CFD modelling of buoyancy-driven natural ventilation

CIBSE Natural Ventilation and Building Simulation groups
30th April 2014

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Contributions from Dr Faisal Durrani

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- Why model?
- Background: early work
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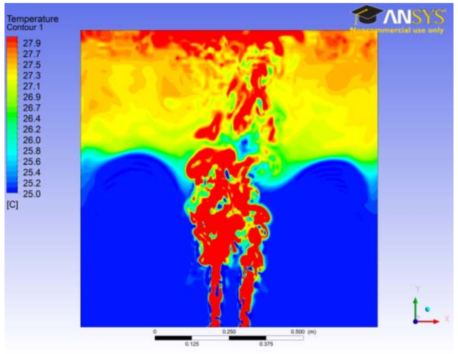
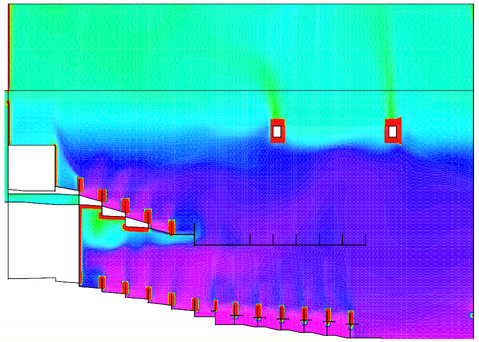
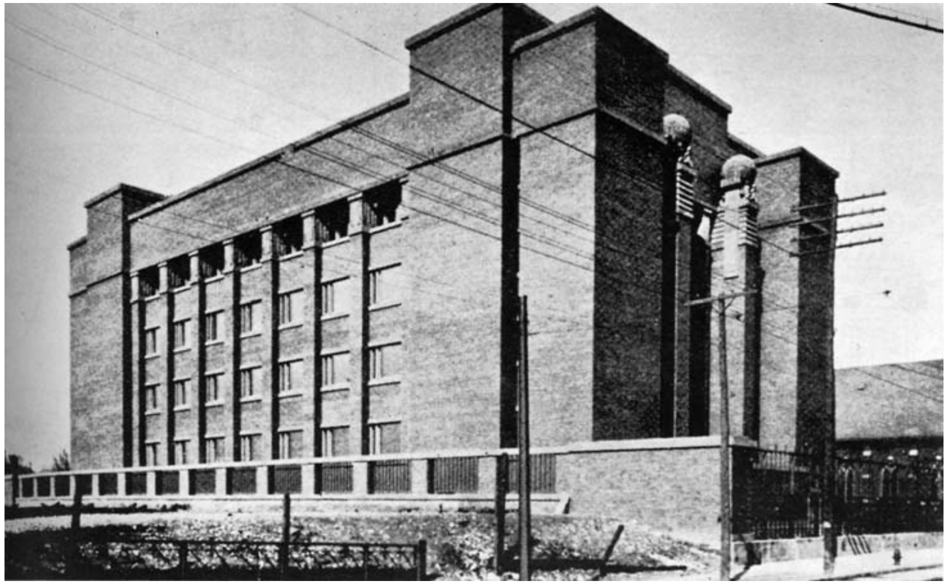
  - LES and RANS
- Solution multiplicity (Benchmark 2)
  - LES and URANS
- Findings and Guidelines
- Full scale application





Why model natural ventilation ?



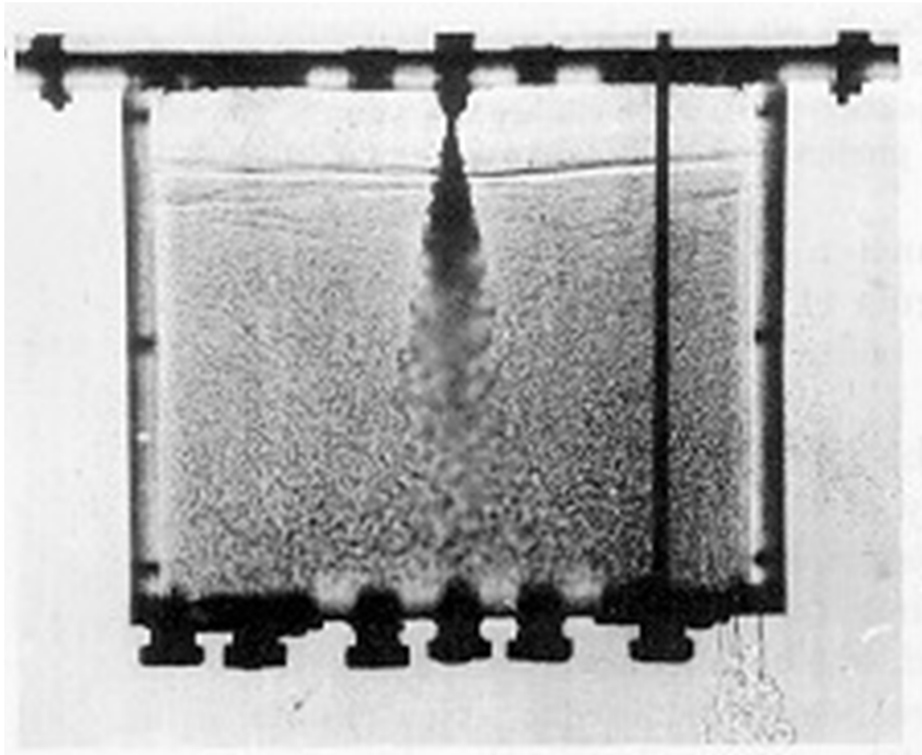
Larkin Administration Building in Buffalo, NY, USA

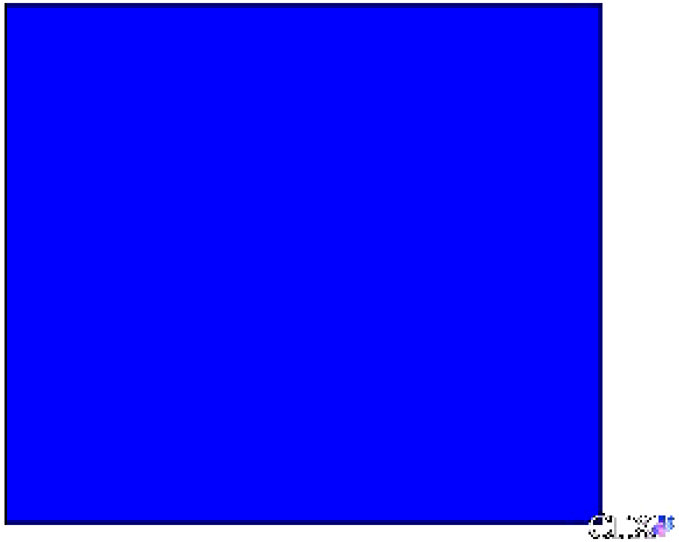
"The Larkin administration building was a simple cliff of brick hermetically sealed … to keep the interior space clear of the poisonous gases in the smoke from the New York Central trains that puffed along beside it"
F. L. Wright (1943)

The Queens Building, De Montfort University, UK

→ ***AIRFLOW MODELLING***

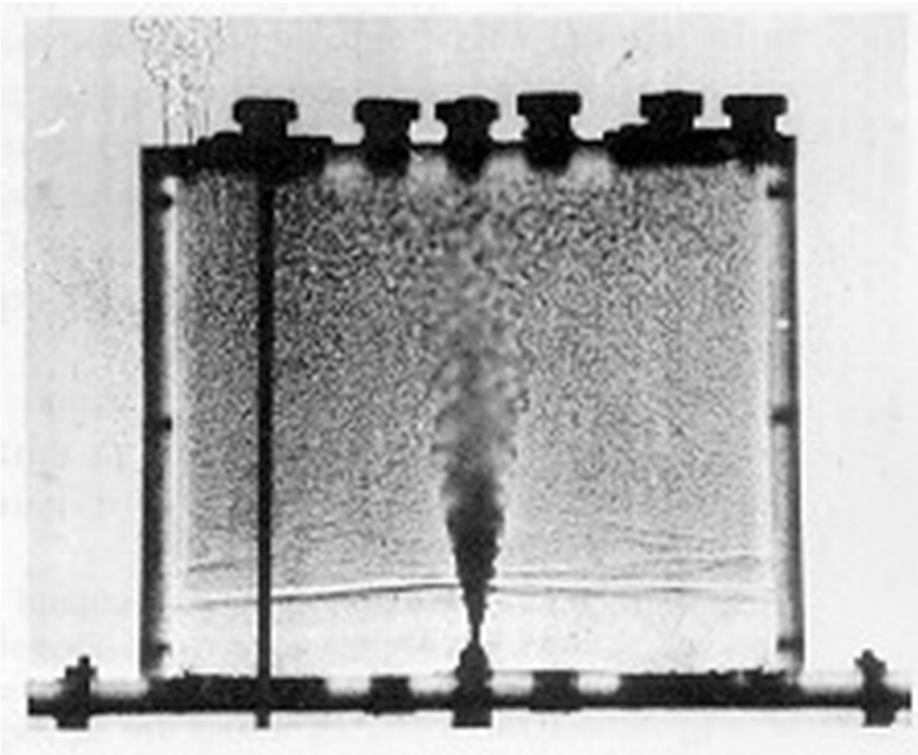
Background: early work

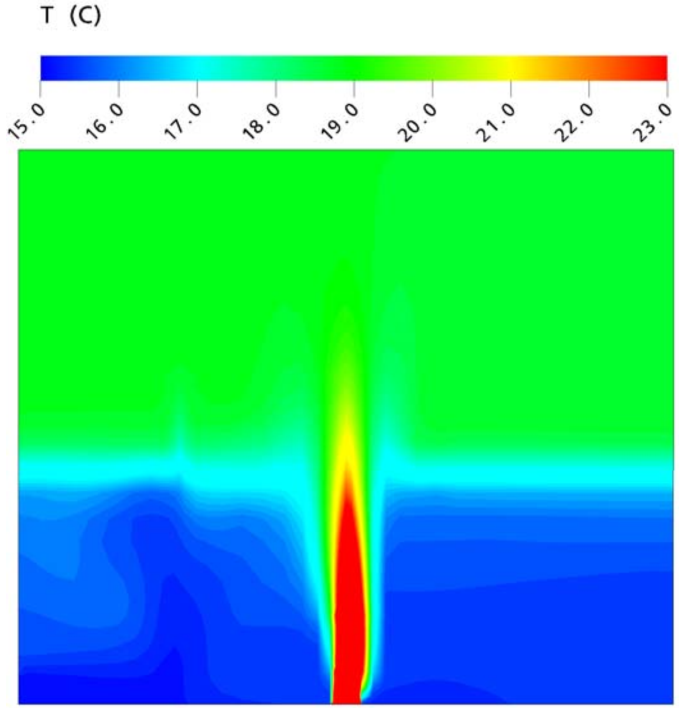




Emptying Filling Boxes: *Cambridge Work (Linden et al.)*

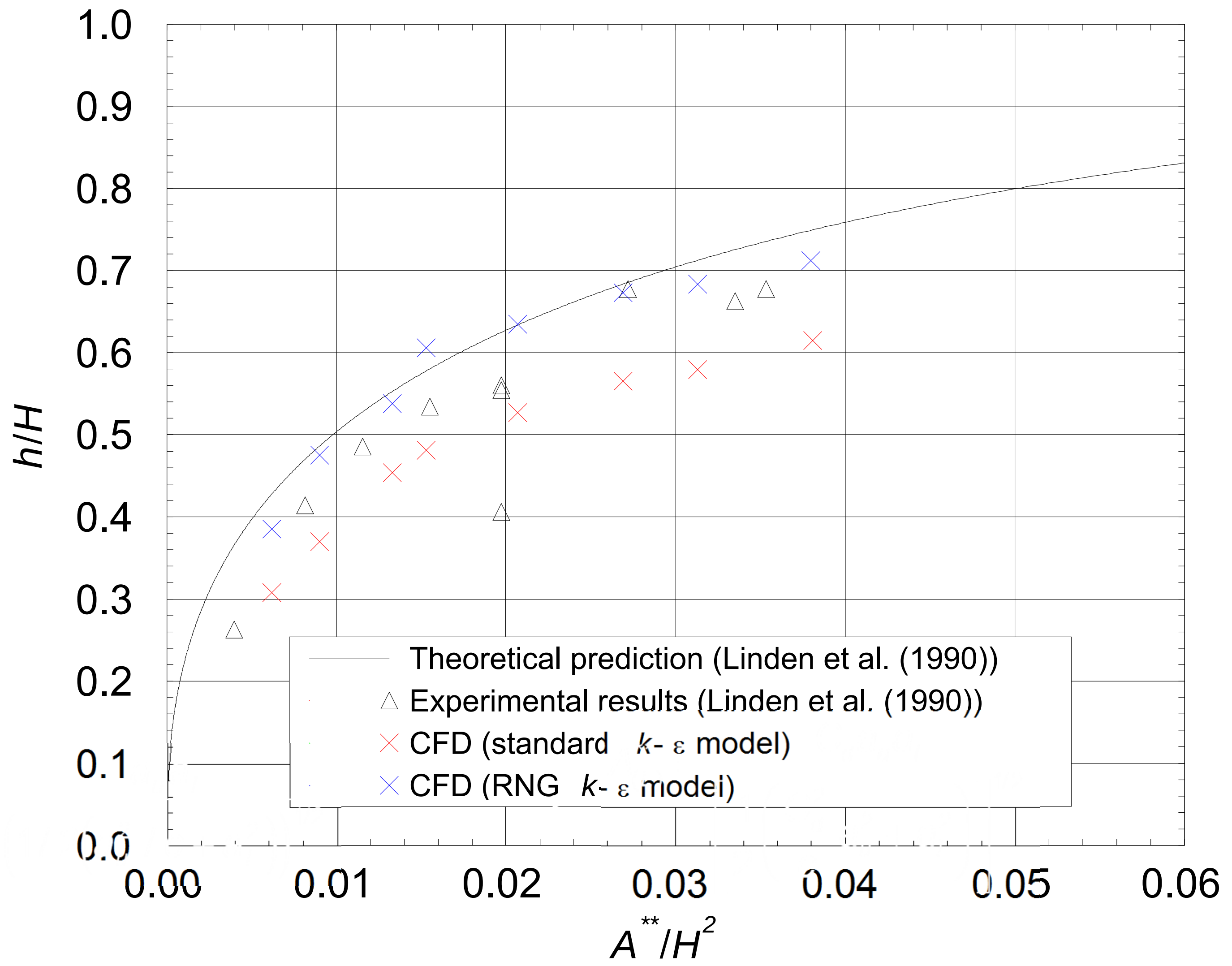
Background: early work



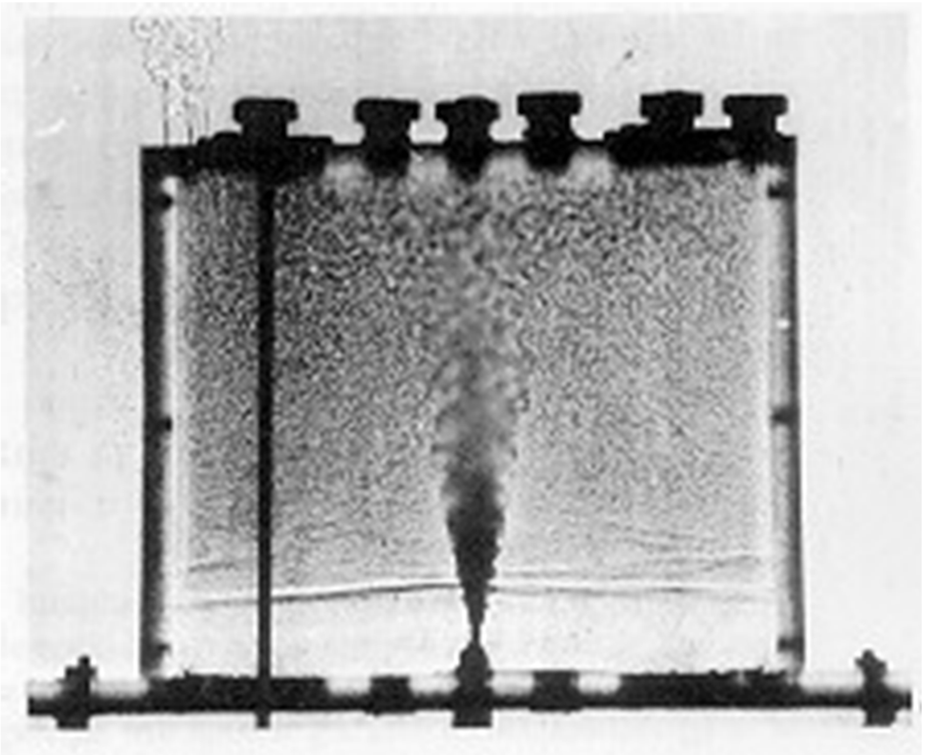


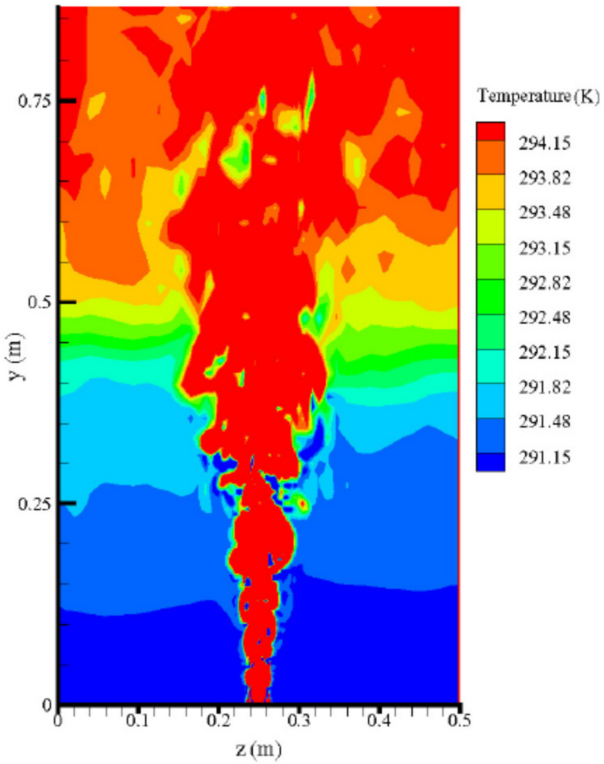
Emptying Filling Boxes: *Cambridge Work (Linden et al.)*

Background: Emptying Filling Boxes: *Interface Properties*



Background: The potential of LES

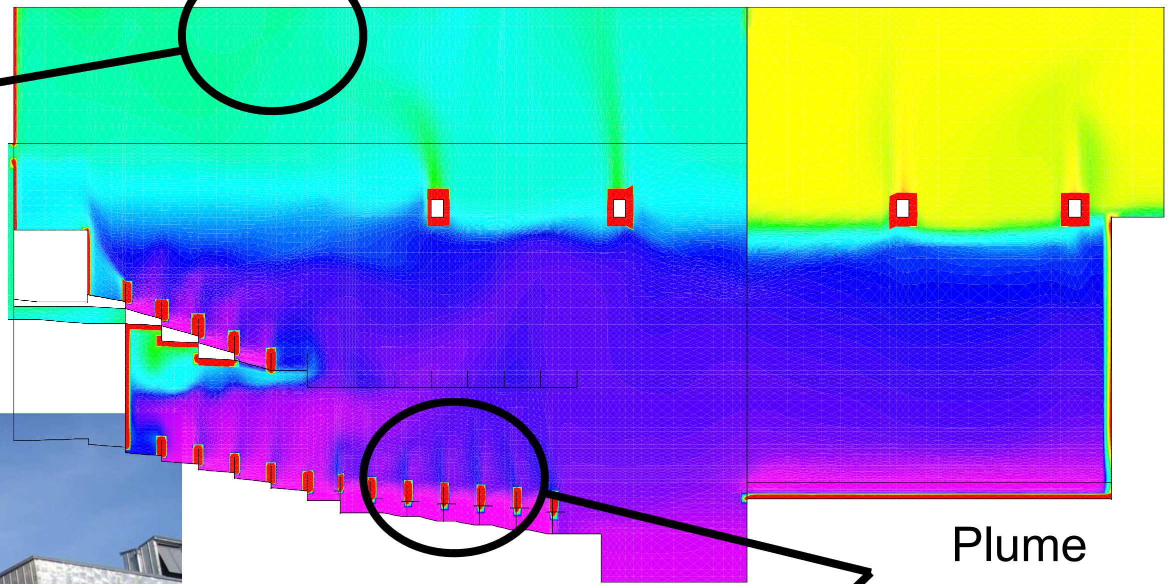




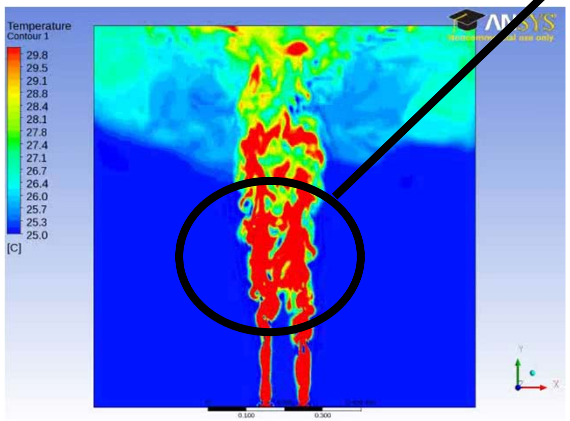
Engineering Applications of CFD:
Abdalla, Cook and Hunt

Background ~ Transients and solution multiplicity

Large openings

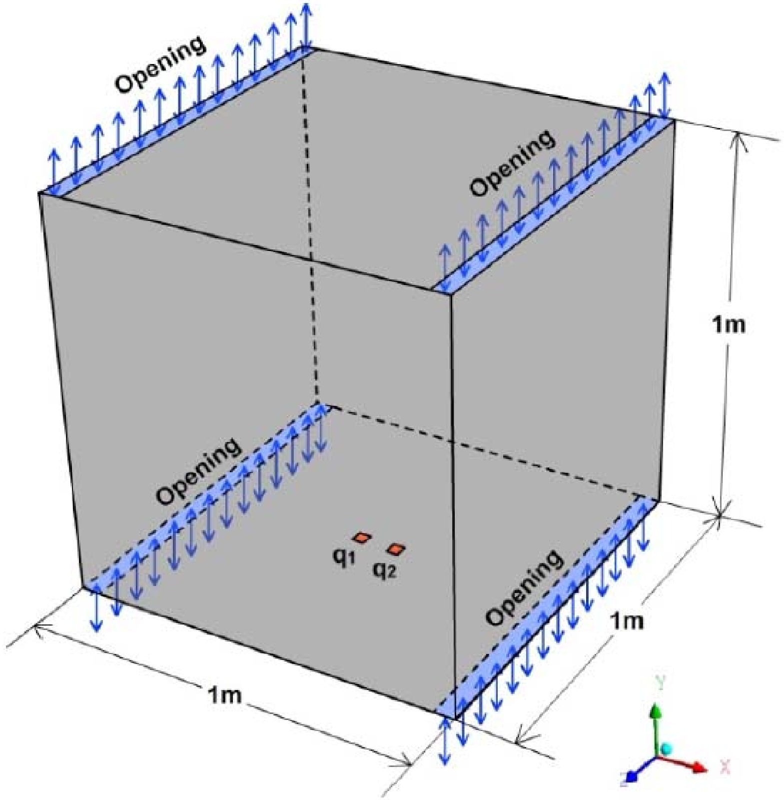


Plume interactions



Benchmark 1 (Plume Interactions)

- Experimental validation:
  - Kaye and Linden (2004)



Numerical Parameters and Opening Boundary Conditions (RANS)

- Ansys
  - Finite volume method
  - Structured mesh
  - RNG k- ε model
  - Buossinesq approx.

- Openings (Air = 25ºC)
  - Outflows:

$$p_{opening} = p_{ref} + \frac{1}{2} f \rho U_n^2$$

  - Inflows:

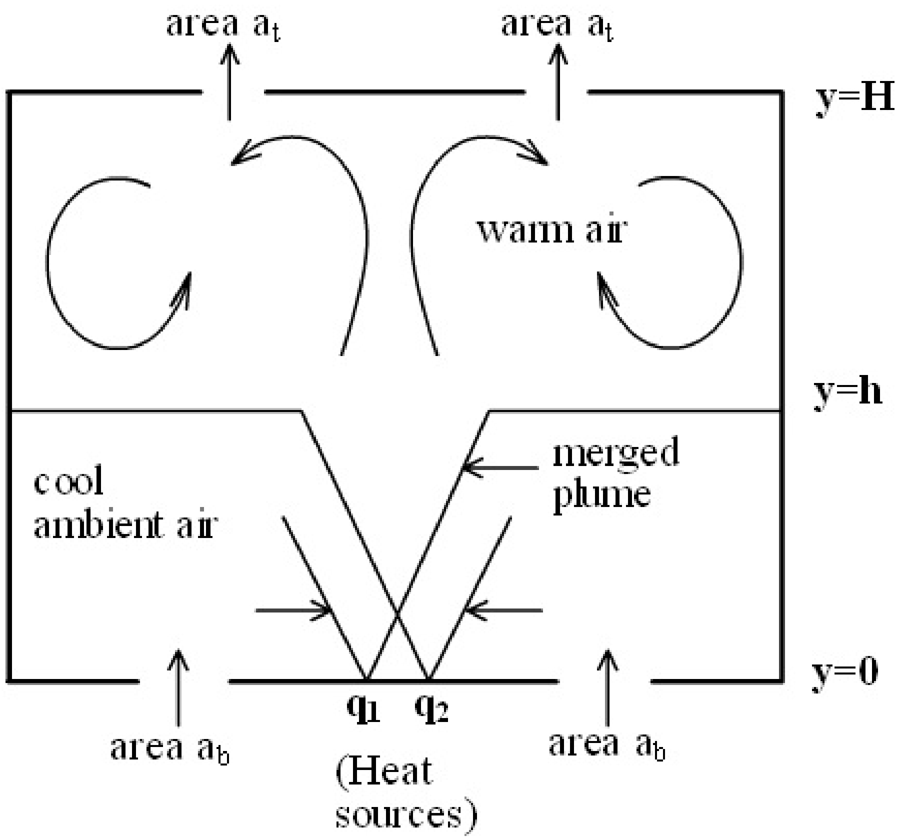
$$p_{opening} = p_{ref} - \frac{1}{2} f \rho U_n^2$$

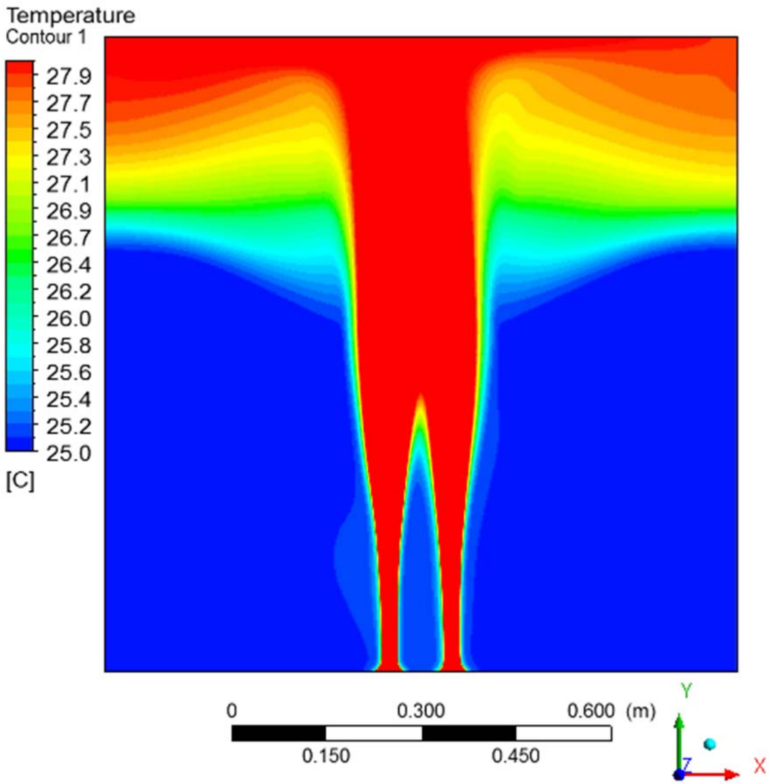
  - where

$$p_{ref} = 0\,\text{Pa}$$

- Heat flux: 20W and 10W

Benchmark 1 Results: Temperature Field (RANS)





Kaye and Linden (2004)

Numerical Parameters (LES)

- LES Model: LES Smagorinsky

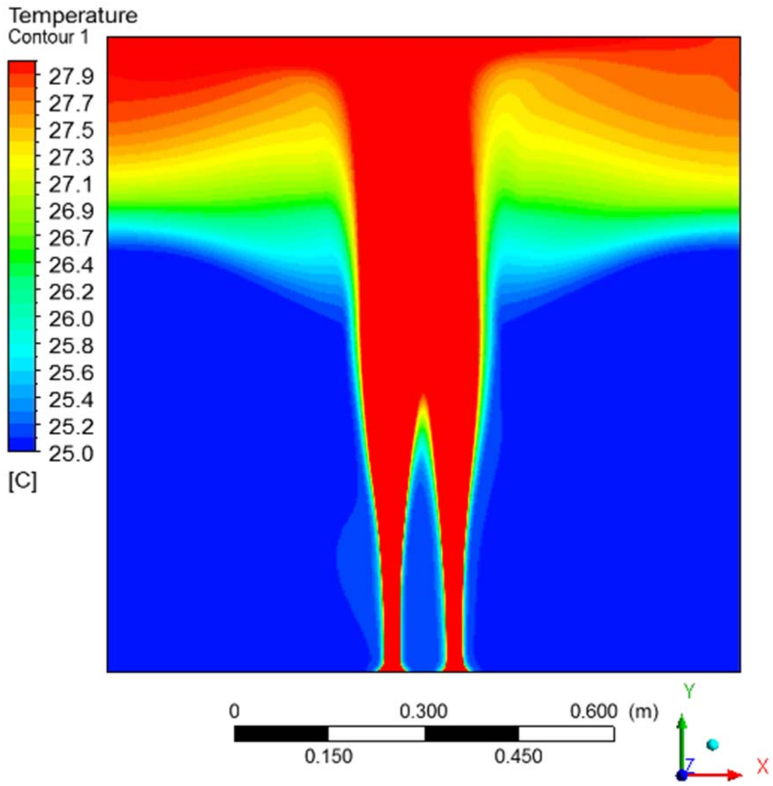
$$CFL = \frac{u \times \Delta t}{\Delta x}$$

- Time steps:
  - Adaptive (initially) based on RMS Courant number
  - Constant (once RMS CFL number within acceptable range)

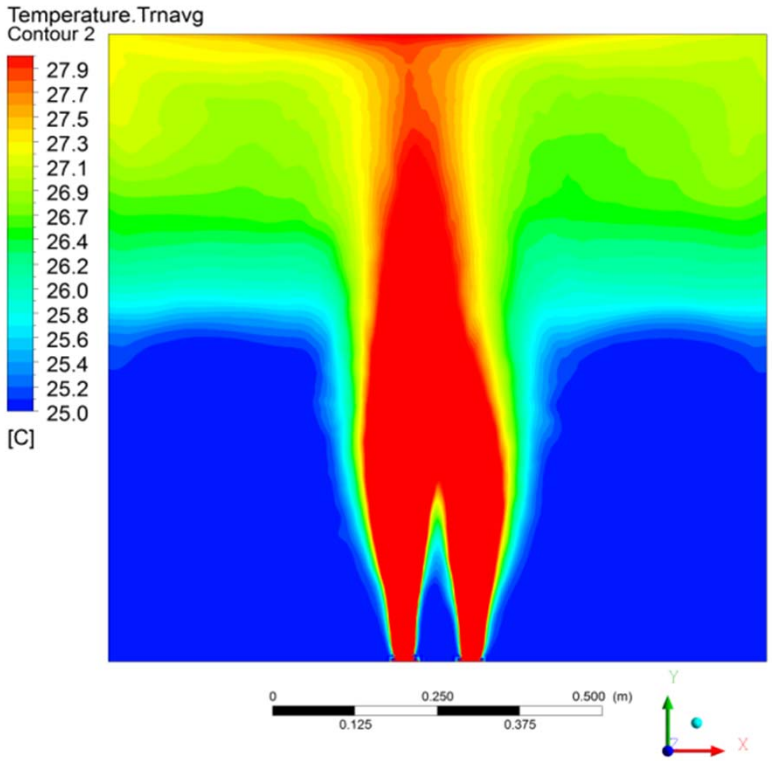
- Target RMS Courant Number: 0.5 (constant)
  - Running averages and FFT analysis

- Target conservation residuals: 1E-06

Benchmark 1: RANS vs LES (averaged)

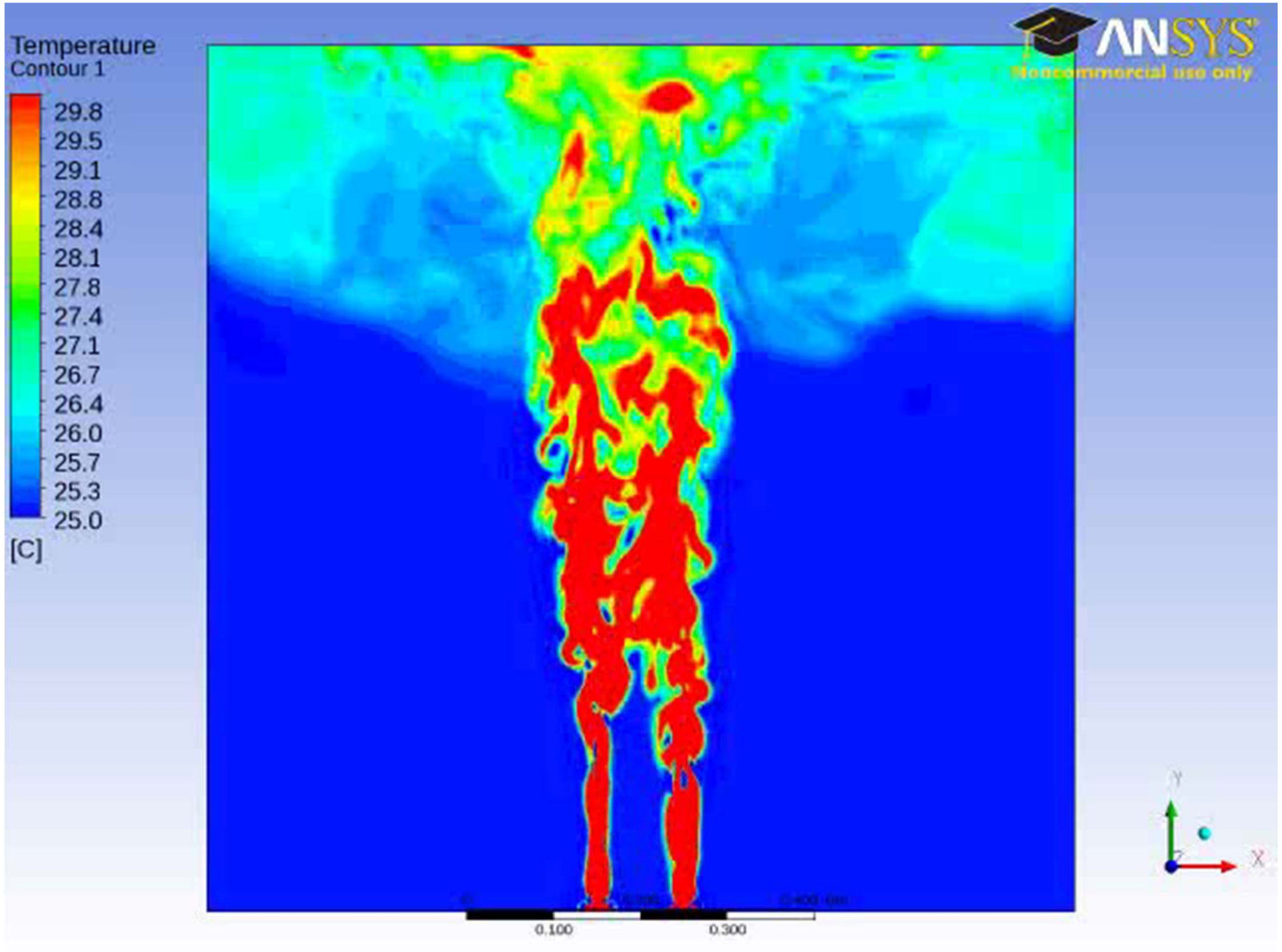


RANS

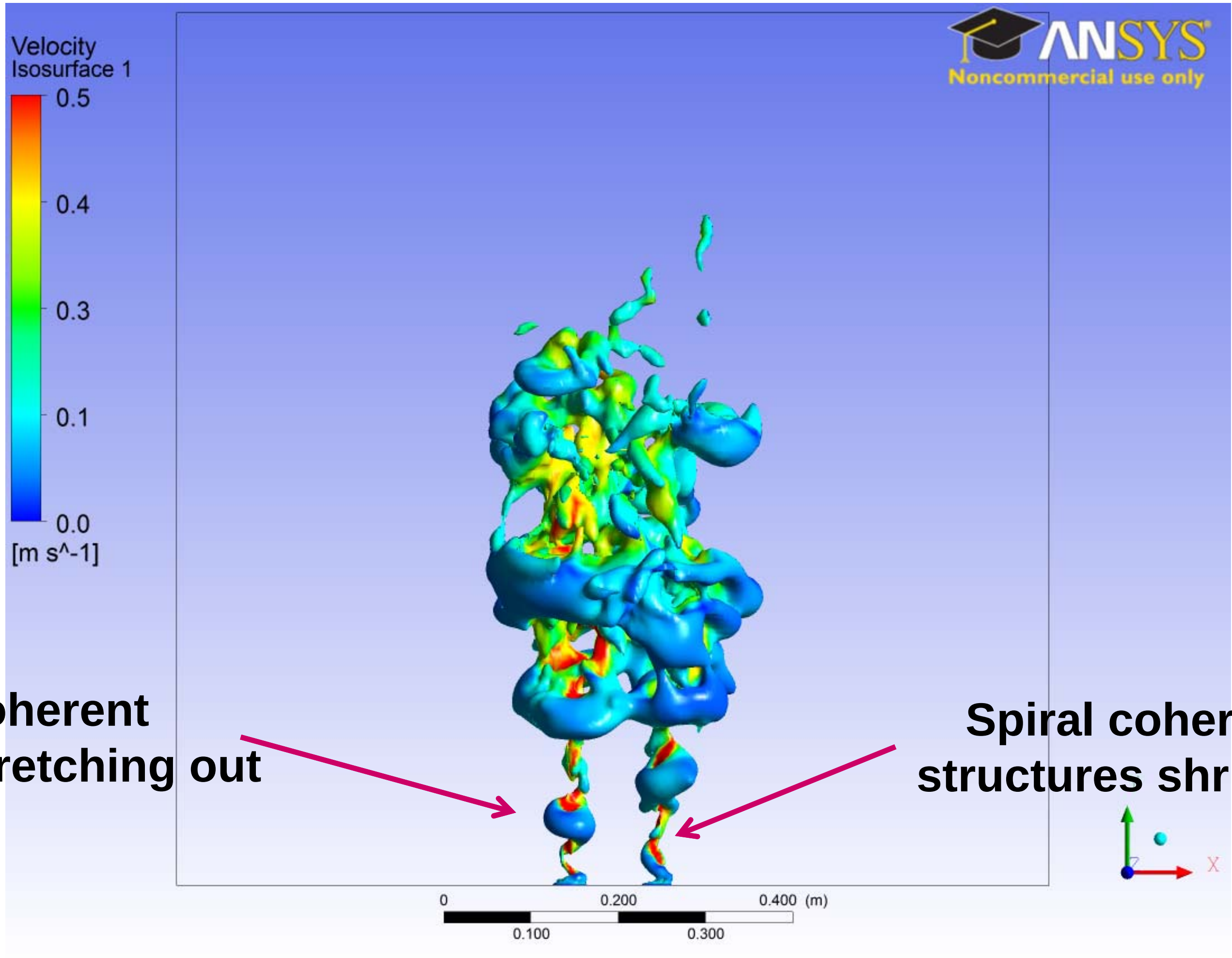


LES

Benchmark 1: Evolution of the interface using LES



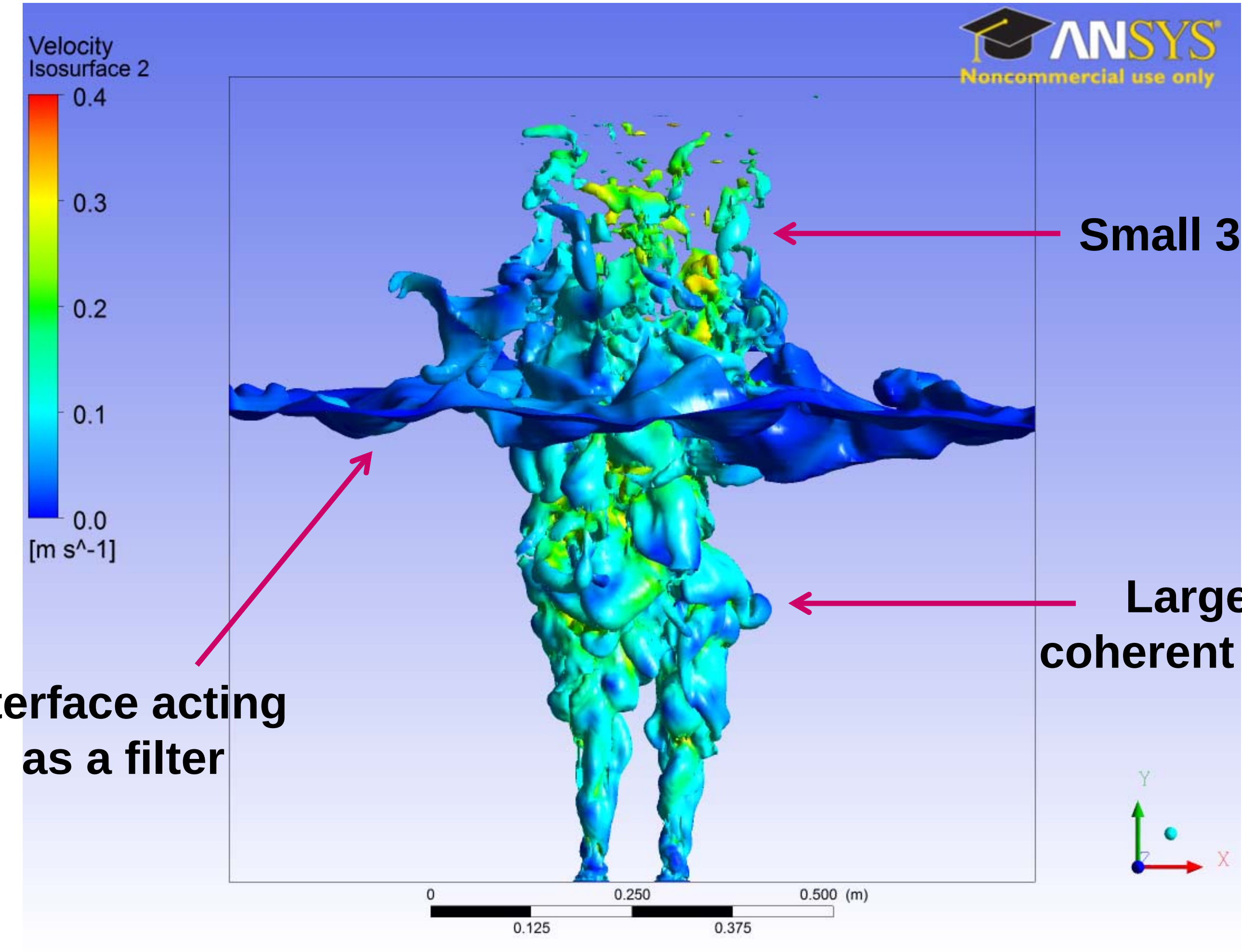
Benchmark 1: Low pressure isosurface



Spiral coherent structures stretching out

Spiral coherent structures shrinking

Benchmark 1: Temperature isosurface

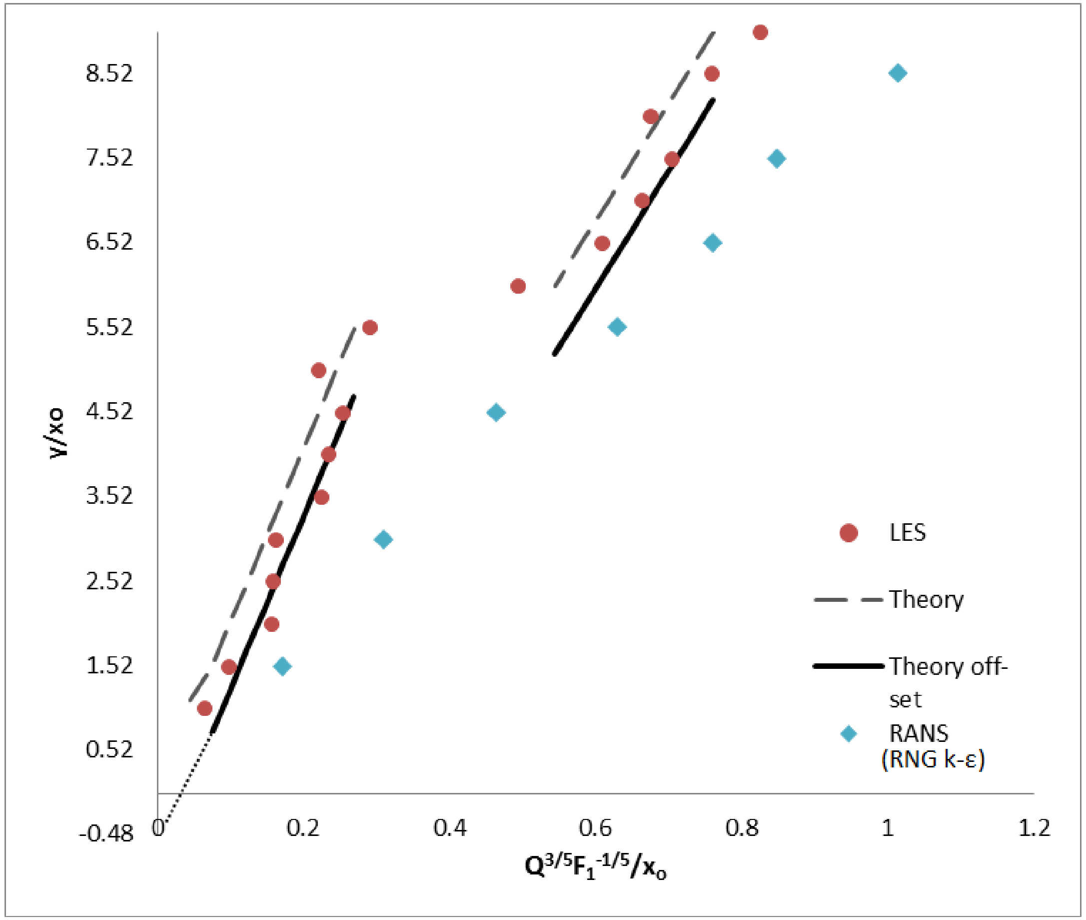


Small 3D structures

Large spiral coherent structures

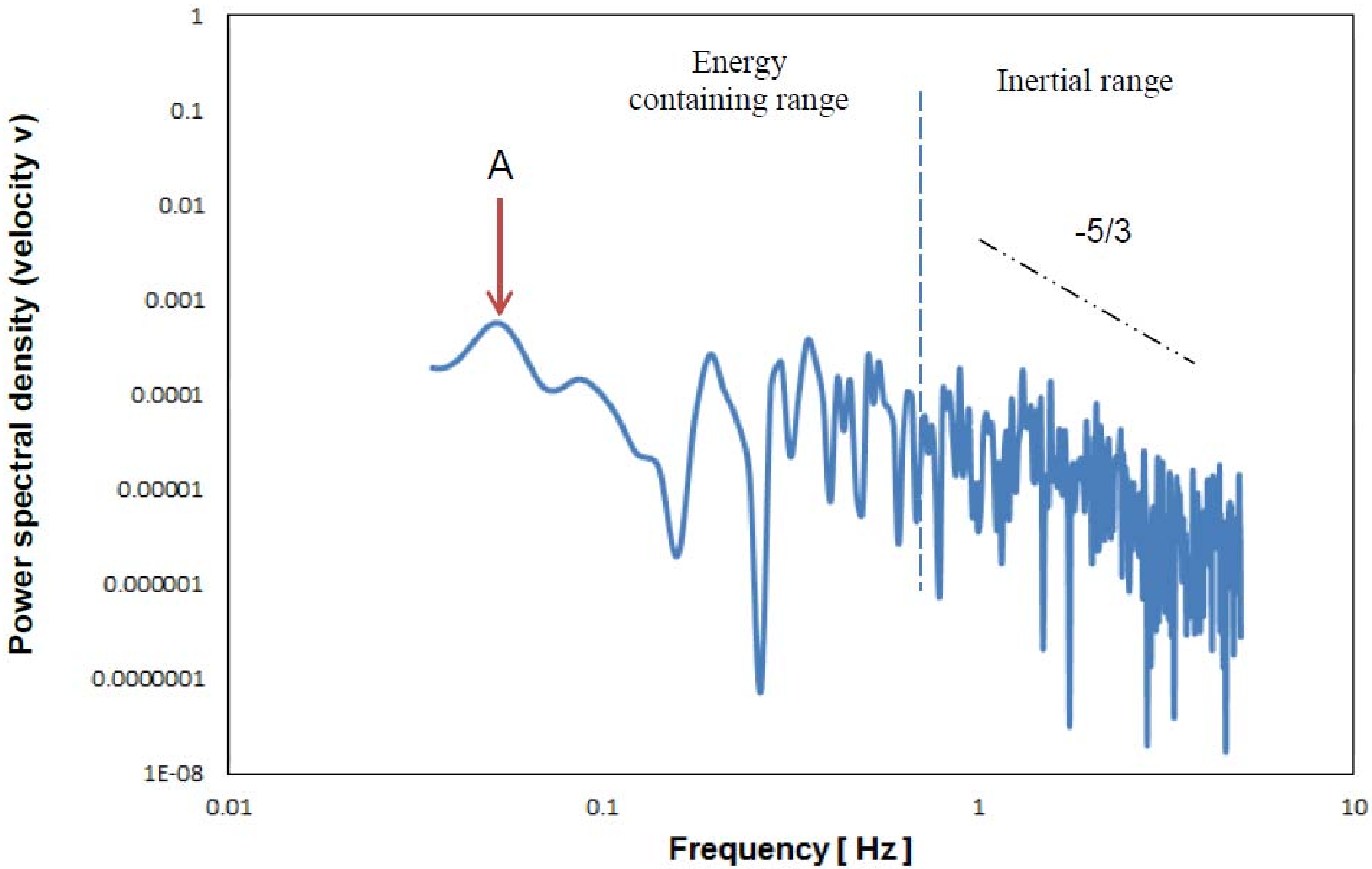
Interface acting as a filter

Benchmark 1: Quantitative Results (LES)



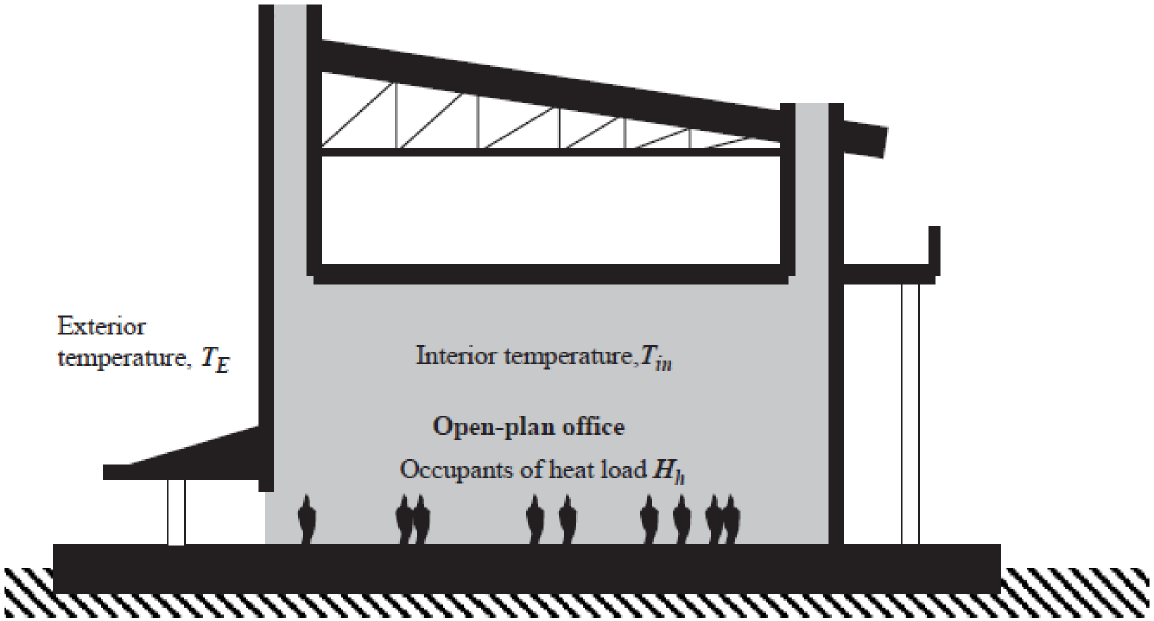
Variation of plume flow rates with height above the heat source

Benchmark 1: Quantitative Results (LES)



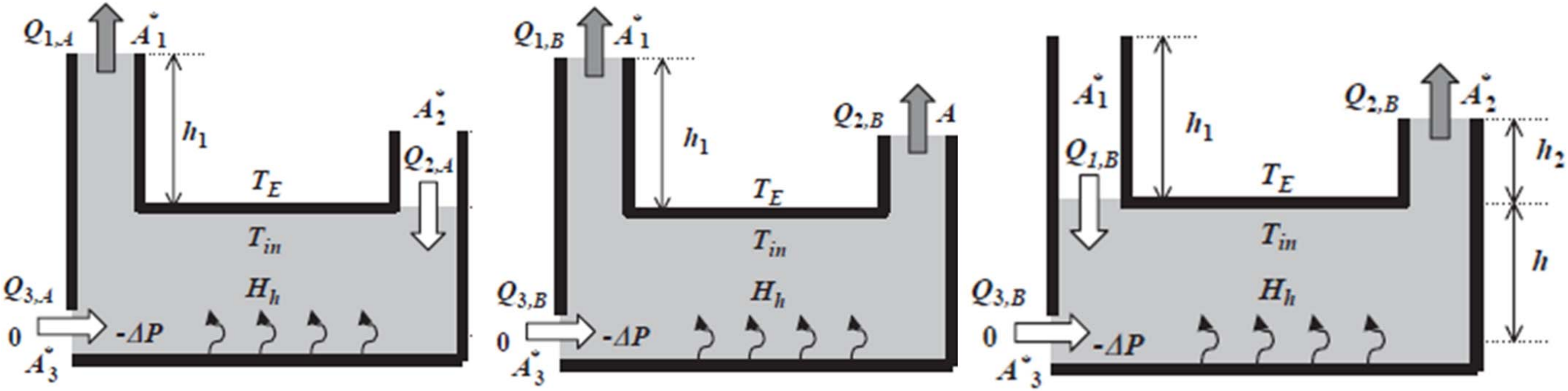
Benchmark 2: Solution Multiplicity

Aim:
To evaluate the performance of LES and URANS for predicting multiple steady-states in naturally ventilated enclosures



Chenvidyakarn and Woods (2005)

Benchmark 2: Solution Multiplicity

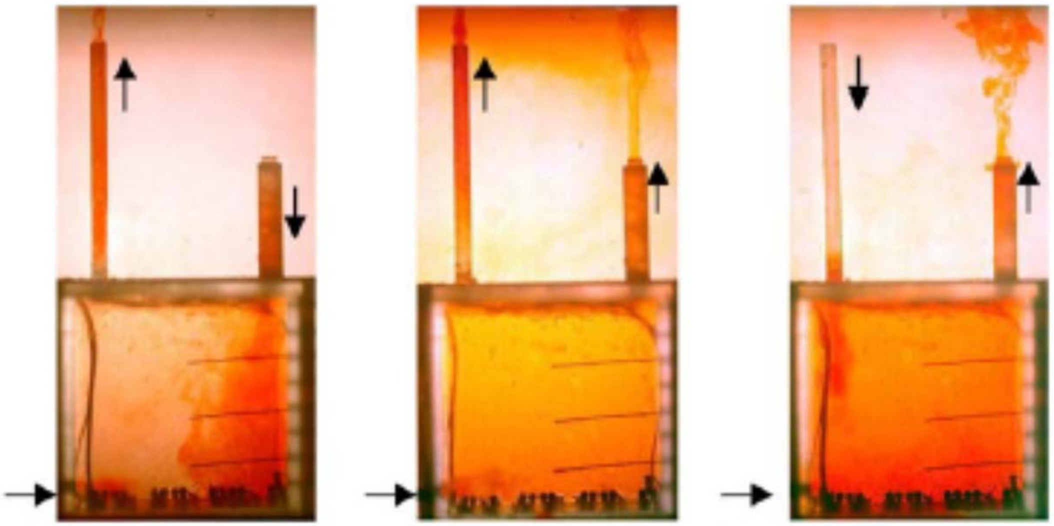


Regime A ***Regime B*** ***Regime C***

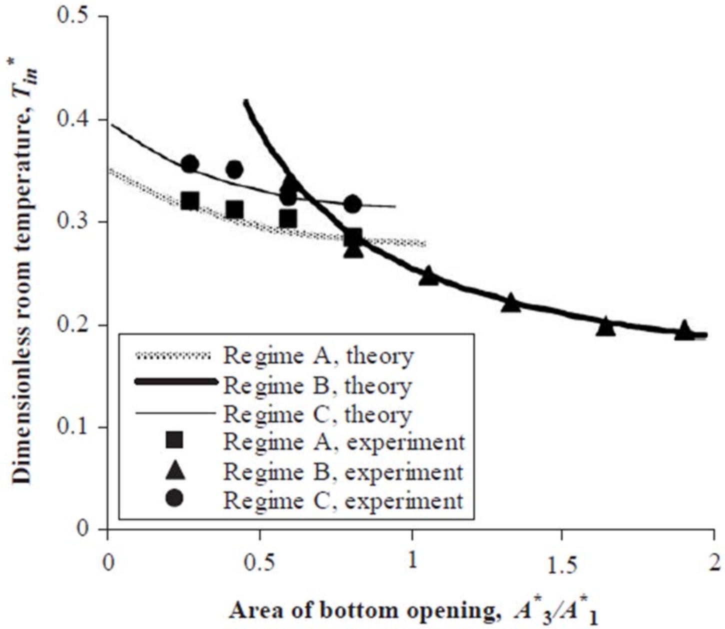
Three steady state ventilation regimes in an open plan office building (after Chenvidyakarn and Woods, 2005)

- Regime depends on:
  - Geometry of the enclosure
  - Flow history

Benchmark 2: Experimental Models



Regime A ***Regime B*** ***Regime C***



Three steady state ventilation regimes reported
(after Chenvidyakarn and Woods, 2005)

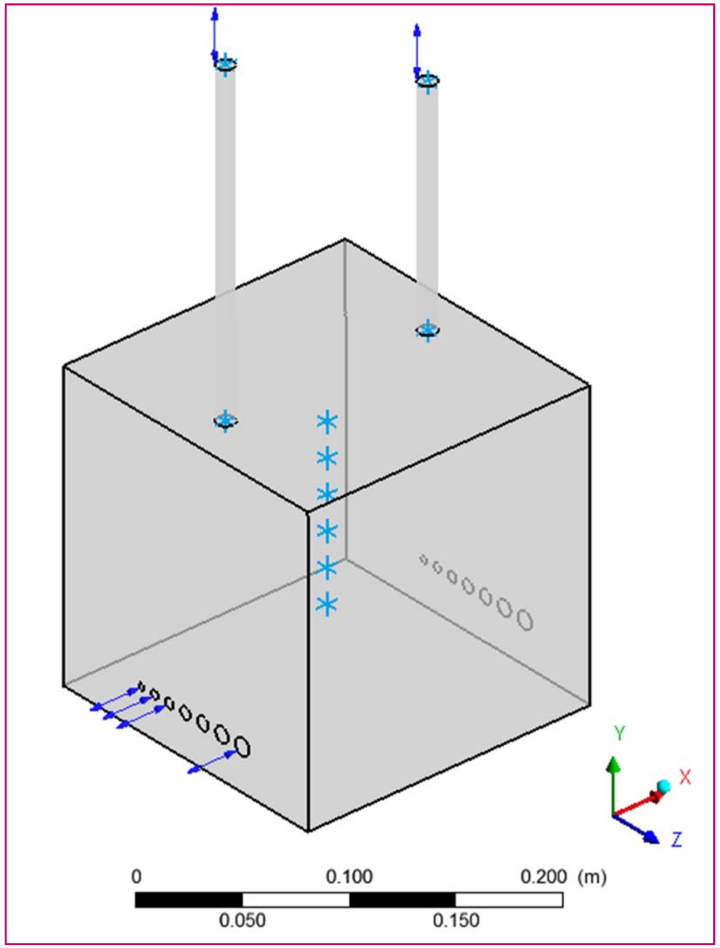
Benchmark 2: CFD Model

- Identical geometry: 17.5cm x 17.5cm x 17.5cm
- Identical fluid: water at 23C

- Boundary conditions
  - Floor: 90W
  - All inlets and outlets: $\Delta p_{loss} = -\frac{1}{2} f \rho {U_n}^2$

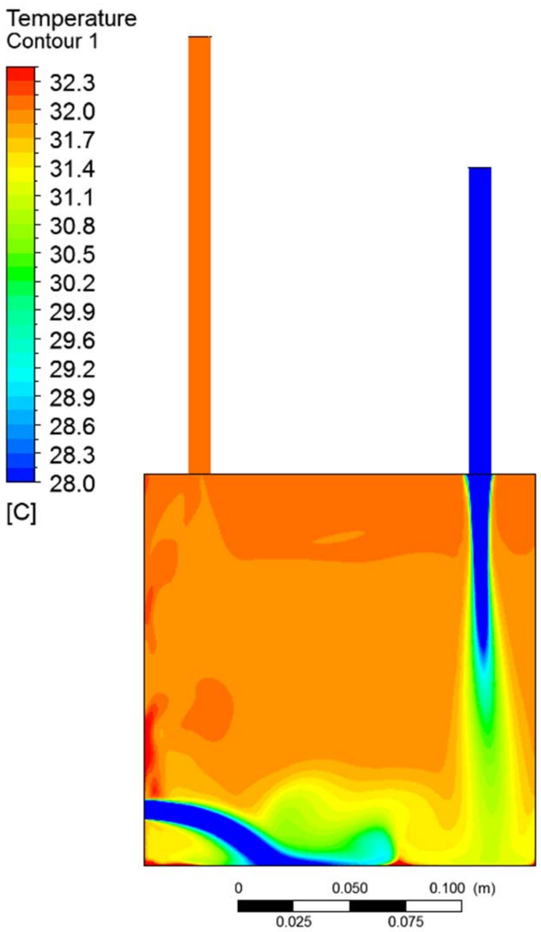
- URANS turbulence model: RNG k-ε
- LES sub-grid model: Smagorinsky

- Mesh sizes:
  - URANS: 1.6M
  - LES: 27M

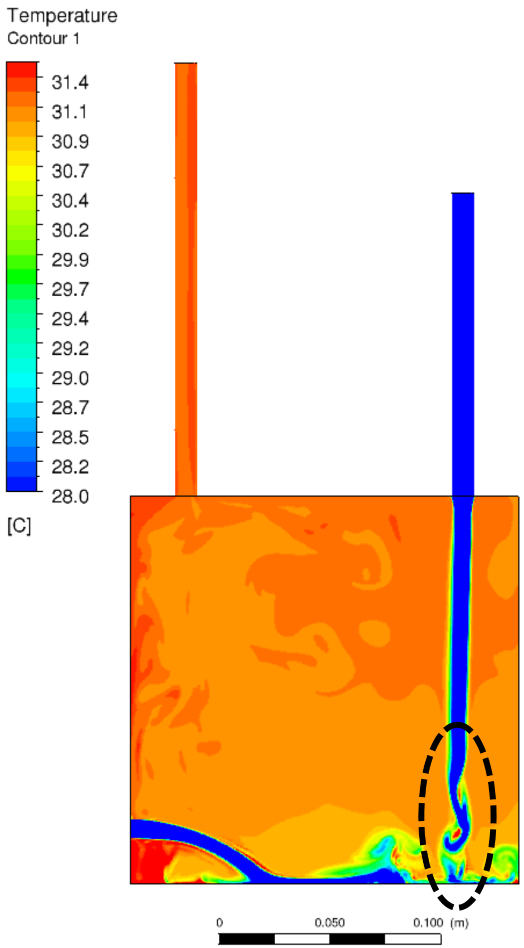


- **Initial conditions:** ambient air introduced through stacks for 30s

Benchmark 2 Results: *Regime A*

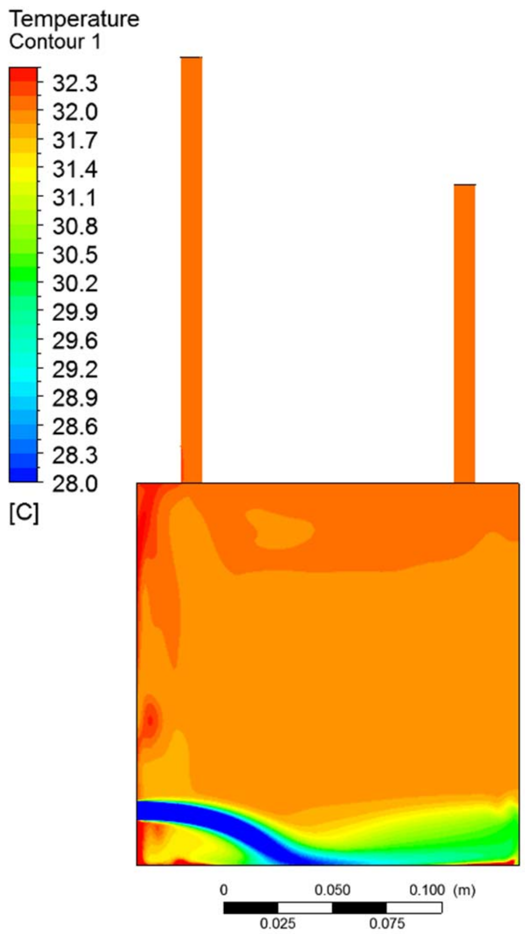


URANS

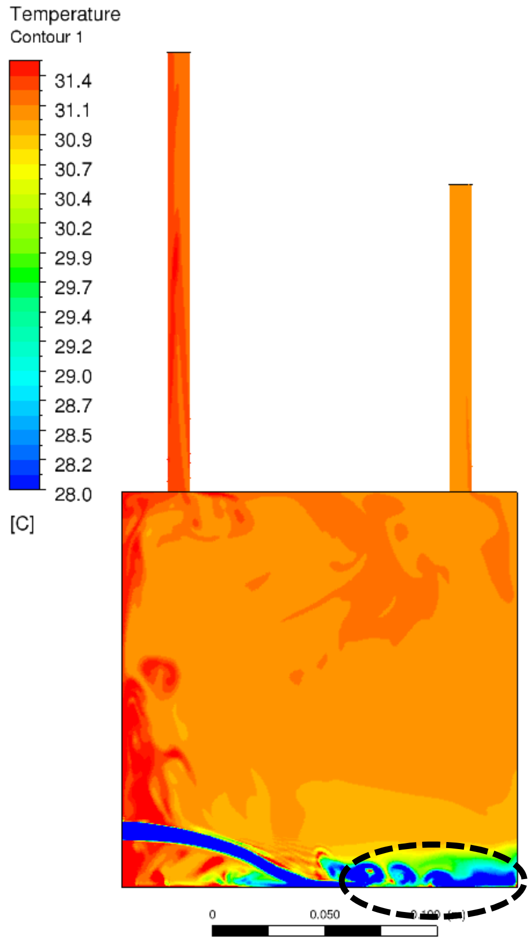


LES

Benchmark 2 Results: *Regime B*

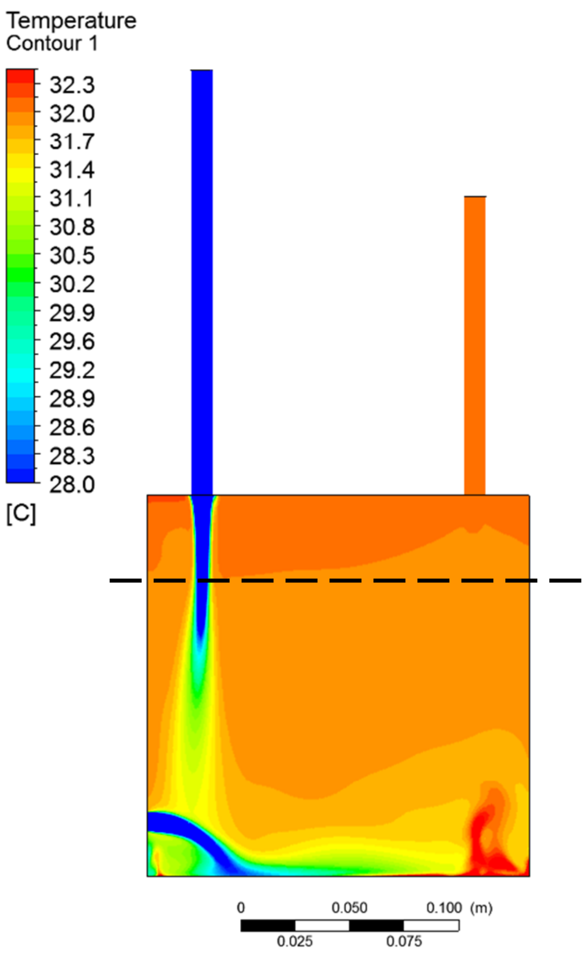


URANS

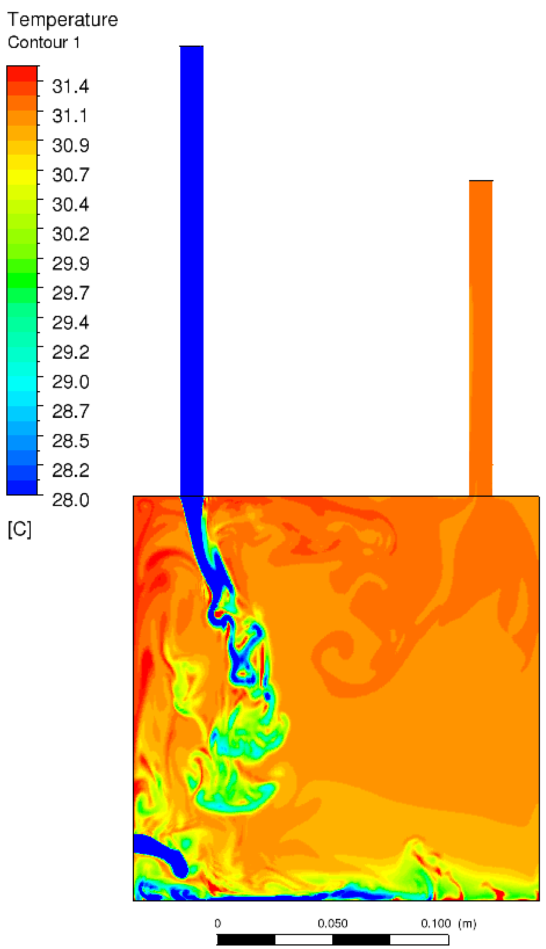


LES

Benchmark 2 Results: *Regime C*



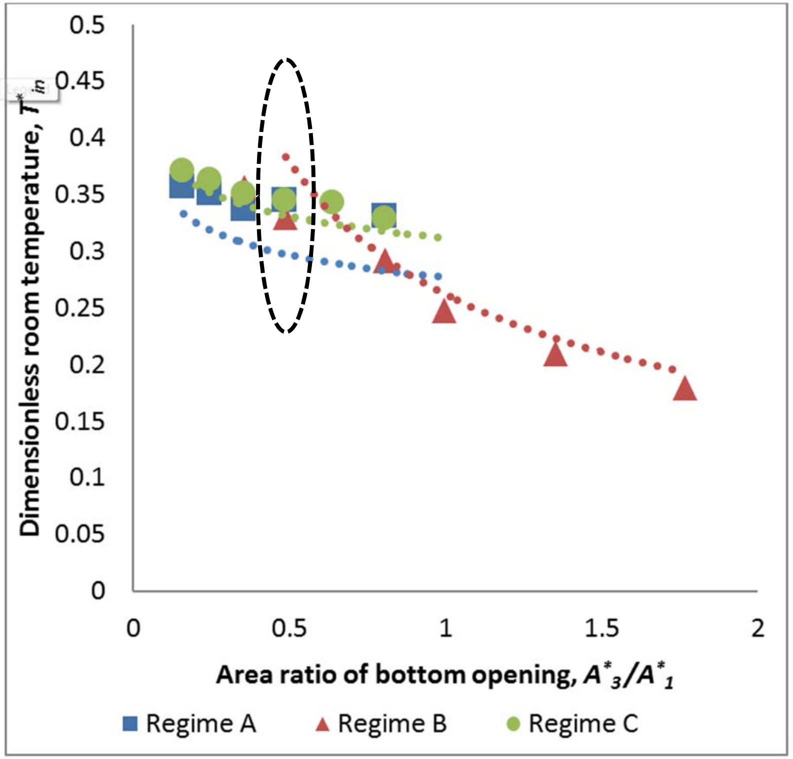
URANS



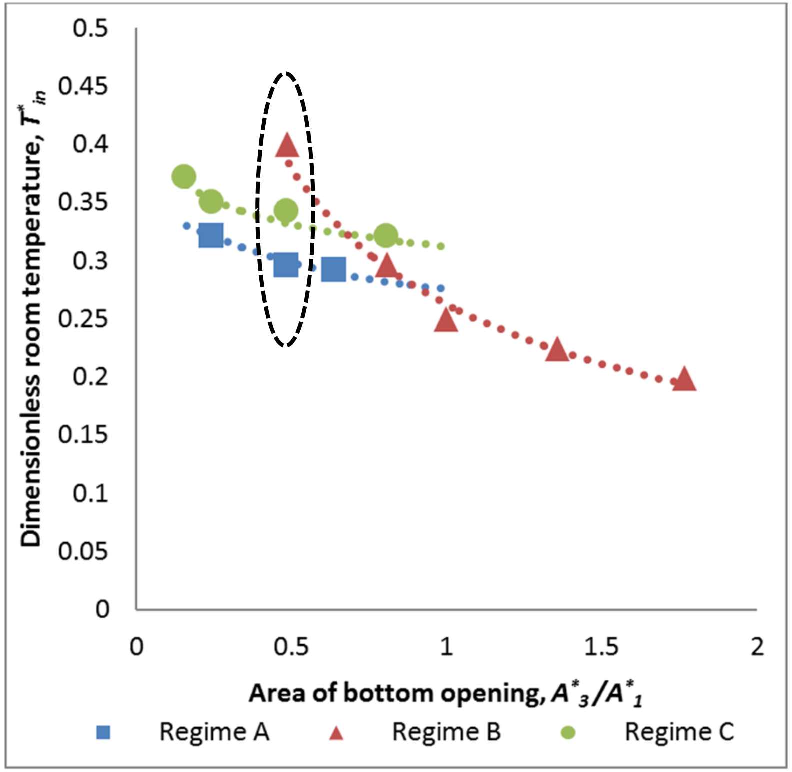
LES

Benchmark 2: Quantitative Results

variation of room temperature with area ratio

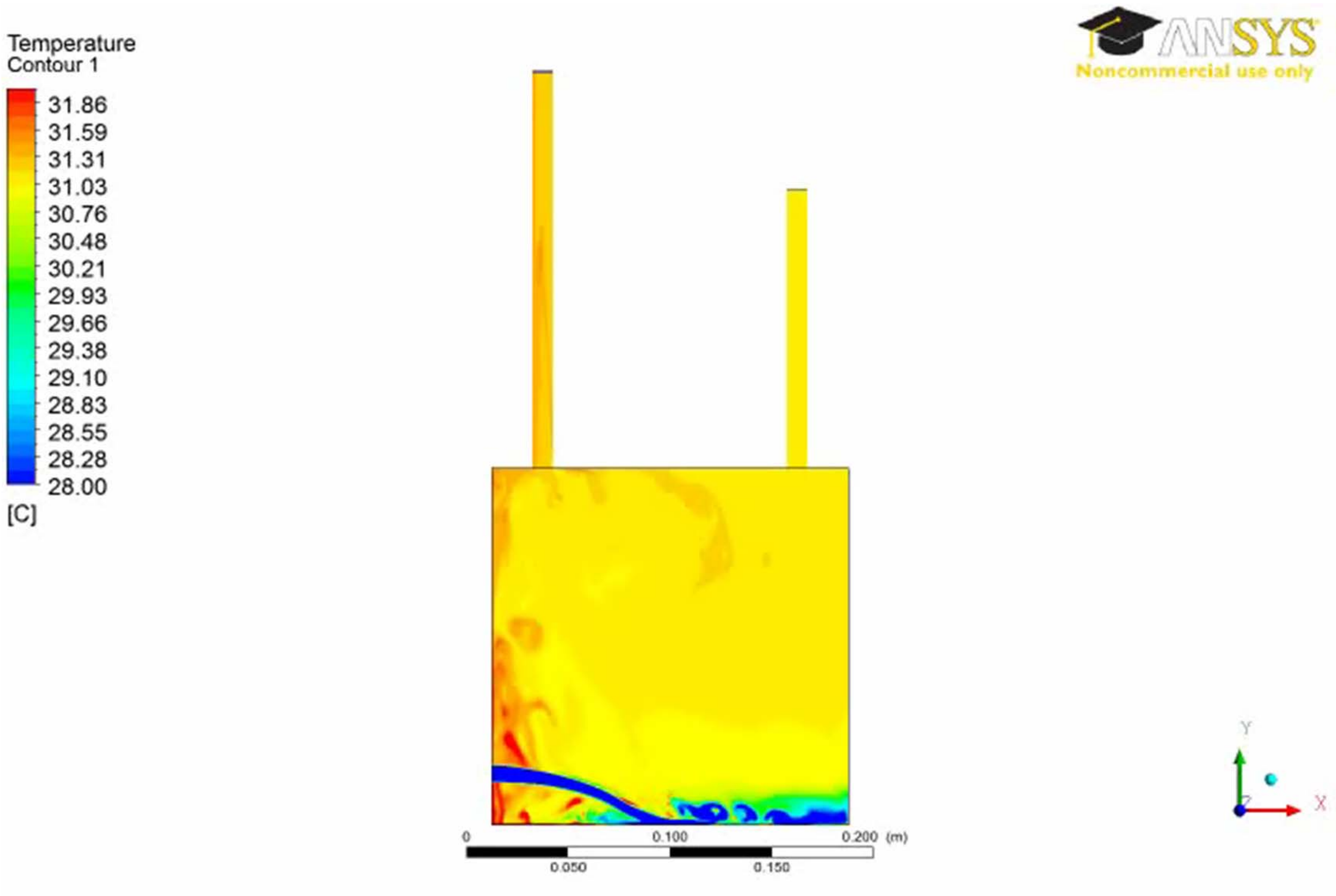


URANS



LES

Benchmark 2 Results: *transient behaviour (C -> B)*



Findings

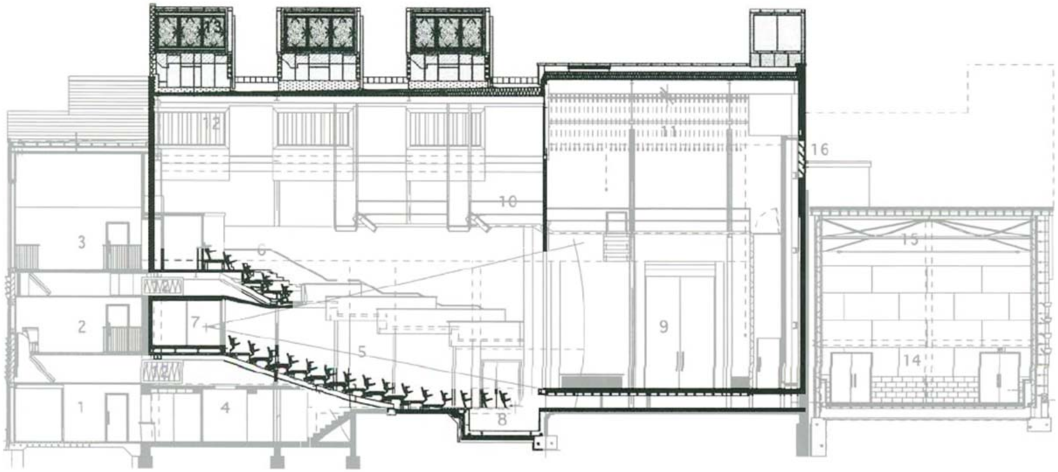
- Benchmark 1 (twin plume)
  - LES provided better prediction of plume volume flux, especially in merge vicinity
  - Pressure and temperature iso-surfaces (LES) gave greater insight into entrainment phenomena
  - Spectral analysis revealed low frequency motions (poss. plume meander)

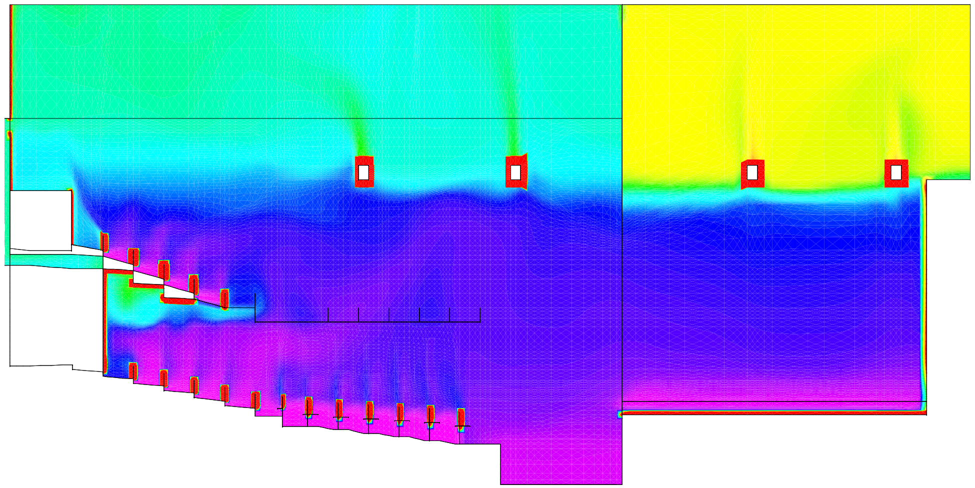
- Benchmark 2 (solution multiplicity)
  - LES and URANS both successfully predicted three steady states
  - URANS under-predicted mixing
  - LES predicts solution multiplicity well (URANS poor for A_3 < 6mm dia)
  - LES also demonstrated potential for switching modes
  - Simulation time
    - LES:URANS = 500:1 !!

Guidelines

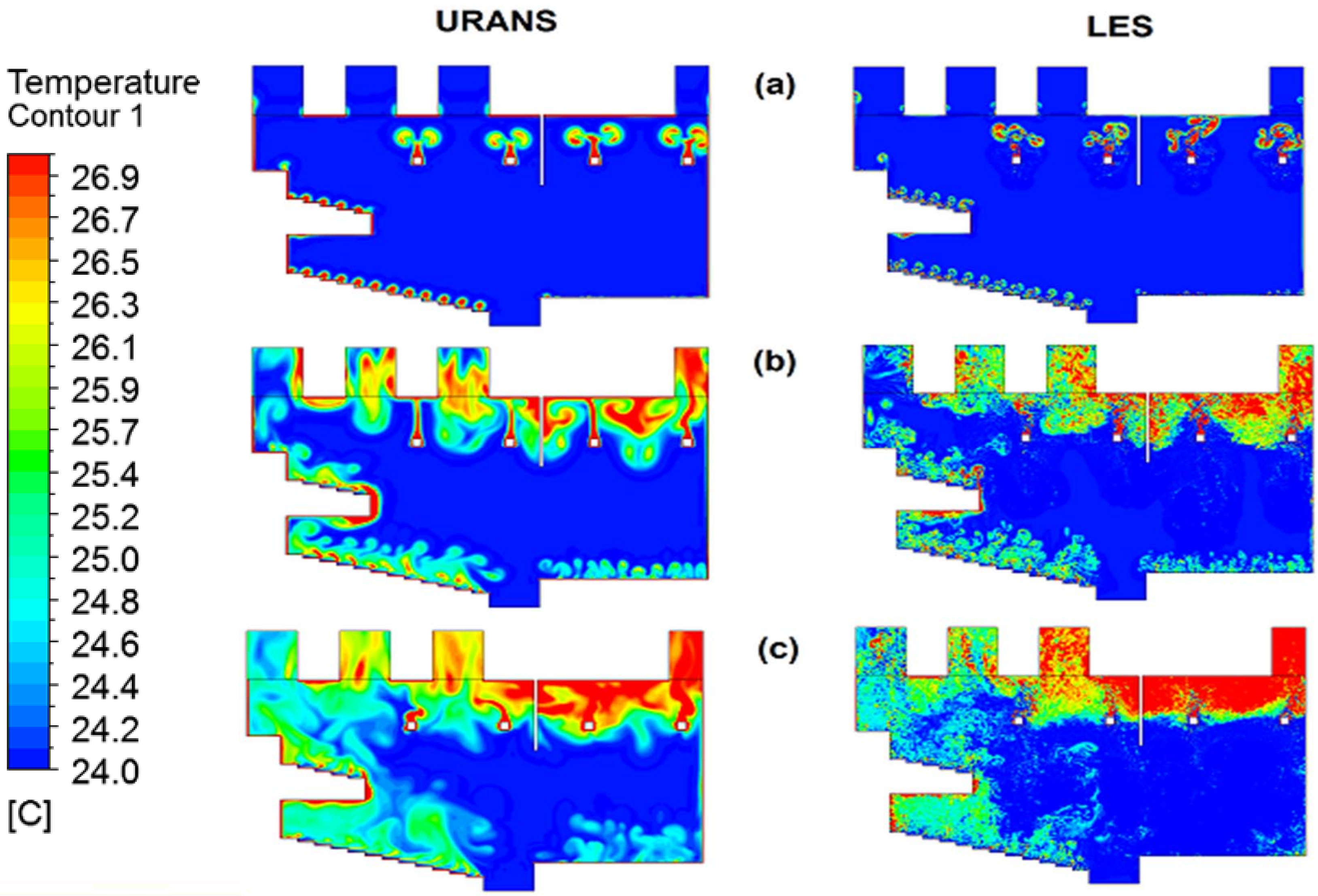
- Mesh structure
  - L/ Δ > 12
    - L = Integral turbulent length scale
    - Δ = filter width
    - $k_{RES}/k > 0.8$ [>80% of the domain is being resolved and less than 20% is being modelled]
- Time steps:
  - Maintain $0 < CFL_{max} < 0.5$
  - If planning FFT, keep time-step constant
- If flow evolution not important, use RANS to evolve flow, then LES
- Use lots of hardware!
  - Approx. 100 processors in parallel to run viable LES (2013)

Application: The Lichfield Garrick

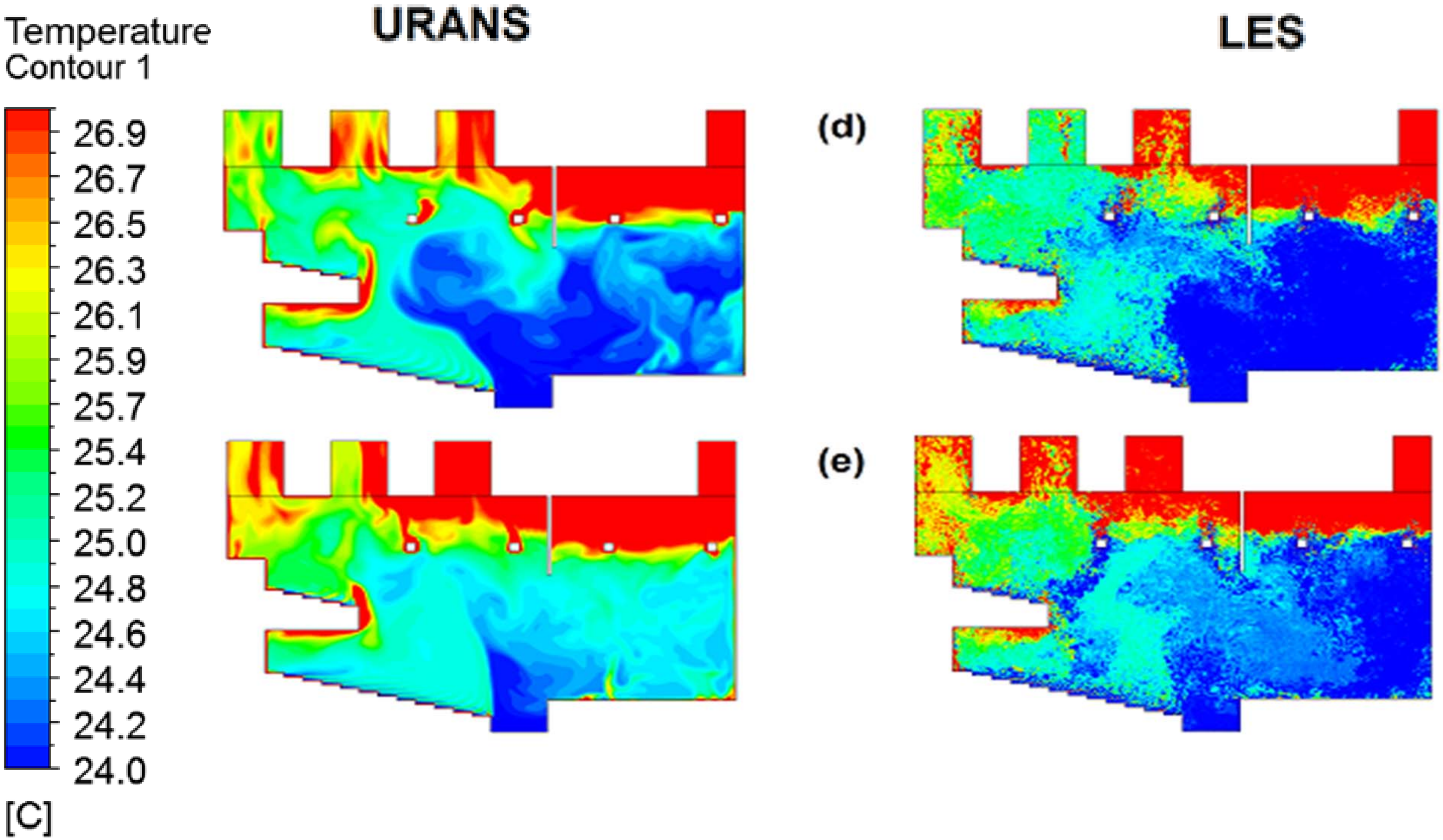




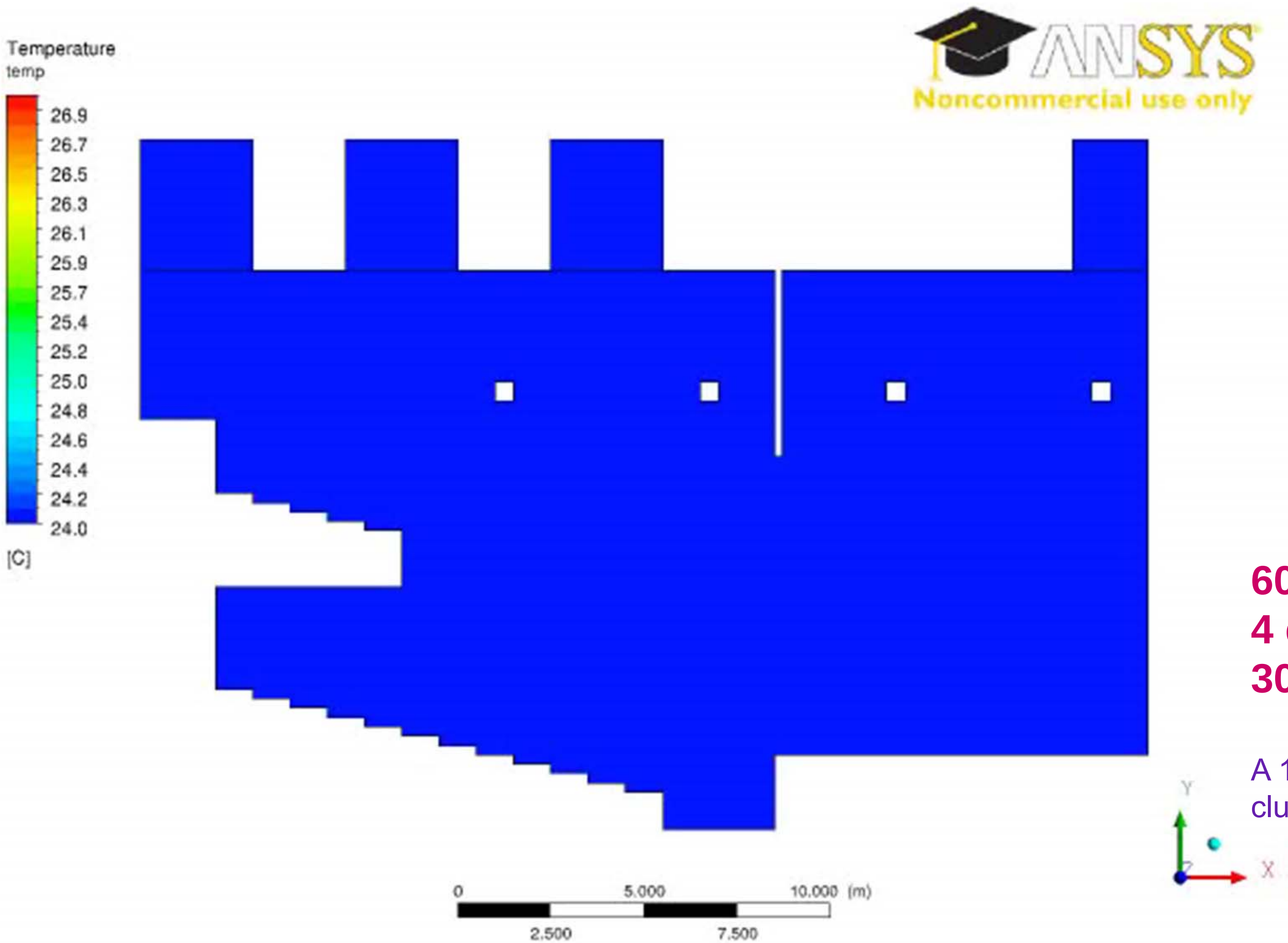
Application: The Lichfield Garrick: URANS vs LES



Application: The Lichfield Garrick: URANS vs LES



Application: The Lichfield Garrick



60 processors
4 days
30s simulation !

A 1956-core 64-bit Intel Xeon cluster supplied by Bull

Hardware development

Date	Machine type	Processor	Memory
1993-1996	SPARCstation 2	Single processor (single core)	8 MB - 64MB
2008	Toshiba Laptop	Two dual core processors (4 cores)	2 GB
September 2010	HPC Cluster	118 12-core nodes (1,416 cores)	2.8 TB
June 2011	HPC Cluster extension	163 12-core processors (1,956 cores)	3.9 TB

Loughborough University

THANK YOU !

http://www.lboro.ac.uk/departments/cv/

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