

Temperature wall function adaptation for mixed convection airflows: LBM-LES simulations of a hot wall jet developing in a room

Speaker:

Teddy Gresse

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

Contributors:

Teddy Gresse¹, **Lucie Merlier**², **Jérôme Jacob**³, **Frédéric Kuznik**¹

¹ *Univ Lyon, INSA Lyon, CNRS, CETHIL, UMR5008, Villeurbanne, F-69621, France*

² *Univ Lyon, UCBL, INSA Lyon, CNRS, CETHIL, UMR5008, Villeurbanne, F-69621, France*

³ *Aix Marseille Univ, CNRS, Centrale Marseille, M2P2, UMR 7340, Marseille, 13451, France*

Introduction

- **Indoor airflows characteristics**

- Wall bounded interactions, vortices, buoyancy
- Turbulent, transient and laminar regions
- Low velocities, low Re

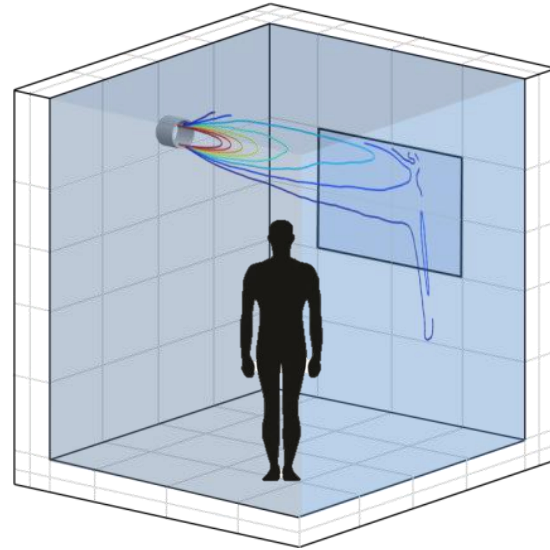
- **Challenges for CFD**

- Turbulence modeling
- Buoyancy modeling
- Near-wall modeling

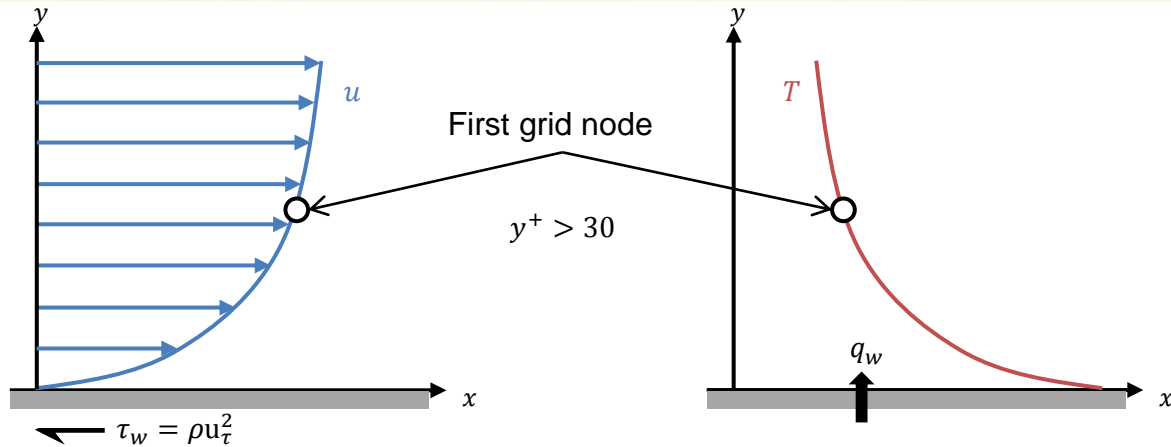
- **Limits of standard wall functions**

- Developed for high Re forced convection flows
- Underestimate the convective heat transfer for mixed convection indoor airflows (*X. Yuan and al. 1999*)

→ **How can the wall functions be adapted ?**



Standard wall functions



- One-dimensional boundary layer (BL) equations

Momentum:
$$v \frac{\partial u}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2}$$

Energy:
$$v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2}$$



$$\begin{cases} u^+ = \frac{1}{\kappa} \ln(y^+) + B \\ T^+ = Pr_{t,w}(u^+ + P) \end{cases}$$

$$y^+ = \frac{y u_\tau}{\nu}$$

$$u^+ = \frac{u}{u_\tau}$$

$$T^+ = \frac{(T_w - T) \rho c_p u_\tau}{q_w}$$

Note: no adverse pressure gradient and friction

Adaptation for mixed convection flows

1. Adjustment of the turbulent Prandtl number $Pr_{t,w}$

Outdoor (T. Defraeye and al 2012)
Indoor (T. Zhang and al. 2013)

$$q_w = \frac{(T_w - T)\rho c_p u_\tau}{Pr_{t,w} \left[\frac{1}{\kappa} \ln(y^+) + B + P \right]}$$

→ Increasing q_w by decreasing $Pr_{t,w}$

Limits: no physical basis, lack universality

2. Integration of the buoyancy effect in the BL equations (B. Chen and al. 2021)

Momentum: $v \frac{\partial u}{\partial y} = v \frac{\partial^2 u}{\partial y^2} + g\beta(T_w - T)$



Energy: $v \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2}$

$$\begin{cases} u^+ = \frac{1}{\kappa} \left(2\sqrt{1 - y^+ T^+ S^+} - \ln \frac{1 + \sqrt{1 - y^+ T^+ S^+}}{1 - \sqrt{1 - y^+ T^+ S^+}} \right) + C_u \\ T^+ = \frac{1 - \sqrt{1 - 2y^+ S^+ Pr_t (u^+ + C_t)}}{y^+ S^+} \end{cases}$$

$$S^+ = \frac{g\beta v q_w}{\rho c_p u_\tau^4}$$

$$y^+ T^+ S^+ = \frac{y g \beta (T_w - T)}{u_\tau^2}$$

$$y^+ S^+ = \frac{y g \beta q_w}{\rho c_p u_\tau^3}$$

Limits: - only for horizontal walls

- strong validity conditions $0 < y^+ T^+ S^+ < 1$

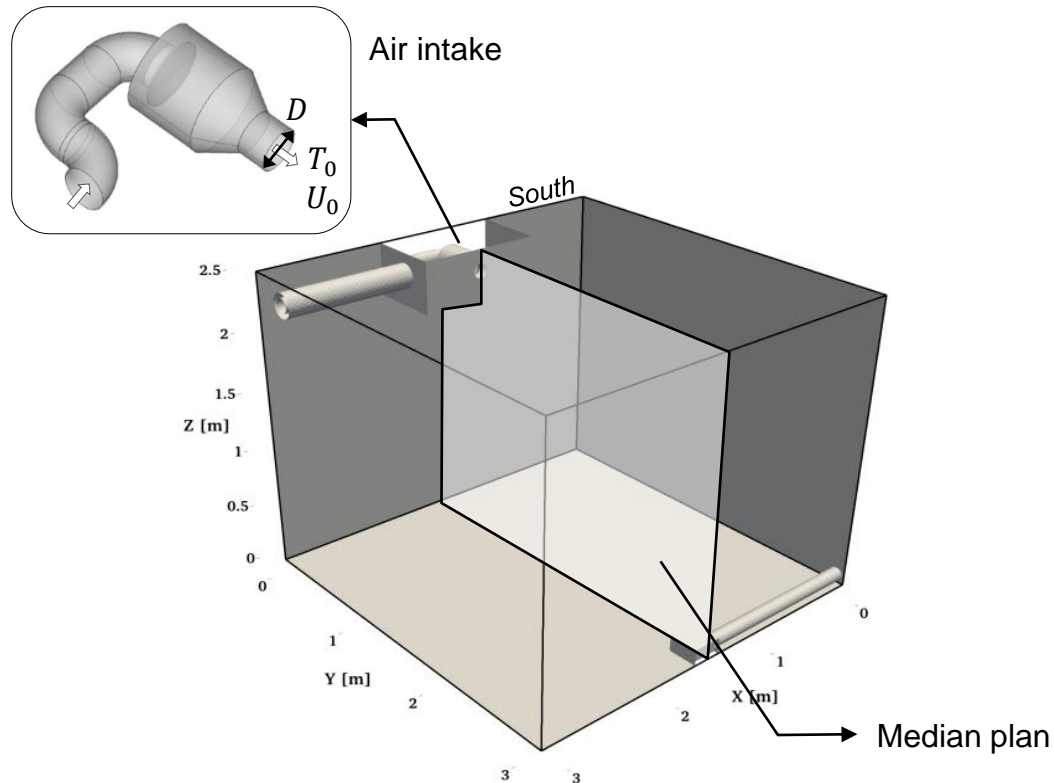
$2y^+ S^+ Pr_t (u^+ + C_t) < 1$

T. Defraeye, B. Blocken, and J. Carmeliet (2012) "CFD simulation of heat transfer at surfaces of bluff bodies in turbulent BL: Evaluation of a forced-convective temperature wall function for mixed convection" Build. Environ.

T. Zhang, H. Zhou, and S. Wang (2013) "An adjustment to the standard temperature wall function for CFD modeling of indoor convective heat transfer", Build. Environ.

B. Chen, S. Liu, J. Liu, N. Jiang, and Q. Chen (2021) "A new wall function for indoor airflow with buoyancy effect", Build. Environ.

MINIBAT test-cell *(Kuznik 2005)*



Experimental conditions: hot jet

- Inlet

T_0 [°C]	Re_D	U_0 [m/s]
30.9	21600	2.70

- Wall temperatures [°C]

South	North	East	West	Floor	Ceiling
24.4	25.0	24.6	24.7	24.5	25.5

CFD modeling



Thermal LBM

- LBM-BGK equation (velocity and density)

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

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

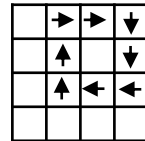
f_i^{eq} : 3rd order equilibrium distribution function

f_i^{neq} : Hybrid Recursive Reconstruction procedure ([Jacob and al. 2018](#))

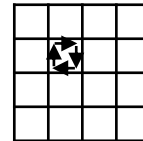
- Energy equation (temperature)
→ FV method
- Boussinesq source term

LES

- Principle:



Resolved



Modeled

- Eddy viscosity paradigm:

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

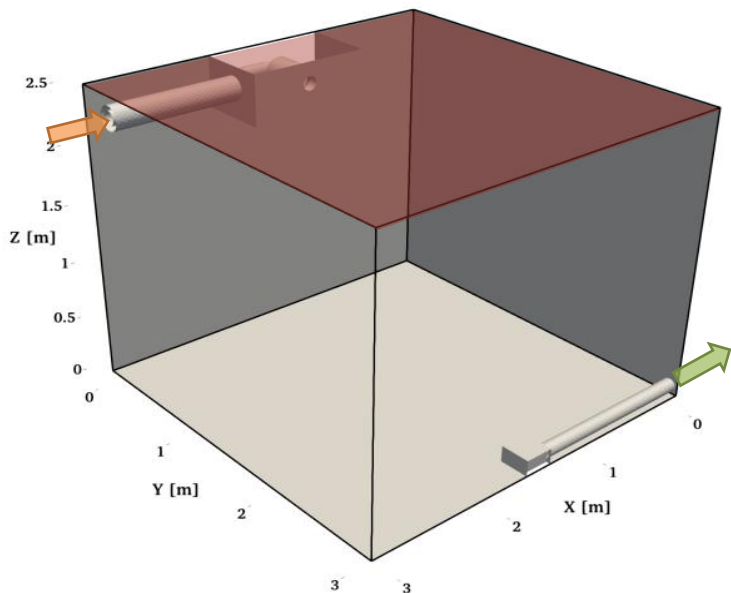
- $\nu = \nu_{mol} + \nu_t$ in the relaxation time

Boundary conditions

- Immersed boundary approach
- Macroscopic quantities at boundary nodes:
 - Dirichlet: interpolation
 - Neumann: extrapolation
 - Wall functions
- Computation of the velocity gradients on boundary nodes
- Reconstruction of the distribution functions

→ Need validation for application to indoor airflows with thermal effects

Boundary conditions



Inlet Dirichlet velocity
Neumann density



Outlet Dirichlet density
Neumann velocity

Walls



Ceiling



Other walls

*Eddy
viscosity
modelling*

$$f(v_t^{RANS}, v_t^{LES}) \quad v_t^{LES}$$

$$v_t^{RANS} \quad \frac{v_t^{RANS} + v_t^{LES}}{2} \quad v_t^{LES}$$

*Velocity
wall function*

Explicit log law
(Cai and Sagaut 2021)

Implicit log law
(Afzal 1996)

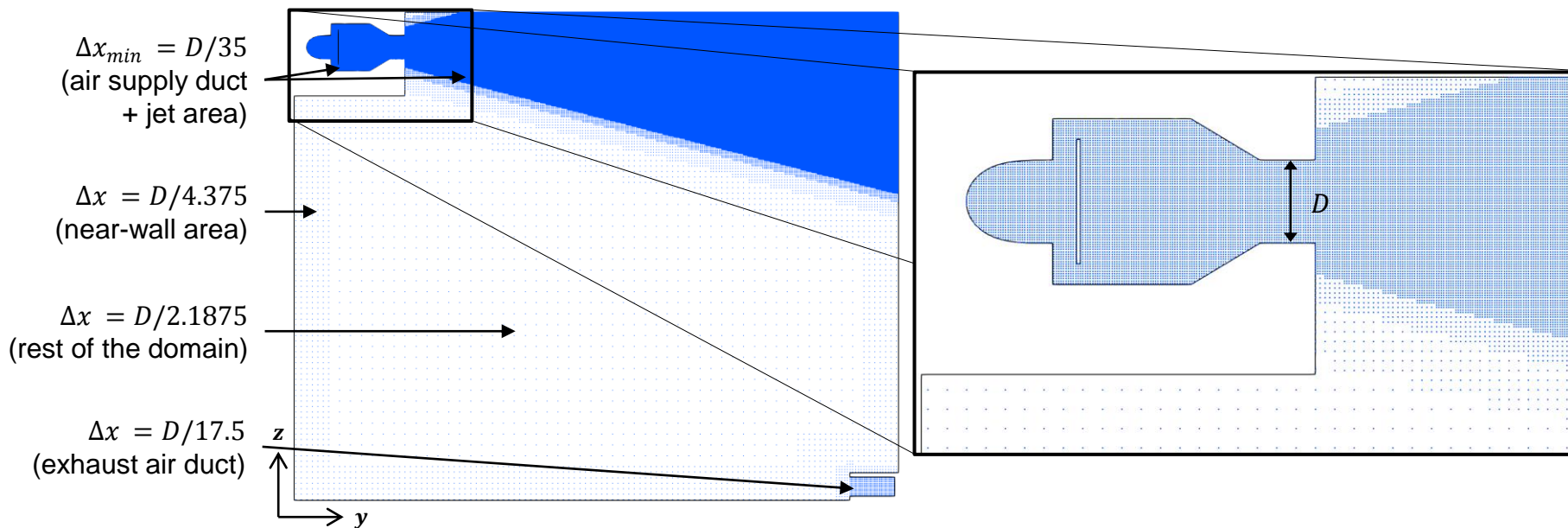
*Temperature
wall function*

Log law (Kader 1981)
with $Pr_{t,w} = 0.2$

Log law (Kader 1981)
with $Pr_{t,w} = 0.025$

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

Computational grid



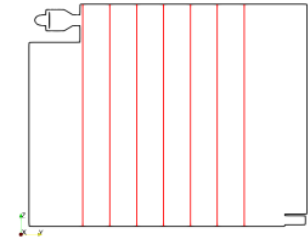
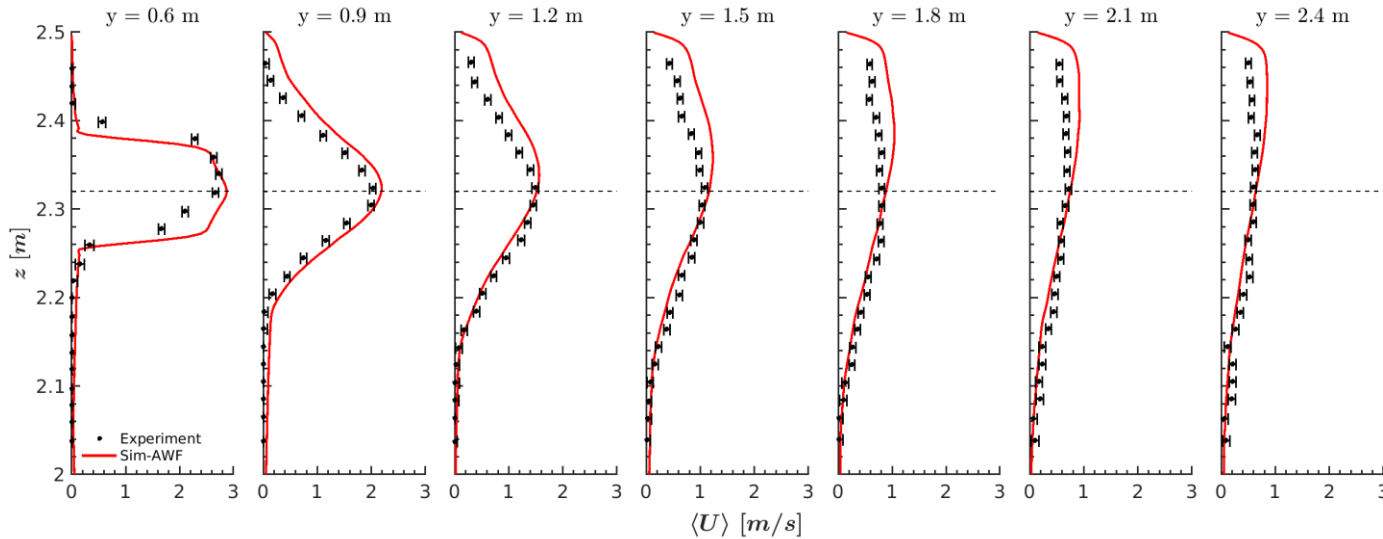
Number of elements	31.2×10^6 nodes
timestep	3.37×10^{-5} s
Calculation cost	1.7×10^5 h _{CPU} over 816 processors

Note: Steady state after $75T^*$

Statistical averaging over $15T^*$

$$T^* = L_c/U_c = 4.65/2 \text{ s}$$

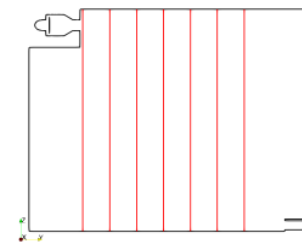
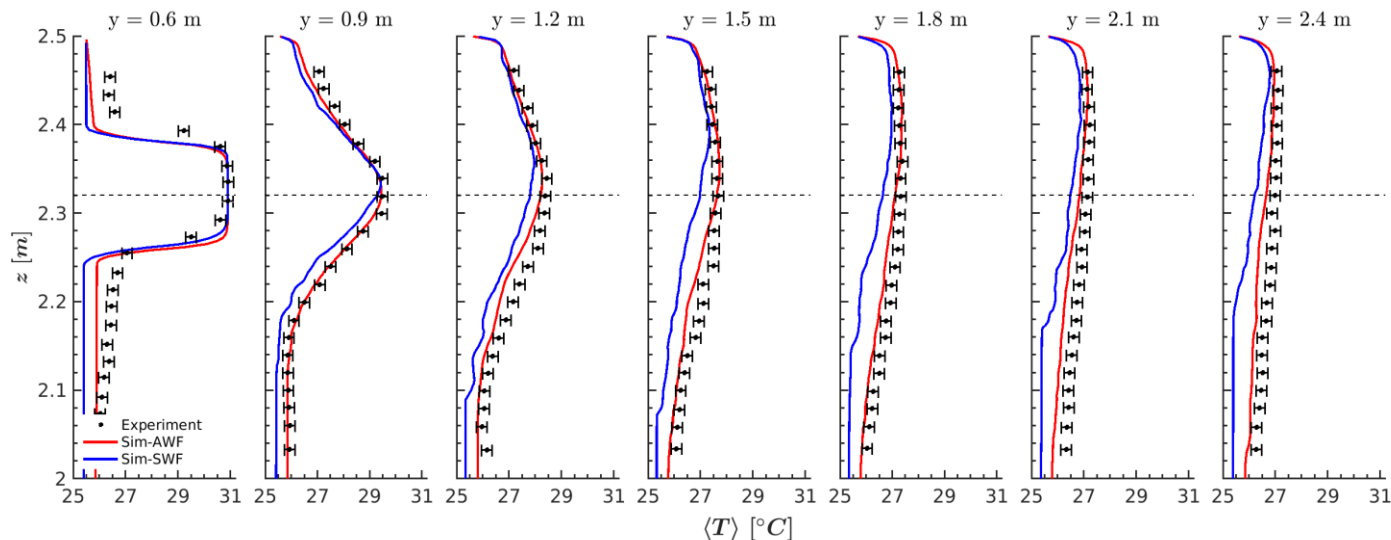
Mean velocity profiles on median plan



AWF: Adjusted wall function

- Good agreement with experimental profiles
- Deviation close to the ceiling $< 0,4$ m/s
→ Underestimation of the shear stress, buoyancy

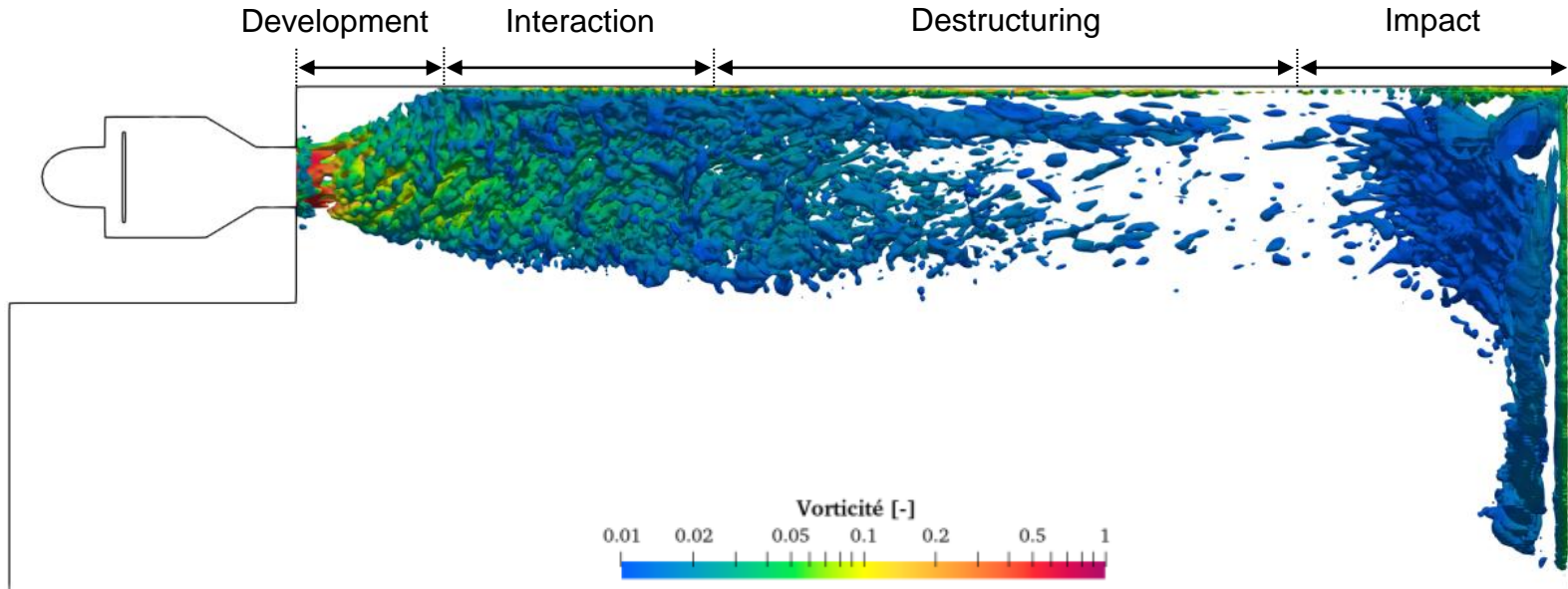
Mean temperature profiles on median plan



AWF: Adjusted wall function
 SWF: Standard wall function

- AWF in better agreement with experimental profiles
- Deviation on the center of the room : $0.6^\circ\text{C} \rightarrow 0.1^\circ\text{C}$
 → Improvement of the convective heat fluxes prediction

Turbulent structures visualization with Q-criterion



Conclusions

- ✓ Capacity of the LBM-LES approach to simulate thermal airflows within buildings
- ✓ Adjustment of the $Pr_{t,w}$ allows to recover correct temperature profiles

Work in progress

- Derivation of an adaptive formula based on the Richardson number to calculate the $Pr_{t,w}$ (*J. Allegrini and al. 2013*)
- Implementation of the new wall functions integrating the buoyancy effect

Perspectives

- Extension to natural ventilation
- Coupling with a dynamic and three-dimensional building model (*Gresse and al. 2021*)
- Thermal confort dynamics study with thermo-physiological human model

Temperature wall function adaptation for mixed convection airflows: LBM-LES simulations of a hot wall jet developing in a room

Questions & Comments

Speaker:

Teddy Gresse

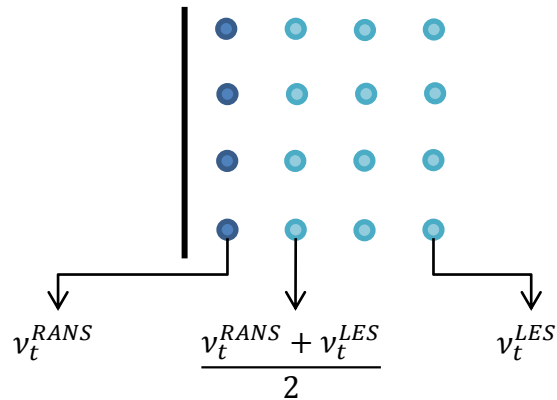
*Univ Lyon, INSA Lyon, CNRS, CETHIL,
UMR5008, 69621 Villeurbanne, France*

Contacts:

teddy.gresse@insa-lyon.fr

- Subgrid viscosity

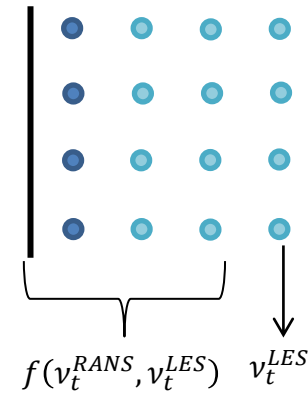
Viscosity « simple »



$$v_t^{RANS} = (\kappa y^+ A(y^+))^2 \left| \frac{\partial u}{\partial y} \right|$$

v_t^{LES} from subgrid model

Viscosity « blending »
(Maeyama et al. 2021)



$$f = K^\gamma v_t^{LES} + (1 - K^\gamma) v_t^{RANS}$$

$$K = \max \left[\min \left(\frac{d_{IP} - y}{d_{IP}(1 - \alpha')}, 1 \right), 0 \right]$$

• Velocity wall functions

- Implicit (Afzal 1996):
$$u^+ = \left(1 - e^{\frac{-y^+}{c_{11}}}\right) \left[\frac{1}{\kappa} \ln(y^+) + B + f_{\text{pres}} + f_{\text{courb}} + f_{\text{rough}}\right]$$
- Explicit (Cai et al. 2021):
$$u^+ = Re_y \left[\left(1 - \tanh\frac{Re_y}{s}\right)^p \sqrt{Re_y} + \left(\tanh\frac{Re_y}{s}\right)^p \frac{1}{E} e^{W(\kappa E Re_y)} \right]^{-1}$$

• Temperature wall function

- (Kader 1981):
$$T^+ = e^\Gamma T_{lam}^+ + e^\Gamma T_{turb}^+$$

$$\Gamma = \frac{0.01(Pr y^+)^4}{1+5Pr^3 y^+}, \quad T_{lam}^+ = Pr y^+, \quad T_{turb}^+ = Pr_{t,w} \left(\frac{1}{\kappa} \ln(y^+) + B + P_J\right)$$

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

N. Afzal (1996) « Wake layer in a turbulent boundary layer with pressure gradient: a new approach. », Gersten, K. (eds.) IUTAM Symposium.

B. A. Kader (1981) "Temperature and concentration profiles in fully turbulent boundary layers." International Journal of Heat and Mass Transfer.