Validation studies of flow modelling around buildings

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Overview

1. Urban flows
2. Validation
3. Results
   - Atmospheric Boundary Layer
   - One building
   - Array of buildings
   - Idealized city centre
4. Conclusion
5. Outlook

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Urban flow modeling

Challenges:

- Atmospheric Boundary Layer (ABL)
- Bluff bodies
- Large distances
- Scalar transport

Urban flow modeling

Purpose: Computational Wind Engineering (CWE)

- Wind load on buildings
- Wind comfort
- Pollutant dispersion

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Validation

Compare to analytical or measurement data:

- Profile comparison
- Contour plots
- Validation metrics

$$q = \frac{1}{N} \sum_{i=1}^{N} \delta_i$$

$$\delta_i = \begin{cases} 1 & \text{for} \quad \left| \frac{P_i - O_i}{O_i} \right| \leq 0.25 \quad \text{or} \quad |P_i - O_i| \leq W \\ 0 & \text{for} \quad \text{else} \end{cases}$$

Test cases

CEDVAL and CEDVAL-LES database:

1. Atmospheric Boundary Layer (ABL)
2. Flow around a cube (1 building)
3. Flow around an array of cubes (Mock Urban Setting Test - MUST)
4. Idealized Central-European city sentre (Michel-Stadt)

Environmental Wind Tunnel Laboratory
University of Hamburg

OpenFOAM details

- simpleFoam
- standard $k-\epsilon$, realizable $k-\epsilon$, RNG $k-\epsilon$, $k-\omega$, nonlinear Shih $k-\epsilon$
- rough wall-function and modifications
- upwind and cellLimited linearUpwind convection schemes
- inlet defined with timeVaryingMappedFixedValue or GroovyBC
- coded Function Objects and sampling for post processing

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Linear versus nonlinear approach

Reynolds Averaged Navier-Stokes Equations (RANS)

In the standard $k-\epsilon$ model: isotrophic eddy viscosity

$$R_{ij} = \overline{u_i u_j} = \frac{2}{3} k \delta_{ij} - \nu_t S_{ij}$$

$$\nu_t = C_\mu \frac{k^2}{\epsilon} \; C_\mu = 0.09$$

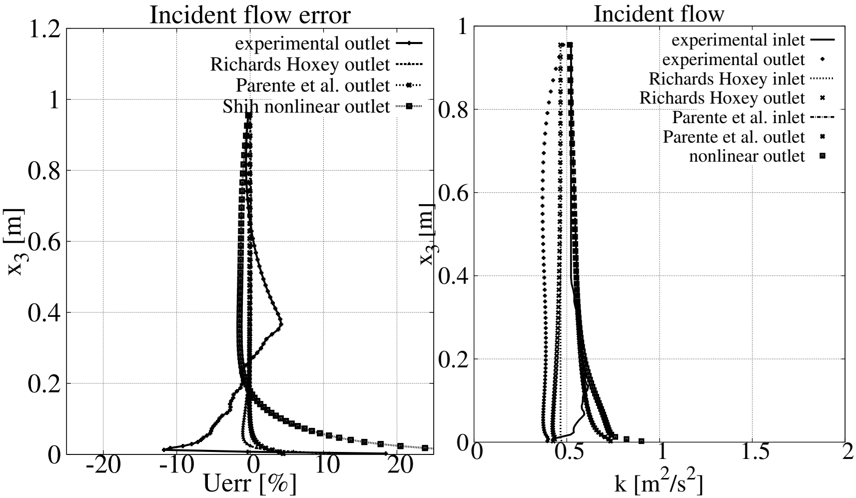
Nonlinear

$$R_{ij} = \overline{u_i u_j} = \frac{2}{3} k \delta_{ij} - \nu_t S_{ij} + f(S_{ij}, \Omega_{ij})$$

$+$ **nonlinear stress**

Model	C_μ	c_1 $(c_{\tau 1})$	c_2 $(c_{\tau 2})$	c_3 $(c_{\tau 3})$
Craft et al. 1993	$C_{\mu Craft}$	-0.1	0.1	0.26
Shih et al. 1993	$C_{\mu Shih}$	-4	13	-2

Atmospheric Boundary Layer



Test case 1 - Atmospheric Boundary Layer

Analytical solution

Linear: $R_{11} = R_{22} = R_{33} = \frac{2}{3}k$

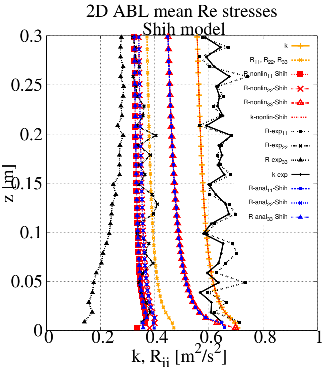
Non-linear:

$$R_{11} = \frac{2}{3}k + c_\mu \frac{k^3}{\epsilon^2}(U_{1,3})^2 \left(\frac{2}{3}c_{\tau 2} - \frac{1}{3}c_{\tau 3}\right)$$

$$R_{22} = \frac{2}{3} + c_\mu \frac{k^3}{\epsilon^2}(U_{1,3})^2 \left(-\frac{1}{3}c_{\tau 2} - \frac{1}{3}c_{\tau 3}\right)$$

$$R_{33} = \frac{2}{3}k + c_\mu \frac{k^3}{\epsilon^2}(U_{1,3})^2 \left(\frac{2}{3}c_{\tau 3} - \frac{1}{3}c_{\tau 2}\right)$$

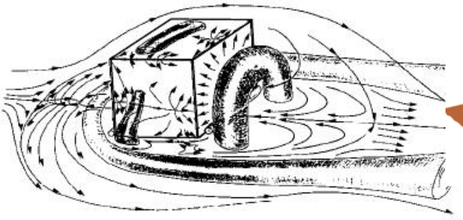
Experiments: $R_{11} > R_{22} > R_{33}$

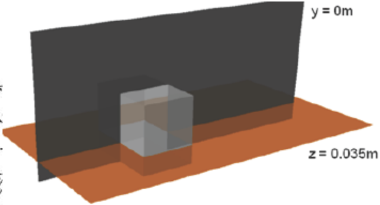


Conclusion

There is a switch in OpenFOAM in R_{11} and R_{33}?

The bluff body problem



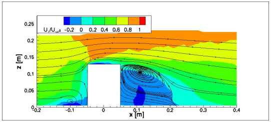


Martinuzzi and Tropea 1993

The bluff body problem

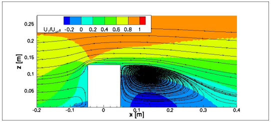
Usual approach: RANS with linear $k - \epsilon$ model

Overpredicted wake



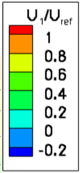
$L = 1.76H$

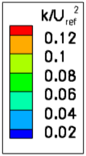
Experiment



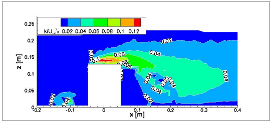
$L = 2.72H$

Standard $k - \epsilon$

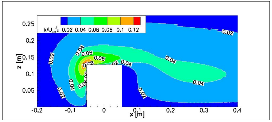




High k in stagnation



Experiment



Standard $k - \epsilon$

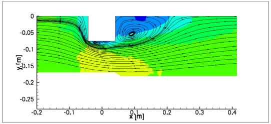
Solving one causes troubles with the other

In cooperation with Carlo Benocci, Von Karman Institute for Fluid Dynamics

The bluff body problem - different view

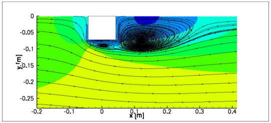
Usual approach: RANS with linear $k-\epsilon$ model

Overpredicted wake



$L = 1.76H$

Experiment



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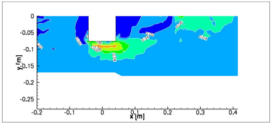
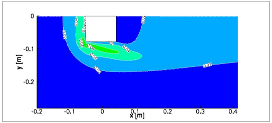
Standard $k-\epsilon$

High k in stagnation

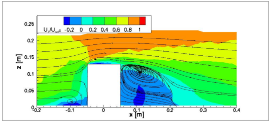


Experiment



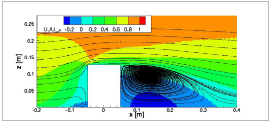
Standard $k-\epsilon$

Test case - First results with nonlinear model



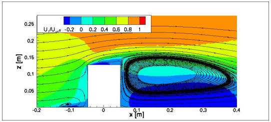
$L = 1.76H$

Experiment



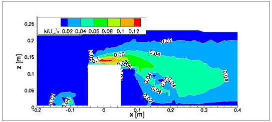
$L = 2.72H$

Standard $k - \epsilon$

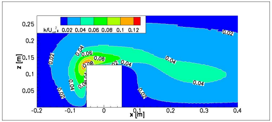


$L = 3.92H$

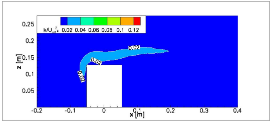
Shih nonlinear $k - \epsilon$



Experiment

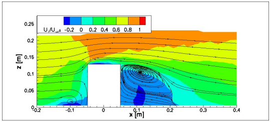


Standard $k - \epsilon$



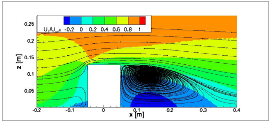
Shih nonlinear $k - \epsilon$

Test case - First results with nonlinear model



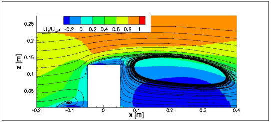
$L = 1.76H$

Experiment



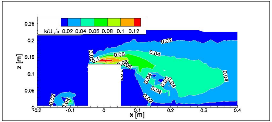
$L = 2.72H$

Standard $k - \epsilon$

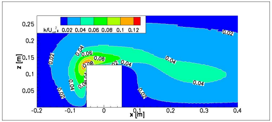


$L = 3.68H$

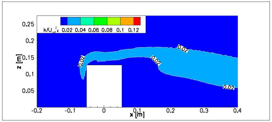
Shih nonlinear $k - \epsilon$ modified



Experiment

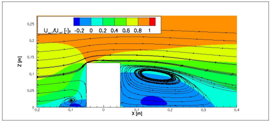


Standard $k - \epsilon$

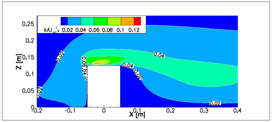


Shih nonlinear $k - \epsilon$ mod

Test case - Importance of C_μ

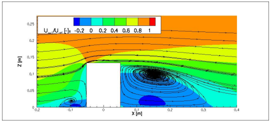


$L = 2.64H$

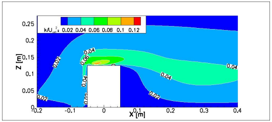


Nonlinear Craft

Nonlinear Craft

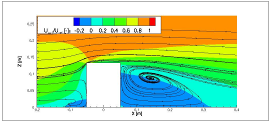


$L = 2.60H$

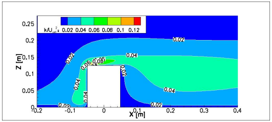


"Linearized Craft"

"Linearized Craft"



$L = 2.60H$



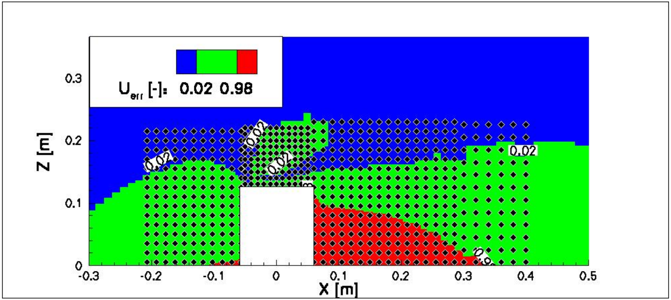
Parente 2011

Parente 2011

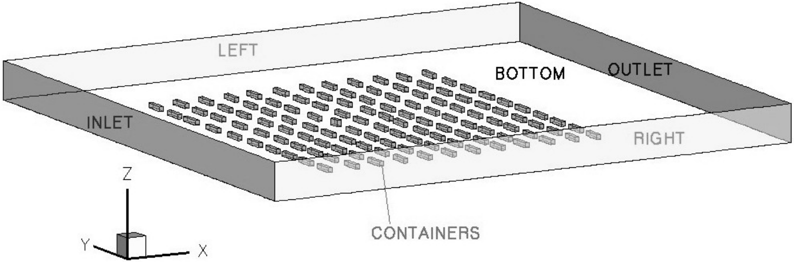
Parente, A., Gorlé, C., van Beeck, J., Benocci, C., (2011), A Comprehensive Modelling Approach for the Neutral Atmospheric Boundary Layer: Consistent Inflow Conditions, Wall Function and Turbulence Model, Boundary Layer Meteorology, Volume: 140, Issue: 3, Pages: 411-428

Metrics

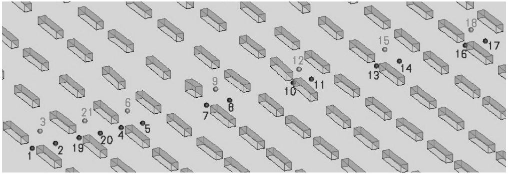
Model	Hit rates for U_1/U_{ref}	Hit rates for k/U_{ref}^2
Std $k-\epsilon$	0.66	0.55
Craft $k-\epsilon$ $b=5$	0.68	0.60
"Linearized Craft" $b=5$	0.68	0.60
Parente 2011 ASQ	0.62	0.61



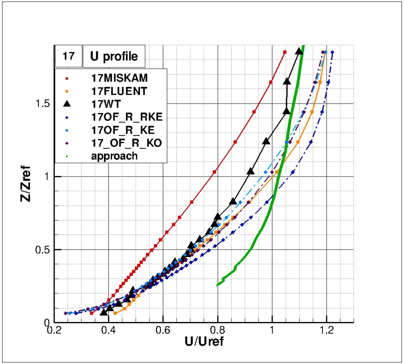
Mock Urban Setting Test (MUST)



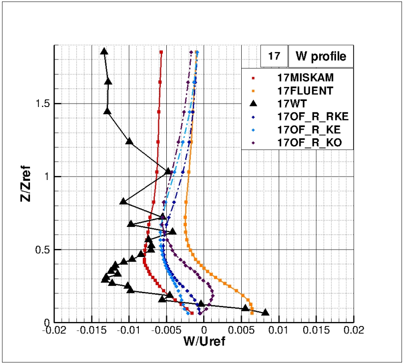
Profile 17 comparisons



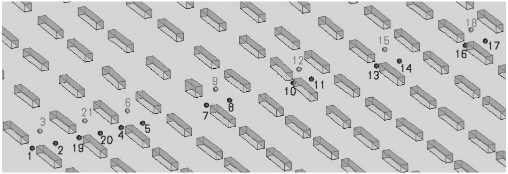
Streamwise velocity



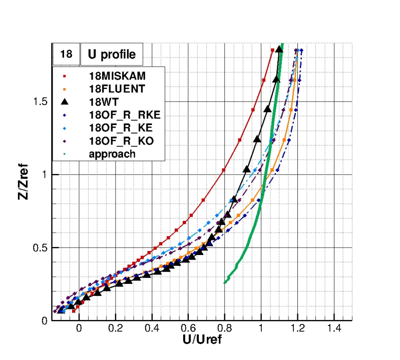
Lateral velocity



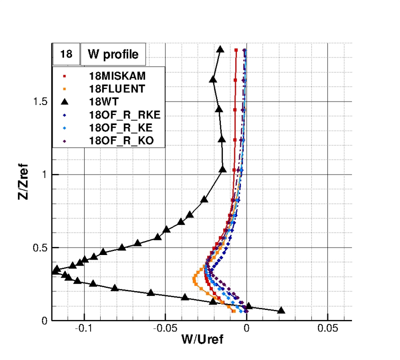
Profile 18 comparisons



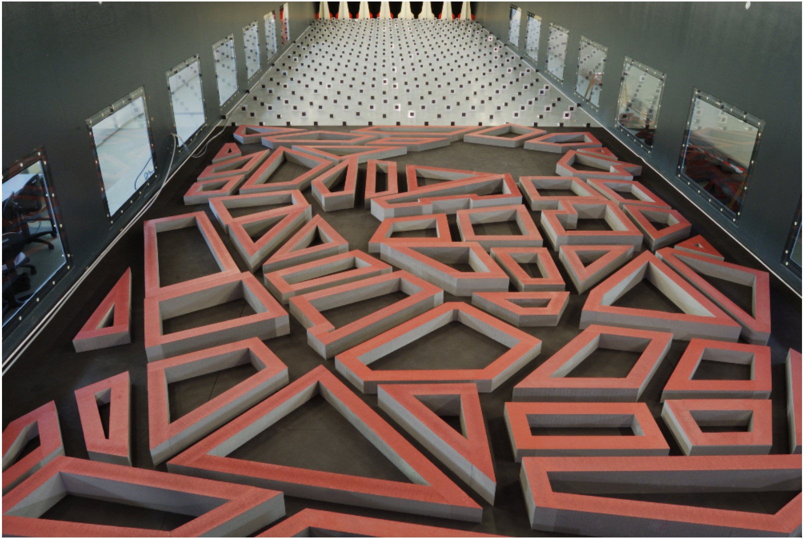
Streamwise velocity



Lateral velocity

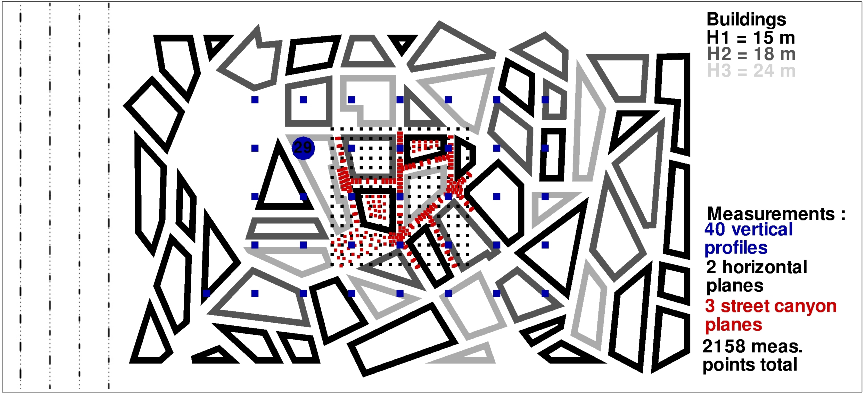


Michel-Stadt wind tunnel model



Michel-Stadt numerical model

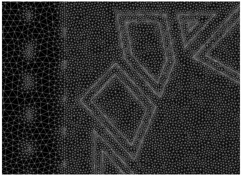
COMPUTATIONAL DOMAIN (FULL SCALE)

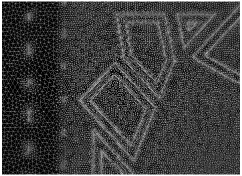


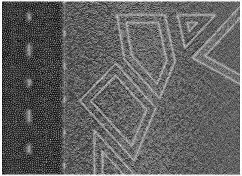
In cooperation with Jörg Franke, University of Siegen

Meshes

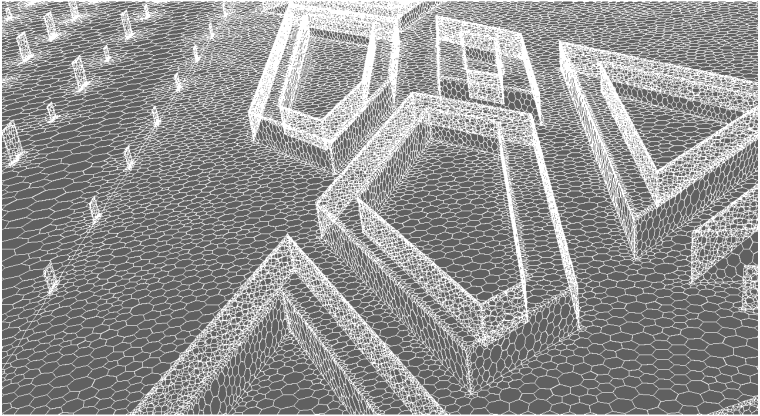
	coarse	medium	fine
polyhedral	$1.73 \cdot 10^6$ (P3)	$3.21 \cdot 10^6$ (P2)	$6.17 \cdot 10^6$ (P1)
tetrahedral	$6.65 \cdot 10^6$ (T3)	$13.17 \cdot 10^6$ (T2)	$26.79 \cdot 10^6$ (T1)





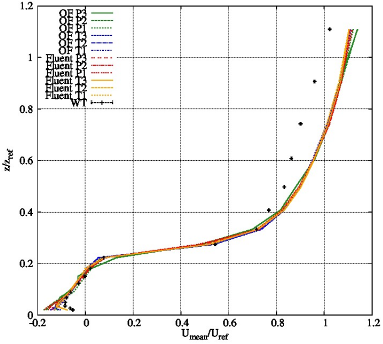


Polyhedral mesh

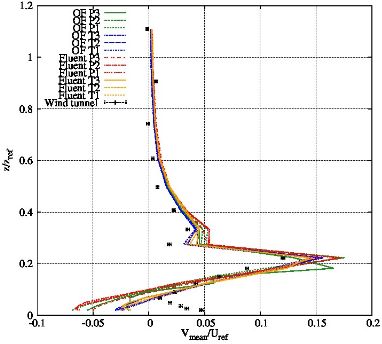


Profile 29 comparisons

Streamwise velocity

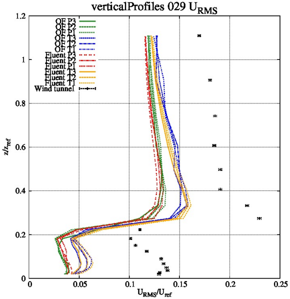


Lateral velocity

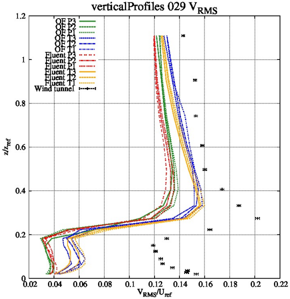


Profile 29 comparisons

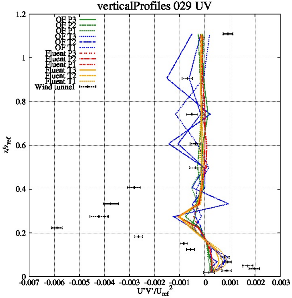
Streamwise velocity RMS



Lateral velocity RMS



Turbulent shear stress



Hit rates

$$W_{U_{mean}/U_{ref}} = 0.033$$
$$W_{V_{mean}/U_{ref}} = 0.0576$$

Table: Hit rates for OpenFOAM / Fluent

U_{mean}/U_{ref}	coarse	medium	fine
polyhedral	0.66/ 0.64	0.68/ 0.68	0.69/ 0.69
tetrahedral	0.72/ 0.69	0.76/ 0.75	0.76/ 0.75
V_{mean}/U_{ref}	coarse	medium	fine
polyhedral	0.78/ 0.78	0.79/ 0.78	0.78/ 0.78
tetrahedral	0.82/ 0.80	0.82/ 0.82	0.83/ 0.82

Rakai, A. and Franke, J. - Validation of two RANS solvers with flow data of the flat roof Michel-Stadt case, Proc. 8th International Conference on Air Quality - Science and Application, Athens, Greece, 2012

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Conclusion

- OpenFOAM can be used for CWE
- Ideal tool for model testing
- Difficulties without documentation

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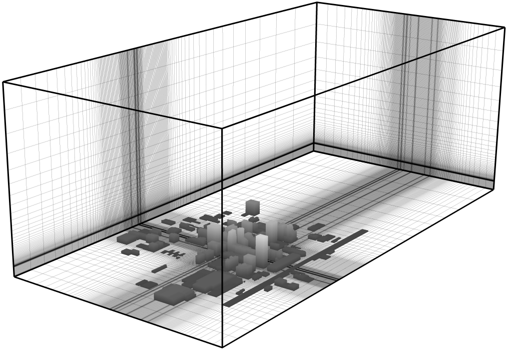
Suggestions for future work

- More complicated gemoetry: Oklahoma
- Dispersion
- More meshing (snappyHexMesh)



Acknowledgements

- Von Karman Institute of Fluid Dynamics
- DAAD research scholarship with Jörg Franke, Siegen University
- The work reported in the paper has been developed in the framework of the project "Talent care and cultivation in the scientific workshops of BME" project. This project is supported by the grant TAMOP-4.2.2.B-10/1–2010-0009

Thank you for your attention!

Hit rate

$$q = \frac{1}{N}\sum_{i=1}^{N}\delta_i \quad (1)$$

$$\delta_i = \begin{cases} 1 & \text{for} \quad \left|\frac{P_i - O_i}{O_i}\right| \leq 0.25 \quad \text{or} \quad |P_i - O_i| \leq W \\ 0 & \text{for} \quad \text{else} \end{cases} \quad (2)$$

$$k(x_3) = \frac{1}{2}((U_1 \cdot U_{1turb})^2 + (U_1 \cdot U_{2turb})^2 + (U_1 \cdot U_{3turb})^2) \quad (3)$$

0.012 for U_1/U_{ref}
$0.0316(k/U_{ref}^2)^{0.518}$ for k/U_{ref}^2

Turbulence model

The equation for turbulent kinetic energy:

$$\frac{\partial k}{\partial t} + \frac{\partial \bar{U}_j k}{\partial x_j} = -\overline{u_i^{'} u_j^{'}} \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left[\frac{1}{\sigma_k} \frac{k}{\epsilon} \overline{u_i^{'} u_j^{'}} \frac{\partial k}{\partial x_j} \right] - \epsilon$$

For its dissipation:

$$\frac{\partial \epsilon}{\partial t} + \frac{\partial \bar{U}_j \epsilon}{\partial x_j} = -C_{1\epsilon} \frac{\epsilon}{k} \overline{u_i^{'} u_j^{'}} \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left[\frac{1}{\sigma_\epsilon} \frac{k}{\epsilon} \overline{u_i^{'} u_j^{'}} \frac{\partial \epsilon}{\partial x_j} \right] - c_{2\epsilon} \frac{\epsilon^2}{k}$$

Developed ABL profile – Comprehensive approach

Inlet

- Velocity from Richard and Hoxey JWEIA 1993

$$U(z) = \frac{u^*}{\kappa} ln\left(\frac{z + z_0}{z_0}\right)$$

- Tke from Parente BLM 2011

$$k(z) = A ln(z + z_0) + B$$

- ϵ from equilibrium hypothesis

$$\epsilon = \frac{u^{*3}}{\kappa(z + z_0)}$$

- Height dependent C_μ
- Height dependent source term in ϵ equation

Developed ABL profile – Comprehensive approach

An additional source term was suggested by Pontiggia et al. (2009) for the dissipation:

$$S_\epsilon(z) = \frac{\rho u^{*4}}{(z+z_0)^2}\left(\frac{(C_2 - C_1\sqrt{C_\mu})}{\kappa^2} - \frac{1}{\sigma_\epsilon}\right)$$

The model parameter C_μ was generalized by Gorlé et al. (?) to be dependent on the distance from the wall:

$$C_\mu(z) = \frac{u^{*4}}{k(z)^2}$$

To satisfy the turbulent kinetic energy transport equation a further source term was added:

$$S_k(z) = \frac{\rho u^{*4}}{(z+z_0)}\frac{\partial}{\partial z}\left((z+z_0)\frac{\partial k}{\partial z}\right)$$

Developed ABL profile – Comprehensive approach

Wall function

Engineering: sand grain roughness

$$U(y) = \frac{u^*}{\kappa} ln \left(\frac{Ey^+}{C_s k_s^+} \right)$$

Meteorology: physical roughness

$$U(z) = \frac{u^*}{\kappa} ln \left(\frac{z + z_0}{z_0} \right)$$

Implemented in OpenFOAM by Balogh VKI RM report 2010

Numerical details

- simpleFoam
- linearUpwind
- parallel on 4 nodes

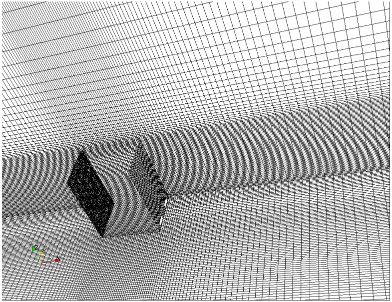
Model scale 1:200, simulations done in model scale

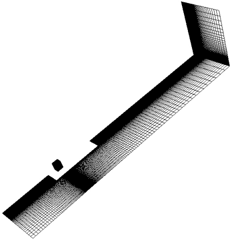
Name	Symbol	Value	Name	Symbol	Value
Reynolds number	Re	37250	Roughness height	z_0	0.0007 m
Friction velocity	u_*	0.377 m/s	Offset height	δ_0	0
Power law exponent	n	0.21	Turbulent length scale	L	0.32
Obstacle height	H	0.125 m	Reference velocity	U_{ref}	6 m/s
Reference height	z_{ref}	0.5 m			

Used computational grids

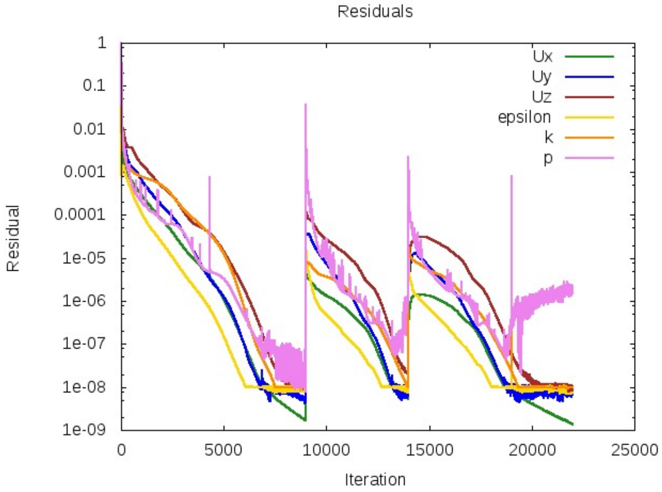
- 1.7 million cells
- structured hexahedra
- smallest cell height 0.0075 m

Domain	x_1	x_2	x_3
min	-1	-0.75	0
max	3	0	1
Number of hexa cells: 1741894			

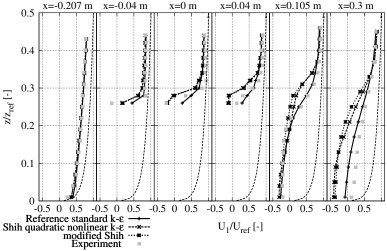


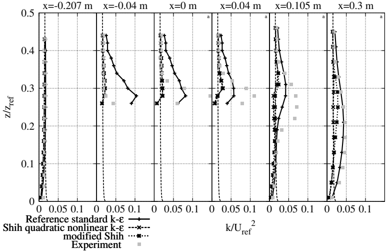


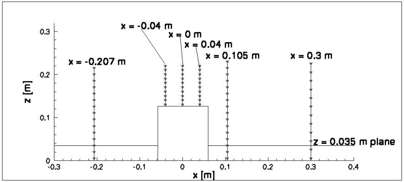
Convergence



Test case - First results with nonlinear model

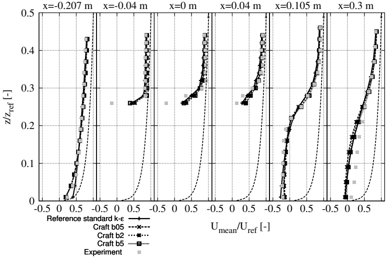


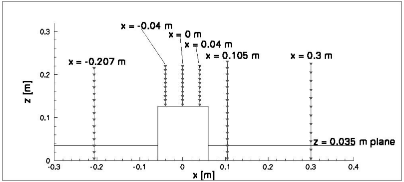




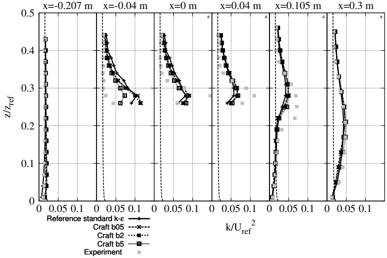
Hit rates:

Test case - Results with zonal nonlinear model





Hit rates:



Quadratic Stress Relation

$$R_{ij} = \overline{u_i u_j} = \frac{2}{3}k\delta_{ij} - \nu_t S_{ij} +$$

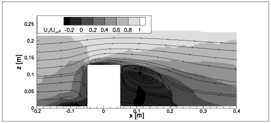
$$+c_1 \nu_t \frac{k}{\epsilon}(S_{ik}S_{jk} - (1/3)S_{mk}S_{mk}\delta_{ij}) +$$

$$+c_2 \nu_t \frac{k}{\epsilon}(\Omega_{ik}S_{kj} + \Omega_{jk}S_{ki}) +$$

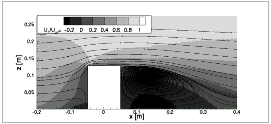
$$+c_3 \nu_t \frac{k}{\epsilon}(\Omega_{ik}\Omega_{ji} - (1/3)\Omega_{lk}\Omega_{lk}\delta_{ij})$$

Model	C_μ	c_1 ($c_{\tau 1}$)	c_2 ($c_{\tau 2}$)	c_3 ($c_{\tau 3}$)
Craft et al. 1993	$C_{\mu Craft}$	-0.1	0.1	0.26
Shih et al. 1993	$C_{\mu Shih}$	-4	13	-2

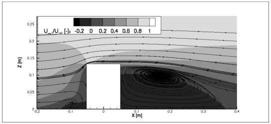
Test case - Check with Fluent



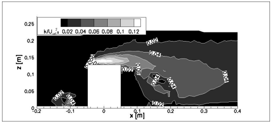
Experiment



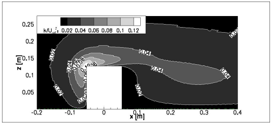
Standard $k-\epsilon$



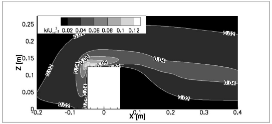
Shih nonlinear $k-\epsilon$ b = 5



Experiment



Standard $k-\epsilon$

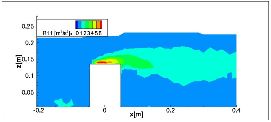


Shih nonlinear $k-\epsilon$

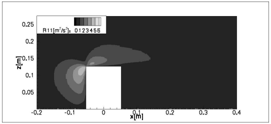
"Conclusion"

Shih is worse with zonal model also

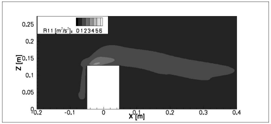
Test case - Reynolds stresses



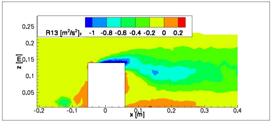
Experiment



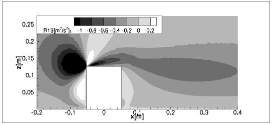
Linear model



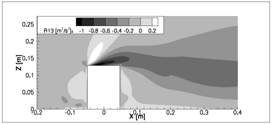
Nonlinear model



Experiment



Linear model



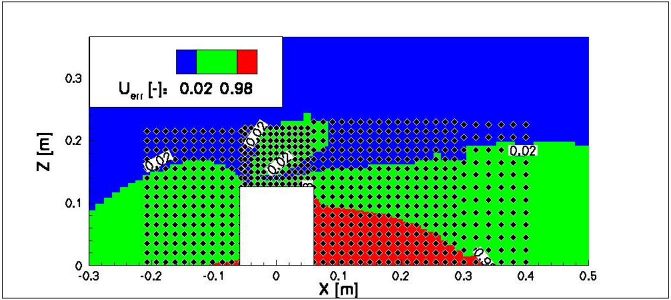
Nonlinear model

Conclusion

Reynolds stresses resemble more for the nonlinear model

Fitness for purpose

Model	Hit rates for U_1/U_{ref}				Hit rates for k/U_{ref}^2				L
	ups.	building	downs.	all	ups.	building	downs.	all	
Experiment	1	1	1	1	1	1	1	1	1.76H
Std $k-\epsilon$	0.87	0.75	0.51	0.66	0.24	0.33	0.62	0.46	2.72H
RNG $k-\epsilon$	0.89	0.80	0.45	0.64	0.24	0.14	0.45	0.33	3.04H
NI $k-\epsilon$	0.92	0.70	**0.38**	0.60	0.30	0.33	0.15	0.22	3.68H
NI $k-\epsilon$ $b=0.5$	0.87	0.73	0.45	0.62	0.59	0.40	0.58	0.55	2.96H
NI $k-\epsilon$ $b=2$	0.90	0.76	0.50	0.66	0.62	0.40	0.61	0.57	2.72H
NI $k-\epsilon$ $b=5$	0.91	0.76	0.52	0.68	0.63	0.38	0.66	0.60	2.64H



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Horizontally Homogenous Atmospheric Boundary Layer and Bluff Bodies

[5] Parente, A., Gorlé, C., van Beeck, J., Benocci, C., (2011), A Comprehensive Modelling Approach for the Neutral Atmospheric Boundary Layer: Consistent Inflow Conditions, Wall Function and Turbulence Model, Boundary Layer Meteorology, Volume: 140, Issue: 3, Pages: 411-428

[9] M. Balogh, A. Parente, C. Benocci, (under review), RANS simulation of ABL flow over complex terrains applying an enhanced $k-\epsilon$ model and wall function formulation: Implementation and comparison for Fluent and OpenFOAM, Journal of Wind Engineering and Industrial Aerodynamics

[10] Catherine Gorlé, (2010), Dispersion of fine and ultrafine particles in urban environment. Contribution towards an improved modeling methodology for computational fluid dynamics, Ph.D. thesis at the von Karman Institute/Universiteit Antwerpen, Belgium, ISBN 978-2-87516-003-4

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[16] Ehrhard, J., Kunz, R., Moussiopoulos, N., (2000), On the performance and applicability of nonlinear two equation turbulence models for urban air quality modelling, Environmental Monitoring and Assesment, Volume: 65, Pages: 201-209

[15] Wright, N.G., Easom, G.J., (2003), Non-linear $k-\epsilon$ turbulence model results for flow over a building at full scale, Applied Mathematical modelling, Volume: 27, Pages: 1013-1033.

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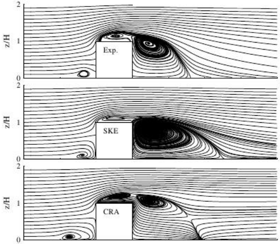
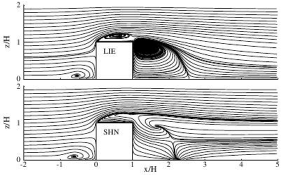
Ehrhard et al. 2000





Wright and Easom 2003

Table 2
Cube normal to incident wind

Turbulence model	Roof reattachment	Wake reattachment
Standard *k*–epsilon	None	2.2*H*
M.M.K. *k*–epsilon	No reattachment	3.12*H*
RNG *k*–epsilon	0.84*H*	2.5*H*
Non-linear quadratic, *k*–epsilon	0.75*H*	2.15*H*
Differential stress	No reattachment	2.0*H*
Experimental (S.R.I. 1999)	0.7*H*	1.2–1.4*H*

H = cube dimension.

Linear approach

Reynolds Averaged Navier-Stokes Equations (RANS)

In the standard $k - \epsilon$ model: isotrophic eddy viscosity

$$R_{ij} = \overline{u_i u_j} = \frac{2}{3} k \delta_{ij} - \nu_t S_{ij}$$

with

$$\nu_t = C_\mu \frac{k^2}{\epsilon}$$

$$C_\mu = 0.09$$

Non-linear approach

Non-Linear Eddy-Viscosity Models:

$$R_{ij} = \overline{u_i u_j} = \frac{2}{3} k \delta_{ij} - \nu_t S_{ij} + f(S_{ij}, \Omega_{ij})$$

Original definition of Reynolds stress tensor

+ **nonlinear stress**

Different C_μ definition.

Compromise between cost and accuracy

Model	C_μ	c_1 ($c_{\tau 1}$)	c_2 ($c_{\tau 2}$)	c_3 ($c_{\tau 3}$)
Craft et al. 1993	$C_{\mu Craft}$	-0.1	0.1	0.26
Shih et al. 1993	$C_{\mu Shih}$	-4	13	-2

Test case 1 - Atmospheric boundary layer

Analytical solution

Linear: $R_{11} = R_{22} = R_{33} = \frac{2}{3}k$

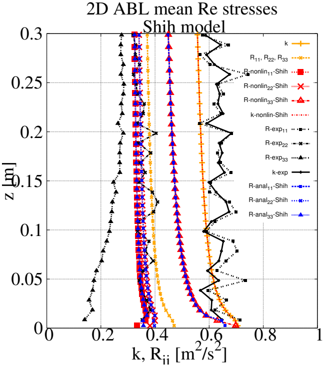
Non-linear:

$$R_{11} = \frac{2}{3}k + c_\mu \frac{k^3}{\epsilon^2}(U_{1,3})^2 \left(\frac{2}{3}c_{\tau 2} - \frac{1}{3}c_{\tau 3}\right)$$

$$R_{22} = \frac{2}{3} + c_\mu \frac{k^3}{\epsilon^2}(U_{1,3})^2 \left(-\frac{1}{3}c_{\tau 2} - \frac{1}{3}c_{\tau 3}\right)$$

$$R_{33} = \frac{2}{3}k + c_\mu \frac{k^3}{\epsilon^2}(U_{1,3})^2 \left(\frac{2}{3}c_{\tau 3} - \frac{1}{3}c_{\tau 2}\right)$$

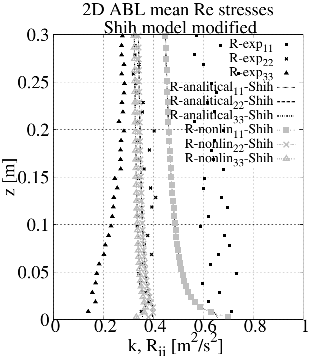
Experiments: $R_{11} > R_{22} > R_{33}$



Conclusion

There is a switch in OpenFOAM in R_{11} and R_{33}

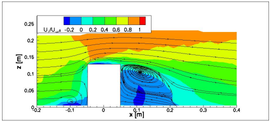
Test case 1 - Atmospheric boundary layer



Conclusion

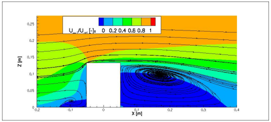
It is because of transposing ∇U

Test case - Results with zonal nonlinear model



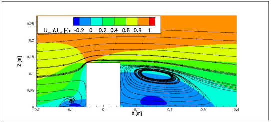
$L = 1.76H$

Experiment



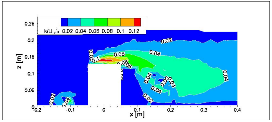
$L = 2.96H$

Nonlinear Craft $b = 0.5$

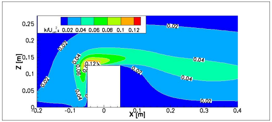


$L = 2.64H$

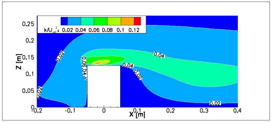
Nonlinear Craft $b = 5$



Experiment



Nonlinear Craft $b = 0.5$



Nonlinear Craft $b = 5$

Conclusion

Results are sensitive to zone transition