CFD modelling of buoyancy-driven natural ventilation

CIBSE Natural Ventilation and Building Simulation groups
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Contributions from Dr Faisal Durrani
Content

- Why model?
- Background: early work
- Plume interactions (Benchmark 1)
  - 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

![Graph showing the relationship between \( h/H \) and \( A^*/H^2 \). The graph compares theoretical predictions (Linden et al. 1990) with experimental results (Linden et al. 1990) and CFD simulations using standard and RNG \( k-\varepsilon \) models.]

- **Theoretical prediction (Linden et al. 1990)**: Line representing theoretical predictions.
- **Experimental results (Linden et al. 1990)**: Triangles indicating experimental data points.
- **CFD (standard \( k-\varepsilon \) model)**: Crosses for simulations using the standard \( k-\varepsilon \) model.
- **CFD (RNG \( k-\varepsilon \) model)**: Plus symbols for simulations using the RNG \( k-\varepsilon \) model.

The graph illustrates the accuracy of different modeling approaches in predicting the behavior of fluid layers during emptying filling processes.
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:
    \[ p_{\text{opening}} = p_{\text{ref}} + \frac{1}{2} f \rho U_n^2 \]
  - Inflows:
    \[ p_{\text{opening}} = p_{\text{ref}} - \frac{1}{2} f \rho U_n^2 \]
  - where
    \[ p_{\text{ref}} = 0 \text{ Pa} \]
  - 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)
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

- **Interface acting as a filter**
- **Small 3D structures**
- **Large spiral coherent structures**
Benchmark 1: Quantitative Results (LES)

Variation of plume flow rates with height above the heat source
Benchmark 1: Quantitative Results (LES)
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

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
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 $k-\varepsilon$
- 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: \textit{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 $A_3 < 6\text{mm dia}$)
  - LES also demonstrated potential for switching modes
  - Simulation time
    - LES:URANS = 500:1 !!
Guidelines

- **Mesh structure**
  - \( L / \Delta > 12 \)
    - \( L \) = Integral turbulent length scale
    - \( \Delta \) = 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

![Temperature Contour](image)

**URANS**

(a)

(b)

(c)

**LES**
Application: The Lichfield Garrick: URANS vs LES

Temperature Contour 1

URANS

LES

(d)

(e)
Application: The Lichfield Garrick

60 processors
4 days
30s simulation!

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

<table>
<thead>
<tr>
<th>Date</th>
<th>Machine type</th>
<th>Processor</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993-1996</td>
<td>SPARCstation 2</td>
<td>Single processor (single core)</td>
<td>8 MB - 64MB</td>
</tr>
<tr>
<td>2008</td>
<td>Toshiba Laptop</td>
<td>Two dual core processors (4 cores)</td>
<td>2 GB</td>
</tr>
<tr>
<td>September 2010</td>
<td>HPC Cluster</td>
<td>118 12-core nodes (1,416 cores)</td>
<td>2.8 TB</td>
</tr>
<tr>
<td>June 2011</td>
<td>HPC Cluster extension</td>
<td>163 12-core processors (1,956 cores)</td>
<td>3.9 TB</td>
</tr>
</tbody>
</table>
THANK YOU!

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

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