

Turbulent Flow around a Square Cross-section Cylinder in the Proximity of a Solid Wall.

CFD2K Benchmark Challenge CFD Society of Canada

OVERVIEW

The performance of computer codes in simulating the velocity, Reynolds stress and surface pressure fields for time-periodic and stationary turbulent flows is to be assessed. The geometry is a square cross-section, two-dimensional prism, of characteristic side length D , mounted a distance S from a solid wall. When this bluff body is sufficiently far from the wall, the wake flow is time-periodic due to von Karman vortex shedding. For small separations, shedding is suppressed and the turbulent wake flow is stationary. The challenge consists in comparing simulation and experimental results for configurations $S/D=1$ (periodic case) and $S/D=0.25$ (stationary case) at a nominal Reynolds number of 22,000 based on the on-coming stream velocity and D . The free-stream turbulence intensity is about 1%. Contributions are welcome to either or both cases. Assessment will be made based on:

- 1) **For All Methods**: Mean velocity, Reynolds Stress, surface mean and rms pressure distributions.
- 2) **For Unsteady Methods**:
 - Shedding frequency and convective speed estimations.
 - For periodic case ($S/D=1$): phase-averaged velocity and surface pressure fields.
 - For three-dimensional, transient simulations: Comparison of span-wise correlation lengths and phase relations for pressure field on the obstacle and wall surfaces.

NOMENCLATURE

C_p	$=(P-P_\infty)/(\frac{1}{2}\rho U_\infty^2)$ (Mean pressure coef.)
$C_{p\text{rms}}$	Root Mean Square of C_p
C_D	$=D/(\frac{1}{2}\rho U_\infty^2 D)$ Drag coefficient
C_L	$=L/(\frac{1}{2}\rho U_\infty^2 D)$ Lift coefficient
D	Drag per unit length
D	Obstacle side dimension.
f	frequency
k	turbulence kinetic energy.
L	Lift per unit length
P	Mean pressure.
P_∞	Free-stream pressure.
p	Fluctuating pressure.
Re	Reynolds number ($=U_\infty D/\nu$).
S	Separation (gap height) between the cylinder lower face and solid wall.
Tu	Turbulence intensity ($=\sqrt{k_\infty}/U_\infty$)
u, v, w	Instantaneous, fluctuating x, y, z velocity components.
U, V, W	Mean velocity in x, y and z directions.
$\overline{u^2}, \overline{v^2}, \overline{uv}$	Reynolds stresses
U_∞	Free-stream velocity.
x, y, z	Stream, vertical and span-wise axes.
α	back flap hinge angle
δ	boundary layer thickness
ρ	density of air.
ν	kinematic viscosity of air
∞	Free-stream conditions.
—	Over-bar: time-averaged quantities.
< >	Phase-averaged quantities.

BACKGROUND

When a bluff body is placed in the proximity of a solid wall, the structure and dynamic behavior of the flow changes significantly as a function of the obstacle-to-wall gap height, S . The flow around a square cylinder immersed in a uniform stream is independent of Reynolds number, based on side dimension D , in the range 10000 to 100000. The wake flow is highly turbulent and characterized by the nearly regular passage of large-scale coherent structures (shed "von Karman" vortices). The formation and shedding of these vortices is related to the flow separation at the leading edges giving rise to intense shear layers over each of the lateral faces which oscillate at a nearly constant phase difference of 180° .

If the cylinder is mounted close to the wall below a critical gap height, vortex shedding can be completely suppressed. The mechanism causing suppression is still unclear, but appears to be related to opposing effects due to the production of counter-rotating vorticity in the wall boundary layer and the increased circulation produced on the lower cylinder face.

DESCRIPTION of the FLOW

The experimental geometry is defined in Figure 1. Experiments were performed in a 0.45m X 0.45m suction-type wind tunnel. A smooth, flat plate, 0.92m long and 5mm thick, was placed about 0.15m from a tunnel wall. The plate had a sharpened leading edge and a trailing edge flap to control the plate boundary layer and leading edge separation. A square cylinder

of side dimension $D=30\text{mm}$ was placed $14.5D$ downstream of the plate leading edge. The cylinder span-to-height aspect ratio was 15 and the blockage ratio was 6.6%.

Experiments were conducted for a Reynolds number (Re , based on D and U_∞) of 22,000. The oncoming free stream turbulence intensity was 1%. The boundary layer thickness was controlled by adjusting the plate end flap. Thicker turbulent boundary layers were obtained by tripping the oncoming flow at the leading edge. For these tests, when the cylinder is not present, the boundary layer was a fully turbulent with thickness of $\delta \approx 1.5D$ at $x/D=0$ (i.e. $15D$ from plate leading edge).

One hundred eleven pressure taps were located along the $z/D=0$: 79 on the plate, 32 along the cylinder circumference. The pressure tubing was constricted to provide full frequency response to 200Hz.

Two hot-wire probes were located $2.2D$ downstream of the cylinder. These were mounted at a fixed distance relative to the cylinder in the shear layers symmetrically about the cylinder centerline. Free stream conditions were continuously measured from a pitot-static tube located $5D$ upstream of the cylinder and $4D$ away from the tunnel wall. The pressure taps, pitot-static tube and hot-wires were sampled simultaneously at 400Hz for 60s to 120s.

Two-component Laser Doppler Velocimetry measurements were conducted at several locations along a single stream-wise plane. Measurements were made in coincidence mode at data rates ranging from 500Hz to 4000Hz. The average data sampling time interval was thus 3 to 7 times the Taylor time microscale.

Sample data and estimated experimental uncertainty are provided in the appendix.

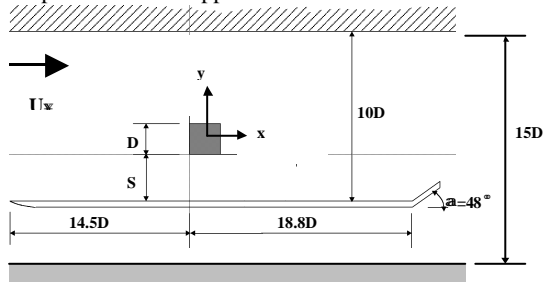


Figure 1 Experimental Geometry and Nomenclature.

COMPUTATIONAL CONSIDERATIONS

Parameters:

- Medium: air; $P_\infty=1\text{atm}$; $T=18^\circ\text{C}$
- $Re=22,000$; $S/D=0.25$ and 1
- Blockage 6.6%; $\alpha=48^\circ$ $Tu \approx 1\%$
- $\delta \approx 1.5D$ at $x/D=0$ (fully turbulent, measured without cylinder)

Information Available:

- $\overline{u^2}, \overline{v^2}, \overline{uv}, U, V$ along $z/D=0$
- $C_p, C_{p_{rms}}, \langle C_p \rangle$ on plate and cylinder surface along $z/D=0$ and $x/D=0$ (middle of face).
- $C_L, C_D, \langle C_L \rangle$ and $\langle C_D \rangle$
- Time series for U, V upon request.

Domain Considerations:

- It is recommended that the calculation inlet domain be at least $5D$ upstream of the plate leading edge. The base plate should be modeled as an infinitely thin plate with leading edge $14.5D$ upstream of the cylinder windward face. The exit conditions should be such to maintain a zero pressure gradient. These conditions should simulate those achieved with the wind tunnel wall curvature. The computational domain is shown schematically in Fig. 2.
- Blockage ratios are known to be significant above 8%.
- The roof of the channel is set to zero-pressure gradient conditions at the end of the plate. Our experience indicates that this is only approximately met. We estimate that the effective blockage ratio was about 6.6%.
- Experiments have shown span-to-height aspect ratios of less than 12 contain important three-dimensionality in the wake. The experiments were conducted with an aspect ratio of 15.
- Reliable statistical information for shedding and spectra experimentally requires averages over at least 150 cycles.

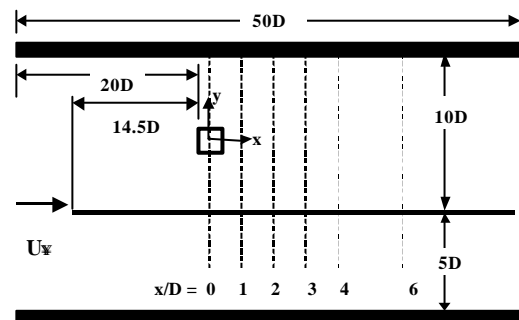


Figure 2: Schematic representation of the proposed computational domain.

REQUIREMENTS for PARTICIPANTS:

Preliminary information: In addition to the results of simulations/computations, please provide:

- Name
- Affiliation
- Details of computation method:
 1. General description of code & solution algorithm

2. Discretization scheme
3. Estimates of spatial and temporal (if applicable) error bounds.
4. Mesh size, type and refinement strategy.
5. Turbulence models (field and near-wall)
6. Convergence criteria
7. Any additional modeling, assumptions or simplifications.

Presentation of Simulation Data: The following results are requested:

1. Definition of co-ordinate system: $x=0$, $y=0$ at centre of cylinder.
2. Vector plots of the mean velocity along $z/D=0$.
3. Profiles of mean velocity and Reynolds Stresses normal to the centre of the cylinder and in the wake at locations downstream of the trailing edge:
 - for $S/D=1$; $x/D=0, 1, 2, 3$ and 4 .
 - for $S/D=0.25$; $x/D=0, 1, 2, 4$ and 6 .
 (see Fig. 2).
4. C_p and $C_{p_{rms}}$ along $z/D=0$ on the cylinder faces and plate surface.
5. Contour plots along $z/D=0$ for Reynolds Stresses.
6. For three-dimensional calculations, include distributions for plate and cylinder surface C_p and $C_{p_{rms}}$ along $x/D=0$ as a function of z/D .
7. For unsteady calculations, include phase averaged data. The shedding cycle is to be divided into 10 equal intervals (phase bins).

The data will be made available in excel format six weeks before the workshop. This information should be included in the graphs.

TIMELINE and INQUIRIES

A special panel session will be held to discuss the benchmark computational results and their interpretation during the:

*8th Annual Conference of the CFDSC
New Frontiers in CFD
Montreal June 11-13, 2000*

A meeting of the organizers and contributors will be held on DAY 1 of the conference to coordinate the benchmark.

Please note the following important dates and deadlines:

- Jan. 28, 00: Inform organizers of intent to participate.
- April 28, 00: Submit preliminary set of results.
- May 1, 00: Results will be made available to challenge participants.
- May 19, 00: Submit final set of results.

Address inquiries concerning the challenge to:

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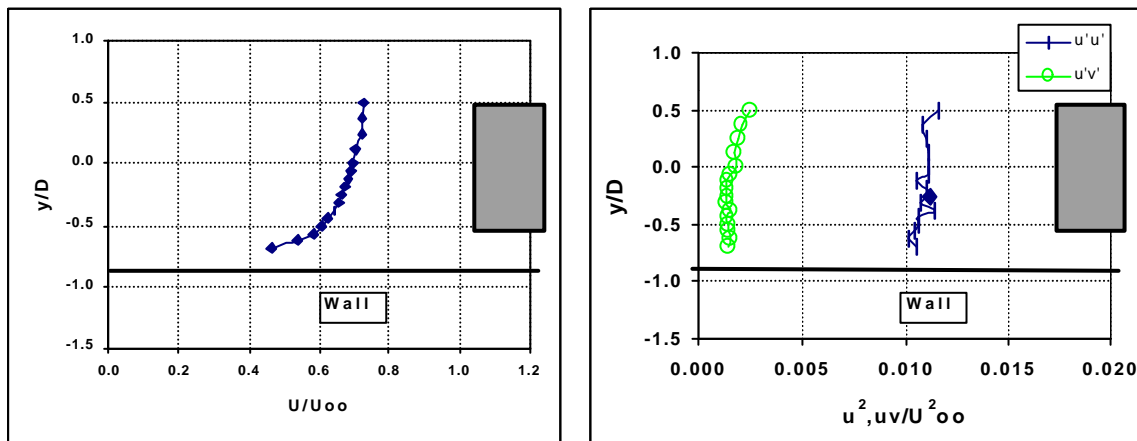


Figure 3: Velocity and Reynolds Stress profiles upstream of cylinder for $S/D=0.25$ at $x/D=-4$.

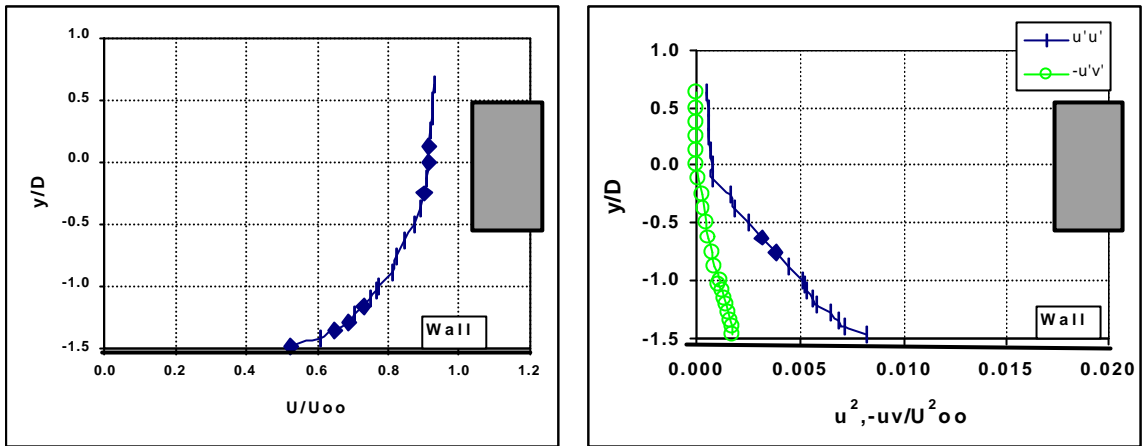


Figure 4: Velocity and Reynolds Stress Profiles upstream of cylinder for $S/D=1$ at $x/D=-4$

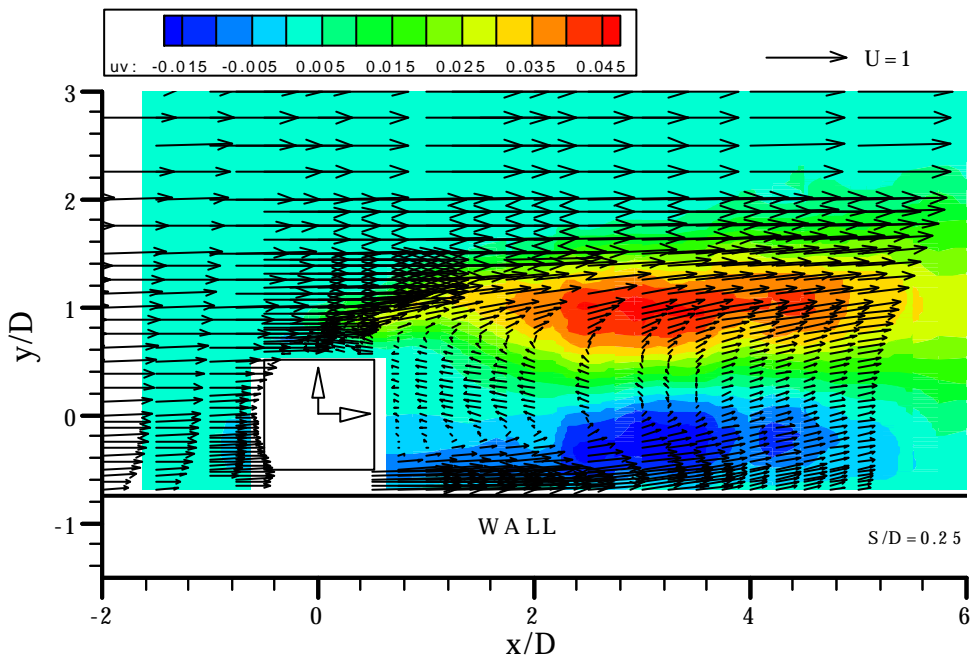


Figure 5: Vector representation for $S/D=0.25$ of the mean velocity field. Contours show uv Reynolds Stress. All results normalised with free-stream velocity. Uncertainty: mean flow field: $0.02U_{\infty}$; for Reynolds Stress field: $0.002U_{\infty}^2$.

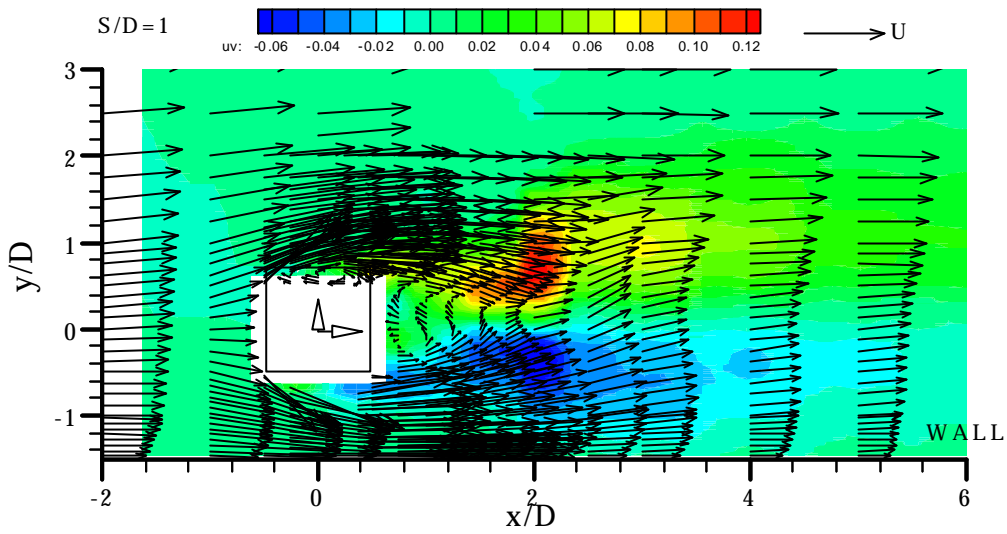


Figure 6: Vector representation for $S/D=1$ of the mean velocity field. Contours show uv Reynolds Stress. All results normalised with free-stream velocity. Uncertainty: mean flow field: $0.02U_\infty$; for Reynolds Stress field: $0.002U_\infty^2$.

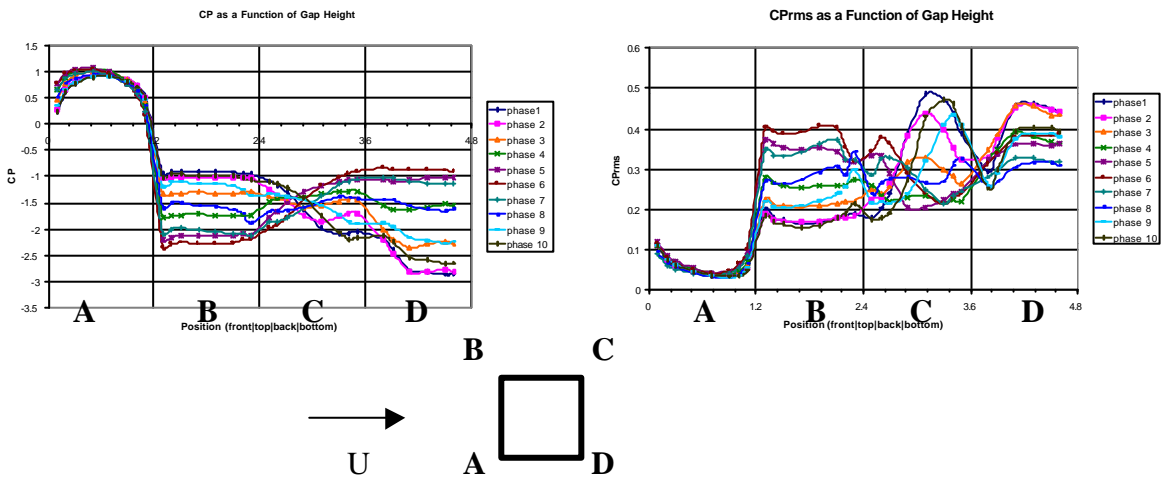


Figure 7: Phase averaged representation of the pressure distribution along the surface of the cylinder at $S/D=1$.