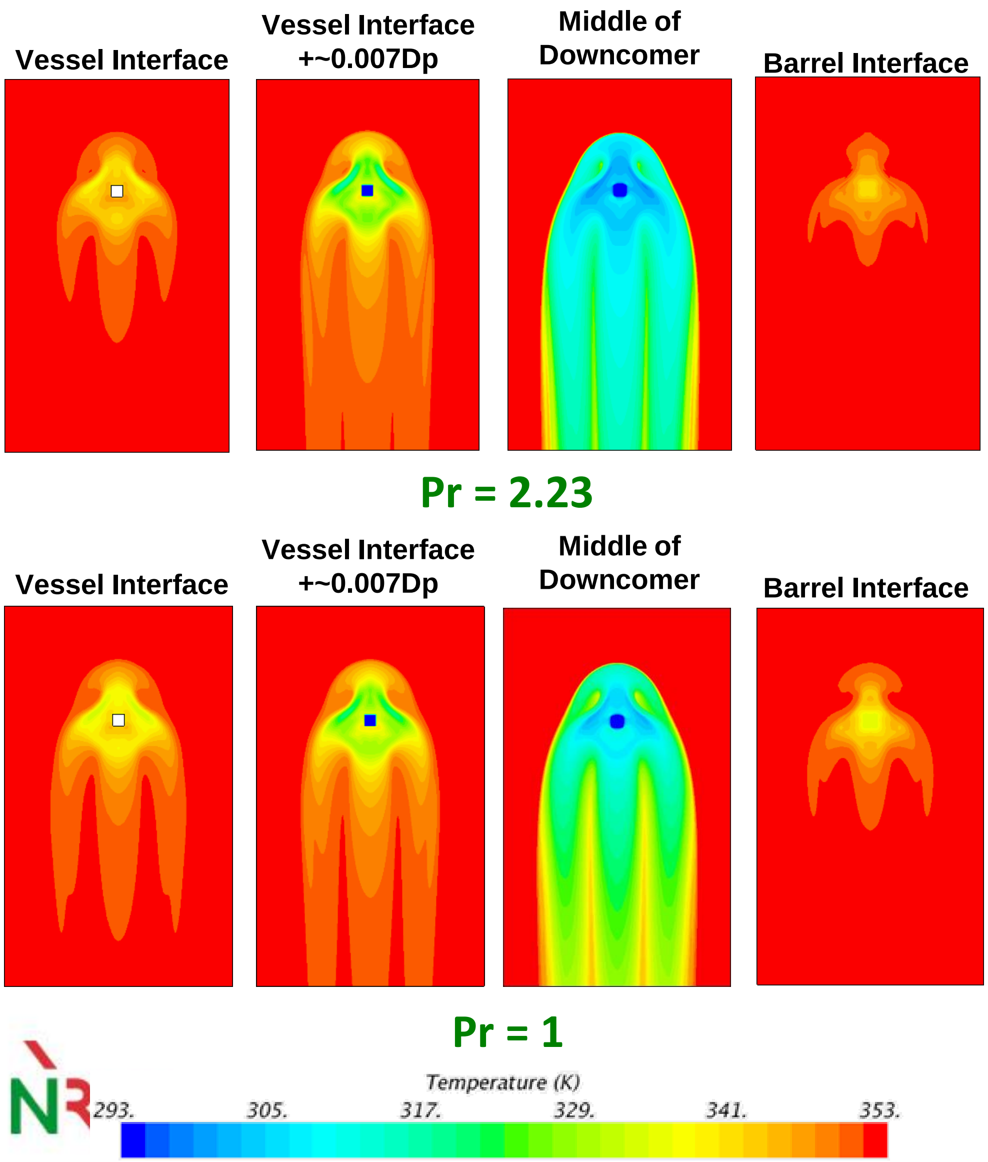
Still challenging for the currently available computer power.

Step 7 – Scaling of Prandtl number to 1

Step 7 – Scaling of Prandtl number to 1



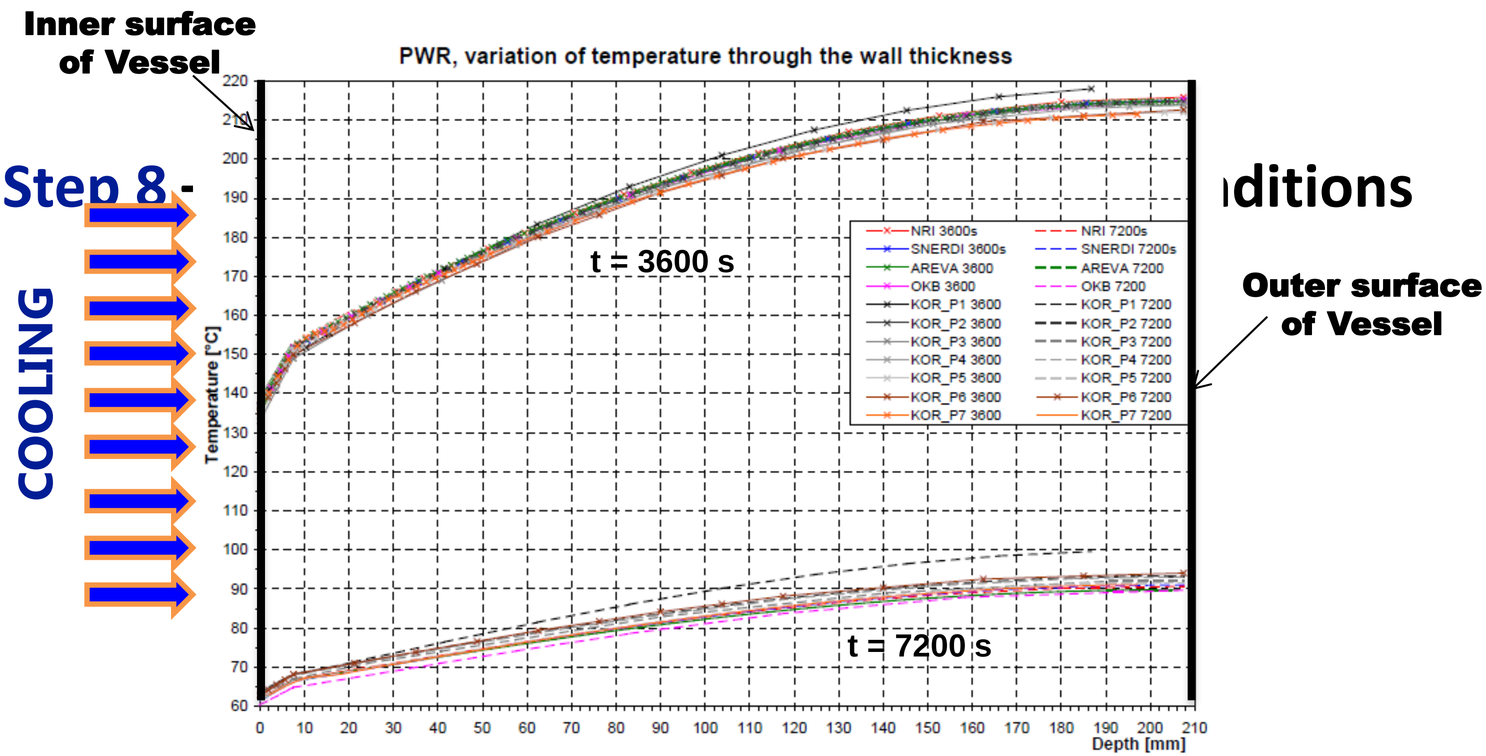
Temperature at Interfaces



Mesh estimations for DNS

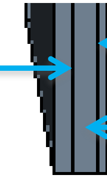
~ 0.9 billion grid points
for conjugate heat transfer case

Step 8 - … ditions

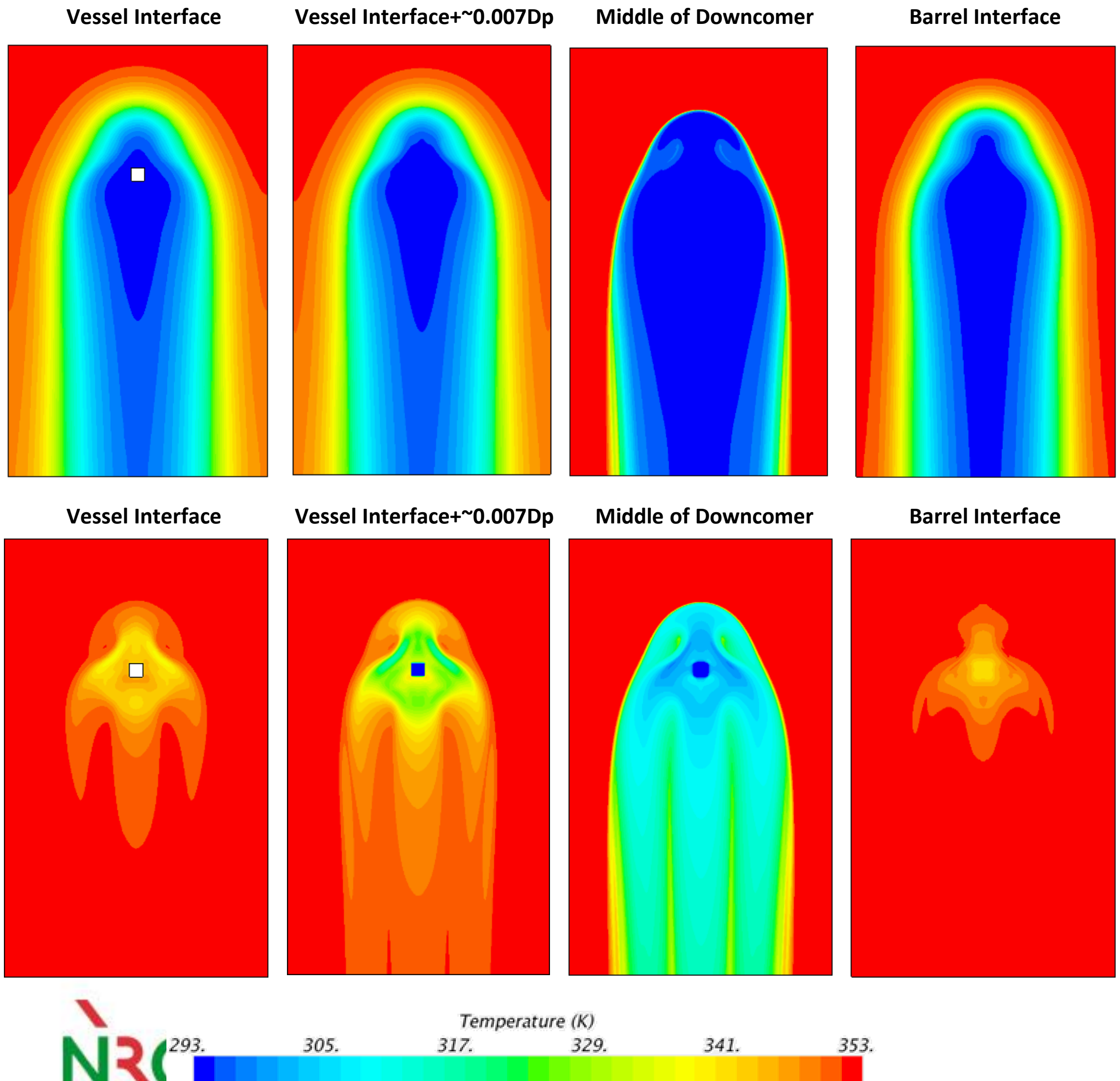


From IAEA-TECDOC-1627: *Pressurized Thermal Shock in Nuclear Power Plants: Good Practices for Assessment*

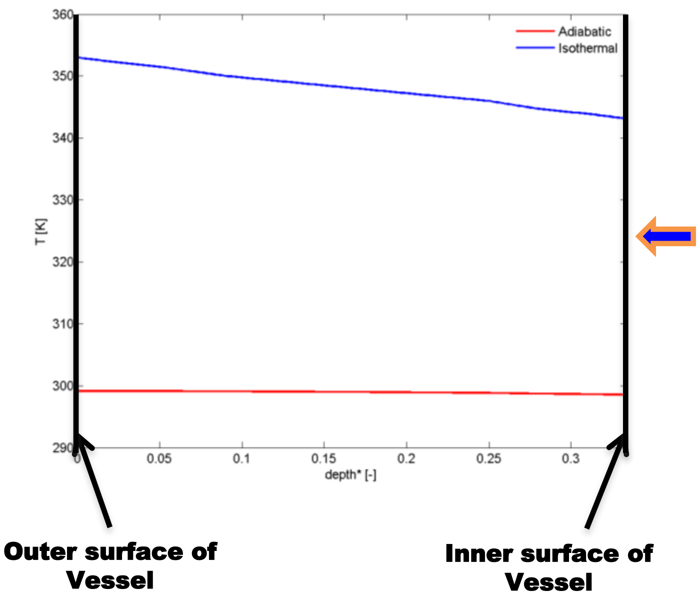
Step 8 – Adiabatic vs Isothermal BC's



Temperature at Interfaces



Variation of Temperature through the vessel wall thickness



Mesh estimations for DNS

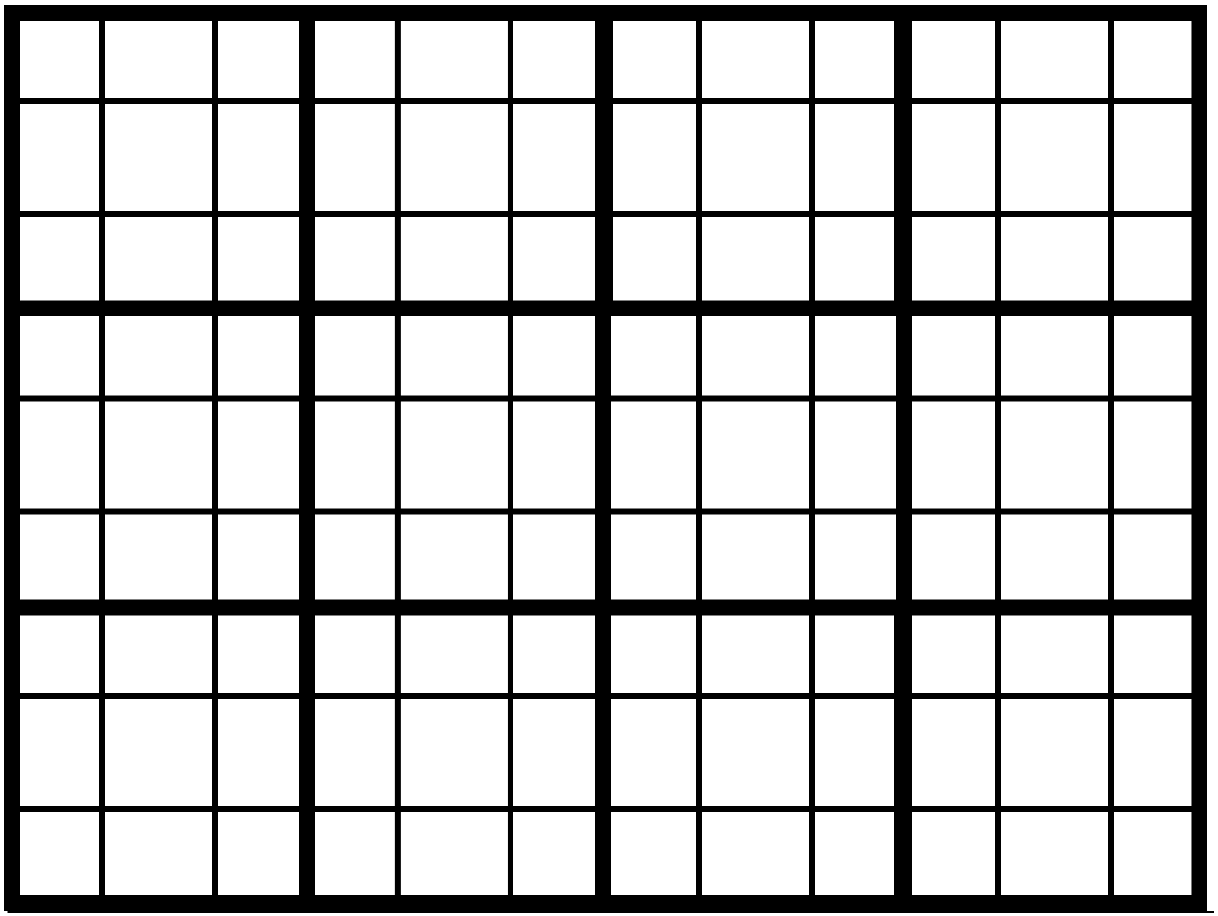
~ 0.55 billion grid points
w/o conjugate heat transfer case

PART II:

Assessment of NEK5000 to perform DNS

NEK5000

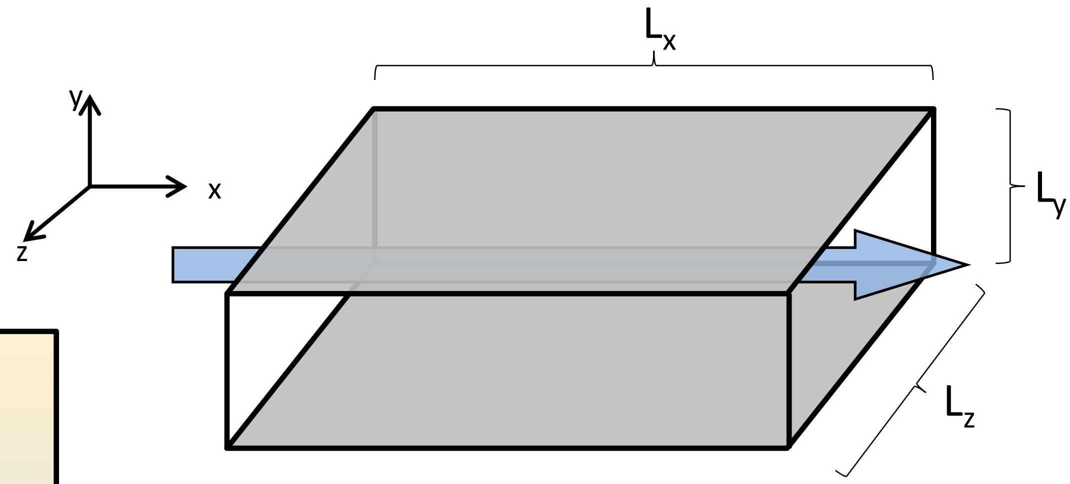
- Open source code (ANL);
- High-order **SEM** - **S**pectral **E**lement **M**ethod;
- GLL as



Simulation parameters

Main parameters, computational domain, mesh distribution

Re_τ = 180



Pol. order *(space)* = 9

Pol. order *(time)* = 3 (*explicit*)

CFL = 0.2

L_x = 12.75 L_y = 2. L_z = 4.25

Elements = 10400

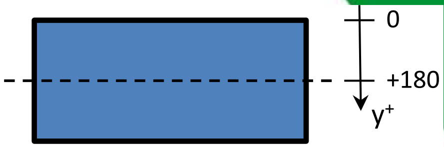
Total Mesh = 7.7 M

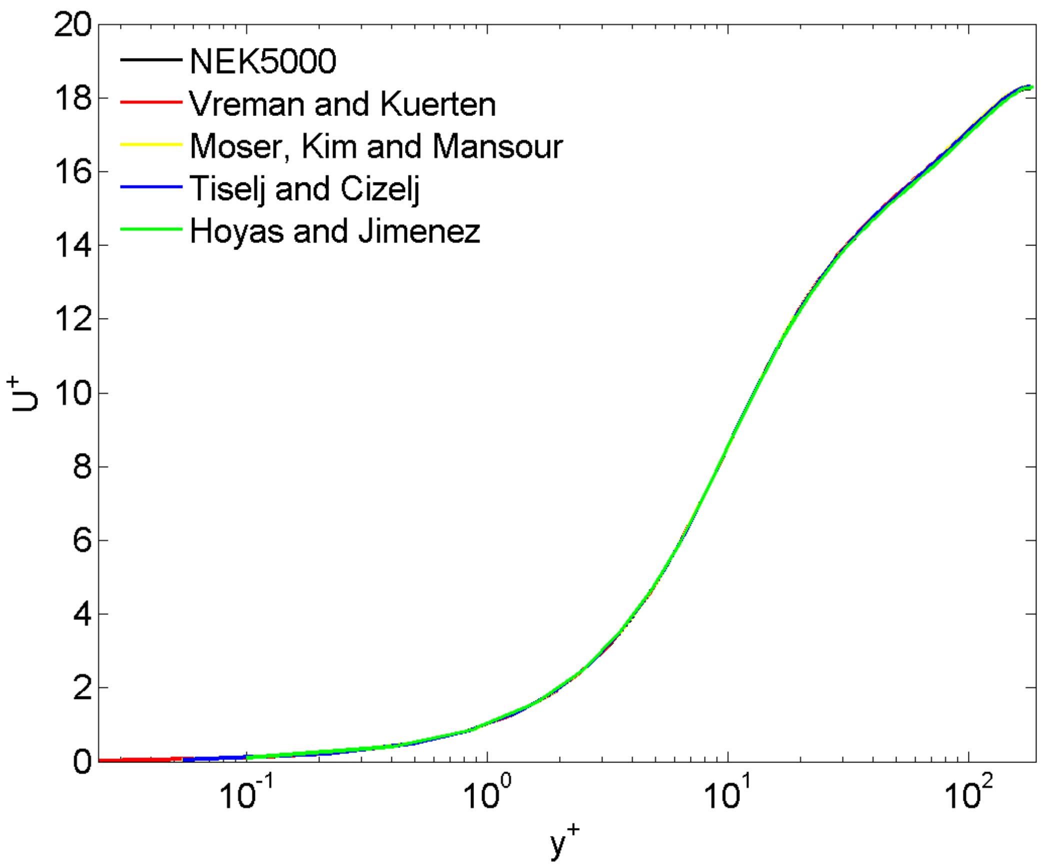
Averaging time:

$$t^+ = t\frac{u_\tau^{\ 2}}{\nu} = 16\,140$$

NRG

Velocity: Mean





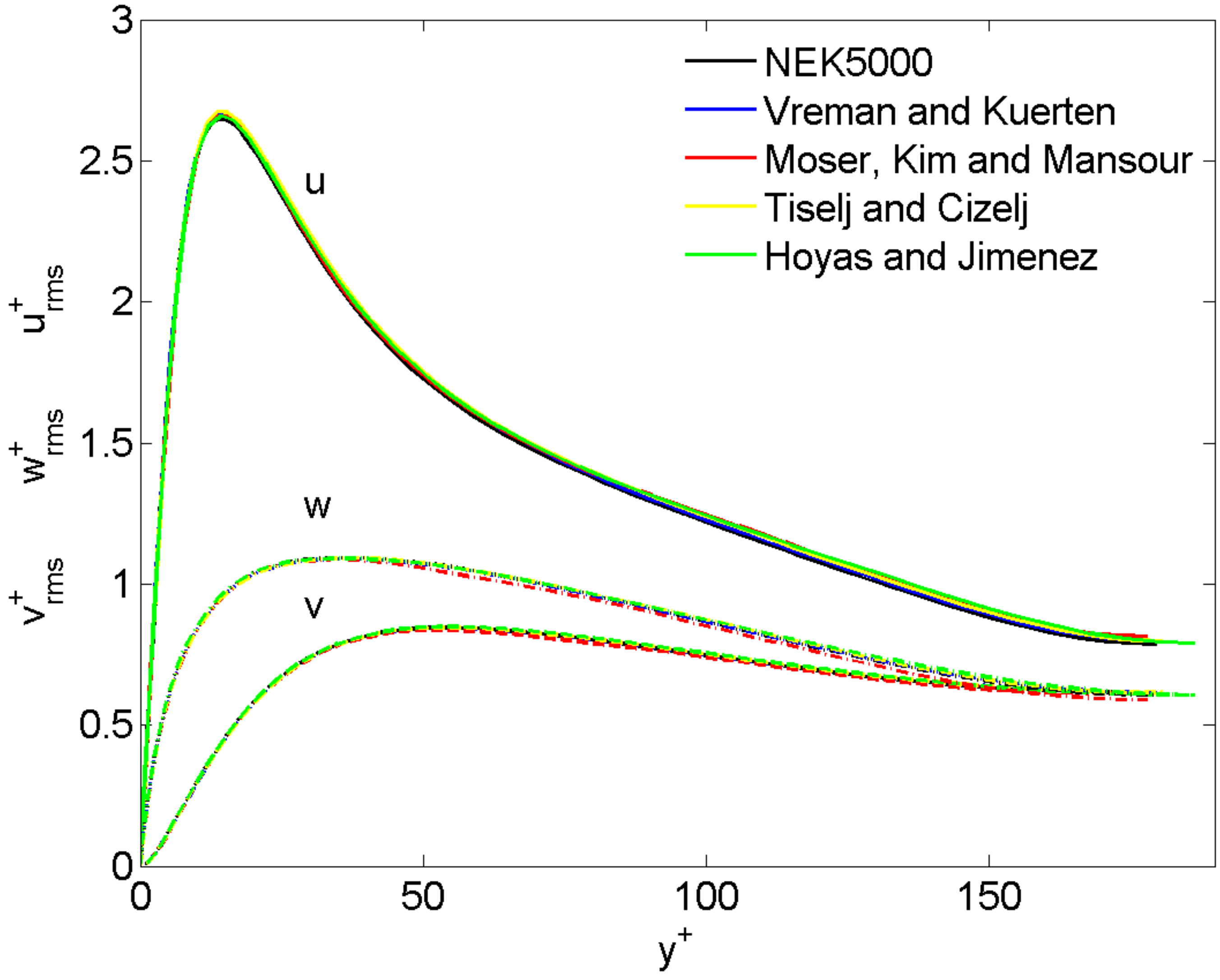
Database	Year	Method	
Vreman and Kuerten	2014	Pseudo spectral	- FC
Moser, Kim and Mansour	1998	Pseudo spectral	- FC

Database	Year	Method	
Tiselj and Cizelj	2012	Pseudo spectral	- FC
Hoyas and Jimenez	2006	Pseudo spectral	- FC

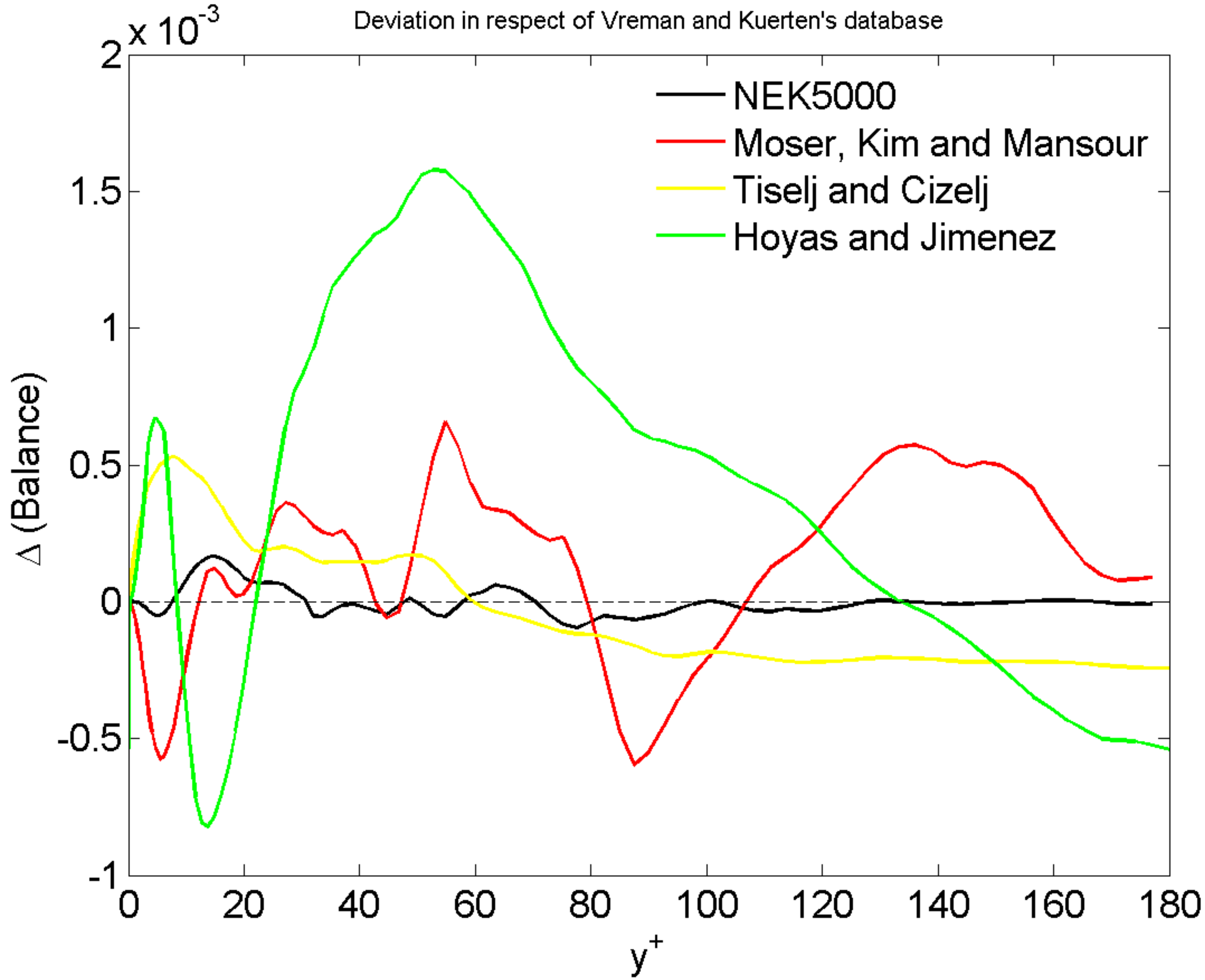
(*) FC = Fourier and Chebyshev polynomials

NRG

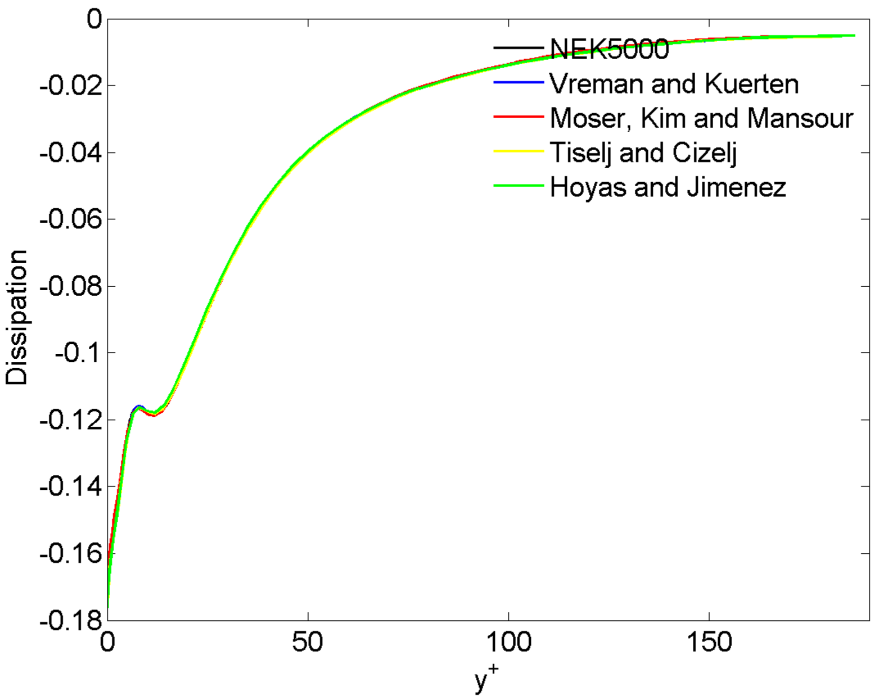
Velocity: RMS

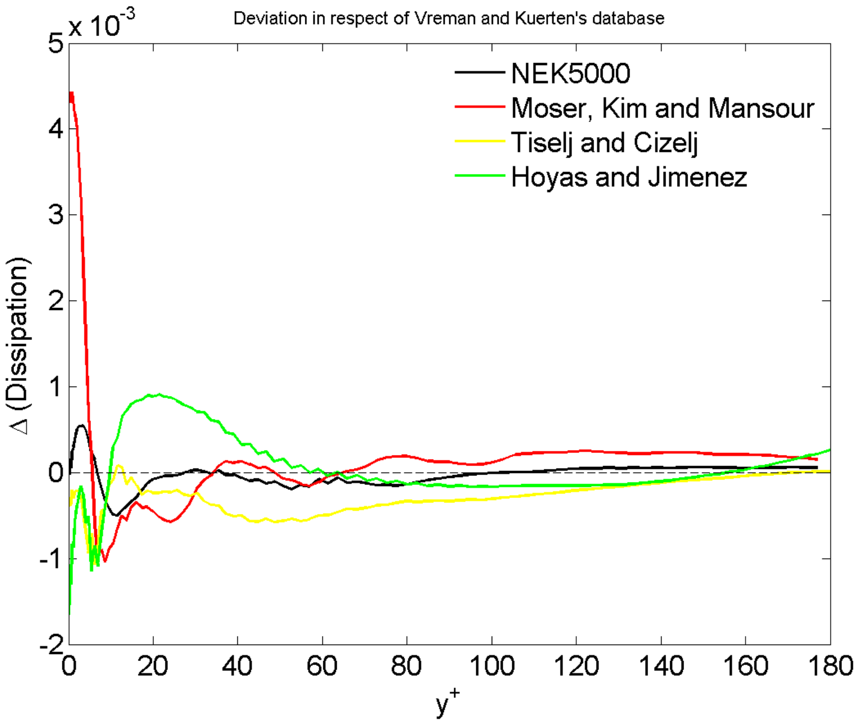


Budget terms: balance



Budget terms: dissipation





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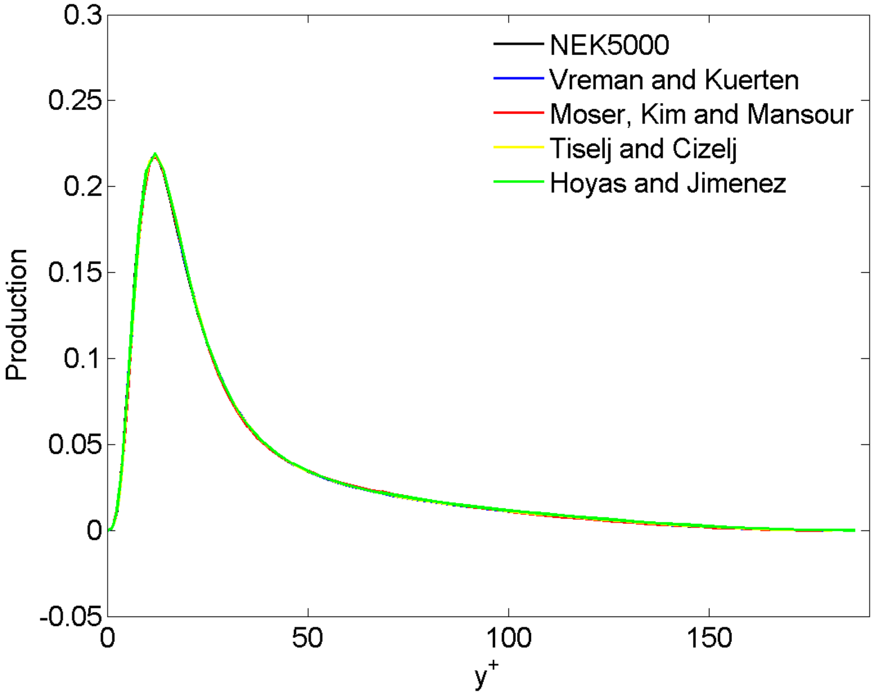
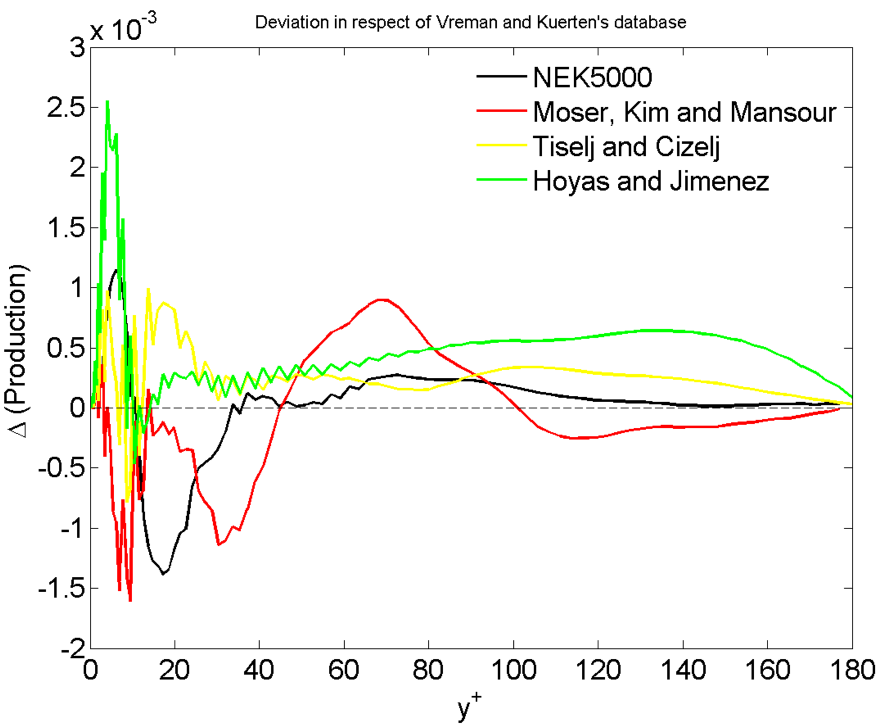
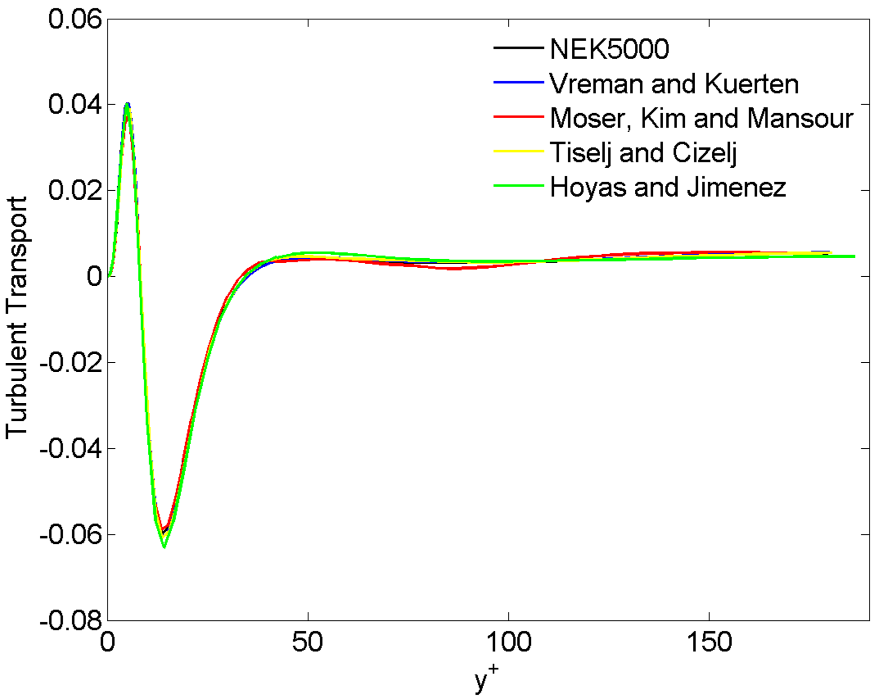
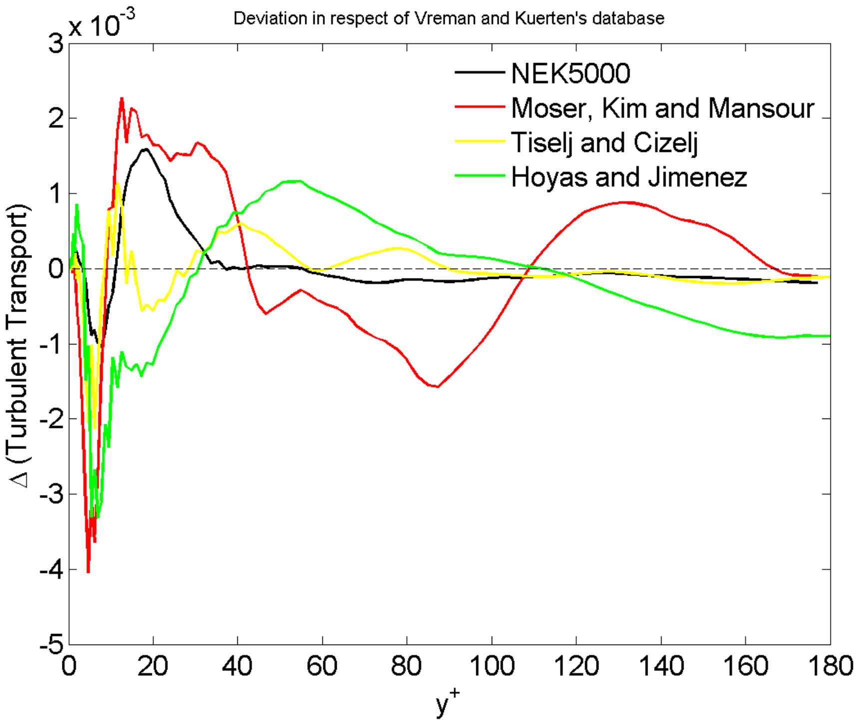
Budget terms: production



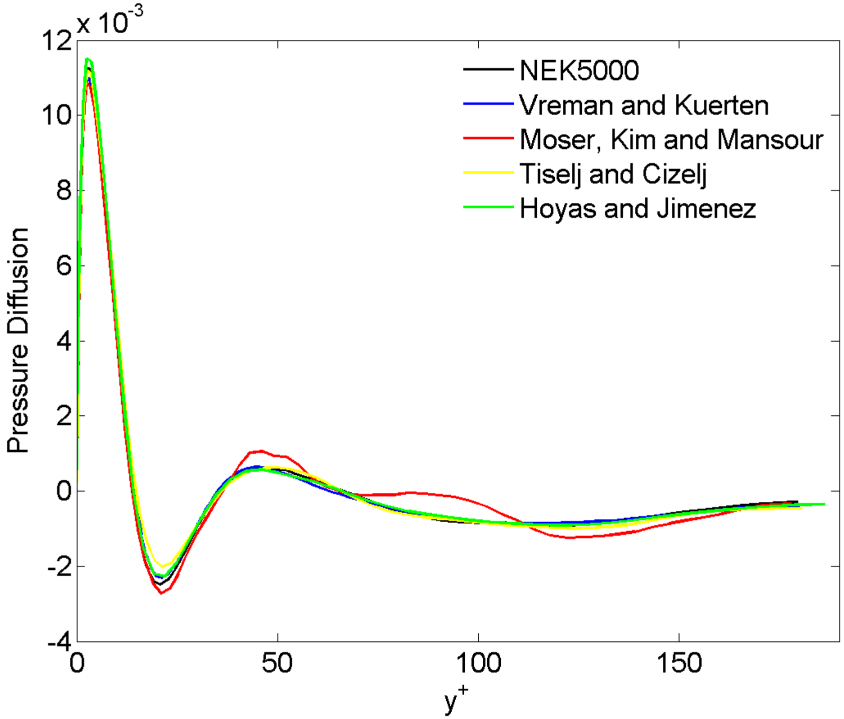


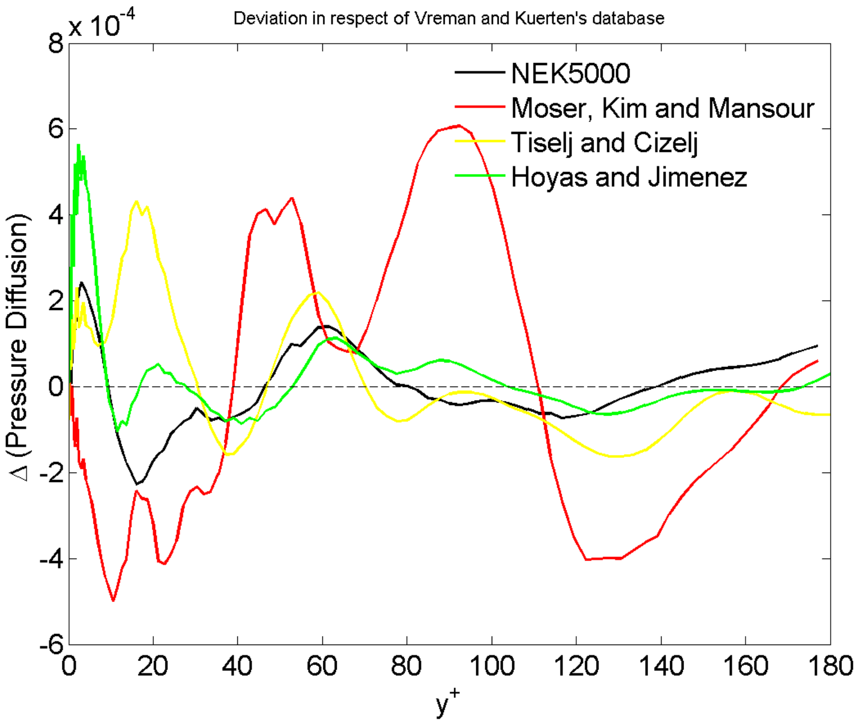
Budget terms: turbulent transport





Budget terms: pressure diffusion





PART III:

Towards the DNS of the PTS configuration

Simulation parameters (only fluid)

$Re_{\tau,duct}$ = 180

Pr = 1

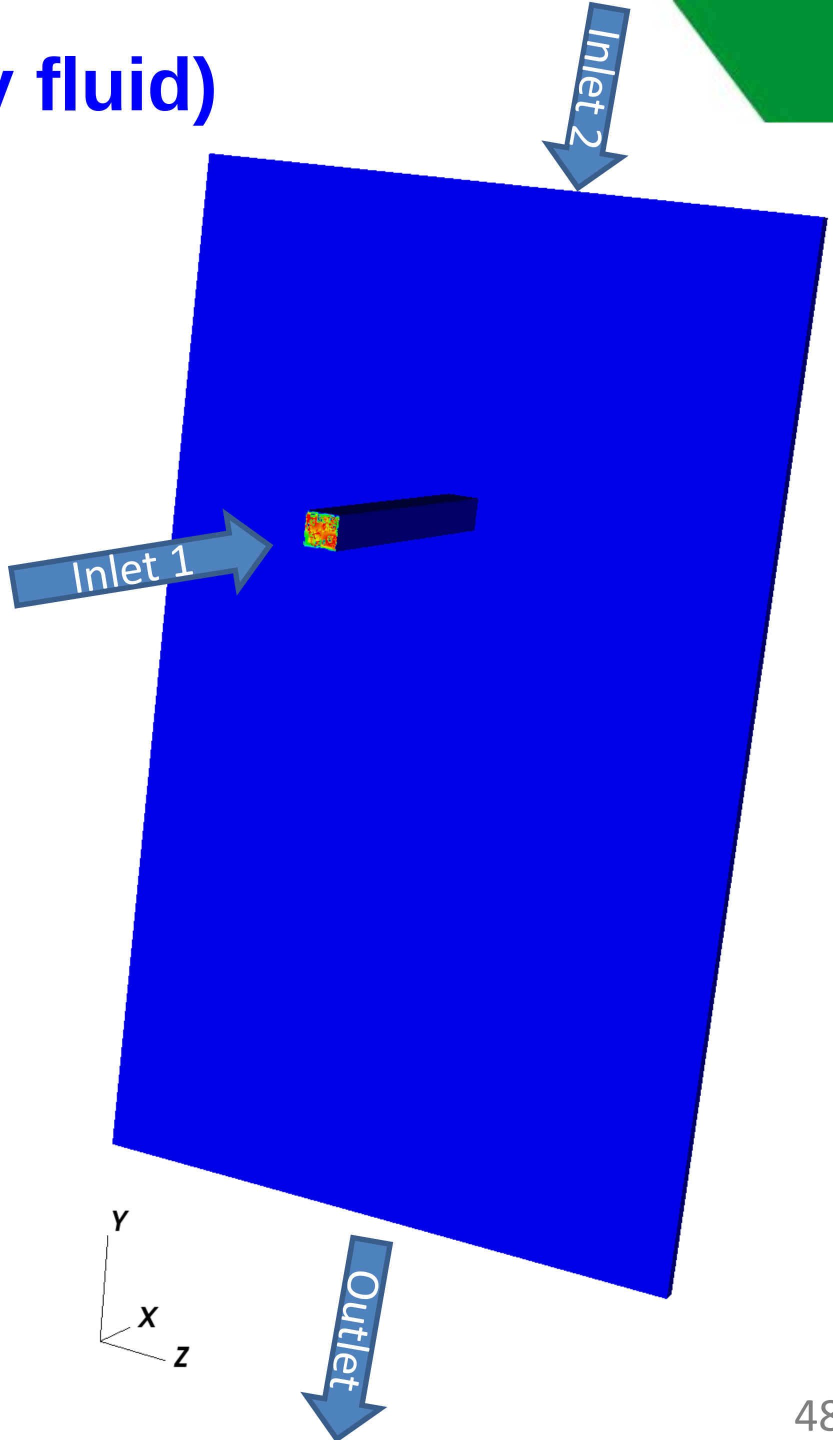
Two Passive Scalars (PS) to represent:

(i) iso-flux and (ii) isothermal B.C's

Pol. order (space)	= 9
Pol. order (time)	= 3 (*explicit*)
CFL	= 0.2

Mesh:

- **550 Million points**
- **0.76 Million Elements**



Boundary conditions (only fluid)

INLET 1
- U = 1.
- T = 0.
- T = 0.

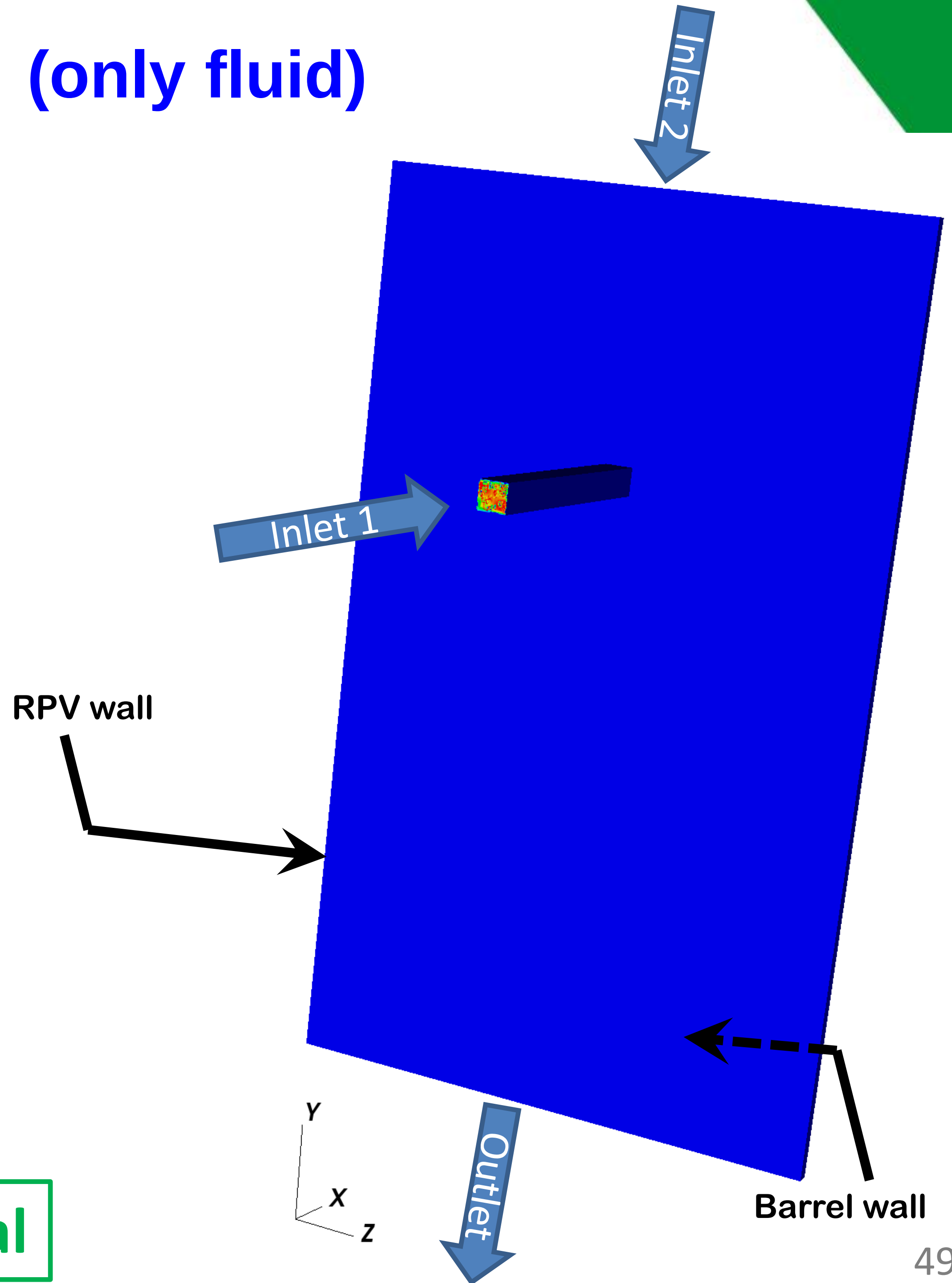
INLET 2
- U = 0.1
- T = 1.
- T = 1.

BARREL & RPV WALLS
- No-slip
- q'' = 0.
- T = 1.

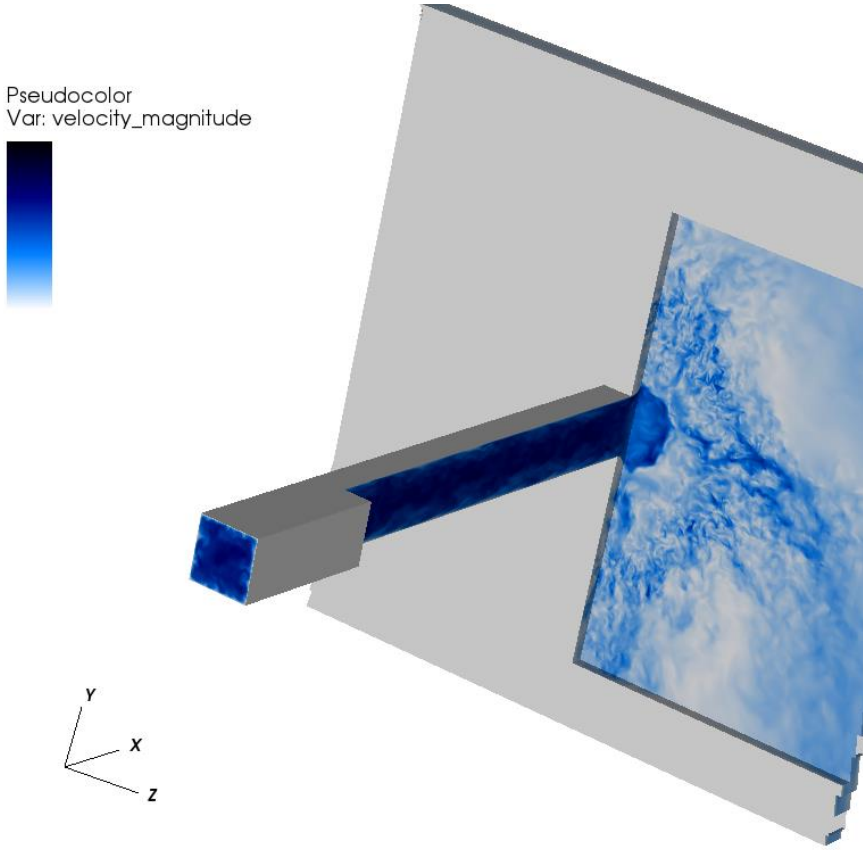
Flow field

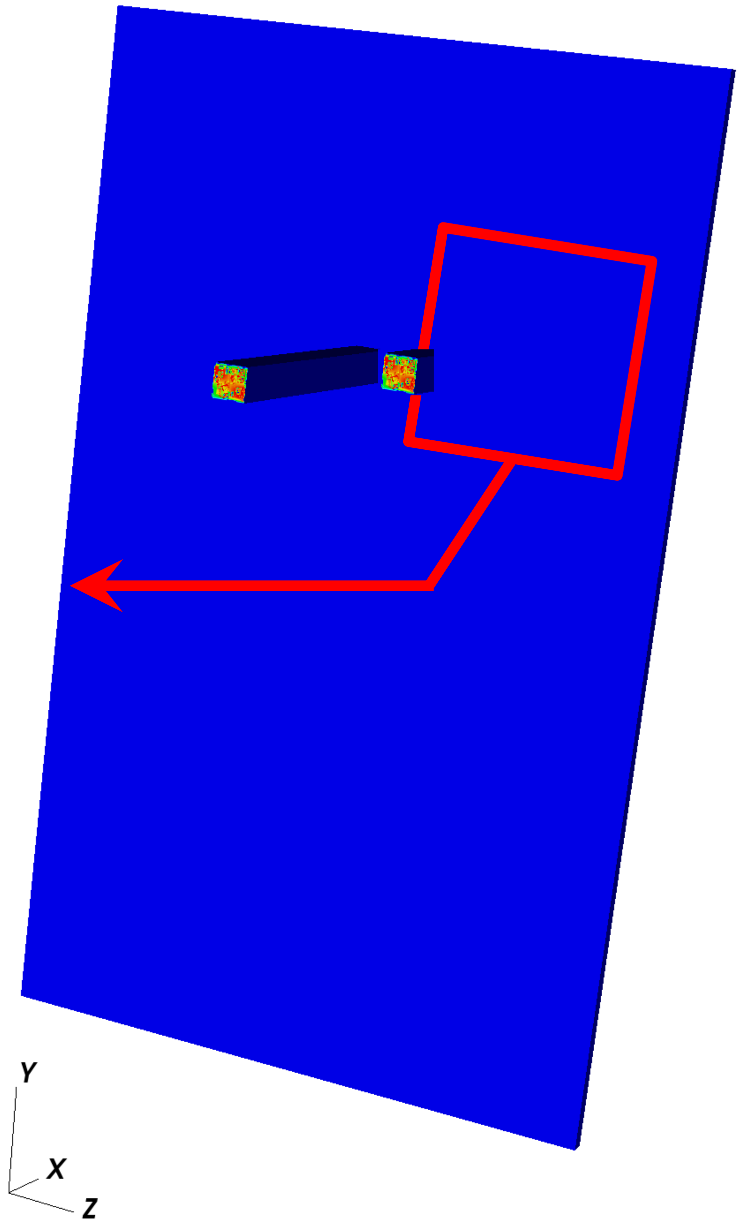
PS 1: Isoflux

PS 2: Isothermal

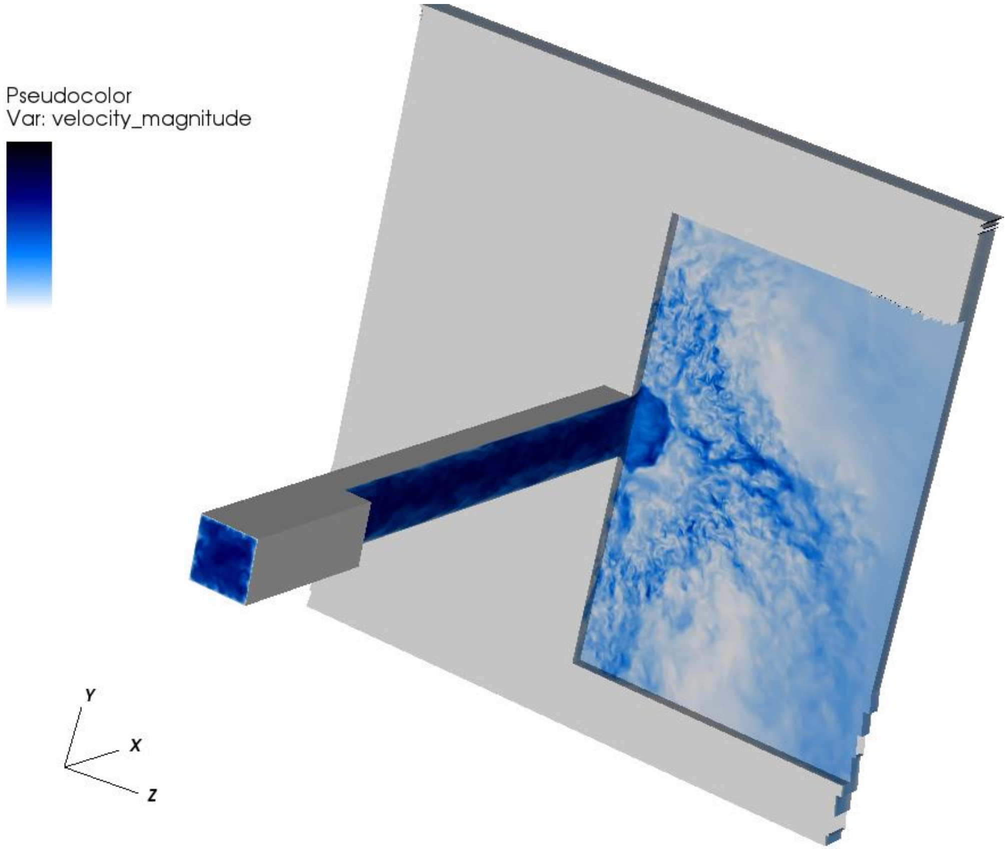


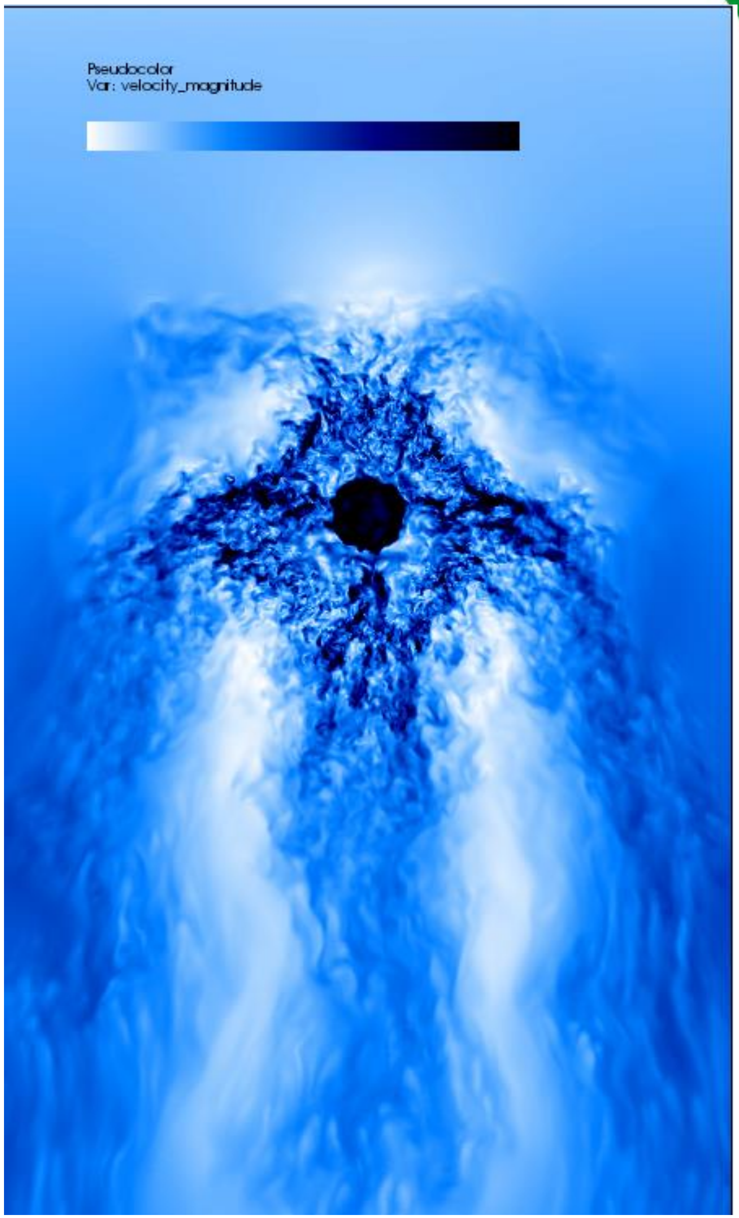
Flow field: On-going Computations @ N=3





Flow field: On-going Computations @ N=3





Outlook

- As a part of this **NRG-NCBJ** Collaboration:
  - PTS case with **N5** will be performed on
  - **5000** processors for **several months**
  - **Result**: Under resolved **DNS**
- To achieve a **high quality DNS** this PTS computation needs to be performed with **N7** (or N9).

Questions?

Disclaimer

EU DuC = N

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