Towards Real-Time CFD Simulation of Indoor Environment

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Outline

Introduction

Indoor environment. State of art

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

Indoor environment simulation models

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

Objectives

To investigate the capabilities of CFD to perform real-time and even faster simulations of indoor environment.

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

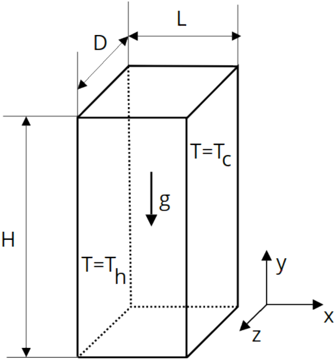
To discuss possibilities of using CFD for design and short-term thermal behaviour prediction purposes.

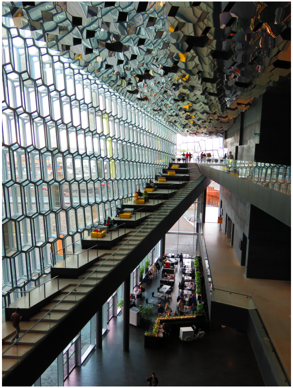
Physical problem and governing equations

Problem description

$H/L = 3.84$ [1]
$D/L = 0.86$

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





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[1] D. Saury, N. Rouger, F. Djanna and F.Penot. Natural convection in an air-filled cavity: Experimental results at large Rayleigh numbers. *Int Comm Heat Mass Transf*, 38(6):679-687, 2011.

Physical problem and governing equations

Governing equations

$$
\begin{aligned}
&\nabla \cdot \mathbf{u} = 0 \\
&\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = PrRa^{-1/2}\nabla^2\mathbf{u} - \nabla p + \mathbf{f} \\
&\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla)T = Ra^{-1/2}\nabla^2 T \\
&\mathbf{f} = (0, PrT, 0)
\end{aligned}
$$

Reference quantities:

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

Numerical methods

RANS approach

RANS simulations are performed by the open source CFD code **OpenFOAM** using *"buoyantBoussinesqPimpleFoam"* solver.

RANS models used:

- **SST** $\boldsymbol{k-\omega}$ model - under-predicting overall heat transfer, highest computational cost among all three models. comparison with LES models.
- $\boldsymbol{k-\epsilon}$ model - good overall performance, low computational cost.
- **RNG** $\boldsymbol{k-\epsilon}$ model - good overall performance, computational cost is higher than $k-\epsilon$ model.

Numerical methods

LES discretization

Collocated grid - in-house CFD code **Termofluids** applied to unstructured meshes.

Staggered grid - in-house CFD code **STG** based on a fourth-order symmetry-preserving finite volume discretization on structured grids.

Numerical methods

LES on collocated grid

Simulations are performed by the in-house CFD code **Termofluids**.

LES models used:

- **LES-WALE** - good overall performance, moderate computational cost.
- **LES-VMS(WALE)** - good overall performance, high computational cost.

Numerical methods

LES on staggered grid

Simulations are performed by the in-house **STG** based on a fourth-order symmetry-preserving finite volume discretization on structured staggered grids.

LES models used:

- **LES-WALE** - good overall performance, moderate computational cost.
- **LES-QR** - least accurate results for the coarse grids, moderate computational cost.
- **LES-S3PQ** - good overall performance, low computational cost.

Numerical methods

Models chosen

Collocated grid:

- RANS $k - \epsilon$
- LES-WALE
- No model

Staggered grid:

- LES-S3PQ
- No model

Numerical methods

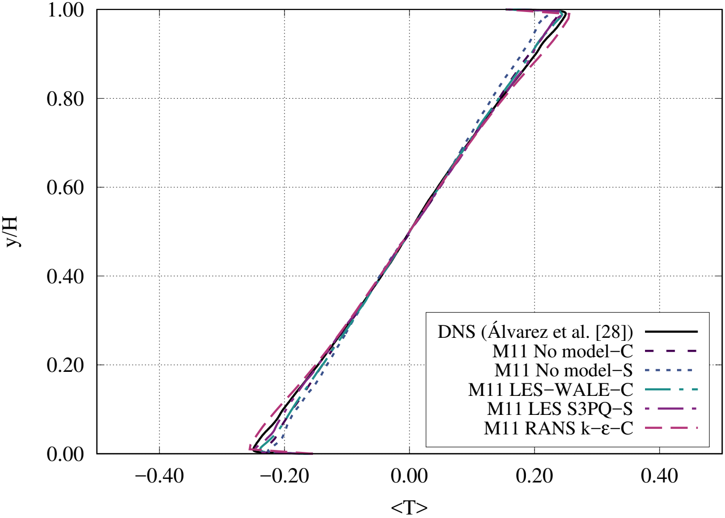
Simulation details

Case	N_x	N_y	N_z	N_{total}	γ_x	$(\Delta x)_{min}$
M0 (DNS)	450	900	256	1.04×10^8	2.00	4.28×10^{-5}
M1	8	30	4	9.60×10^2	2.00	7.97×10^{-3}
M3	12	50	8	4.80×10^3	2.00	4.46×10^{-3}
M5	18	80	12	1.73×10^4	2.00	2.70×10^{-3}
M7	30	120	20	7.20×10^4	2.00	1.49×10^{-3}
M10	70	240	40	6.72×10^5	2.00	5.40×10^{-4}
M11	100	320	40	1.28×10^6	2.00	4.05×10^{-4}

Simulation duration: DNS - 600 time units; LES - 1200 time units; RANS - 250 time units.

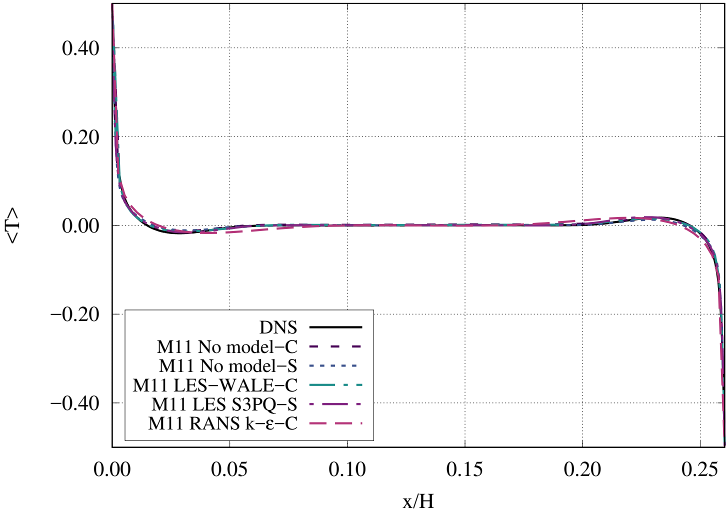
Results

Verification



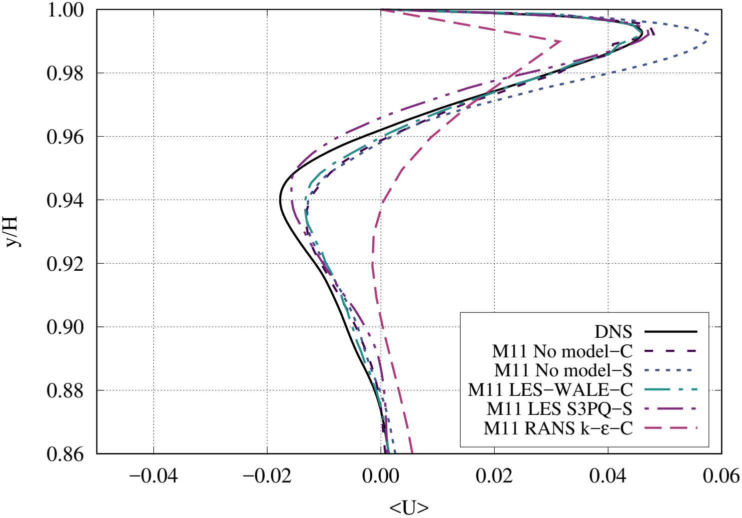
Results

Verification



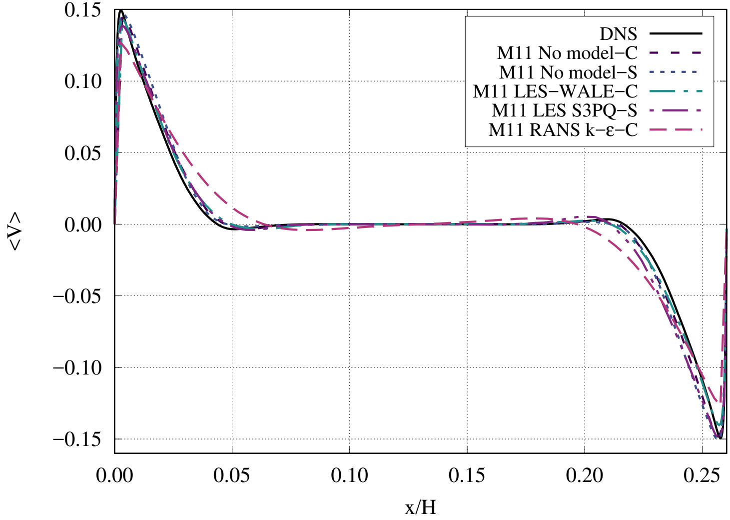
Results

Verification



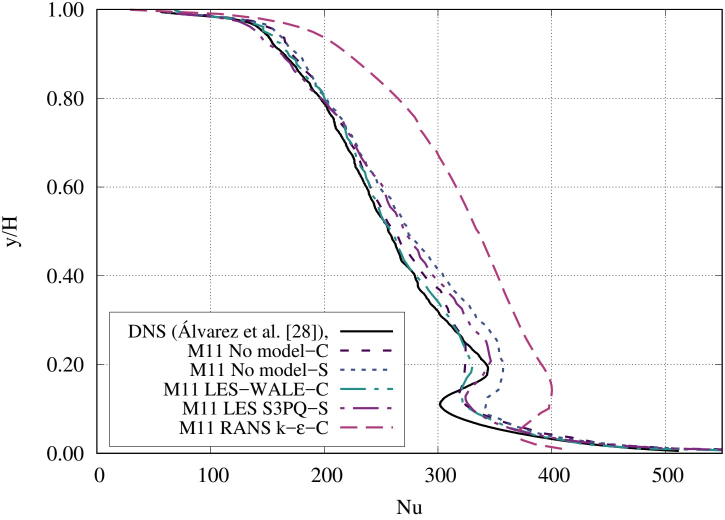
Results

Verification



Results

Verification



Results

Accessing real-time and faster than real-time simulations

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

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

$$t_{tgt} = t_{ref} \frac{BW_{ref}}{BW_{tgt}} \frac{CPU_{ref}}{CPU_{tgt}} \frac{NODE_{ref}}{NODE_{tgt}}$$

$$R = \frac{t_{wc}}{t_{phy}}$$

$$R < 1$$

Results

Global quantities checked

Average Nusselt number $$< Nu >= \int_0^1 \frac{\partial < T >}{\partial x} dy \bigg|_{x=0}$$

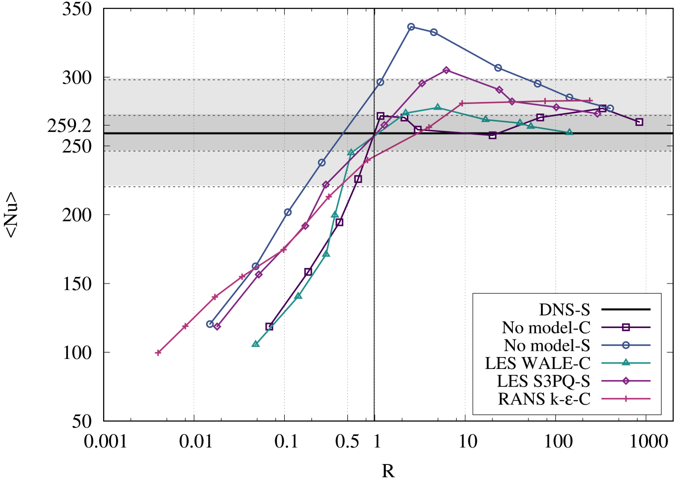
Average stratification $$< S >= \frac{\partial < T >}{\partial y} dx \bigg|_{y=0.5}$$

Average kinetic energy $$< E >= \int_V \frac{< \mathbf{u}^2 >}{2} dV$$

Average enstrophy $$< \Omega >= \int_V < \omega^2 > dV$$

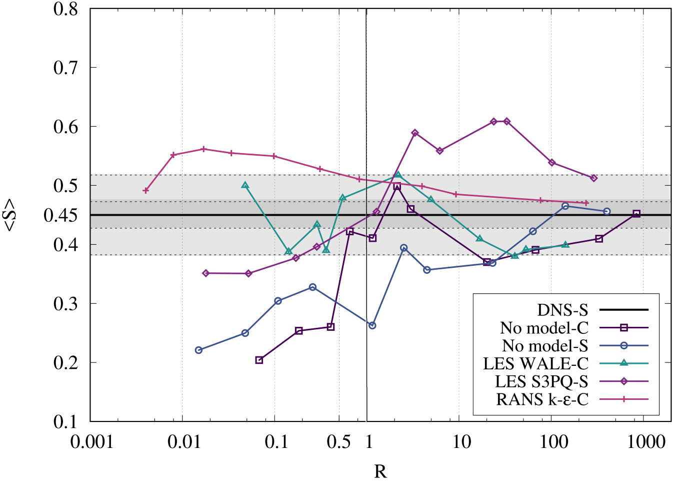
Results

Global quantities - $< Nu >$



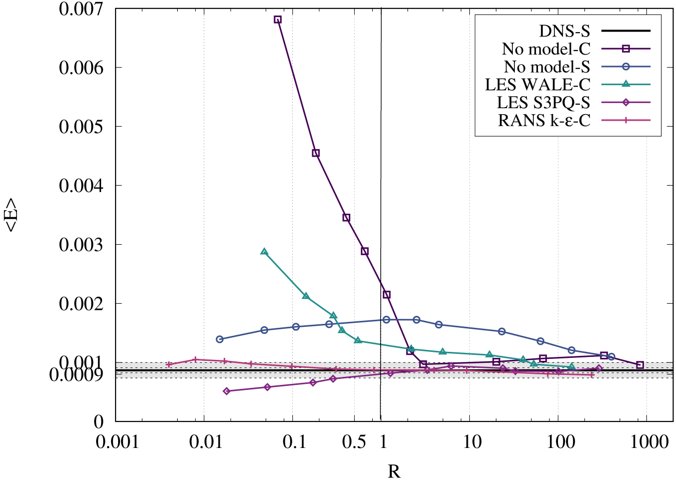
Results

Global quantities - $< S >$



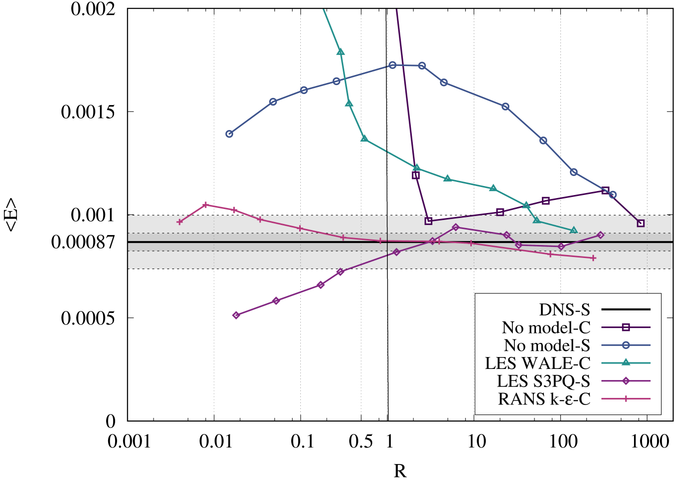
Results

Global quantities - $< E >$



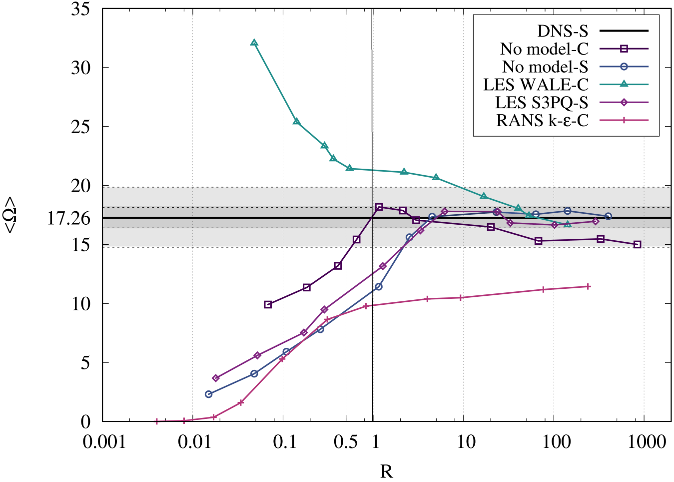
Results

Global quantities - $< E >$ zoomed



Results

Global quantities - $< \Omega >$



Results

Model chosen

LES-S3PQ model on staggered grid showed the best overall performance and is chosen for further tests.

Applications

Potential of real-time simulations for design and control purposes

	Conceptual design	**Detailed design**	**Control**
Simulation duration	24 hours	24 hours	15 minutes
Time ratio	$R \leqslant 0.5$	$R \leqslant 0.5$	$R \leqslant 0.1$
Computational resources	6 cores	72 cores	6 cores
Relative error	15 %	5 %	5 %

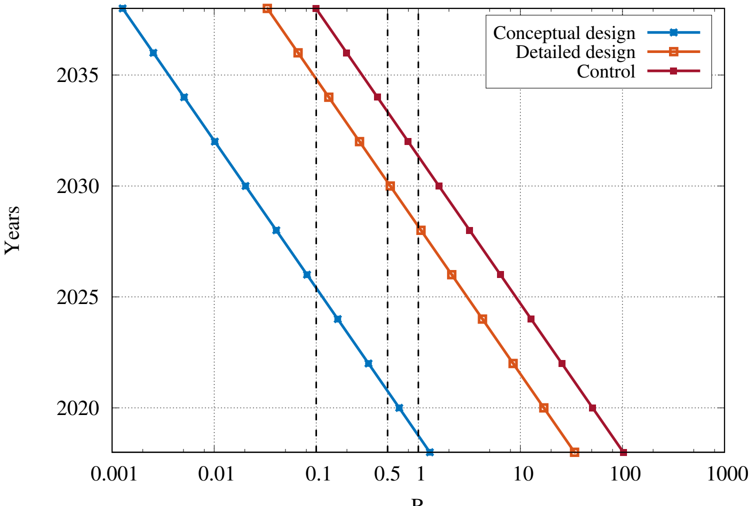
Applications

Potential of real-time simulations for design and control purposes

	Conceptual design	**Detailed design**	**Control**
Grid resolution	17280	672000	672000
Wall-clock time, sec	$t_{wc} = 1533$	$t_{wc} = 40690$	$t_{wc} = 122057$
Time ratio	$\mathbf{R \approx 1.3}$	$\mathbf{R \approx 34}$	$\mathbf{R \approx 100}$

Applications

Potential for the future applications



Results

Accessing real building scale

Experimental scale:	**Simulated scale:**	**Generic building scale:**
$\Delta T = 20^\circ C$	$\Delta T = T_{hot} - T_{cold} = 28^\circ C - 23^\circ C = 5^\circ C$	$\Delta T = T_{hot} - T_{cold} = 28^\circ C - 23^\circ C = 5^\circ C$
$L \times H \times D = 1.00 \times 3.84 \times 0.86m$	$L \times H \times D = 1.59 \times 6.10 \times 1.37m$	$L \times H \times D = 10 \times 10 \times 10m$
$V = 3.30m^3$	$V = 13.29m^3$	$V = 1000m^3$

Results

Accessing real building scale

A generic building is approximately 75 times bigger than simulated cavity.

Assuming that the computational cost scales linearly with the volume.

$R \approx 100$ for 15% relative error using 6 CPU cores.

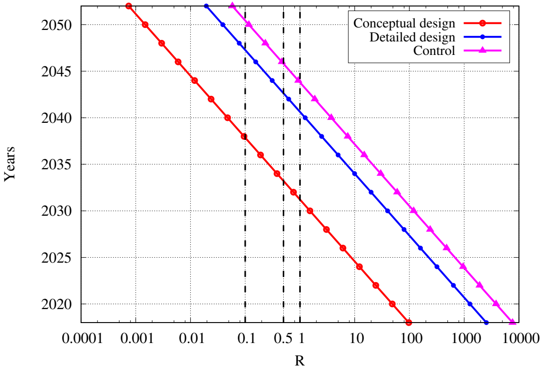
$R \approx 7650$ for 5% relative error using 6 CPU cores.

$R \approx 2550$ for 5% relative error using 72 CPU cores.

Results

Complete building scale

CFD simulations for a complete building would be available in less than 10 yeas for early design stage, in approximately 15 years for detailed design and within three decades for MPC systems.



Conclusions

- LES turbulence models in overall show better performance than RANS.
- The simulations stability could be improved using a staggered symmetry-preserving discretization together with turbulence modelling.
- At this moment CFD simulations are not affordable for indoor environment.
- CFD would be available for design purposes within two decades.
- HVAC predicting control systems equipped with CFD simulation tools will get affordable in approximately two-three decades.

Future work

- The problems analyzed would be extended to ventilated cavities with heat sources and domains with complex geometry.
- The simulations financial costs in terms of electrical power spent per CPU hour would be analyzed.
- Existing numerical algorithms would be optimized and accelerated using a fully-portable, algebra-based framework for heterogeneous computing on GPUs.

THANKS FOR YOUR ATTENTION!

Ready for your questions!