On the Feasibility of CFD for Transient Airflow Simulations in Buildings

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Outline

• Introduction

• Physical problems and governing equations

• Numerical methods

• Results

• Applications

• Conclusions
Introduction

Heating, ventilation and air conditioning (HVAC) systems control main indoor air parameters (temperature, velocity, relative humidity, etc.) and create comfortable indoor environment.

Air distribution can be typically evaluated by:
- analytical models
- experimental measurements
- computer simulations

The complexity of indoor airflow makes experimental or analytical investigation extremely difficult and expensive.
Introduction

• **Multizone (airflow network) models** - low computational cost and low accuracy.

• **Zonal models** - moderate computational cost and moderate accuracy, but high case dependence.

• **Computational Fluid Dynamics (CFD)** - high computational cost and high accuracy.
Introduction

• The airflow inside the building is subject to intermittent disturbances caused by opening doors and windows, occupants behavior, weather changes, etc.

• These disturbances play a major role in model predictive control (MPC) applications.

• Transient simulations should be carried out in order to develop high quality models.
Objectives

• To investigate the capabilities of CFD to perform transient simulations of indoor environment.

• To choose a reliable model to perform CFD simulations of indoor environment with minimal computational cost and adequate accuracy.

• To discuss possibilities of using CFD for thermal behavior prediction purposes.
Governing equations

\[ \nabla \cdot \mathbf{u} = 0 \quad \text{(1)} \]
\[ \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = \nu \nabla^2 \mathbf{u} - \frac{1}{\rho} \nabla p + \beta g (T - T_0) \quad \text{(2)} \]
\[ \frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T = \alpha \nabla^2 T, \quad \text{(3)} \]

where \( \mathbf{u} \) is the velocity vector, \( t \) the time, \( p \) the pressure, \( T \) the temperature, \( T_0 \) the reference temperature, \( \nu \) the kinematic viscosity, \( \rho \) the density, \( g \) the gravitational acceleration, \( \beta \) the thermal expansion coefficient and \( \alpha \) the thermal diffusivity.
Test case 1: Differentially heated cavity

\[ \frac{H}{L} = 3.84 \]
\[ \frac{D}{L} = 0.86 \]

\[ Pr = 0.71 \]
\[ Ra = 1.2 \times 10^{11} \]

\[ t_{ref} = Ra^{-1/2} H^2 \alpha^{-1} \]
\[ u_{ref} = Ra^{1/2} (\alpha / H) \]
\[ T_{ref} = \Delta T = T_h - T_c \]

Simulation details for the test case 1

<table>
<thead>
<tr>
<th>Case</th>
<th>$N_x$</th>
<th>$N_y$</th>
<th>$N_z$</th>
<th>$N_{total}$</th>
<th>$\gamma_x$</th>
<th>$\gamma_y$</th>
<th>$\gamma_z$</th>
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<tbody>
<tr>
<td>M1.1</td>
<td>8</td>
<td>30</td>
<td>4</td>
<td>$9.60 \times 10^2$</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>M1.3</td>
<td>12</td>
<td>50</td>
<td>8</td>
<td>$4.80 \times 10^3$</td>
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<td>0.0</td>
<td>0.0</td>
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<tr>
<td>M1.5</td>
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<td>80</td>
<td>12</td>
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<td>0.0</td>
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<tr>
<td>M1.7</td>
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<td>120</td>
<td>20</td>
<td>$7.20 \times 10^4$</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>M1.9</td>
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<td>180</td>
<td>30</td>
<td>$2.70 \times 10^5$</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>M1.11</td>
<td>100</td>
<td>320</td>
<td>40</td>
<td>$1.28 \times 10^6$</td>
<td>2.0</td>
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<td>0.0</td>
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<tr>
<td>REF1</td>
<td>140</td>
<td>500</td>
<td>70</td>
<td>$4.90 \times 10^6$</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

All grids are Cartesian, uniform in the vertical ($y$) and spanwise ($z$) directions and refined near the walls in the horizontal ($x$) direction. Simulation duration - 25 non-dimensional time units.
Test case 2: Mixed convection

\[ A_h = \frac{L}{L} = 1^2 \]
\[ A_d = \frac{D}{L} = 0.3 \]
\[ A_{in} = \frac{L_{in}}{L} = 0.017 \]
\[ A_{out} = \frac{L_{out}}{L} = 0.023 \]

\[ Pr = 0.71 \]
\[ Ra = 2.4 \times 10^9 \]
\[ Fr = 5.24 \]
\[ Re = 684 \]

\[ t_{ref} = L^{5/2}(\alpha Fr)^{-1}(L_{in}Ra)^{-1/2} \]
\[ u_{ref} = L^{-3/2}\alpha Fr(L_{in}Ra)^{1/2} \]
\[ T_{ref} = \Delta T = T_h - T_c \]

Simulation details for the test case 2

<table>
<thead>
<tr>
<th>Case</th>
<th>$N_x$</th>
<th>$N_y$</th>
<th>$N_z$</th>
<th>$N_{in}$</th>
<th>$N_{out}$</th>
<th>$N_{total}$</th>
<th>$\gamma_x$</th>
<th>$\gamma_y$</th>
<th>$\gamma_z$</th>
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<td>2</td>
<td>3</td>
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<td>2.0</td>
<td>0.0</td>
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<tr>
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<td>4</td>
<td>2</td>
<td>3</td>
<td>$2.40 \times 10^3$</td>
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<td>0.0</td>
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<tr>
<td>M2.5</td>
<td>30</td>
<td>25</td>
<td>10</td>
<td>3</td>
<td>4</td>
<td>$9.60 \times 10^3$</td>
<td>1.5</td>
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<td>0.0</td>
</tr>
<tr>
<td>M2.7</td>
<td>45</td>
<td>40</td>
<td>16</td>
<td>4</td>
<td>6</td>
<td>$3.60 \times 10^4$</td>
<td>1.5</td>
<td>2.0</td>
<td>0.0</td>
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<tr>
<td>M2.9</td>
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<td>6</td>
<td>10</td>
<td>$1.44 \times 10^5$</td>
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<tr>
<td>M2.11</td>
<td>120</td>
<td>94</td>
<td>40</td>
<td>10</td>
<td>16</td>
<td>$5.76 \times 10^5$</td>
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</tr>
<tr>
<td>REF2</td>
<td>150</td>
<td>120</td>
<td>50</td>
<td>20</td>
<td>20</td>
<td>$1.20 \times 10^6$</td>
<td>1.5</td>
<td>2.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

All grids are uniform in the spanwise ($z$) direction. In the horizontal ($x$) and vertical ($y$) direction grids are refined near the walls. Simulation duration - 25 non-dimensional time units.
Numerical methods

- **URANS** simulations are performed by the open source CFD code OpenFOAM using transient PIMPLE algorithm and $k$-$\varepsilon$ turbulence model.

- **LES** simulations are performed by the in-house CFD code Termofluids applied to unstructured collocated grids using LES-WALE turbulence model.

- **No-model** simulations are as well performed by the in-house CFD code Termofluids.
Results. Accessing real-time and faster than real-time simulations

**Reference machine:** AMD Opteron 2350, 24 Gb/s memory bandwidth, 1 - 32 cores and 1-4 nodes.

**Target machine:** Intel Core i7-8700K, 41.6 Gb/s memory bandwidth, 6 CPU cores and 1 node.

\[
t_{tgt} = t_{ref} \frac{BW_{ref}}{BW_{tgt}} \frac{CPU_{ref}}{CPU_{tgt}} \frac{NODE_{ref}}{NODE_{tgt}}
\]

\[
R = \frac{t_{wc}}{t_{phy}}
\]

\[
R < 1
\]
Simulation requirements

• Simulation duration: 4-5 hours;

• Computational resources: 6 CPU cores;

• Time ratio: $R \leq 0.2$;

• Relative error: $\leq 15 \%$. 
Spearman's rank correlation coefficient

Spearman’s rank correlation coefficient measures the quality of transient prediction:

\[
rs = \frac{\sum_i (a_i - \langle a \rangle)(b_i - \langle b \rangle)}{\sqrt{\sum_i (a_i - \langle a \rangle)^2 \sum_i (b_i - \langle b \rangle)^2}},
\]

(4)

where \(a_i, b_i\) are the i-th members of the compared sets of data and \(\langle a \rangle, \langle b \rangle\) are the mean values of the same sets of data.
Global quantities checked

Nusselt number

$$Nu = \left. \int_0^H \frac{\partial T}{\partial x} dy \right|_{x=0}$$

Kinetic energy

$$E = \int_V \frac{u^2}{2} dV$$

Enstrophy

$$\Omega = \int_V \omega^2 dV$$

Temperature at the center of the cavity

$$T$$
Test case 1. Time evolution of Nu number on the hot wall and its Spearman's rank correlation for different grids and turbulence models.
Test case 1. Time evolution of kinetic energy and its Spearman's rank correlation for different grids and turbulence models.
Test case 1. Time evolution of enstrophy and its Spearman's rank correlation for different grids and turbulence models.
Time evolution of temperature for the differentially heated cavity case. A DNS study.
Test case 2. Time evolution of temperature at the center of the cavity and its Spearman's rank correlation for different grids and turbulence models.
Test case 2. Time evolution of kinetic energy and its Spearman's rank correlation for different grids and turbulence models.
Test case 2. Time evolution of enstrophy and its Spearman's rank correlation for different grids and turbulence models.
Time evolution of velocity magnitude for mixed convection case. A DNS study.
**Potential of accessing transient CFD simulations for MPC applications**

<table>
<thead>
<tr>
<th>Model</th>
<th>Differentially heated cavity</th>
<th>Mixed convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid resolution</td>
<td>$8.30 \times 10^3$</td>
<td>$3.60 \times 10^4$</td>
</tr>
<tr>
<td>Time ratio</td>
<td>$R \approx 1$</td>
<td>$R \approx 23$</td>
</tr>
</tbody>
</table>

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Potential availability of transient CFD simulations on office workstation computers for MPC systems over the next years

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Conclusions

• Turbulence modelling in coarse grid CFD simulations is not very beneficial.
• URANS approach failed to predict the transient evolution of the airflow correctly.
• Nowadays it is not possible to use transient CFD simulations for MPC systems of buildings.
• With the rapidly growing computational capacity, CFD would be feasible for control purposes on office workstations within the next 5 years for closed systems and within 10 years for open systems.
Future work

• Increase the complexity of the problems analyzed.

• Optimize the existing numerical algorithms and accelerate them using a fully-portable, algebra-based framework for heterogeneous computing on GPUs.

• Improve the predictions quality and reduce the computational cost using a machine learning system of training CFD simulations on previously-run data sets.
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Questions and Comments

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