

Large-Eddy Simulation of an axisymmetric and isothermal jet developing in a room based on the Lattice Boltzmann Method

Speaker:

Teddy Gresse

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Contributors:

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- **Introduction**
- MINIBAT test-cell
- The LBM-LES approach
- Numerical modelling
- Isothermal jet analysis
- Conclusions and perspectives



Introduction

- Important **role of HVAC** induced convective flows on **thermal comfort in buildings**

HVAC : Heating, Ventilation and



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HVAC : Heating, Ventilation and Air-Conditioning / RANS : Reynolds Averaged Navier-Stokes

Zhai, Z, Zhang, Z, Zhang, W, and Chen Q.. 2007. «Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part-1: Summary of Prevalent Turbulence Models.» *HVAC&R Research*.
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- **LBM very efficient** for dealing with separated low Mach flows in complex geometries

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→ **Objective : Evaluation of the ability of a LBM-LES modelling to predict a turbulent jet flow developing in a room equipped with a ventilation system**

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- **MINIBAT test-cell**
- The LBM-LES approach
- Numerical modelling
- Jet analysis
- Conclusions and perspectives

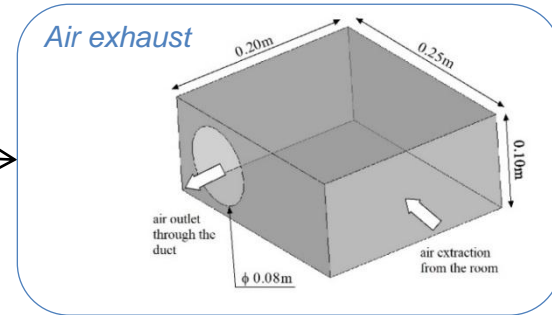
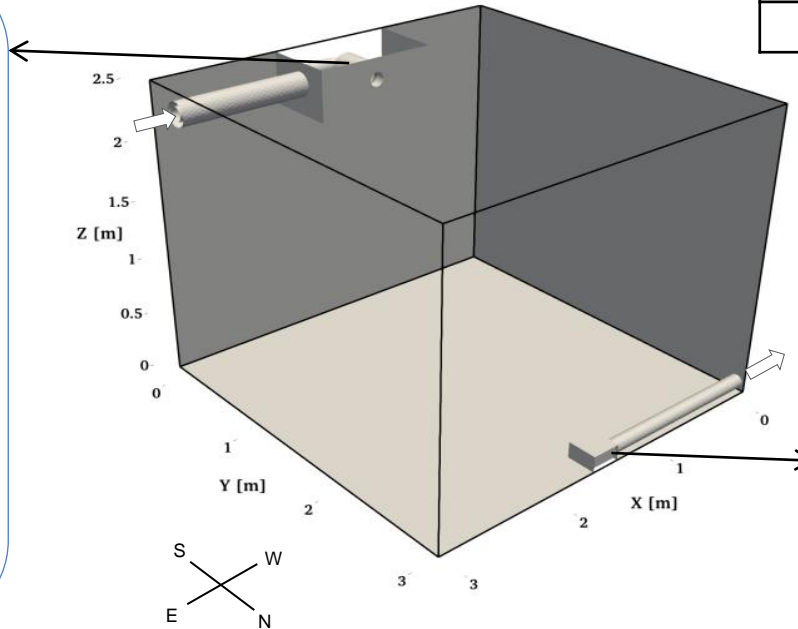
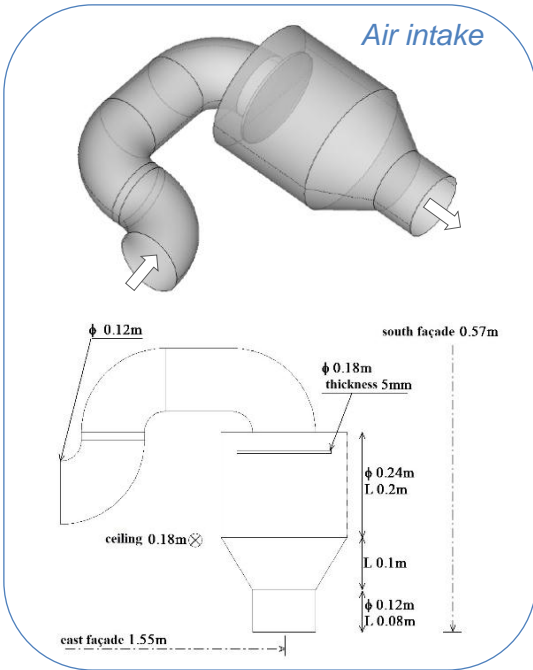


MINIBAT test-cell

→ Experiment from *Kuznik 2005*

Experimental conditions: isothermal jet

T_0 [°C]	Re_D	U_0 [m/s]
21.8	23680	2.96



Kuznik, F. 2005. «Étude expérimentale des jets axisymétriques anisothermes horizontaux se développant près d'une paroi : application à la modélisation numérique des cavités ventilées.» Thèse de doctorat, l'INSA de Lyon.



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The LBM-LES approach



HRR-LBM

- LBM-BGK equation:

$$f_i(x + c_i \delta t, t + \delta t) = f_i^{eq}(x, t) + \left(1 - \frac{1}{\tau}\right) f_i^{neq}(x, t)$$

With

$$\tau = \frac{\nu}{c_s^2} + \frac{\Delta t}{2} \text{ the relaxation time}$$

f_i^{eq} : 3rd order equilibrium distribution function

$f_i^{neq} = f_i - f_i^{eq}$: Hybrid Recursive Reconstruction procedure for the off-equilibrium distribution function (*Jacob et al. 2018*)

→ Multiscale expansions to recover the weakly compressible Navier-Stokes equations ($M_a < 0.1$)

Jacob, J, Malaspinas, O, and Sagaut, P. 2018. «A new hybrid recursive regularised bhatnagar–gross–krook collision model for lattice boltzmann method-based large eddy simulation.» *Journal of Turbulence*.



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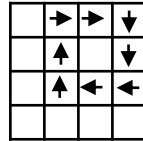
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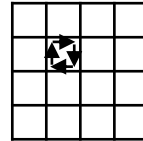
→ Multiscale expansions to recover the weakly compressible Navier-Stokes equations ($M_a < 0.1$)

LES

- Principle:



Resolved



Modeled

→ Eddy viscosity paradigm:

$$R_{ij} = \overline{u'_i u'_j} \cong -2\nu_t S_{ij} + R_{kk} \delta_{ij}$$

- Vreman's subgrid scale model (Vreman 2004)

$$\nu_t = 2.5 C_{sm} \sqrt{\frac{B_\beta}{\alpha_{ij} \alpha_{ij}}} \text{ with } \alpha_{ij} = \frac{\partial \bar{u}_i}{\partial x_j}, \beta_{ij} = \Delta_x^2 \alpha_{ij} \alpha_{ij}$$

- $\nu = \nu_{mol} + \nu_t$ in the relaxation time

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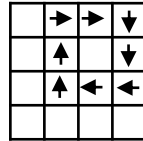
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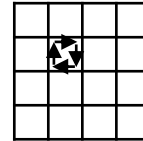
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- $\nu = \nu_{mol} + \nu_t$ in the relaxation time

Boundary conditions

- Immersed boundary approach
- Macroscopic quantities at boundary nodes:
 - Dirichlet: interpolation
 - Neumann: extrapolation
 - Wall functions
- Computation of the velocity gradients on boundary nodes (first-order biased finite difference scheme)
- Reconstruction of the distribution functions

⇒ Validated for pollutant dispersion and urban flows in complex geometries (*Jacob, et al. 2021*)

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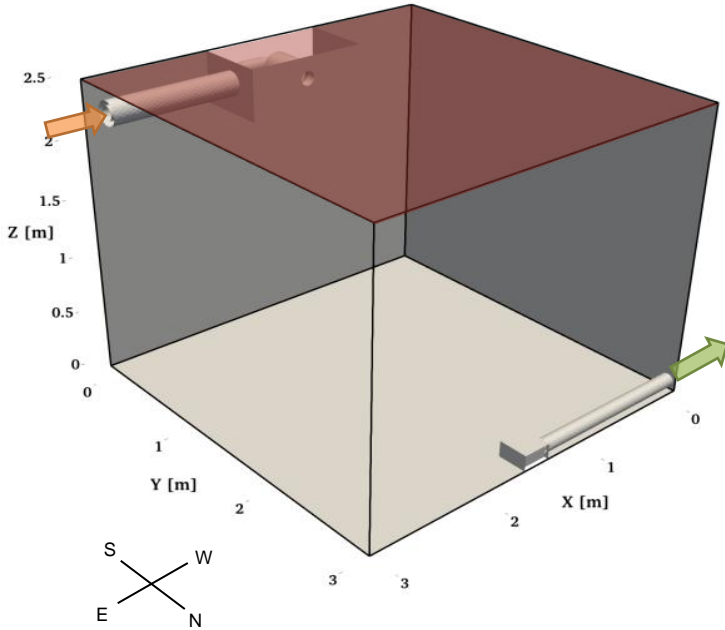


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Numerical modelling

Boundary conditions



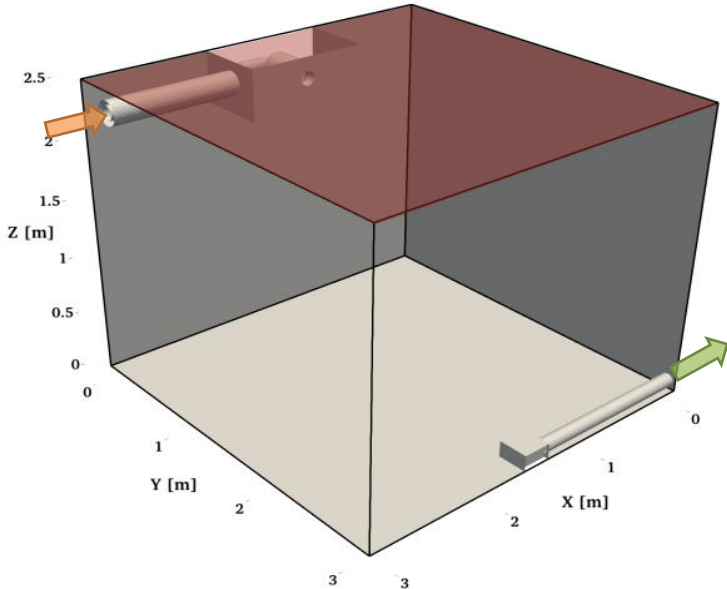
Inlet: constant mass flow





Outlet: constant mass flow

Numerical modelling

Boundary conditions

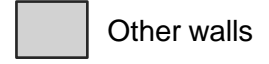


 **Inlet:** constant mass flow
 **Outlet:** constant mass flow

Walls:



Ceiling



Other walls

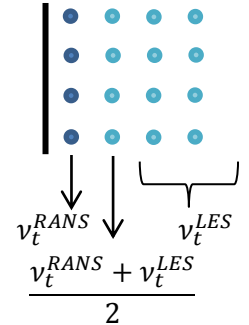
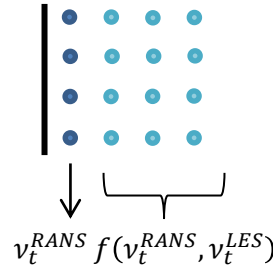
Law of the wall

Explicit log law (*Cai and Sagaut (2021)*)

Classical implicit log law (*Afzal (1996)*)

Eddy viscosity modelling

→ viscosity blending



v_t^{RANS} : mixing length model / v_t^{LES} : Vreman's SGS model ($C_{smag} = 0.1$)

Cai, S.G, and Sagaut, P. 2021. « Explicit wall models for large eddy simulation ». Physics of Fluids.

Afzal, N. 1996. « Wake layer in a turbulent boundary layer with pressure gradient: a new approach. » Gersten, K. (eds.) IUTAM Symposium on Asymptotic Methods for Turbulent Shear Flows at High Reynolds Numbers.



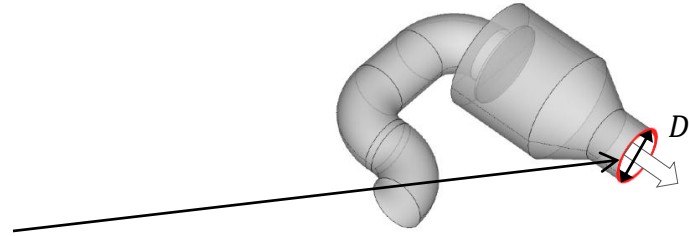
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Numerical modelling

Grid sensitivity analysis

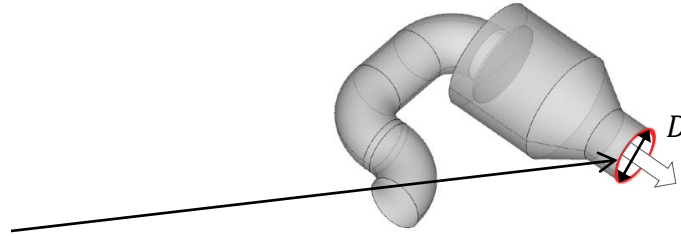
- Criteria:
 - Mean resolved turbulent kinetic energy k_{turb} at the air intake



Numerical modelling

Grid sensitivity analysis

- **Criteria:**
 - Mean resolved turbulent kinetic energy k_{turb} at the air intake
- **Grid refinements** in the air supply duct:
 - Coarse: $\Delta x = D/17.5$
 - Medium: $\Delta x = D/35$
 - Fine: $\Delta x = D/70$



Numerical modelling

Grid sensitivity analysis

- **Criteria:**

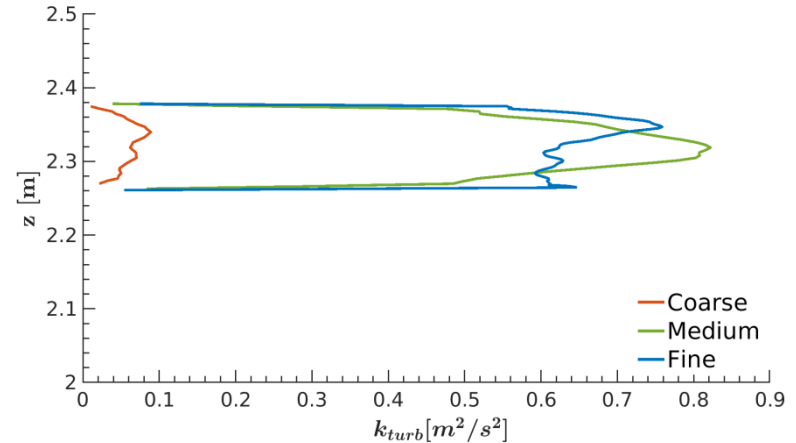
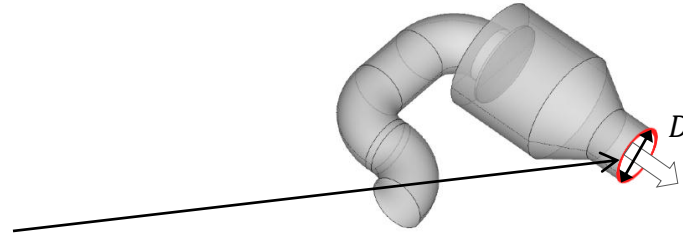
- Mean resolved turbulent kinetic energy k_{turb} at the air intake

- **Grid refinements** in the air supply duct:

- Coarse: $\Delta x = D/17.5$
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- Fine: $\Delta x = D/70$

- **Result:**

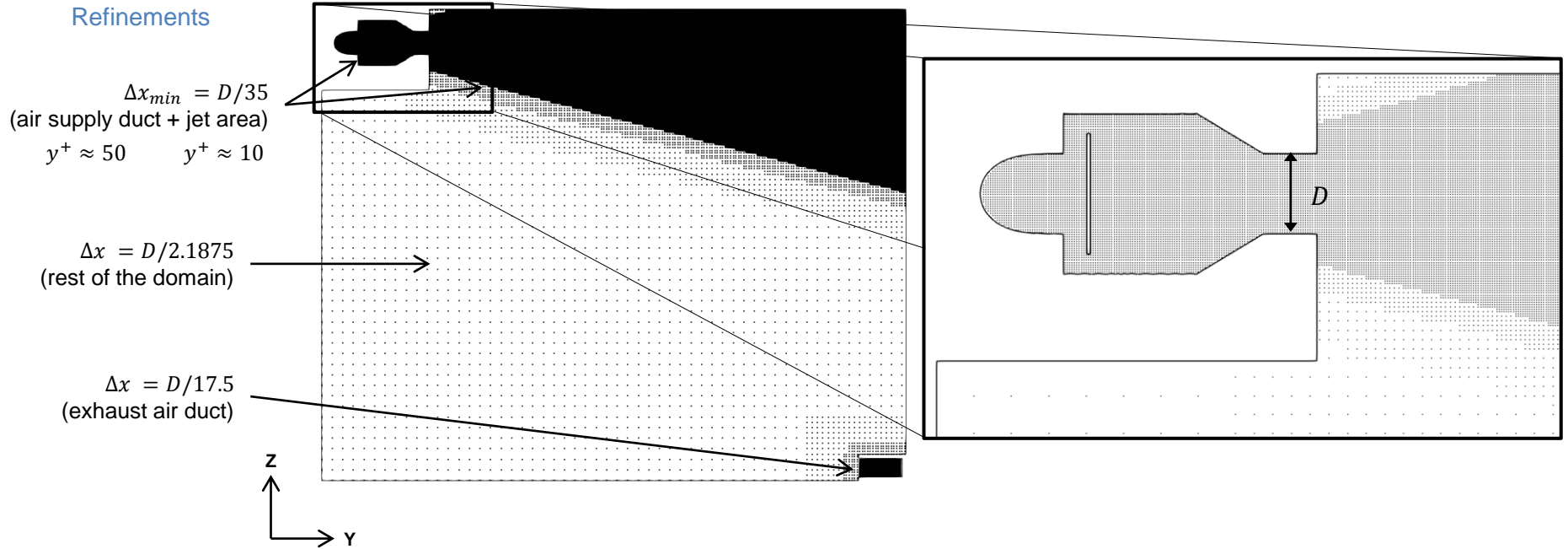
Medium refinement sufficient to recover a correct amount of k_{turb}



Numerical modelling

Final computational grid – median plan

Refinements



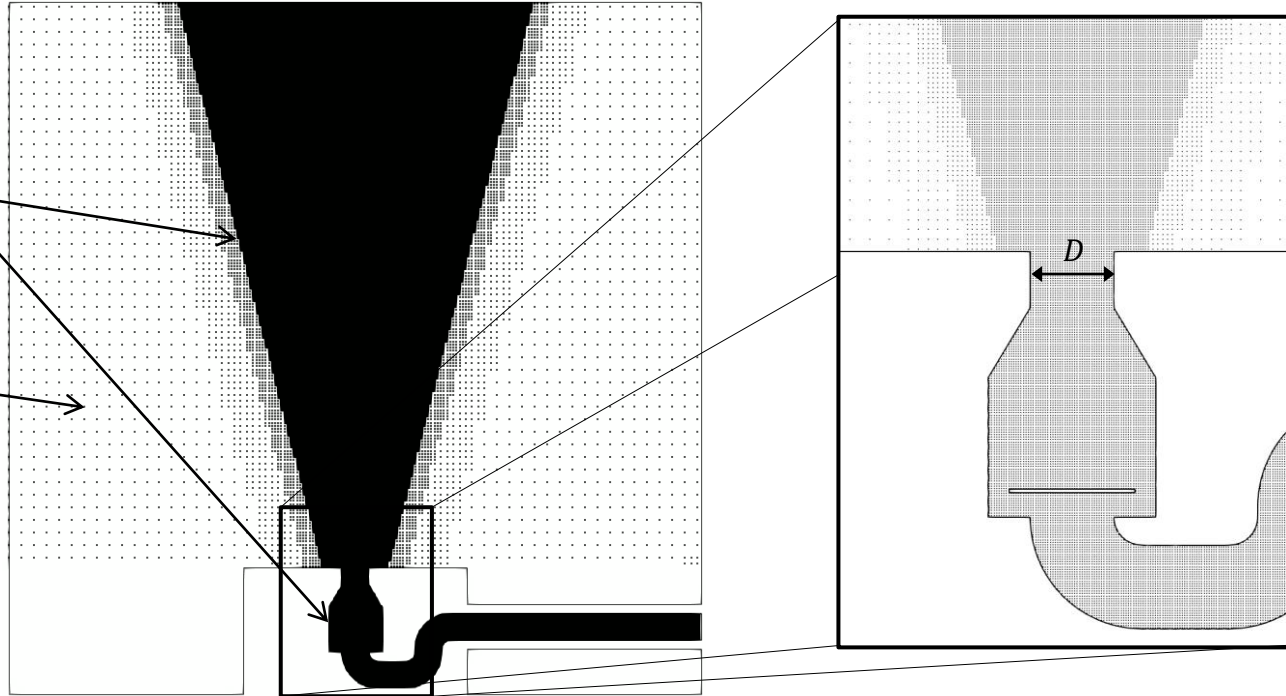
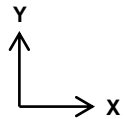
Numerical modelling

Final computational grid – horizontal plan

Refinements

$\Delta x_{min} = D/35$
(air supply duct + jet area)
 $y^+ \approx 50$ $y^+ \approx 10$

$\Delta x = D/2.1875$
(rest of the domain)



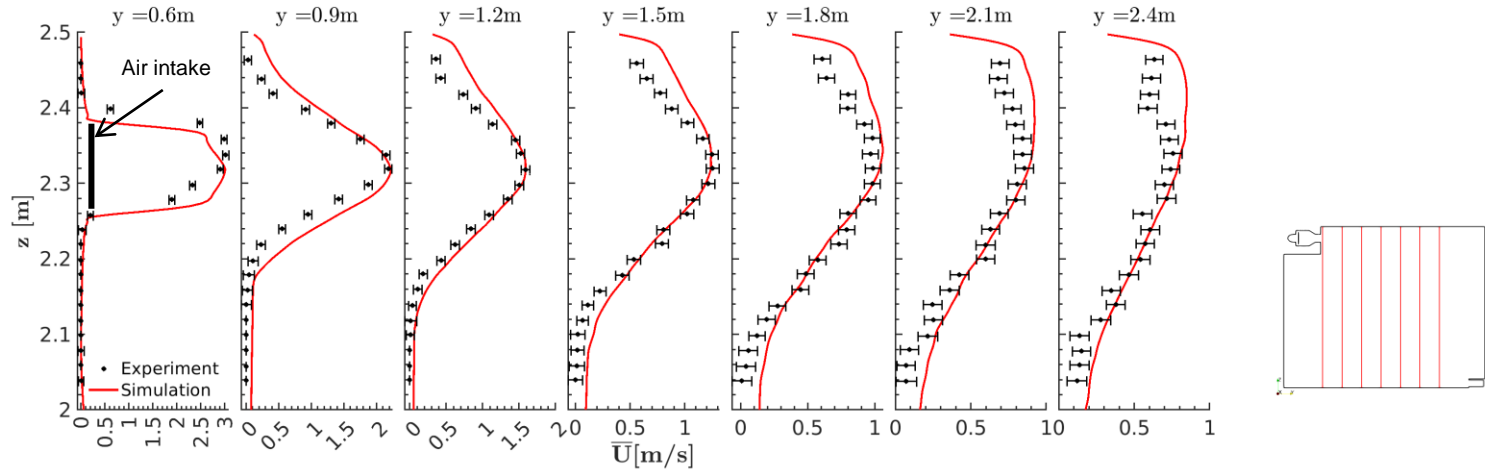
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Jet analysis

Steady state after $45T^*$ with $T^* = L_c/U_c = 4.65/2$ s
Statistical averaging over $15T^*$

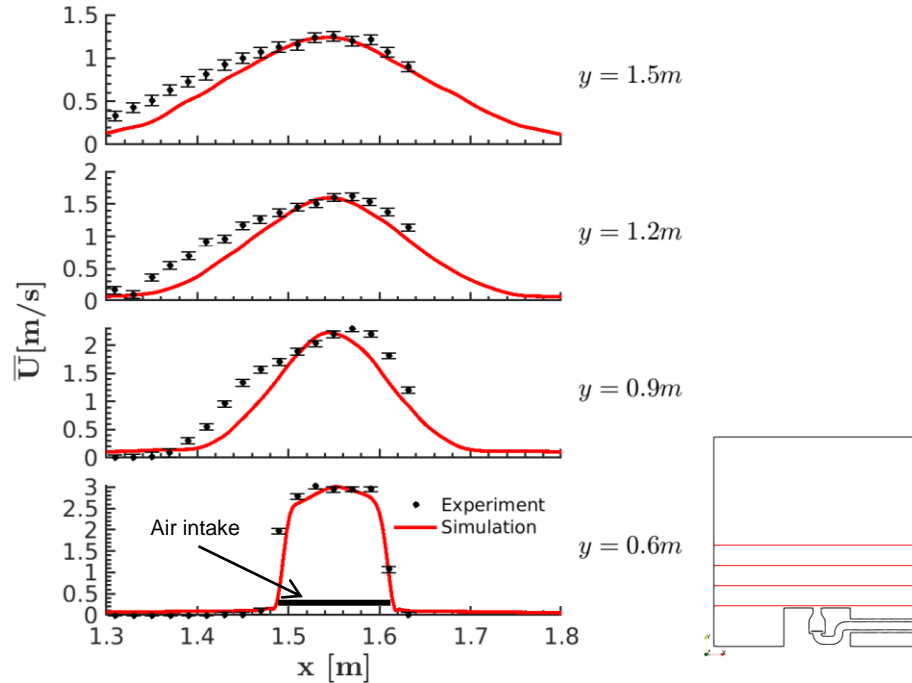
Mean velocity profiles – median plan



- Good agreement with experimental profiles
 - Value and location of the maximum velocity
 - Vertical jet expansion
- Small underestimation of the shear stress close to the ceiling

Jet analysis

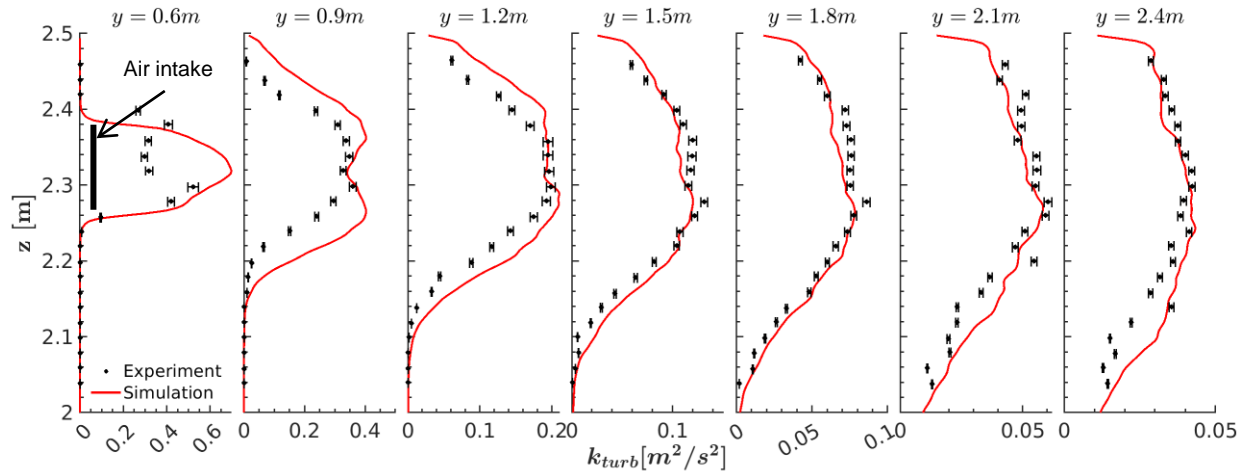
Mean velocity profiles – horizontal plan



- Good agreement with experimental profiles
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 - Lateral jet expansion

Jet analysis

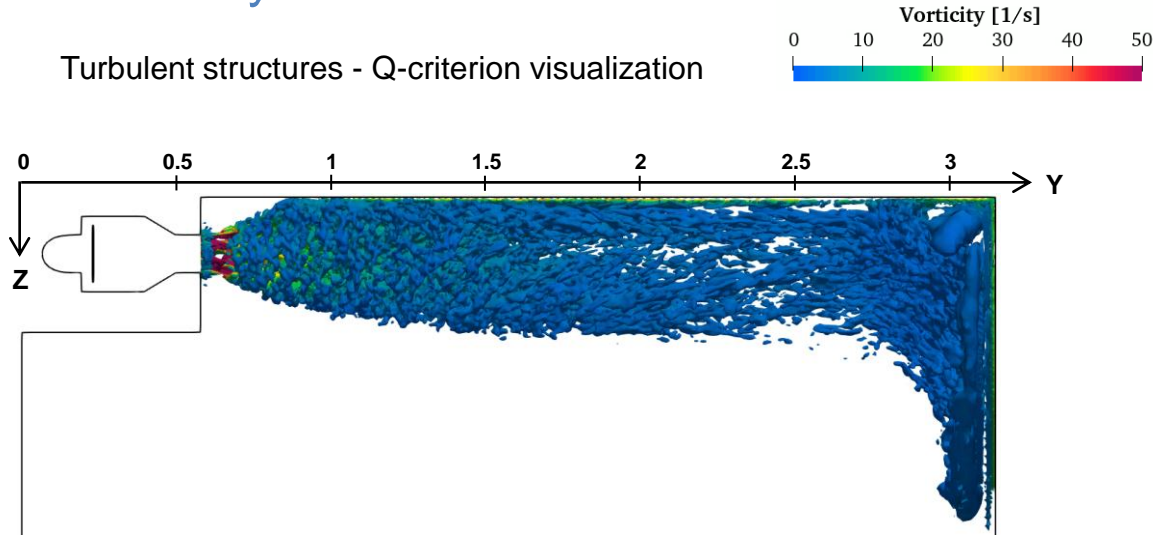
Turbulent kinetic energy profiles – median plan



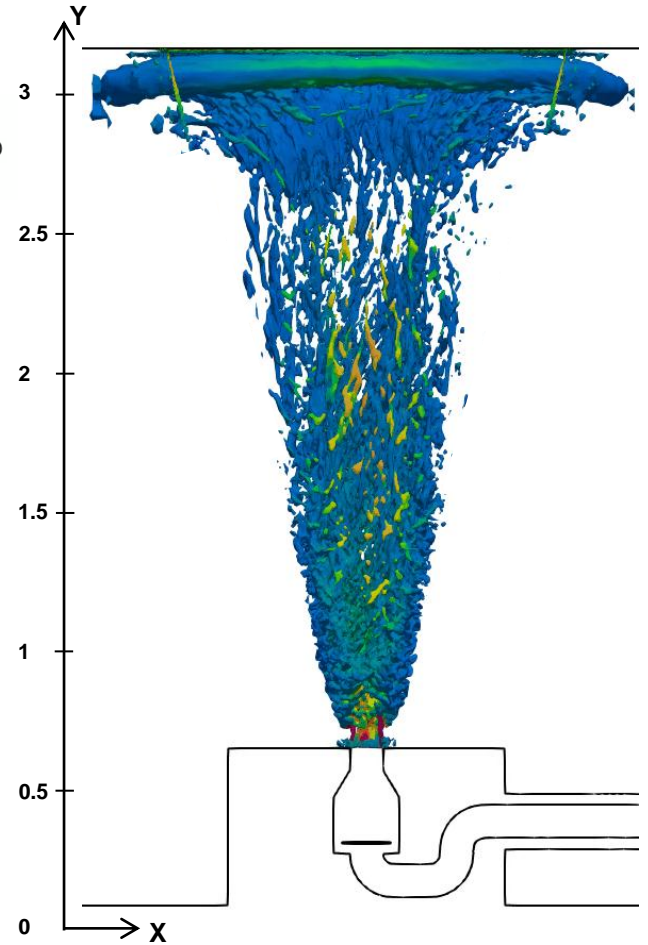
- Good agreement with experimental profiles ($y \geq 1.2m$)
- Overestimation close to the air intake
↳ Modelling of the flow in the air supply duct

Jet analysis

Turbulent structures - Q-criterion visualization



- Development of vortex rings at the air intake (Kelvin-Helmoltz instability)
 - Distortion of the vortex rings due to interaction with the ceiling
 - Remain mainly longitudinal vortices
- Axisymmetric expansion of the turbulence of the jet

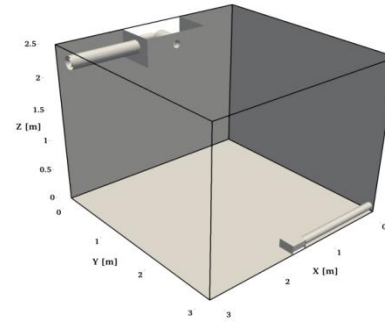


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Conclusions

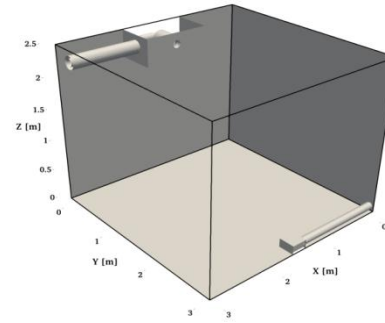
- ✓ Axisymmetric isothermal turbulent jet developing near the ceiling of the MINBAT test-cell



- ✓ LBM-LES with ProLB software

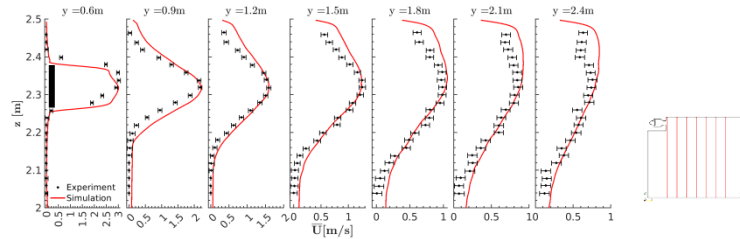
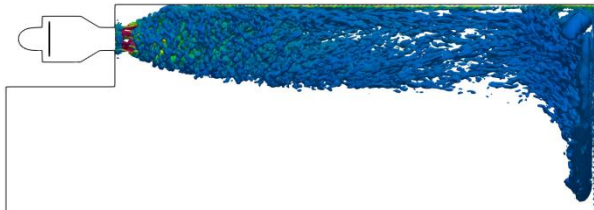
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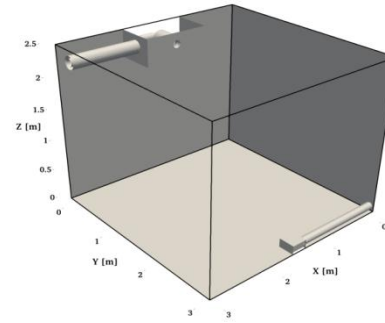
- ✓ Good predictions of the mean velocity and turbulent kinetic energy profiles



- ✓ Analysis of the turbulent structures in the jet with Q-criterion visualization

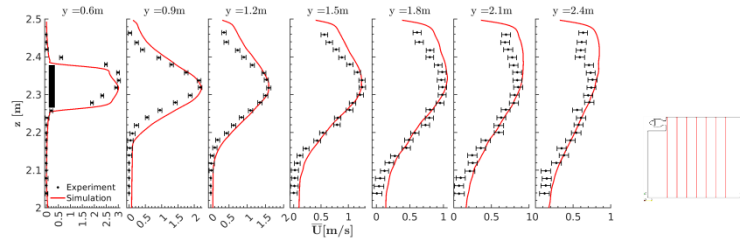
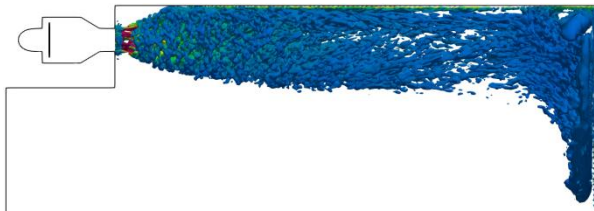
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- ✓ LBM-LES with ProLB software

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→ **Modelling approach suitable for the simulation of isothermal flows within buildings**

Perspectives

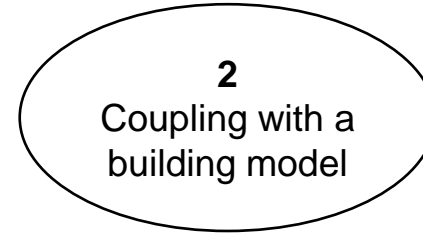
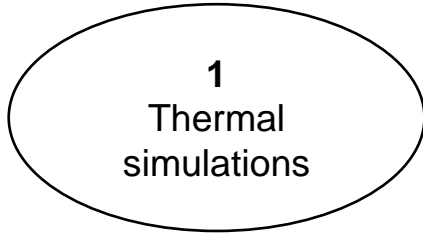
1 Thermal simulations

- Application to hot and cold jet in MINIBAT
(*Kuznik 2005*)
- Modelling issues:
 - Heat transfers at walls
 - Buoyancy effects

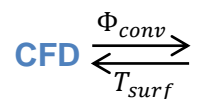
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Perspectives



- Application to hot and cold jet in MINIBAT (*Kuznik 2005*)
- Modelling issues:
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- High resolution building model (*Gresse, et al. 2021*)
- Dynamic boundary conditions at walls 
- Detailed evaluation of heat transfers at walls and thermal confort dynamics

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Gresse, T, Merlier, L, Roux, J-J, and Kuznik, F. 2021. «Development of a 3D and high resolution dynamic thermal model of a room with sun patch evolution for thermal confort applications.» *Building Simulation Conference Proceeding*.





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Questions & Comments

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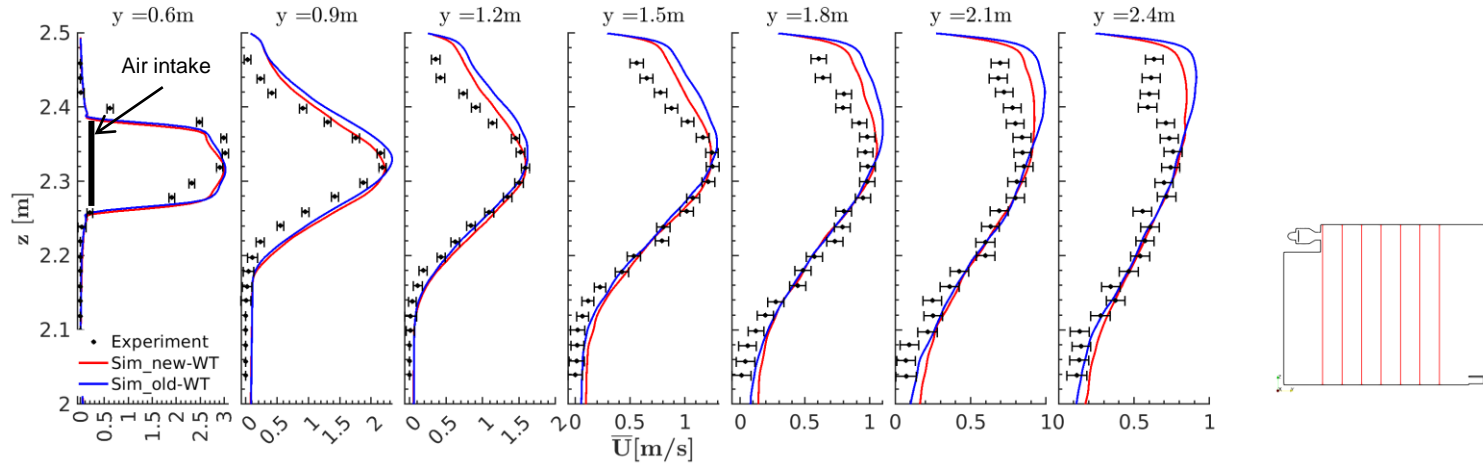
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Appendix

Mean velocity profiles – median plan

Comparison with an old wall treatment at the ceiling



Old wall treatment = implicit log law + simple viscosity blending



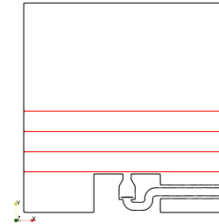
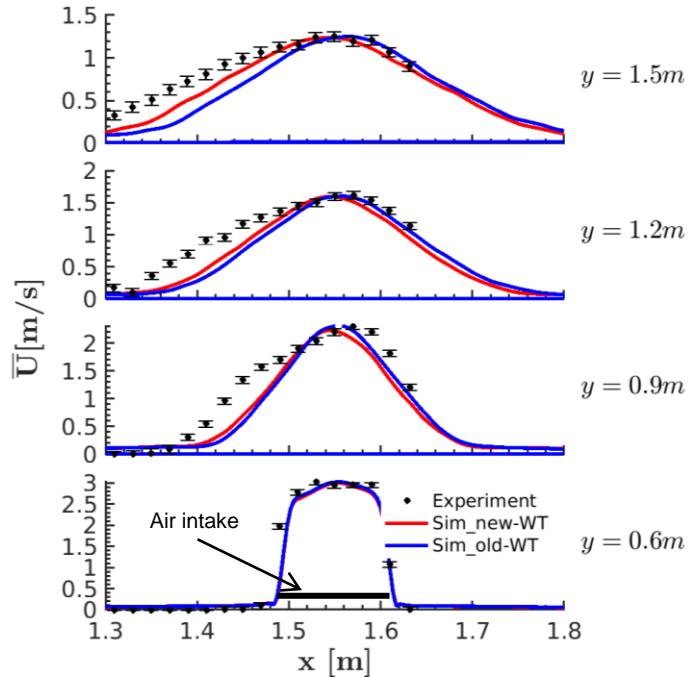
Large-Eddy Simulation of an axisymmetric and isothermal jet developing in a room based on the Lattice Boltzmann Method

Teddy Gresse, Univ Lyon, INSA Lyon, CNRS, CETHIL, UMR5008, Villeurbanne, F-69621, France

Appendix

Mean velocity profiles – horizontal plan

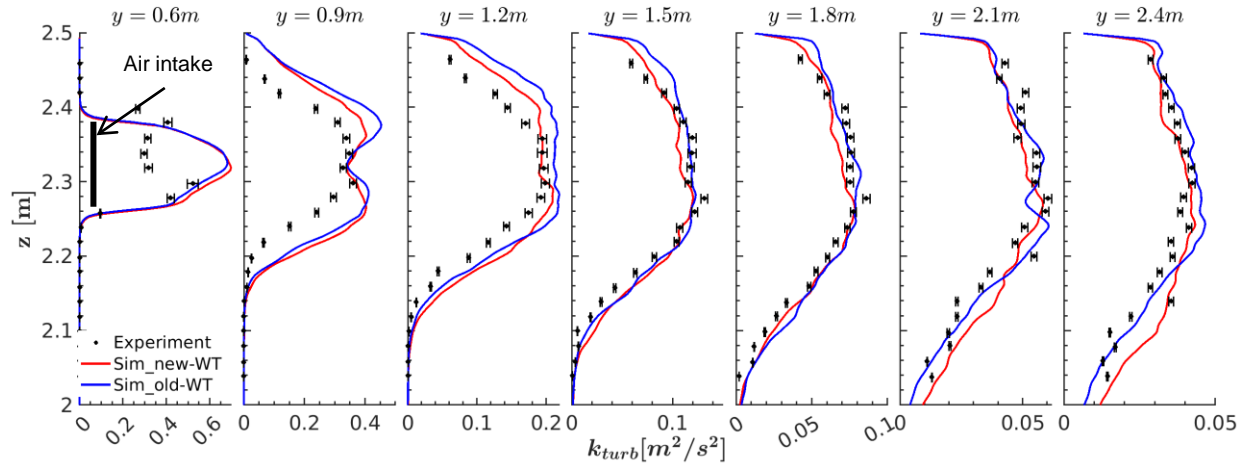
Comparison with an old wall treatment at the ceiling



Appendix

Turbulent kinetic energy profiles – median plan

Comparison with an old wall treatment at the ceiling



Appendix

- Velocity gradient tensor

$$\frac{\partial u_i}{\partial x_j} = \underbrace{\frac{1}{2} \cdot \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)}_S + \underbrace{\frac{1}{2} \cdot \left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right)}_\Omega$$

strain rate tensor

rotation rate vorticity tensor

$$Q = \frac{1}{2} (\|\Omega\|^2 - \|S\|^2)$$

- Q-criterion: positive isovalue of Q → areas in the flowfield where the vorticity dominates