Towards the DNS of a closely-spaced bare rod bundle: A Collaborative Effort Between NCBJ-NRG

NATIONAL CENTRE FOR NUCLEAR RESEARCH
ŚWIERK

Afaque Shams (NRG)
Tomasz Kwiatkowski (NCBJ)

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- Introduction and goal
- Design of a sub-channel of a bare rod bundle
- Calibration and optimization of the Hooper case
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Introduction

NCBJ-NRG COOPERATION

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- AGREEMENT regarding science and research cooperation signed in December 2016:
  - February 2017 Dr. Shams visited NCBJ
  - July 2017 Kwiatkowski study visit at NRG

- Scope of the research:

  In the frame of this agreement, two high fidelity numerical simulations will be performed for:

  1. Pressurized thermal shock (PTS)
  2. Sub-channel of a bare rod bundle (Hooper type case)

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1. Pressurized thermal shock (PTS)
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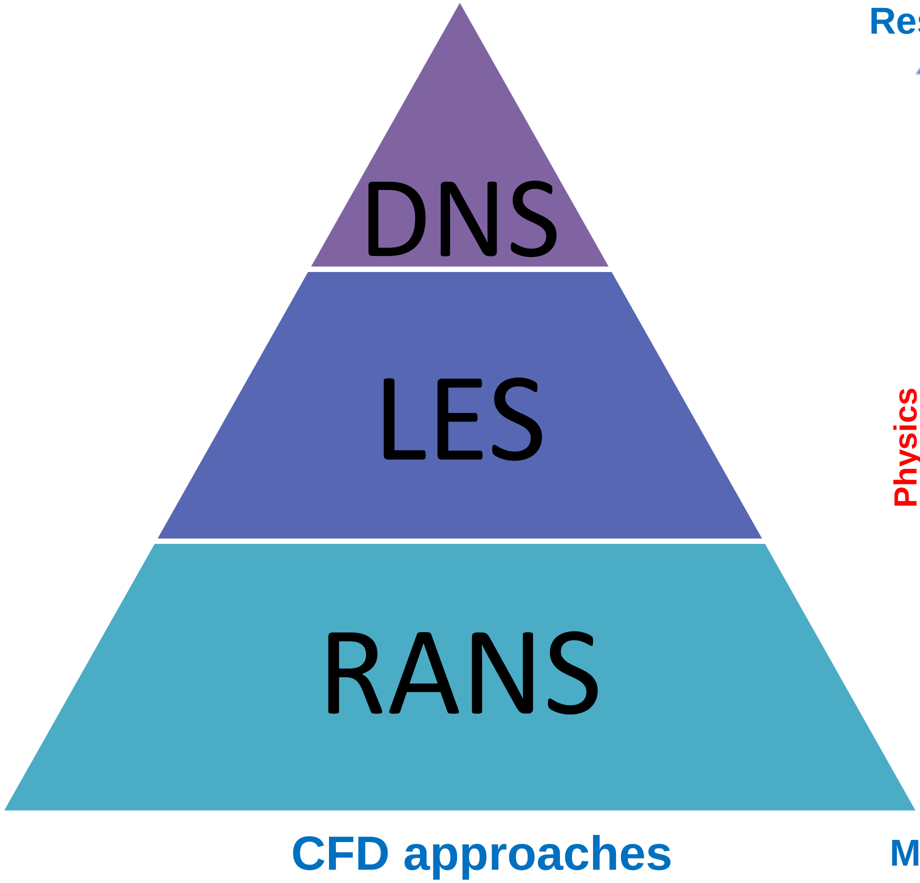
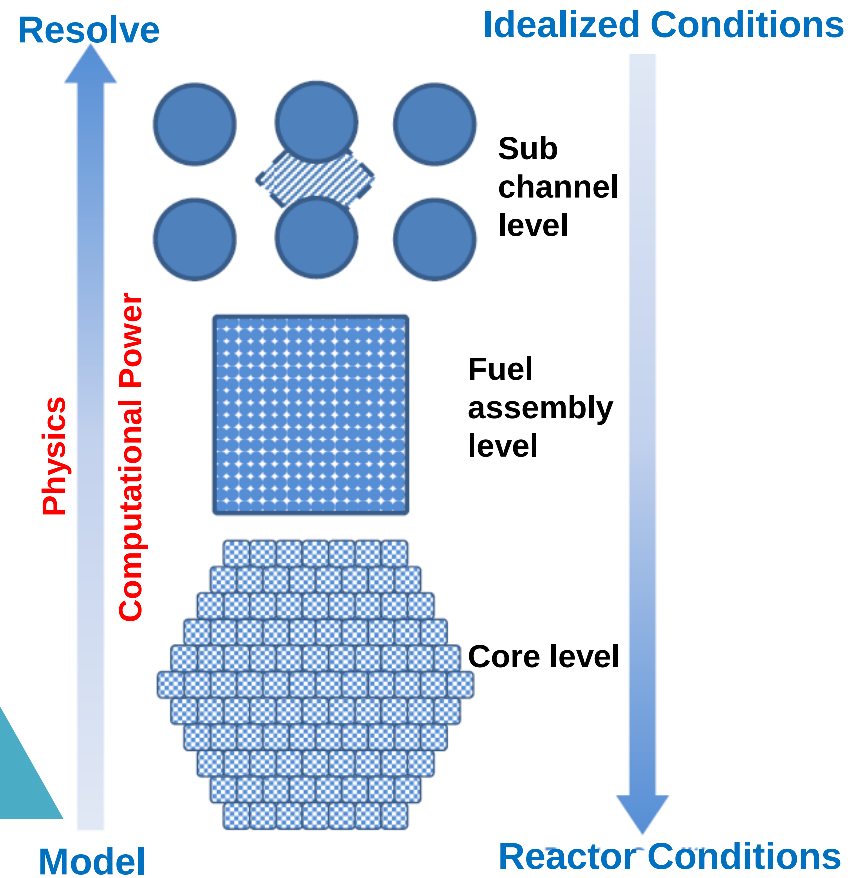
INTRODUCTION AND GOAL

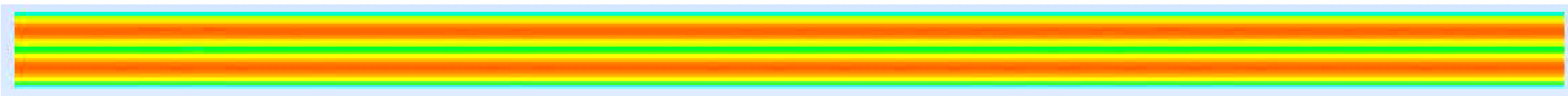
Introduction and goal





Introduction and goal

- **Main issues for single-phase sub-channel of a bare rod bundle:**
  - Turbulent mixing of the coolant
  - Heat transfer



Introduction and goal

- **Main issues for single-phase sub-channel of a bare rod bundle:**
  - Turbulent mixing of the coolant
  - Heat transfer

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

- CFD (pragmatic) models need to be validated for sub-channel of a bare rod bundle:
  - Experimental data
  - Direct Numerical Simulation (DNS) data

Introduction and goal

The main objective is to generate a DNS database.

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The obtained high fidelity CFD results will yield in an extensive validation database for flow and the thermal fields representing different reactor coolants.

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Introduction and goal

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↓

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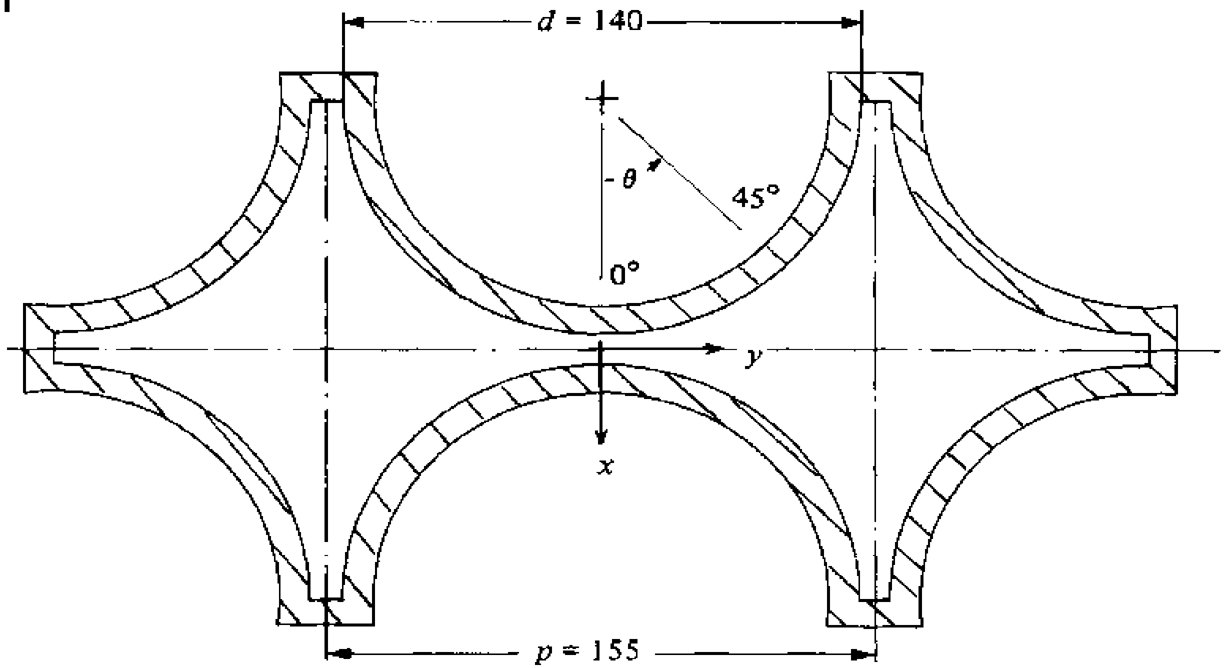
↑

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

DESIGNE OF A HOOPER CASE

Hooper geometry

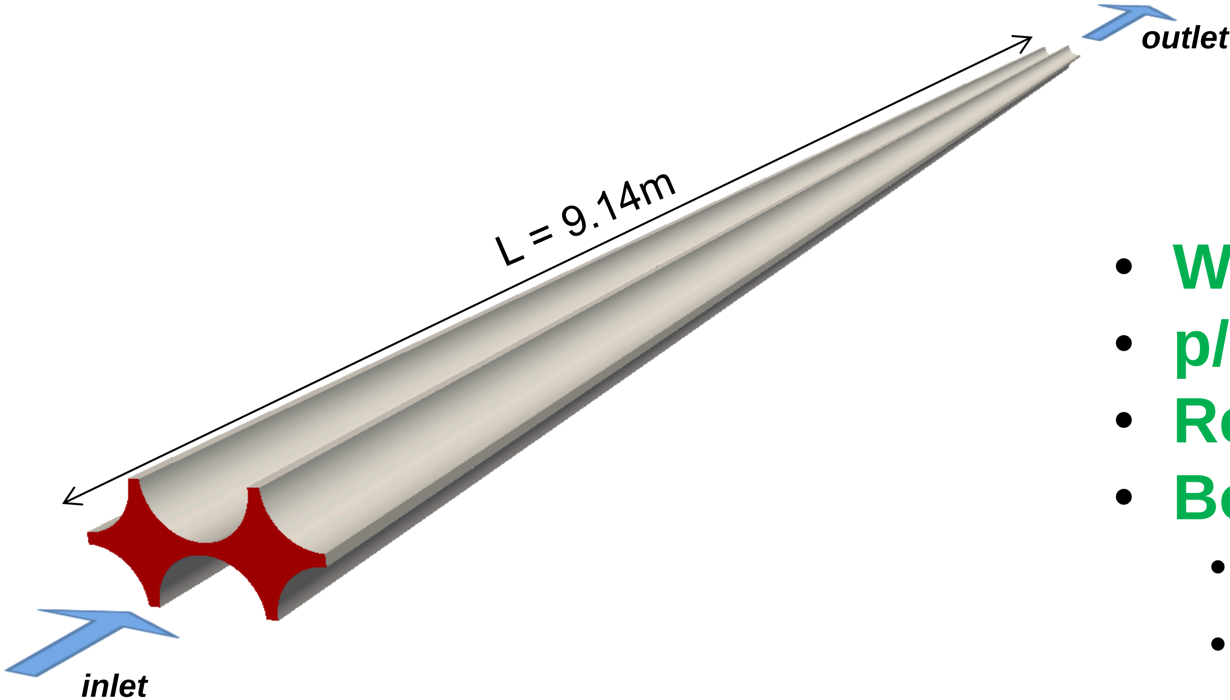
- Symmetrical square-pitch rod cluster: a sub-channel geometry of a hydraulic experiment on a bare rod-bundle configuration performed by Hooper



* Hooper J. D., Rehme K., *Large-scale structural effects in developed turbulent flow through closely-spaced rod arrays*, J. Fluid Mech. (1984), vol. 145, pp 305-337

Hooper geometry

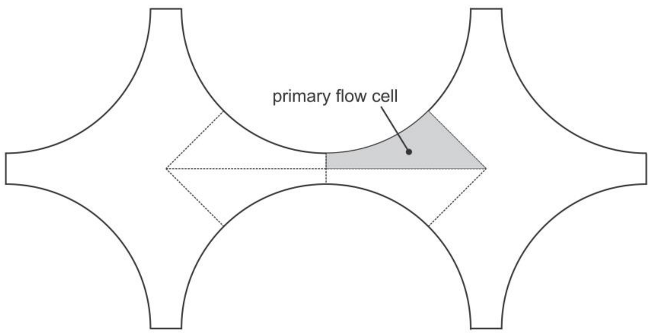
- A real geometry of a hydraulic experiment test section



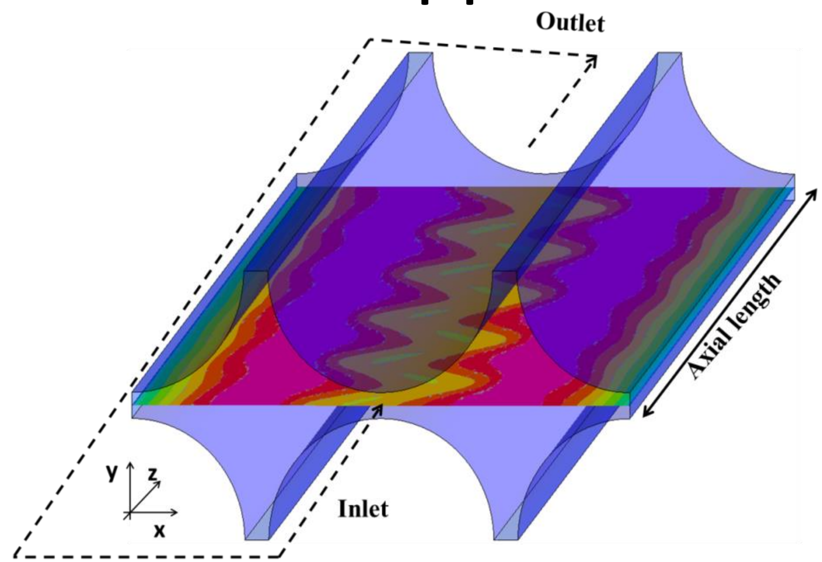
- **Working fluid: air**
- **p/d = 1.107**
- **Re = 49000**
- **Boundary conditions:**
  - Periodic in- and outlet
  - $\dot{m} = 0.213\,\frac{kg}{s}$

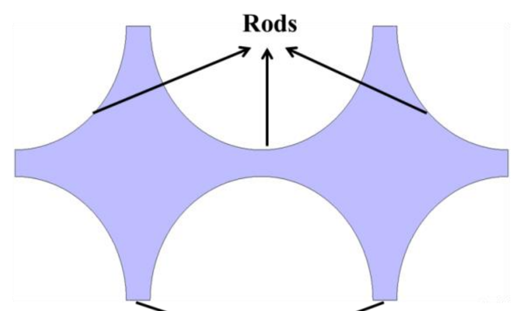
Computational domain

- Previous studies



- Current approach





CALIBRATION AND OPTIMIZATION OF THE HOOPER CASE

Design calibration and optimization

- Calibration and optimization of the Hooper case based on pre-cursor URANS analyses
  - an initial mesh estimation for real Hooper case would required a total of 14 billion grid points only for the flow field to performe a true DNS.

- Main characteristics of the pre-cursor URANS computations
  - ANSYS Fluent v 17.2.0 CFD code
  - URANS: k-ω SST model
  - Second order upwind schemes
  - Mesh ~ 6.8 M (y+ < 1)

Design calibration and optimization

- Meshing strategy :
  - ANSYS Meshing version 17.2.0

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  - Step 1: A 2D mesh for the cross-section is generated
  - Step 2: Afterwards, this 2D mesh is uniformly extruded in the steamwise direction

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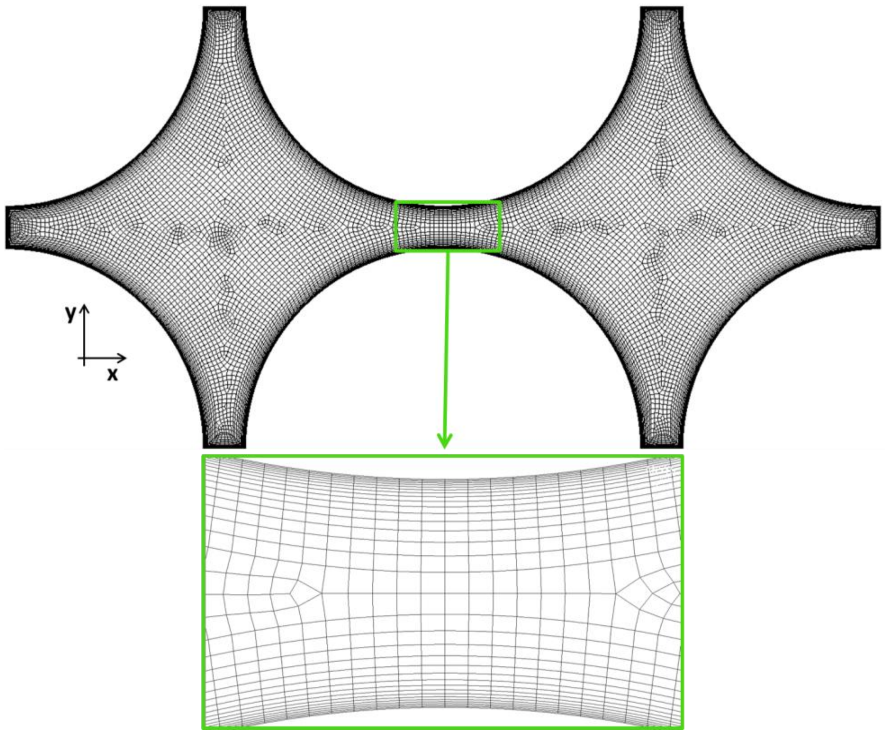

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Design calibration and optimization

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Step 1 – Scaling of the Reynolds number

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Step 1 – Scaling of the Reynolds number

Step 2 – Optimization of the computational domain

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Step 3 – Introduction of the thermal fields

Step 1

SCALING OF THE REYNOLDS NUMBER

Scaling of the Reynolds number

List of test cases considered for the scaling of the Reynolds number

Reference case

Cases	Nomenclature	Scale down	Re	Mass flow rate [kg/s]
1	R1	R1	49 000	0.2134
2	R2	R1 / 2	24 500	0.1063
3	R3	R1 / 3	16 333	0.0708
4	R4	R1 / 4	12 250	0.0531
5	R5	R1 / 5	9 800	0.0425
6	R6	R1 / 6	8 167	0.0354
7	R7	R1 / 7	7000	0.0304
8	R8	R1 / 8	6125	0.0267
9	R12	R1 / 12	4083	0.0178
10	R16	R1 / 16	3063	0.0134
11	R32	R1 / 32	1531	0.0067

Scaling of the Reynolds number

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Scaling of the Reynolds number

Reduce the level of turbulence

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✓ Increase the size of the turbulence length scales

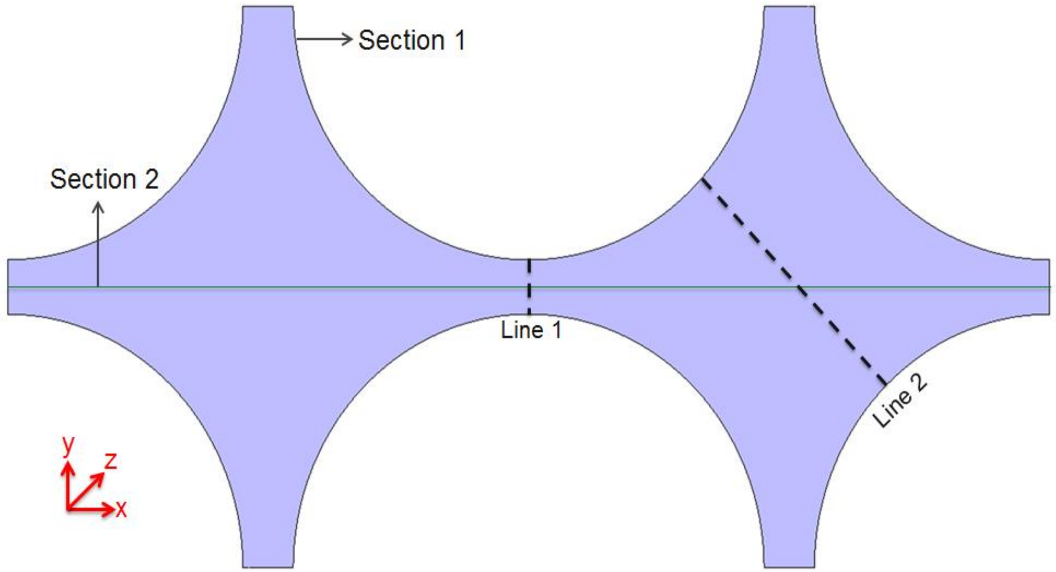
Scaling of the Reynolds number

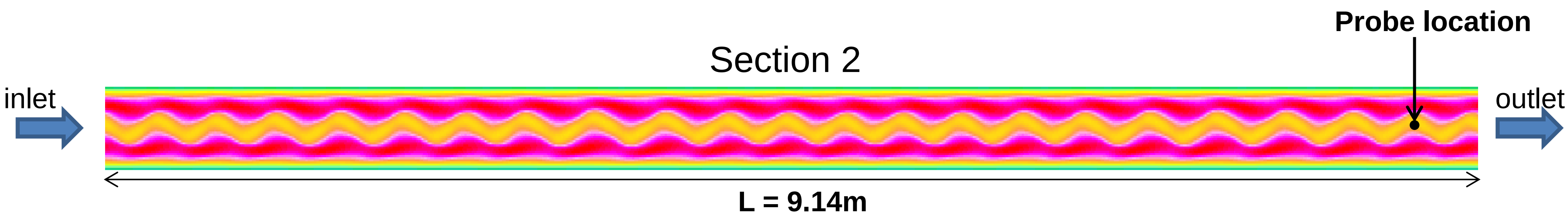
Reduce the level of turbulence

- ✓ Increase the size of the turbulence length scales
- ✓ Reduce the overall cost of the DNS

Scaling of the Reynolds number

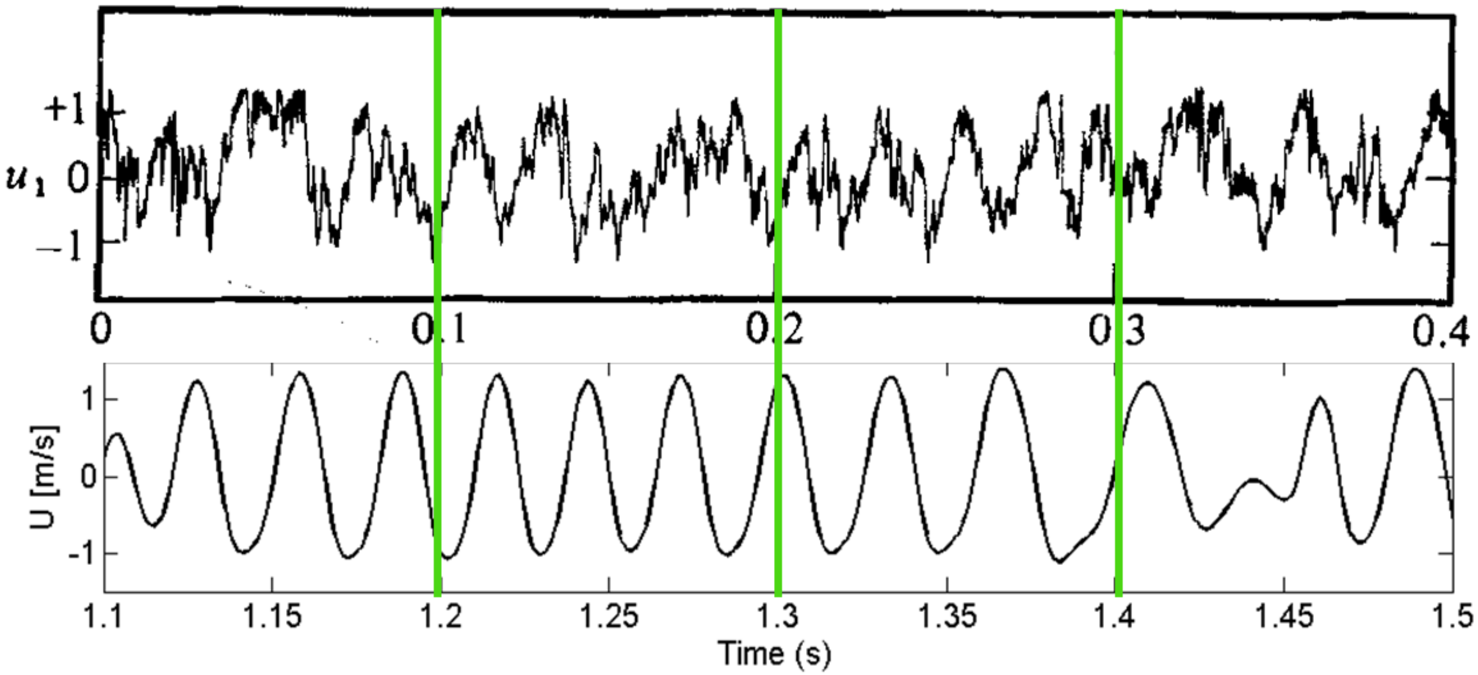
Selection of the cross-sections and the lines for the post-processing purpose





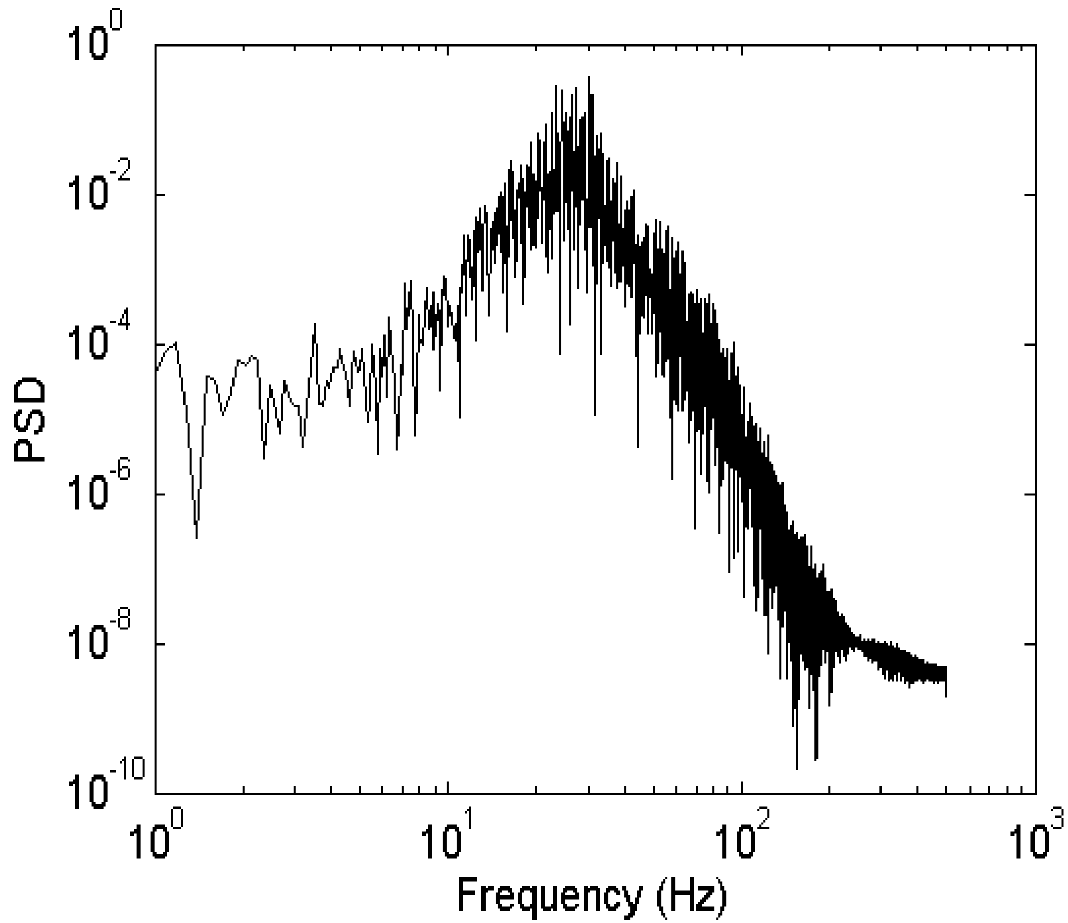
Scaling of the Reynolds number

Comparison of the URANS reproduction of flow oscillations versus the measured turbulent-velocity component *u* located at the rod-gap centre (Hooper and Rehme, 1984)



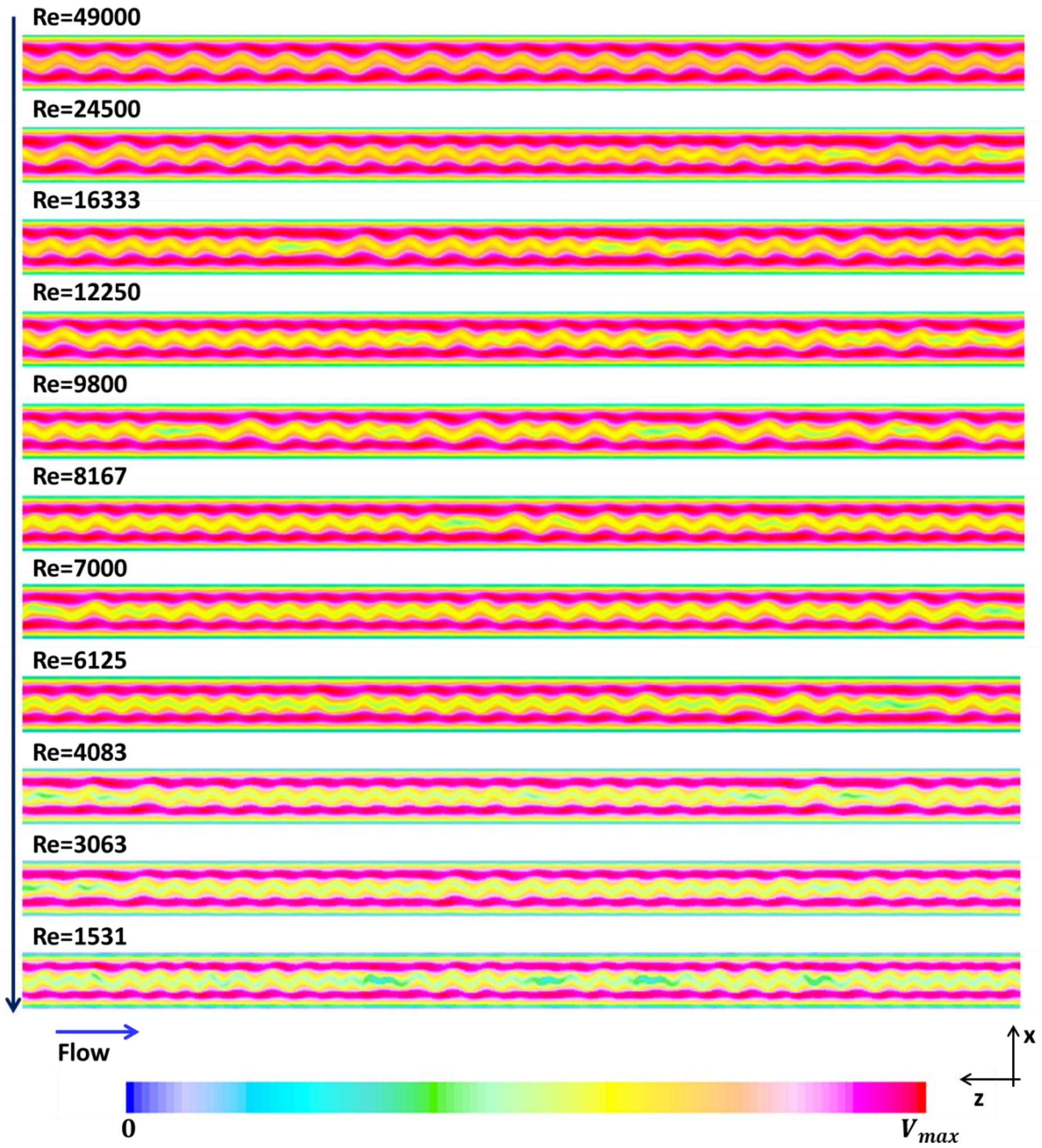
Scaling of the Reynolds number

The PSD of analyzed axial velocity fluctuations for Re = 49 000.



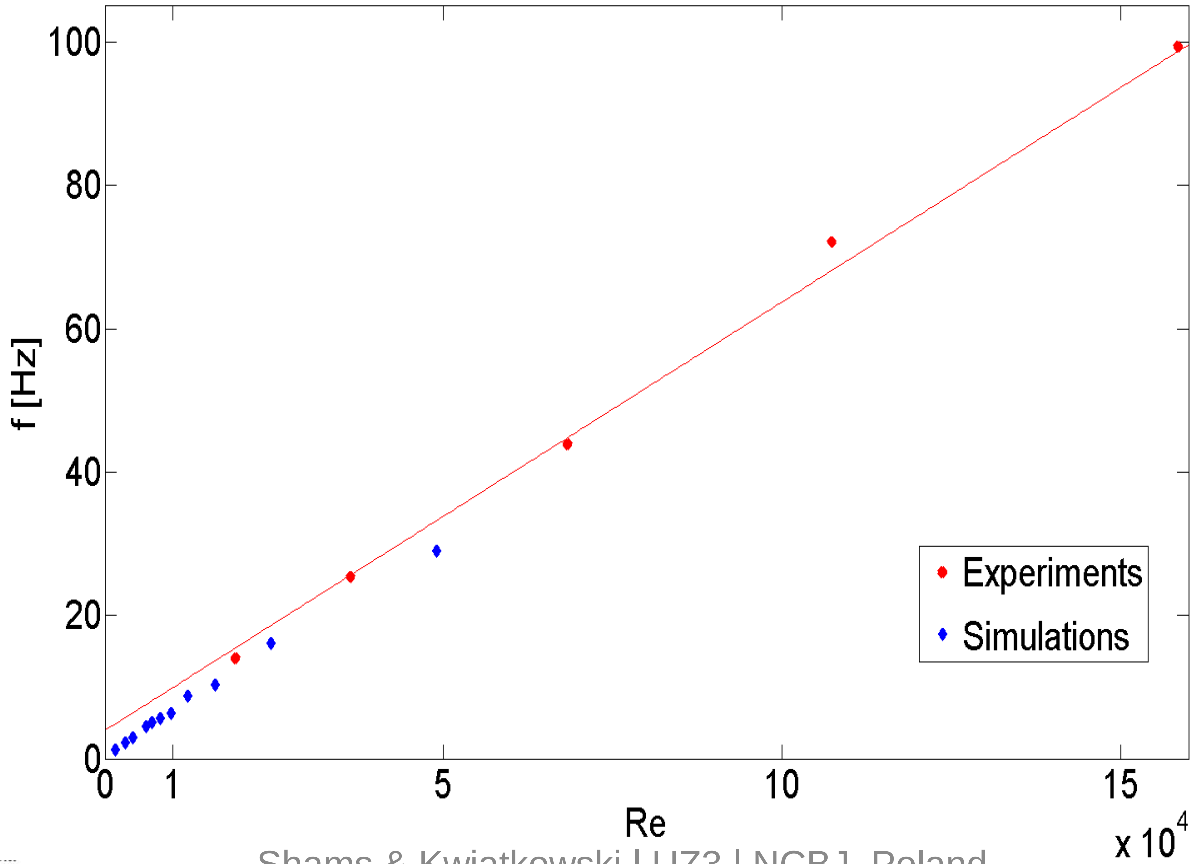
Iso-contours of velocity magnitude for different Reynolds numbers corresponding to cross-section 2

The overall phenomenology of the flow field remains the same, i.e. the very existence of the axial flow pulsations.



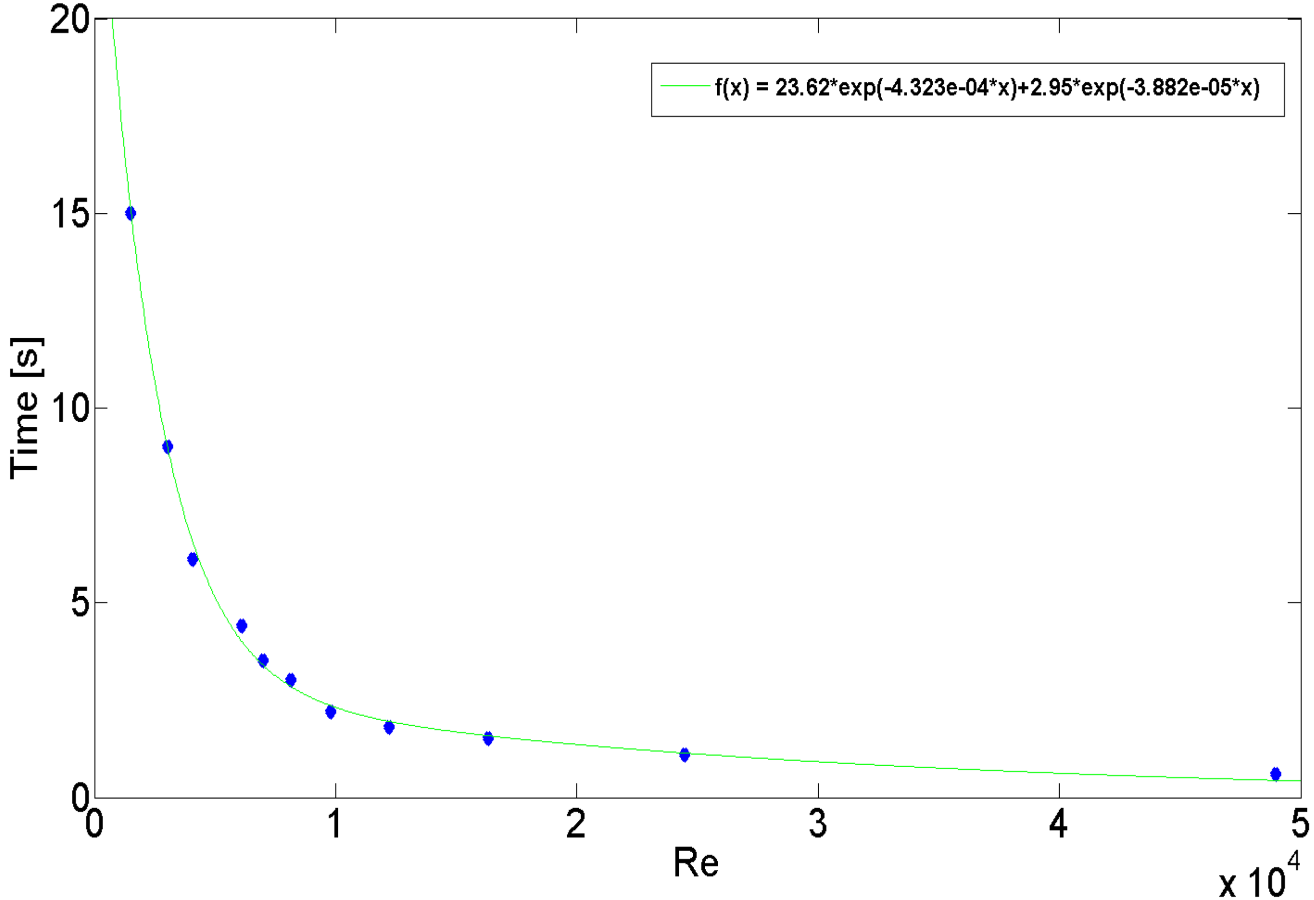
Scaling of the Reynolds number

Mean cyclic frequency of large-scale turbulent structure in the open rod gap as a function of Reynolds number (Hooper and Rehme, 1984)



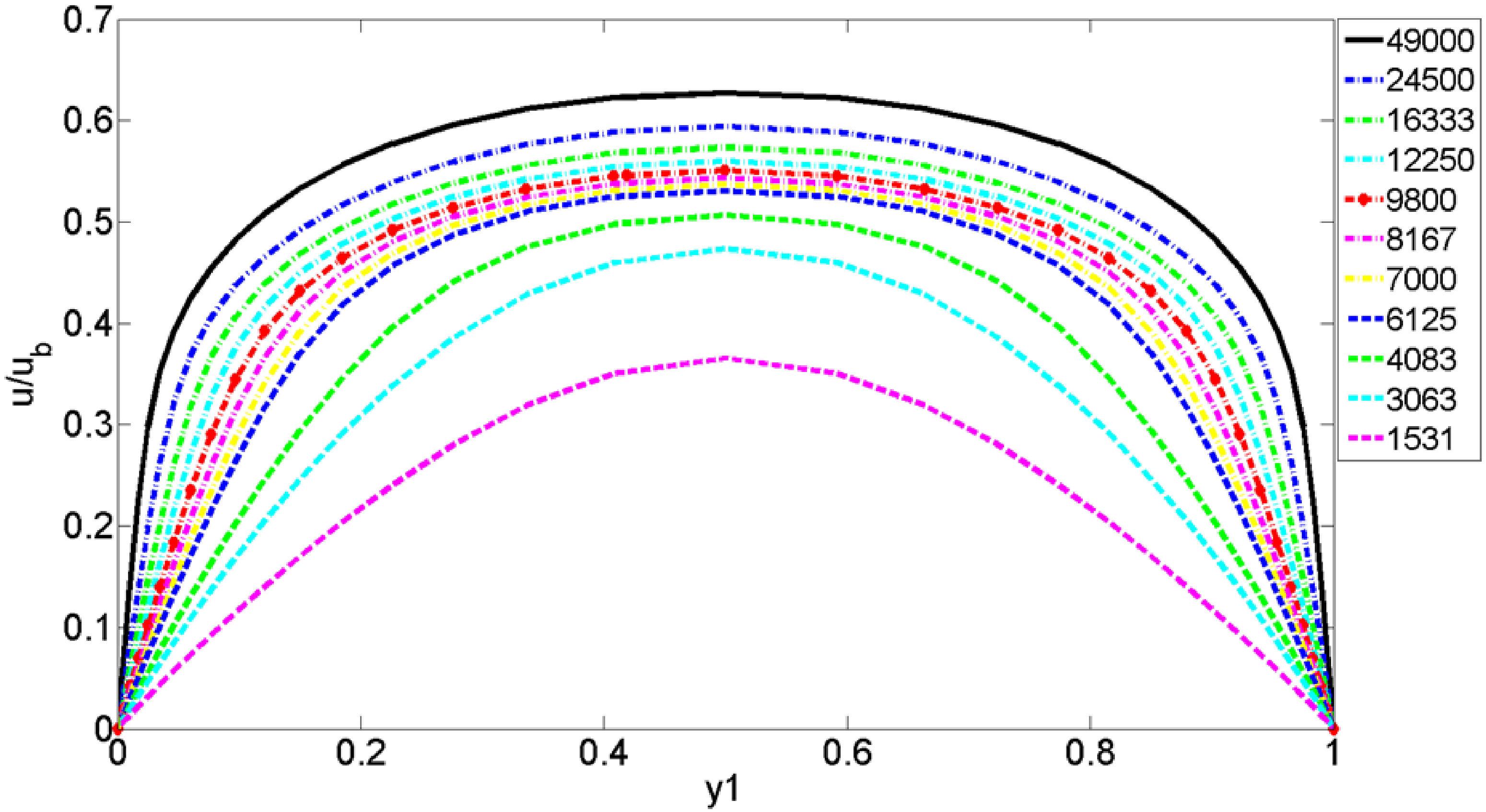
Scaling of the Reynolds number

Evolution of the physical time for the appearance of the axial flow pulsations w.r.t. different Reynolds numbers.



Scaling of the Reynolds number

Velocity profiles across line 1.



Scaling of the Reynolds number

Computed friction Reynolds number for all eleven test cases.

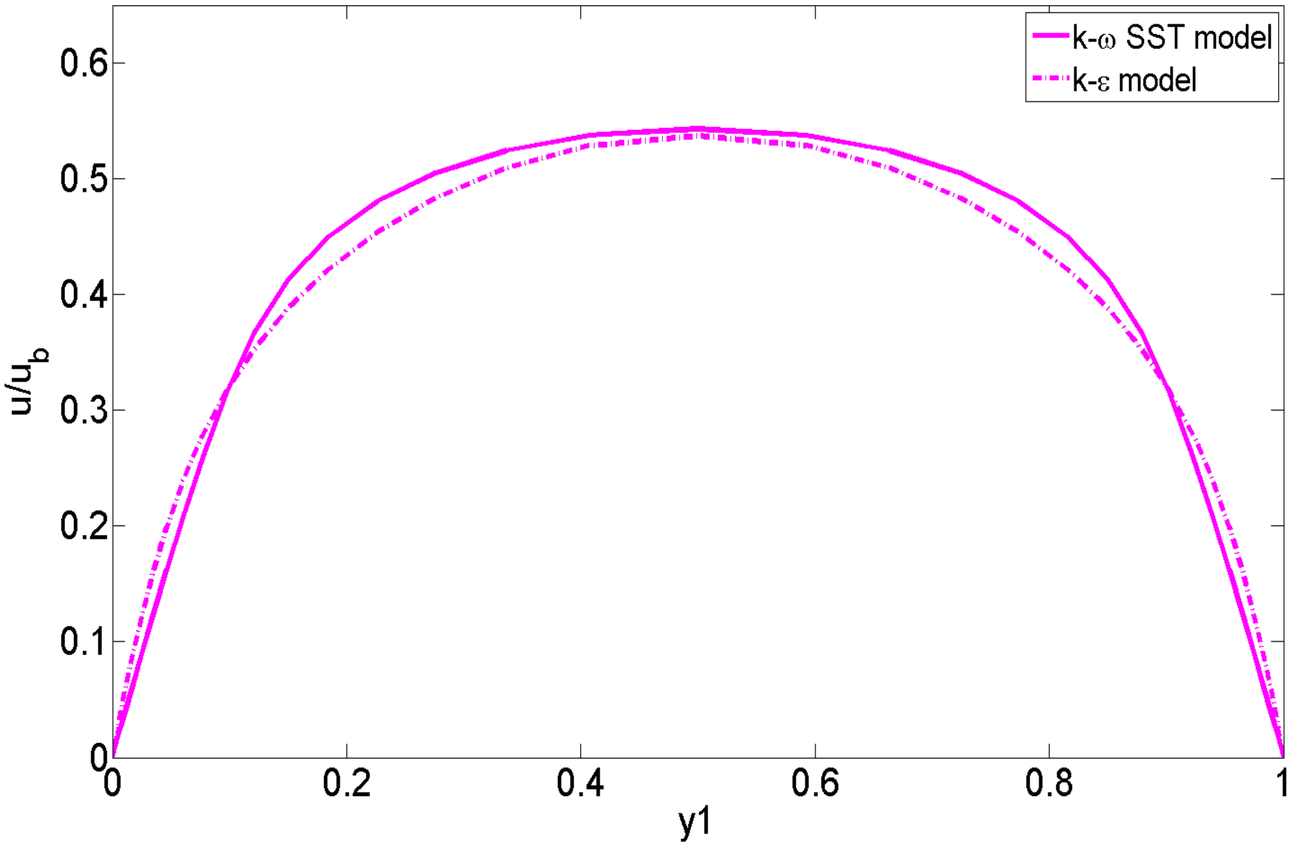
Re	Re_τ
R1	1812
R2	973
R3	683
R4	532
R5	439
R6	376
R7	330
R8	295
R12	211
R16	167
R32	100

$$Re_\tau = \frac{u_\tau \cdot D_h}{\nu}$$

where:
u_τ - is an average friction velocity in the rod surface
D_h - is hydraulic diameter
ν – is the kinematic velocity of the fluid

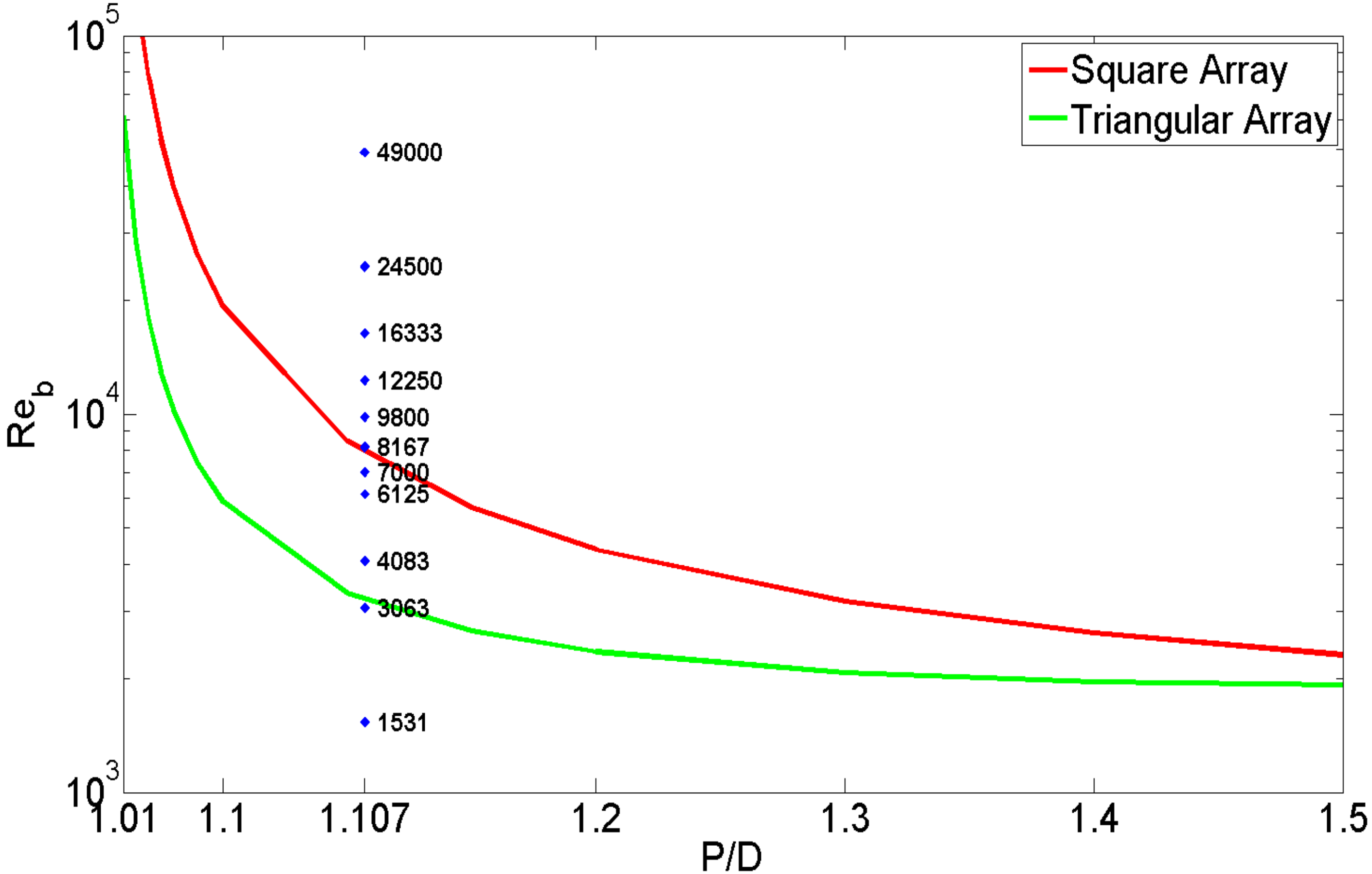
Scaling of the Reynolds number

Velocity profiles across line 1 for k-ω SST and k-ε model for the case R6 (i.e. Re=8167).



Scaling of the Reynolds number

Prediction of the onset and extent of laminarization in infinite triangular and square arrays along with the Hooper case for different Reynolds numbers.



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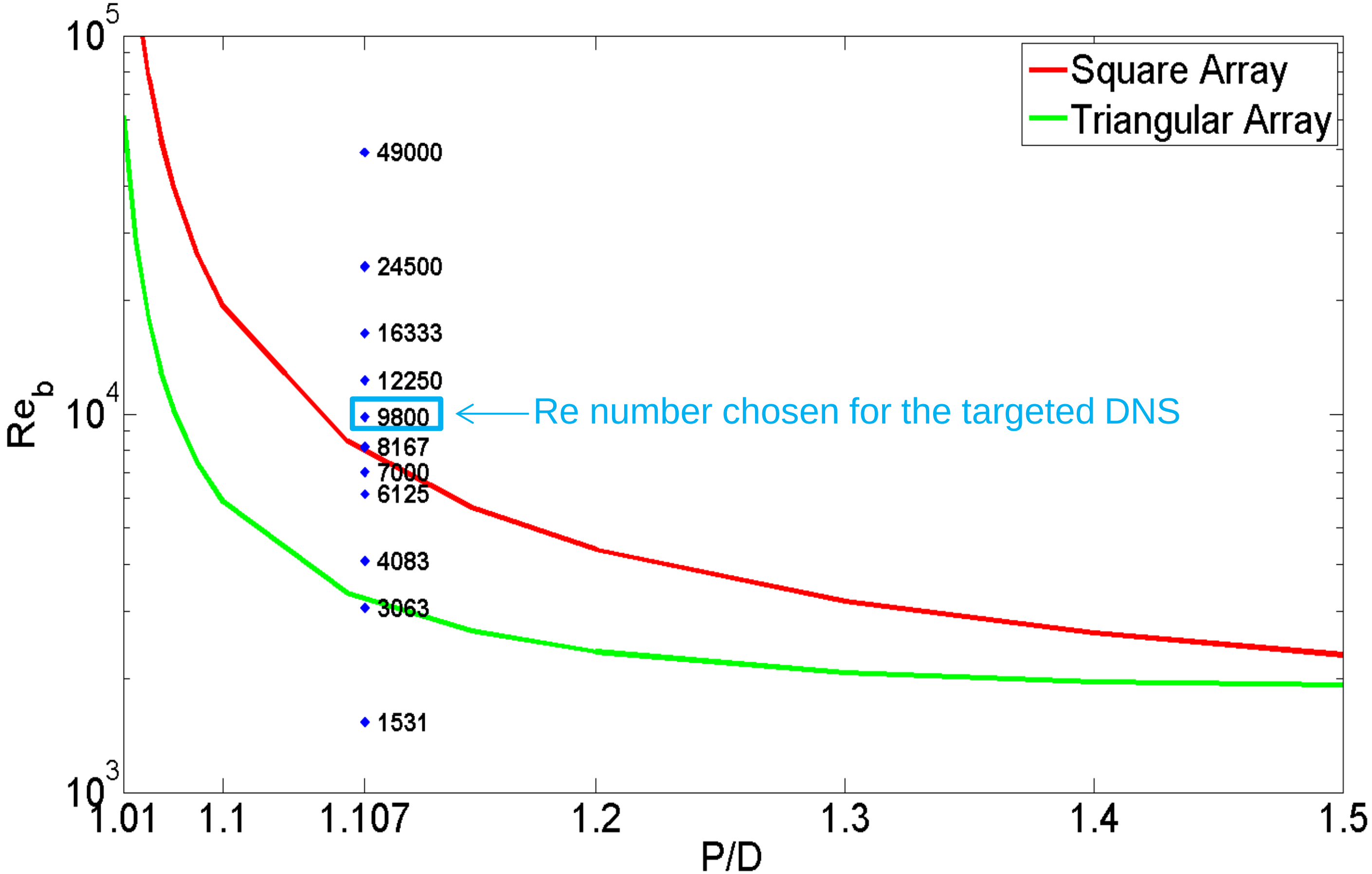


Step 2

OPTIMIZATION OF THE COMPUTATIONAL DOMAIN

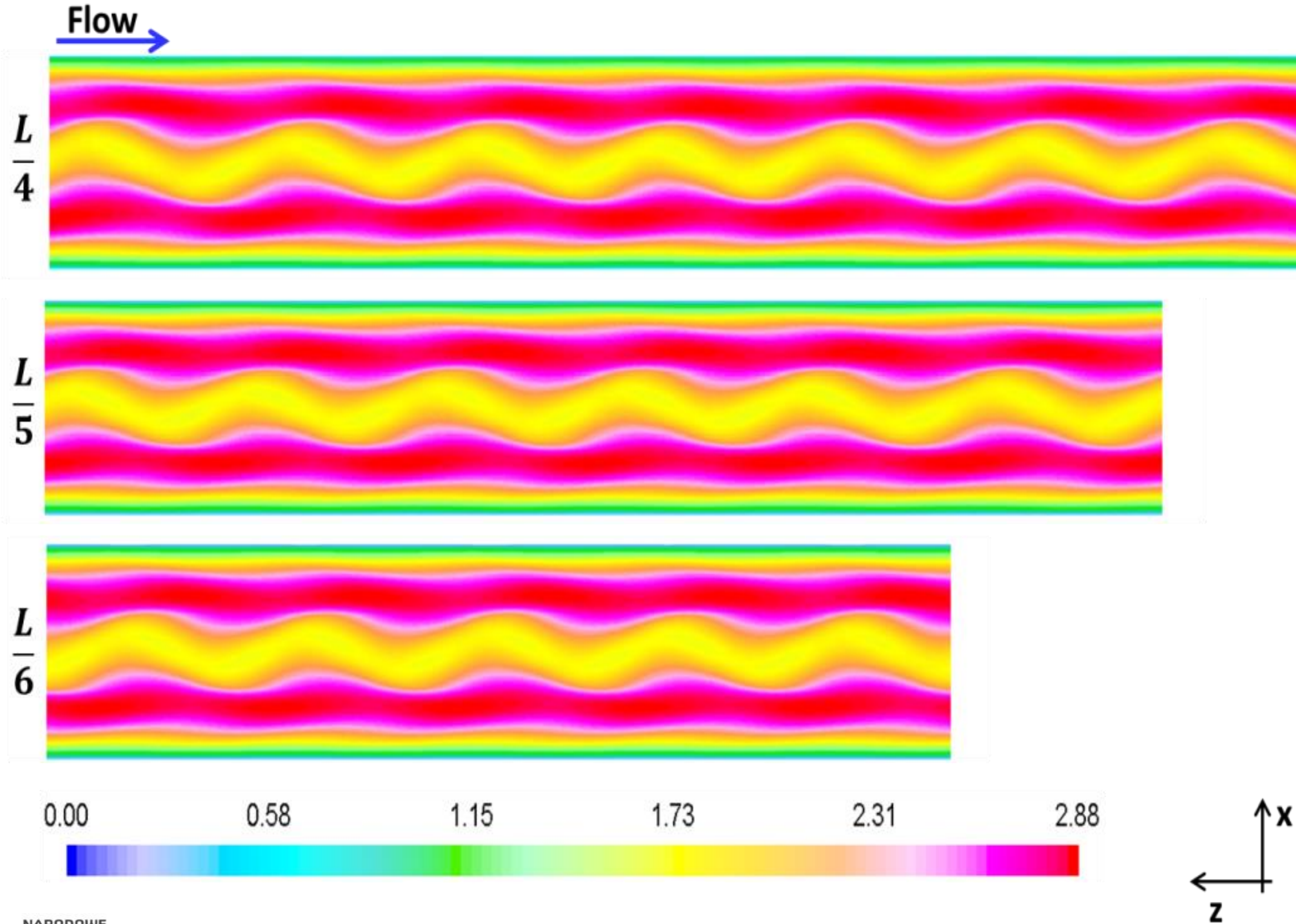
Optimization of the computational domain

List of test cases considered to design the numerical experiment.

Cases	Re	Length [m]	Mesh [mln]	Mass flow rate [kg/s]
12	9 800	2.285	1.7	0.042506
13	9 800	1.828	1.35	0.042506
14	9 800	1.523	1.13	0.042506

Optimization of the computational domain

Iso-contours of velocity magnitude for different length of computational domain.



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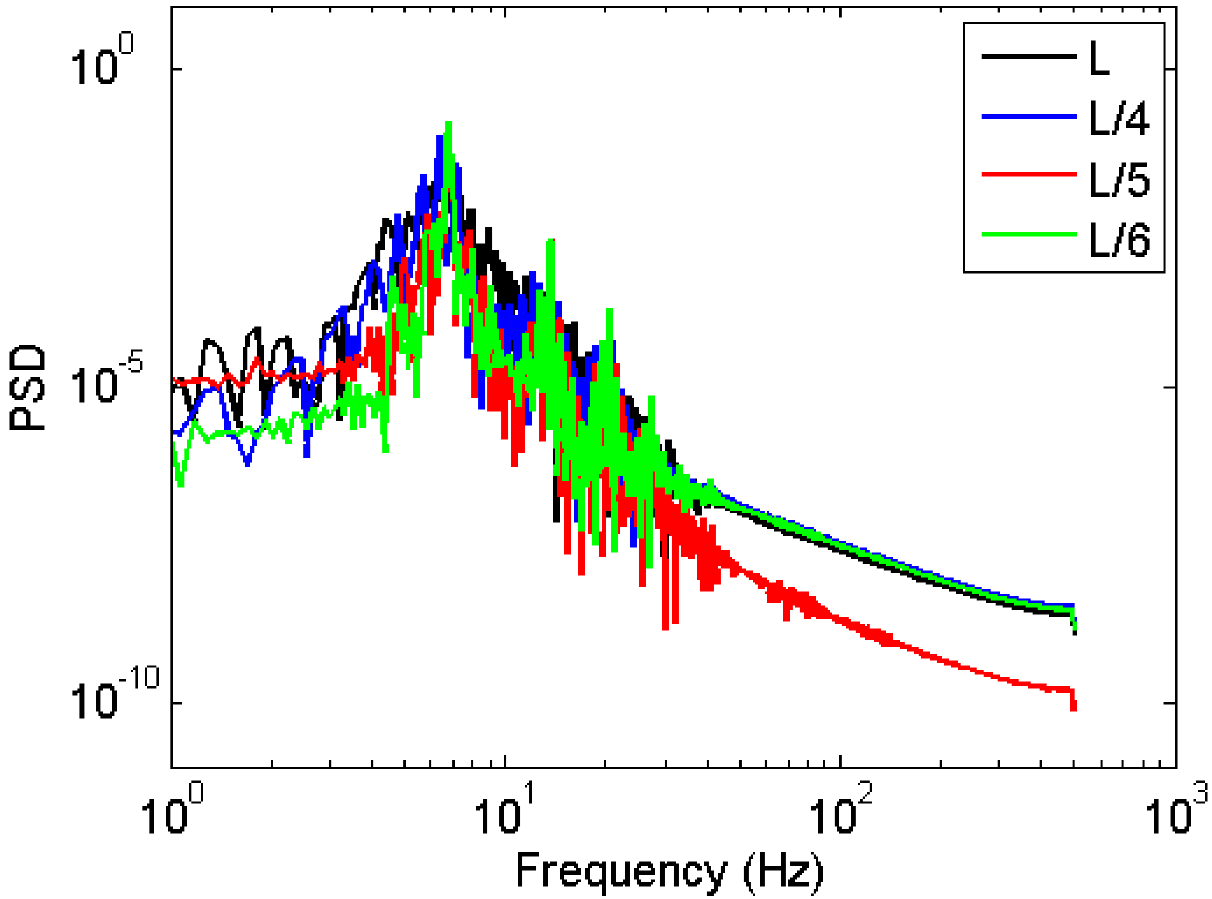
Optimization of the computational domain

The PSD of analyzed axial velocity fluctuations for Re = 9 800 corresponding to different axial lengths of the computational domain.



Step 3

INTORDUCTION OF THE THERMAL FIELDS

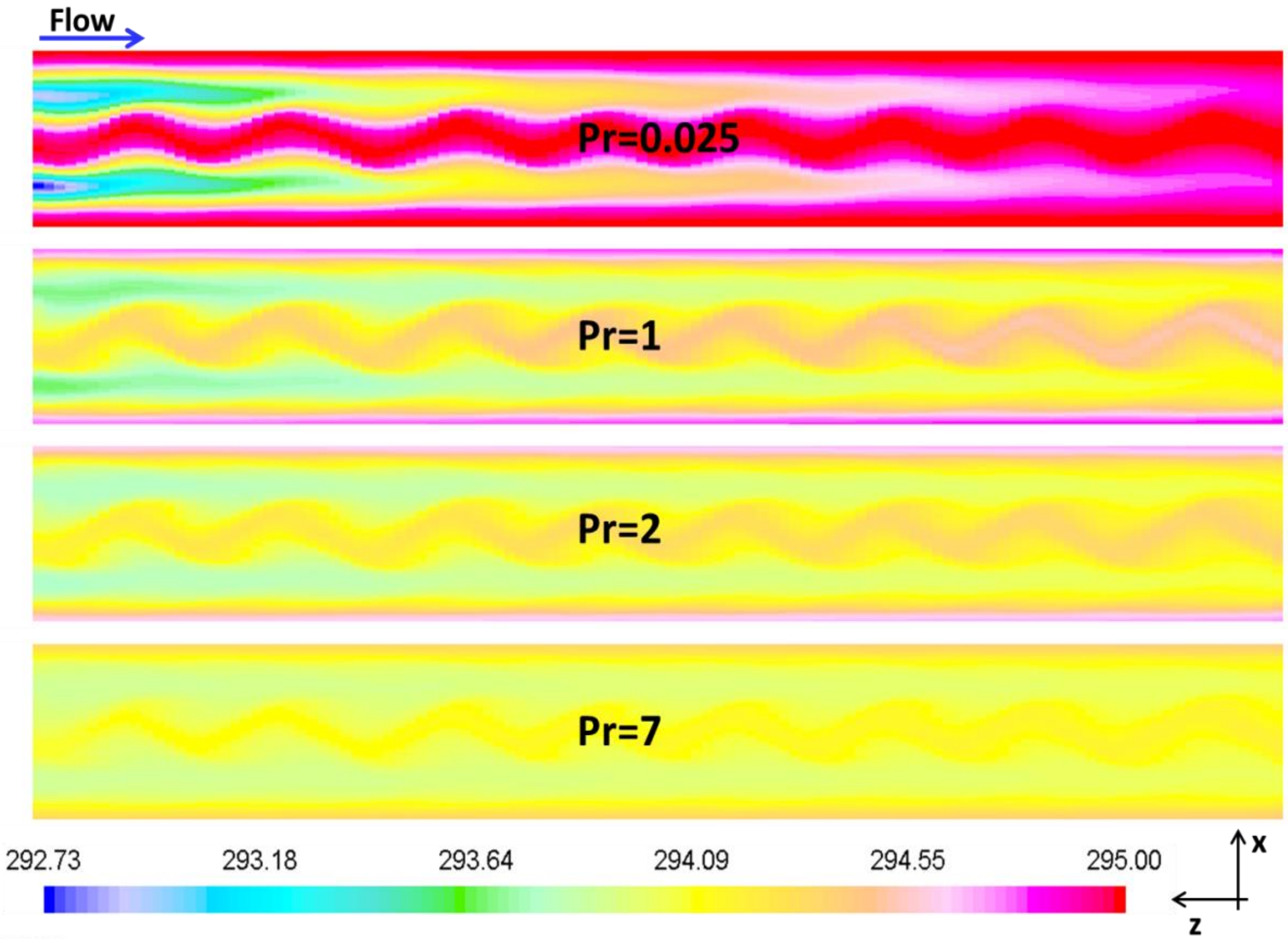
Introduction of the thermal fields

List of test cases considered to design the numerical experiment.

Cases	Re	Length [m]	Mesh [mln]	Pr	Mass flow rate [kg/s]	Temperature [K]	Heat flux [W/m^2]
15	9 800	2.285	1.7	0.025	0.042506	295	-
16	9 800	2.285	1.7	1	0.042506	295	-
17	9 800	2.285	1.7	2	0.042506	295	-
18	9 800	2.285	1.7	7	0.042506	295	-
19	9 800	2.285	1.7	0.025	0.042506	-	0.12
20	9 800	2.285	1.7	1	0.042506	-	0.12
21	9 800	2.285	1.7	2	0.042506	-	0.12
22	9 800	2.285	1.7	7	0.042506	-	0.12

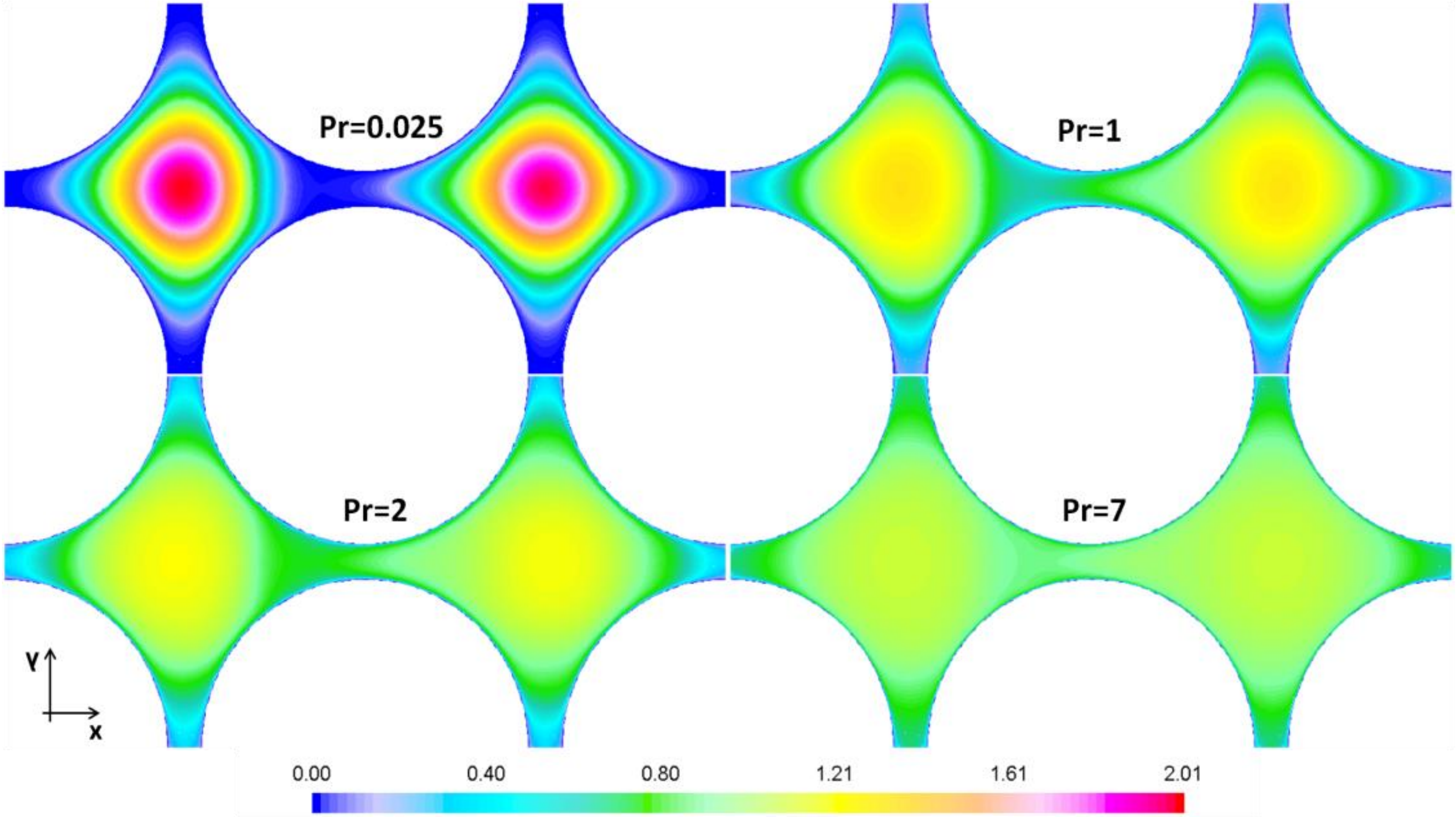
Constant temperature on rods

Stream-wise iso-contours of static temperature.



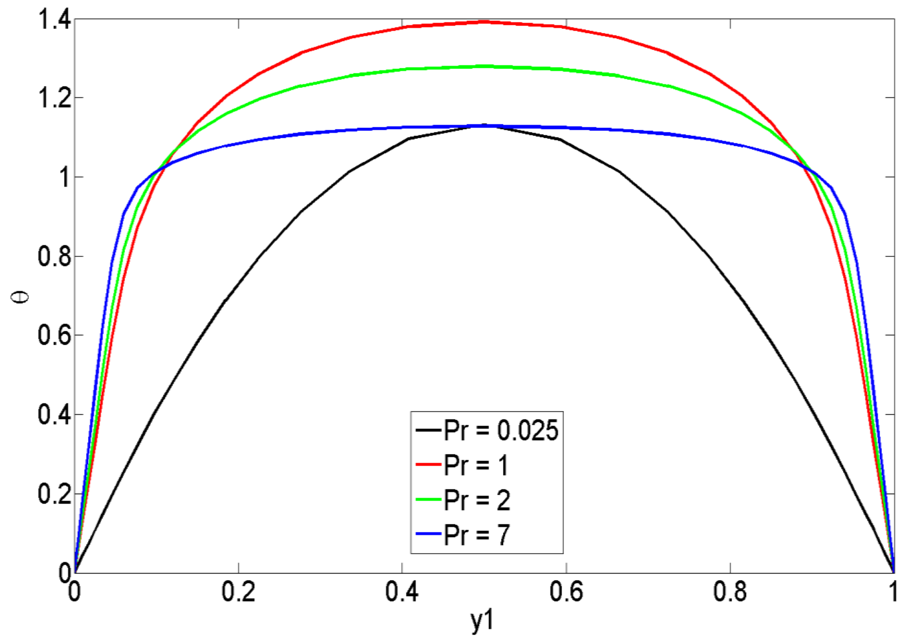
Constant temperature on rods

Iso-contours of scaled temperature for Dirichlet boundary condition on temperature at cross-section in the middle of the domain.

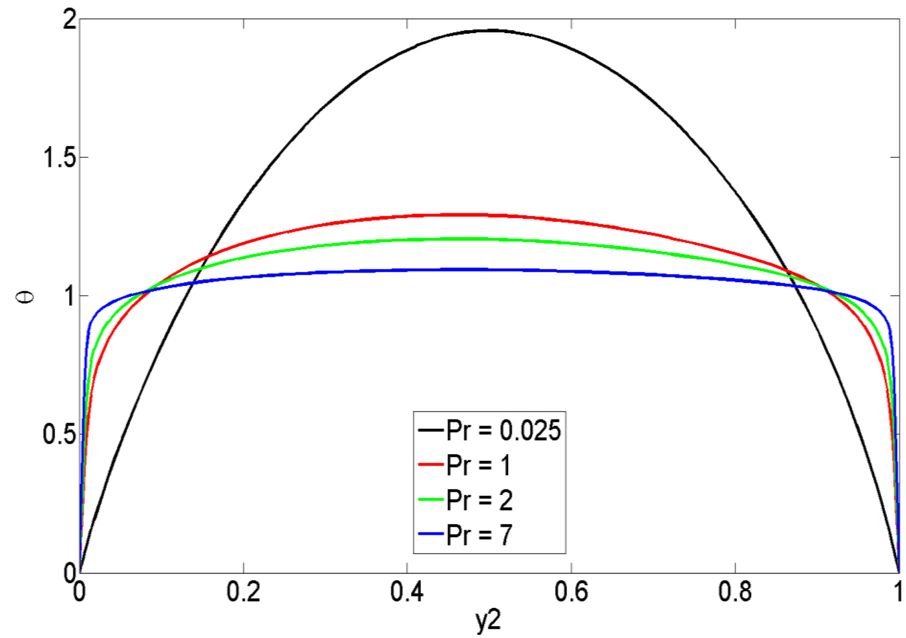


Constant temperature on rods

Thermal boundary layer at line 1

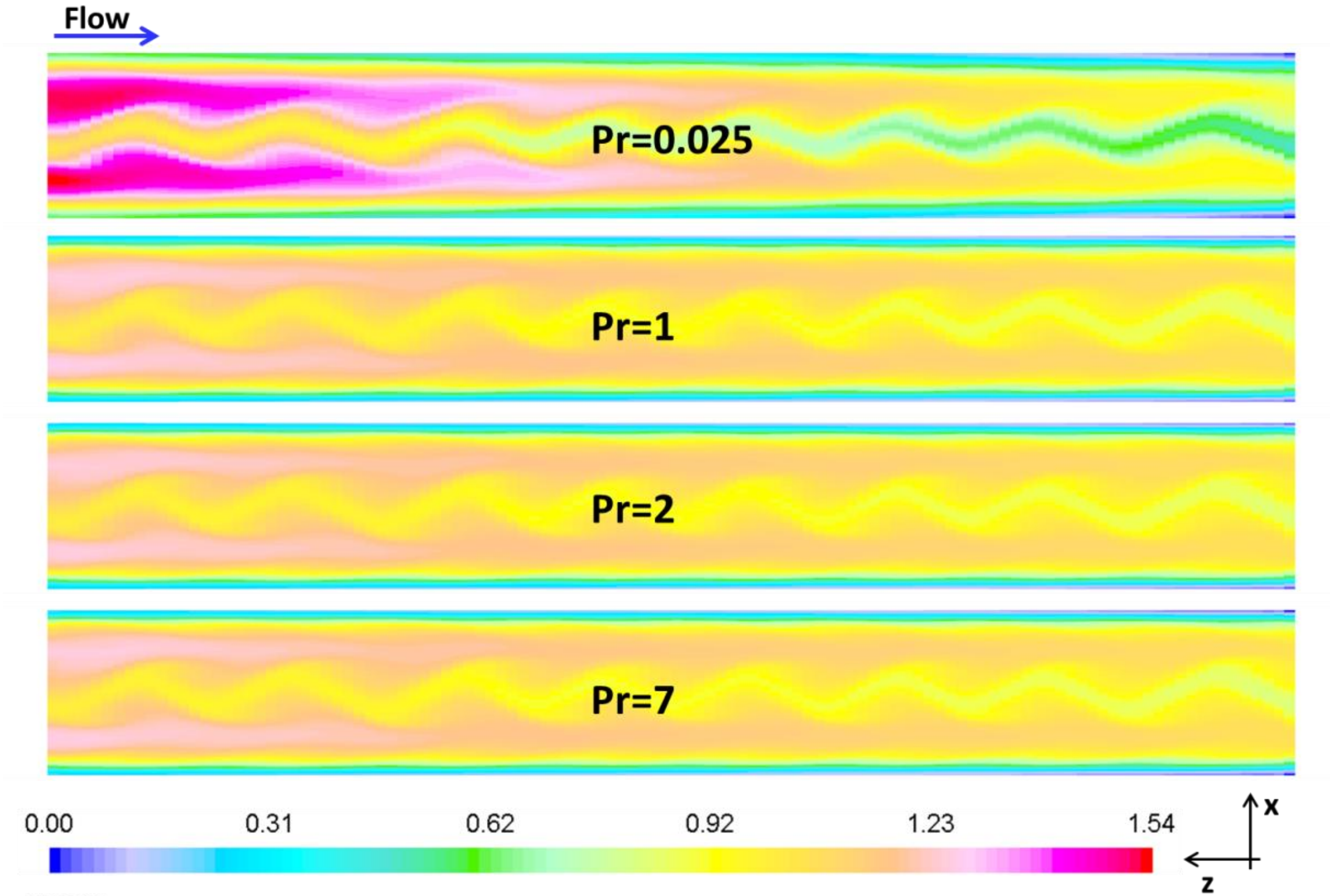


Thermal boundary layer at line 2



Constant heat flux on rods

Stream-wise iso-contours of scaled temperature.



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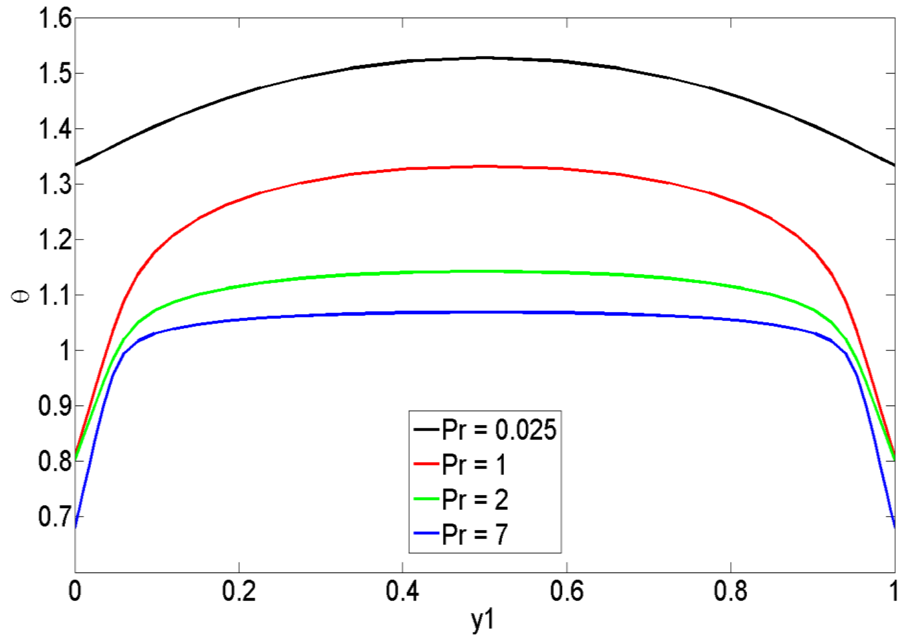
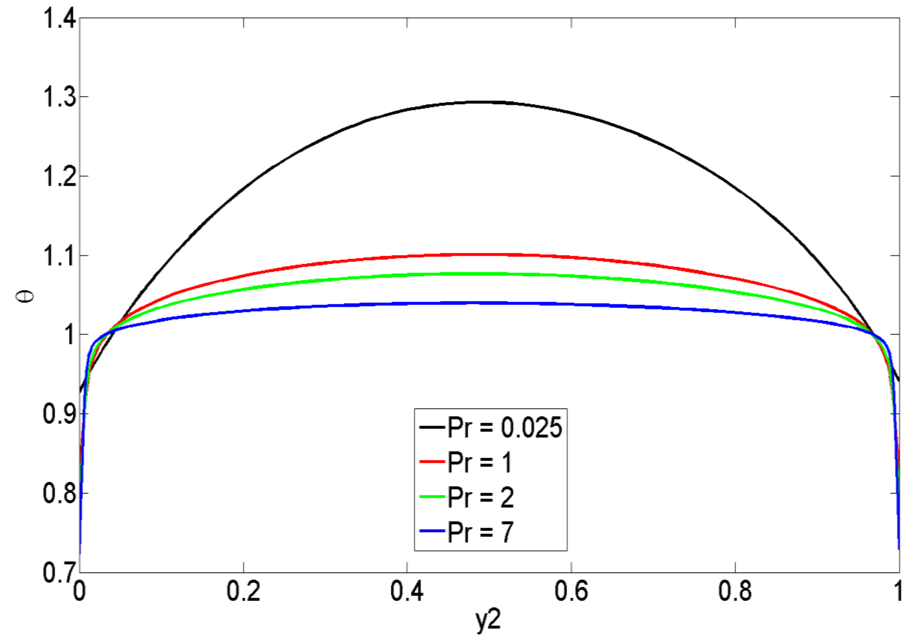
Constant heat flux on rods

Thermal boundary layer at line 1



Thermal boundary layer at line 2



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FINALIZED CLOSELY-SPACED ROD BUNDLE CONFIGURATION

Finalized rod bundle configuration

Important parameters of the loosely-spaced bare rod bundle (based on the Hooper case) for the DNS study:

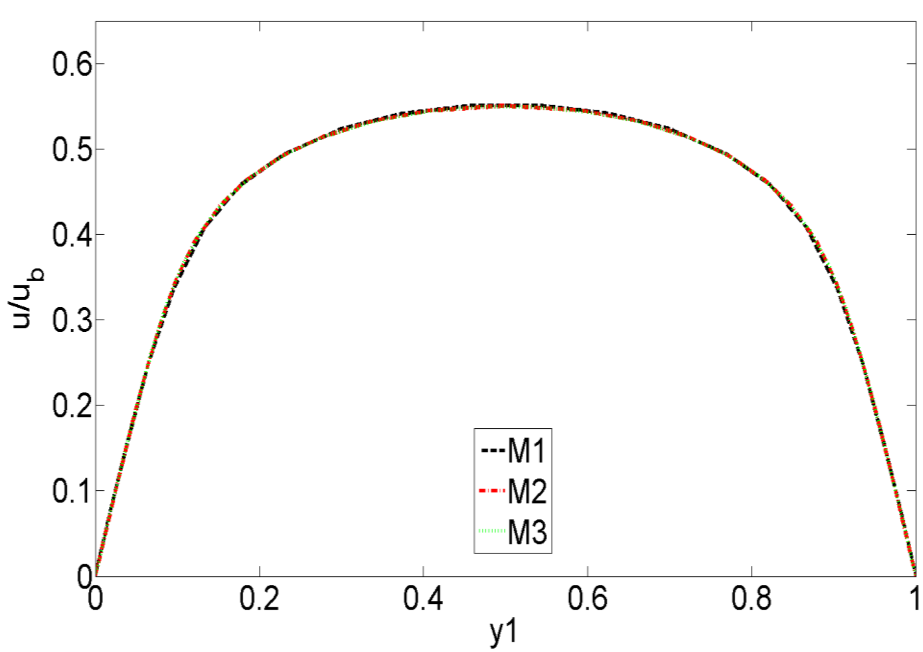
Parameters	Value	Units
Rod Diameter (D)	14	cm
Pitch (P)	15.5	cm
P/D	1.107	-
Re	9 800	-
Mass flow rate	0.043	kg/s
Axial Length	2.285	m
Selected Pr numbers	1, 2, 7, 0.025	-
Temperature on the rods	295	K
Heat flux on the rods	0.12	W/m^2

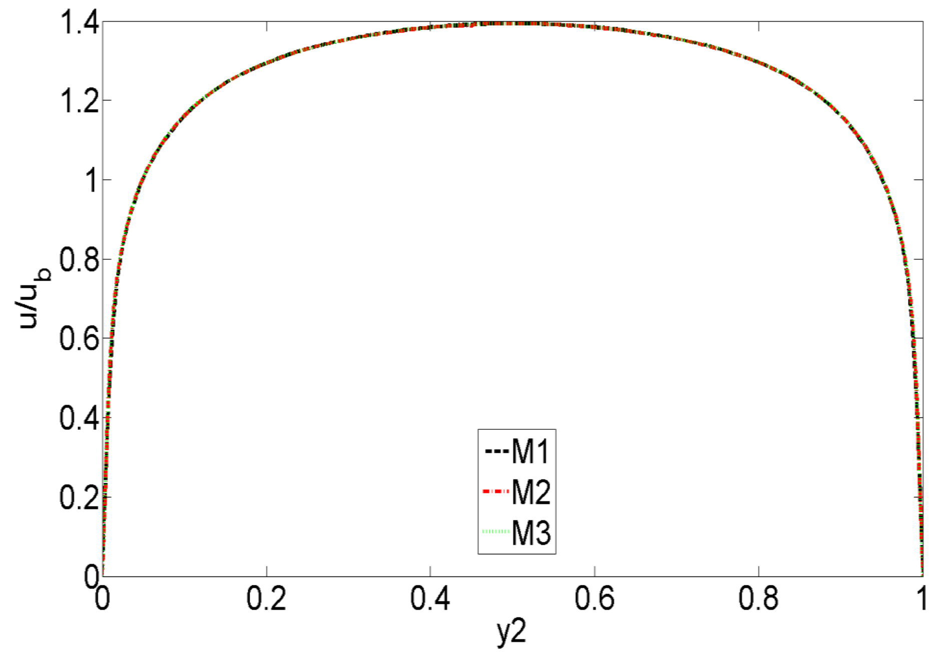
MESH ESTIMATION FOR DNS

Mesh estimation for DNS

Mesh sensitivity study:

Mesh	No. of grid points (million)
M1	0.9
M2	1.7
M3	4.1





Mesh estimation for DNS

Scales:

- Kolmogorov length scale (KLS) = $\eta = (\frac{\nu^3}{\varepsilon})^{0.25}$
- Batchelor length scale (BLS) = $\eta_\theta = \left(\frac{\alpha^2 \nu}{\varepsilon}\right)^{0.25}$

where:

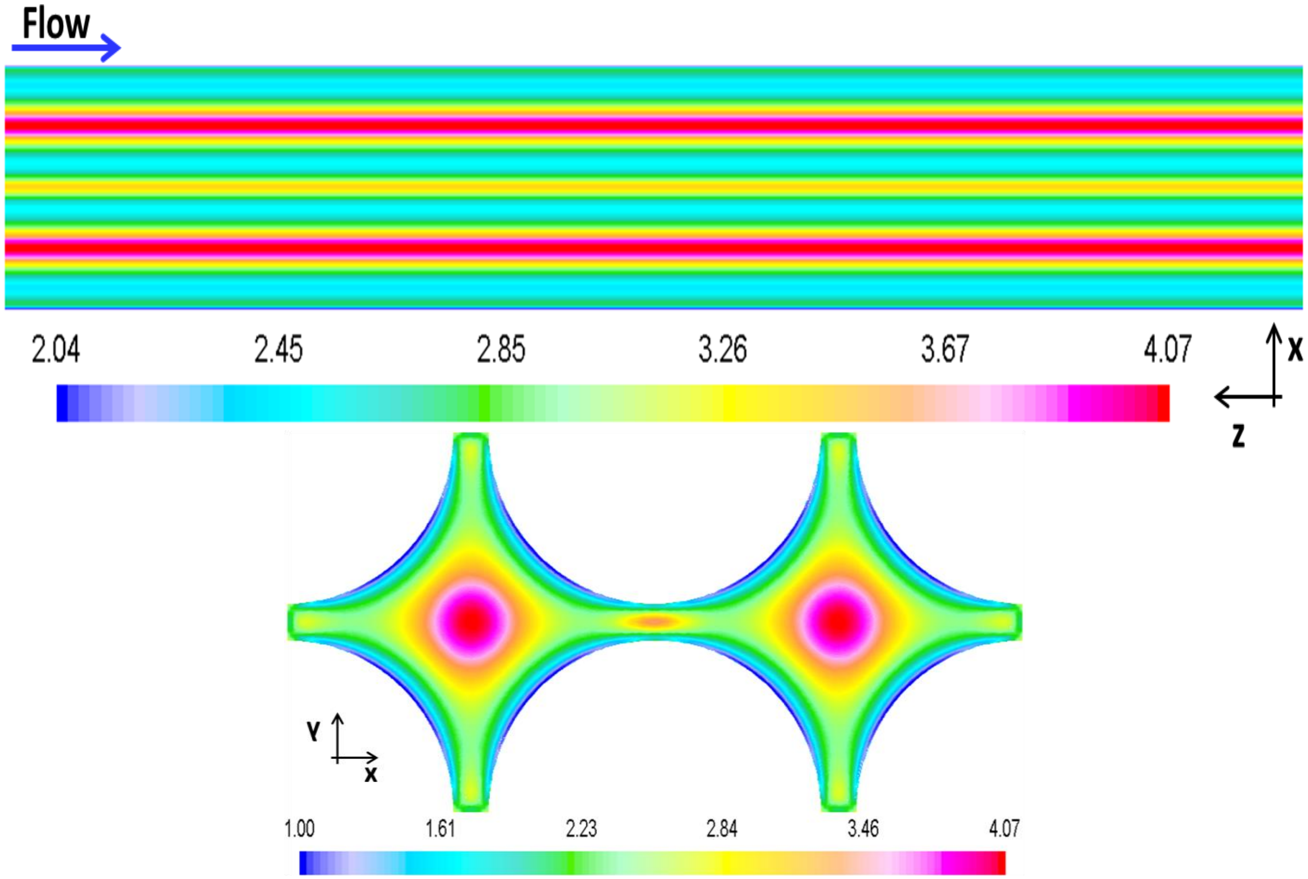
ν – is the kinematic viscosity

ε – is the turbulence dissipation rate

α – is the thermal diffusivity

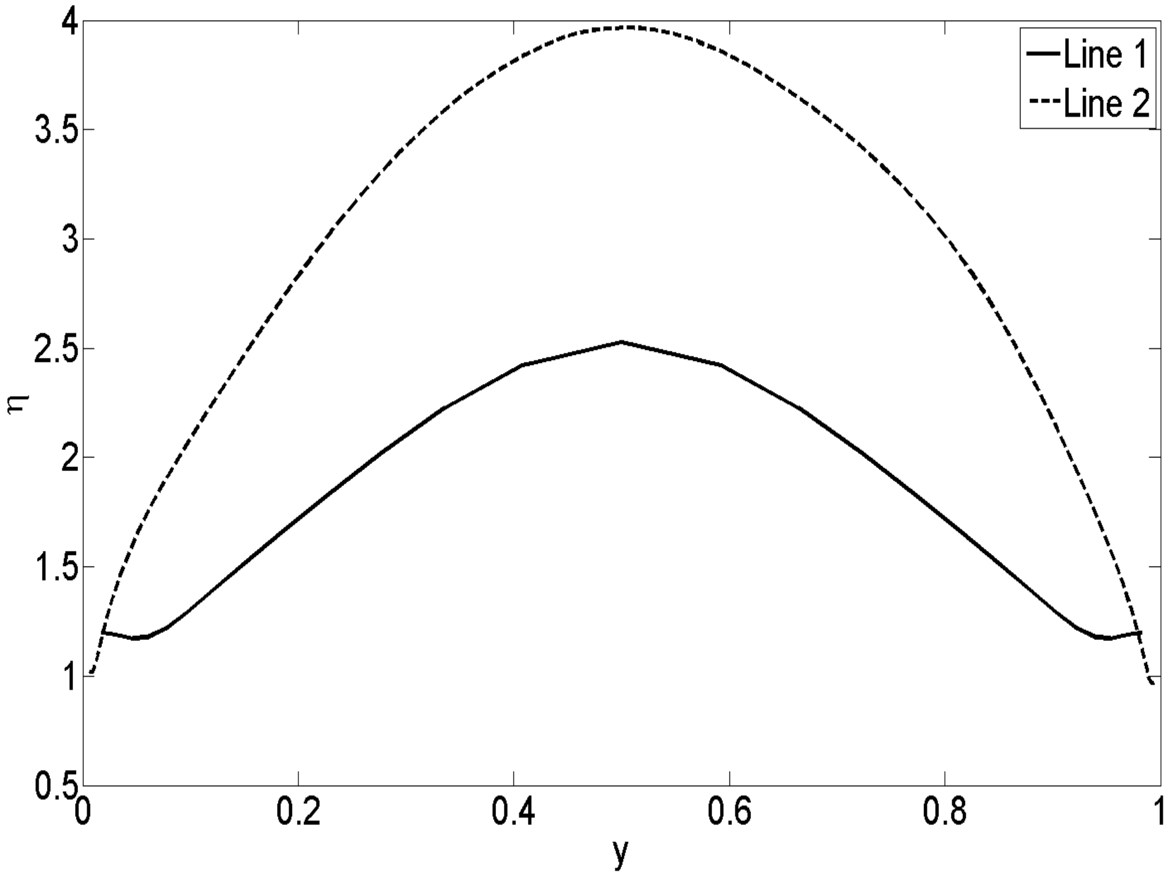
Mesh estimation for DNS

Iso-contours of KLS



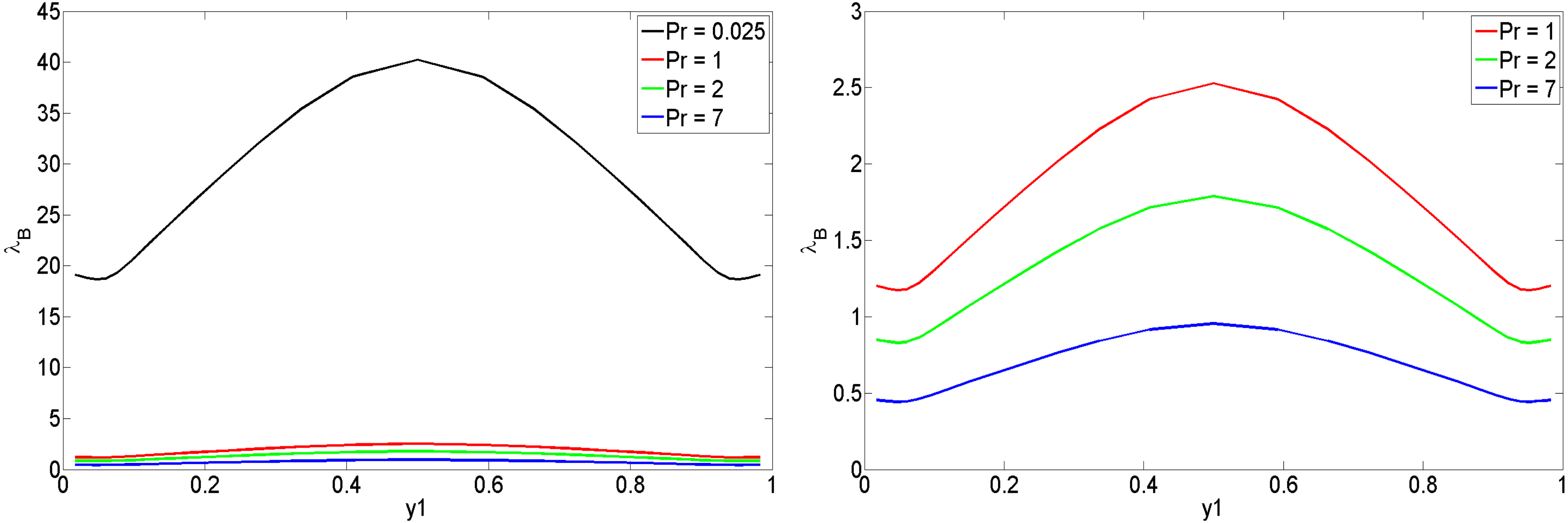
Mesh estimation for DNS

Non dimensional Kolmogorov length scale



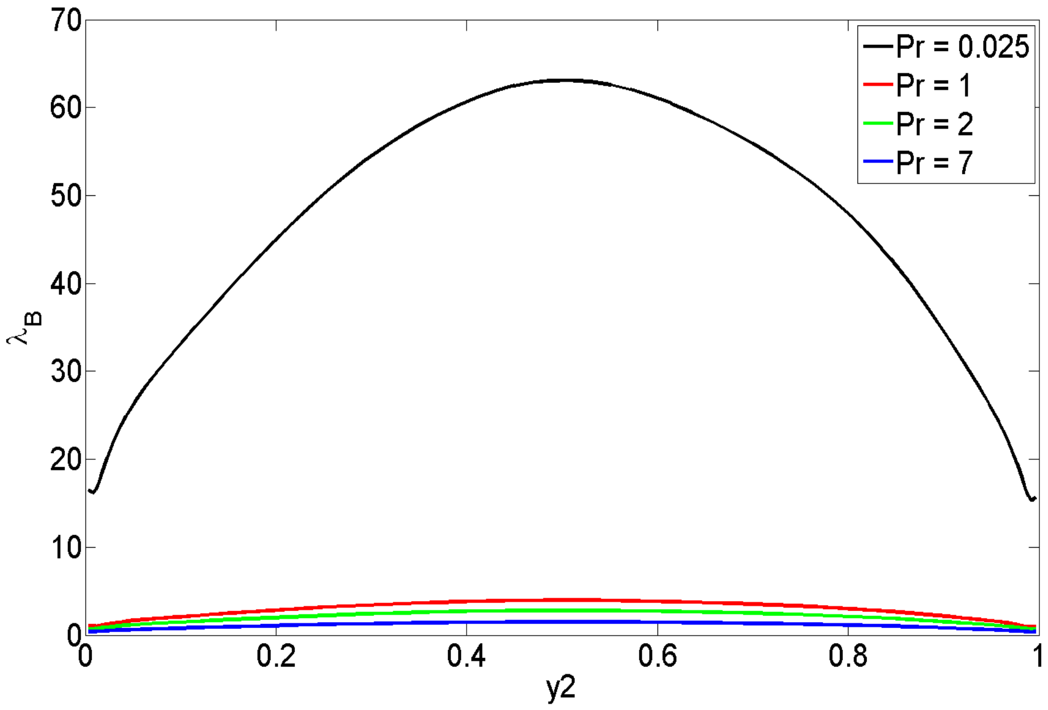
Mesh estimation for DNS

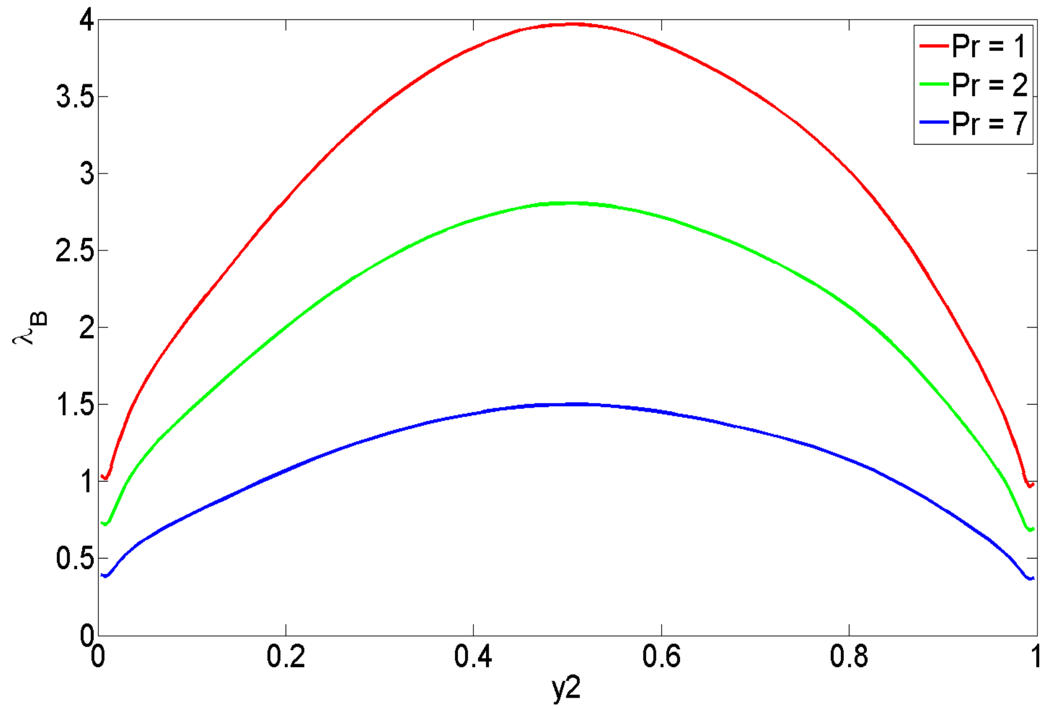
Non dimensional Batchelor length scale in narrowest gap region.



Mesh estimation for DNS

Non dimensional Batchelor length scale alonf the line 2.





SUMMARY

Summary

- In total **22 test cases** of URANS computations were run.
- All the simulations were performed on the CIS cluster, by using an average of **130 processors.**
- A total computational time of **~0.3 million core hours** were used to performe this work
- With the use of extensive URANS study **several aspects** of the Hooper case, namely geometry (axial length) and **boundary conditions were calibrated and optimized.**
- The obtained RANS results are used in order to **estimate the overall meshing requirements for the targeted DNS**: **~600 million** grid point for case of Pr = 2 or **~1 billion** grid point for all passive scalars.

Summary

- ICONE26: **International Conference on Nuclear Engineering** (London, July 2018):
  - **Design of a closely-spaced rod bundle for a reference Direct Numerical Simulation (oral presentation and conference papaer)**

- Journal publication: ***Towards the Direct Numerical Simulation of a closely-spaced bare rod bundle,*** *Annals of Nuclaer Energy, Impact factor: 1.312 –* ***under review***

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Acknowledgments

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Questions?

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