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CFD in Ventilation Design

by

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The Audience

The user of the design book is mainly considered to be a consulting engineer who has to:

- order a CFD prediction
- consider and work with a CFD prediction
- discuss CFD and the CFD quality with a supplier of a CFD prediction

In principle the book is not written for engineers who are making CFD predictions already
CFD in Ventilation Design

Authors: Francis Allard, Hazim B. Awbi
Lars Davidson, Alois Schälin and Peter V. Nielsen

Computational fluid dynamics in a nutshell
Symbols and glossary
Mathematical background
Turbulence models
Numerical methods
Boundary conditions
Quality control
CFD combined with other prediction models
Application of CFD codes in building design
Case studies
Benchmark tests
CFD in Ventilation Design

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Development in Computer Cost

![Graph showing development in computer cost over years from 1970 to 2005. The y-axis represents calculation speed in Flops, ranging from $10^7$ to $10^{14}$, and the x-axis represents years from 1970 to 2005. The graph shows an increasing trend in calculation speed as time progresses.]
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Mathematical Background

From the general description

\[
\frac{\partial (\rho \Phi)}{\partial t} + \text{div} (\rho \vec{V} \Phi) = \text{div} (\Gamma_{\Phi} \text{grad} \Phi) + S_{\Phi}
\]

to a two-dimensional time dependent transport equation

\[
\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = D \left( \frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} \right)
\]
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Turbulence Models

Laminar flow/turbulent flow
2D steady state

\[ \rho u \frac{\partial c}{\partial x} + \rho v \frac{\partial c}{\partial y} = \Gamma_c \frac{\partial^2 c}{\partial y^2} + S_c \]

A discussion of different turbulence models as e.g. the \( k-\varepsilon \) model, the \( k-\omega \) model, the \textit{SST} model and the \textit{Reynolds Stress} model

The \textit{Large Eddy Simulation} is also discussed
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One-Dimensional Case

The case can be considered as a small part of a flow, which in certain areas is one-dimensional, parallel with grid lines and steady.

\[ \rho u \frac{dc}{dx} = \Gamma_c \frac{d^2c}{dx^2} + S_c \]
One-Dimensional Discretization Equation

Control volume formulation:

\[ \rho(u_e c_e - u_w c_w) = \Gamma_c \left[ \left( \frac{dc}{dx} \right)_e - \left( \frac{dc}{dx} \right)_w \right] + S_p \Delta x \]

It is necessary to replace values at the cell surfaces \( e \) and \( w \) with values from the grid points \( WW, W, P, E \) and \( EE \) to have a final version of the discretization equation.
Different Discretization Equations, 1

The flow is studied in a case where the length $x$ is equal to 4. The boundary values $c_o$ and $c_3$ are equal to 1.0 and 0.0.

Central differences is e.g. $c_e = (c_P + c_E)/2$ and $u = 0.1$
Different Discretization Equations, 2

Central differences e.g. \( c_e = \frac{(c_p + c_E)}{2} \) and \( u = 3.0 \)

Wiggly for \( Pe = \frac{\rho \Delta x u}{\Gamma_c} \) larger than 2
History and Numerical Schemes, 1

The sixties
The central difference scheme becomes unstable (wiggly) when the Peclet number is large. The cure is to decrease the grid size.

The seventies
Upwind difference opened the way for infinitely high Reynolds numbers, but false diffusion could in many cases be larger than diffusion of physical kind.

The eighties and the nineties
Second order schemes decreased the effect of false diffusion.
Different Discretization Equations, 3

The flow is studied in a case where the length $x$ is equal to 4. The boundary values $c_0$ and $c_3$ are equal to 1.0 and 0.0.

Upwind scheme e.g. $c_e = c_P$ and $u = 3.0$
History and Numerical Schemes, 2

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False Diffusion
Higher Order Schemes

Second order upwind scheme is an example of a new scheme developed in the middle of the seventies.

The one-dimensional case with the velocity $u = 3.0$ and 1st and 2nd order upwind scheme
False Diffusion and Order of the Schemes

Flow from an opening, which is inclined at ~30 deg. to the mesh. Three-dimensional flow.

Profile at the upper surface at a distance of 1 m from the opening.

Dispersive error
Diffusive error
The sixties
The central difference scheme becomes unstable (wiggly) when the Peclet number is large. The cure is to decrease the grid size.

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Boundary Conditions

- Wall boundary
- Free boundary
- Plane of symmetry
- Air supply opening
- Air exit opening
- Obstacle boundary

Air supply opening
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Quality Control

Quality control consists of these major steps:
- recognize possible sources of errors
- check for these errors in your own simulations
- estimate the accuracy of the simulations
- improve the simulations, if possible

Main items in this chapter are:
- Steps in a CFD simulation
- Sources of errors and uncertainties
- How to ensure high quality predictions (recommendations)
- Questions to ask the CFD engineer as regards the work reported
- Additional advice and remarks
- A short check list
Quality Control, Sources of Errors and Uncertainties

Some examples: 2D treatment instead of 3D

Simplification, modelling level

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Cell Quality

Large atrium in shopping center
- $V = 100\text{m} \times 30\text{m} \times 15\text{m} = 45000\text{m}^2$
- $N = 2.6 \text{ Mio. cells}$

$N = 44.4 \times 10^3 V^{0.36}$

Office room
- $V = 5\text{m} \times 4\text{m} \times 2.5\text{m} = 50\text{m}^2$
- $N = 200'000 \text{ cells}$

Monitoring velocities versus number of cells in the prediction
Cell Quality

- Higher resolution boundary layer area
- Low resolution potentially critical area

- Potentially critical area due to distorted cells
  - Expansion ratio
  - Aspect ratio
Turbulence Model

3D wall jet in a room simulated by a *k-epsilon Model* and a *Reynolds Stress Model*.

Profile near ceiling seen from above. *k-epsilon* model. White core: velocities > 3.5 m/s.

Profile near ceiling seen from above. RSM model. White core: velocities > 3.5 m/s.

Side view of profile in mid-plane. *k-epsilon* model. White core near ceiling: velocities > 3.0 m/s.

Side view of profile in mid-plane. RSM model. White core near ceiling: velocities > 3.0 m/s.

Schälin and Nielsen
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CFD Combined with Other Prediction Models

- Thermal simulation
- Energy storage
- Electromagnetism
- Forces/structure
- Mass balance
- Energy balance
- Navier Stokes transport equations
- Turbulence
- Radiation
- Other...
- Comfort
- Particles
- Sound
- Humidity or other gaseous pollutants

Main effects included in CFD codes
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Application of CFD Codes in Building Design

The applications of CFD in buildings may be grouped under the following headings:

- Prediction of air jet diffusion
- Analysis of Room air movement
- Prediction of contaminant dispersal
- Modelling emission from materials and equipment in buildings
- Indoor air quality prediction
- Thermal comfort assessment
- Mean age of air and ventilation effectiveness predictions
- Prediction of fire and smoke spread
- Wind flow around buildings
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## Case Studies on Different Air Distribution Systems

Five air distribution systems are compared with each other. They are all installed in the same room, and they all handle the same situation and the same load.

<table>
<thead>
<tr>
<th>System</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing ventilation with end wall mounted diffuser.</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>Vertical ventilation with a textile terminal.</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Displacement ventilation. End wall mounted low velocity diffuser.</td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>Mixing ventilation generated by a ceiling mounted radial diffuser.</td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>
The Test Room

The test room is the IEA Annex 20 room with length, width and height equal to 4.2 m, 3.6 m and 2.5 m. The heat load consists of two PCs, two desk lamps and two manikins producing a total heat load of 480 W. One work place is used in some of the experiments (240 W).
Case Study, Mixing Ventilation with Wall Mounted ATD
Simulation of the Diffuser

Diffuser A

Diffuser B

\[ u \text{ (m/s)} \]

\[ z \text{ (m)} \]

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Mixing Ventilation with End Wall Mounted Diffuser
Case Study, Vertical Ventilation
Vertical Ventilation, Diffuser

A

B

C

D

E

F

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Vertical Ventilation, Diffuser

1st order steady state equations, $k-\varepsilon$ turbulence model, 300,000 cells
Vertical Ventilation

BC: Diffuser F
Vertical Ventilation, Quality Control

Velocity in y-direction

Monitoring points

Velocity

Number of grid points

0 10^5 2 \cdot 10^5 3 \cdot 10^5
Vertical Ventilation

Predictions in the whole room

\( n = 5 \text{ h}^{-1} \)

218,400 grid points
Case Study, Displacement Ventilation
Diffuser for Displacement Ventilation
Displacement Ventilation
Case Study, Mixing Ventilation with Ceiling Mounted ATD
Mixing Ventilation with Ceiling Diffuser, Diffuser Models

- Fixed-flow diffuser
- Diffuser with horizontal surface
Diffuser Model

Measurements

Diffuser with horizontal surface
CFD Simulations

Temperatures

Velocities at the height of 1.80 m close to the side walls
Simulation of Unsteady Flow
(Time Dependent Equations)
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CFD Manikins

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Additional literature


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