Analysis of Building Performance using Computational Fluid Dynamics (CFD)

Richard Chitty
Content

• Computational Fluid Dynamics (CFD)
• Natural Ventilation System
• Wind Application
• Fire Safety Application
• Conclusion
CFD modelling - in one slide

- Discretise geometry
- Select physical sub-models
- Apply boundary conditions
- Solve coupled equations
- Process solution data

conservation equations imposed at each mesh element

Σ = 0
CFD study of a Novel Naturally Ventilated Building

BRE Environmental Office
Opened 1997

Protecting People, Property and the Planet
Ventilation system

• Cooling is achieved by:
  – Cross ventilation
  – Groundwater cooling

• Exposed ceiling slab with air channels
• 5 external ventilation shafts
• CFD simulations were undertaken to study the environmental conditions in the first-floor open plan office during a warm summer day with a light southerly breeze

- ambient air = 24°C
- wind speeds of 0.5 m/s & 1.5 m/s (at 10 m height)
- ceiling channels open to the outside
- external shaft windows open
- cooling by the ceiling slab
- 20 W/m² thermal load
Ventilation shafts

Air is drawn from the office space and upwards through the shaft with the assistance of:

• wind flow across the top
• solar warming of the glass panels
• a low power fan inside the shaft

Little understanding of their actual effect when the building was constructed.
CFD simulations

- A ‘slice’ of the building and external atmosphere has been simulated, allowing
- fine numerical resolution
- interaction of the breeze with the building to be modelled, removing the need for assumed pressure coefficients.
External breeze

An inlet boundary condition placed upstream to provide a logarithmic wind profile
- 1.5 m/s breeze
- outside temp at 24 °C
- ceiling slab at 21 °C
- shaft panels at 29 °C

Unstructured mesh of 470000 elements

Volume heat sources
CFD Simulations using CFX-5

- Fully coupled momentum-pressure solver, eliminating need for pressure-correction
- Unstructured numerical mesh of triangular surface elements, boundary layer prisms and tetrahedral volume elements
- Symmetry boundary conditions either side of the modelled ‘slice’
- ‘Standard’ k-ε turbulence model
- Volume heat sources to represent vdu’s and people
- Boussinesq buoyancy approximation
CFD Simulations

- 1.5 m/s breeze
- Outside temp at 24 °C
- Ceiling slab at 21 °C
- Shaft panels at 29 °C

$$\text{ACH}^{-1} \approx 7$$

The building design specification states a maximum office temperature of 25 °C for 95% of the working year.
Summary of conclusions

• A parametric CFD analysis has provided additional insight into the summer time operation of the BRE’s Environmental Building

• With a light warm breeze and a combination of cross- and external shaft ventilation, conditions inside the first floor office shown to be acceptable

• Air change rates quite high in the presence of a 1.5 m/s breeze

• Solar heating of the external shafts not critical, as assumed in the building design

• ‘Hot’ daytime operation would likely require trickle ventilation and, in some instances, groundwater cooling (as happens in practice)
Wind Engineering
Background

- Wind tunnel technology well established
- CFD now provides an alternative/complimentary tool
- BUT, wind engineering community has reservations
Bluff Body Aerodynamics

• Buildings are bluff bodies within the surface boundary layer, generating:
  – stagnation
  – separation
  – reattachment
  – vortex generation

• Flow field is inherently unsteady
  – time-averaged flow field may be quite different to the instantaneous one
Gloucester Road Development

1:200 scale wind tunnel model of city centre development

1.2 million element CFX-5 model
SST turbulence model
Gloucester Road Selected Wind Direction

Impingement, separation, re-circulation, stagnation etc all present
Gloucester Road Pedestrian Velocities (1.2m)

- Measured $v \approx 1.5 \text{ m/s}$
- CFD $v \approx 2.75 \text{ m/s}$
- Measured $v \approx 1.9 \text{ m/s}$
- CFD $v \approx 3.15 \text{ m/s}$
- Measured $v \approx 2.1 \text{ m/s}$
- CFD $\approx 2.5 \text{ m/s}$
Comments

• Wind tunnels still have an important role
  – unsteady phenomena
  – boundary layer generation

• COST best practice guide
“Blind” CFD simulation of a fire experiment

- Part of CIB W14 programme
  - Design specification issued
    - experiment details
    - scenario to be modelled
  - ‘Blind’ predictions made and submitted
  - Experimental measurements released
    - comparison with predictions made
    - new ‘open’ predictions allowed
Fire experiment

- Conducted at VTT in 1980s
  - compartment with single opening
  - concrete block construction

- wood crib fire sources
- measurements
  - temperature
  - gas species
  - wall fluxes
Fire experiment

plan view

ignition point

view from back of compartment
Fire Experiment

- Two softwood cribs
  - Fire peaks at 5 MW after 25 minutes

Fire simulations do not usually predict fire size so this was part of the input data
Experiment: 8 minutes
Experiment: 38 minutes

- Room flashed over
- Flames emerging from window
Experiment: 48 minutes
JASMINE

- Finite volume CFD fire model
  - developed at FRS for more than 20 years
  - Based on early version of PHOENICS
  - validated for various smoke movement applications
- Six-flux radiation model
- Standard k-ε turbulence model
  - with buoyancy modifications
- Specific heat & density
  - functions of species and temperature
- Solid surface temperature calculation
  - one-dimensional quasi-steady conduction approximation
- Two-second time-step
  - full two hour simulation

Protecting People, Property and the Planet
Geometry and Mesh

- Domain extended into Test Hall
- 46,000 cells
  - finer grid at solid boundaries
  - grid sensitivity study with 370,000 cells
Combustion Model

• Simplified crib
  – fuel released from top surface
    \[ \dot{Q} = \dot{m}\Delta H_{\text{eff}} \]

• Approximate one-step chemistry

\[ CH_2O + O_2 \rightarrow CO_2 + H_2O \]

• Eddy dissipation reaction mechanism

\[ S_{fu} = -\rho \frac{\varepsilon}{k} C_R \min \left( m_{fu}, \frac{m_{o2}}{s} \right) \]
Predicted temperature at flashover
Predicted & Measured Temperature

- Rear thermocouple tree
Predicted & Measured Temperature

- Centre thermocouple tree
Predicted & Measured Temperature

- Corner thermocouple tree
Effective Heat of Combustion

- Constant value used for simulation

Graph showing the time dependence of the effective heat of combustion with circles indicating moisture release and charring.
Adjusted Temperature Prediction

- Prediction ‘modified’ according to varying heat of combustion
Predicted & Measured Fluxes

• Conduction fluxes into ceiling and side wall

![Graph showing heat flux vs time with points and lines indicating predicted and measured fluxes. The labels Flux2 - Jasmine, Flux3 - Jasmine, Flux2 - expt, and Flux3 - expt are shown on the graph.](image)
Conduction Model

- Flux balance at surface
  \[ \dot{q}''_{\text{conv}} + \dot{q}''_{\text{rad}} = \dot{q}''_{\text{conduction}} \]

- One-dimensional quasi-steady conduction approximation
  \[ \dot{q}''_{\text{conduction}} \approx k \frac{(T_w - T_0)}{\delta} \approx 2\left(\frac{k}{\rho c} t\right)^{\frac{1}{2}} \]
Outcome of comparison

• Overall agreement between prediction and measurement good
  – peak temperatures within 15%
  – species concentrations similar

• Temporal shift and discrepancy in decay stage
  – variation in $\Delta H_{\text{eff}}$ an important factor here

• Solid boundary heat fluxes under-predicted during ‘flashover’
  – ‘simple’ quasi-steady conduction model
  – soot formation
Conclusions

• CFD has been demonstrated to accurately simulate a number of building related problems by comparison with measured data.

• BUT if it goes wrong…

Ventilation
Open a window, loose energy

Wind
Discomfort injuries

Fire
Large financial losses
People die
Conclusions

• Fire and Low Energy Technologies
  – Better insulation (not just U value)
  – Better air tightness
  – Chilled ceilings
  – Phase change materials

• Some CFD issues
  – Free software (e.g. OpenFoam, FDS)
  – Training
  – Data sources
    • Garbage in = Garbage out
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