

# FUN3D Solutions for Tandem Cylinders

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# Outline

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

# Objectives

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- Assess the applicability of an unstructured grid flow solver, FUN3D, for Tandem Cylinder Configurations
- Examine turbulence modeling sensitivity

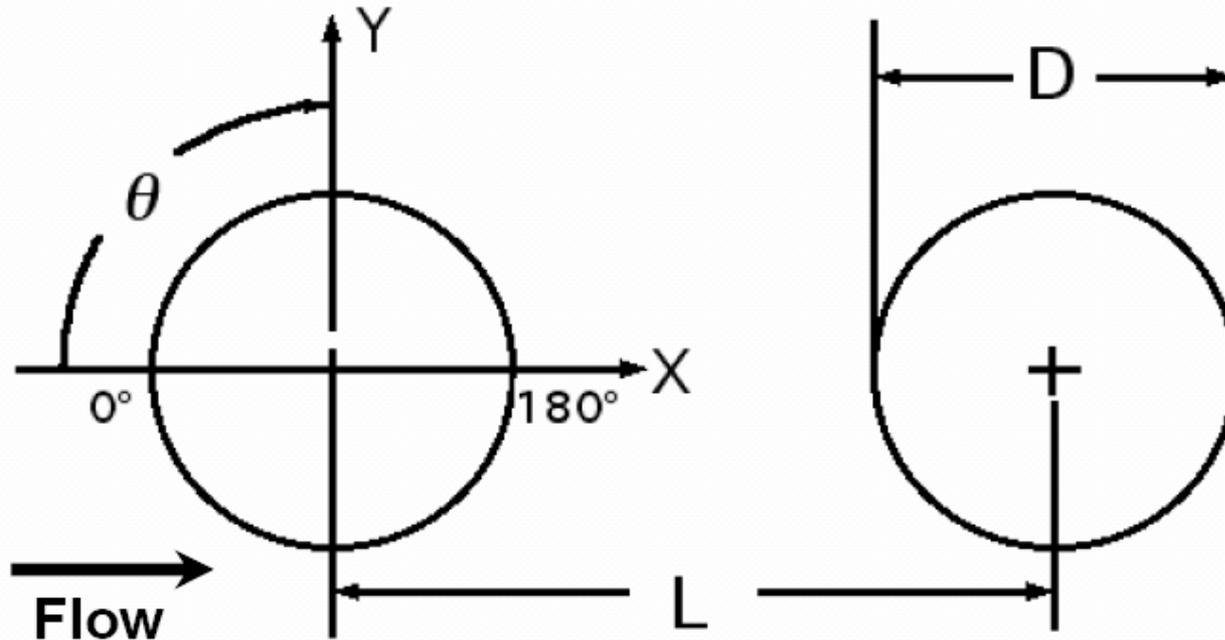


# Numerical Method

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- Equations solved
  - Unsteady Reynolds-averaged Navier-Stokes (URANS) equations  
Fully unstructured node-based flow solver (FUN3D)
  - Modified Menter's two-equation shear stress transport (SST) model  
(Ref. Khorrami et al. AIAA-2006-3203)
  - Hybrid RANS/LES model (Ref. Lynch et al. AIAA-2008-3854)
  - MDDES hybrid RANS model (Ref. Vatsa AIAA-2010-4001)
- Spatial and temporal discretizations
  - Roe's flux-difference splitting scheme without flux limiter
  - Second order spatial accuracy
  - Optimized second-order backward difference (BDF2OPT) scheme  
for temporal discretization
- Boundary Conditions
  - Adiabatic walls, Riemann invariants at far-field, spanwise periodicity

# Flow Conditions in Simulations

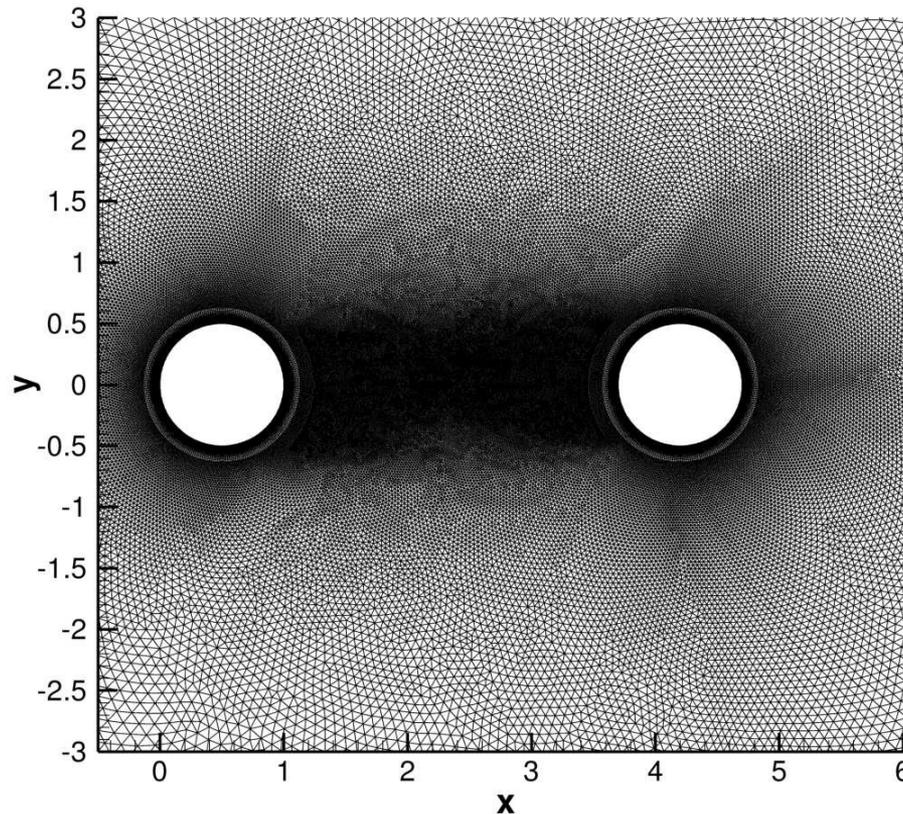


- $Re = 166,000$  based on  $D$ 
  - Flow code run in fully turbulent mode
  - Surface Transition occurs approx. at  $\theta = 60-70$  deg.
- $M = 0.166$

# Computational grid (partial view)



- Grid type: Structured near solid surfaces, unstructured away from boundary-layer regions
- Grid size: 8.7 million nodes, 97 spanwise planes
- Extent of grid: Far-field 25 D in x-y plane, span of 3 D





# Results

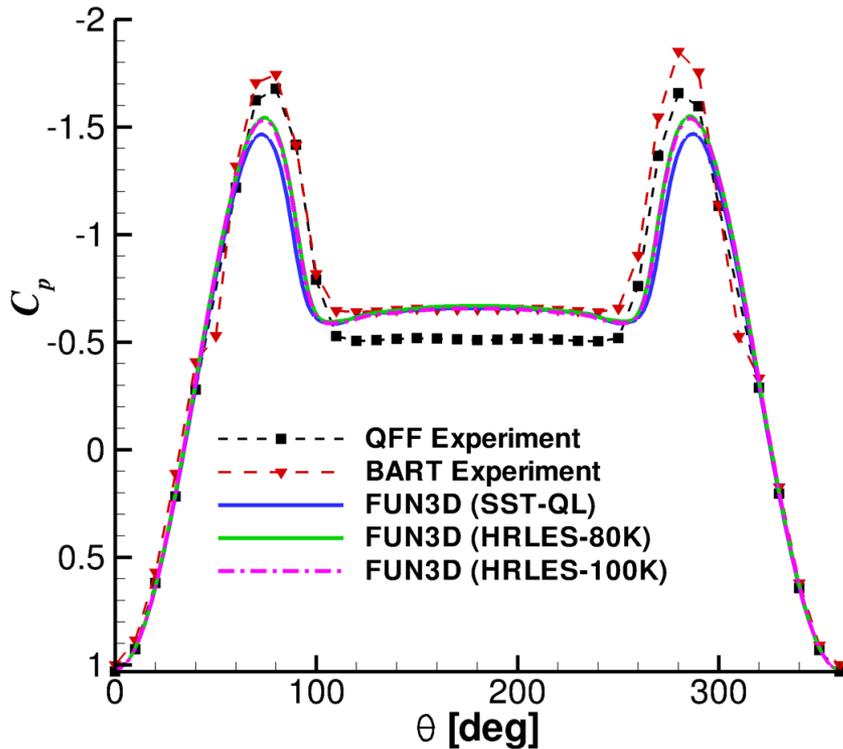
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- Time step
  - $1.69 \times 10^{-5}$  seconds
- Number of time steps run
  - Total : 80,000 – 100,000 time steps
  - Sampling : Minimum of 50,000 time steps
- Shedding frequency
  - 160 Hz
- Time-averaged Drag ( $C_d$  per unit span)
  - 0.637 on front, and 0.446 on rear cylinder for SST-QL
    - 0.436 on front, and 0.207 on rear cylinder for “MDDES other solution”
- Convergence information
  - $C_p$  and  $C_{p_{rms}}$  checked after every 10,000 time steps

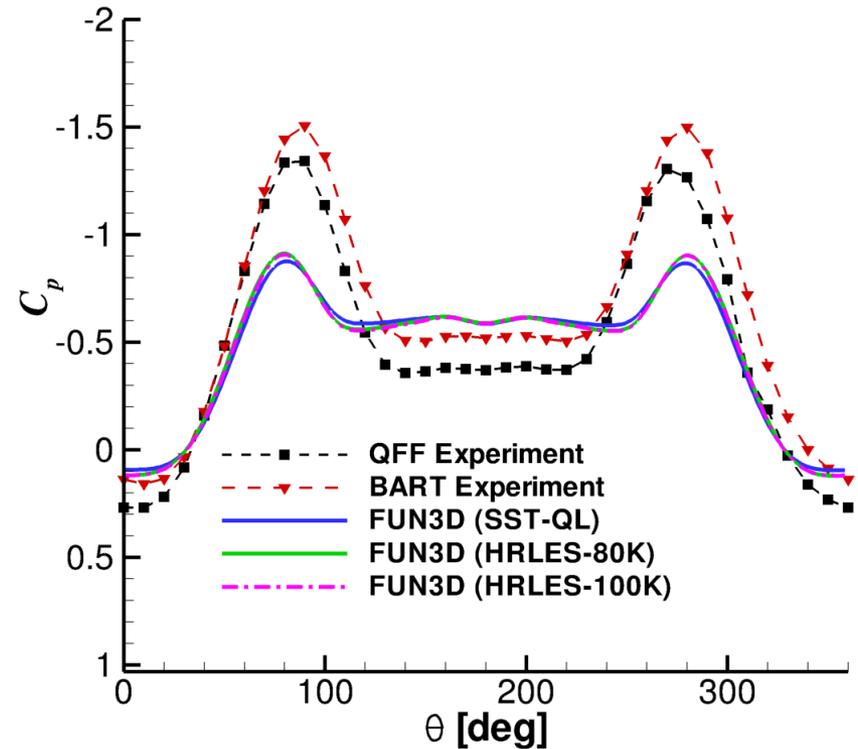
# Surface Pressure



- Collect time-average surface pressure data after initial transients exit computational domain
- Average the surface data along span for given  $\theta$



Front cylinder

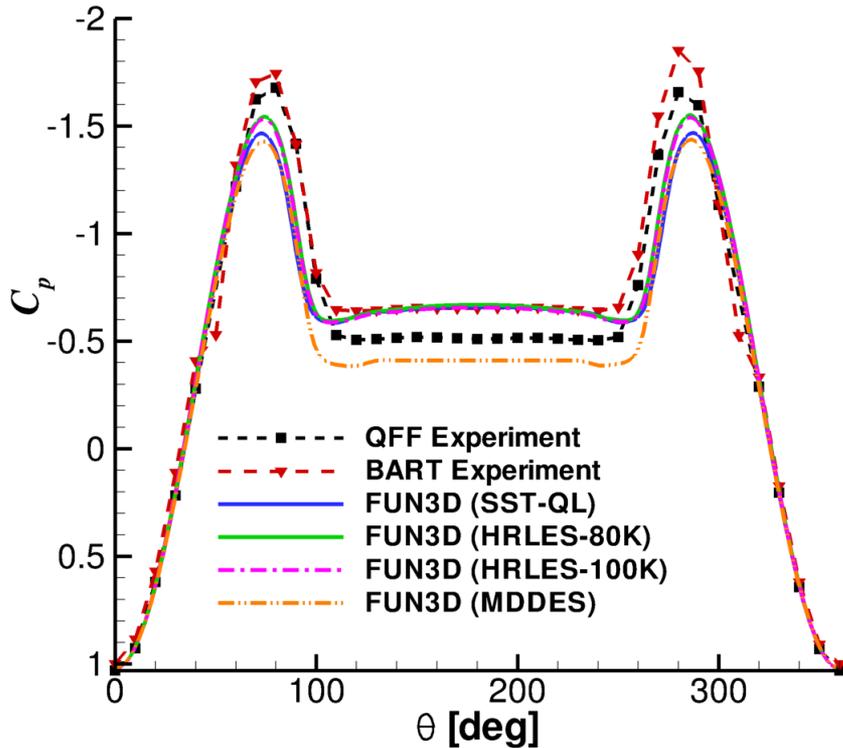


Rear cylinder

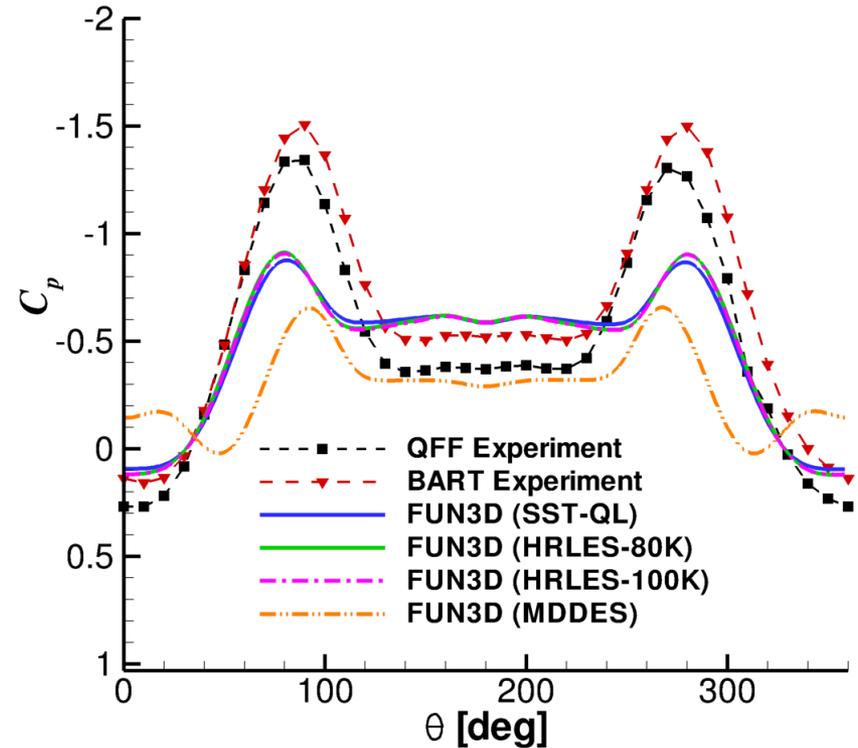
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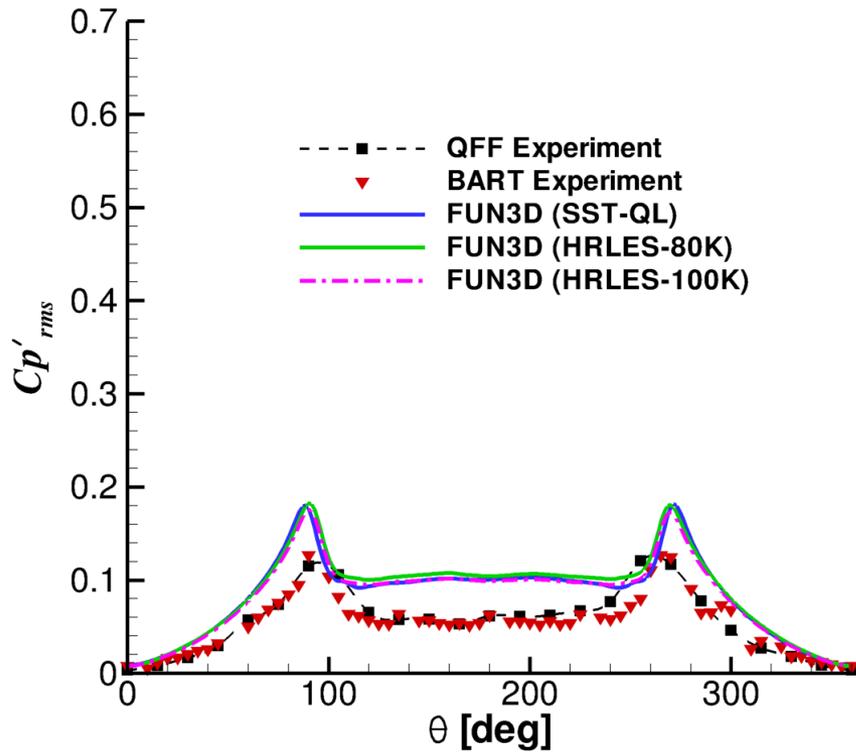


Front cylinder

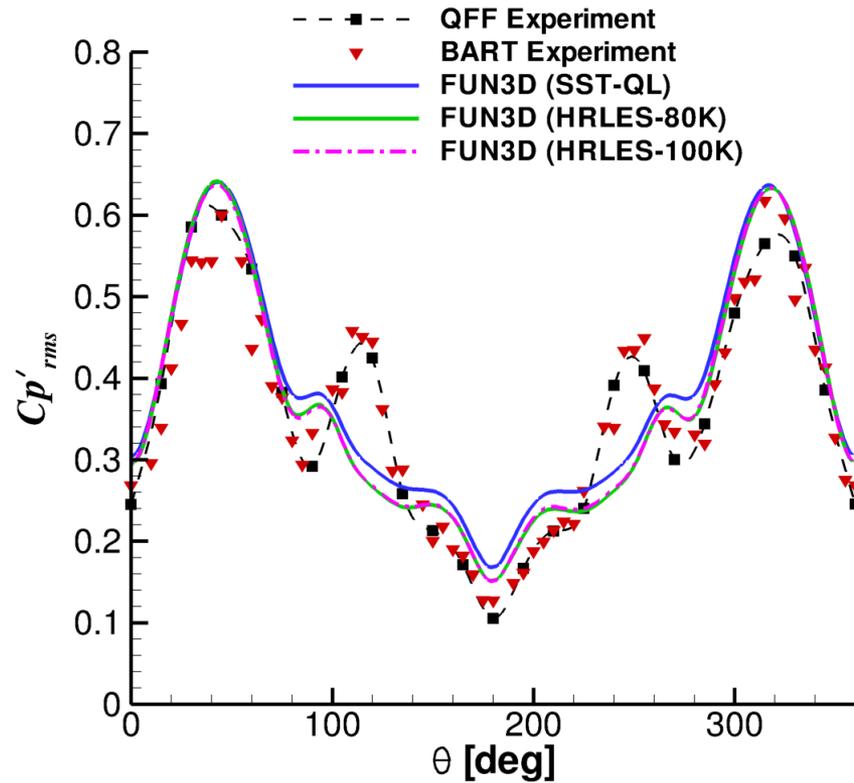


Rear cylinder

# RMS of Surface Pressure

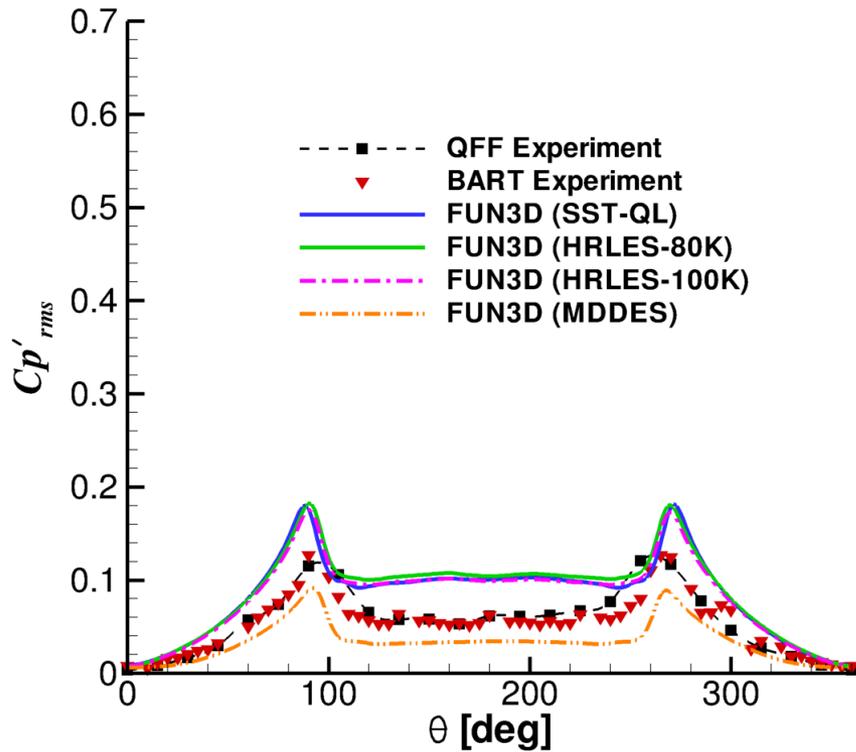


Front cylinder

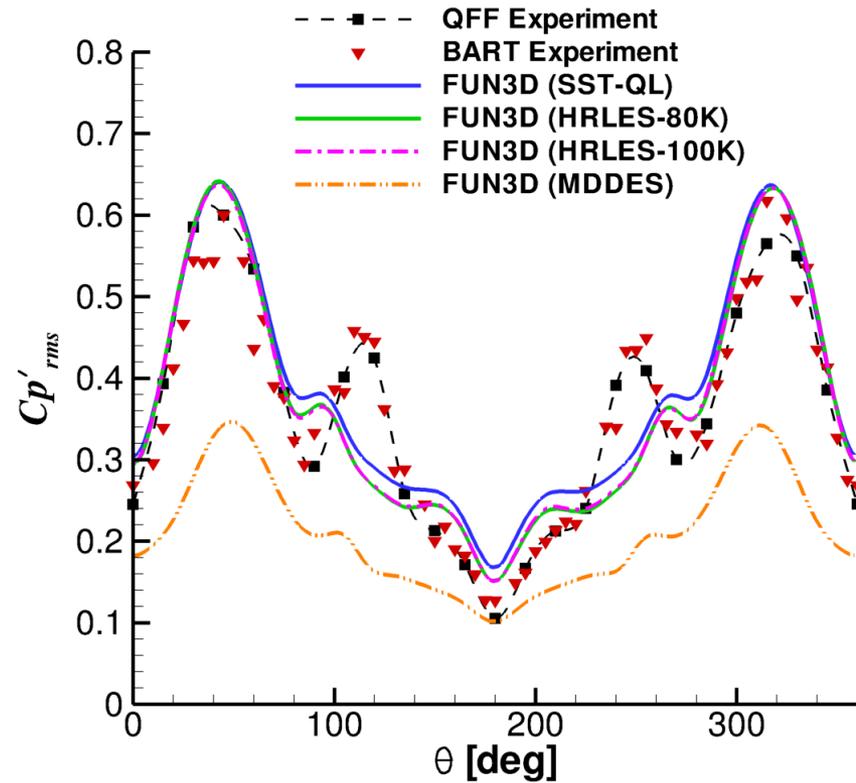


Rear cylinder

# RMS of Surface Pressure

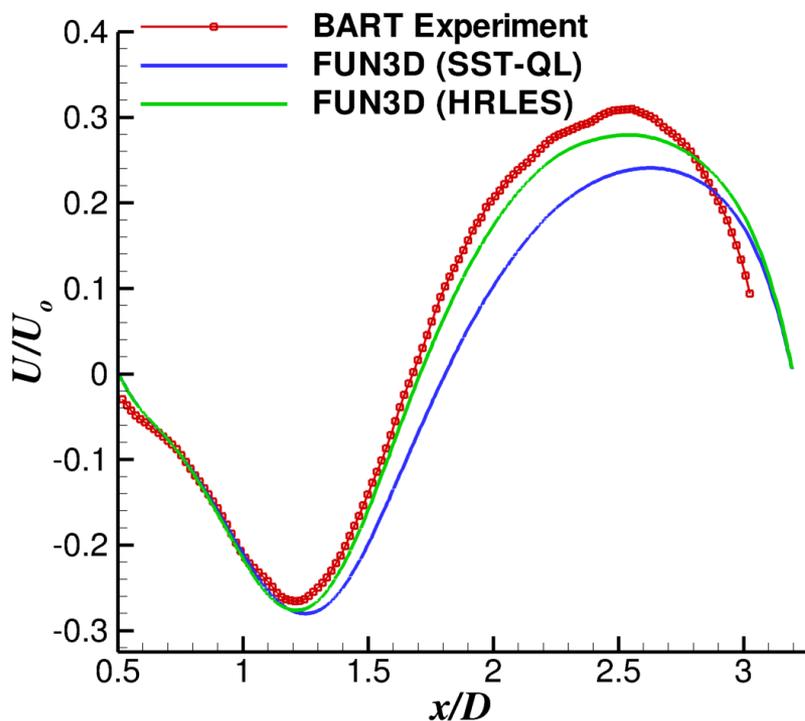
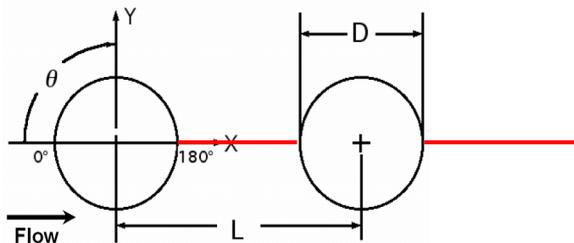


Front cylinder

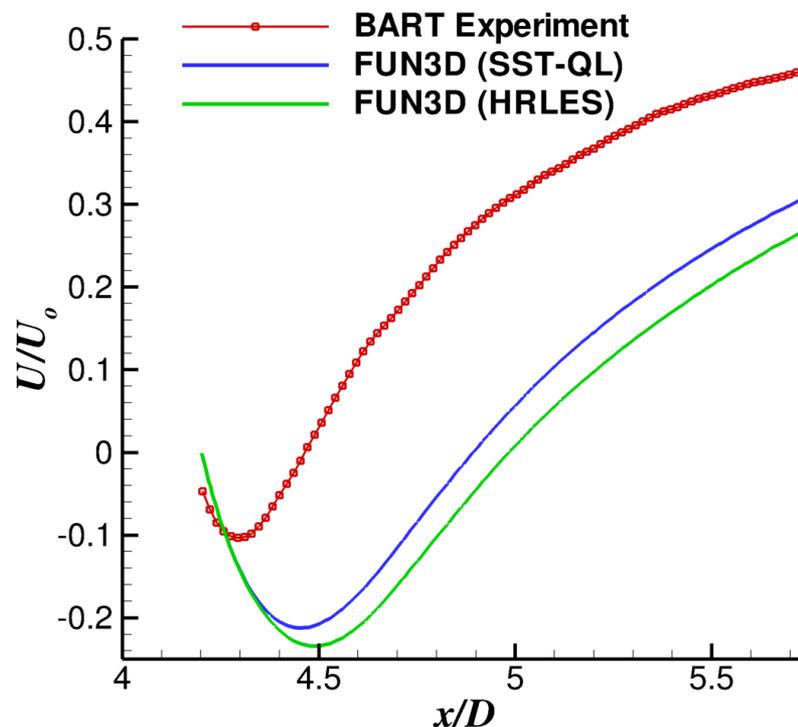


Rear cylinder

# Mean Velocity along $y/D=0$

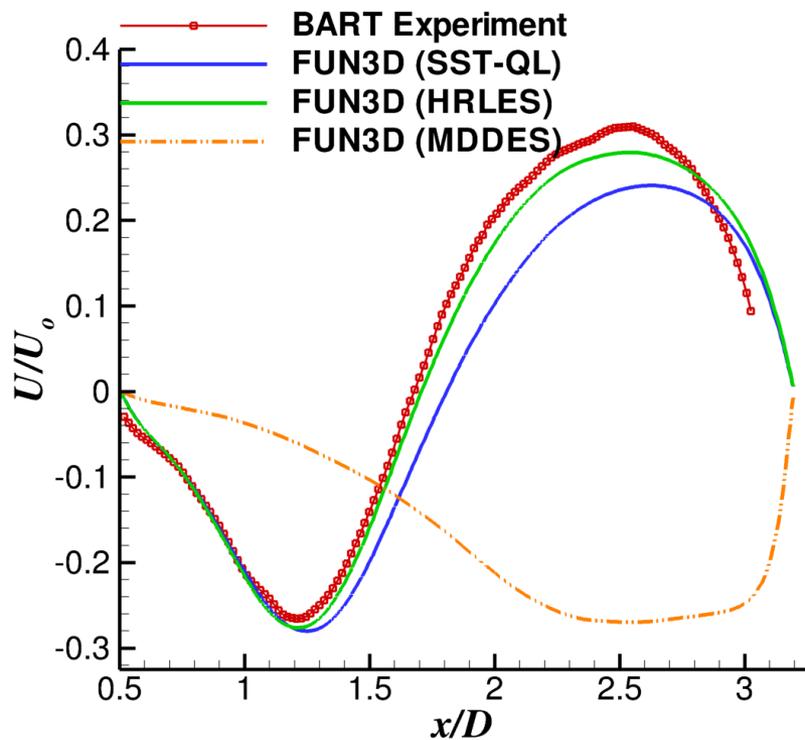
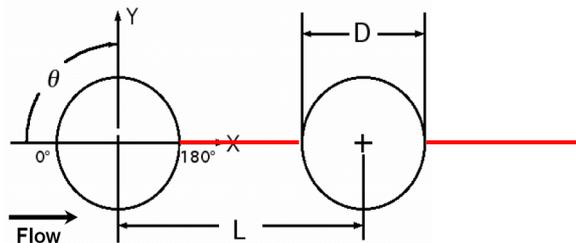


Gap Region

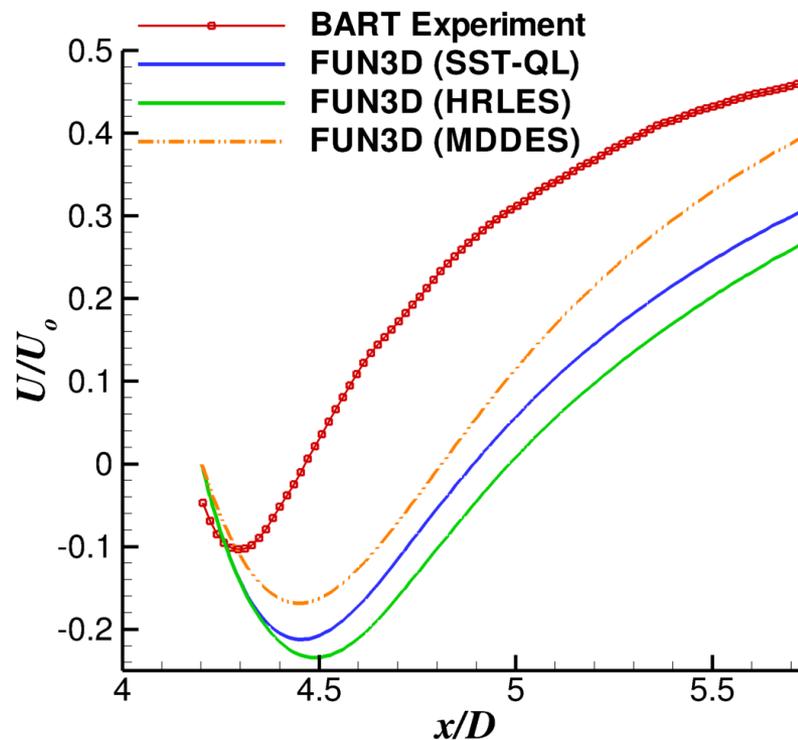


Aft of Downstream Cylinder

# Mean Velocity along $y/D=0$



Gap Region

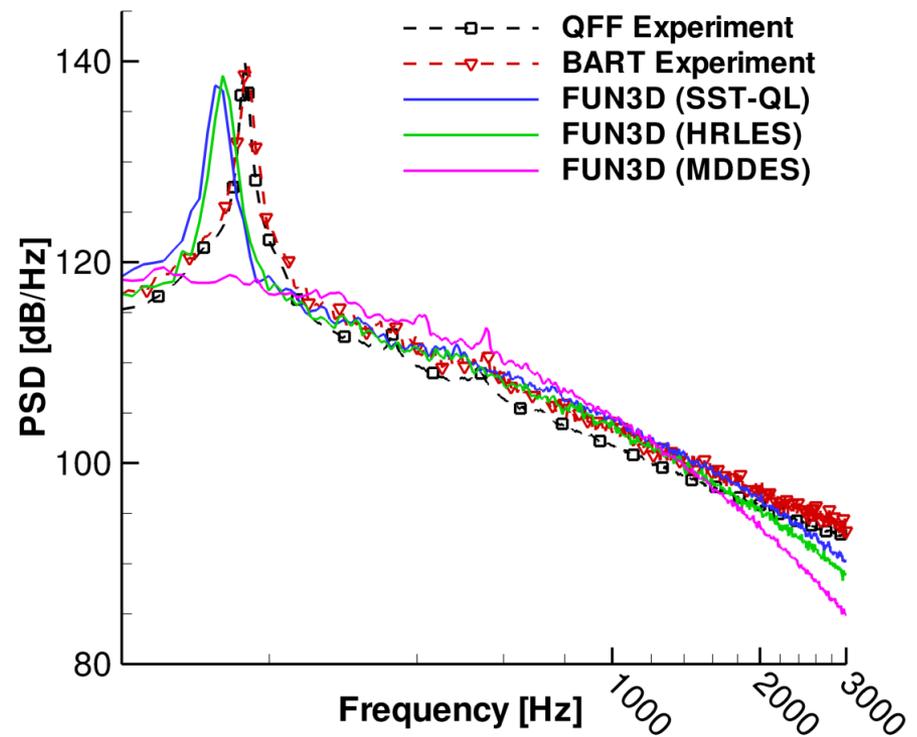
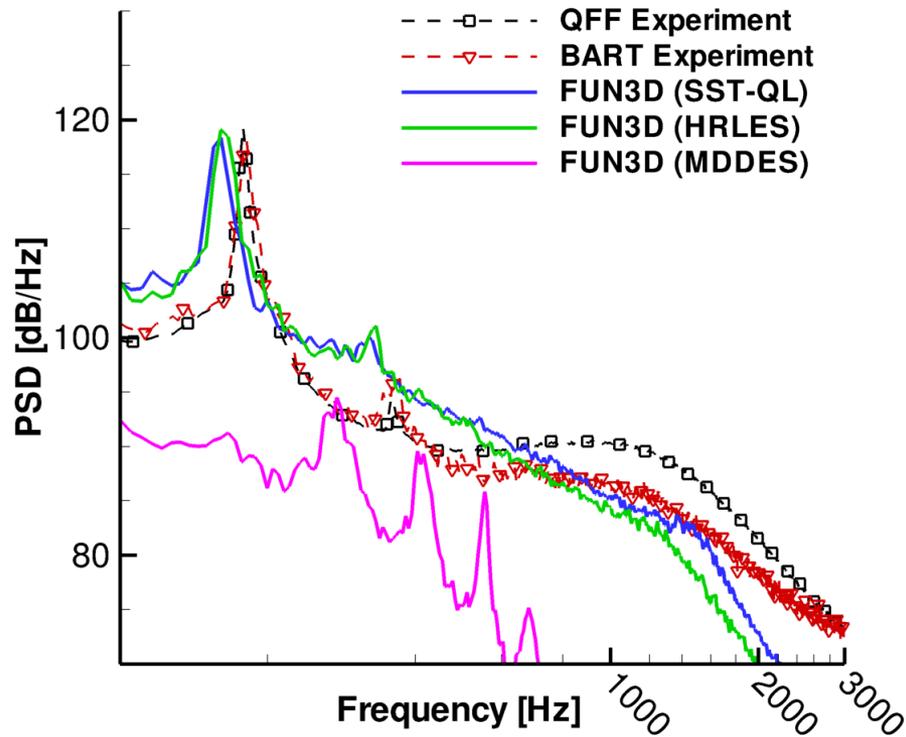


Aft of Downstream  
Cylinder

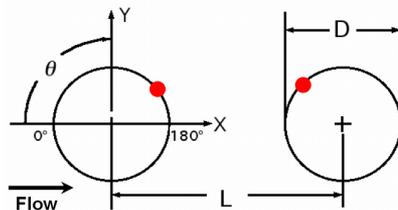
# Surface Pressure Spectra



## • Power Spectral Density



Upstream,  $\theta = 135^\circ$



Downstream  $\theta = 45^\circ$

# Computational Resources



- Computer hardware
  - CPU: 128 nodes/256 cores of Wolfdale 3 GHz single cpu/dual core cluster
  - Interconnect: Gigabit ethernet
- Resources
  - CPU (or wall clock) Time / time step : 32.4 secs.
    - 80,000 time steps in simulation
  - CPU (or wall clock) Time / 1 sec of simulation time: 532 hrs.
    - 59,200 time steps needed for 1 sec of simulation time
  - Memory used
    - Per cpu: 550 MBytes
    - Total: 70.4 GBytes

# Observations



- What did you learn?
  - Computational challenges
    - Significant computational effort for statistically meaningful results
    - Constructing suitable grids very challenging
  - New insights into the physics
    - Transition difficult to simulate, large sensitivity to transition location
  - Assessment of state-of-the-art based on your simulation for the problem category of interest
    - Encouraging results with unstructured grid flow code FUN3D, solutions capture salient flow features
    - Uncertainty due to grids, transition and turbulence modeling
  - Benchmark deficiencies
    - Reynolds number too low, transition sensitive
  - Recommendations for follow-on efforts
    - Additional measurements: Need high Reynolds number tests
    - Procedures for computations or measurements: Need systematic grid refinement studies, better turbulence/transition modeling

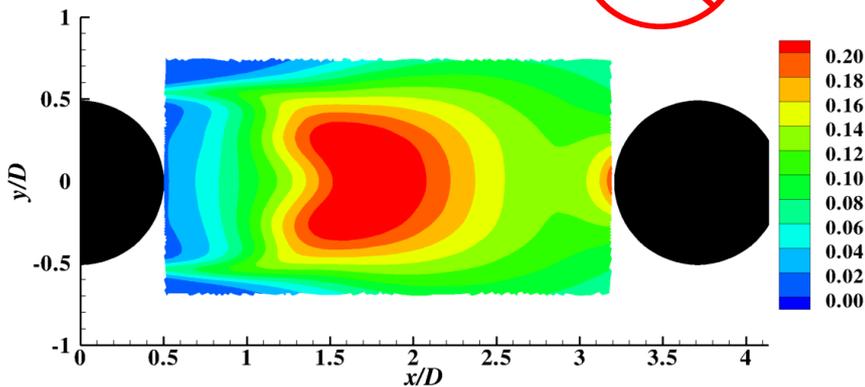


# OPTIONAL SLIDES

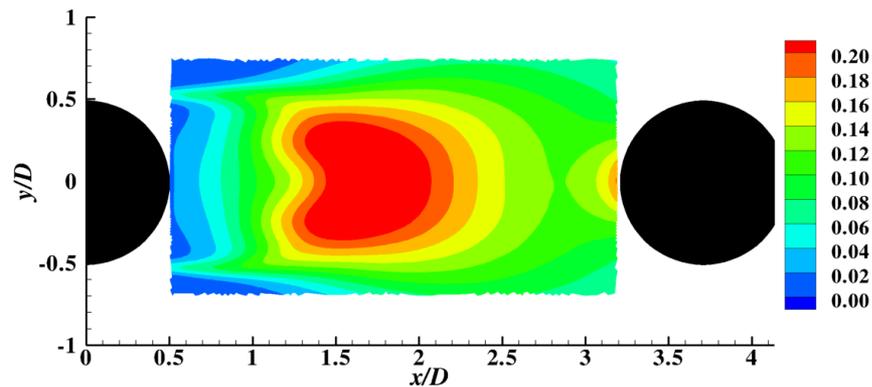
# 2-D TKE contours in gap region



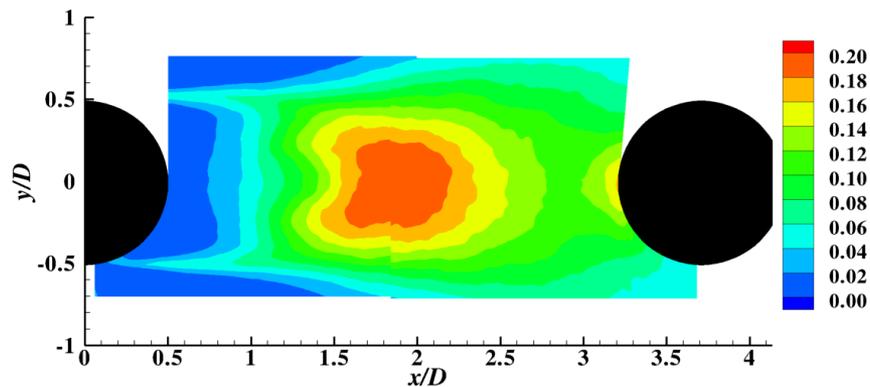
•  $1/2 (u' u' + v' v' + \cancel{w' w'}) / U_0^2$



FUN3D (SST-QL)

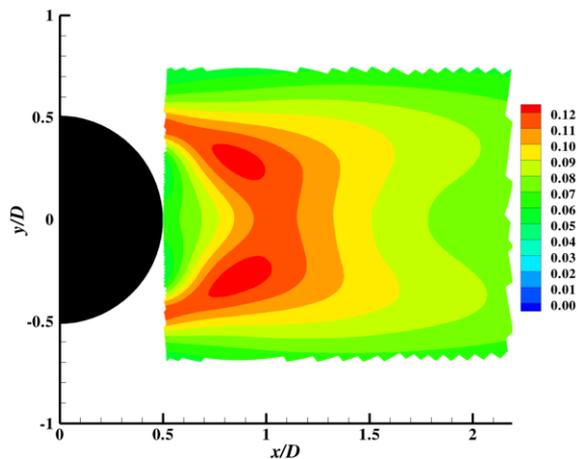


FUN3D (HRLES)

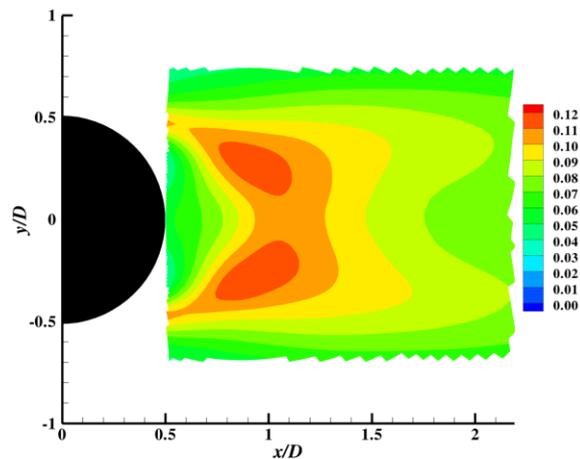


Exp. PIV Data (BART)

# 2-D TKE contours aft of rear cylinder

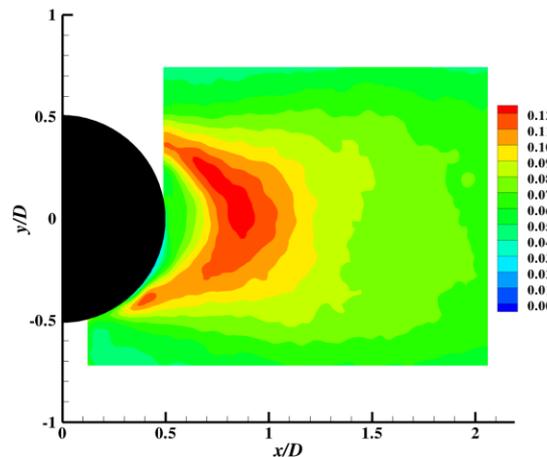


FUN3D (SST-QL)



FUN3D (HRLES)

•  $1/2 (u' u' + v' v' + \cancel{w' w'}) / U_o^2$

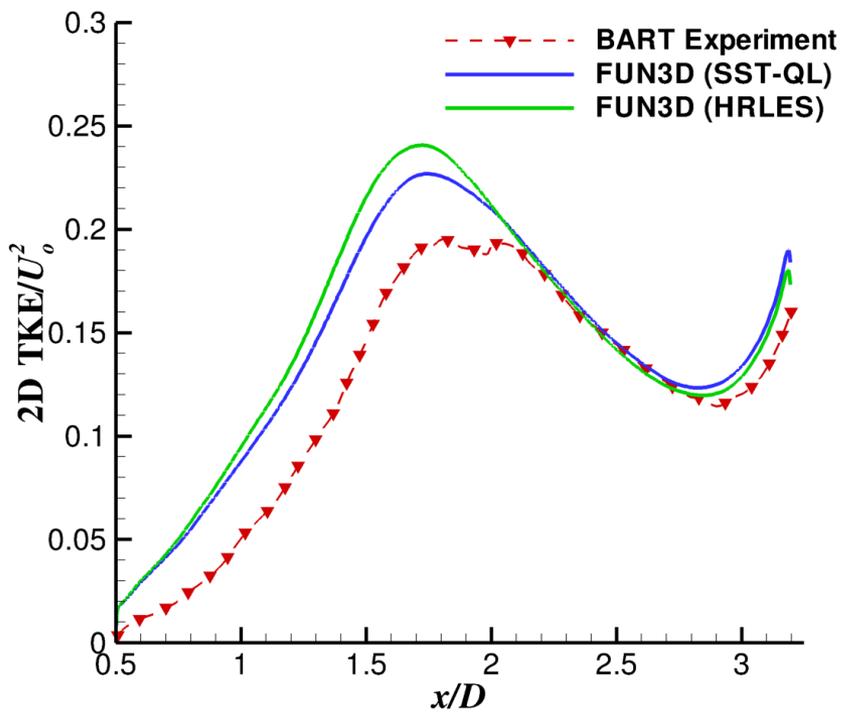
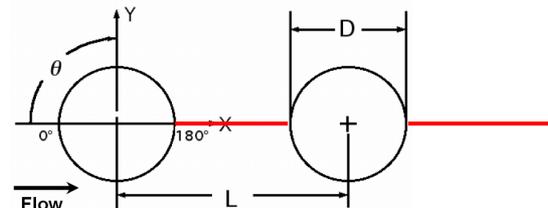


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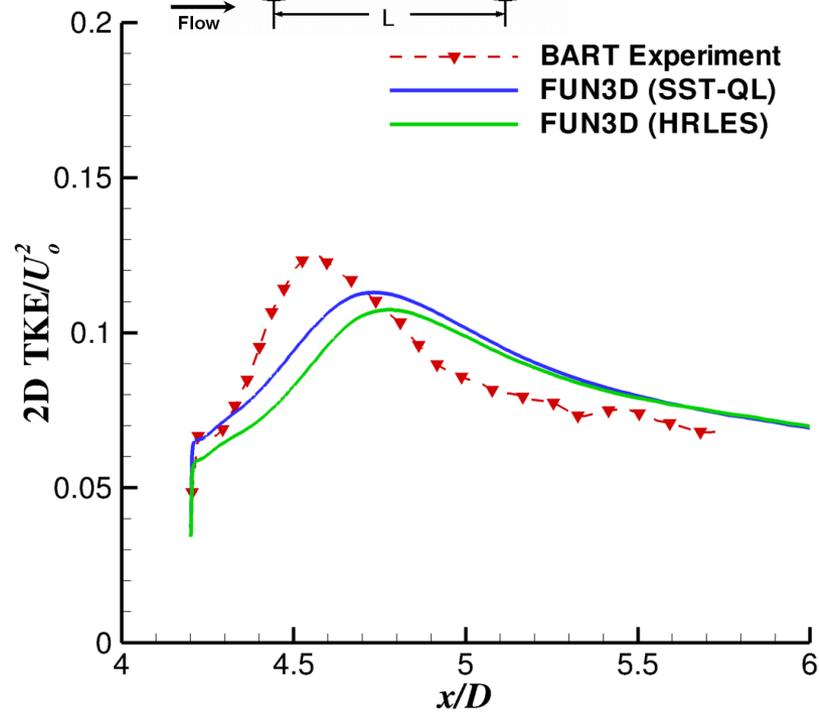
# 2D TKE comparisons along $y/D=0$



•  $1/2 (u' u' + v' v' + \cancel{w' w'}) / U_0^2$



Gap region between cylinders

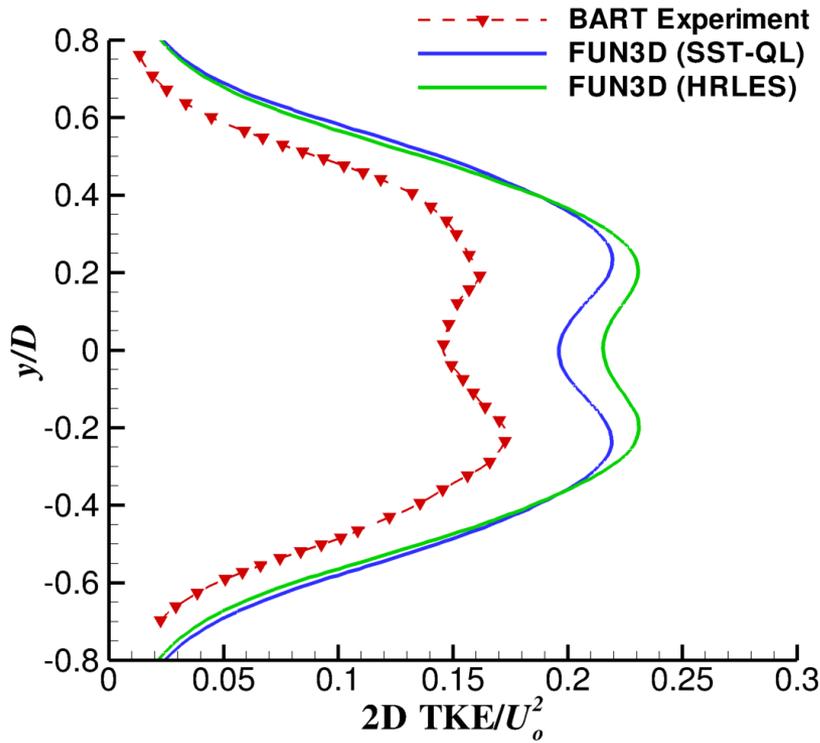
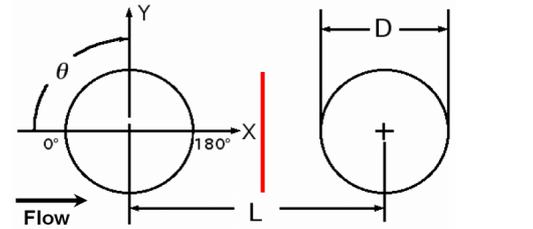


Aft region of rear cylinder

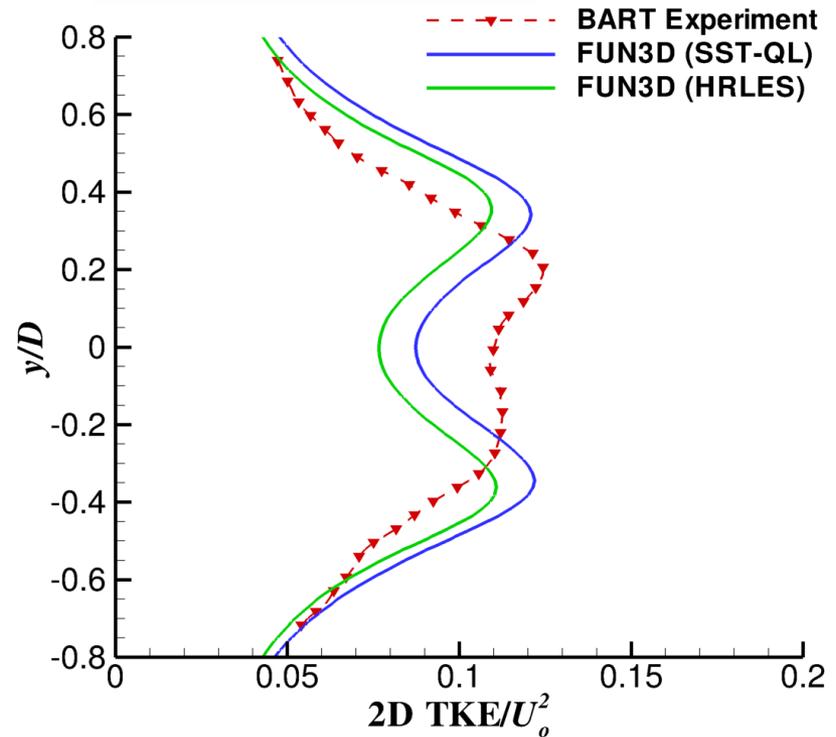
# 2D TKE comparisons at fixed x locations



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



**x = 1.5 D, Gap region**



**x = 4.45 D, Aft region**