DDES and IDDES of Tandem Cylinders

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Outline

- Objectives
- Numerical Method
- Flow Conditions
- Grids
- Results
- Computational Resources
- Observations

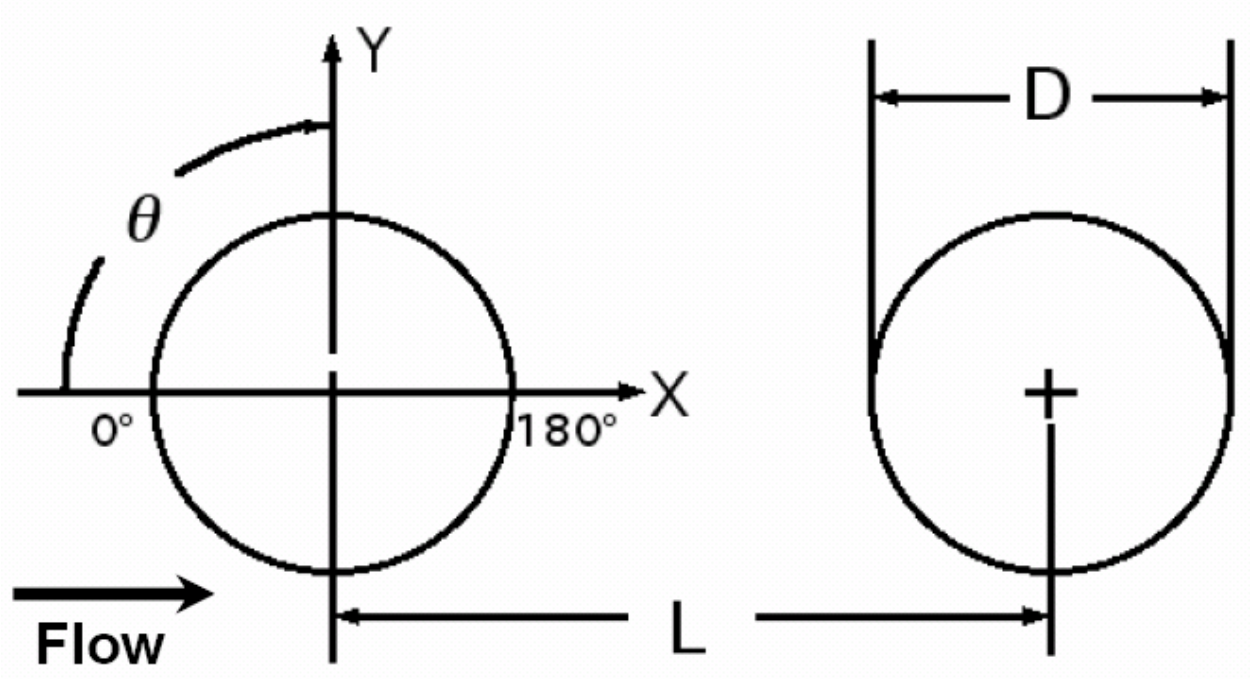
Objectives

- Validation of Delayed Detached-Eddy Simulation (DDES) and DDES with Improved wall-modeling capabilities (IDDES) approaches to turbulence simulation

Numerical Method

- Equations solved
  - Incompressible hybrid (URANS-LES) equations of DDES and IDDES approaches
  - Spalart-Allmaras (S-A) background RANS model
- Spatial and temporal discretizations
  - FV hybrid (weighted centered/upwind-biased) flux-difference scheme based on Rogers and Kwak method
  - Design accuracy: 4^{th} centered / 5^{th} upwind-biased for inviscid fluxes;
    2^{nd} order centered for viscous fluxes;
    2^{nd} implicit time integration (3 layer scheme)
- Boundary Conditions
  - Inflow:
    - Uniform streamwise and zero lateral velocity components
    - Eddy viscosity equal to molecular one
  - Cylinder walls
    - No-slip
  - WT section side walls
    - Free-slip
  - Spanwise
    - Periodic
  - Outflow
    - Specified pressure

Flow Conditions in Simulations

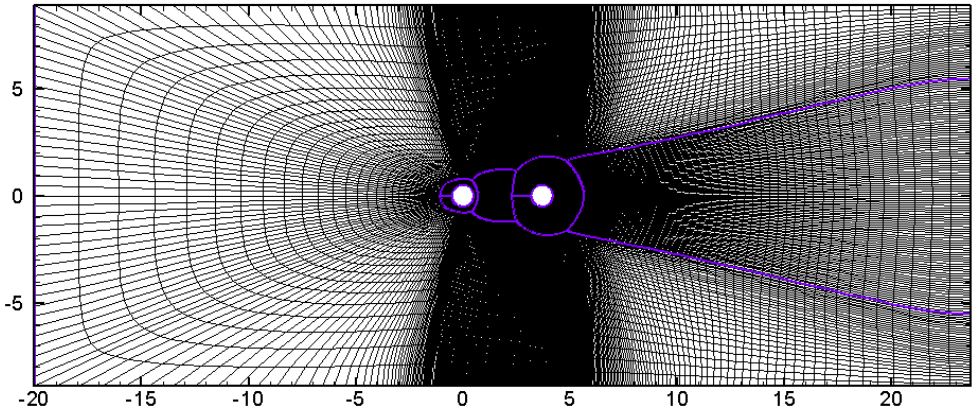


- Re = 166,000 based on D
- Turbulence model run fully turbulent
- Incompressible flow

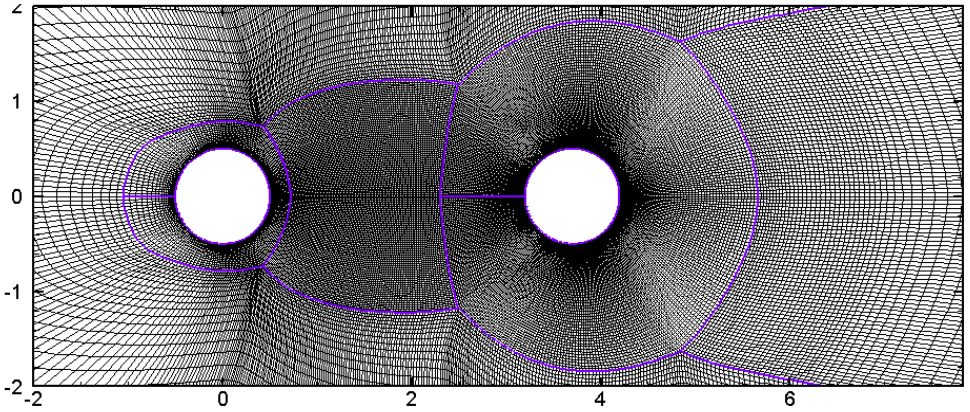
Grids

- Block-structured overset of Chimera type
- Total grid count is 11 M for $Lz=3D$ and 60 M for $Lz=16D$
- Uniform grid in spanwise direction with the step $\Delta z=0.02D$

Full domain



Zoomed fragment



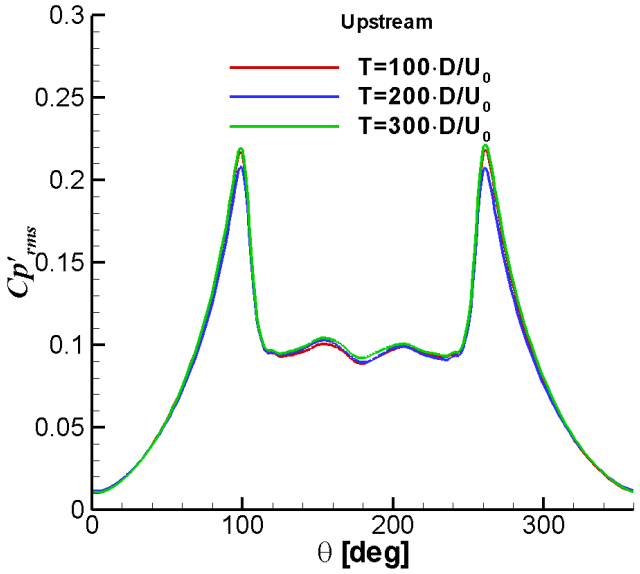
Results

- Time step
  - 0.02D / V_0 ($2.6 \cdot 10^{-5}$s) for Lz=3
  - 0.005D / V_0 ($6.5 \cdot 10^{-6}$s) for Lz=16
- Number of time steps run (total and for sampling)
  - 350 convective time units, D/V_0, with 300 units used for sampling
- Observed shedding frequency
  - 188 Hz for both DDES runs
  - 192.5 Hz for IDDES
- Time-averaged drag per unit span ($C_D = f_D/(D\ 0.5\ \rho_o\ |V_o|^2)$

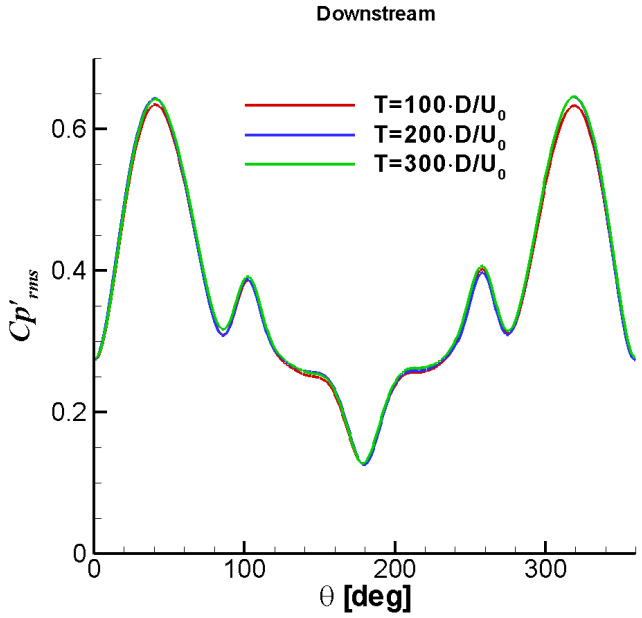
Approach	Lz/D	Upstream Cyl.	Downstream Cyl.
IDDES	3	0.51	0.40
DDES	3	0.48	0.42
DDES	16	0.46	0.43

Results:

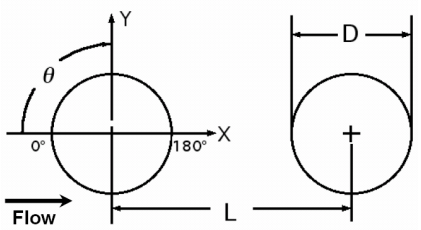
- Convergence information
  - RMS of surface pressure (Cp_{rms}) computed based on samples of 100, 200, and 300 convective times units



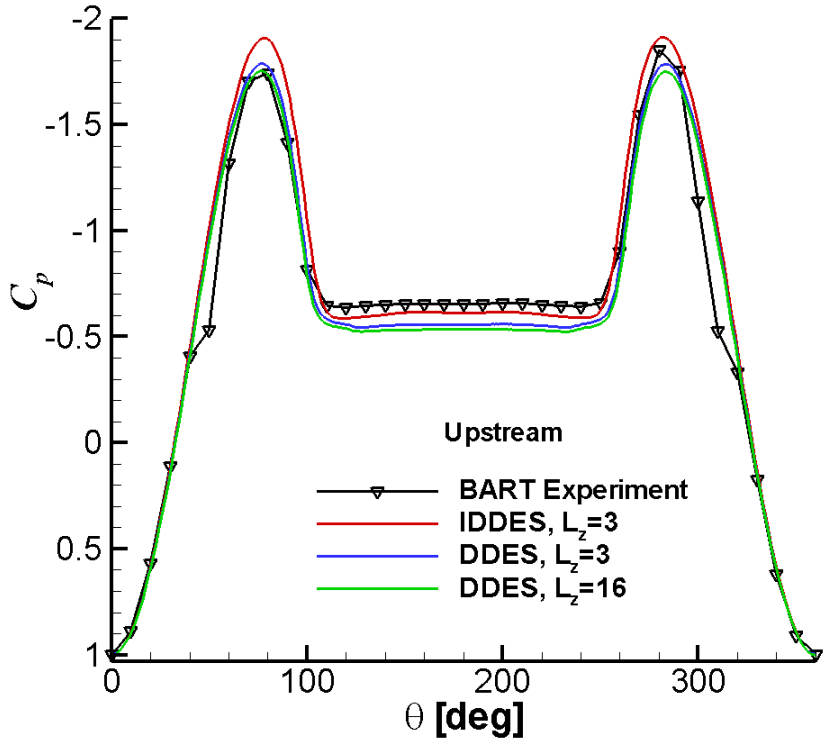
Upstream

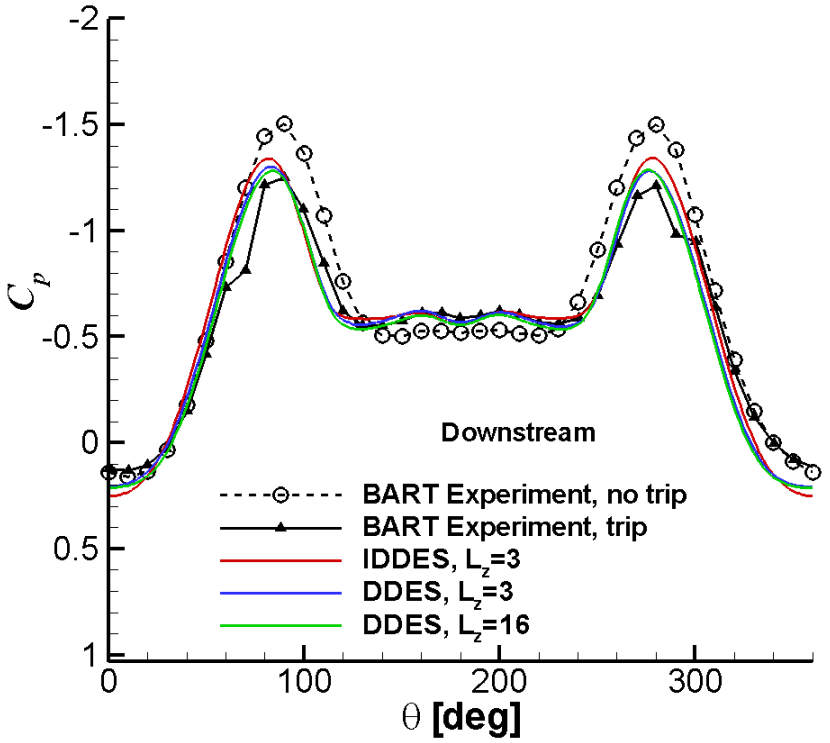


Downstream



Surface Pressure





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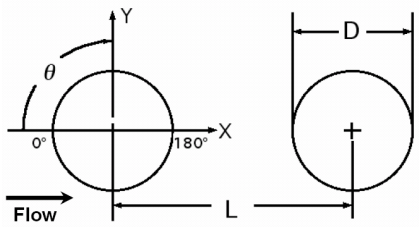
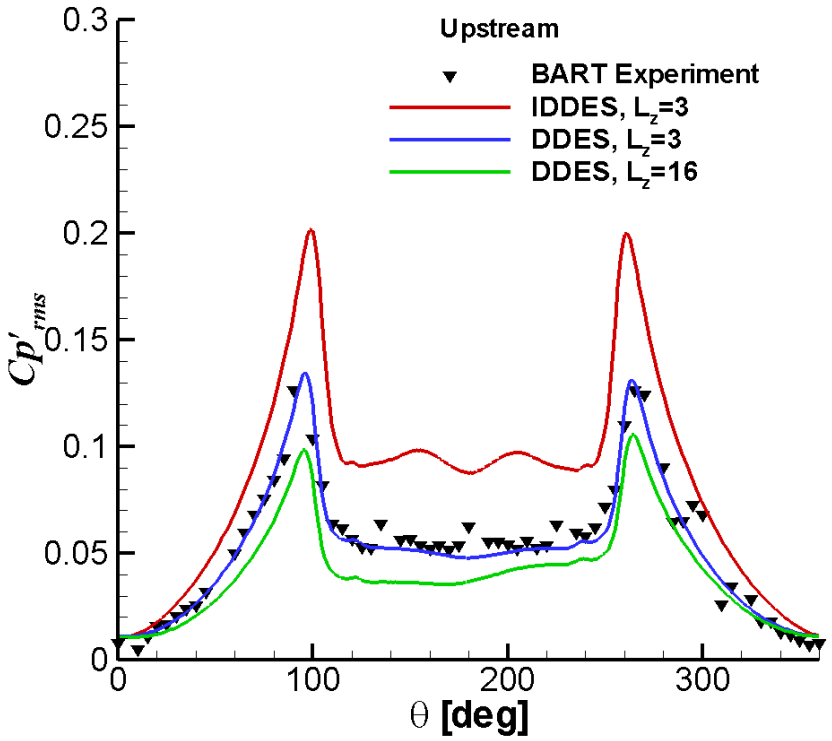
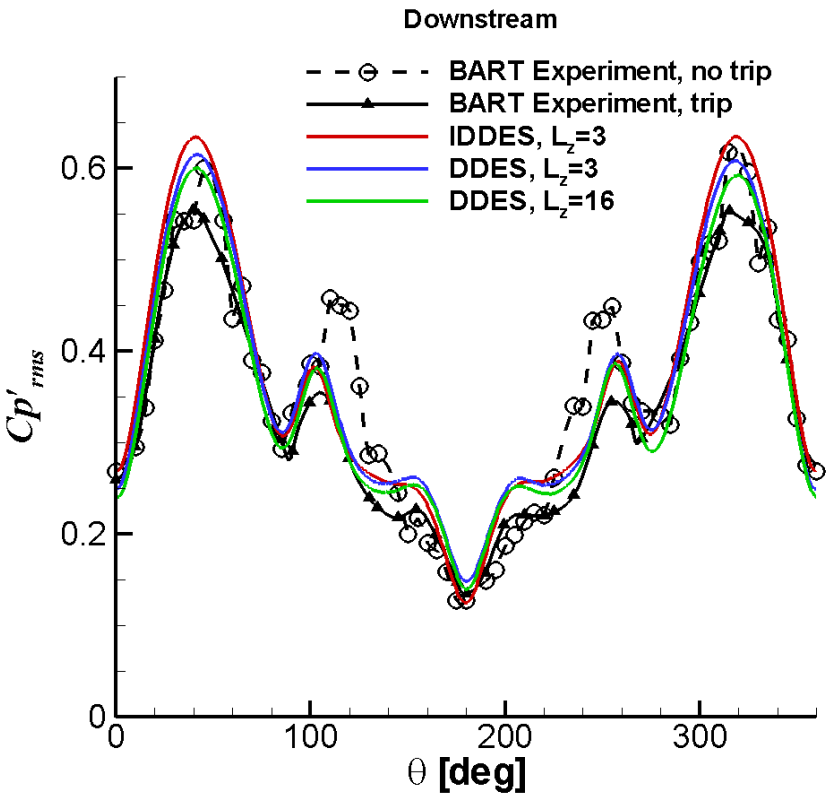


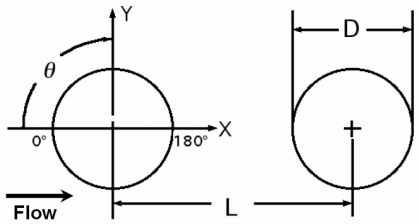
Downstream

RMS of Surface Pressure





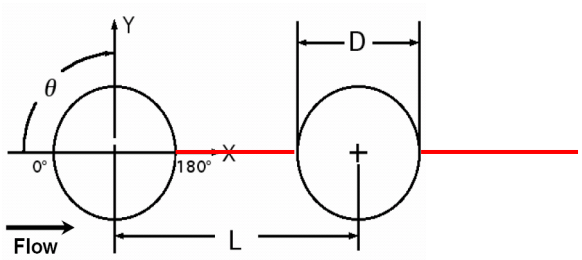
Upstream

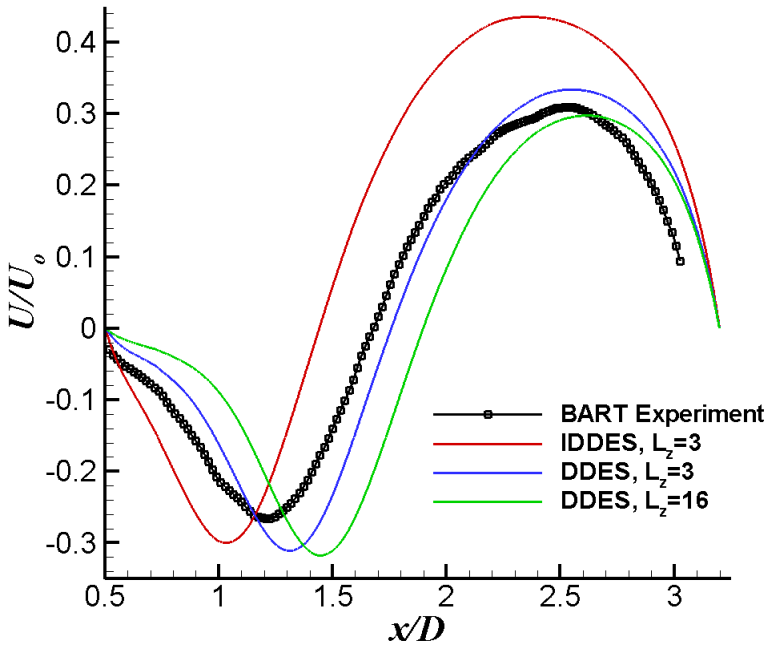


Downstream

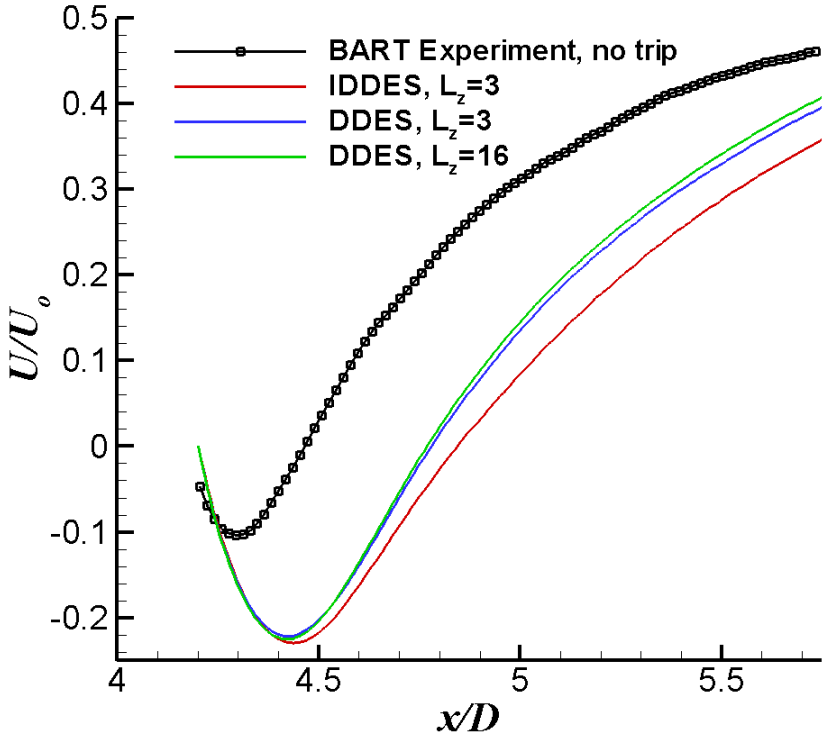
Mean Velocity

- Along y/D=0





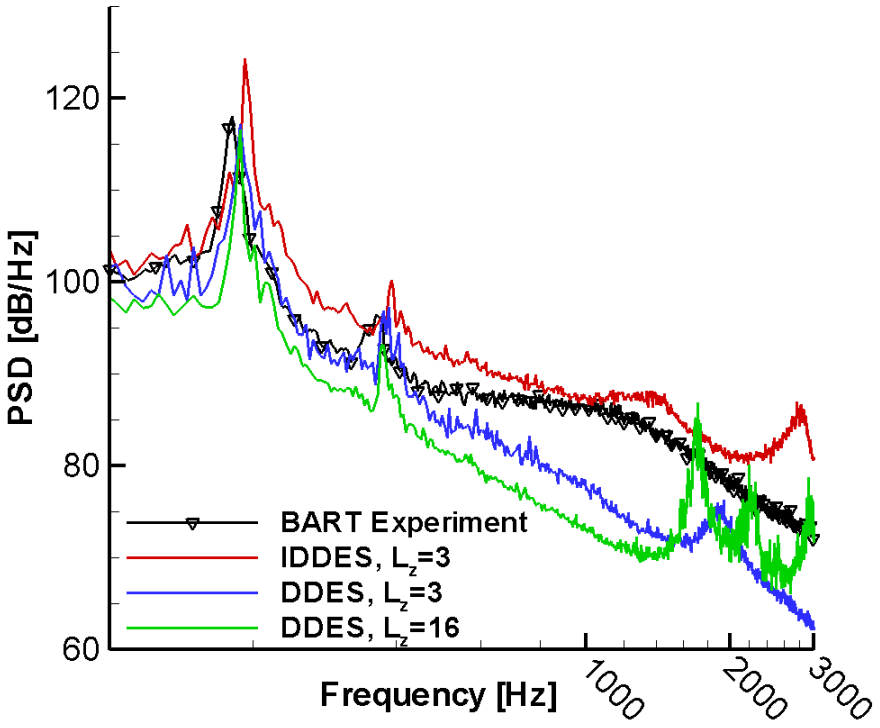
Gap Region



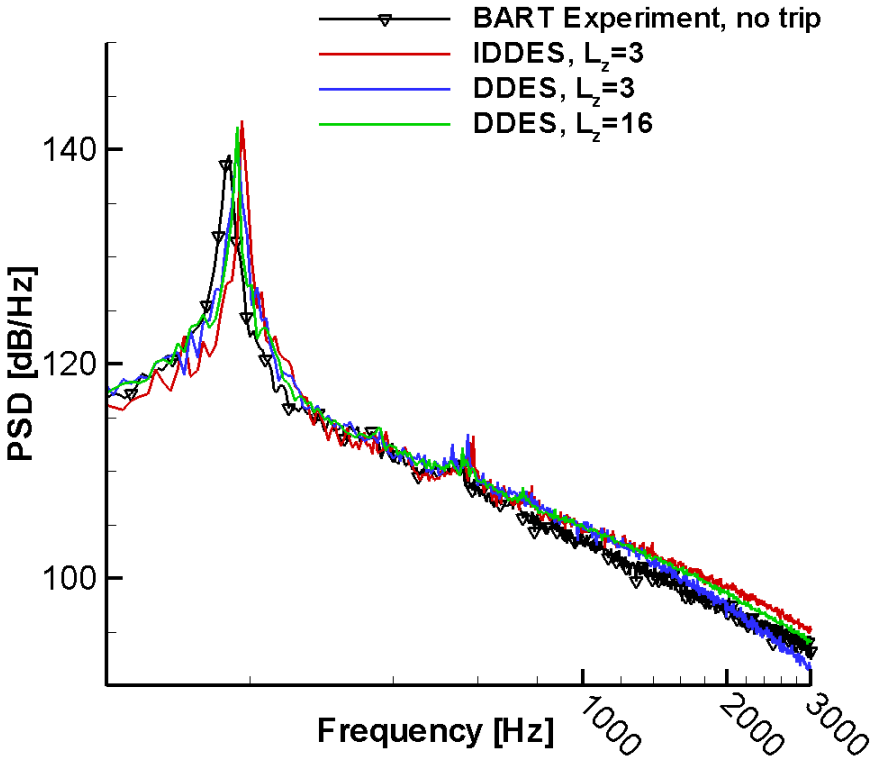
Aft of Downstream Cylinder

Surface Pressure Spectra

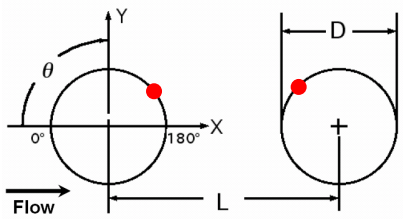
- Power Spectral Density



Upstream, θ = 135°



Downstream, θ = 45°



Computational Resources: Lz=3D (11M Cells)

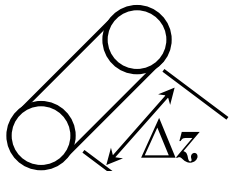
- Computer hardware
  - 4 nodes of NTS cluster (one node contains two 4-core processors Intel Xeon E5345 (2.33GHz) and 8Gb memory)
  - Gigabit network
- Resources
  - wall clock Time / time step: ~2.5 min
    - # of time steps in simulation ~17500
  - wall clock Time / 1 sec of simulation time ~66 days
    - # of time steps needed for 1 sec of simulation time ~38500
  - Memory used
    - Per cpu ~ 2Gb
    - Total ~8Gb

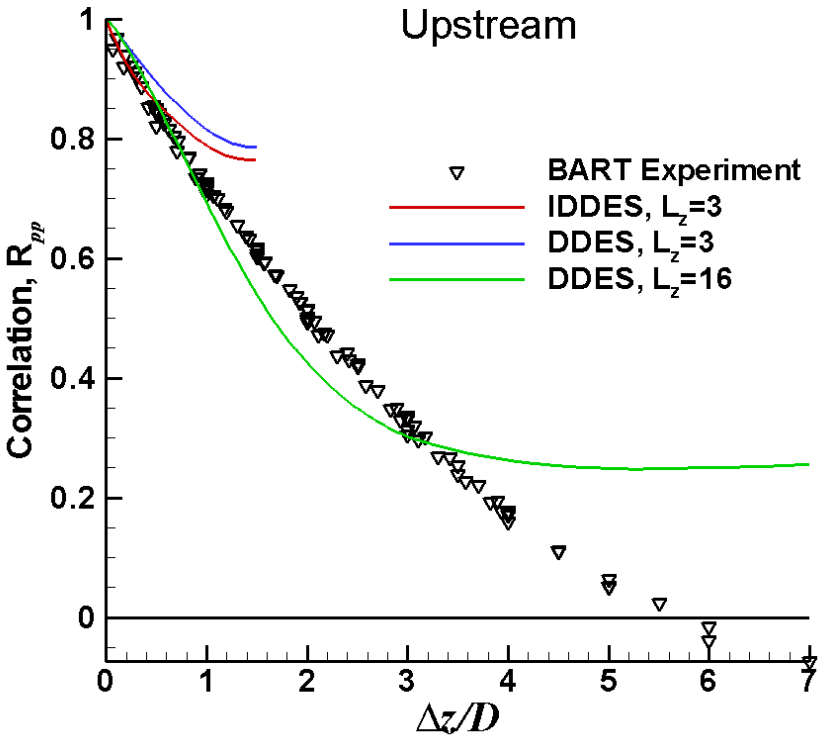
Computational Resources: Lz=16D (60M Cells)

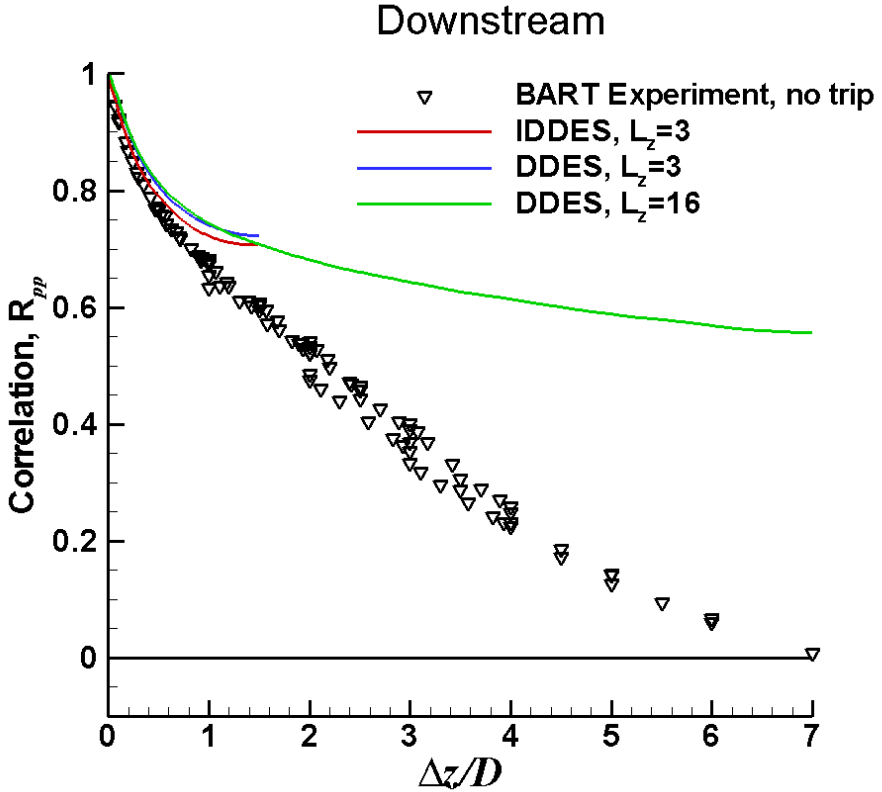
- Computer hardware
  - 8160 nodes on the Intrepid (Argonne National Laboratory, Blue Gene/P architecture, each node has as its processor an IBM PowerPC 450 (850MHz) and 2 Gb memory).
  - Blue Gene Network
- Resources
  - wall clock Time / time step: ~12 sec
    - # of time steps in simulation ~78000
  - wall clock Time / 1 sec of simulation time ~22 days
    - # of time steps needed for 1 sec of simulation time~154000
  - Memory used
    - Per cpu ~ 2Gb
    - Total ~16Tb (due to massive parallelization)

Surface Pressure Correlation

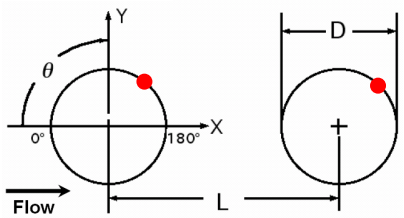
- Spanwise row of sensors at θ=135 deg







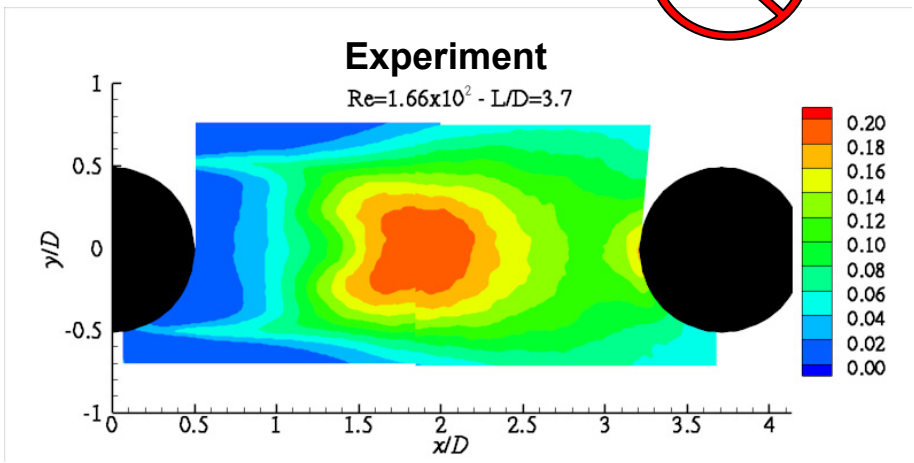
Upstream

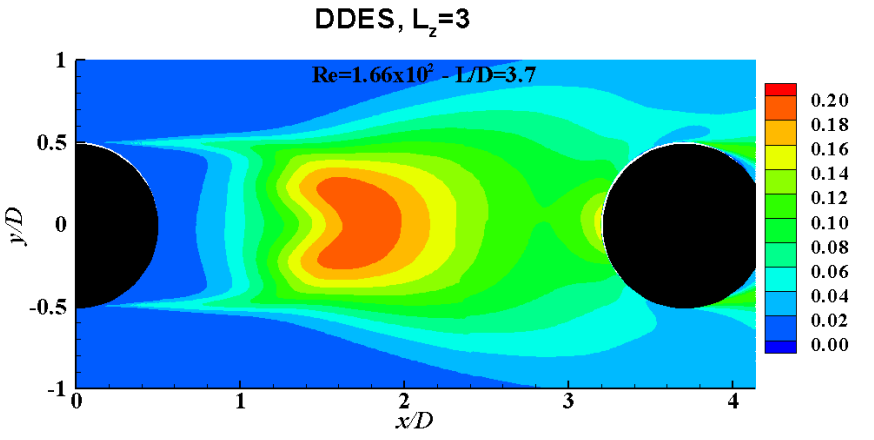


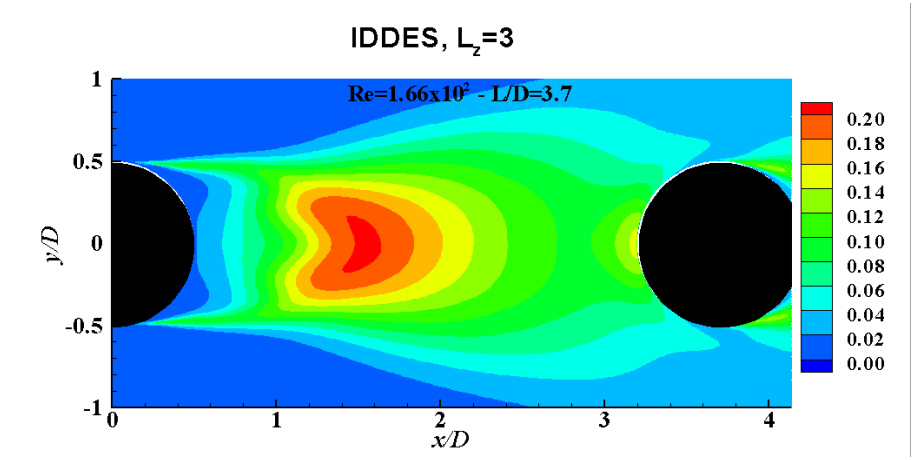
Downstream

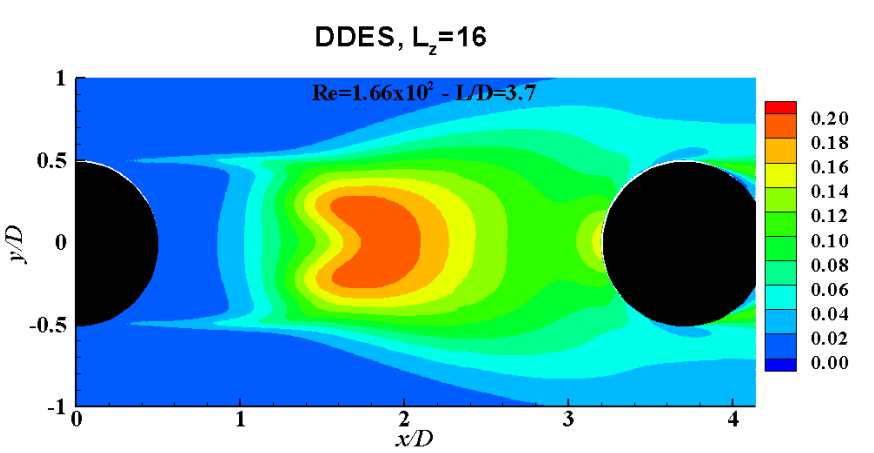
2D TKE

- $1/2\ (\overline{u'\,u'} + \overline{v'\,v'} + \overline{w'\,w'})/)/V_o^2$





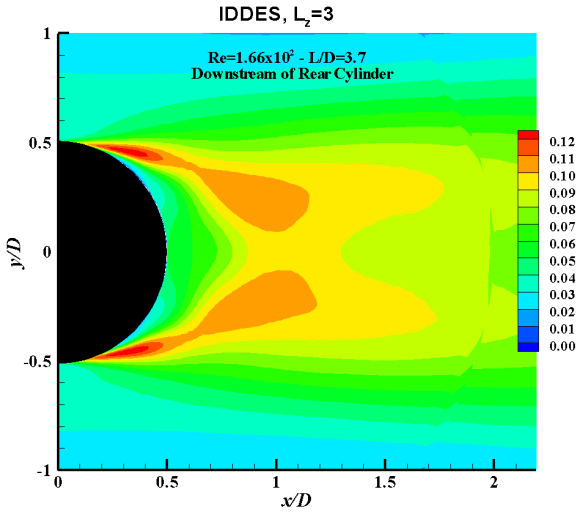


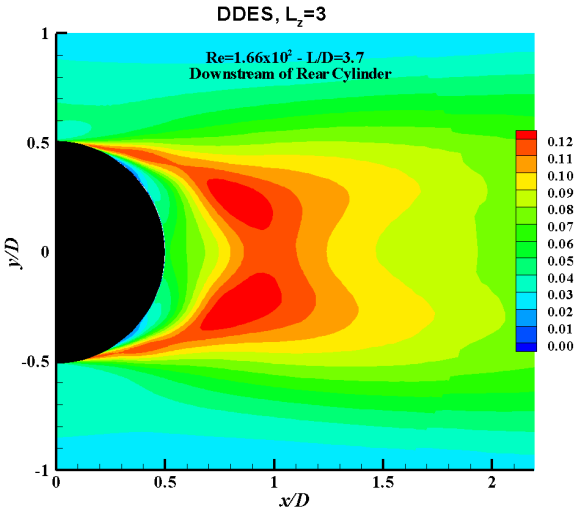


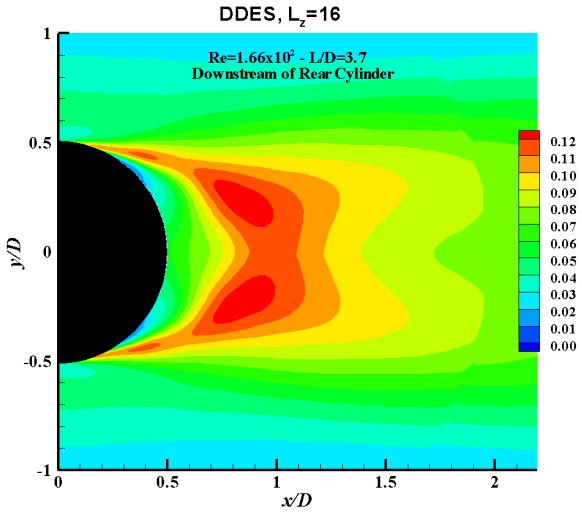
Gap Region

2D TKE

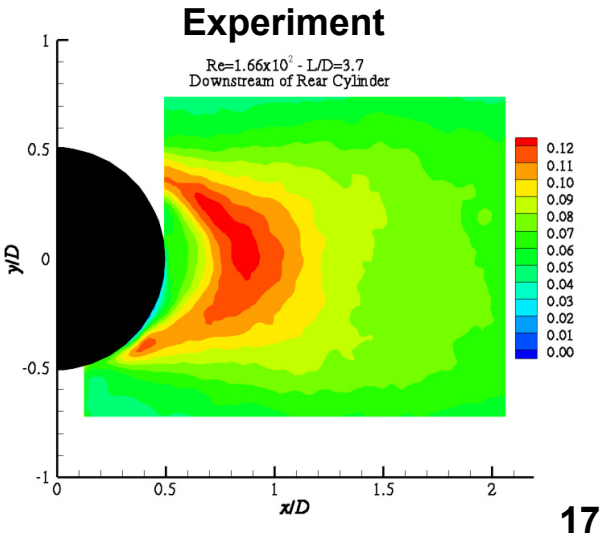
- $1/2\ (\overline{u'u'} + \overline{v'v'} + \overline{w'w'})/)/V_o^2$





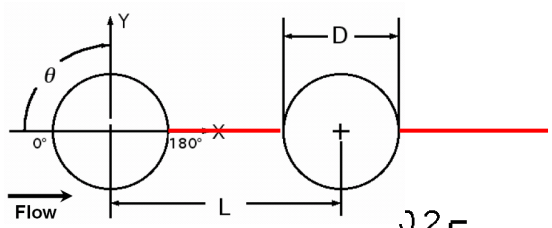


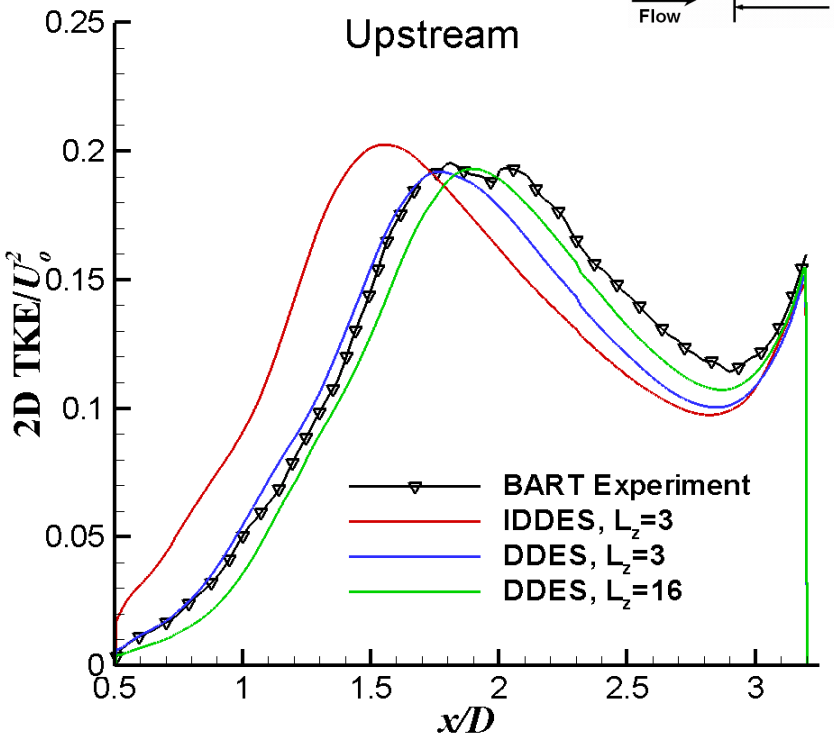
Aft of Downstream Cylinder



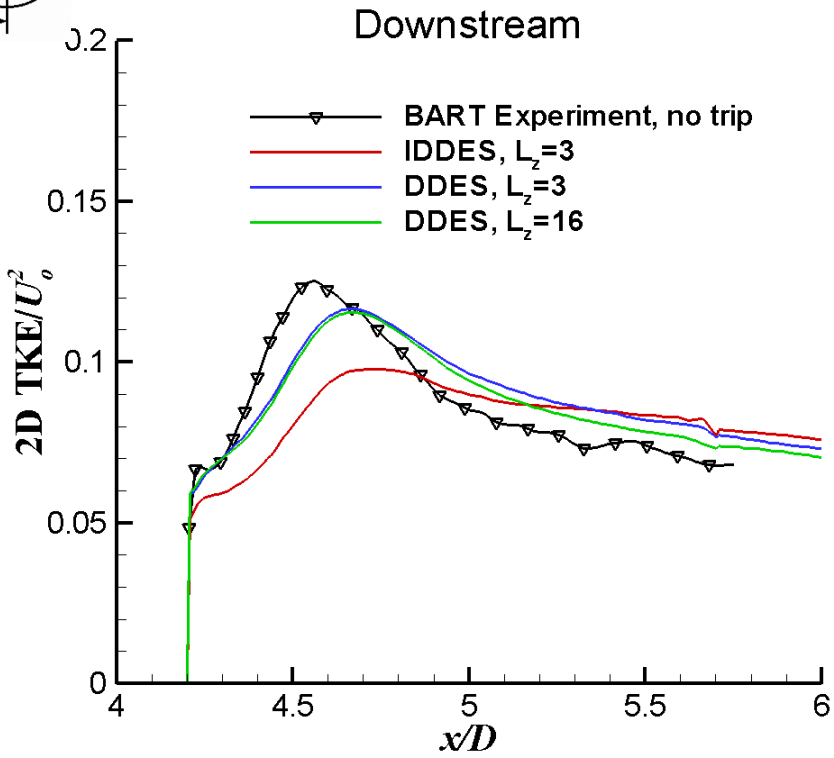
2D TKE

- 1/2 ($\overline{u'u'} + \overline{v'v'} + \overline{w'w'}$)/$V_o^2$ along ***y/D***=0





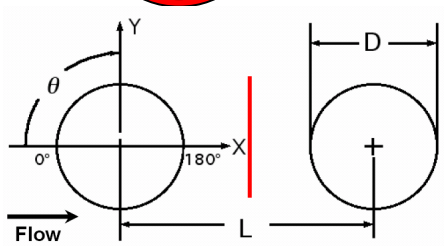
Gap Region



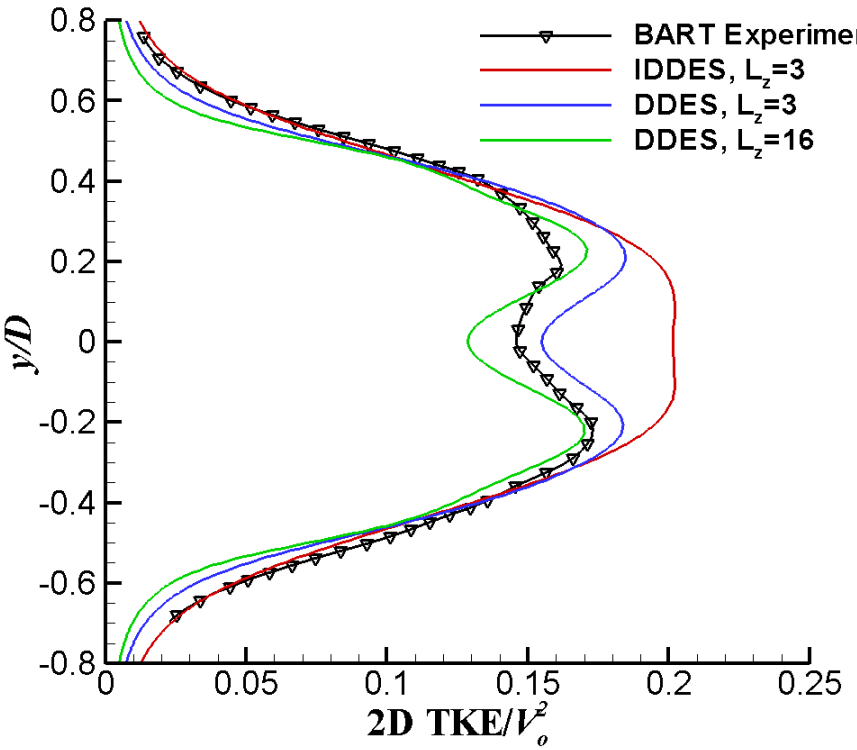
Aft of Downstream Cylinder

2D TKE

- 1/2 ($\overline{u'u'} + \overline{v'v'} + \overline{w'w'}$)/)/$V_o^2$

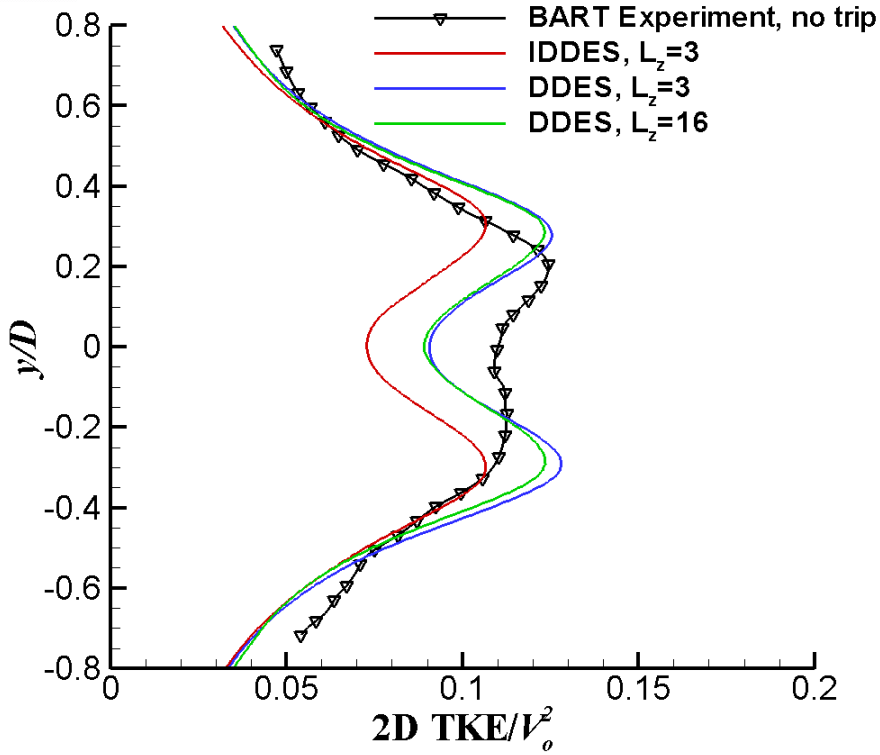


Upstream



Gap Region, x/D=1.5

Downstream



Aft of Downstream Cylinder, x/D=4.45

Observations-1

- Lessons Learned
  - Major physical and computational issue
    - Adequate representation of the onset of instability in the turbulent shear layer forming after separation of the turbulent boundary layer from the upstream cylinder
  - Assessment of state-of-the-art
    - No definite preference to one of two considered approaches can be given. Although DDES results at $Lz=3D$ agree with the data reasonably well (in general, tangibly better than those of the two other simulations), it may well be a result of cancellation of modeling errors and those associated with the insufficient spanwise size of the computational domain
    - Although grid and numerics used in the simulations seem to be “good enough”, a substantial grid-refinement may well also change the current assessments

Observations-2

- Lessons Learned
  - Benchmark deficiencies
    - No tripping of the downstream cylinder in most of experiments (makes comparison of FT CFD with the data not quite conclusive)
    - No measurements of skin-friction (does not permit quantitative evaluation of accuracy of prediction of separation)
  - Recommendations for follow-on efforts
    - Additional measurements
      - Cf distributions over both cylinders
    - Desired additions/modifications to problem statement
      - Tripping of the downstream cylinder
  - Procedures for computations or measurements
    - Grid-sensitivity study and noise prediction