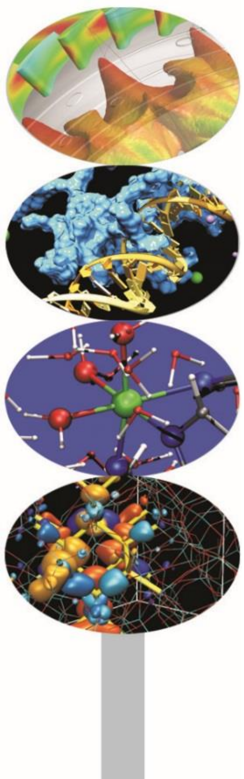

Simulation of detached flows using OpenFOAM®

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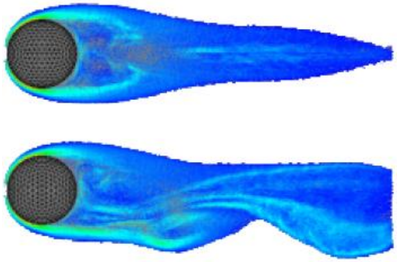
8 April 2016

Motivation

- **Flow separation is an important phenomena in industrial and environmental applications**

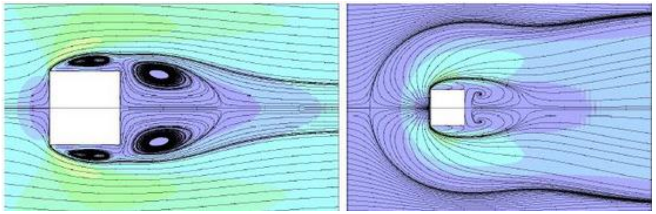
- **Most of the models having problem to predict the separation and reattachment poins**

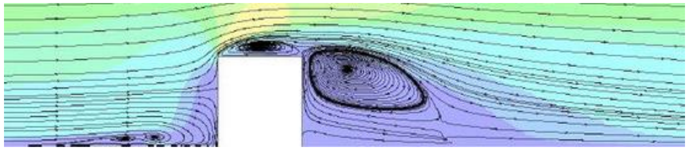
Benchmark cases in order to test applicative meshes:



✓ Flow past a sphere

✓ Flow around Surface-Mounted cubical obstacle





Numerical scheme

Turbulence models:

- **RANS (standard $k - \varepsilon$ model)**

$$\begin{cases} \frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k \bar{u}_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k - \rho\varepsilon \\ \frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon \bar{u}_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_k - C_{2\varepsilon}^{*}\rho\frac{\varepsilon^2}{k} \end{cases}$$

P_k is the rate of production of k by the mean flow

$$C_{2\varepsilon}^{*} = C_{2\varepsilon} + \frac{C_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta\eta^3}$$

$\eta = Sk/\varepsilon$ with S the modulus of the mean rate-of-strain

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

$C_\mu = 0.09$ $\sigma_k = 1.00$ $\sigma_\epsilon = 1.30$ $C_{1\epsilon} = 1.44$ $C_{2\epsilon} = 1.92$

Numerical scheme

Turbulence models:

❑ LES

- standard Smagorinsky : $\nu_{eff} = \nu + \nu_t$

$$\boldsymbol{\nu_T} = (\boldsymbol{C_s \bar{\Delta}})^2 |\bar{\boldsymbol{S}}| \; , c_s = \sqrt{c_k \sqrt{2 \frac{c_k}{c_\varepsilon}}}$$

- Smagorinsky with van Driest damping

$$\Delta = min\left(\Delta_{mesh}, \left(\frac{k}{C_\Delta}\right) y\left(1 - e^{-y^+/A^+}\right)\right)$$

- dynamic Lagrangian

$$c_s^2(\mathbf{x}, t) = \frac{\mathcal{I}_{LM}}{\mathcal{I}_{MM}}$$

$$M_{ij} = 2\Delta^2 \left[\widehat{|\bar{S}|\bar{S}_{ij}} - 4|\bar{\bar{S}}|\bar{\bar{S}}_{ij} \right]$$

$$\mathcal{I}_{MM}(\mathbf{x}, t) = \int_{-\infty}^{t} M_{ij} M_{ij}(\mathbf{z}(t'), t') \; W(t - t') \; dt'.$$

$$\mathcal{I}_{LM}(\mathbf{x}, t) = \int_{-\infty}^{t} L_{ij} M_{ij}(\mathbf{z}(t'), t') \; W(t - t') \; dt',$$

Meneveau et al (1996)

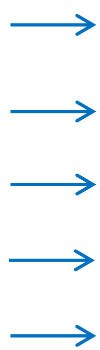
Numerical scheme

- Second order schemes
- Central difference for advective terms
- PISO algorithm for LES,
  SIMPLE for RANS.

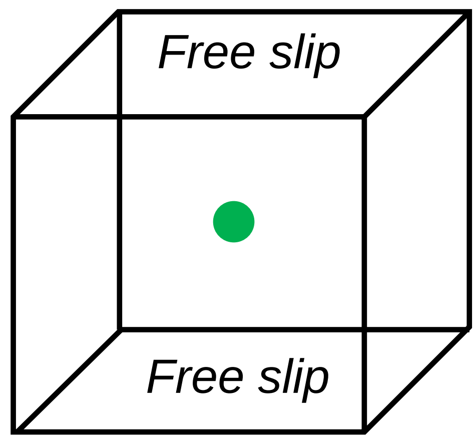
Flow around sphere

Problem description

$$Re_D = 2rU/\nu = 10000, \qquad r = 1\ m.$$



$$\vec{U} = (1,0,0)$$



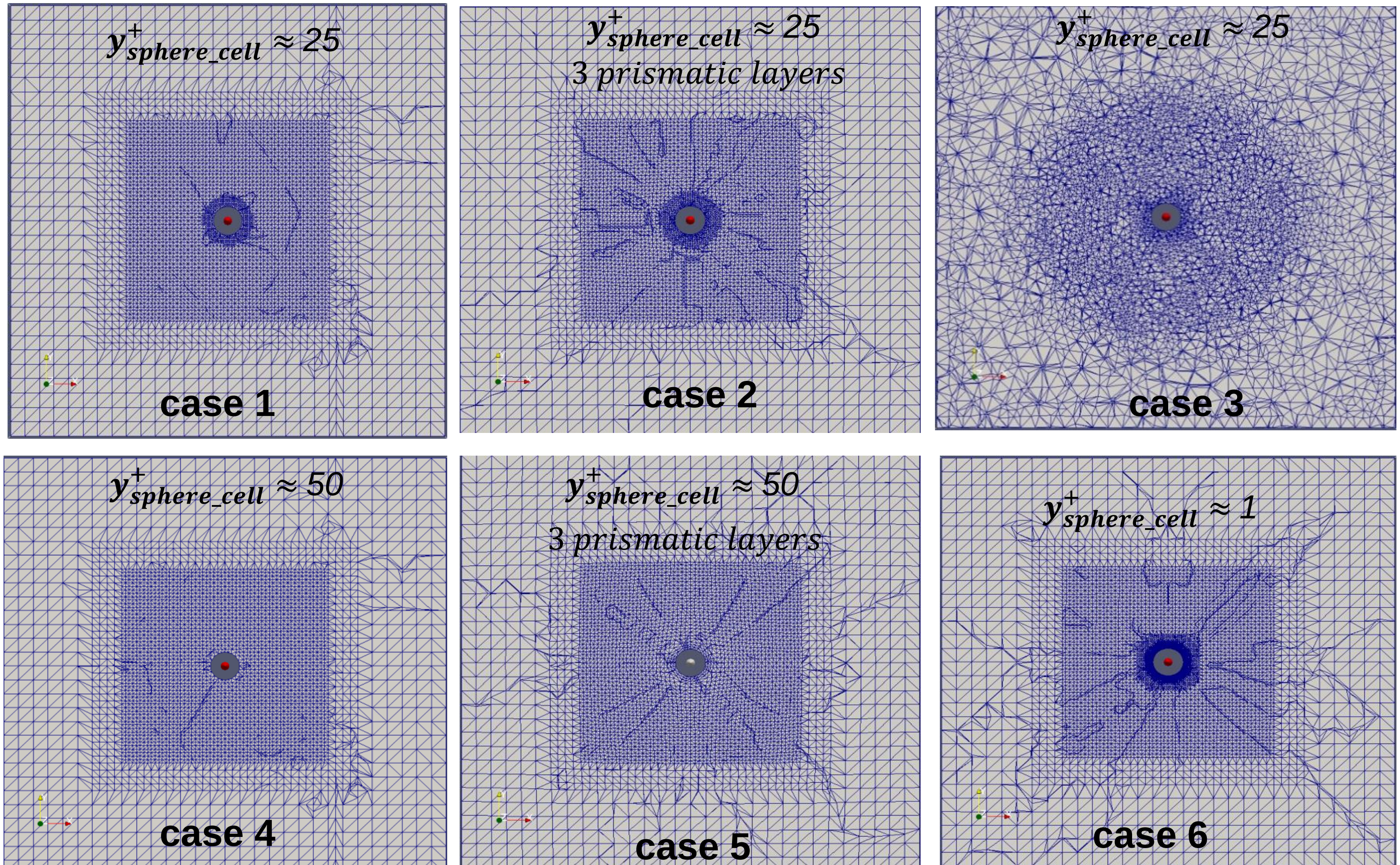
$$l = 30r$$

$$\nabla \vec{U} = 0$$

Constantinescu & Squires (2003)

Flow around sphere

$30 \times 30 \times 30$ cells

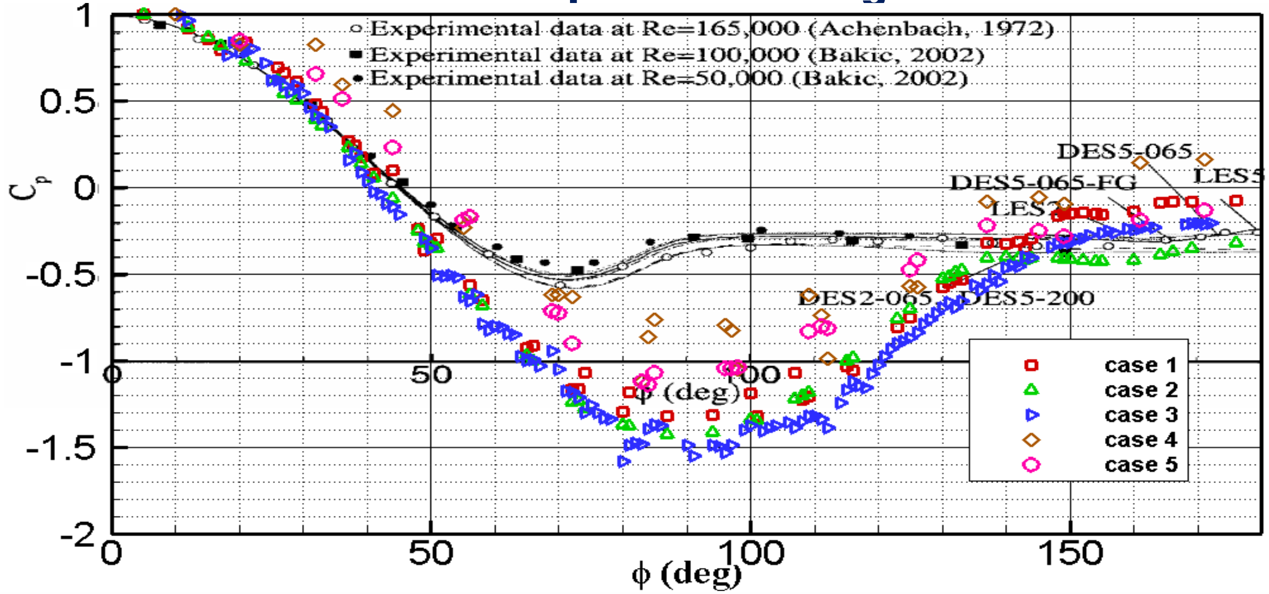


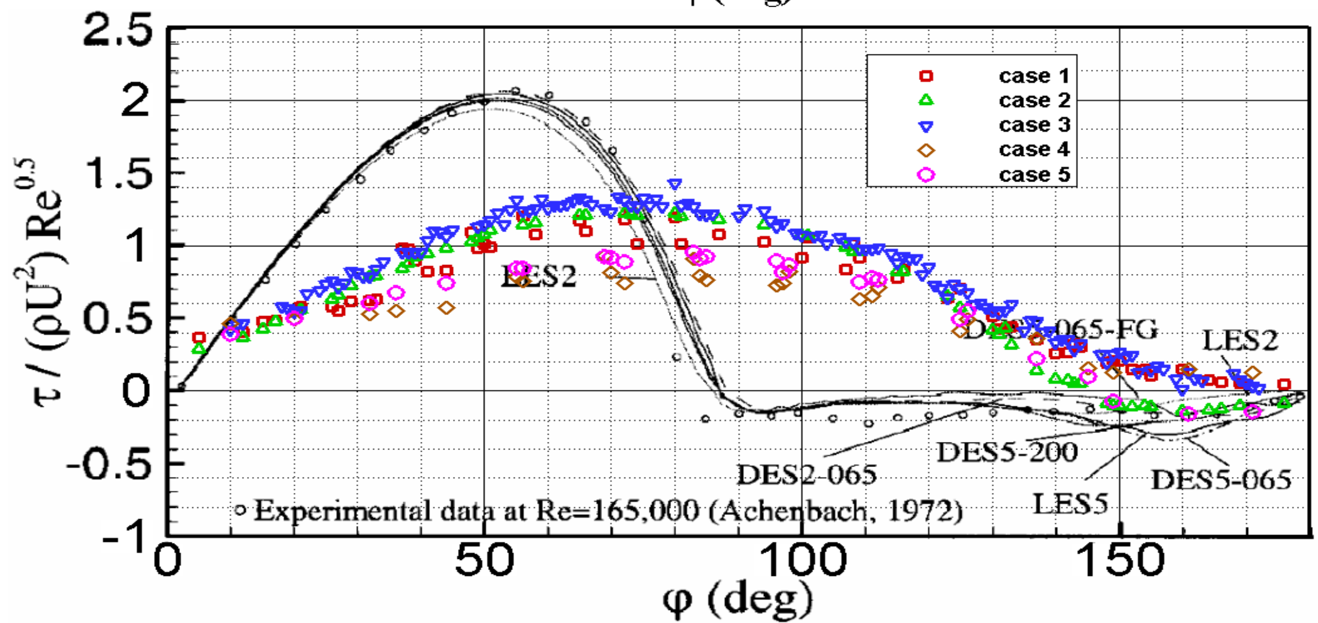
OpenFOAM Grid:
case 1
case 2
case 4
case 5
case 6

ANSYS ICEM Grid:
case 3

Flow around sphere

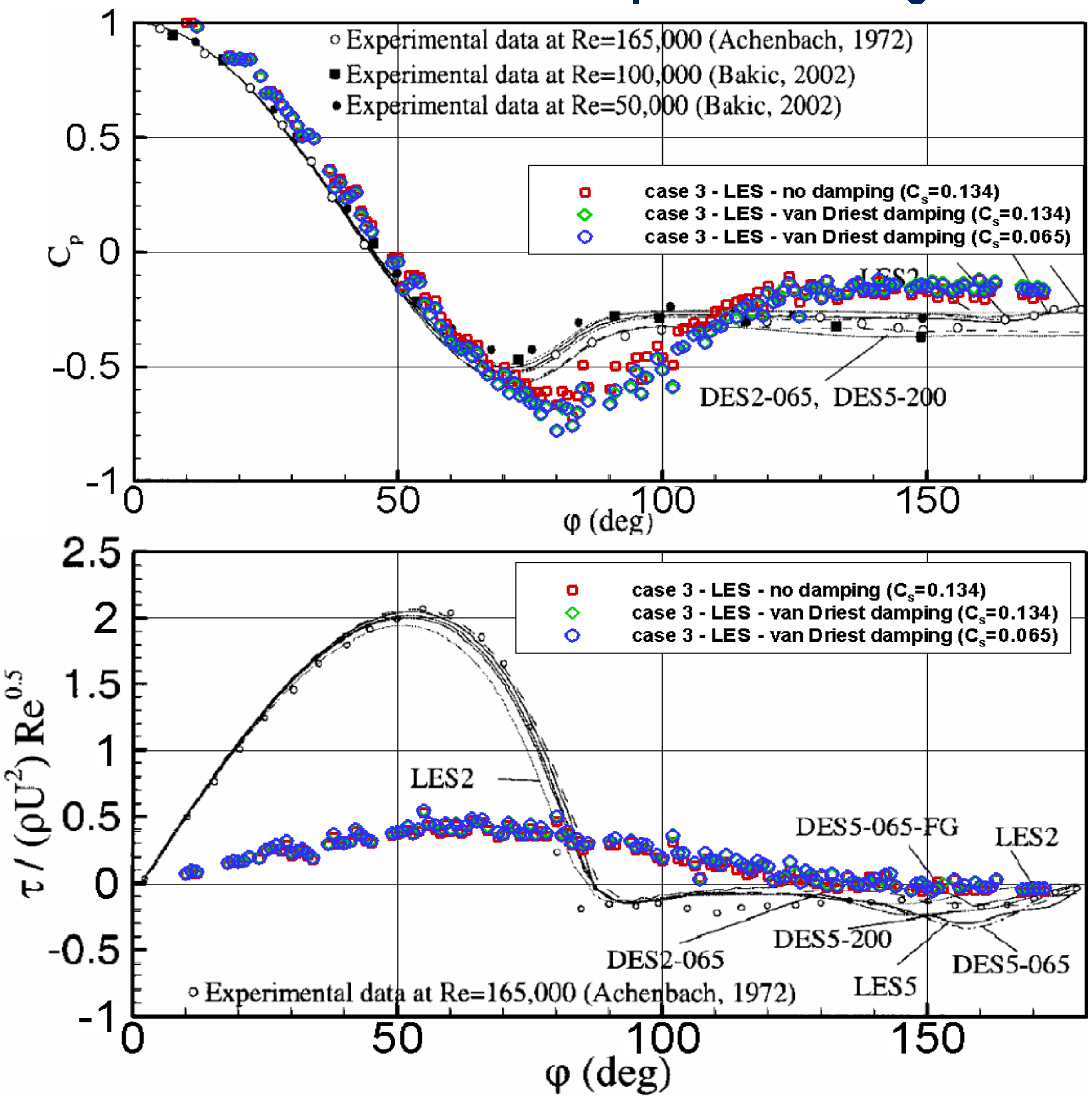
Results of simulation with OpenFOAM using standard $k-\varepsilon$ model

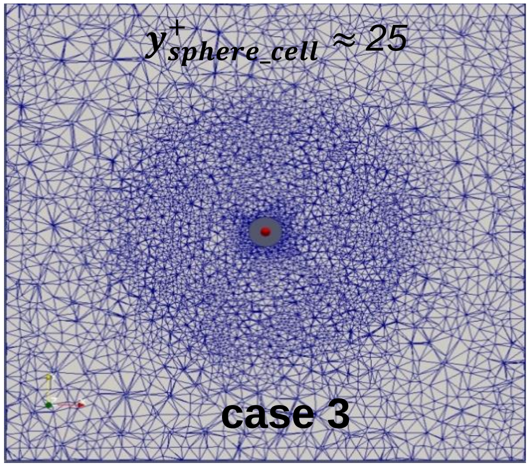




Flow around sphere

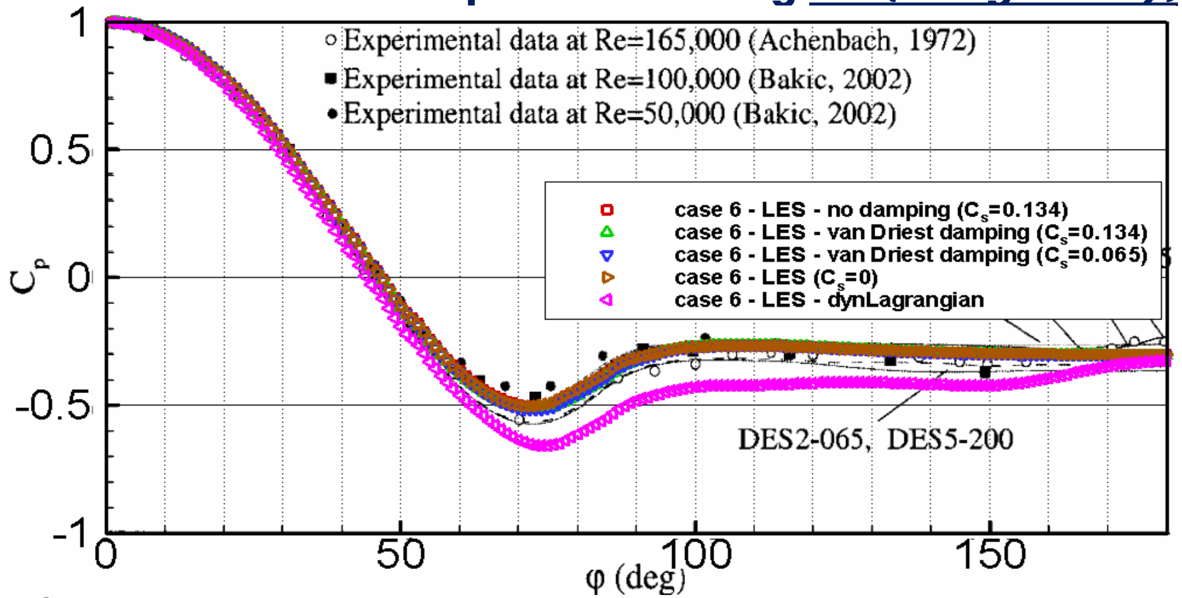
Results of simulation with OpenFOAM using LES for case 3

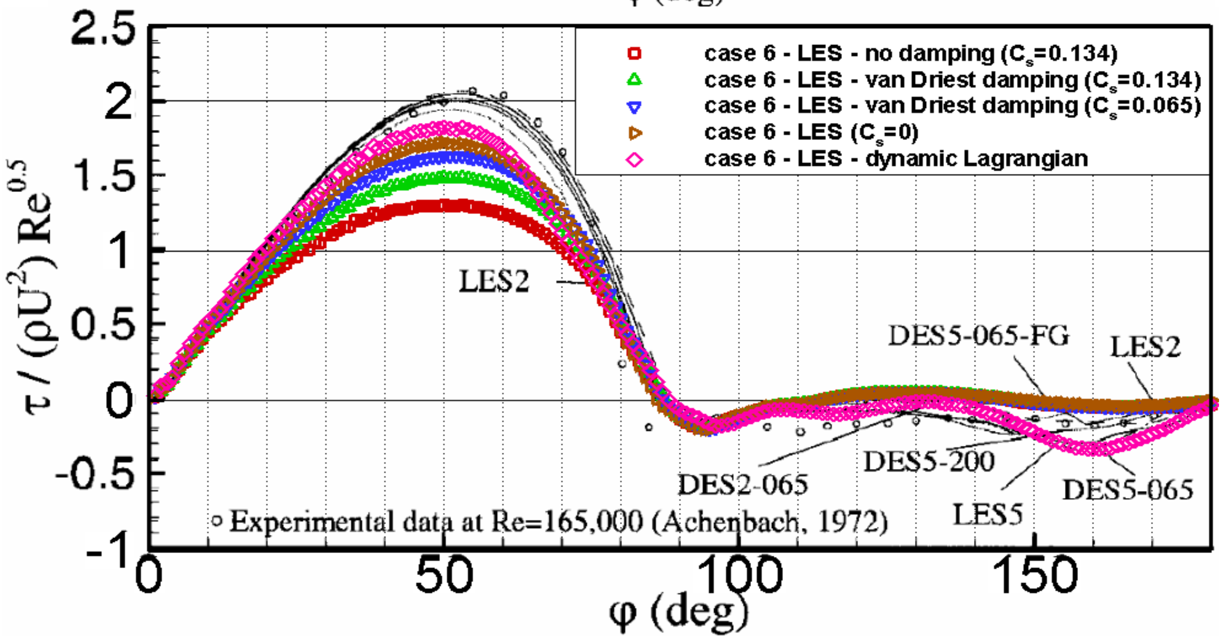


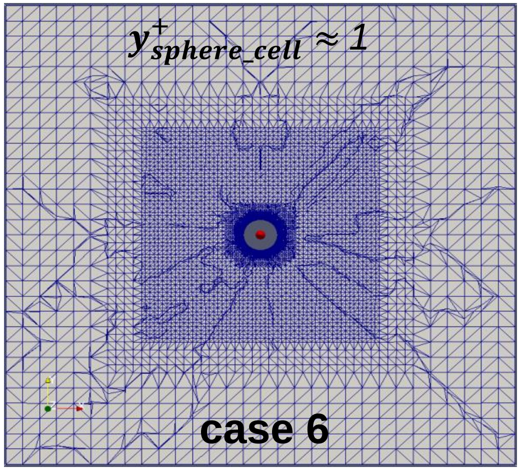


Flow around sphere

Result of simulation with OpenFOAM using *LES (Smagorinsky)* for case 6

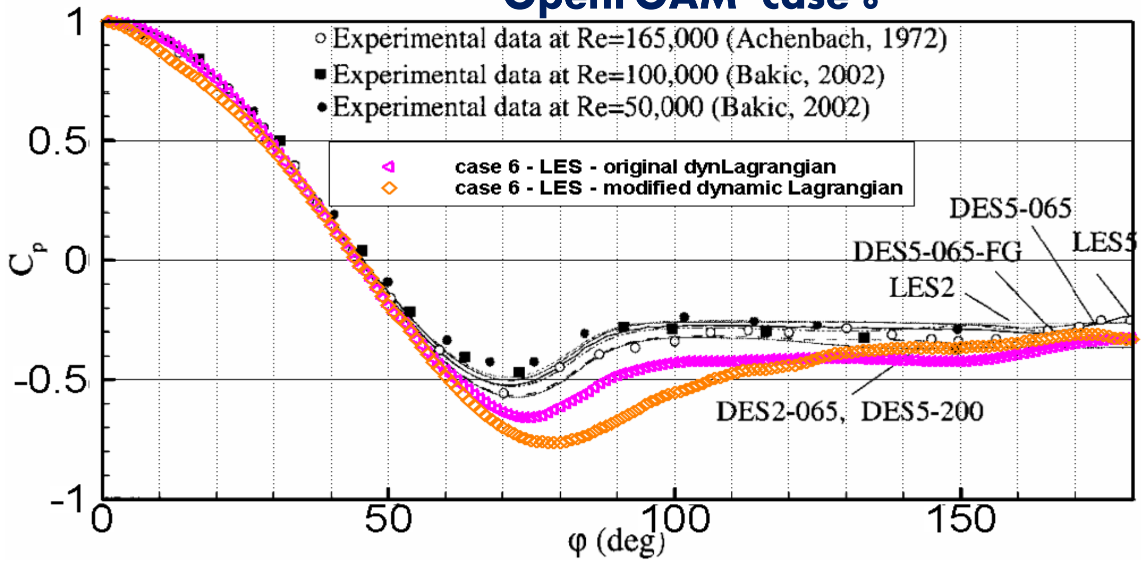


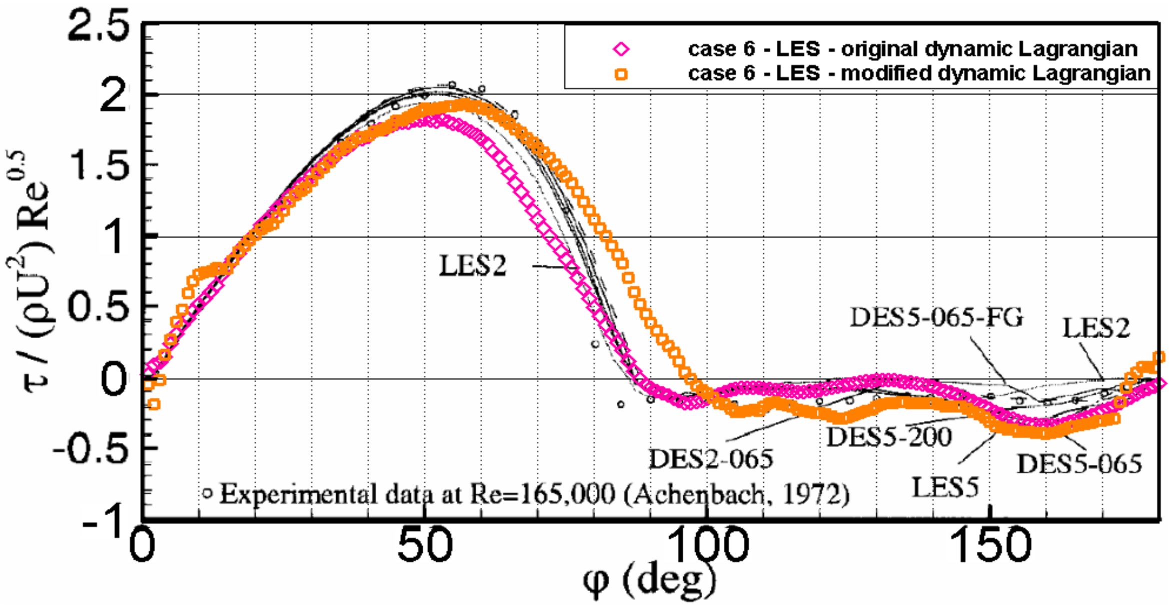


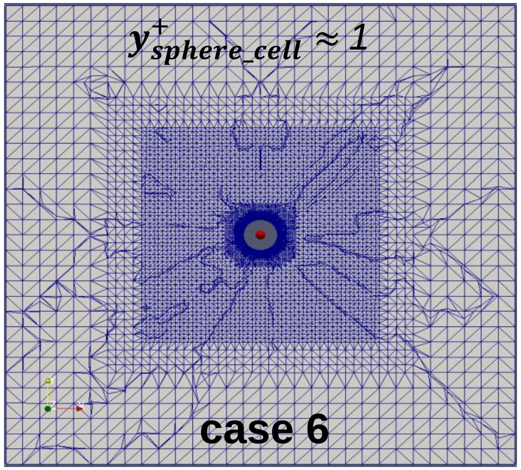


Flow around sphere

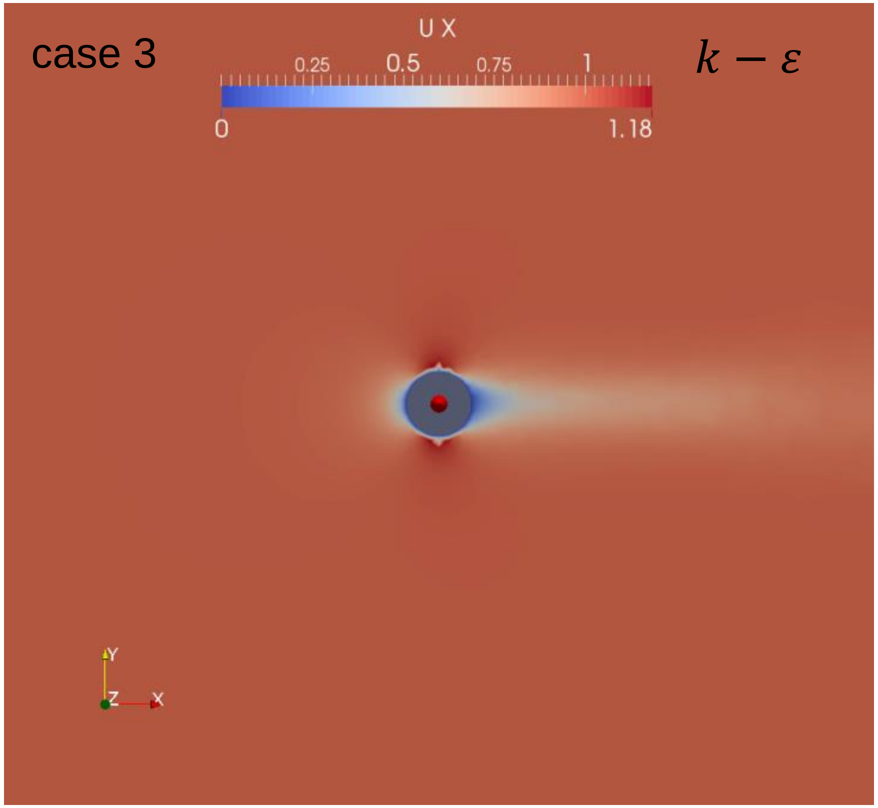
Results of simulation with *LES-dynLagrangian* : our modification and the original of OpenFOAM case 6

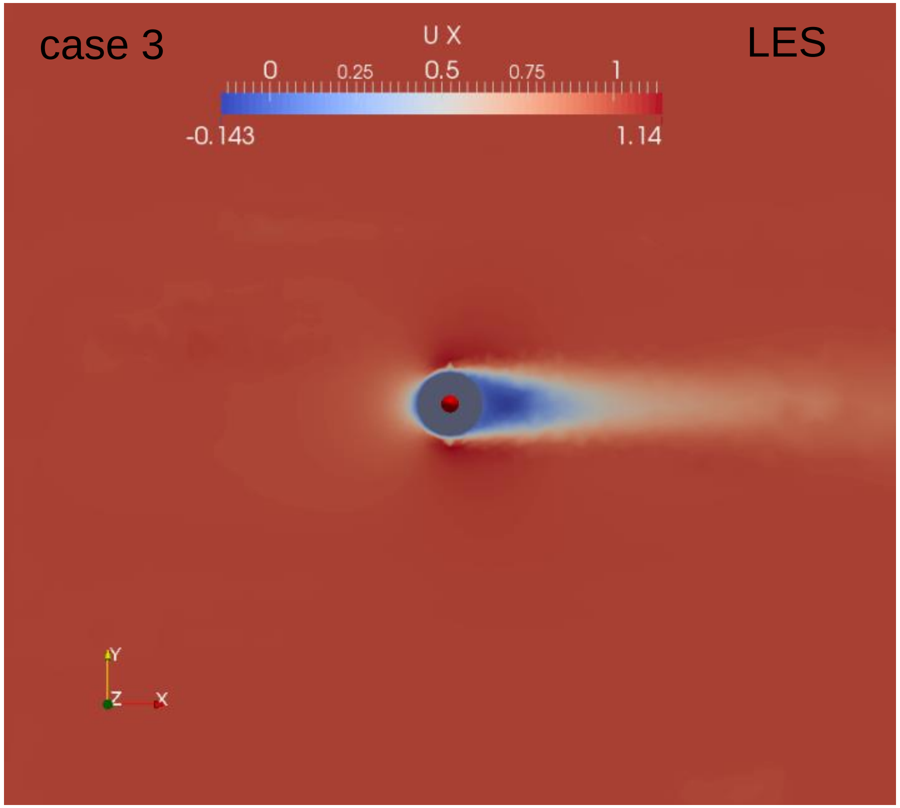






Flow around sphere

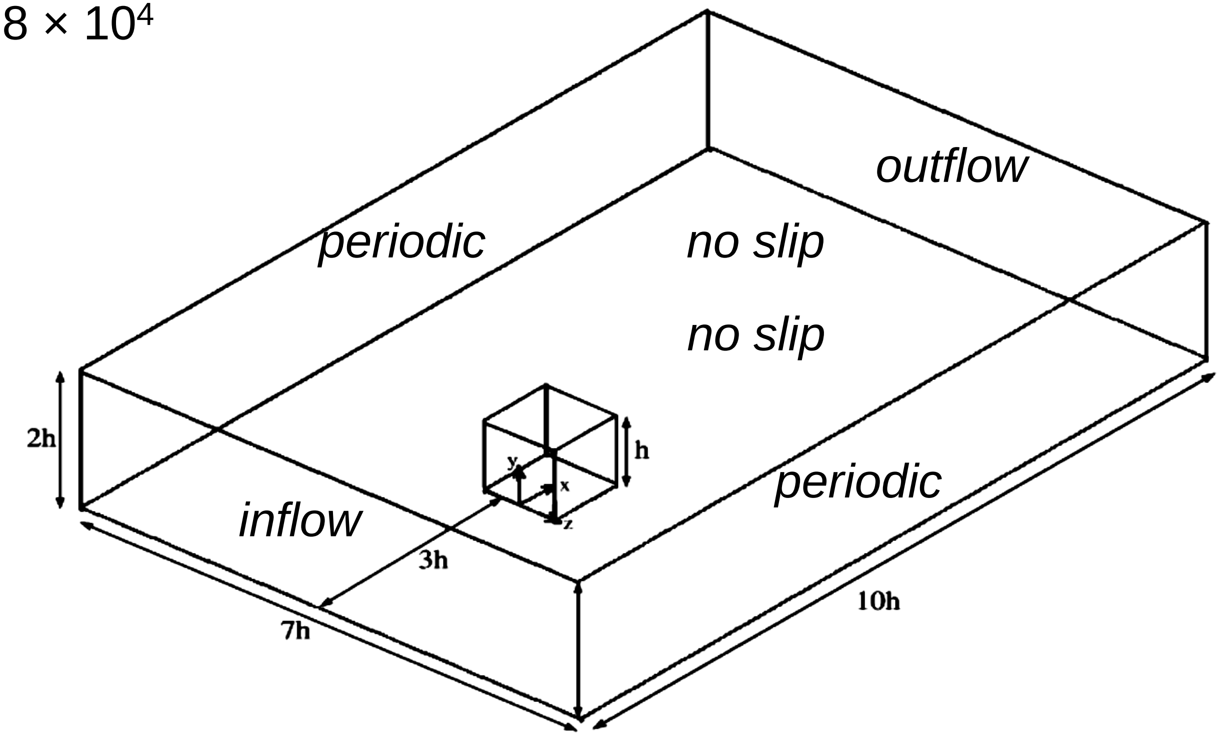




wall-mounted box

Problem description

$\boldsymbol{Re_h = U_B h/\nu} = 8 \times 10^4$
$\boldsymbol{h}$ =*0.025 m*



experiment by Martinuzzi and Tropea (1993)
ERCOFTAC database

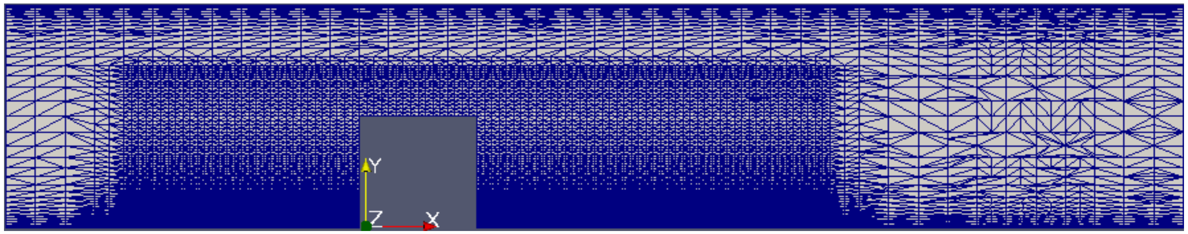
Flow over box

Grid generated by OpenFOAM

case 1

$y^+ \approx 25$

Near wall

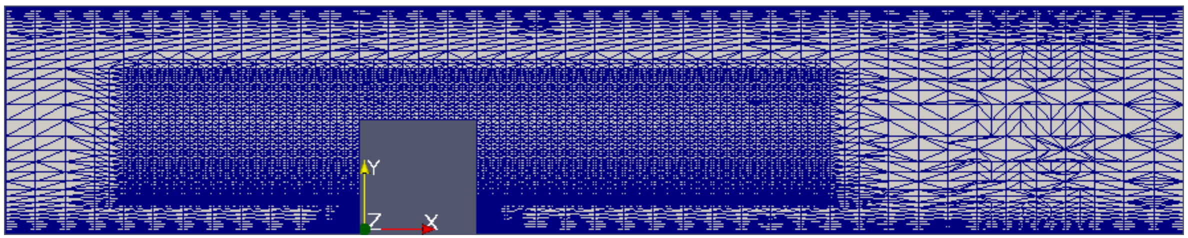


$y^+ \approx 64$ **Near cube**

Refinement box from bottom

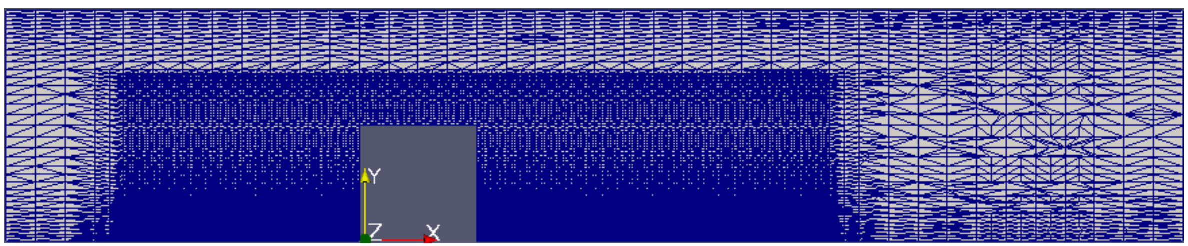
case 2

$y^+ \approx 25$



case 3

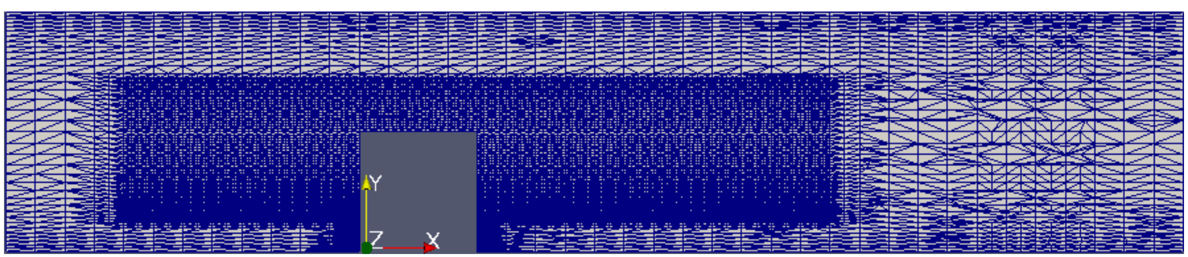
$y^+ \approx 50$



Refinement box from bottom

case 4

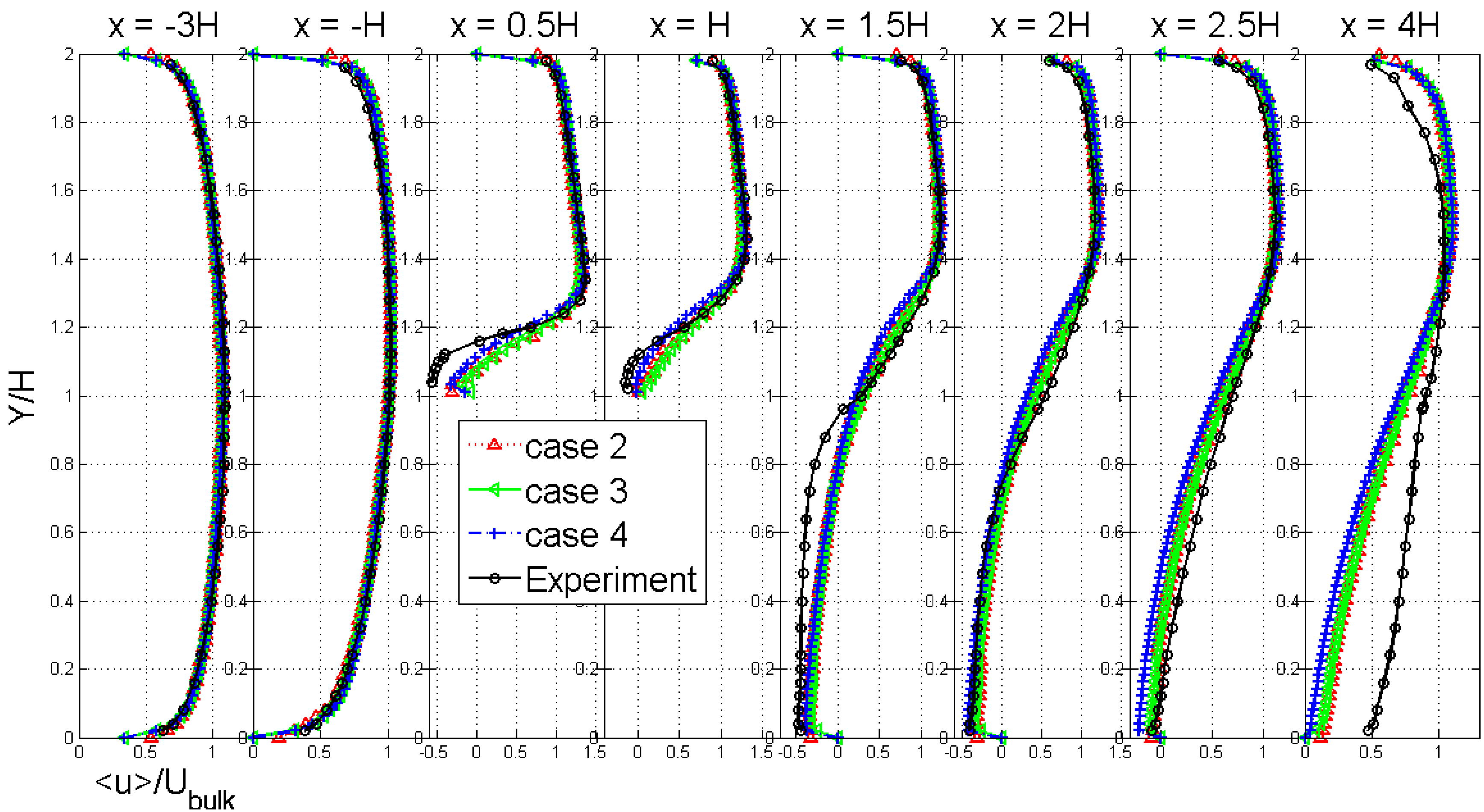
$y^+ \approx 50$



$40 \times 36 \times 24$ **cells**

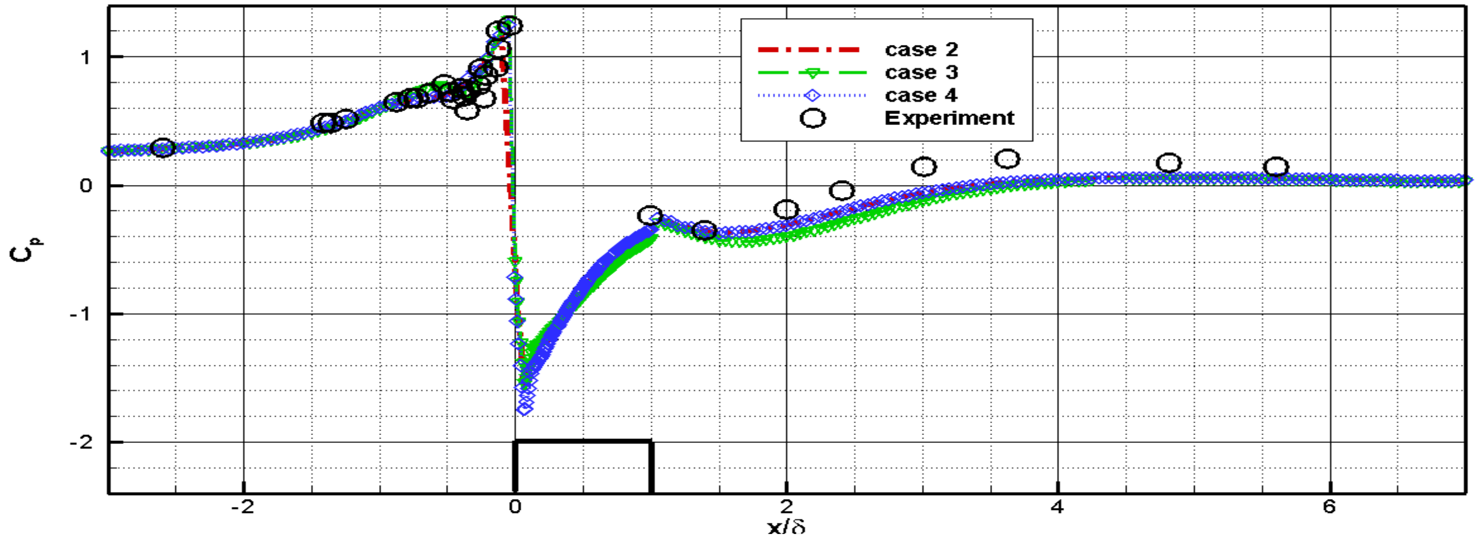
Flow over box

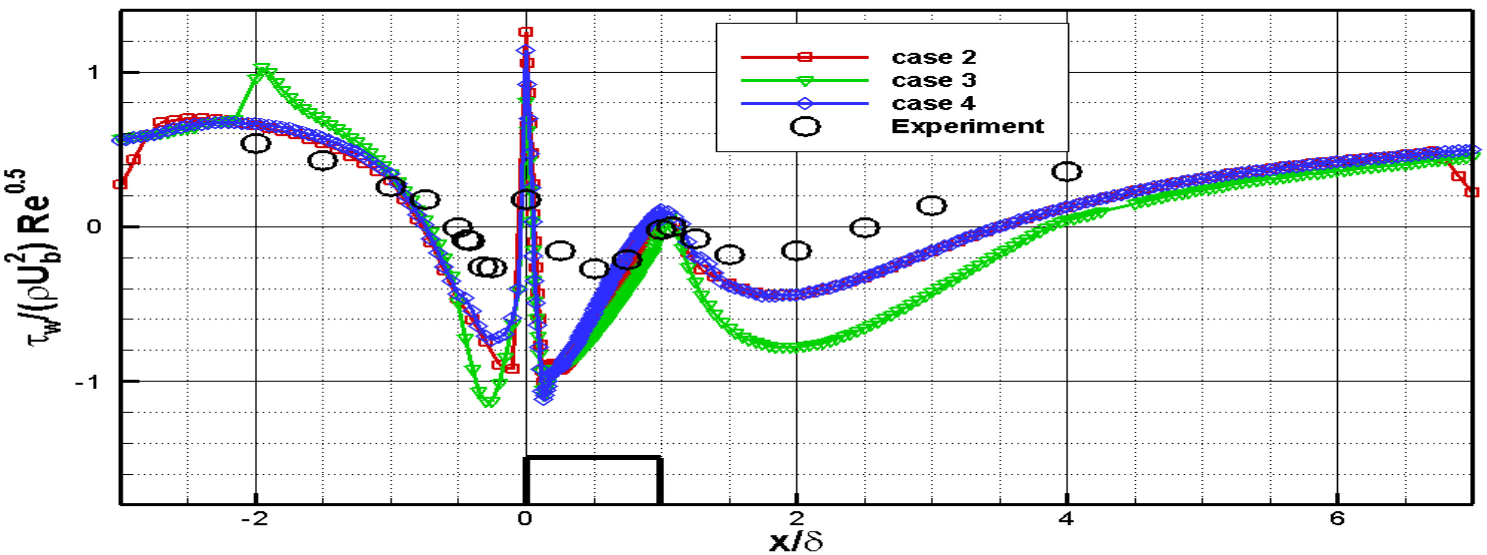
Results of simulation with OpenFOAM using standard $k-\varepsilon$ model



Flow over box

Results of simulation with OpenFOAM using standard $k-\varepsilon$ model

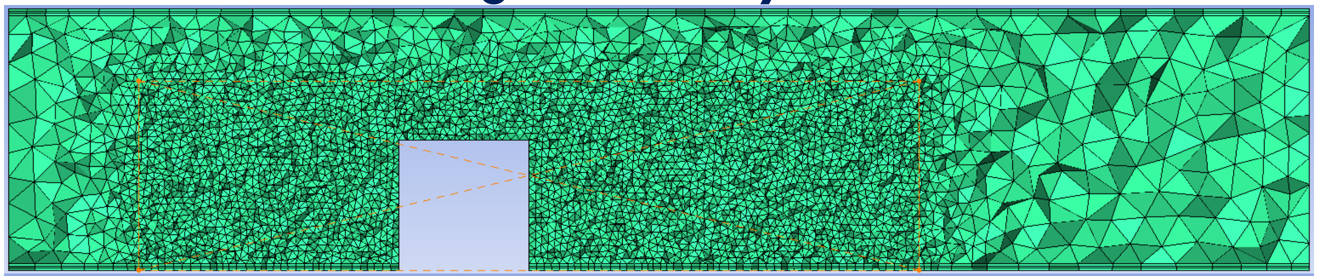




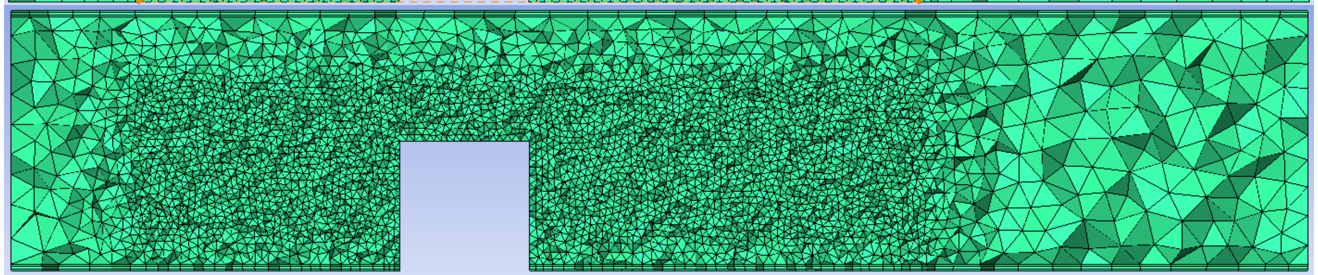
Flow over box

Grid generated by ANSYS ICEM

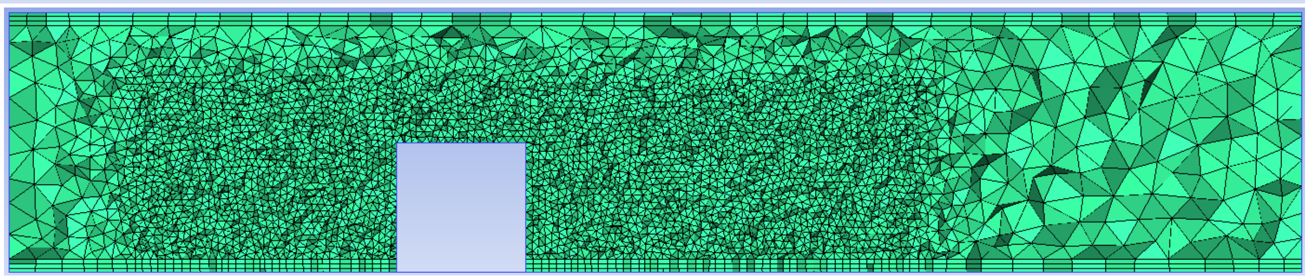
case 1



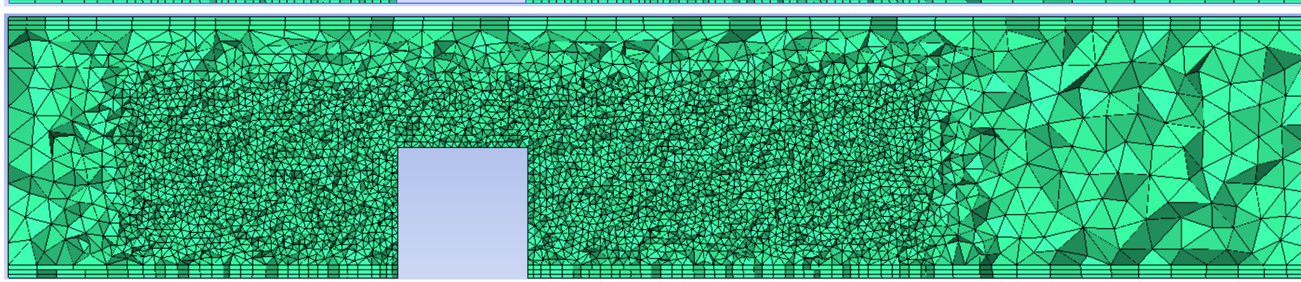
case 2



case 3

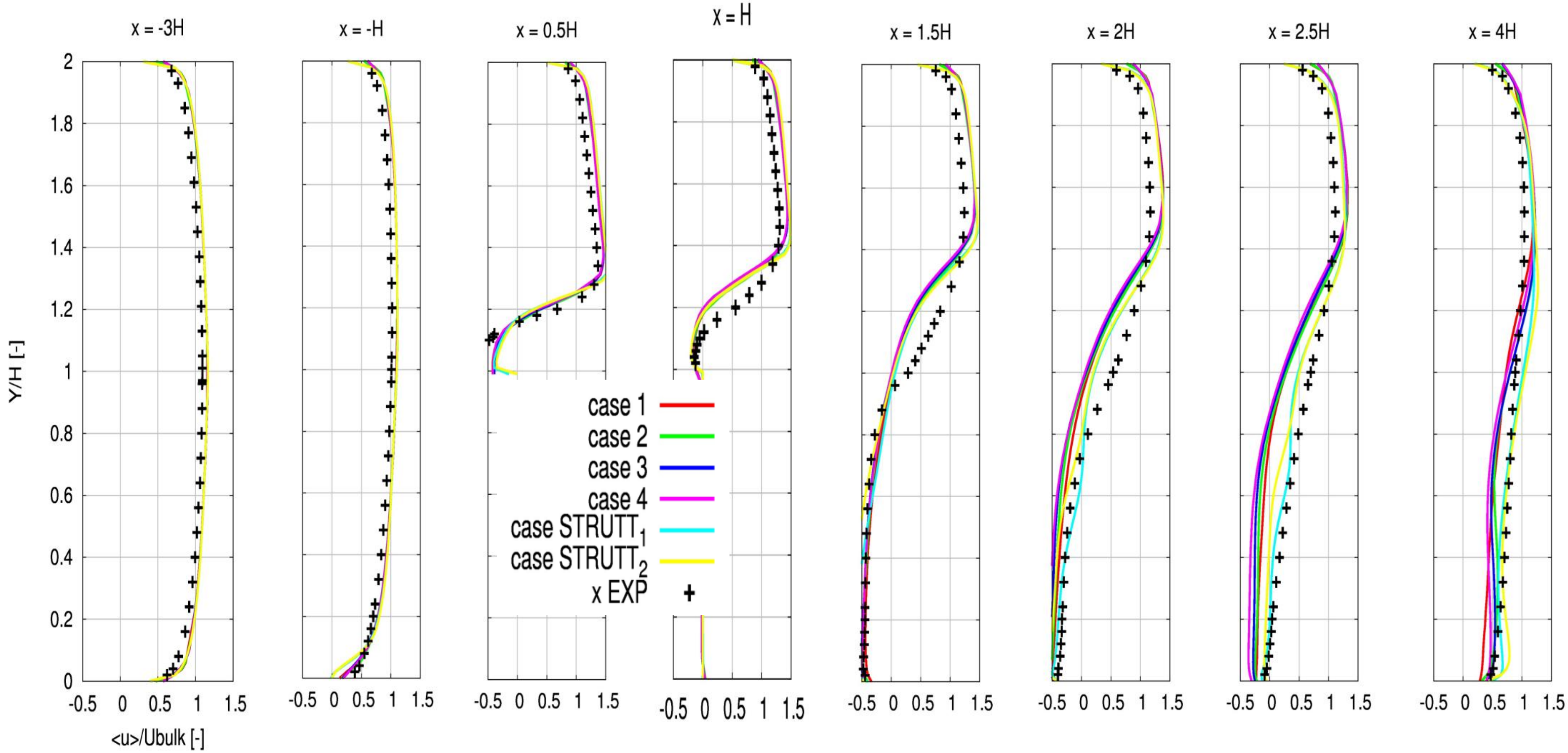


case 4



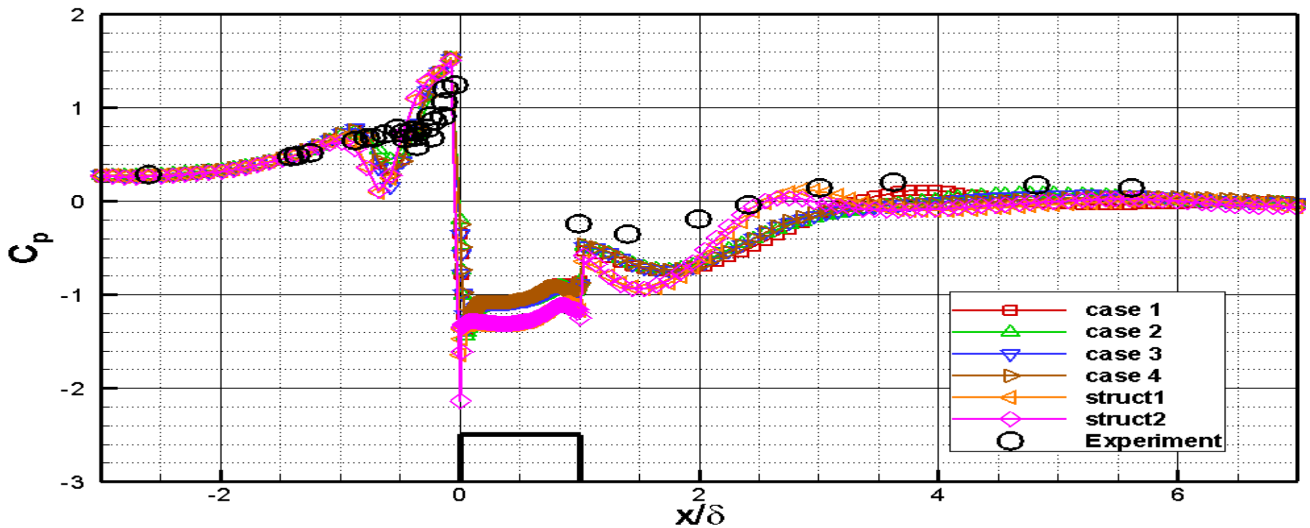
Flow over box

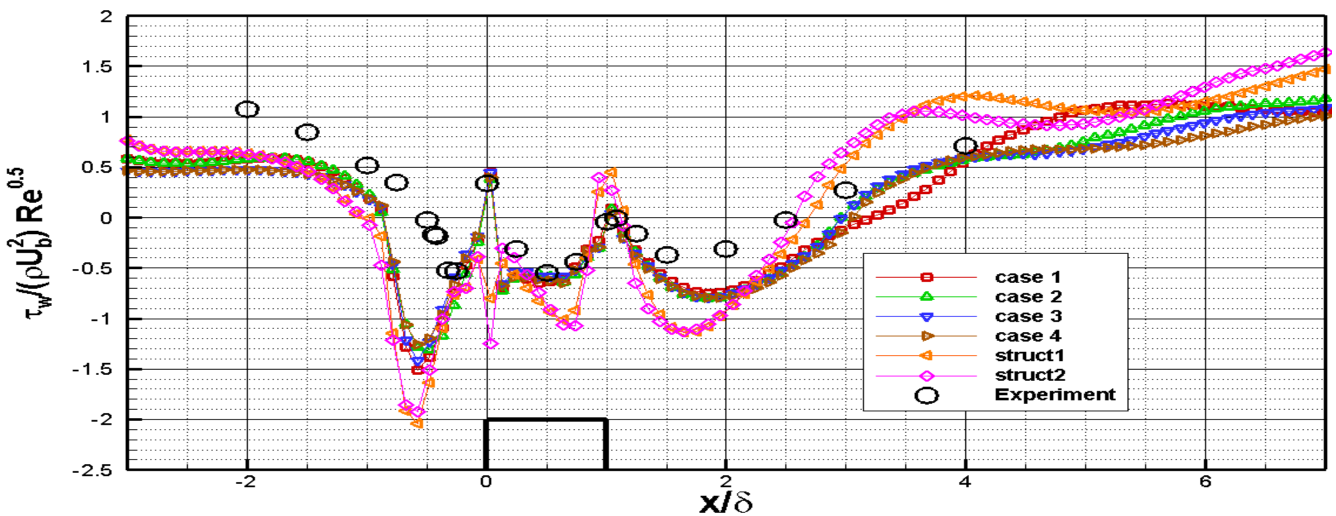
Result of simulation with ANSYS CFX using $SST\ k-\omega$ model



Flow over box

Results of simulation with ANSYSCFX using $SST\ k-\omega$ model





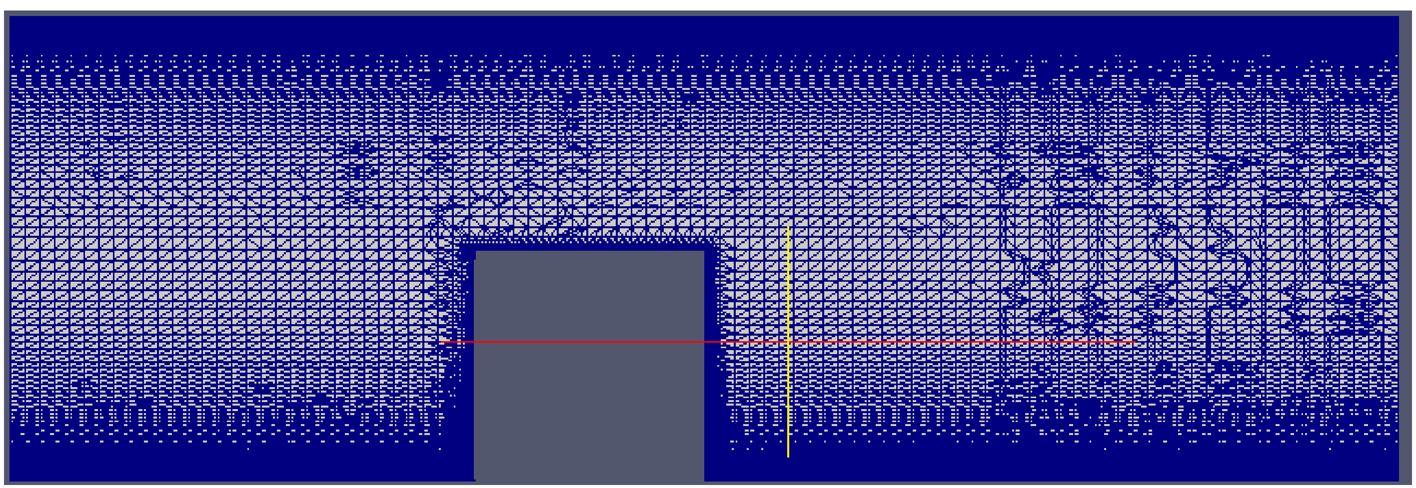
Flow over box

Wall-bounded fully developed turbulent flows passing around bluff-bodies.

A random noise is added to the specific inlet velocity
from a defined turbulence level

Inlet
{
Type turbulenceInlet;
referenceField nonuniform
fluctuationScale (0.02 0.01 0.01)
Value nonuniform
}

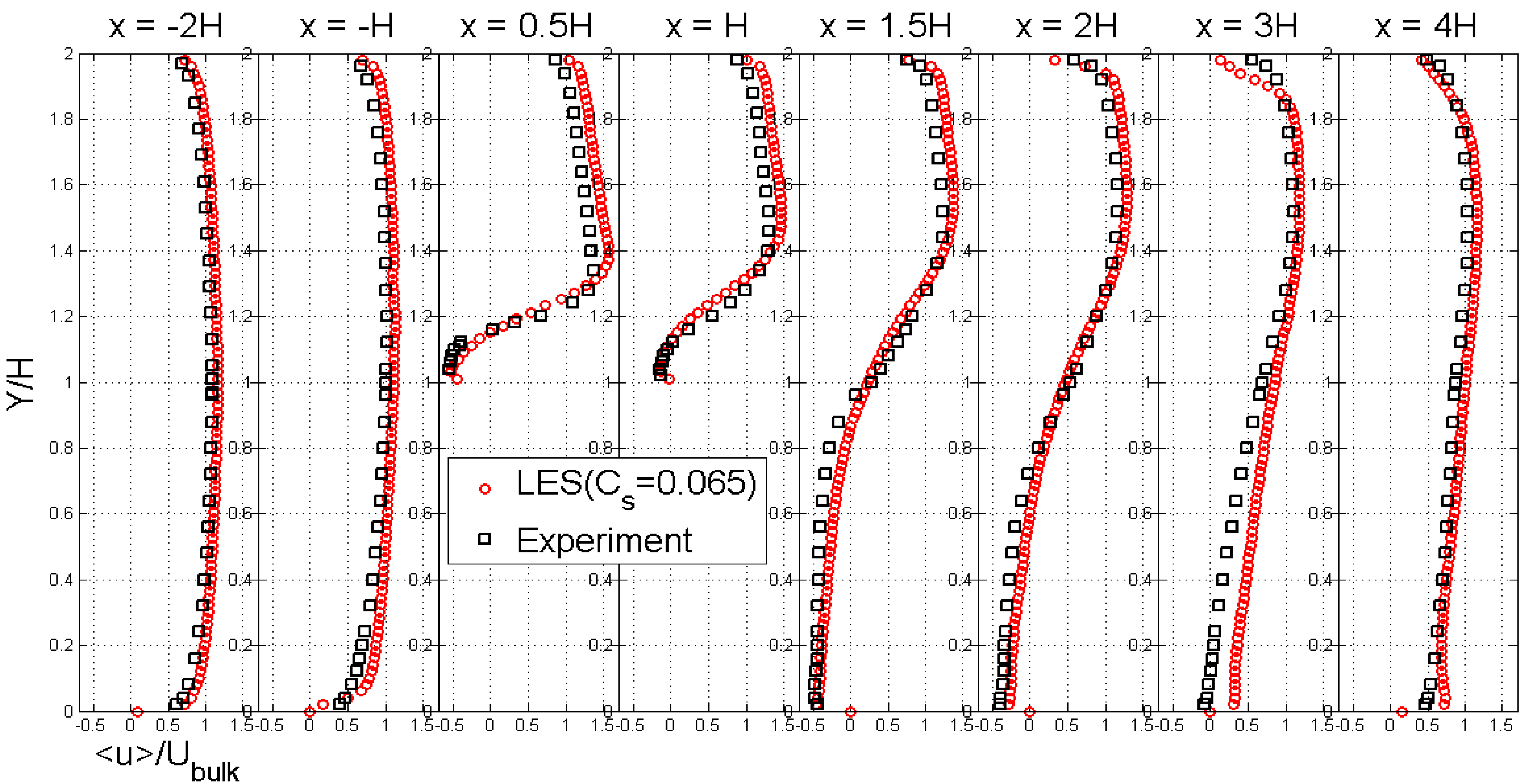
$$u_p^+ = \begin{cases} \frac{1}{k}\log(y_p^+) + B, & y_p^+ > 11 \\ y_p^+, & y_p^+ \leq 11 \end{cases}$$



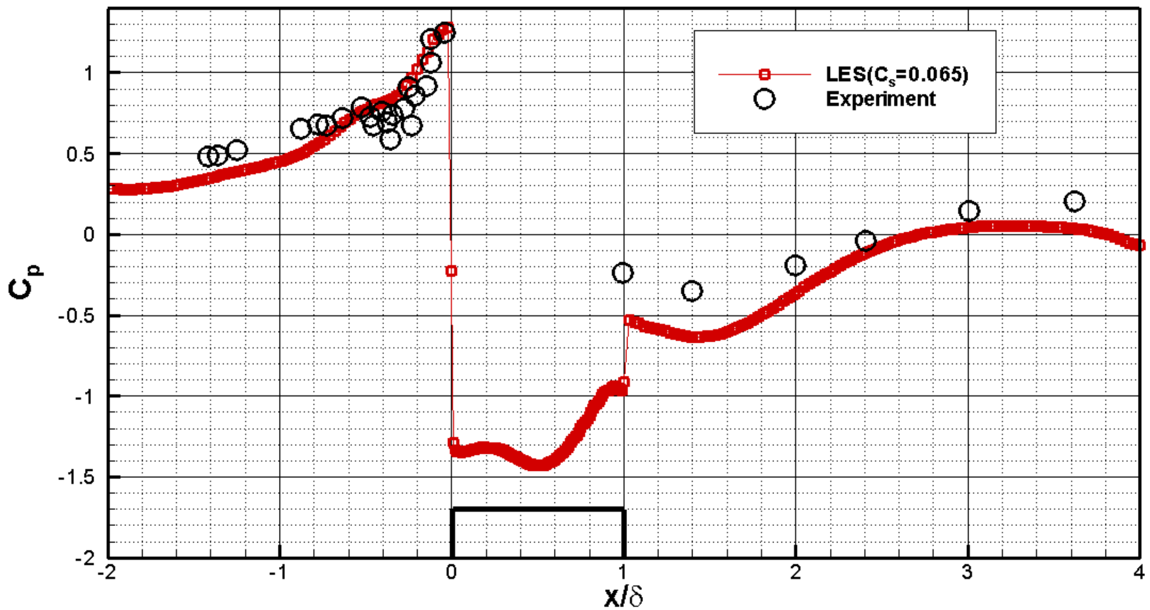
$6\delta \times 2\delta \times 7\delta$
$94 \times 120 \times 160$ cells

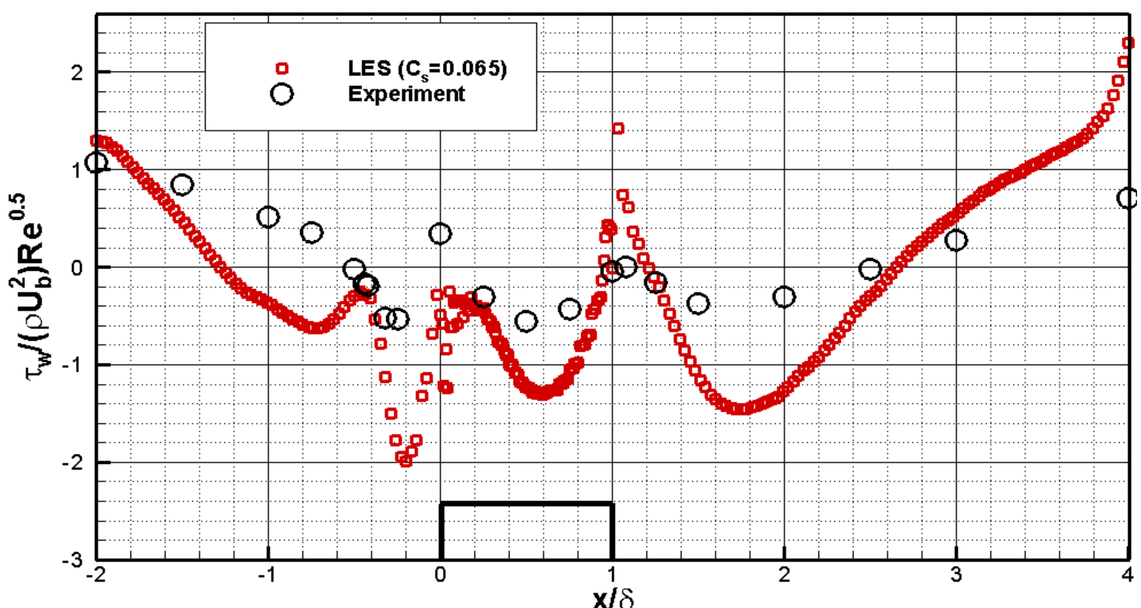
Flow over box

Simulation with OpenFOAM, using standard Smagorinsky (van Driest damping)



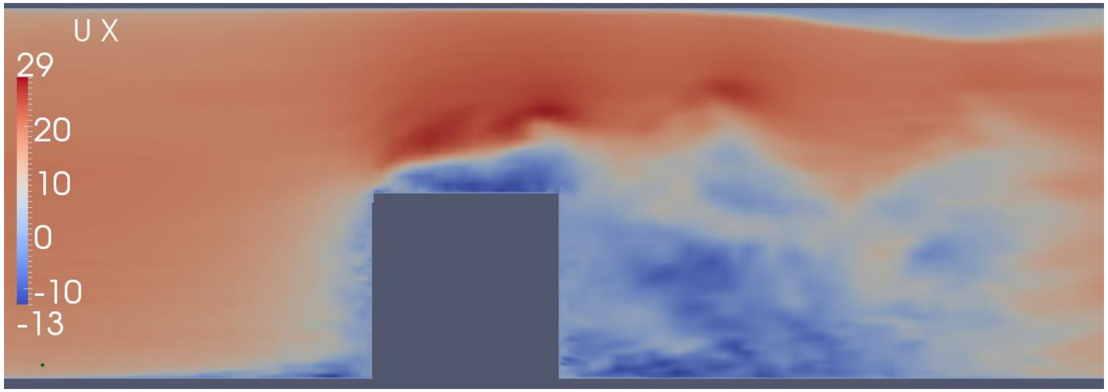
Flow over box



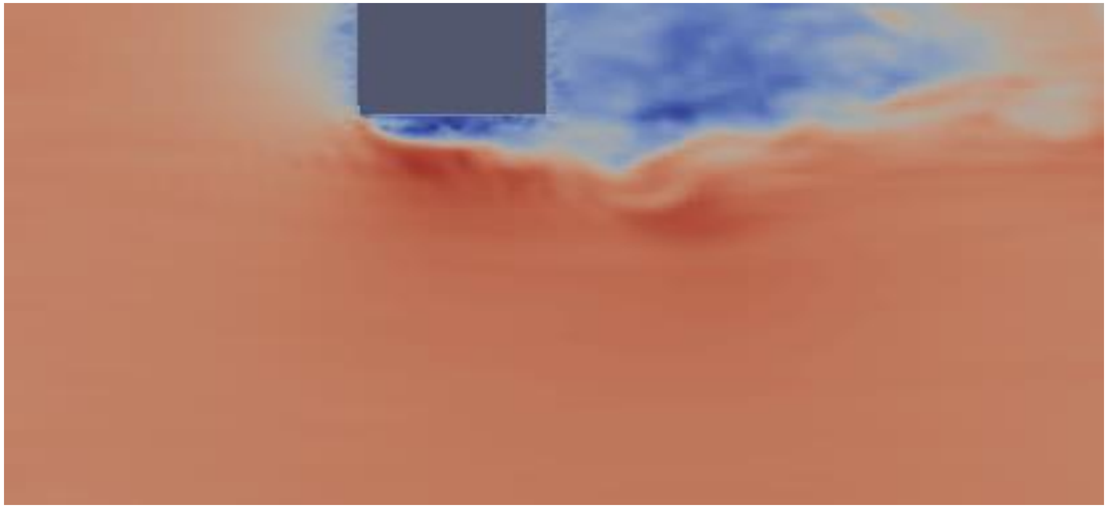


Flow over box

Instantaneous Flow field



Vertical cross section



Horizontal cross section

Why Wall layer model?

- ***Wall bounded flows***, at very ***high Reynolds*** numbers, require ***very fine grid*** near wall to resolve viscous sub-layer

- The resolution even for ***resolved LES*** $(\boldsymbol{Re^{2.5}})$ is comparable to ***DNS*** $(\boldsymbol{Re^{3}})$, using wall function $(\boldsymbol{Re^{0.6}})$ [Piomelli 2008]

- In applications where wall roughness is the rule rather than the exception, it does not make sense to describe the wall boundary in a deterministic sense.

Wall layer model

Filtered Navier Stokes equation for an incompresible flow:

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial(\bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left((\nu + \boldsymbol{\nu_T})\frac{\partial \bar{u}_i}{\partial x_j}\right)$$

Equilibrium stress model:

$$u_p^+ = \begin{cases} \frac{1}{k}\log(y_p^+) + B, & y_p^+ > 11 \\ y_p^+, & y_p^+ \leq 11 \end{cases}$$

$$u_p^+ = u_p/\boldsymbol{u_\tau} = \sqrt{(u^2 + w^2)}/\boldsymbol{u_\tau}, \quad k = 0.41, \ B = 5.1$$

Wall shear stress: $\tau_w = \rho u_\tau^2 \rightarrow \begin{cases} \tau_{w,x} = \rho u_\tau^2 \frac{u}{u_p} \\ \tau_{w,z} = \rho u_\tau^2 \frac{w}{u_p} \end{cases}$

In x direction:

$$(\nu + \boldsymbol{\nu_T})\frac{\partial \bar{u}_1}{\partial x_2} = \tau_{\ w,x}$$

In z direction:

$$(\nu + \boldsymbol{\nu_T})\frac{\partial \bar{u}_3}{\partial x_2} = \tau_{\ w,z}$$

Why Wall layer model?

P in the log region:

$$\bar{S}_{12} = \frac{u_\tau}{k y_p}\frac{\bar{u}}{u_p} + \frac{\partial \bar{v}}{\partial x}, \qquad \bar{S}_{32} = \frac{u_\tau}{k y_p}\frac{\bar{w}}{u_p} + \frac{\partial \bar{v}}{\partial z}$$

P in the viscous layer:

$$\bar{S}_{12} = \frac{u_\tau^2}{\nu}\frac{\bar{u}}{u_p} + \frac{\partial \bar{v}}{\partial x}, \qquad \bar{S}_{32} = \frac{u_\tau^2}{\nu}\frac{\bar{w}}{u_p} + \frac{\partial \bar{v}}{\partial z}$$

$$\boldsymbol{\nu_T} = (\boldsymbol{C_s}\overline{\boldsymbol{\Delta}})^2|\overline{\boldsymbol{S}}|$$

Future works

- WMLES for flows with separation
- Proper Turbulent inflow for LES
- Applying LES (dynamic Lagrangian) to simulate flow around wall-mounted cube
- Applying DES

References

1. Cintolesi C.: OpenFOAM simulations-flow around a Sphere, University of Trieste, report November (2013).
2. Constantinescu K., Squires K.: LES and DES investigation of Turbulent Flow over Sphere at Re=10000. Flow Turbulence and Combustion 70: pp. 267-298 (2003).
3. Ferziger J., Peric M. : Computational methods for fluid dynamics, Springer, Third edition (1996).
4. Isaev S. A., Lysenko D. A. (2009): Calculation of unsteady flow past a cube on the wall of a narrow channel using URANS and the Spalart-Almaras turbulence model, *Journal of Engineering Physics and Thermophysics*, *Vol. 82, No. 3*.
5. Kundu P., Cohen I.: Fluid Mechanics. Elsevier Academic press, Third Edition (2004).
6. MARTINUZZI R., TROPEA C. : The flow around surface-mounted, prismatic obstacles placed in a fully developed channel flow. *Journal of Fluid Engineering, Vol. 115, p. 85* (1993).
7. Meneveau Ch., Lund T., Cabot W. H.: A lagrangian dynamic subgrid-scale model of turbulence, J. Fluid Mech., vol. 319, p. 353-385 (1996)
8. Morrison F. A.: Data correlation for drag coefficient for sphere, report in Michigan Technology University.
9. Penttinen O.: A pimpleFoam tutorial for channel flow, with respect to different LES models, project done as a part of course at Chalmers University of technology (2011).
10. Piomelli U.:Wall-Layer Models For Large-Eddy Simulations, Progress in Aerospace Sciences 44, volume 44, 437-446 (2008)
11. Shah K.B., Ferziger J.H. : A fluid mechanicians view of wind engineering: large eddy simulation of flow past a cubic obstacle, J. Wind Eng. Ind. Aerodyn. 67&68, 211–224 (1997).
12. Yakhot A., Liu H., Nikitin N. : Turbulent flow around a wall-mounted cube: A direct numerical simulation, *International Journal of Heat and Fluid Flow 27, 994–1009* (2006).