High-cycle thermal fatigue in mixing Tees. Large-Eddy simulations compared to a new validation experiment

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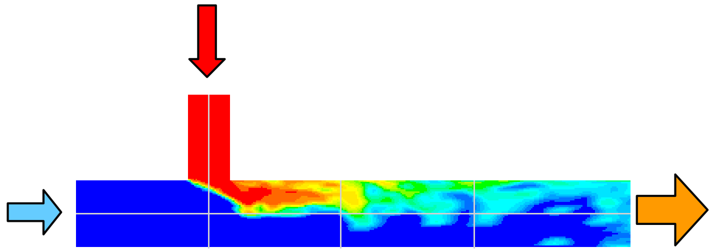
Outline

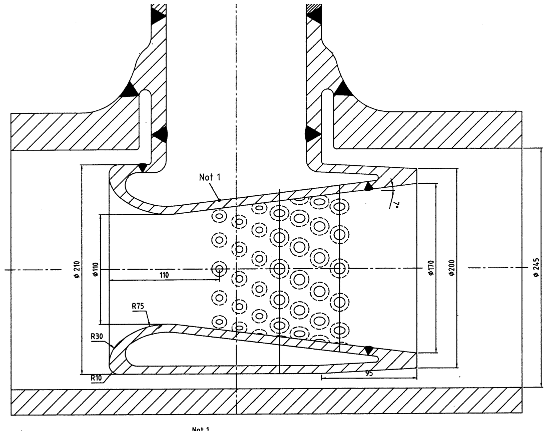
- Background
  - Previous work by the authors
- New experimental validation test case (2006)
- Computational results (Fluent)
  - Mesh dependence study
  - Large Eddy Simulations (LES) compared with Detached Eddy Simulations (DES)
- Concluding remarks

Background (1)
Introduction

- Temperature fluctuations can cause thermal fatigue
- Interesting case for CFD-validation (unsteady flow, large fluctuation levels)
- Static mixers or thermal sleeves can be installed to reduce the risk for thermal fatigue (but expensive)
- Desirable with accurate predictions of the risk for thermal fatigue
- Structural analysis require boundary conditions
  1) Amplitudes of temperature fluctuations
  2) Frequencies of temperature fluctuations
  3) Heat transfer to the wall

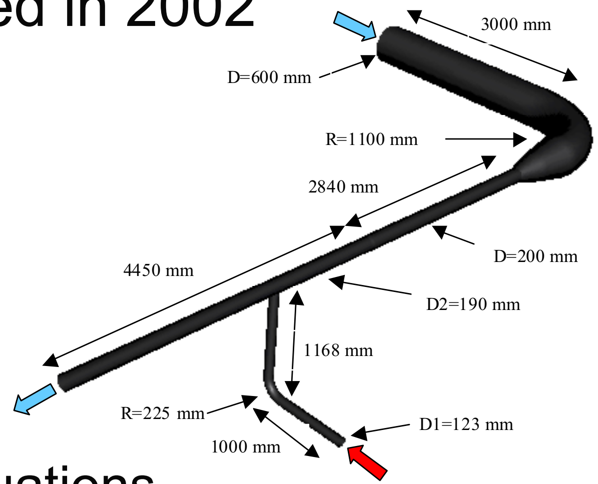


Static mixer (MIX-331)



Background (2)
Previous work by the present authors

- Model test of a plant specific T-junction performed in 2002
  - Geometry including upstream bends
  - Temperature fluctuations near the wall measured with thermocouples
  - Several test cases (flow ratios)

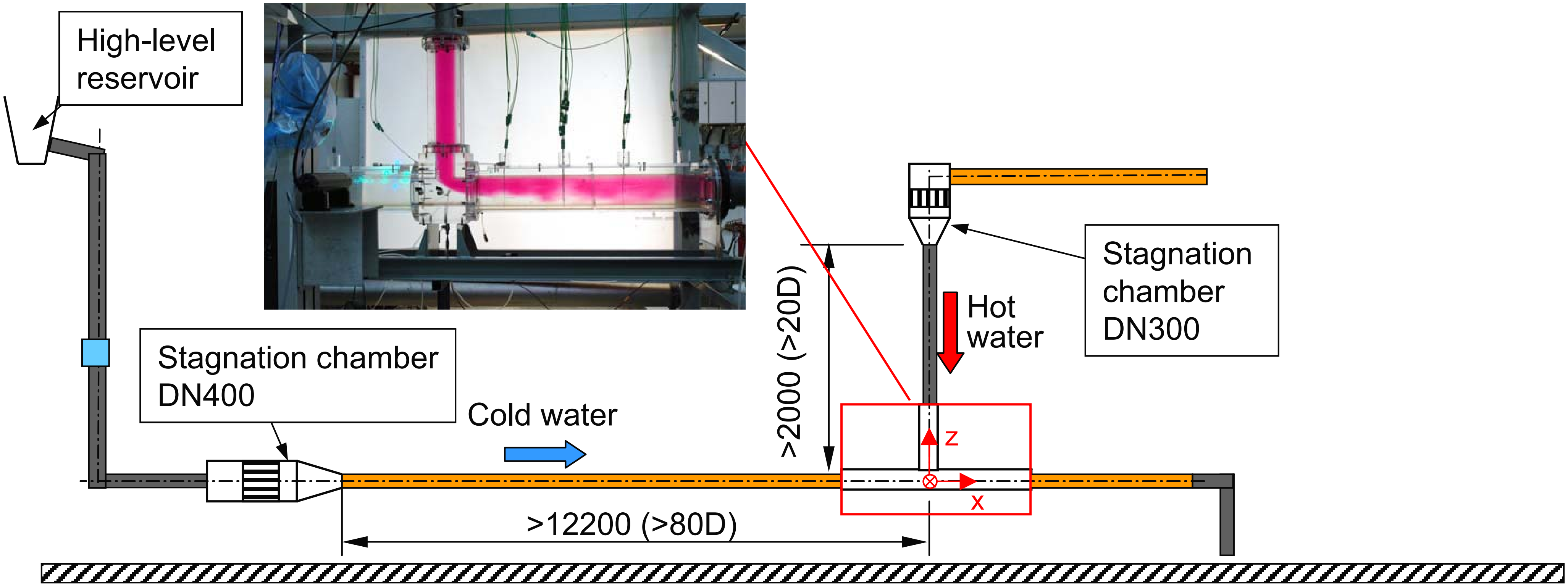


- Computational studies
  - Unsteady RANS failed to predict the temp. fluctuations
  - LES showed promising results
  - Still discrepancies (amplitude and frequencies overpredicted)
  - Complicated and uncertain inflow boundary conditions
- Need for more validation data and well-documented inflow boundary conditions

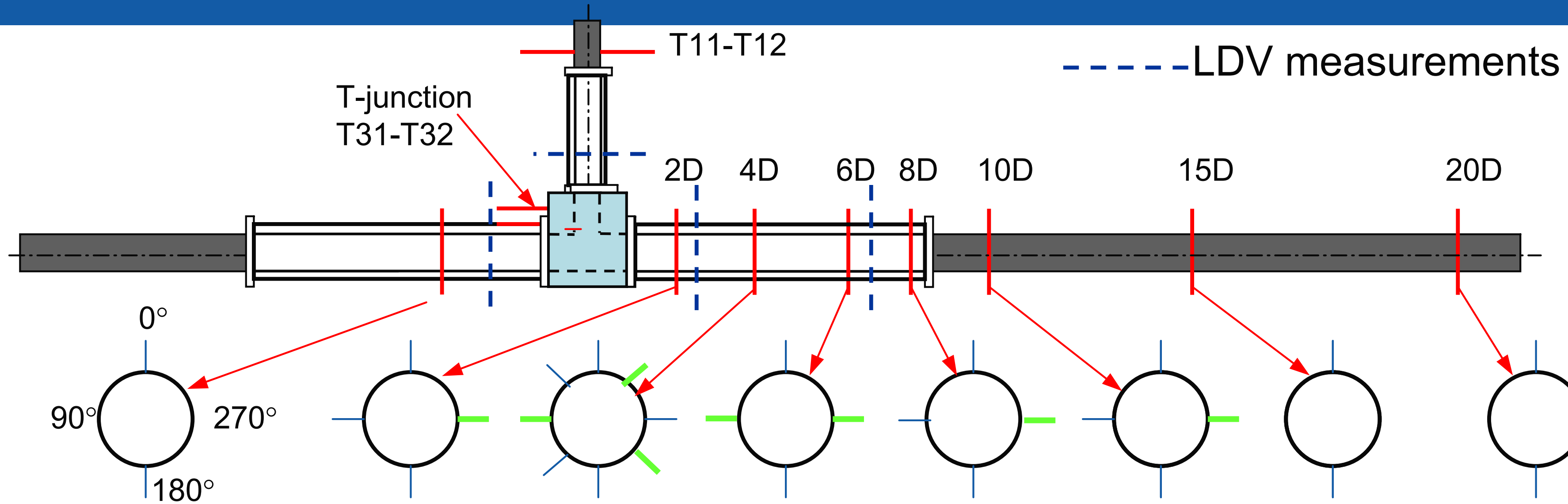
New model tests for validation of CFD (2006)
Test rig overview

- Fully developed pipe flow in the cold water inlet pipe
  (>80 diameters straight section upstream the T-junction)
- Pipe diameters 140 mm (cold) and 100 mm (hot)

- Focus on one test case
  - $\Delta T \approx 15°C$
  - Constant flow ratio $Q_{cold}/Q_{hot}=2$
  - Equal inlet velocities in the cold and hot water pipe

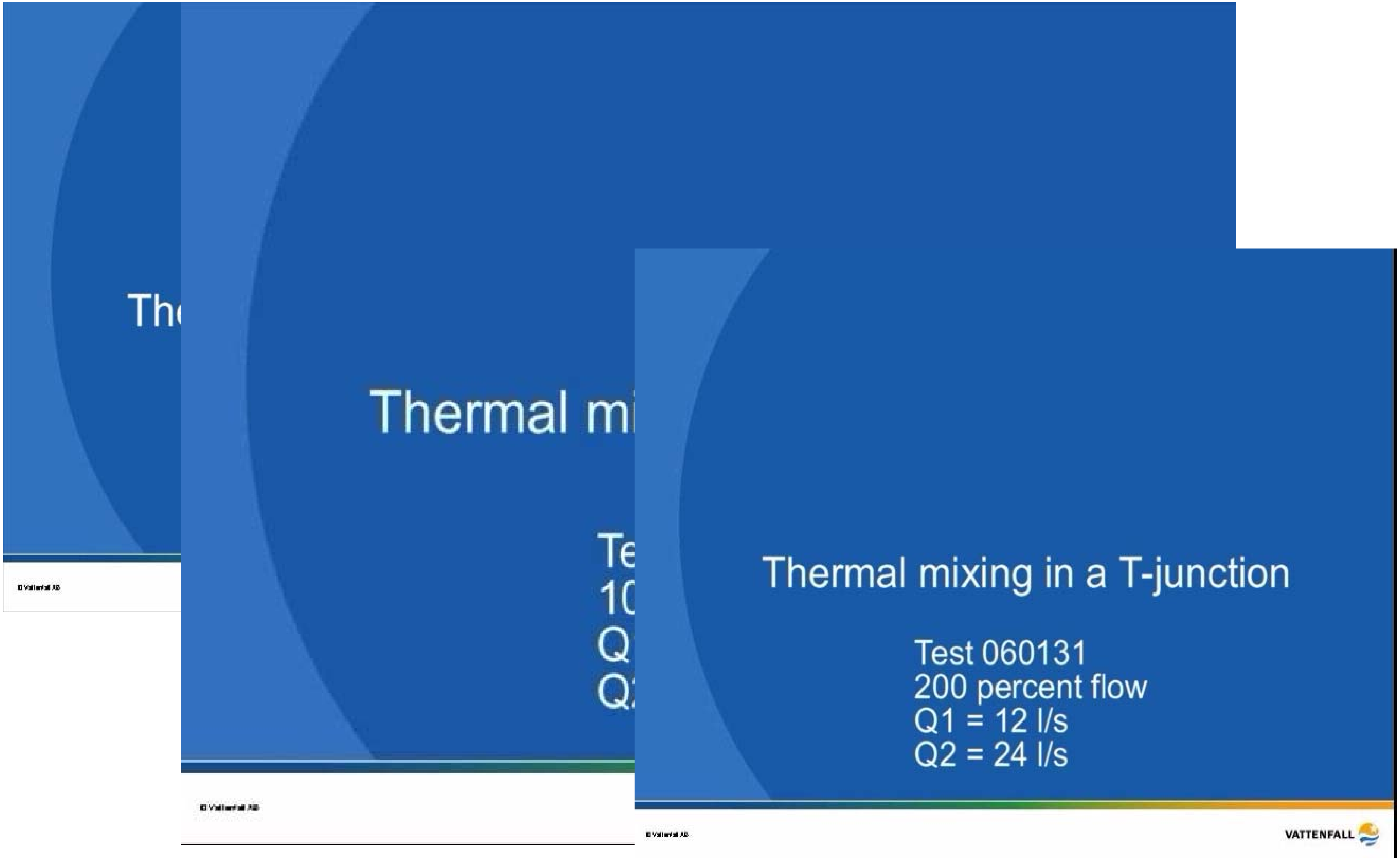


T-junction model and measurements



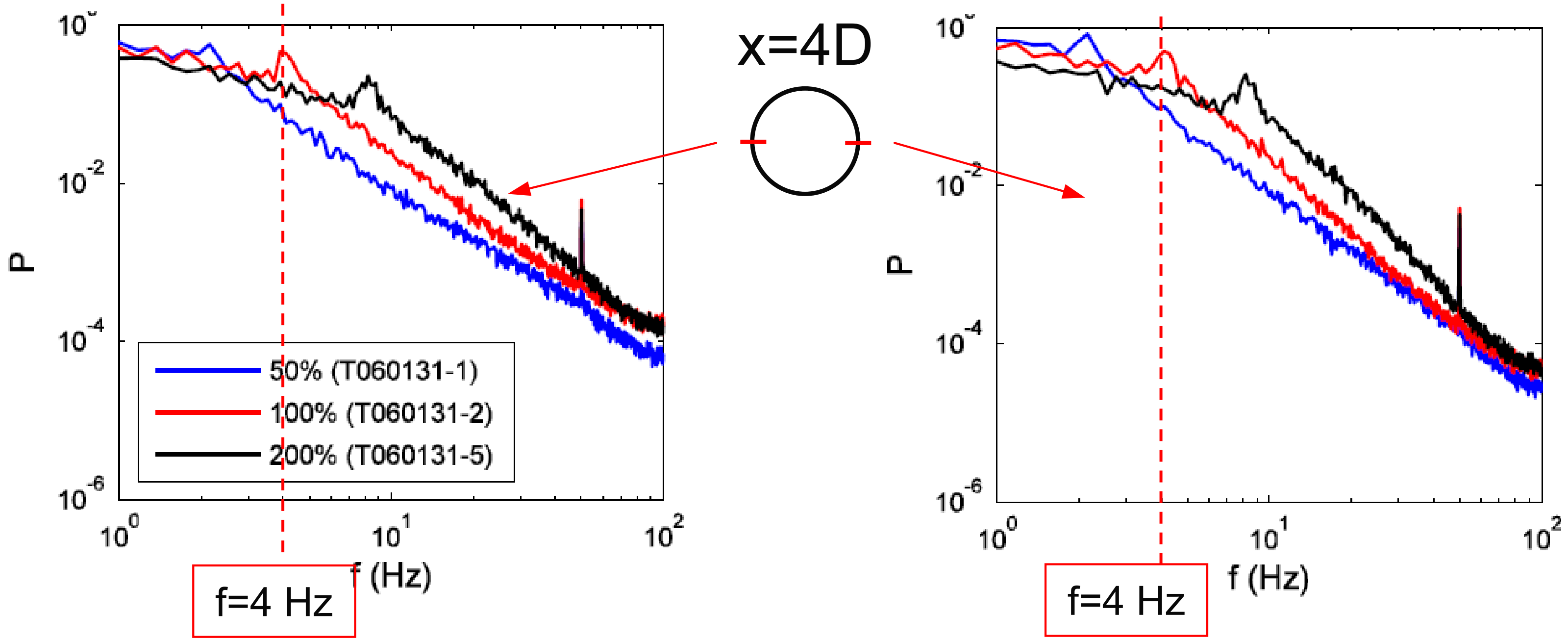
- Thermocouples (∅0.13 and ∅0.07 mm)
  - Located 1 mm from the wall
  - Frequency response 30-45 Hz
- Lased Doppler Velocimetry (LDV)
  - Inlet-BCs at x/D=-3 and z/D=-3.1
  - Profiles at x/D=2.6 and 6.6
  - Measurements at ΔT≈15°C and isothermal
- Single-point Lased Induced Fluorescence (LIF)
  - Conc. measurements at isothermal conditions

Flow visualization: 50%, 100% and 200% flow
(Reynolds number: 0.5×10^5, 1.0×10^5 and 2.0×10^5)

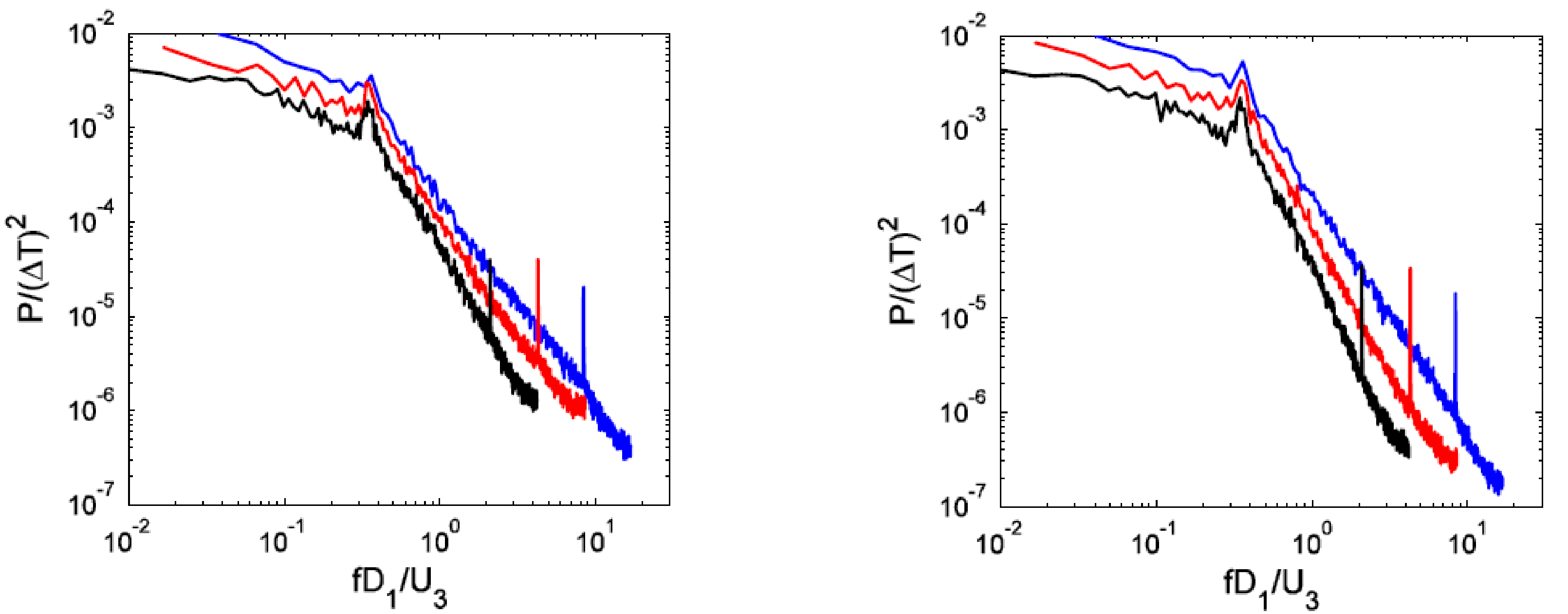


Spectra of temperature fluctuations at x=4D
Various flow rates

P vs f (Hz)
No normalization



$$\frac{P}{(\Delta T)^2} \quad vs \quad \frac{fD_1}{U_3}$$



Performed simulations and numerical settings

Influence of computational mesh

Case	#cells	t_{samp} (s)	Note	Organization
T1vm-FKA	0.52M	29.0	4 boundary layer cells	Forsmark
T1Bvm	0.45M	21.8	no BLcells	Onsala Vattenfall R&D
T2vm	0.93M	19.6	More uniform	Onsala Vattenfall R&D
T3vm	9.5M	8.3	Similar, but refined	Onsala

Influence of unsteady inflow-BC

1) Vortex method
2) No perturbation
3) Scaled isotropic turbulence from separate input files

Comparison LES-DES

LES: WALE (Wall-Adaptive Local Eddy viscosity model)

DES: SST k-ω model

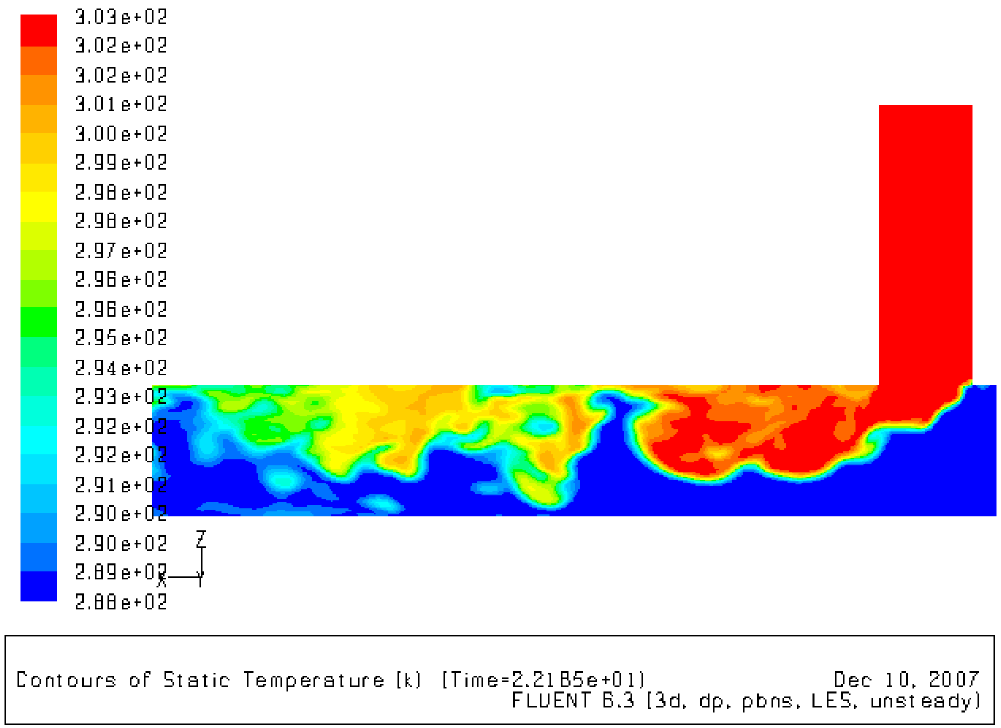
Numerical settings

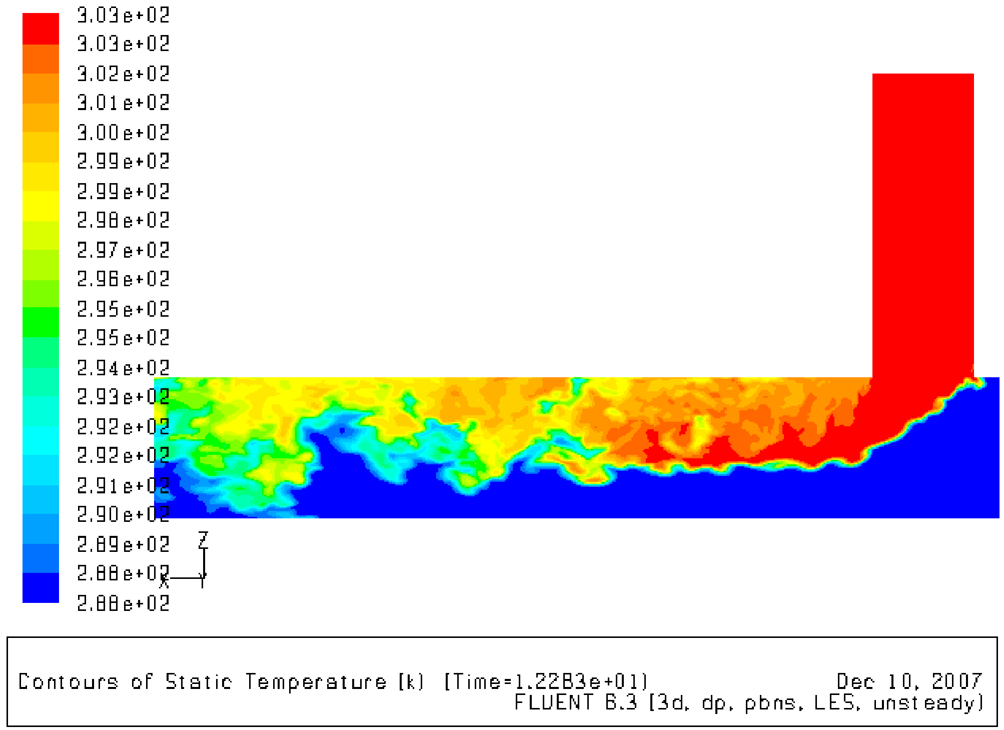
- Non-iterative time advancement (NITA): 2nd order, implicit
- Pressure-velocity coupling: Fractional step
- Momentum eq: Bounded central differences
- Pressure: PRESTO
- “Law-of-the-wall” applied near the wall (y+ typically 20-50)

Instantaneous temperature fields

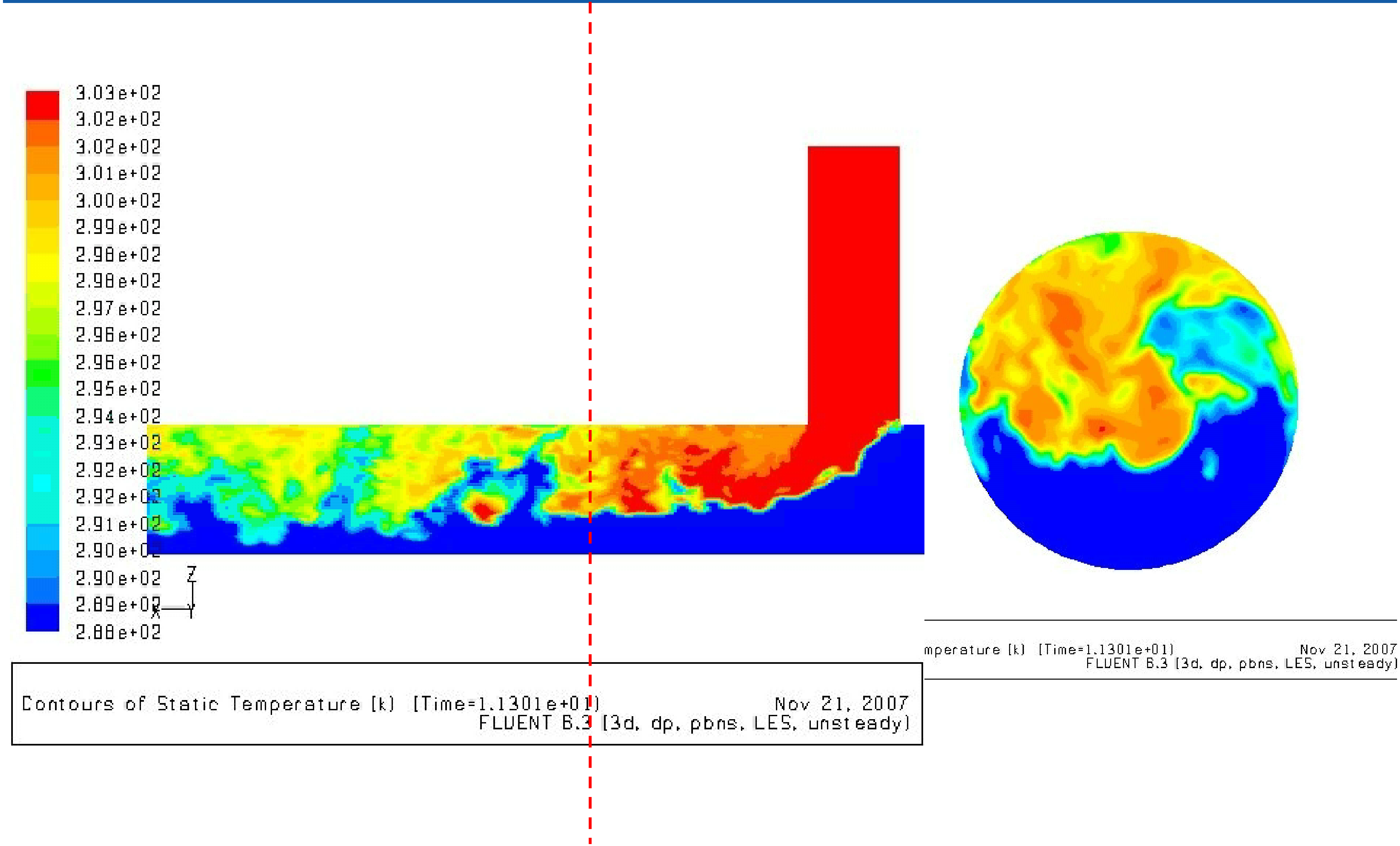
Case T2vm (0.93 Mcell)

Case T3vm (9.5 Mcell)

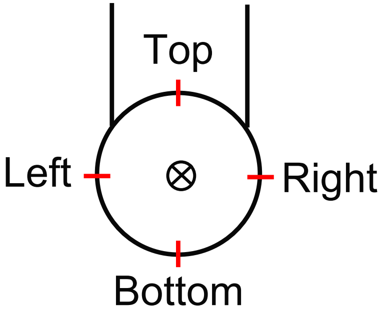




Simulation, 9.5 Mcell

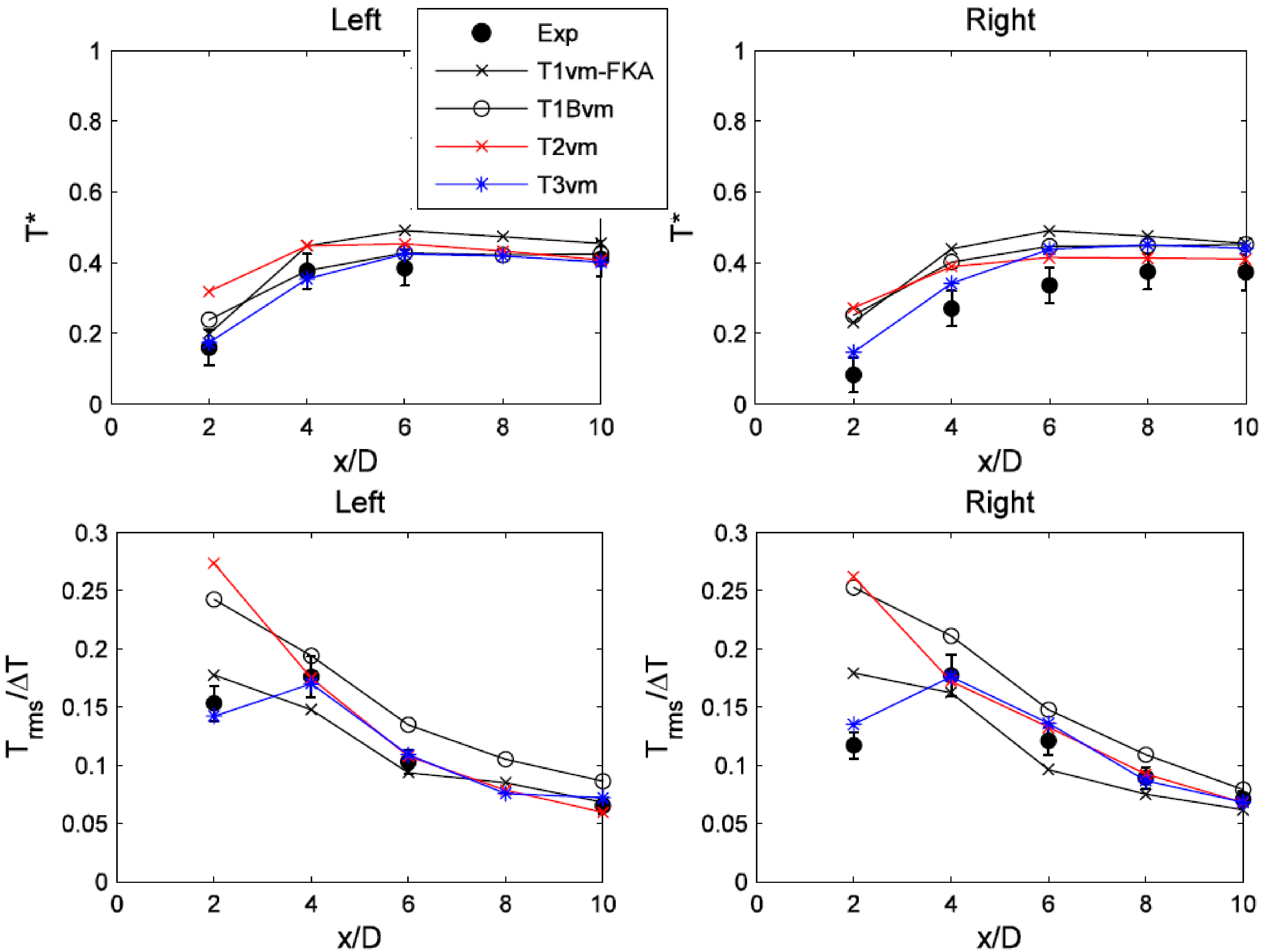


Temperatures near the pipe wall
Different computational mesh



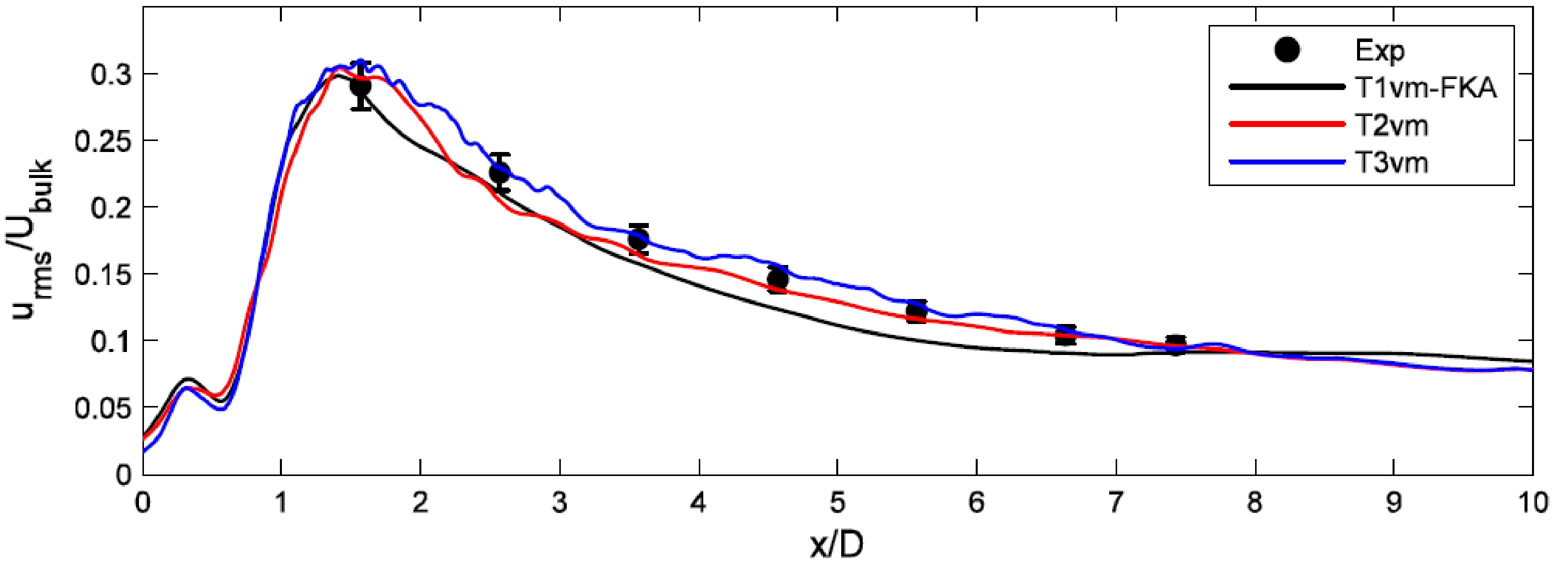
$$T^* = \frac{T - T_{cold}}{T_{hot} - T_{cold}}$$

$$\frac{T_{rms}}{\Delta T} = \frac{T_{rms}}{T_{hot} - T_{cold}}$$

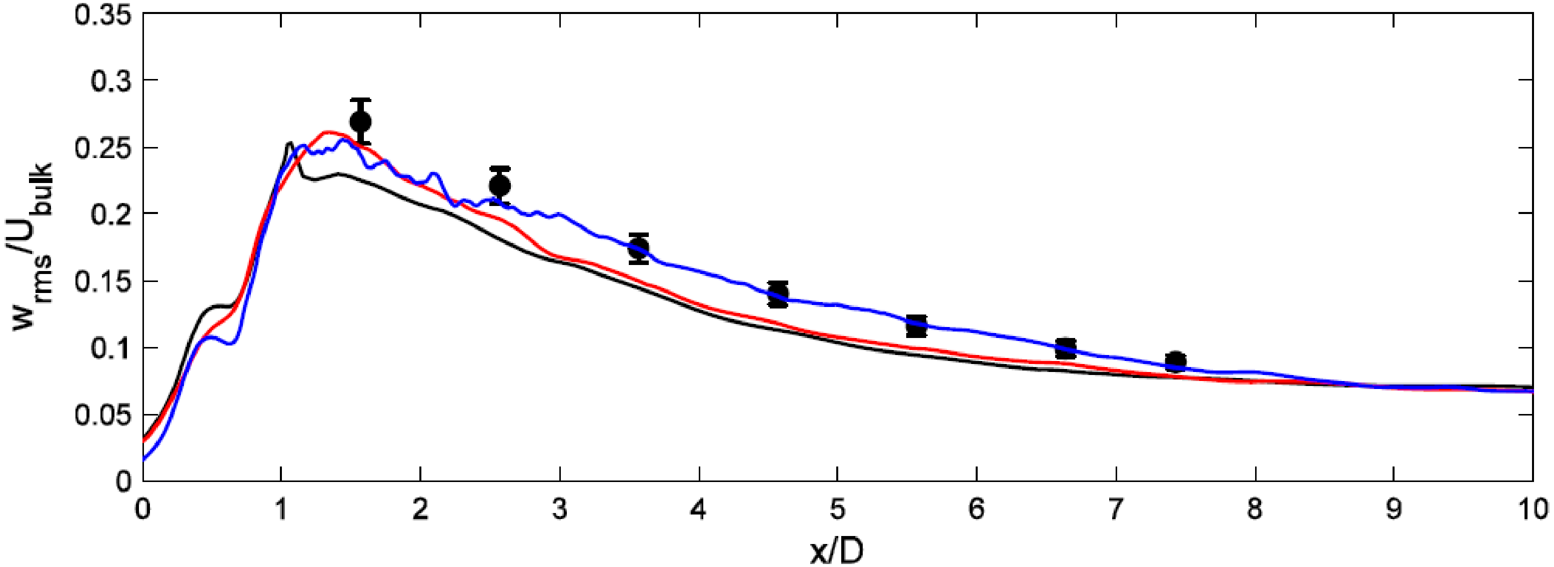


Velocity fluctuations at the pipe centerline
Different computational mesh

$$\frac{u_{rms}}{U_{bulk}}$$

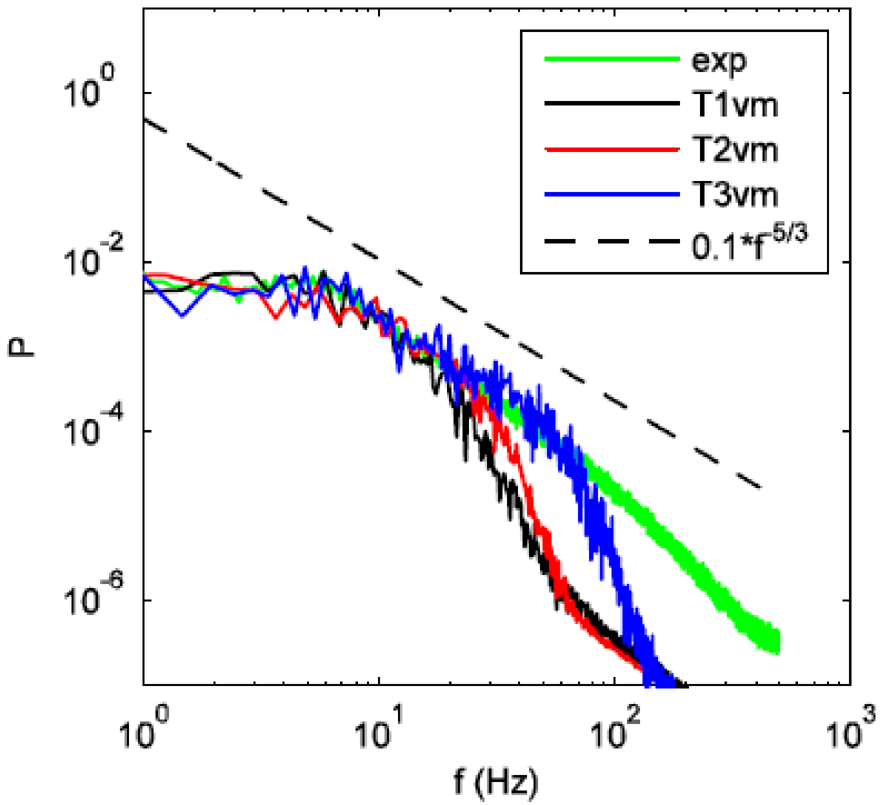


$$\frac{w_{rms}}{U_{bulk}}$$

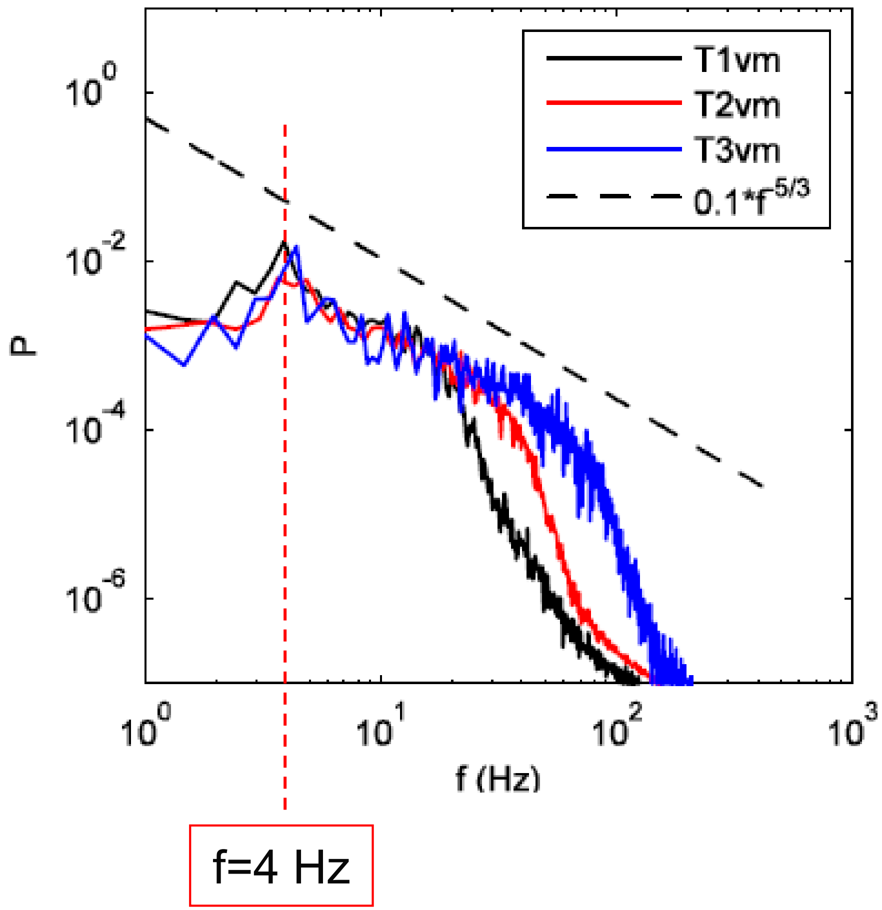


Velcoity spectra, pipe centreline at x=2.6D
Different computational mesh

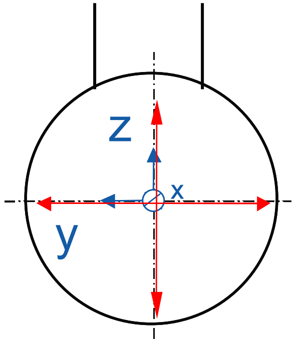
u-component (=streamwise)

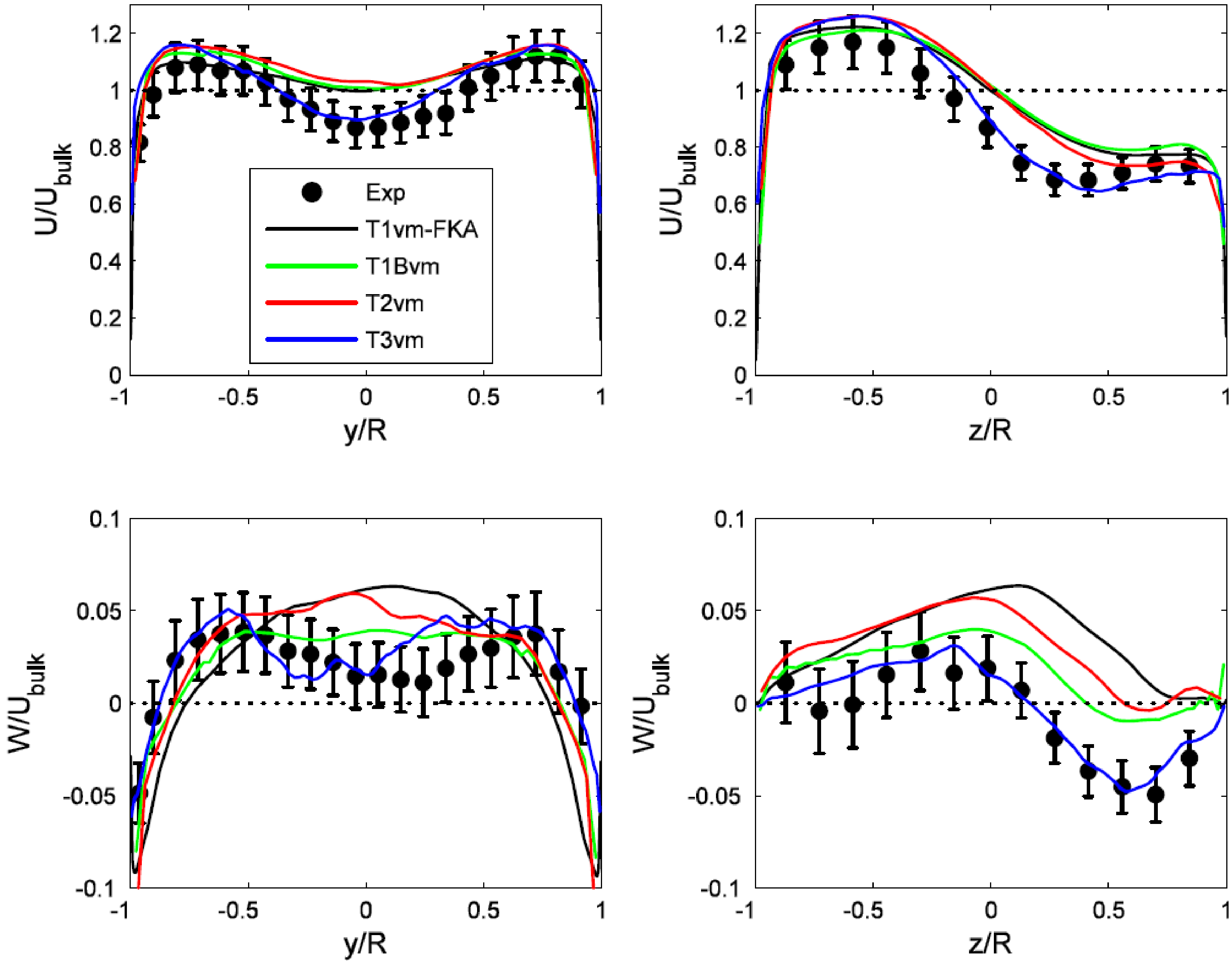


v-component (=spanwise)
(not measured)

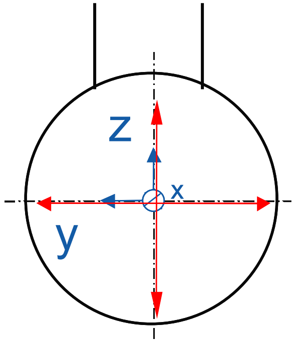


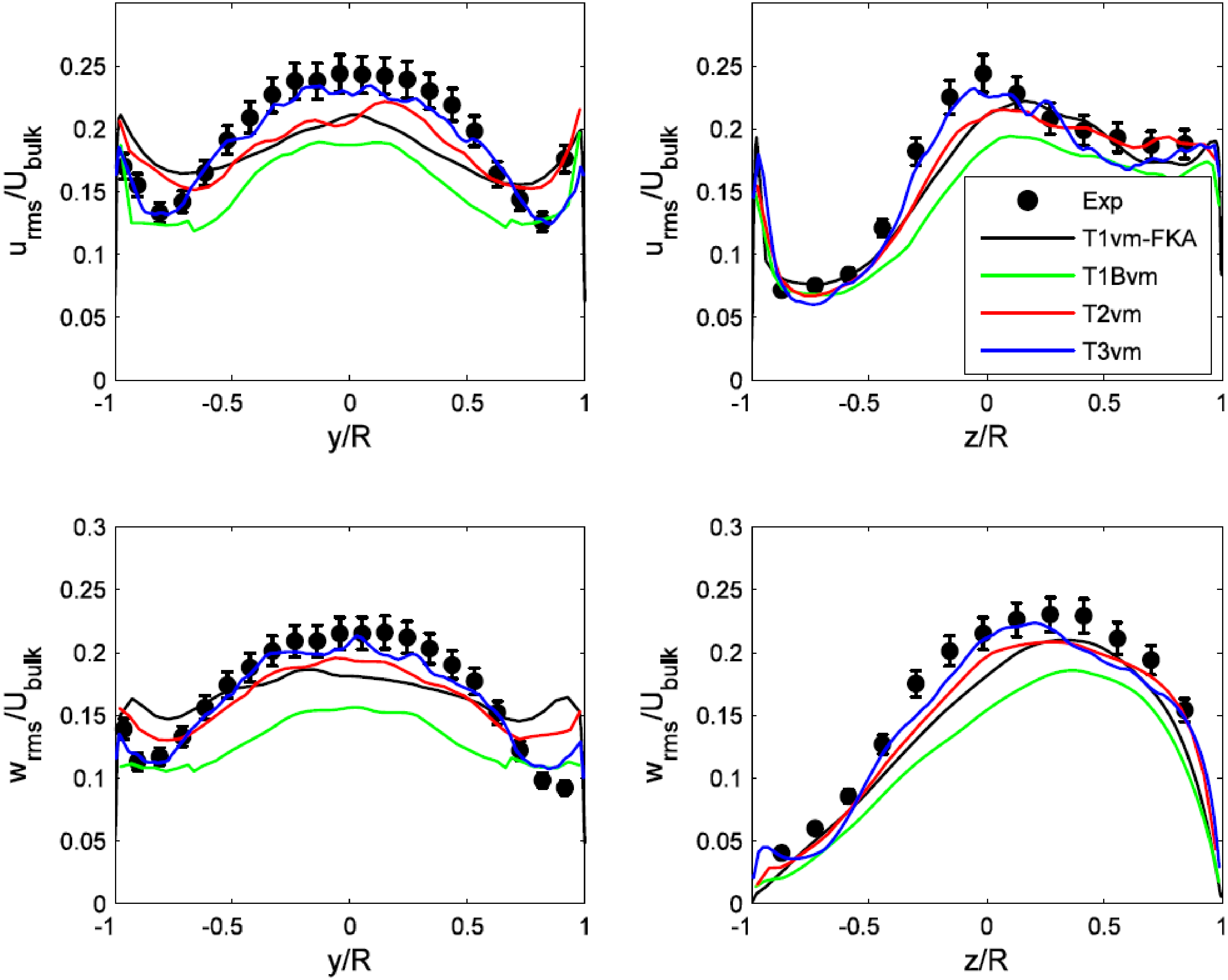
Mean velocity profiles, x/D=2.6
Different computational mesh



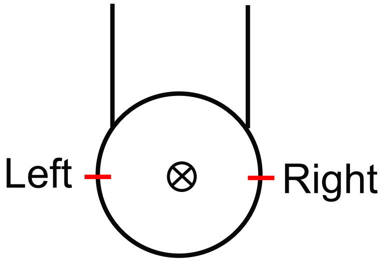


Velocity fluctuations, x/D=2.6
Different computational mesh





Mean and fluctuating temperatures
Comparison LES vs DES (mesh 0.93 Mcell)



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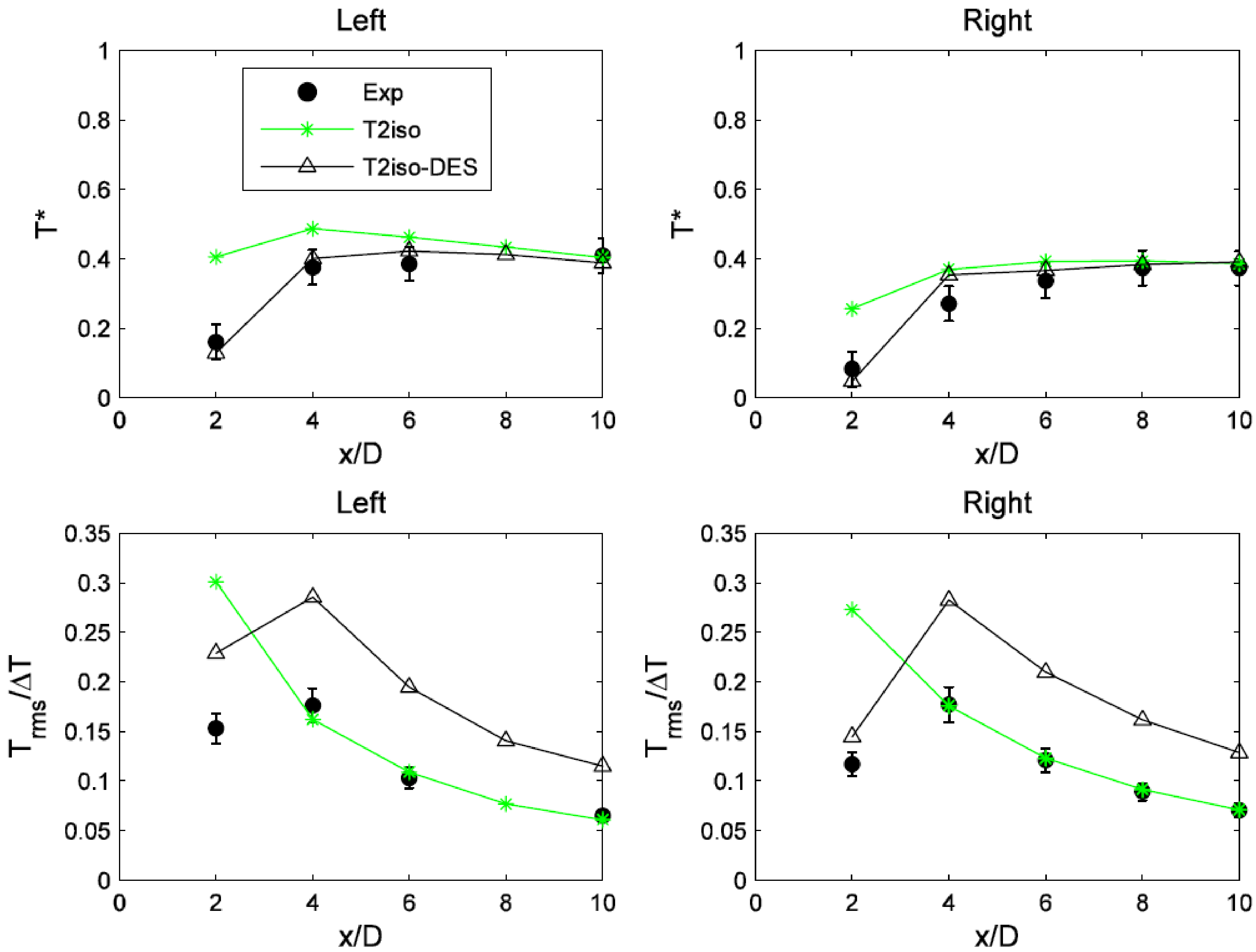
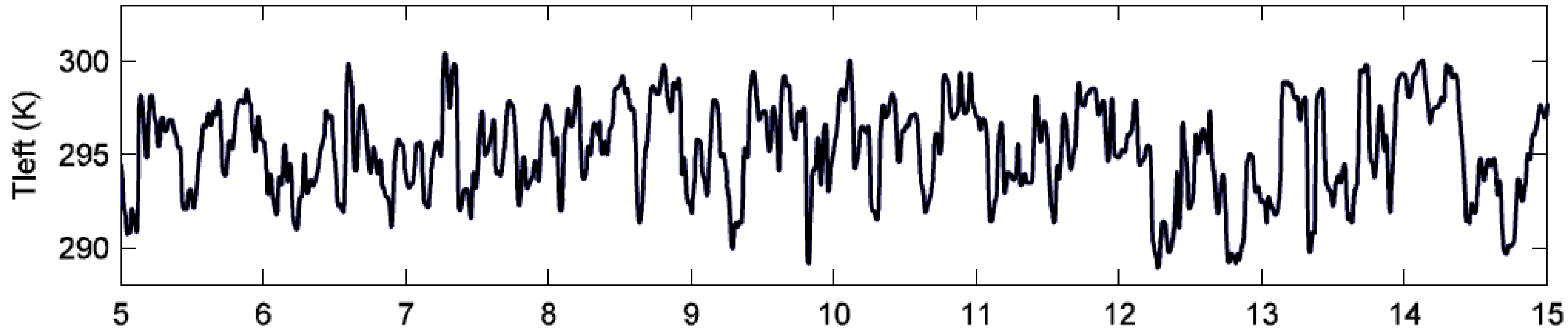
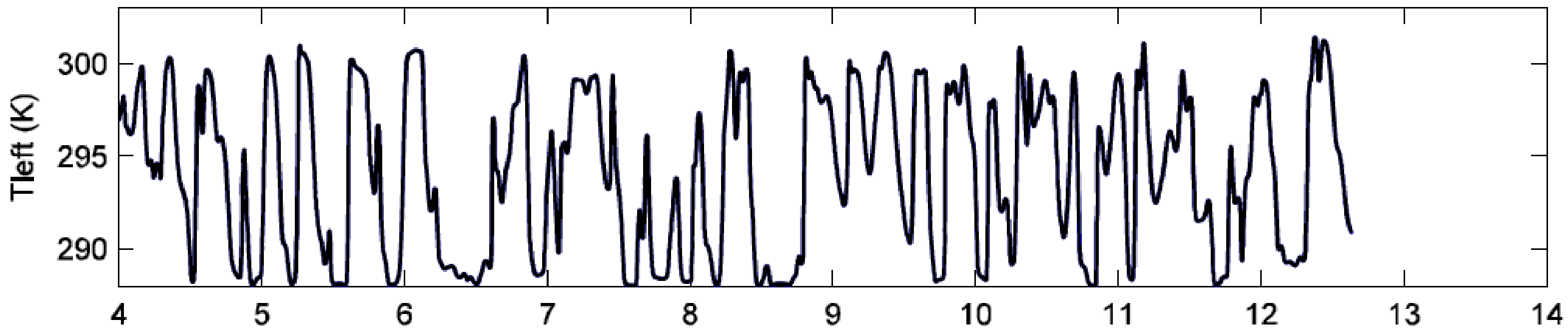


Time signals
Comparison LES vs DES (x/D=4)

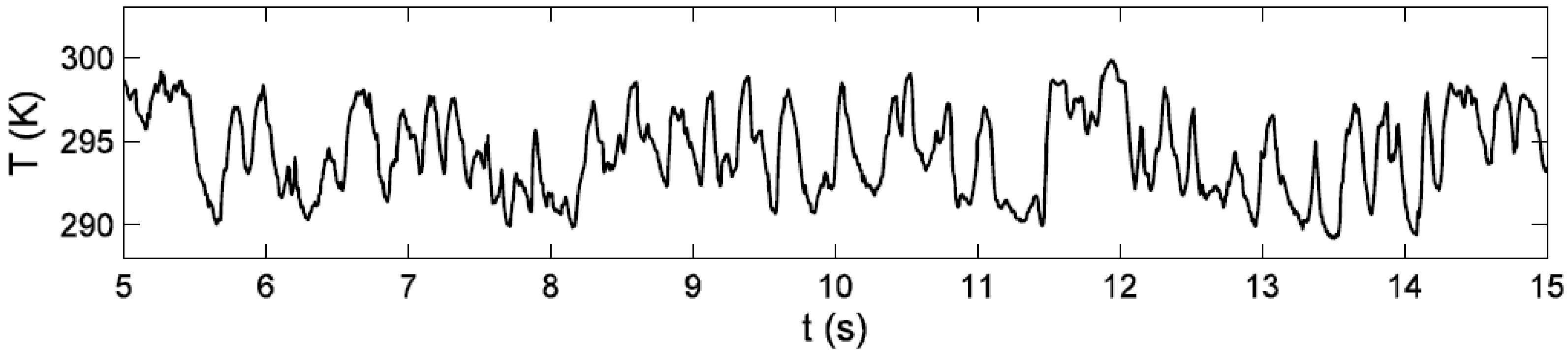
LES



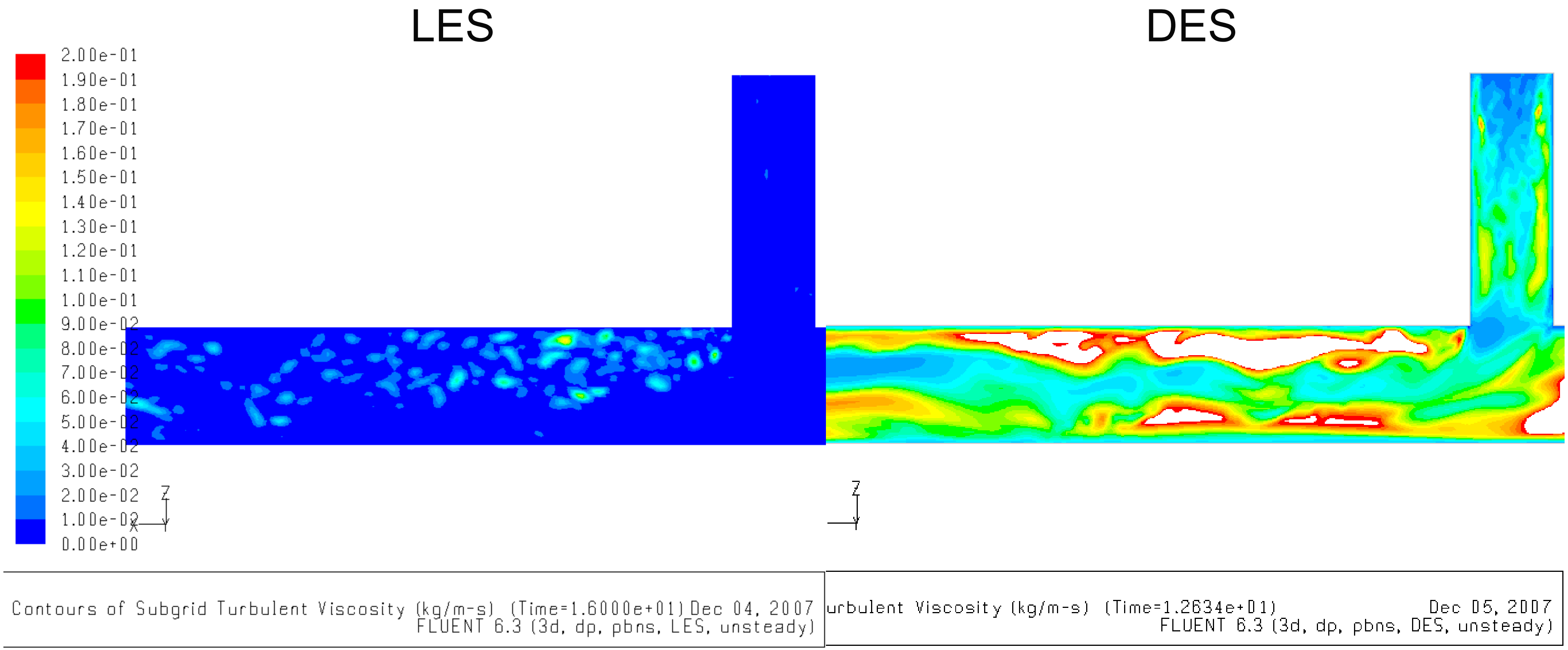
DES



Experiment



Modelled turbulent viscosity
Comparison LES vs DES



Color scale: 0-0.2 kg/(m·s)

Concluding remarks

- Good agreement between simulation and model test results, also with fairly coarse computational mesh
  - Both fluctuation amplitude and spectral distribution show good agreement
  - Considerably better than in previous experiment/simulations
  - (Indicate that the current flow case is quite ”forgiving” for LES)
- Insensitive to variations in the (unsteady) inlet boundary conditions
- However: Clear improvement of the results with a refined mesh
  - Improved results in the entire computational domain with 9.5 Mcell
- Still insufficient resolution near the walls
  - Erroneous prediction of the near-wall mean velocity profile and the wall-shear stress as compared to fully developed turbulent pipe flow
  - Detached Eddy Simulations (DES) results in better near-wall profiles, but the tested model is too dissipative in order to give good predicition of the temperature fluctuations

Interested in the Vattenfall T-junction test case?

- The experimental data can be made available for those who are interested to perform simulations
- In return we expect to get access to the computational results
- No restrictions to publish your results (reference to the source of the data)
- Presently computations are carried out by NRG, The Netherlands (Ed Komen et al.) and ANSYS, Germany (Frank et al.)

If you are interested to use this test case for CFD-validation, contact
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