

# NUMERICAL INVESTIGATIONS (2D URANS) OF FLOW PAST A SQUARE CYLINDER

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MASTER THESIS

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# Introduction

## • Motivation:

Develop a better insight in the computational modelling of turbulent phenomenology

## • Scope:

Study of the canonical square cylinder configuration by applying the URANS approach with the Menter  $k - \omega$  (SST) model.

## • Applications:

- Structural response of skyscrapers;
- Assessing Vortex Induced Vibrations (VIV);
- Aeolian wires e.g. power lines;
- etc.

## • Objectives:

The **main** objective is evaluate the URANS simulation capabilities for predicting the vortex shedding.

- (i) Study theoretical background
- (ii) Use ANSYS CFX & ICEM software
- (iii) Evaluate URANS-SST performance
- (iv) **Compressibility effects** assessment

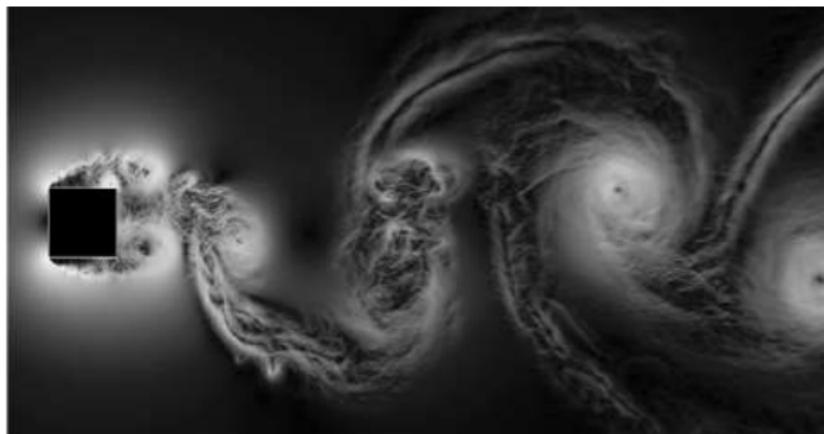
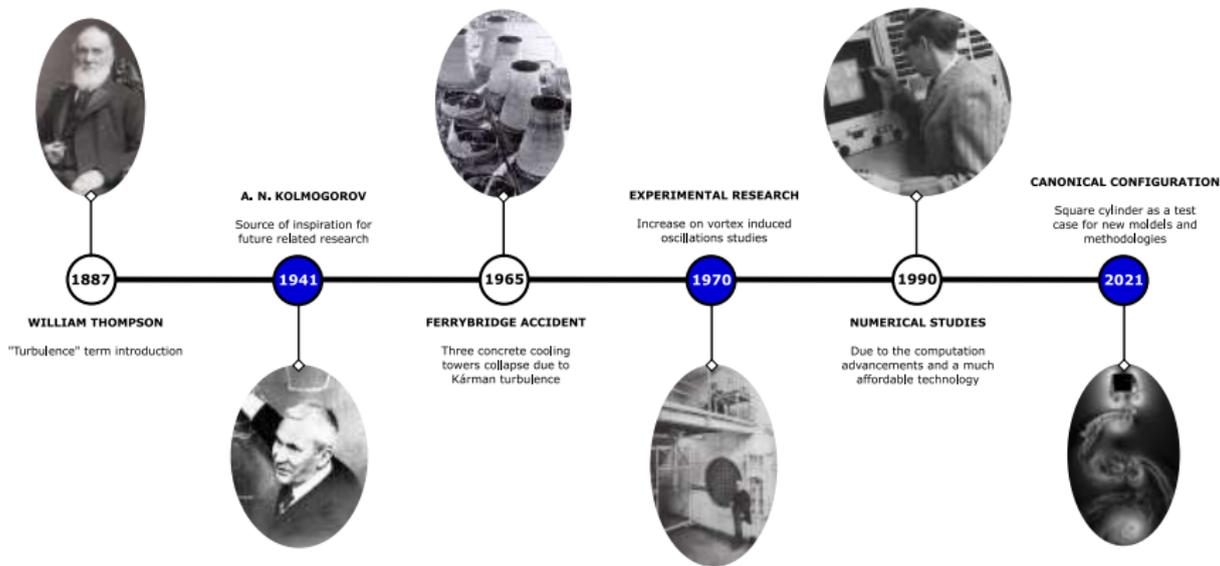


Fig. 1: Coherent structures in the wake of a square cylinder from Trias et al. [1]

# Background

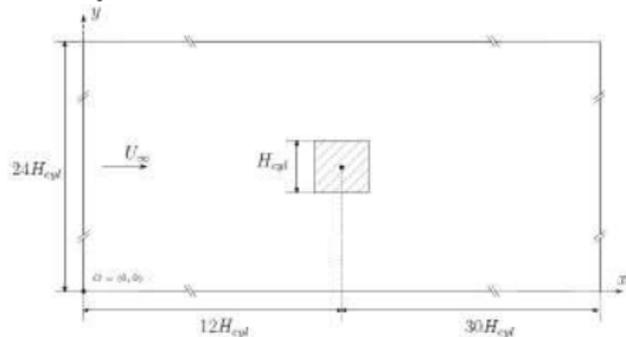


The present study builds up from a previous ITLR research performed by J. Richter et al. [2] in collaboration with Prof. B. Younis from the UCd.



# Numerical Analysis

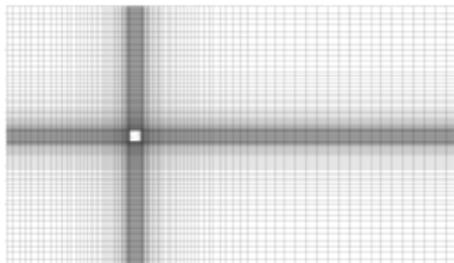
## • Computational Domain & Solver



- (i) Reynolds of study  $Re = 20,000$
- (ii) ANSYS CFX 20.2 software
- (iii) Air at  $T = 15^\circ C$  as fluid of study
- (iv) Two-dimensional URANS - SST
- (v) Fully implicit solver where  $\Delta t$  comes from  $C_{max} = 1$

$$\Delta t = \frac{C_{max} \Delta x}{U_\infty} = 0.0078 \frac{C_{max} H_{cyl}}{U_\infty}$$

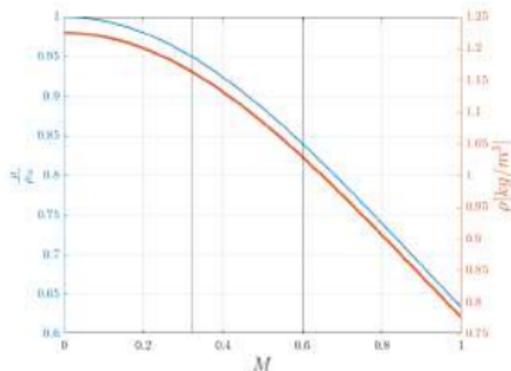
## • Numerical Grid



- (i) Finite volume approach
- (ii) Three-dimensional mesh
- (iii) **Size:** non-uniform and cell-centred 139x122 grid
- (iv) Tested and provided by Younis and Przulj [3]
- (v) Blockage ratio  $B_f = 4.17\%$

# Study Parameters

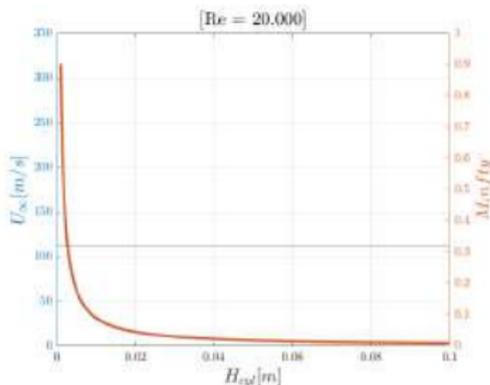
## • Compressibility



- (i) Reference density estimated as  $\rho_\infty \approx 1.225 \text{ [kg/m}^3\text{]}$
- (ii) Air considered compressible when  $M > 0.32$

$$\frac{\rho_\infty}{\rho} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{1/(\gamma - 1)}$$

## • Reynolds Number

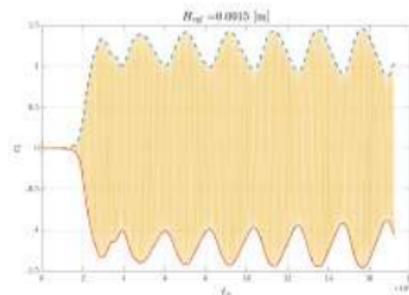
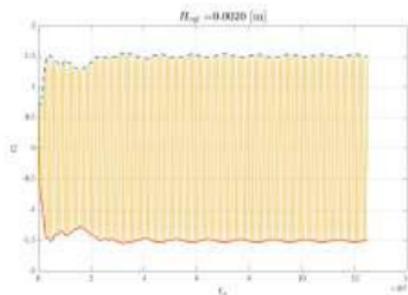
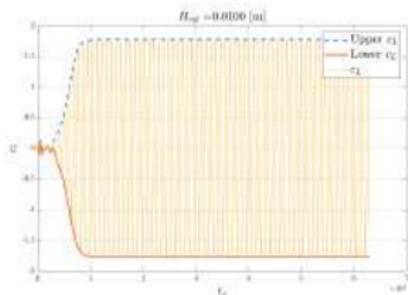


- (i) Dynamic viscosity calculated from Shutterland's law
- (ii) Compressibility effects arise when  $H_{cyl} < 0.0028 \text{ [m]}$

$$Re_\infty = \frac{\rho_\infty U_\infty H_{cyl}}{\mu_\infty}$$

$$H_{cyl} = \{1, 1.5, 2, 2.5, 3, 3.5, 4, 10\} \text{ [mm]}$$

# Vortex Shedding Frequency



## • $C_L$ analysis give:

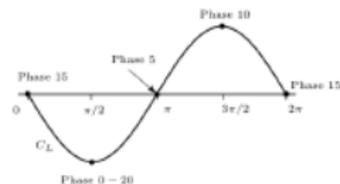
- Simulation steady state;
- Vortex shedding frequency;
- Unexpected behaviours ( $H_{cyl} = 1.5 [mm]$ );
- Time steps to study for result averaging ;

## • Time-Averaging:

Average over all one vortex shedding cycle timesteps ( $\Delta t_s$ )

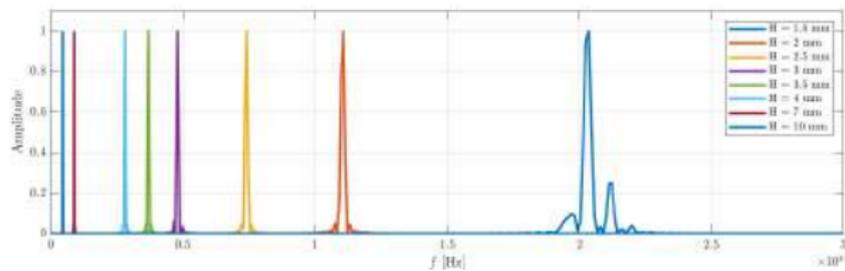
## • Phase-Averaging:

At a phase ( $n_p$ ) along 10 shedding cycles



$H_{cyl} [mm]$	$t [s]$	$t_{s0}$	$t_{s1}$	$\Delta t_s$	$T_v [s]$	$f [Hz]$	$S_t$
1.5	$5.625 \cdot 10^{-8}$	135,592	136,457	865	$4.8656 \cdot 10^{-5}$	$2.0552 \cdot 10^4$	0.15246
2	$1.010 \cdot 10^{-7}$	120,274	121,167	893	$9.0193 \cdot 10^{-5}$	$1.1087 \cdot 10^4$	0.14325
10	$2.500 \cdot 10^{-6}$	52,670	51,770	900	$2.25 \cdot 10^{-3}$	444.4275	0.1413

# Fourier Analysis (FFT)



$H_{cyl}$ [mm]	$\Delta t$ [s]	$U_\infty$ [m/s]	$M_\infty$	$f$ [Hz]	$S_t$
1	$3.130 \cdot 10^{-8}$	249.1	0.7197	-	-
1.5	$5.625 \cdot 10^{-8}$	202.2	0.5840	20355.00	0.151
2	$1.010 \cdot 10^{-7}$	154.8	0.4472	11077.78	0.1431
2.5	$1.563 \cdot 10^{-7}$	124.7	0.3603	7410.97	0.1486
3	$2.250 \cdot 10^{-7}$	104.23	0.3011	4797.92	0.1381
3.5	$3.050 \cdot 10^{-7}$	89.57	0.2588	3696.70	0.1445
4	$3.980 \cdot 10^{-7}$	78.45	0.2267	2808.27	0.1432
10	$2.500 \cdot 10^{-6}$	31.46	0.0914	433.53	0.1404

- **Comments:**

- Shedding freq.  $f$  [Hz]  $\uparrow$  when  $U_\infty$   $\uparrow$
- Secondary freq.  $H_{cyl} = 0.0015$  [m]
- $H_{cyl} = 0.002$  [m] selected

- **Strouhal number ( $S_t$ ):**

$$S_t = \frac{fH_{cyl}}{U_\infty}$$

- **Cases to study:**

$$H_{cyl} = \{1, 1.5, 2, 4, 10\} \text{ [mm]}$$



# Boundary Conditions

- Fluid field:

Initial values	$u$ [m/s]	$v$ [m/s]	$w$ [m/s]	$P_s$ [bar]	$T$ [k]	$T_u$
Magnitude	1	0	0	1	293.15	5%

- Inlet:

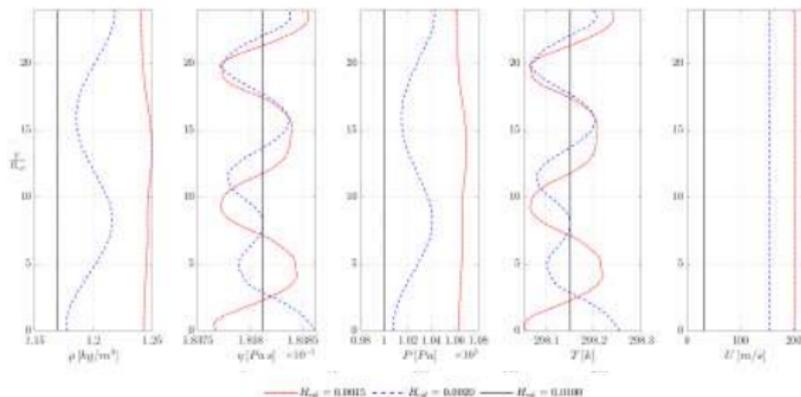
$$(u, v, w) = (U_\infty, 0, 0) \quad T_u = 0.02$$

$$\eta_t/\eta = 88 \quad T_\infty = 298.15k = 25^\circ C$$

- Outlet:  $\delta v/\delta y = 0 \quad P = 1 \text{ bar}$

- Cylinder: Adiabatic smooth and no-slip

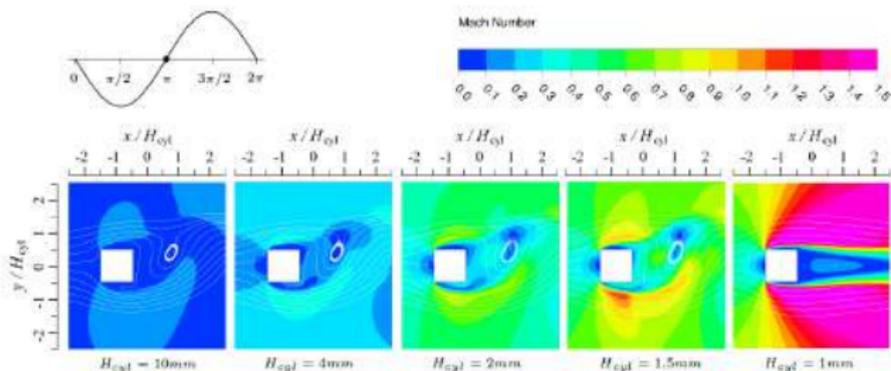
- Walls: Symmetry condition



- Comments:

- The inlet properties remain unaffected for  $H_{cyl} = 0.01$  [m]
- For a higher  $M_\infty$  greater cylinder influence along the upstream region
- The variation of the inlet properties for the compressible case induce to  $Re$  number changes

# Mach Field

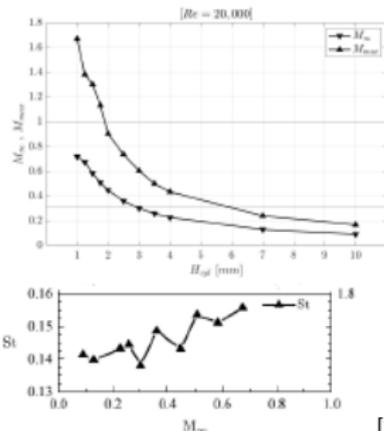


## Comments:

- $H_{cyl} = 1$  [mm] shows an expansion fan ( $M_2 > M_1$ ) without shedding
- $H_{cyl} = 1.5$  [mm]  $\rightarrow M_{max} > 1$  whereas  $H_{cyl} = 2$  [mm]  $\rightarrow M_{max} < 1$
- $H_{cyl} = 1.5$  [mm] present a weak shock wave affecting  $\omega_0$

## Important remarks:

- The present study shows that  $S_t$  increases with increasing *Mach* due to a larger eddy dissipation rate ( $\epsilon$ )
- Nakagawa [3] experiment shows that vortex shedding is present irrespective of shocks appearance and  $S_t$  is barely affected.



## Cases to study:

$$H_{cyl} = \{1.5, 2, 10\} \text{ [mm]}$$

# Mean Flow Parameters

Case	$Re_\infty$	$St$	$\overline{C_D}$	$C'_D$	$C'_L$	$\overline{L_r}/H_{cyl}$
2D URANS, Mentre $k - \omega$ SST, J. Richter et al. [2]	20,000	0.141	1.96	0.081	1.26	0.62
2D URANS, Mentre $k - \omega$ SST, Tian et al. [5]	21,400	0.138	2.060	—	1.492	—
2D URANS, standard $k - \epsilon$ , Younis and Przulj [4]	20,000	0.118	1.54	0.001	0.09	2.39
2D URANS, modified $k - \epsilon$ , Younis and Przulj [4]	20,000	0.141	2.20	0.205	1.39	0.65
3D LES, Smagorinsky SGS model, Cao et al. [6]	22,000	0.132	2.21	0.205	1.26	0.75
3D DNS, F.Xavier Trias et al. [1]	22,000	0.132	2.1	0.205	1.71	0.55
Experiments, Durao et al. [7]	14,000	0.133	—	—	—	0.89
Experiments, Lyn and Rodi [8]	21,400	0.132	2.1	—	—	0.9
Experiments, Bearman and Obasaju [11]	20,000	0.13	—	—	1.30	—
Experiments, Luo et al. [9]	34,000	0.130	2.21	0.180	1.22	0.92
Experiments, Lee [10]	176,000	0.121	2.05	0.230	1.23	—
Experiments, Nakagawa [3], $M_\infty = 0.3762$	34,400	0.1334	—	—	—	—
Present study, $H_{cyl} = 0.01 [m]$ $M_\infty = 0.091$	20,000	0.140	1.972	0.085	1.263	0.619
Present study, $H_{cyl} = 0.002 [m]$ $M_\infty = 0.477$	20,000	0.143	2.194	0.081	1.064	0.703
Present study, $H_{cyl} = 0.0015 [m]$ $M_\infty = 0.590$	20,000	0.151	2.366	0.0881	0.865	0.5806

## • 2D - URANS Simulations

- Present and Richter et al. [2] studies approximately predict  $St$ ,  $\overline{C_D}$  and  $C'_L \rightarrow \{5.66, -6.09, -2.84\}\%$
- Agreement with Tian et al. [5] results ( $St$ ,  $\overline{C_D}$  and  $C'_L$ )
- $\overline{L_r}/H_{cyl}$  and  $C'_D$  are clearly underestimated  $\{-30, -55\}\%$
- Younis and Przulj [4] overcomes the  $C'_D$  implementing a modified  $k - \epsilon$



# Mean Flow Parameters

Case	$Re_\infty$	$St$	$\overline{C_D}$	$C'_D$	$C'_L$	$\overline{L_r}/H_{cyl}$
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3D LES, Smagorinsky SGS model, Cao et al. [6]	22,000	0.132	2.21	0.205	1.26	<b>0.75</b>
3D DNS, F.Xavier Trias et al. [1]	22,000	0.132	2.1	0.205	1.71	<b>0.55</b>
Experiments, Duraó et al. [7]	14,000	0.133	—	—	—	0.89
Experiments, Lyn and Rodi [8]	21,400	0.132	2.1	—	—	0.9
Experiments, Bearman and Obasaju [11]	20,000	0.13	—	—	1.30	—
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Present study, $H_{cyl} = 0.01 [m]$ $M_\infty = 0.091$	20,000	0.140	1.972	0.085	1.263	<b>0.619</b>
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Present study, $H_{cyl} = 0.0015 [m]$ $M_\infty = 0.590$	20,000	0.151	<b>2.366</b>	0.0881	0.865	0.5806

## • Numerical studies

- All of them underestimate  $\overline{L_r}/H_{cyl}$

## • 3D LES & DNS Simulations

- Correct prediction of  $St$

- Accurate description of  $\overline{C_D}$  and  $C'_D$

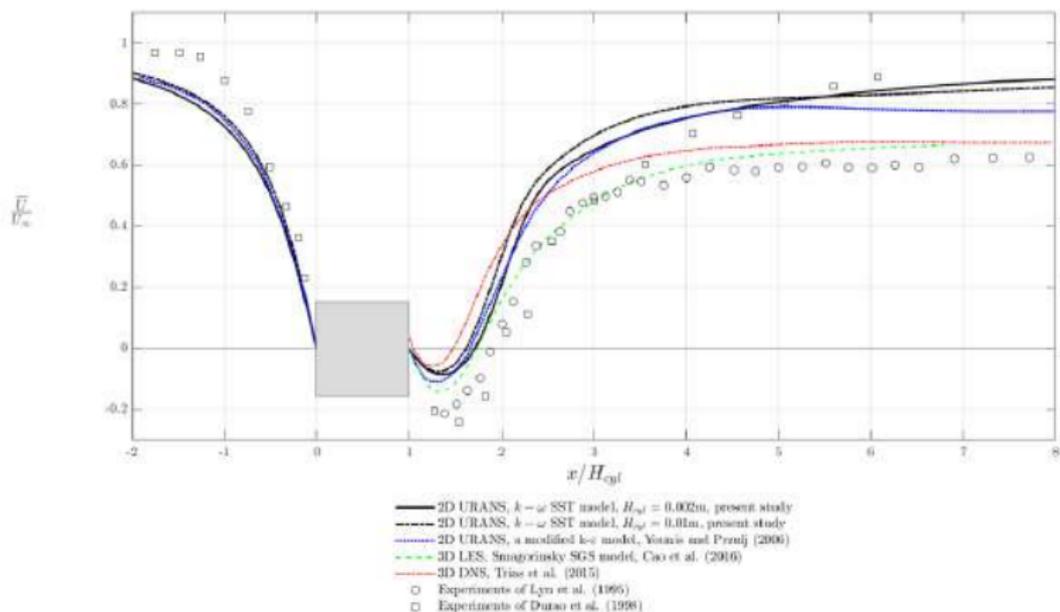
## • Compressible cases

- Increasing  $St$  with  $M_\infty$

-  $\overline{C_D}$  increases since  $Re_x \uparrow$  and skin friction  $\uparrow$

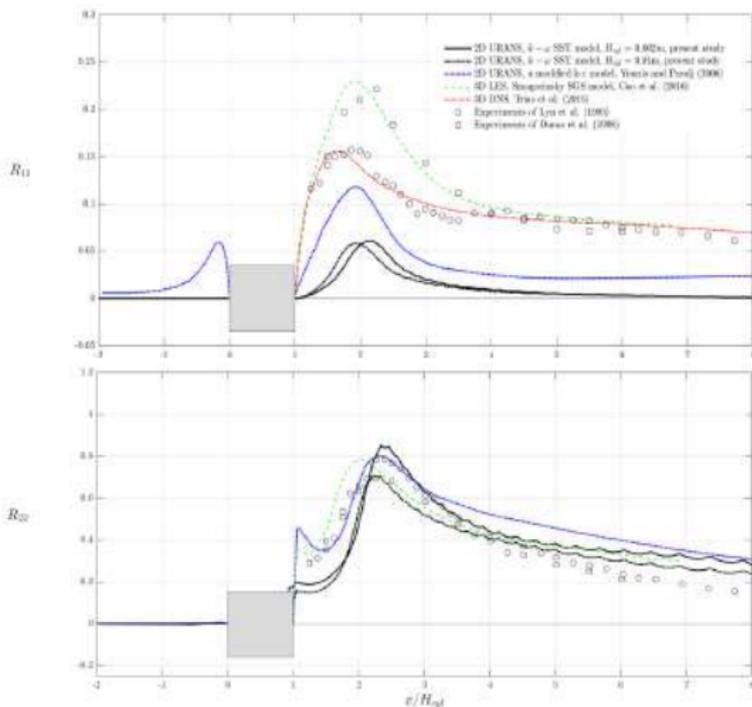


# Centerline Velocity



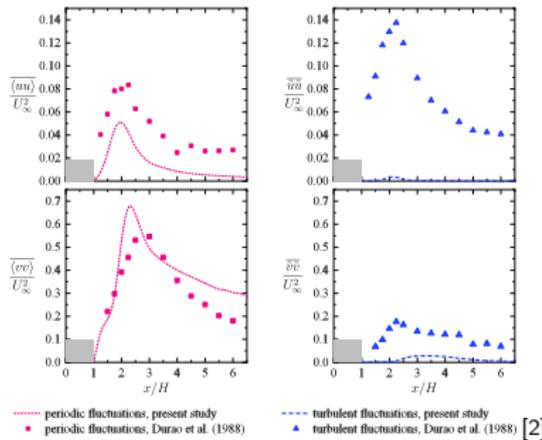
## • Numerical studies

- $\overline{L_r}/H_{cyl}$  and minimum velocity  $\overline{U}/U_\infty$  underestimation
- 2D-URANS agrees with Durao □ exp.
- 3D LES and DNS agree Lyna ○ exp.



•  $R_{11}$ :

- 3D LES - Cao agrees with Durao  $\square$  exp.
- 3D DNS - Trias agrees with Lyn  $\circ$  exp.
- 2D URANS underestimate  $R_{11}$  but Younis and Przulj [4]  $k - \epsilon$  model gives a better agreement



• Fluctuations:

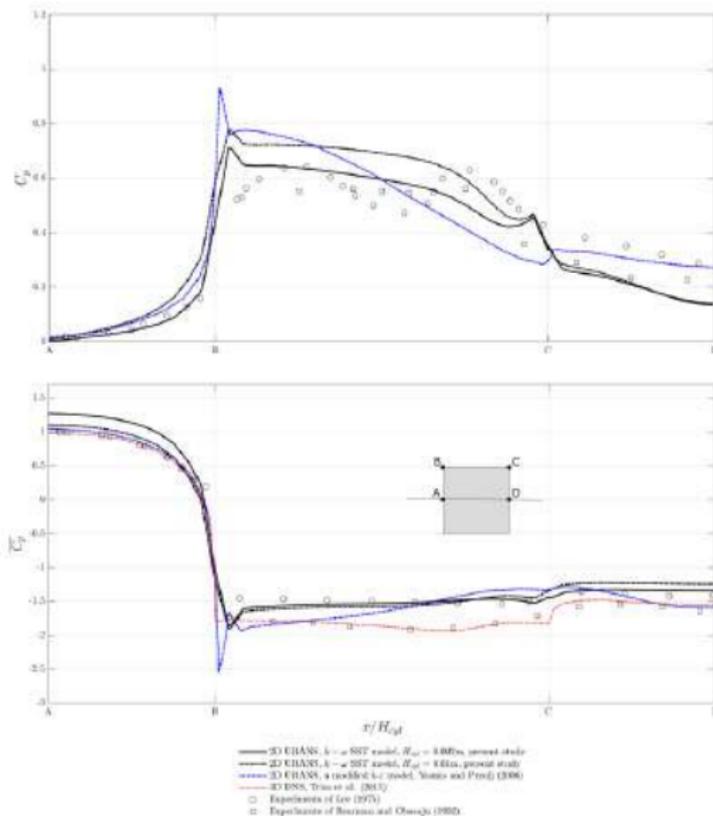
- Richter et al. [2] argue that URANS-SST severely underestimate the turbulent fluctuations

•  $R_{22}$ :

- General agreement between predicted and measured values
- Sensitive to compressibility effects



# Cylinder Pressure



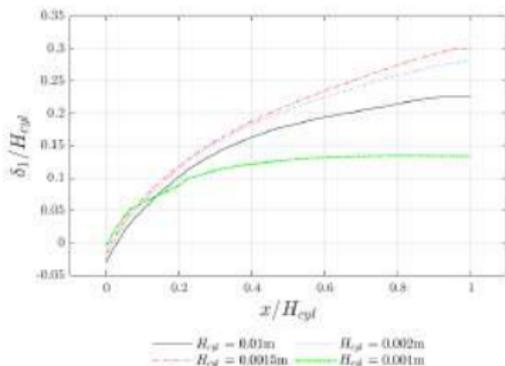
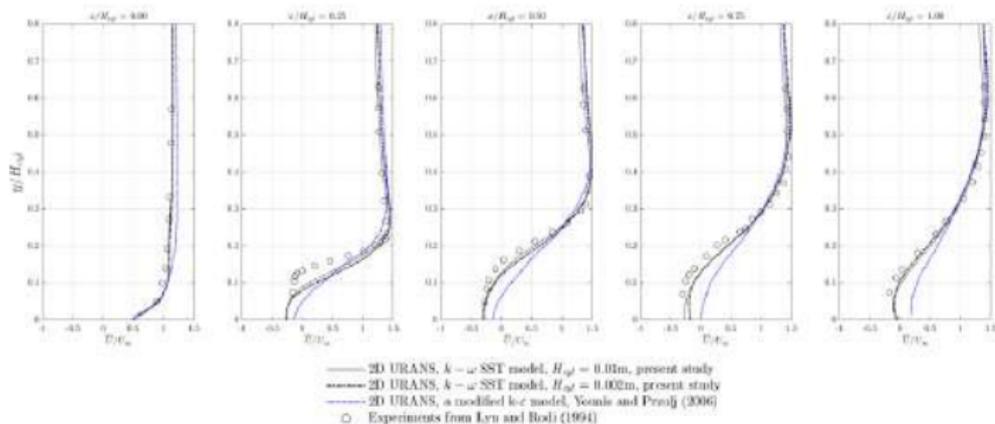
- r.m.s  $C_p'$ :

- Moreover agreement with exp.
- Overestimation of  $C_p'$  drop towards C
- 2D-URANS "overshot" at B

- Time-averaged  $\overline{C_p}$ :

- Present study agrees with **Lee**  $\circ$  exp.
- **Trias** results agree with **Bearman**  $\square$
- Increasing  $U_\infty$  leads to a greater  $\overline{C_p}$  difference between AB and CD, thus increasing  $\overline{C_D}$

# Boundary Layer



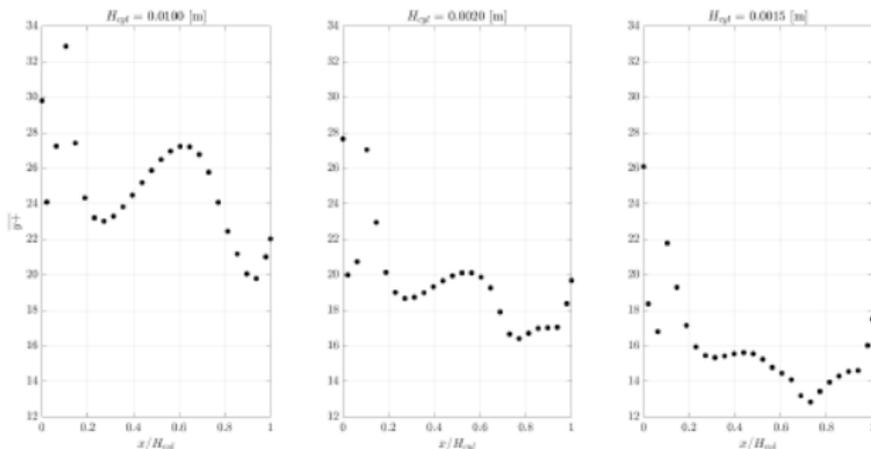
## • Velocity Profiles:

- Velocity profiles are well predicted
- Boundary layer detachment region located close to  $x/H_{cyl} = 0.1$

## • Displacement thickness ( $\delta_1$ ):

- Shows how far the streamlines are displaced by the BL
- Increasing  $U_\infty$  decreases  $\delta_1$  due to compressibility effects

# Dimensionless wall distance ( $y^+$ )



Case [m]	$y_{max}^+$	$y_{min}^+$	$y_{avg}^+$
0.01	33.1517	18.9332	24.8380
0.002	27.9770	15.0191	19.5823
0.0015	26.2388	10.3924	16.0578

## Remarks:

- Present study shows an inaccurate wall modelling
- $y^+ > 10$  could trigger inaccuracies when reproducing physical effects
- Possible source of  $S_t$  inaccuracies (see Nakagawa [3])

## Equation:

$$y^+ = \frac{yu_\tau}{\nu} \quad u_\tau = \sqrt{\frac{|\tau_w|}{\rho}}$$

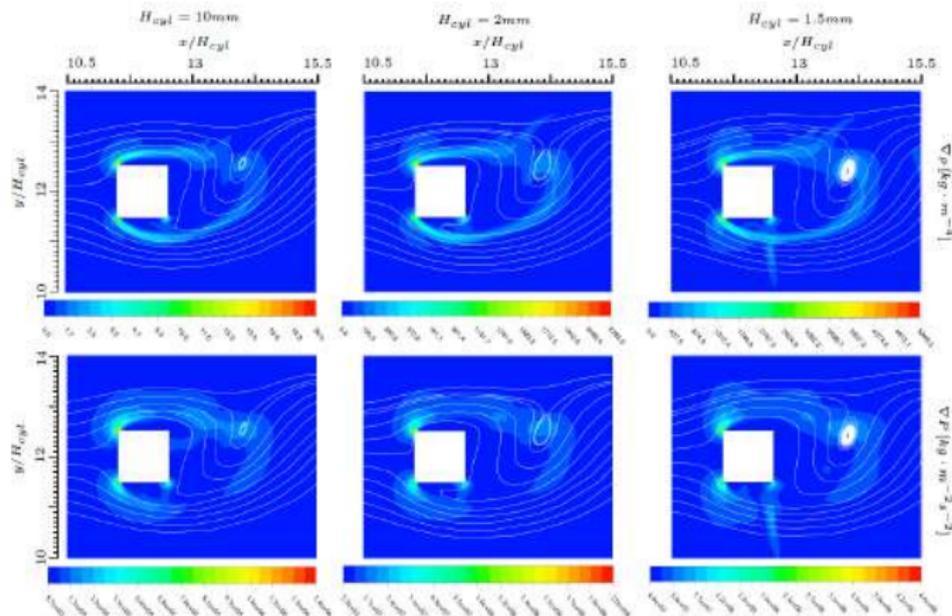
- If wall functions applied  $\rightarrow y^+ \approx 30$
- Near-wall modelling  $\rightarrow y^+ \approx 1$
- ANSYS-CFX expects  $y^+ \approx 10$

## Comments:

- $y^+$  similar for all cases
- Maximum value at Leading Edge
- Maximum point close to BL detachment region where  $\tau_{w,max}$



# Compressibility Effects

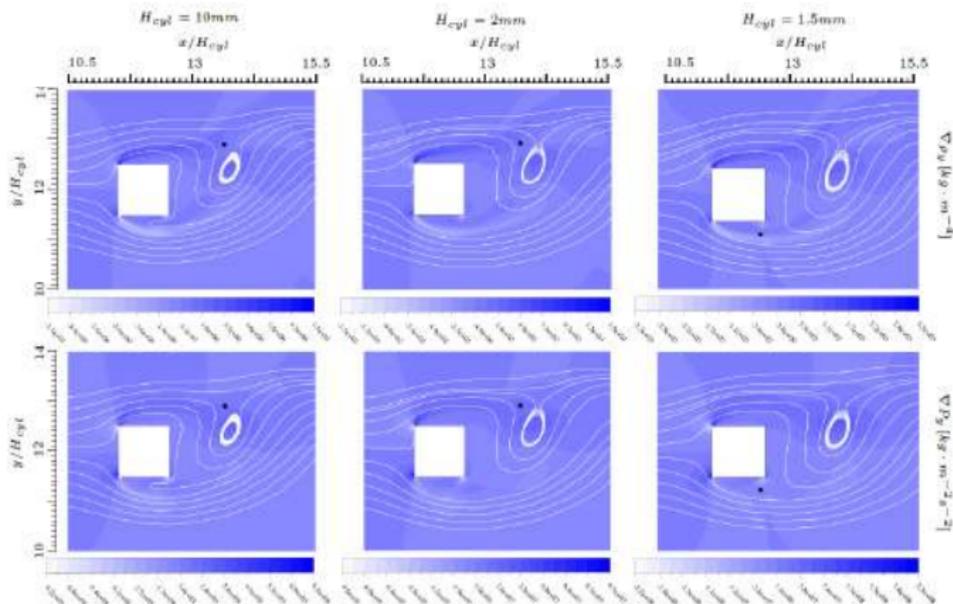


← Phase 0

## • Comments:

- Maximum values located at the front corners (critical regions)
- Shear layer exhibit a minimum density region
- It is represented the weak shock for the  $H_{cyl} = 1.5\text{ [mm]}$  case
- The increasing  $U_\infty$  shows greater gradients

# Compressibility Effects

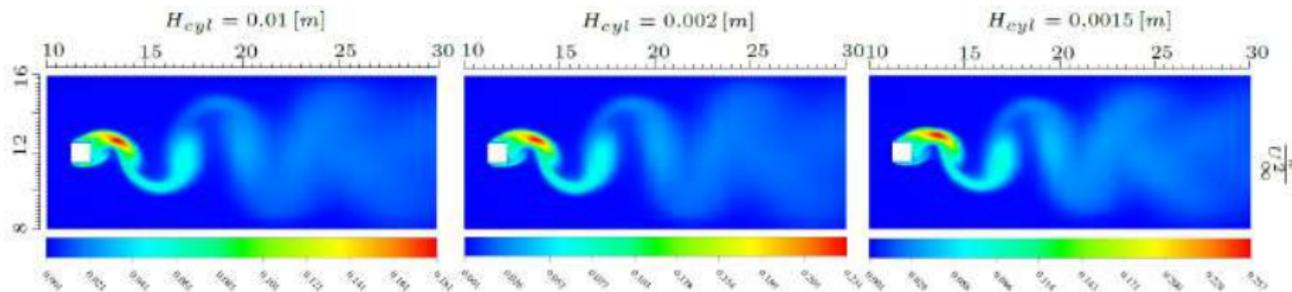


← Phase 0

## • Comments:

- Gradients along the  $y$ -axis are produced by turbulent motions
- There is a maximum gradient region at the vortex core, where the energy is dissipated
- Turbulent motions are thus related to compressibility effects

# Conclusions



- **URANS-SST Capabilities:**

- Fairly predicts the flow mean features
- Suitable performance
- Underestimation of  $R_{11}$

- **Wall resolution &  $S_t$ :**

- A bad wall resolution can induce to a  $S_t$  overestimation
- Nakagawa [3] argues that  $S_t$  is barely affected by  $M_\infty$  increase

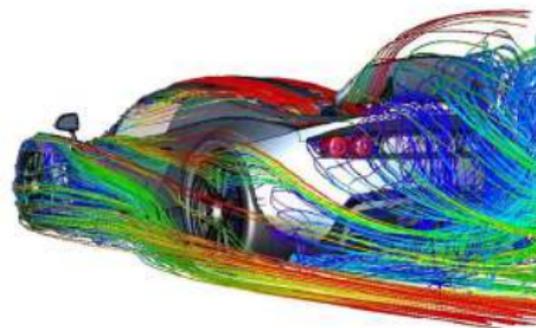
- **Compressibility:**

- Able to capture weak shock flow interactions
- Maximum  $\nabla \rho_y$  and  $\nabla P_y$  at vortex core



# Further research

- (i) **Cylinder-boundary influence**
- (ii) **Reynolds stress study**
- (iii) **Wall resolution**
- (iv) **Compressibility-turbulence coupling**
- (v) **Computational efficiency analysis**



# Questions?

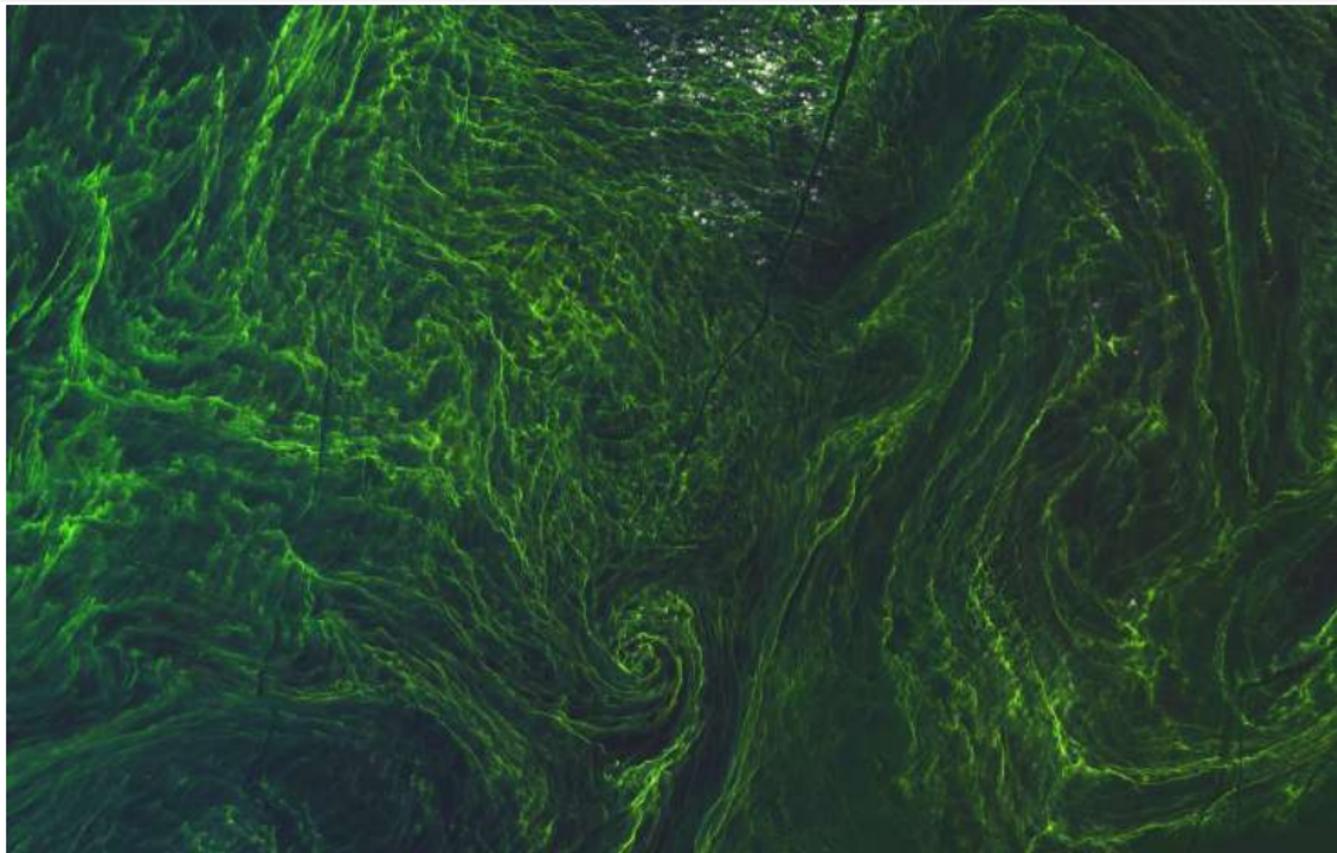


# Bibliography

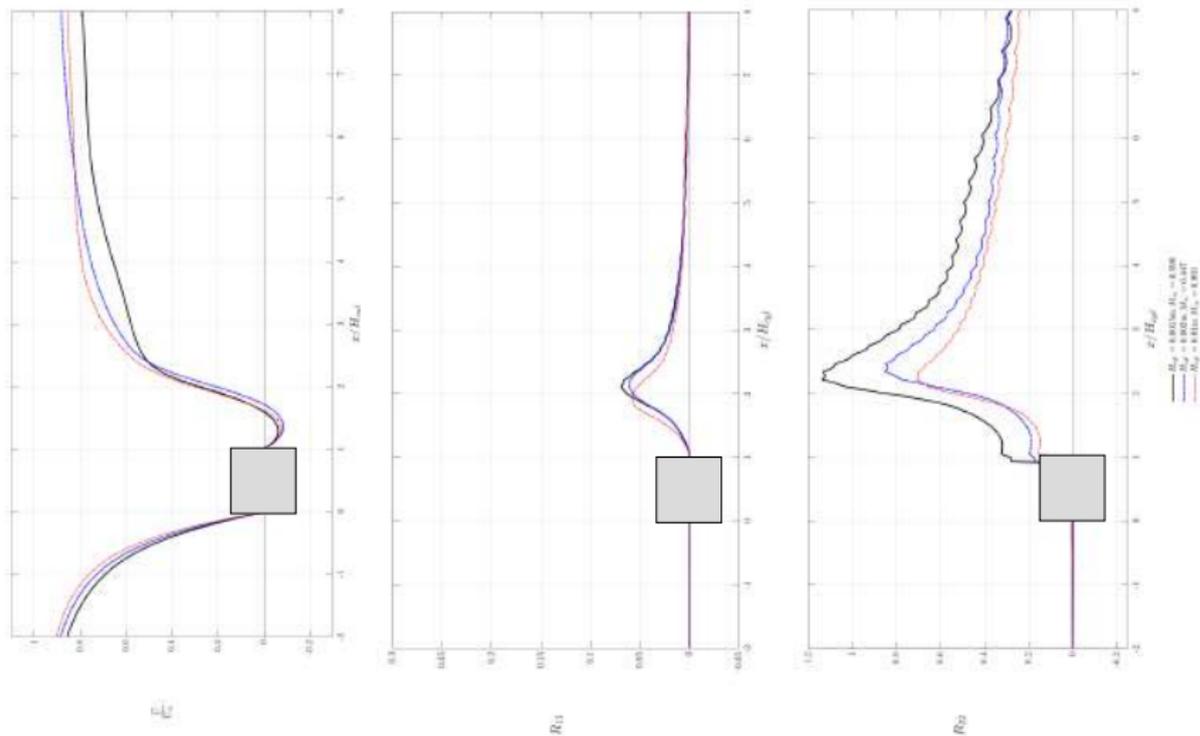
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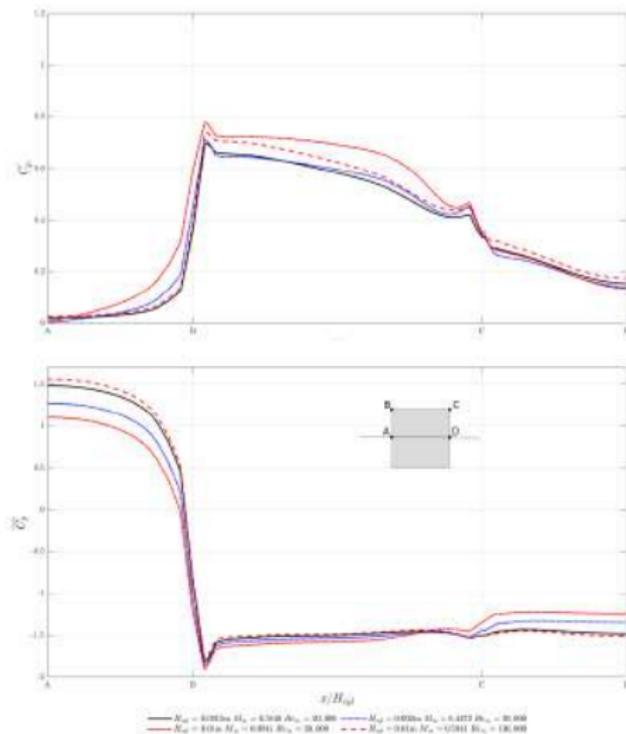
# Backup



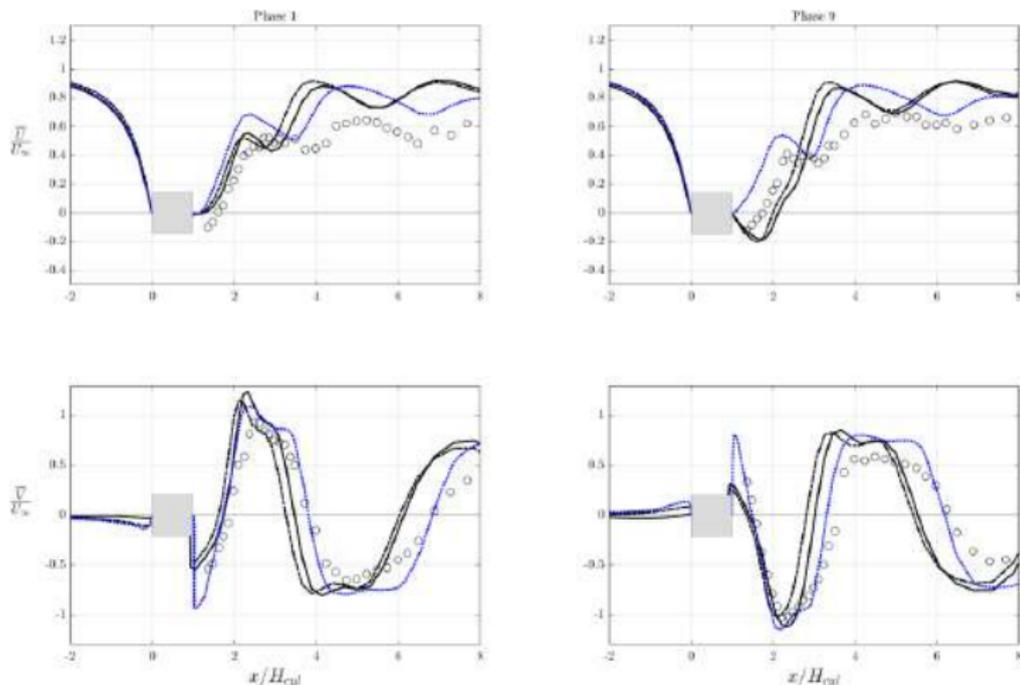
## Centerline Velocity



# Cylinder Pressure

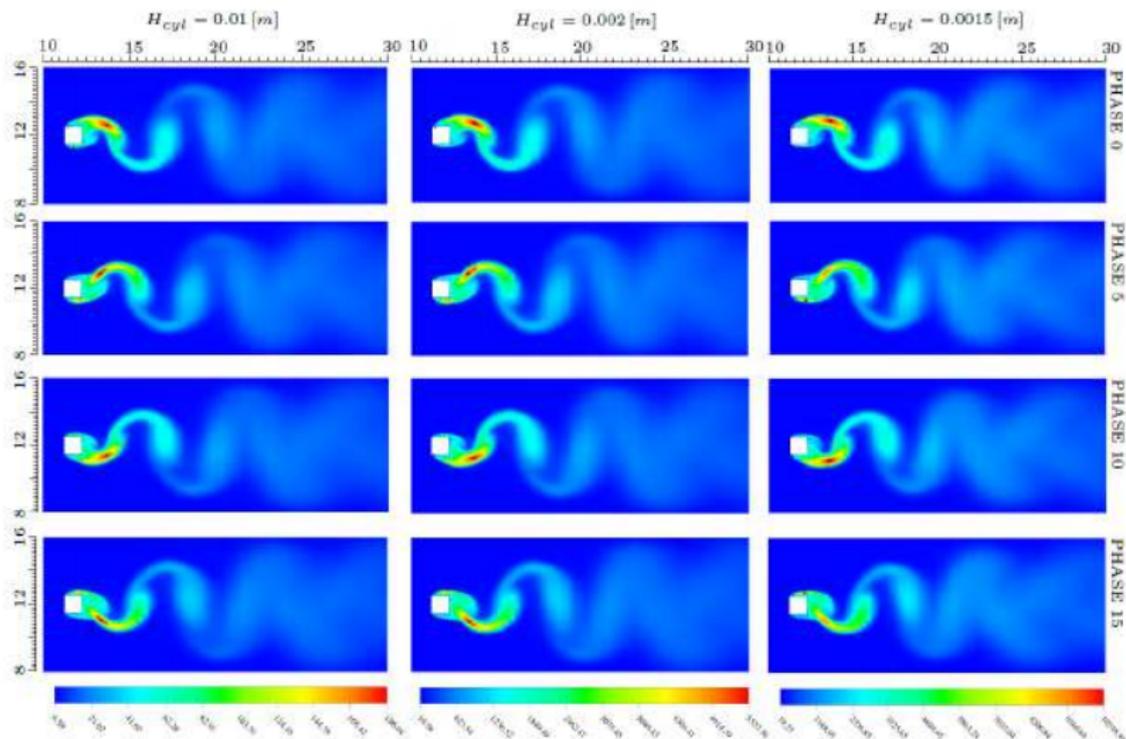


# Phase-Averaging

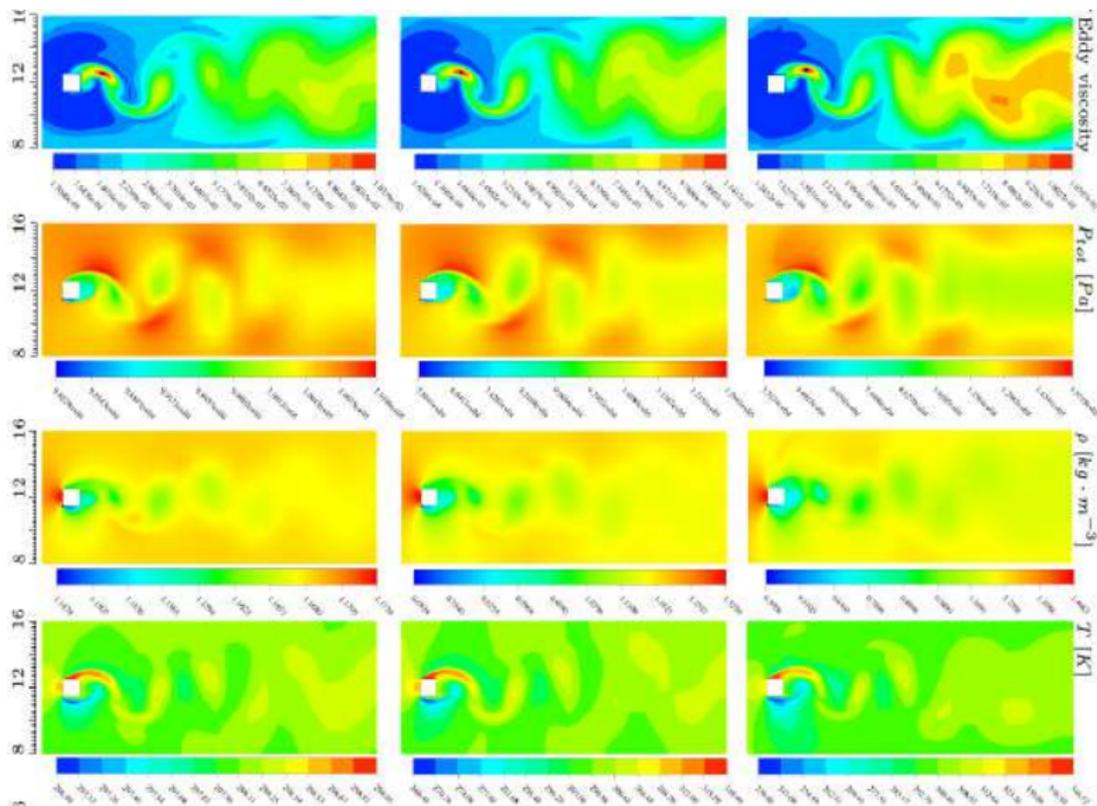


- 2D URANS,  $k-\omega$  SST model,  $H_{cyl} = 0.002m$ , present study
- - - 2D URANS,  $k-\omega$  SST model,  $H_{cyl} = 0.01m$ , present study
- · · 2D URANS, a modified  $k-\epsilon$  model, Younis and Prizaj (2006)
- Experiments of Lyn et al. (1995)

# Turbulent Kinetic Energy



## Flow Field



## Upstream region

