Jožef Stefan Institute

R4 Reactor Engineering Division

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Thermal Fluctuations in Low-Prandtl Fluid Flows over a Backward Facing Step

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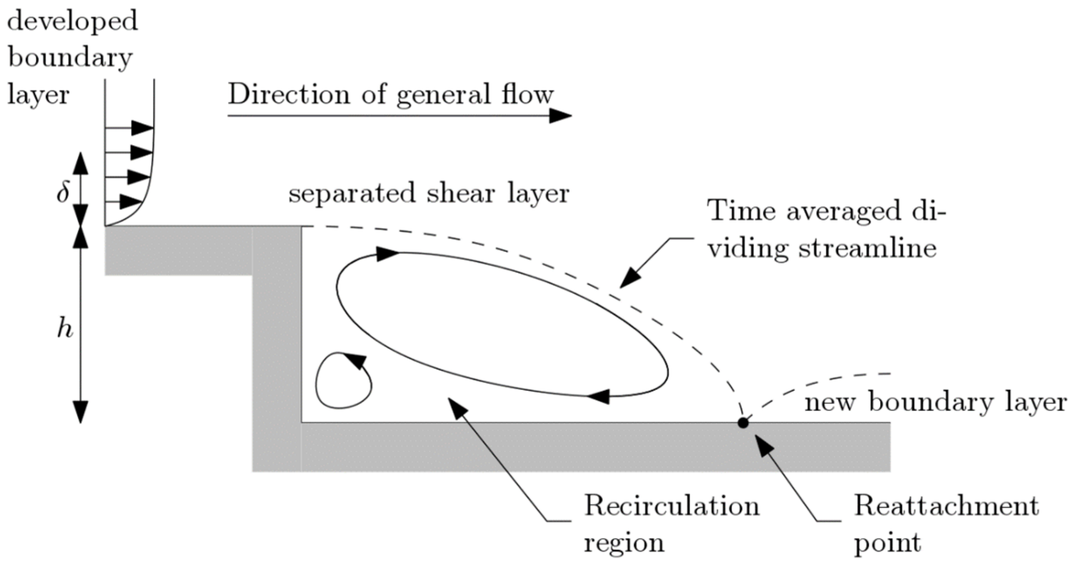
Outline

- Introduction
- Description of experiment
- DNS results, flow structure
- Comparison with RANS simulation

Backward facing step

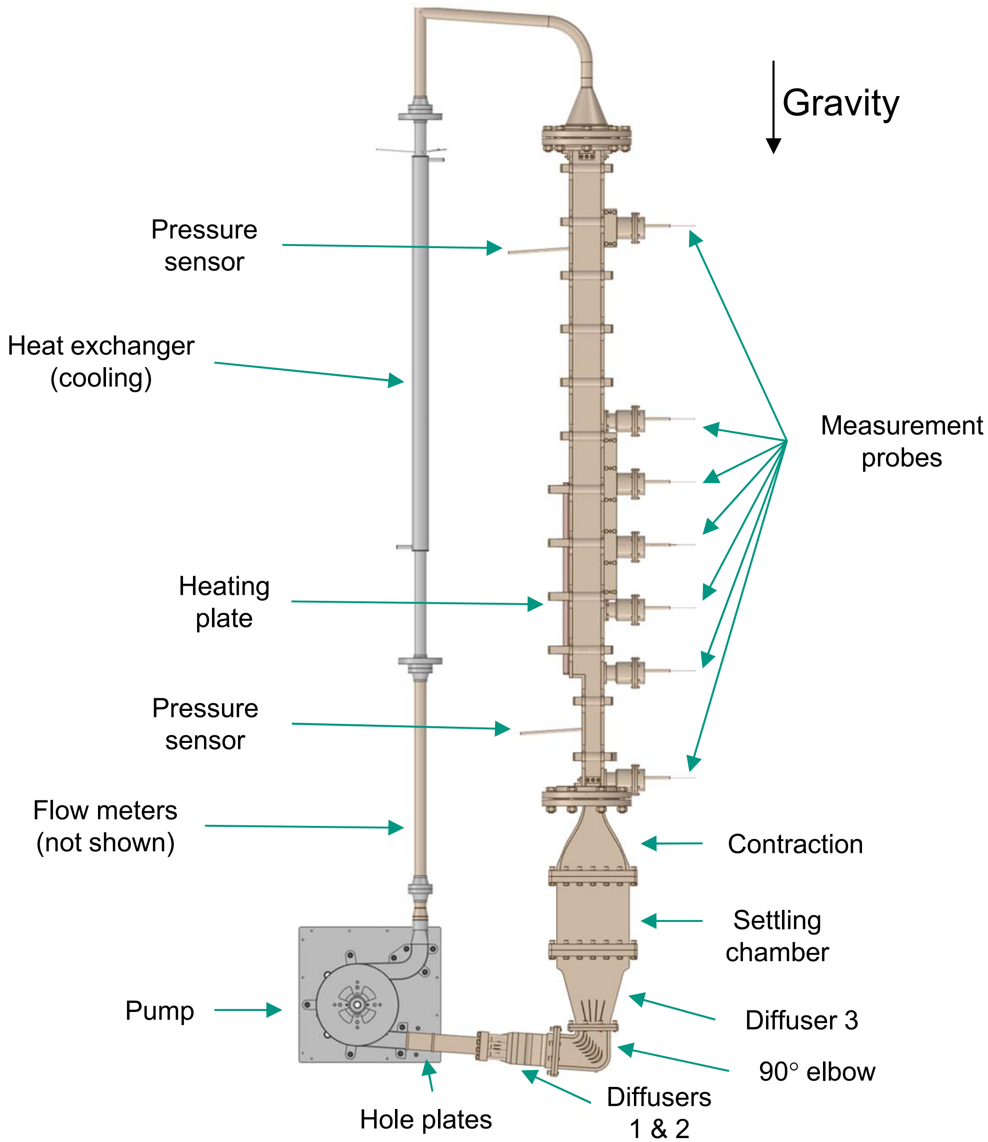


- representative geometry for sudden expansions
- expand reference database
- penetration of thermal fluctuations into solid walls

DITEFA 2 – Facility description

- 30 liters of GaInSn ($Pr = 0.025$ at $50°C$)
- Temperature range: $20 - 80°C$
- Max. flow rate = $1.5\ \frac{l}{s}$
- 2 flow meters (turbine and inductive flow meter)
- 2 hole plates for flow correction
- 3 wide angle diffusers with vanes and screens at inlet and outlet
- Settling chamber with honeycomb and 3 screen stages
- Contraction with 5:1 contraction ratio
- 7 Measurement probes for local velocity and temperature measurement
- Heating plate with 20800 [W/m²]
- Pressure difference measurement in test section

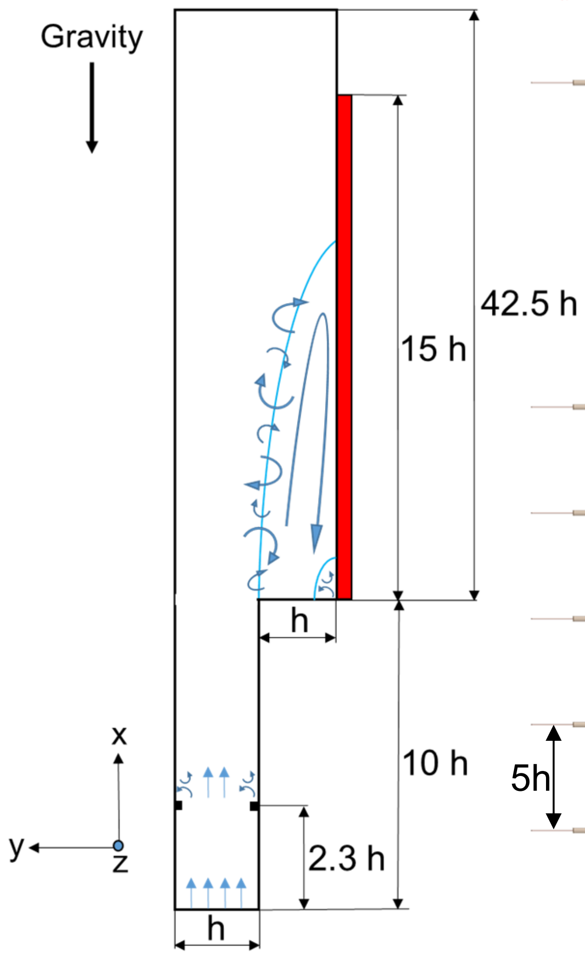
Manufacturing currently in its final stage



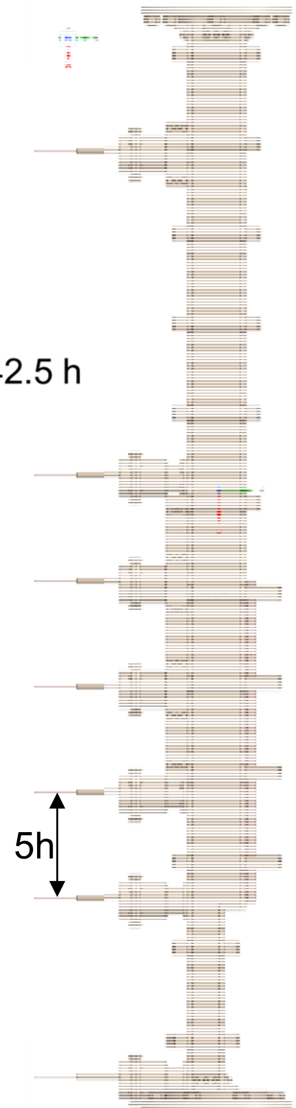
DITEFA 2 – BFS parameters

- Forced and mixed-convection regimes
- BFS aspect ratio = 2
- BFS expansion ratio = 2
- Low turbulence intensity and nearly constant velocity profile at inlet
- Trip-wire for forcing transition from laminar-to-turbulent boundary layer
- 120 thermocouples mounted in heating plate for wall-temperature profile measurement
- Double-walled test section required (metal+plastic)
- Dimensionless number ranges (see table)

	Expected minimum value	Expected maximum value	Comments
T_{inlet}	$20°C$	$80°C$	$\Delta T_{max} = \frac{\dot{q}h}{k_{ref}} \sim 30\ [°C]$
Re_h	4 500	54 000	$Re_h = \frac{U_b h}{\nu}, \nu = \nu(T = 50°C)$
Pr	0.019	0.031	
Pe_h	115	1 400	$Pr = Pr(T = 50°C)$
Ri_h	0.005	0.892	$Ri_h = \frac{g\beta\Delta T h}{U_b^2}$

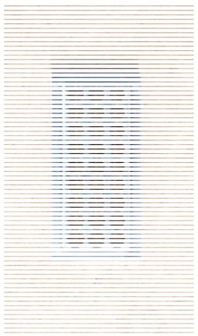


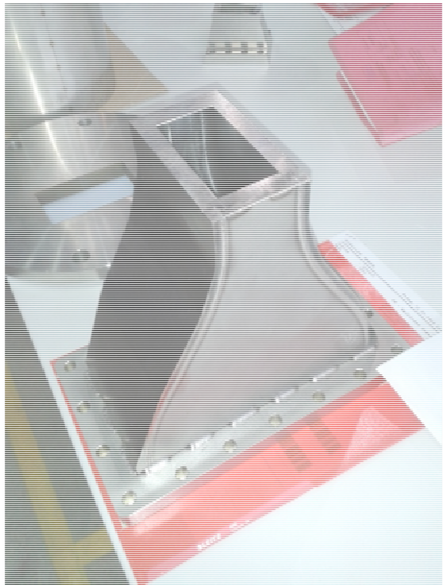
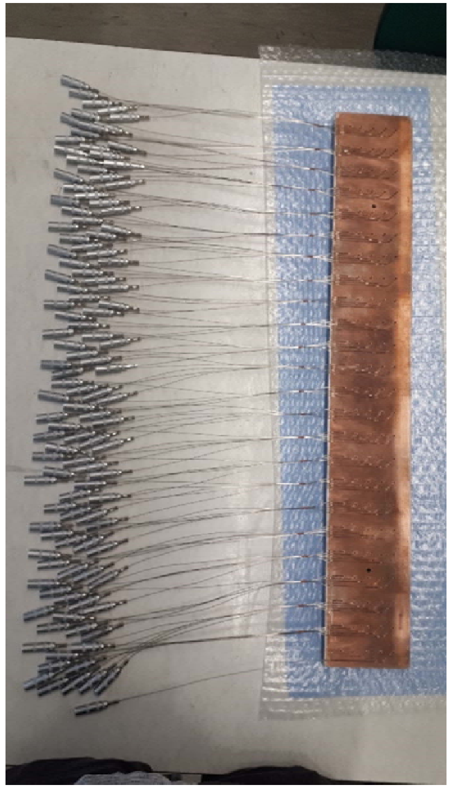
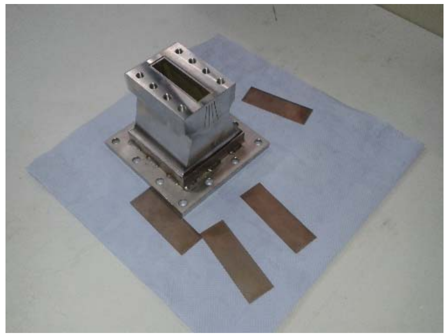
Sketch (not scaled)



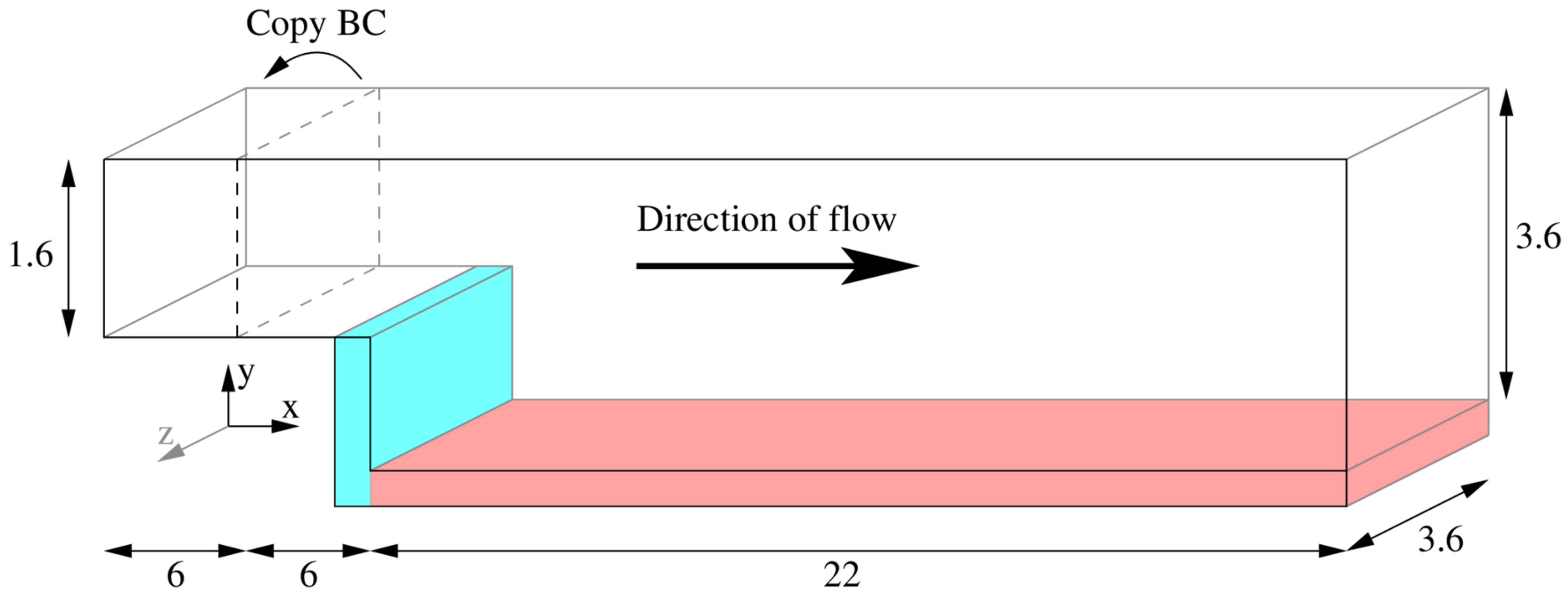
DITEFA 2 – Time line

- Manufacturing of facility: ~ 05.19
- Manufacturing of PMP: ~ 06.19
- Commissioning: ~ 08.19
- Preliminary results ~ 10.19
- Final results ~ 12.19

Geometry



- Walls (for fluid) at all sides except inflow/outflow
- Expansion ratio 2.25
- Thickness of solid walls is 0.25 everywhere
- Recycling inflow boundary condition
  - Imposed average volumetric flux $\langle u_x \rangle = 1$, $\mathrm{Re} = 3200$, $\mathrm{Re}_h = 6400$, $\mathrm{Re}_D = 7089$, $\mathrm{Re}_\tau = 207$
- Outflow pressure zero (with some corrections to eliminate backflow)
- $\frac{\lambda_f}{\lambda_w} = 3$, $\frac{\alpha_f}{\alpha_w} = 10$, $\mathrm{Pr} = 0.005$, $\mathrm{Pr} = 0.1$

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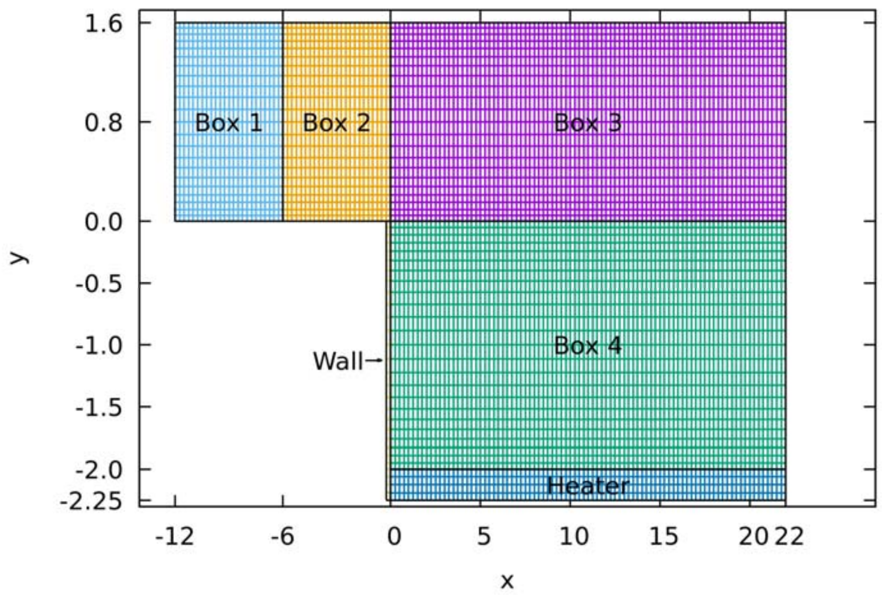
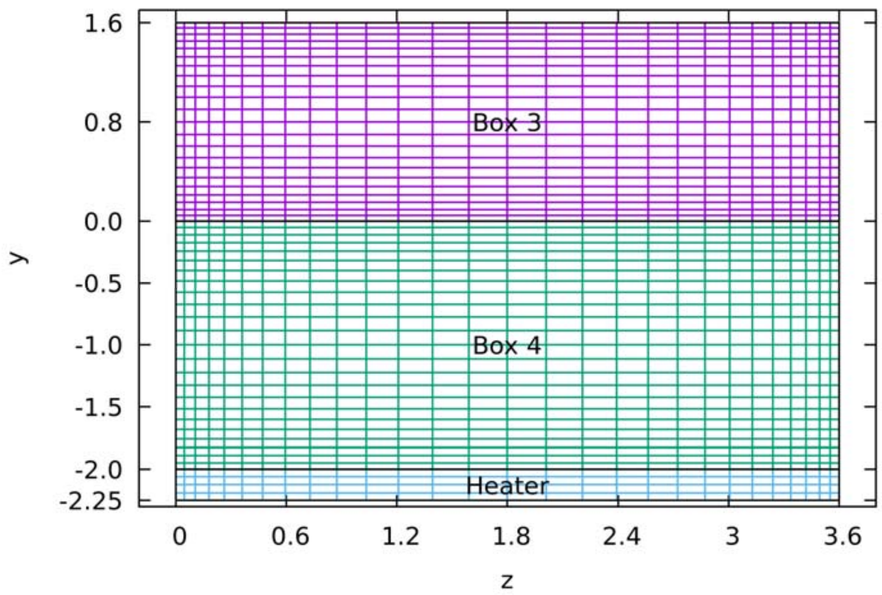
Spectral element method

→ NEK5000 (open source, developed by Argonne NATIONAL LABORATORY)





- Total of $\sim 154 \times 10^3$ elements, 11×10^3 solid elements
- 7 collocation points in each direction
- $\sim 49 \times 10^6$ points, $\sim 31 \times 10^6$ unique points
- CFL ~ 0.1 ($\Delta t = 4 \times 10^{-4}$), $y^+ < 0.8$

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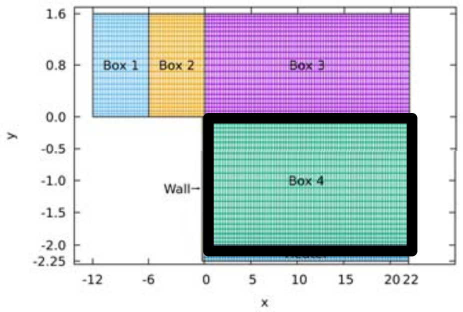
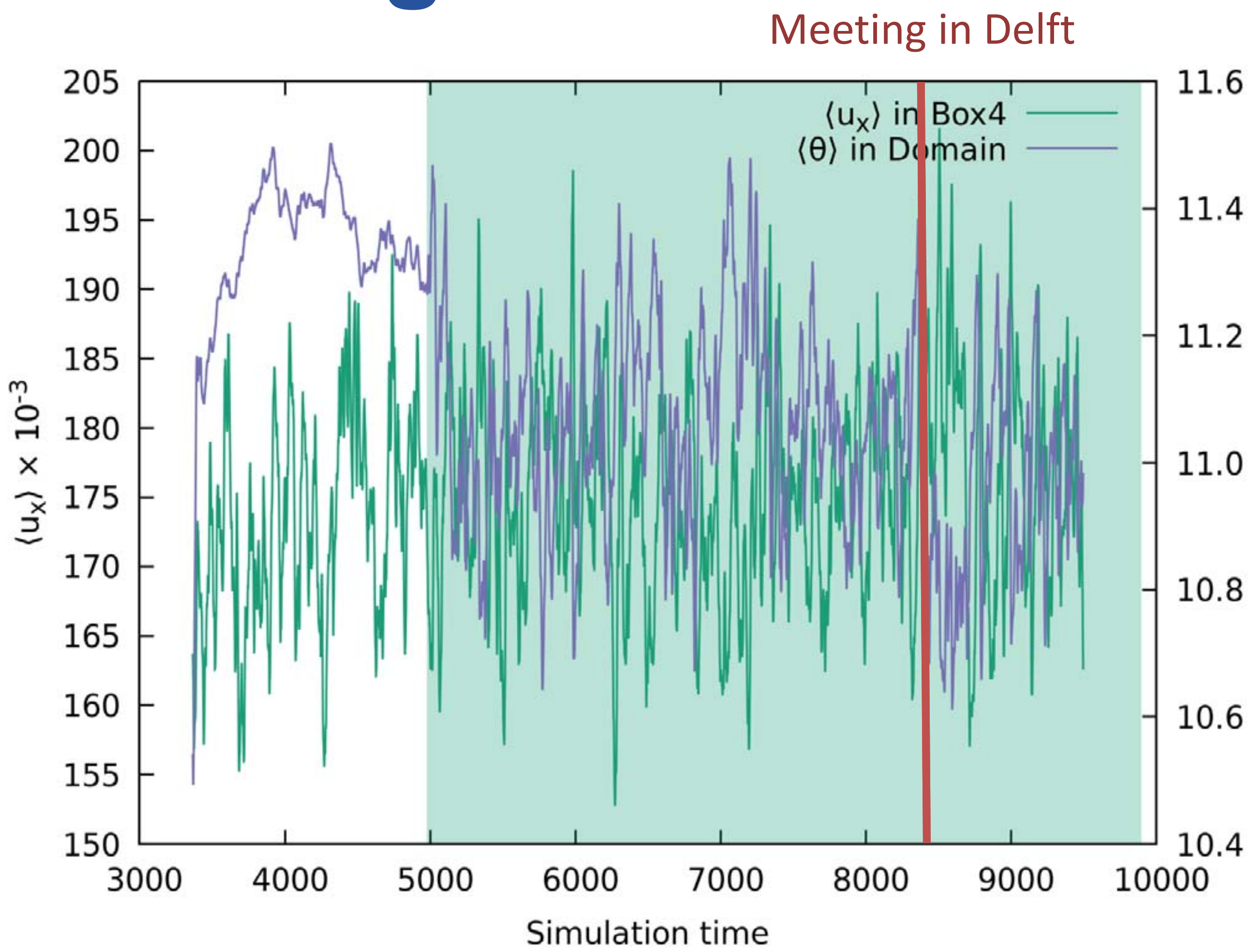


Convergence



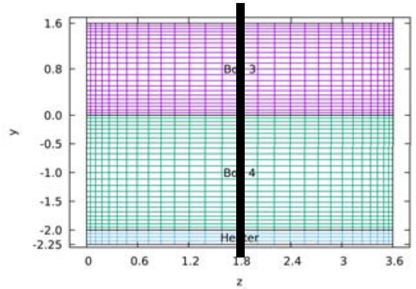
Shaded:
~3M CPU-hrs

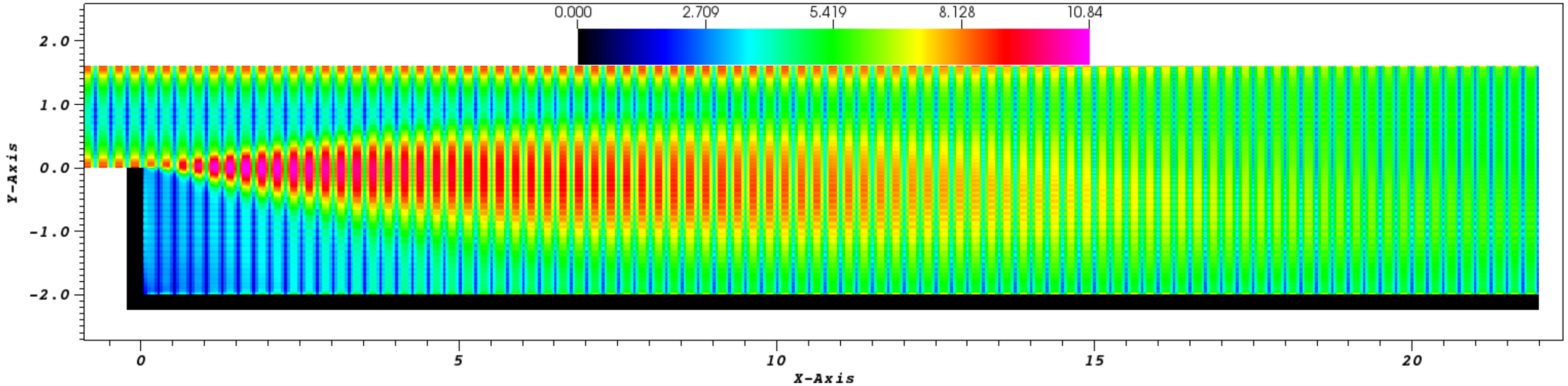
12×10^6 steps

4900 Dimensionless time units

1 dimensionless time unit ~ 0.48s

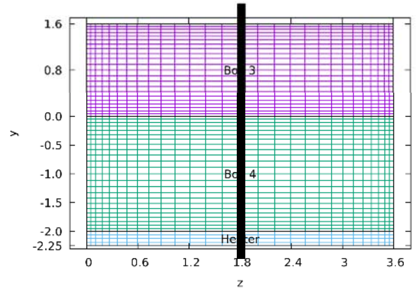
Kolmogorov length scale

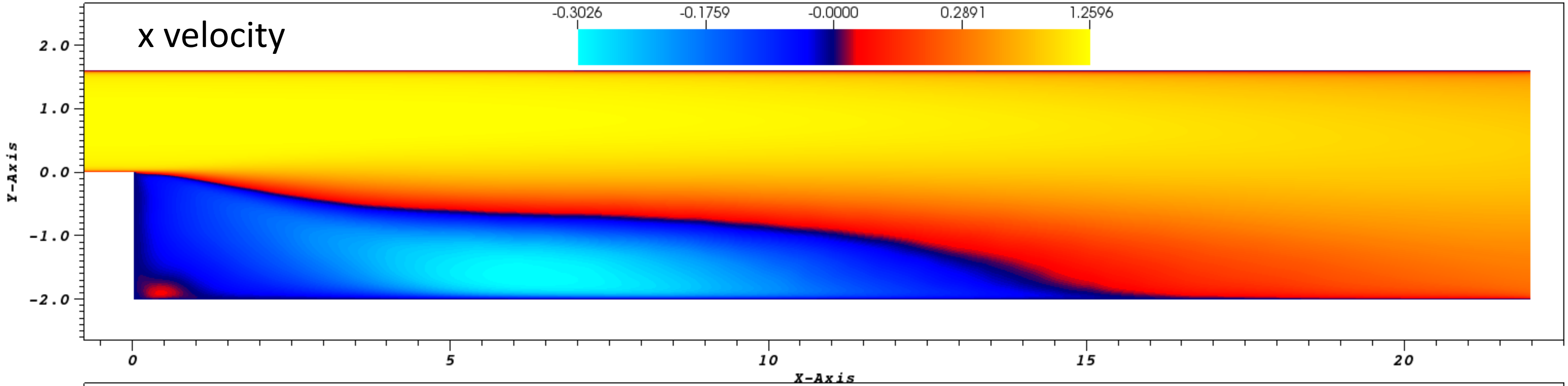


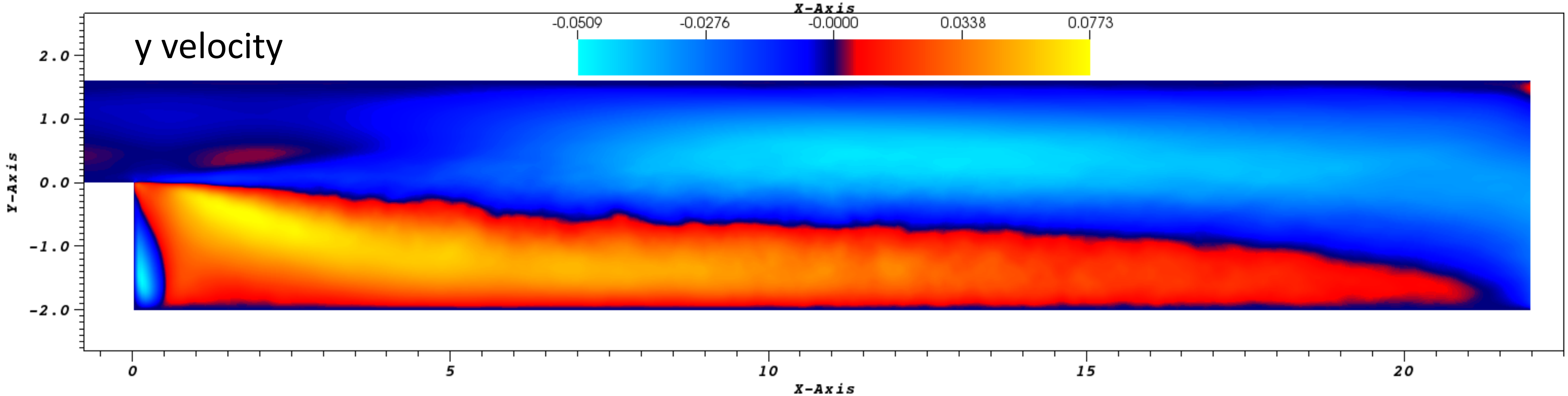


- Maximum diagonal distance between points divided by Kolmogorov length scale
- Ideal $\frac{\Delta x}{\delta} < 2$ but comparable to Moser, Kim, Mansour DNS of channel flow
- Scale: [0.83,10.84]
- First points in the channel upstream of step: $y^+ = 0.77$, $z^+ = 0.83$
- Through domain based on friction Reynolds number in channel upstream of the step ($\mathrm{Re}_\tau = 207$):
  - $x^+ \in [4.39, 12.13]$
  - $y^+ \in [0.77, 5.56]$
  - $z^+ \in [0.83, 10.20]$

Average Flow Structure







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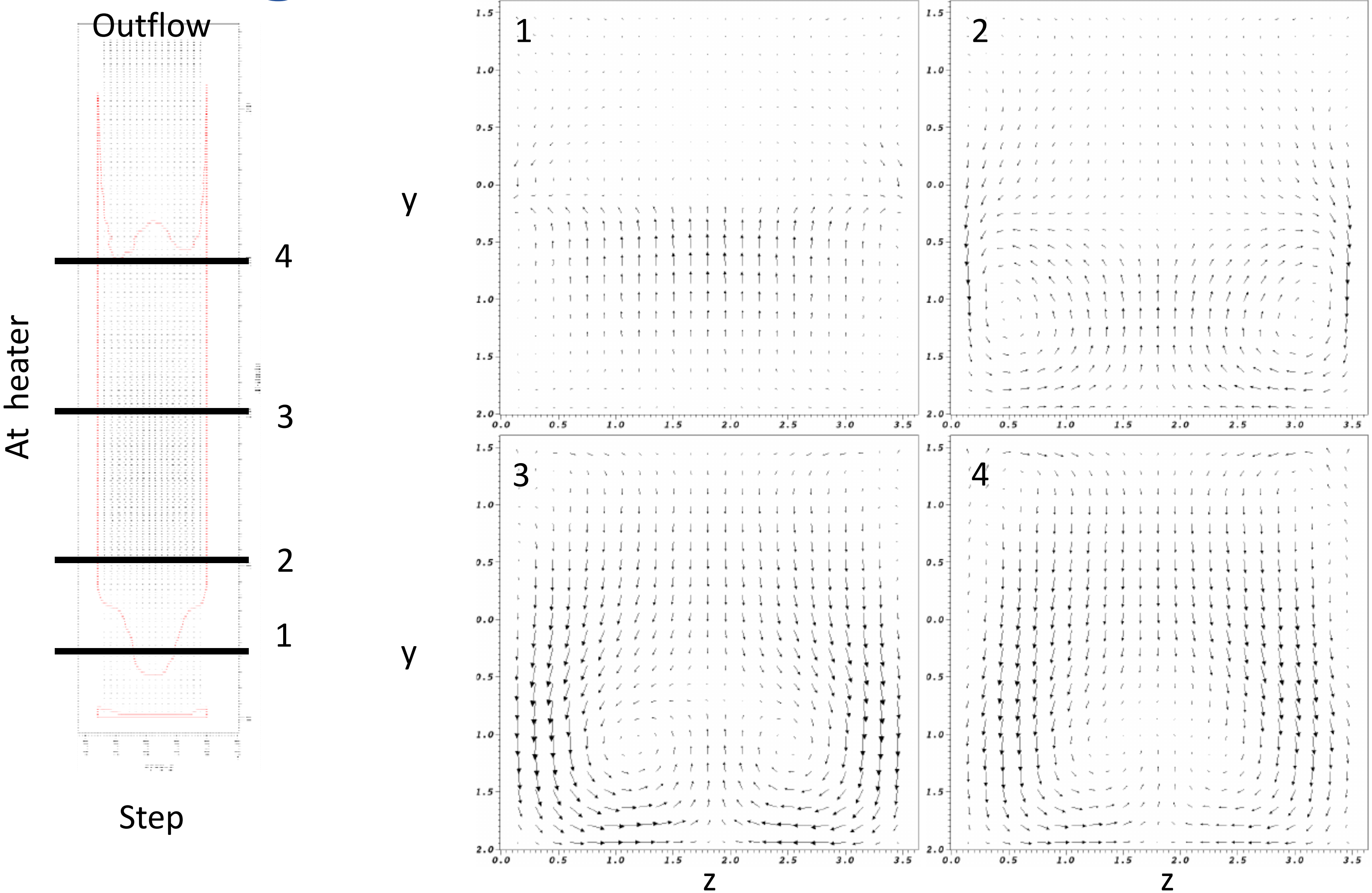
Average Flow Structure



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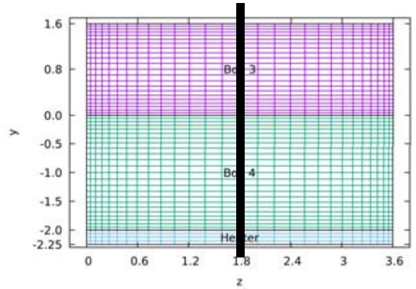
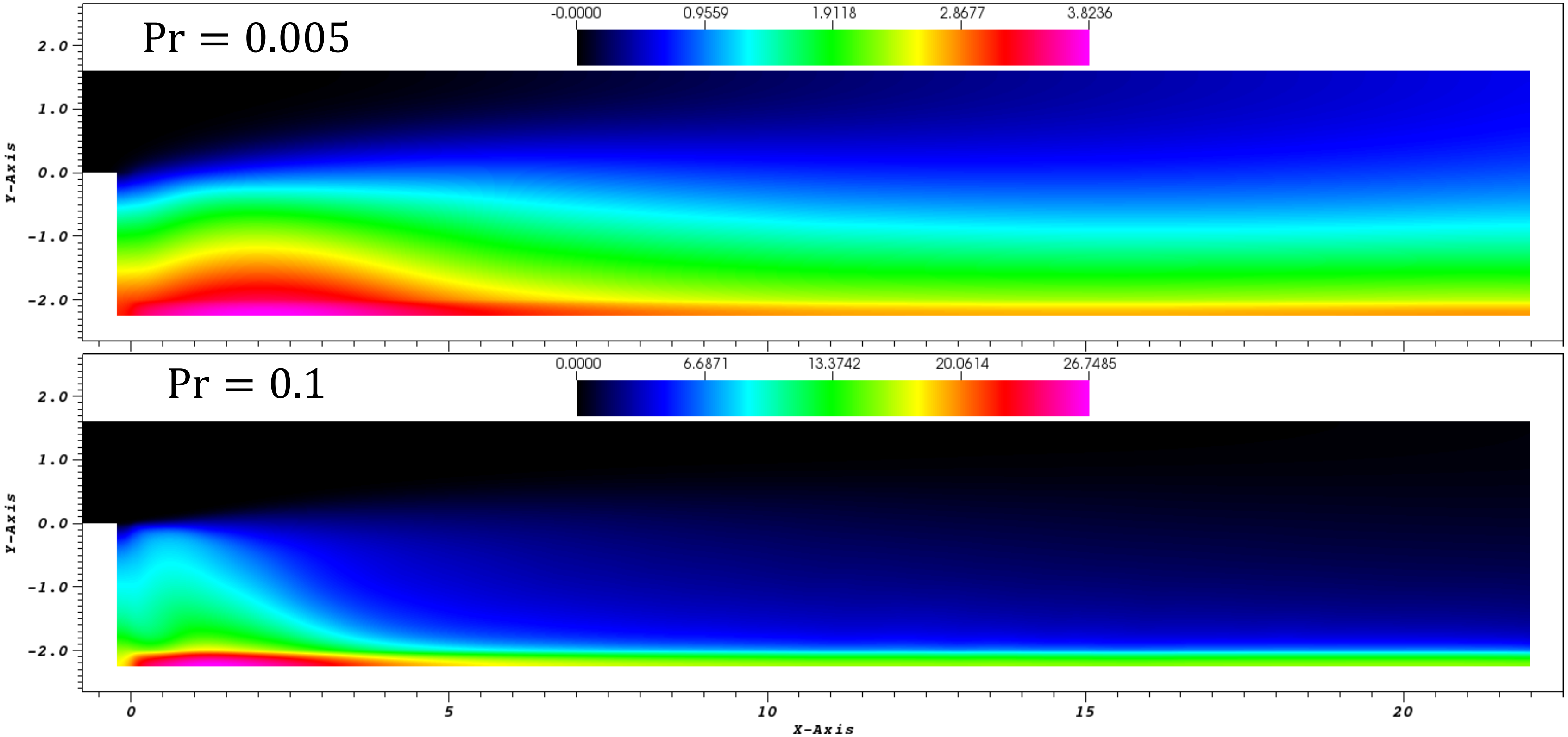
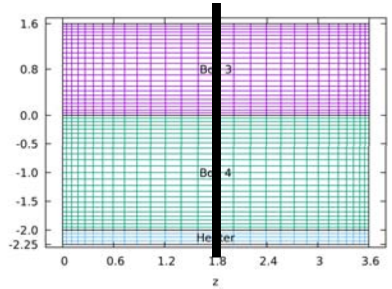
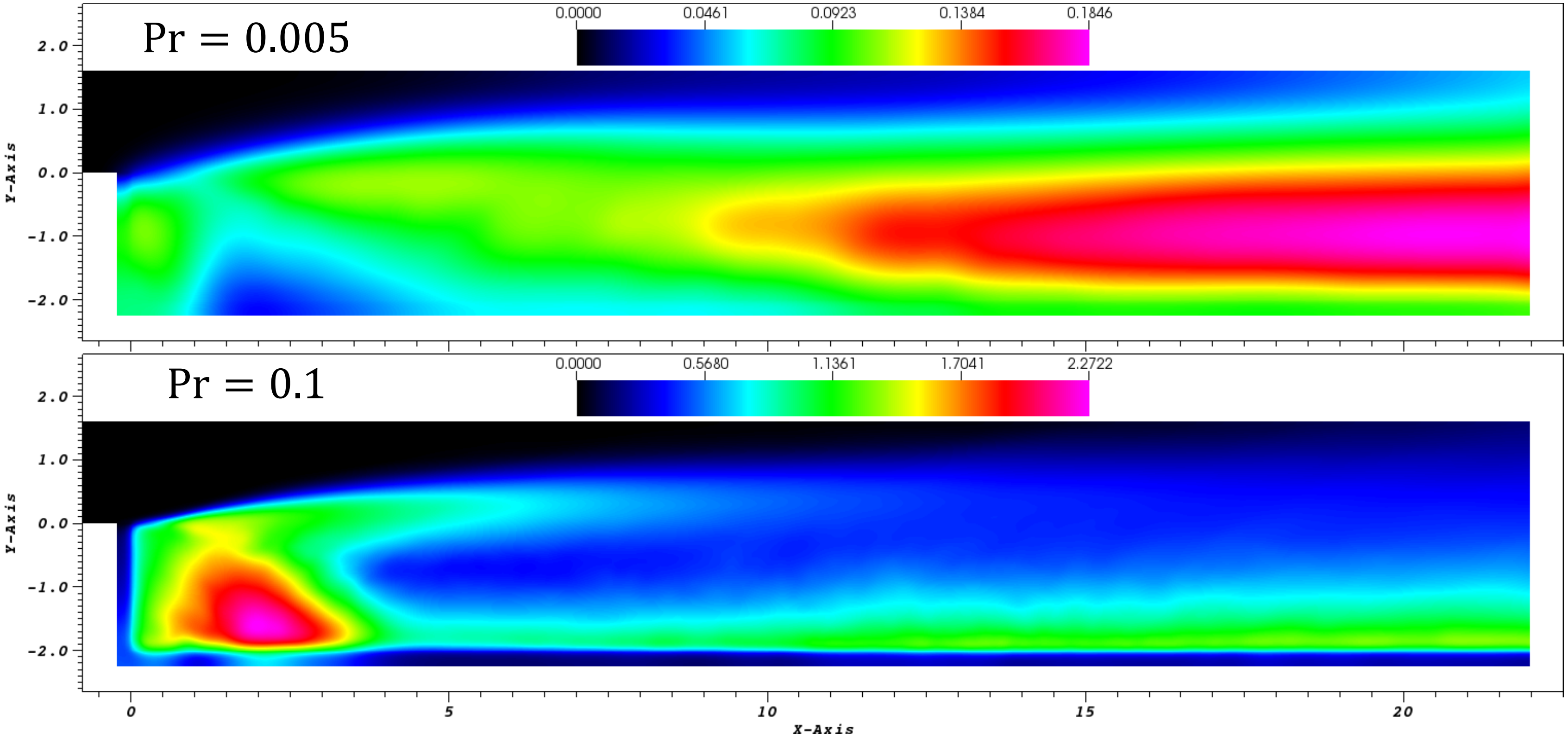
Average temperature (middle)



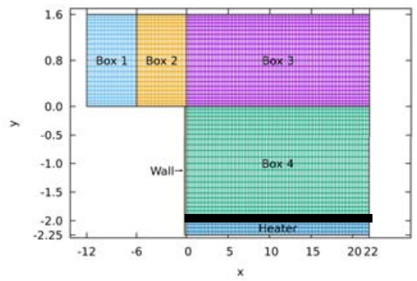


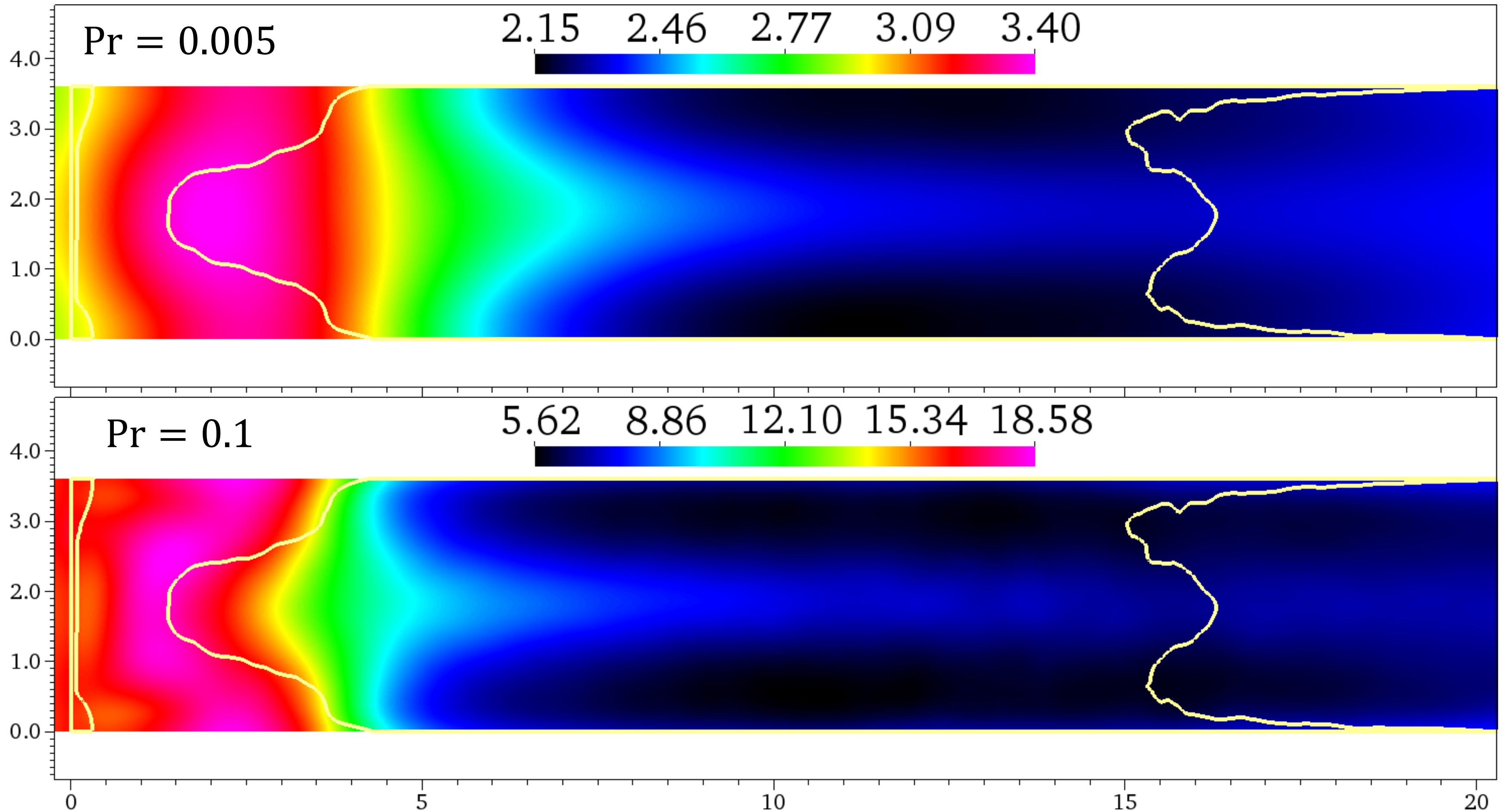


Thermal fluctuations (middle)



Average temperature at heater





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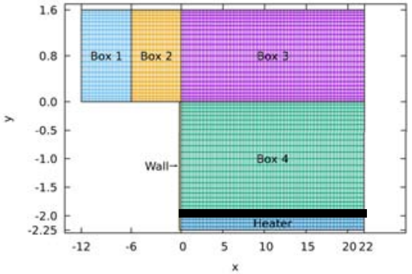
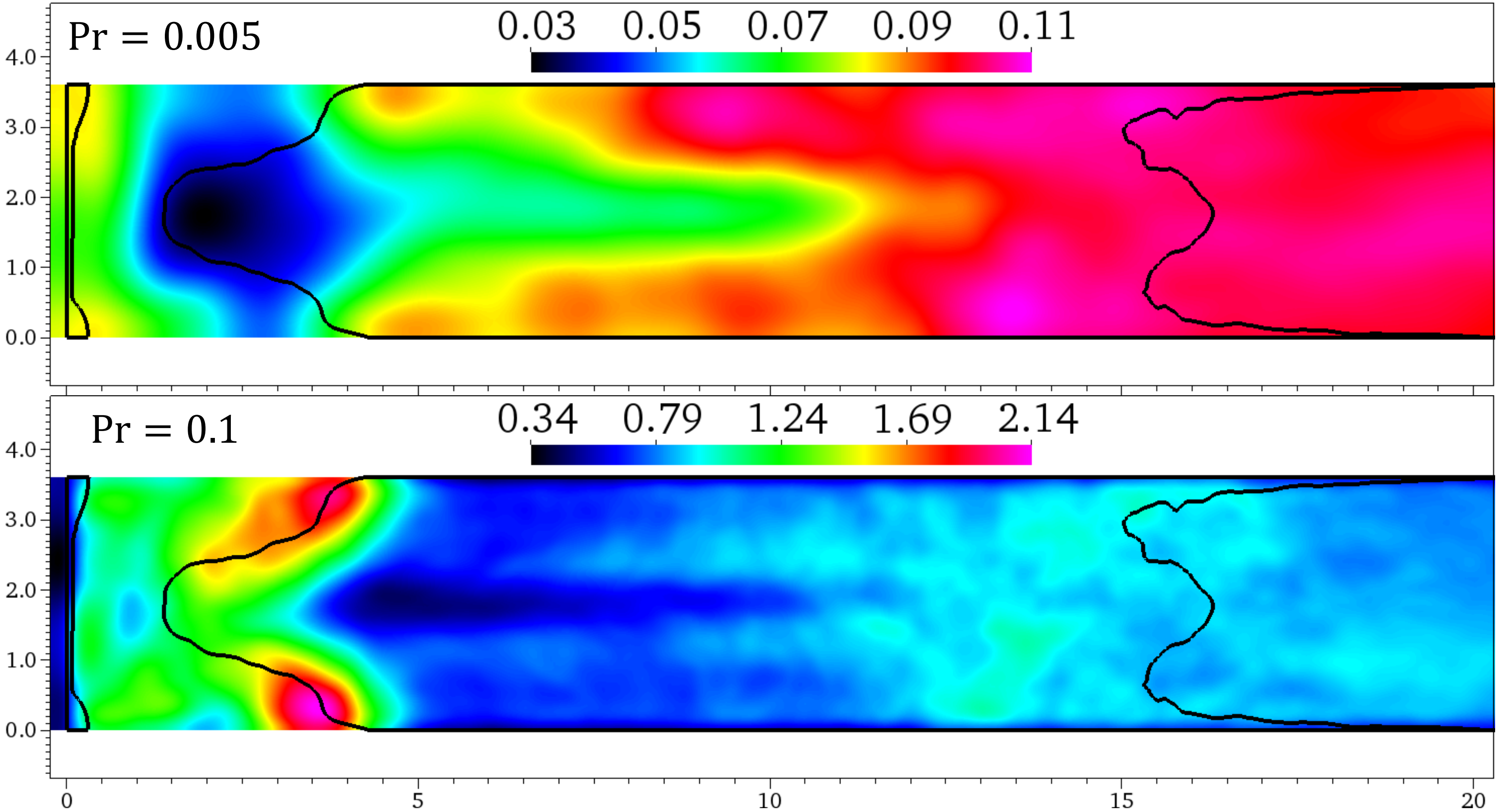
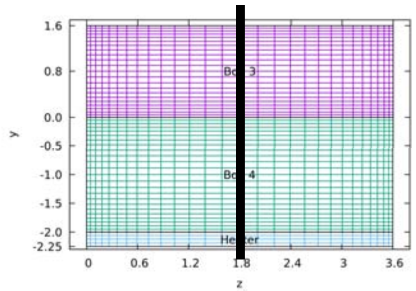


Thermal fluctuations at heater

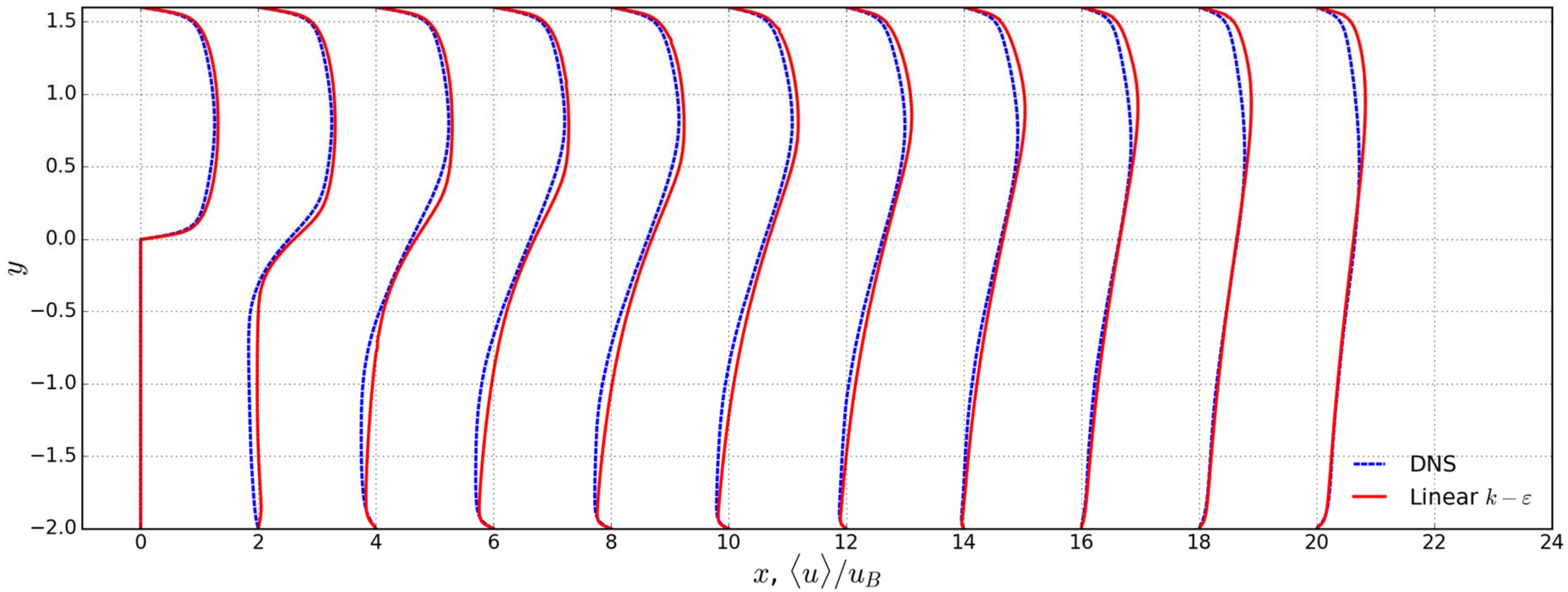


RANS simulation

- Identical domain to DNS (including solid parts)
- 6 meshes ranging from 440k to 24.5M elements (4.4M element mesh selected)
- $y^+ < 1$ in whole domain
- Linear $k - \varepsilon$ model
- AHFM-NRG model



Comparison (streamwise velocity)



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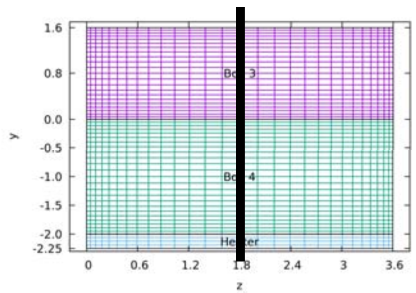
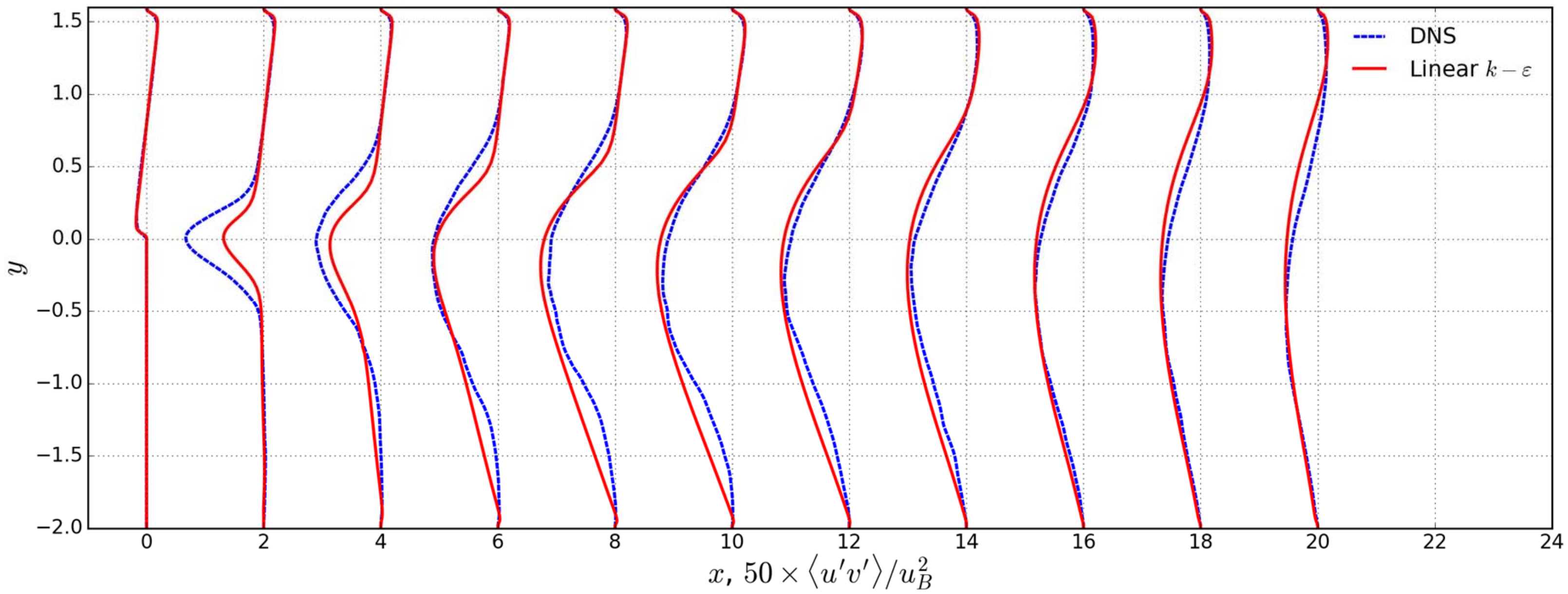
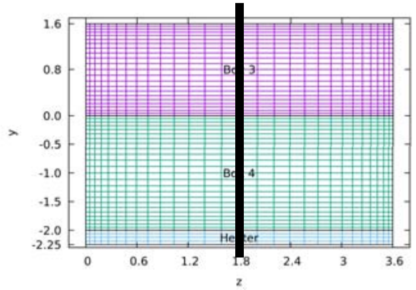


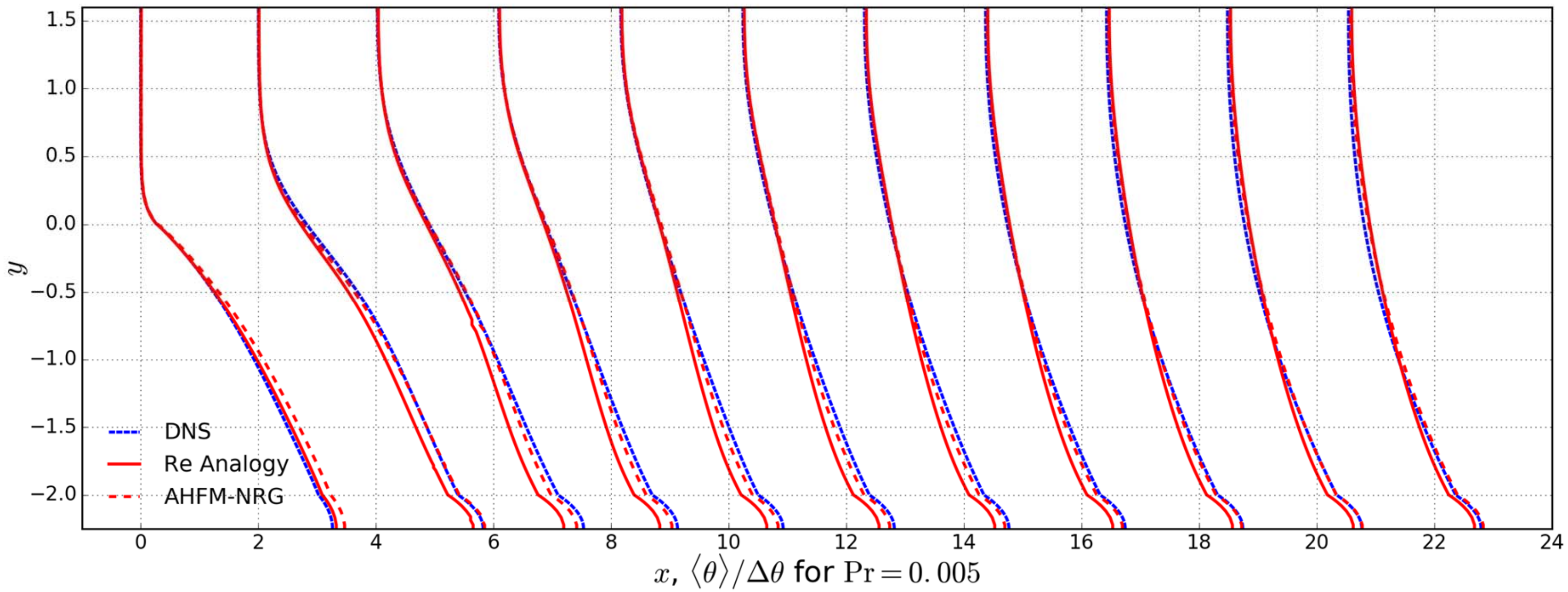
Comparison ($\langle u'v' \rangle$)





Comparison (temperature)

$\mathrm{Pr} = 0.005$



Summary

- Experimental data by end of year
- DNS data available
- More complicated flow structure than in unconfined BFS
- Thermal fluctuations found penetrating into the walls
- Good agreement in first order statistics between DNS and RANS simulation