

Comparison of Surface and Near Wake Flow Quantities Using URANS and LES Simulations

Stephen A. Huyer

Raymond Roberts

Undersea Warfare Weapons, Vehicles, and Defensive Systems Department



Naval Undersea Warfare Center Division Newport, Rhode Island

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PREFACE

The ability to dissipate heat produced by various components is vital toward the successful operation of various naval platforms. Computational fluid dynamics offers a method to predict these vital flow quantities. This research characterizes both unsteady Reynolds-Averaged Navier-Stokes (URANS) and large eddy simulations (LES) to examine the advantages and limitations associated with each of these methodologies by comparing the predicted results with experimental data for flow past a cylinder and a mast. These simple geometries elicit complex flow fields posing a challenge for each methodology. URANS is best for attached turbulent flow with the ability to predict surface pressures correctly, even with relatively low grid resolutions. This makes it an effective tool if a quick turnaround is desired. Surface heat transfer requires properly resolving the temperature gradient and thermal boundary layer. As such higher resolution is required, LES is most effective in this regard, but requires significantly more grid resolution to resolve the small eddies. As such, its usefulness is still limited to the lower velocities. Local flow velocity profiles further highlighted the effectiveness of LES in predicting the correct flow velocities. Both methods have their uses for engineering level problems.

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Hector M. Lopez
Head, Undersea Warfare Weapons, Vehicles, and Defensive Systems
Department



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TABLE OF CONTENTS

Section	Page
LIST OF ILLUSTRATIONS	ii
LIST OF TABLES	vi
LIST OF ABBREVIATIONS AND ACRONYMS	vi
LIST OF NOMENCLATURE AND SYMBOLS	vii
1 INTRODUCTION	1
2 METHODOLOGY	3
2.1 Test Geometries	3
2.2 Experimental Methods	3
2.3 Error Analysis Summary	6
2.4 URANS/LES Formulation	7
2.4.1 Transition Shear Stress Transport (SST) Turbulence Model	7
2.4.2 Large Eddy Simulation	10
2.5 Problem Set-Up	11
2.6 Coordinate System	15
3 RESULTS	17
3.1 Grid Convergence Studies	17
3.2 Cylinder Surface Pressure Distributions	22
3.3 Cylinder Nusselt Number Results	26
3.4 Cylinder Velocity Predictions	29
3.5 Mast Surface Pressure Distributions	35
3.6 Mast Nusselt Number Results	39
3.7 Mast Velocity Predictions	44
4 DISCUSSION	55
5 CONCLUSIONS	61
REFERENCES	63
APPENDIX A—CYLINDER VELOCITY PROFILES	A-1
APPENDIX B—MAST VELOCITY PROFILES	B-1

LIST OF ILLUSTRATIONS

Figure	Page
1	Cylinder and Mast Models in the NUWC Wind Tunnel 4
2	Cylinder CFD Symmetrical Boundary Condition Geometry Set-Up. 12
3	Close-Up View of Cylinder CFD Symmetrical Boundary Condition Geometry Set-Up..12
4	Cylinder CFD Periodic Boundary Condition Geometry Set-Up 13
5	Close-Up View of Mast CFD Symmetrical Boundary Condition Geometry Set-Up 13
6	Close-Up View of Mast CFD Periodic Boundary Condition Geometry Set-Up. 14
7	Cylinder CFD Symmetrical Boundary Condition Global Mesh.....14
8	Cylinder CFD Symmetrical (a) and Periodic (b) Boundary Condition Local Mesh 15
9	Mast CFD Symmetrical (a) and Periodic (b) Boundary Condition Local Mesh 15
10	Comparison of Cylinder Surface Pressure Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Symmetry Boundary Conditions at the Center-Span Average for $U_{\infty} = 32$ m/s, $Re = 710,000$ 18
11	Comparison of Cylinder Nusselt Number Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Symmetry Boundary Conditions at the Center-Span Average for $U_{\infty} = 32$ m/s, $Re = 710,000$ 19
12	Comparison of Mast Surface Pressure Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Periodic Boundary Conditions at the Center-Span Average for $U_{\infty} = 40$ m/s, $Re = 870,000$ 20
13	Comparison of Mast Nusselt Number Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Periodic Boundary Conditions at the Center-Span Average for $U_{\infty} = 40$ m/s, $Re = 870,000$ 21
14	Cylinder Surface Pressure Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 11$ m/s, $Re = 244,000$ 23
15	Cylinder Surface Pressure Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 18.7$ m/s, $Re = 415,000$ 24
16	Cylinder Surface Pressure Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 21.2$ m/s, $Re = 470,000$ 24
17	Cylinder Surface Pressure Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 32$ m/s, $Re = 710,000$ 25
18	Cylinder Surface Pressure Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 42.6$ m/s, $Re = 945,000$ 25
19	Cylinder Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 11$ m/s, $Re = 244,000$ 26
20	Cylinder Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 18.7$ m/s, $Re = 415,000$ 26
21	Cylinder Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 21.2$ m/s, $Re = 470,000$ 27
22	Cylinder Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 32$ m/s, $Re = 710,000$ 28

LIST OF ILLUSTRATIONS (Cont'd)

Figure	Page
23	Cylinder Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 42.6$ m/s, $Re = 945,000$ 28
24	Color Velocity Contours of the Mean Axial Velocity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_{\infty} = 32$ m/s, $Re = 710,000$ 30
25	Color Velocity Contours of Instantaneous Z-Vorticity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_{\infty} = 32$ m/s, $Re = 710,000$ 31
26	Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 120^{\circ}$, 150° and 180° for $U_{\infty} = 11$ m/s, $Re = 244,000$. URANS and LES Simulation with SBC. 32
27	Cylinder Axial and Vertical RMS Velocity Profiles for $\theta = 120^{\circ}$, 150° and 180° for $U_{\infty} = 11$ m/s, $Re = 244,000$. URANS and LES Simulation with SBC. 33
28	Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 120^{\circ}$, 150° and 180° for $U_{\infty} = 32$ m/s, $Re = 710,000$. URANS and LES Simulation with SBC. 34
29	Cylinder Axial and Vertical RMS Velocity Profiles for $\theta = 120^{\circ}$, 150° and 180° for $U_{\infty} = 32$ m/s, $Re = 710,000$. URANS and LES Simulation with SBC. 35
30	Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 10$ m/s, $Re = 230,000$ 37
31	Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 20$ m/s, $Re = 461,000$ 37
32	Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 30$ m/s, $Re = 691,000$ 38
33	Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 40$ m/s, $Re = 921,000$ 38
34	Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 50$ m/s, $Re = 1,152,000$ 39
35	Mast Surface Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 10$ m/s, $Re = 230,000$ 40
36	Mast Surface Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 20$ m/s, $Re = 461,000$ 41
37	Mast Surface Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 30$ m/s, $Re = 691,000$ 42
38	Mast Surface Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 40$ m/s, $Re = 921,000$ 43
39	Mast Surface Nusselt Number Distributions for Periodic and Symmetrical Unsteady RANS and LES Simulations for $U_{\infty} = 50$ m/s, $Re = 1,152,000$ 43
40	Color Velocity Contours of the Mean Mast Axial Velocity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_{\infty} = 40$ m/s, $Re = 921,000$ 44
41	Color Velocity Contours of the Mast Z-Vorticity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_{\infty} = 40$ m/s, $Re = 921,000$ 46
42	Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 1-4 for $U_{\infty} = 30$ m/s and $Re = 691,000$. URANS SBC and LES PBC. 48
43	Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 5-8 for $U_{\infty} = 20$ m/s and $Re = 461,000$. URANS SBC and LES PBC. 49

LIST OF ILLUSTRATIONS (Cont'd)

Figure	Page
44 Mast Streamwise and Vertical RMS Velocity Profiles for Rakes 5-8 for $U_\infty = 20$ m/s and $Re = 461,000$. LES PBC.	49
45 Mast Streamwise and Vertical Mean and RMS Velocity Profiles for Rakes 5-8 for $U_\infty = 30$ m/s and $Re = 681,000$. LES PBC.....	50
46 Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 5-8 for $U_\infty = 40$ m/s and $Re = 921,000$. URANS SBC and LES PBC.	51
47 Mast Streamwise and Vertical RMS Velocity Profiles for Rakes 5-8 for $U_\infty = 40$ m/s and $Re = 921,000$. LES PBC.	52
48 Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 9-12 for $U_\infty = 40$ m/s and $Re = 921,000$. URANS SBC and LES PBC.	53
49 Mast Streamwise and Vertical RMS Velocity Profiles for Rakes 9-12 for $U_\infty = 40$ m/s and $Re = 921,000$. LES PBC.	53
50 Cylinder Axial Velocity and Y-Vorticity Color Contour Plots in the X-Z Plane With Surface Pressure Coefficients at the Cylinder Centerline for URANS and LES Using SBC. $U_\infty = 32$ m/s, $Re = 710,000$	56
A-1 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 11$ m/s, $Re = 244,000$. URANS Simulation with Symmetrical Boundary Conditions.....	A-1
A-2 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 11$ m/s, $Re = 244,000$. LES Simulation with Symmetrical Boundary Conditions.	A-2
A-3 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 21.2$ m/s, $Re = 470,000$. URANS Simulation with Symmetrical Boundary Conditions.....	A-3
A-4 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 21.2$ m/s, $Re = 470,000$. LES Simulation with Symmetrical Boundary Conditions.	A-4
A-5 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 32$ m/s, $Re = 710,000$. URANS Simulation with Symmetrical Boundary Conditions.....	A-5
A-6 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 32$ m/s, $Re = 710,000$. LES Simulation with Symmetrical Boundary Conditions.	A-6
A-7 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 42.6$ m/s, $Re = 945,000$. URANS Simulation with Symmetrical Boundary Conditions.....	A-7
A-8 Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 42.6$ m/s, $Re = 945,000$. LES Simulation with Symmetrical Boundary Conditions.	A-8
B-1 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 20$ m/s, $Re = 461,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-1

LIST OF ILLUSTRATIONS (Cont'd)

Figure	Page
B-2 Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 20$ m/s, $Re = 461,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-2
B-3 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 20$ m/s, $Re = 461,000$. LES Simulation with Periodic Boundary Conditions.	B-3
B-4 Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 20$ m/s, $Re = 461,000$. LES Simulation with Periodic Boundary Conditions.	B-4
B-5 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 30$ m/s, $Re = 691,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-5
B-6 Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 30$ m/s, $Re = 691,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-6
B-7 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 30$ m/s, $Re = 691,000$. LES Simulation with Periodic Boundary Conditions.	B-7
B-8 Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 30$ m/s, $Re = 691,000$. LES Simulation with Periodic Boundary Conditions.	B-8
B-9 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 40$ m/s, $Re = 921,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-9
B-10 Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 40$ m/s, $Re = 921,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-10
B-11 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 40$ m/s, $Re = 921,000$. LES Simulation with Symmetrical Boundary Conditions.	B-11
B-12 Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 40$ m/s, $Re = 921,000$. LES Simulation with Symmetrical Boundary Conditions.	B-12
B-13 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 50$ m/s, $Re = 1,151,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-13
B-14 Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 50$ m/s, $Re = 1,151,000$. URANS Simulation with Symmetrical Boundary Conditions.	B-14
B-15 Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 50$ m/s, $Re = 1,151,000$. LES simulation with Symmetrical Boundary Conditions.	B-15

LIST OF ILLUSTRATIONS (Cont'd)

Figure		Page
B-16	Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 50$ m/s, $Re = 1,151,000$. LES Simulation with Symmetrical Boundary Conditions.	B-16

LIST OF TABLES

Table		Page
1	Nusselt Number Values and Uncertainty.....	7

LIST OF ABBREVIATIONS AND ACRONYMS

2-D	Two-dimensional
3-D	Three-dimensional
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ANSYS	Analysis system
ASME	American Society of Mechanical Engineers
CFD	Computational Fluid Dynamics
cm	Centimeter
Cont'd	Continued
DoD	Department of Defense
DOI	Digital object identifier
Ft/sec	Feet per second
HR	High resolution
Hz	Hertz
ILIR	In-House Laboratory Independent Research
IO	Input/output
ISO	International Organization for Standardization
LES	Large Eddy Simulation
LR	Low resolution
m	Meter
m/s	Meters per second
MR	Medium resolution
NASA	National Aeronautics and Space Administration
NAVSEA	Naval Sea Systems Command
NI	National Instruments
NPT	Newport

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

NUWC	Naval Undersea Warfare Center
NUWCDIVNPT	Naval Undersea Warfare Center Division, Newport
PBC	Periodic Boundary Conditions
PVC	Polyvinylchloride
RANS	Reynolds-Averaged Navier-Stokes
RMS	Root-mean-square
SBC	Symmetry Boundary Conditions
SIMPLE	Semi-implicit method for pressure linked equations
SST	Shear stress transport
URANS	Unsteady Reynolds-Averaged Navier-Stokes
USB	Universal serial bus
VHR	Very high resolution
VLR	Very low resolution
W/m ²	Watts per square meter
WALE	Wall-adapting local eddy-viscosity

LIST OF NOMENCLATURE AND SYMBOLS

A	Area
c_{mast}	Mast Chord Length
C_f	Skin Friction Coefficient = $\tau / (0.5\rho U_\infty^2)$
C_p	Pressure Coefficient = $(p - p_\infty) / (0.5\rho U_\infty^2)$
D_{cyl}	Cylinder Diameter
h	Local heat transfer coefficient
k	Coefficient of thermal conductivity
Nu	Nusselt Number = $(hD_{cyl})/k$ or $(hc_{mast})/k$
P	Static Pressure
p_∞	Atmospheric Pressure
Re	Reynolds Number = $U_\infty / (\nu D_{cyl})$ or $U_\infty / (\nu c_{mast})$,
q	Heat
t	Time (second)
T	Temperature
U_∞	Freestream Velocity
u	Local velocity, positive in the streamwise direction
u_{mean}	Mean velocity in the streamwise direction
u_{rms}	RMS velocity in the streamwise direction
v	Local velocity, positive in the vertical direction
v_{mean}	Mean velocity in the vertical direction
v_{rms}	RMS velocity in the vertical direction
w	Local velocity, positive in orthogonal direction
x	Axial Coordinate in Direction of the Flow
y	Vertical Coordinate

LIST OF NOMENCLATURE AND SYMBOLS (Cont'd)

z	Orthogonal Coordinate to x and y
ρ	Fluid Density (water)
τ	Skin Friction
μ	Viscosity coefficient
ν	Coefficient of dynamic viscosity

COMPARISON OF SURFACE AND NEAR WAKE FLOW QUANTITIES USING URANS AND LES SIMULATIONS

1. INTRODUCTION

The ability to dissipate heat produced by various components is vital toward the successful operation of various Naval platforms.^{1,2} Surface ships, submarines and other undersea vehicles typically operate a vast array of electronic components where the heat generated needs to be dissipated. One methodology is to take advantage of various structures exposed to the external flow and utilize the hydrodynamic and thermodynamic properties to dissipate the heat. Recent experiments conducted at the Naval Undersea Warfare Center (NUWC) specifically examined the heat transfer, surface pressure and near wake velocities of cylindrical and mast shaped structures. The wealth of data acquired provided a basis for comparison and evaluation of current computational fluid dynamic capabilities. It is not practical to measure the heat transfer characteristics of various bluff bodies experimentally so that computational predictions offer an alternative. In order to gain confidence in these predictive capabilities, an understanding of the application and limitations is needed in addition to an understanding of the underlying physics.

There is currently limited data measuring the heat transfer characteristics for external flow past cylindrical shaped objects as many relevant applications are for internal flows and combustion engines. Early work by Geidt³ provided initial measurements of the heat transfer past circular cylinders for a wide range of Reynolds numbers. Richardson⁴ also provides data measuring the heat transfer from a cylinder to the airstream. Several articles have been published examining heat transfer for flow past banks of cylinders as this is a standard application process. Buryk⁵ measured the heat transfer and surface pressure for these applications. Papell⁶ measured the thermal boundary layer and subsequent effects on heat transfer for cylinders in crossflow. Churchill and Bernstein⁷ provide an excellent summary of the experimental data past cylinders over a wide range of conditions providing empirical correlation coefficients regarding heat transfer quantities.

The evolution of computational fluid dynamics (CFD), coupled with high performance computing, has made it possible to predict flow quantities and heat transfer for complex geometries reasonably.⁸⁻¹⁷ Both unsteady Reynolds Averaged Navier-Stokes (URANS) and Large Eddy Simulations (LES) have been used to predict the complex flow-fields and heat transfer characteristics for wall impinging jets, packed cylinders, and flow past square cylinders in cross-flow. Szczepanik et al.⁸ uses a $k-\omega$ turbulence model to predict the surface Nusselt number for cylinder laminar flow cases. The model over-predicted the heat transfer in the aft region of the cylinder. Catalano et. al.⁹ illustrates the effectiveness of LES over URANS in predicting the flow and surface pressure for flow past a cylinder. They did not examine surface heat transfer characteristics. The remaining references utilize Reynolds Averaged Navier-Stokes (RANS) and LES turbulent flow models to predict average surface Nusselt numbers. Chen and Xia¹⁷ were able to obtain excellent agreement of surface Nusselt Number for flow past a square cylinder using LES.

Due to the limited availability of information in the current literature regarding the prediction of surface heat transfer characteristics, experiments and computations were performed to both measure and predict surface heat transfer, surface pressure, and near wake flow quantities for external flow past a cylinder and mast geometries. Both URANS and LES predictions were conducted in order to provide comparisons over a range of Reynolds numbers from 2.3×10^5 to 10^6 , fully encompassing laminar to turbulent boundary layer transition. In the case of a cylinder in cross-flow, the separation point is moved aft for turbulent Reynolds numbers. In contrast, the mast geometry is more complex as separation exists at lower Reynolds numbers with attached flow as the boundary layer becomes turbulent. These cases represent a wide range of flow characteristics providing a challenge in terms of accurately predicting the surface heat transfer. In addition, the comparison provides information regarding the relevant physics that need to be captured in order for more accurate predictions.

2. METHODOLOGY

2.1 TEST GEOMETRIES

Two challenging geometries were chosen for these experiments – a cylinder in cross-flow and a generic submarine mast. The cylinder is one of the most studied geometries, due to its universal application in engineering, and is typical of complex bluff body flow phenomena. It was selected to provide a comparison with previous heat transfer studies. The low aspect ratio (3.6) for cylinder diameter of 12.75 inches (32.385 centimeters) and a 46 inches (1.17 meters) span ensures three-dimensional (3-D) flow effects. The generic mast also is a challenging geometry characterized by separated flow at low Reynolds numbers and attached flow at higher Reynolds numbers. The cross-section consists of an 8-inch (20.32 centimeter) leading edge followed by a straight section that slopes 21° . The trailing edge has a radius of 2 inches (5.08 centimeters). The chord length is 13.25 inches (0.3365 meters). Figure 1 illustrates the cylinder and mast mounted in the wind tunnel.

2.2 EXPERIMENTAL METHODS

All experiments were conducted in the NUWC acoustic wind tunnel. Pictures of the cylinder and mast in the wind tunnel test section are shown in figure 1. Full details regarding the experiments may be found in Roberts et. al.^{1,2} A summary of the experimental methods will be provided here. The test section of this facility is located within a large anechoic chamber that allows free field acoustic measurements. The chamber has been extensively calibrated according to the ANSI and ISO standard inverse square tests and shown to meet all requirements for an anechoic chamber from 100 Hertz (Hz) to 40,000 Hz. The facility is a large, quiet, low Mach number (maximum 0.18) facility, capable of testing at speeds from 0 feet per second (ft/sec) to 200 ft/sec in the tunnel's 4-foot diameter standard test section. Additional information regarding the facility may be found in Gedney et al.¹⁸

The flow field measurements consisted of measuring the free stream velocity outside the boundary layer using Dantec Dynamics X-wires (55R54 probe) to measure the x- and y-components velocities. These measurements were taken around the circumference of the cylinder in 10° increments from the forward stagnation point to the aft location (0° - 180°). The corresponding radial profiles extended 165 millimeter (mm) normal to the surface. Measurements were also taken around the periphery of the mast at specific "Rake" locations. Each rake consisted of 25 points at a distance of 0.5 to 160 mm normal to the mast surface. Rakes 1-4 correspond to mast cylindrical leading edge locations of $\theta = 0^\circ, 30^\circ, 60^\circ$ and 90° . Rake 5 is located at the transition between the cylinder and flat section ($\theta = 110^\circ$). Rakes 6-10 were evenly spaced between $x/c_{\text{mast}} = 0.51 - 0.95$ (corresponding to the transition from the flat section to trailing edge cylindrical section. Rakes 11 and 12 are located on the cylindrical trailing edge at $\theta = 145^\circ$ and 180° respectively.

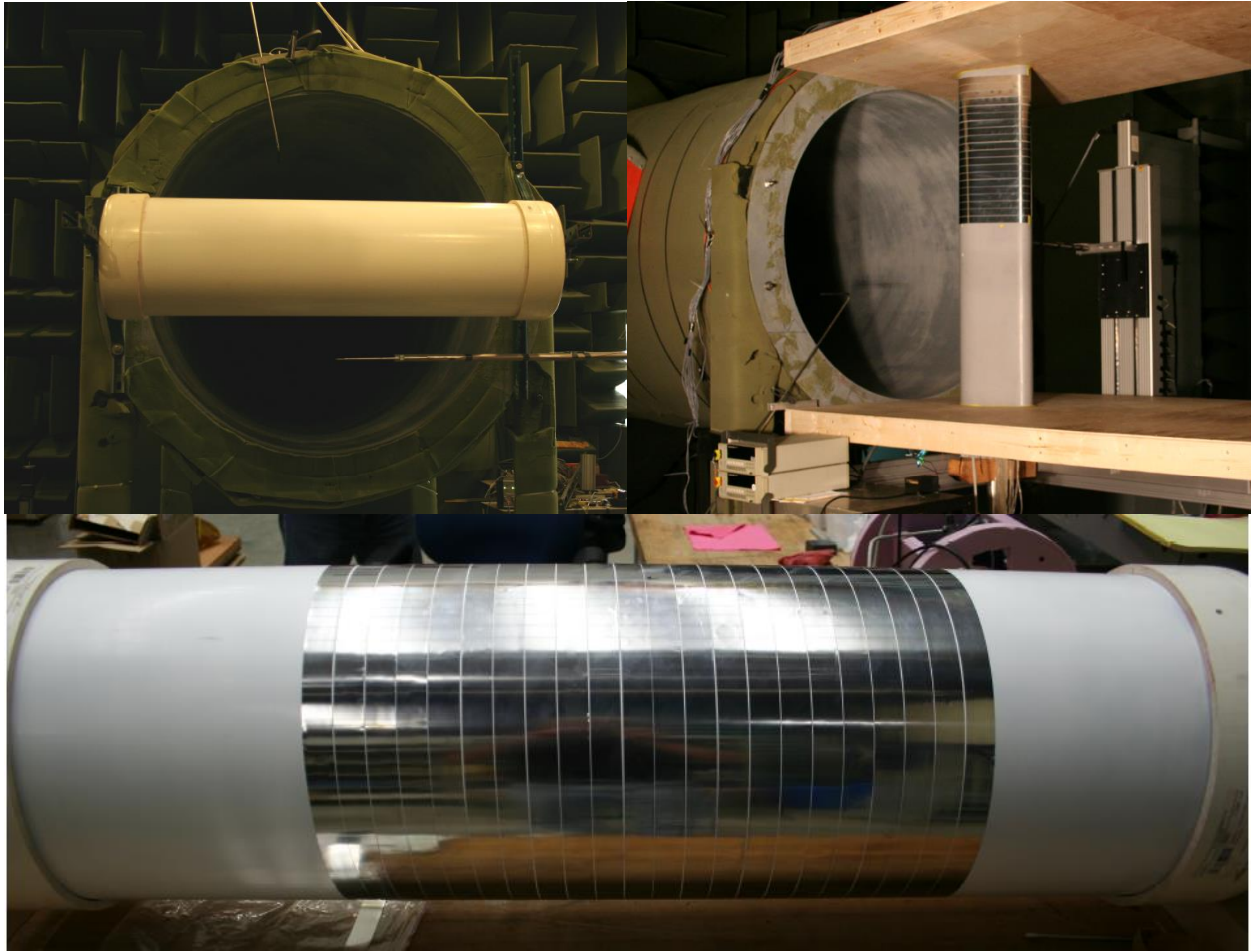


Figure 1. Cylinder and Mast Models in the NUWC Wind Tunnel

The surface static pressure was measured along the periphery of cylinder by drilling a single 1.4 mm (0.055 inch) pressure tap into the cylinder. The cylinder was rotated about its axis to obtain pressure measurements from the stagnation point to the trailing edge. The static pressure was measured using a MKS Instruments, Inc., 100 Torr, Model Number 220DD-00100A23 Baratron[®] connected to a National Instruments (NI) Universal Serial Bus (USB) 6221 multifunction input/output (IO) box. The baratron is a differential pressure transducer. The reference port pressure was supplied by a 3.2 mm (1/8 inch) diameter vinyl tube with the open end placed just upstream and to the left (looking upstream) of the exit plane of the nozzle. The surface pressure was measured every 10° from $\theta = 0^\circ - 90^\circ$ and $\theta = 120^\circ - 180^\circ$ and every 1° between $\theta = 90^\circ - 120^\circ$. The surface static pressure was measured along the periphery of mast by drilling a series of 1.57 mm (0.062 inch) pressure taps into the mast at the mid-span location. The 25 pressure ports were evenly spaced along the arc-length of the mast in 17.8 mm increments with added clustering at the trailing edge.

A separate cylinder of the same size was used to measure the heat transfer coefficient for a constant heat flux surface. A 25.4 mm wide 0.051 mm thick NiChrome V 80/20 ribbon (A.D. Mackay, Inc.) was wrapped in a helix around the outside of the cylinder as shown in figure 1.

The ribbon was wrapped around the cylinder 22 times with a total ribbon linear length of 22.37 meters. The end-to-end resistance of the ribbon was measured using a four-wire measurement technique and was found to have a total resistance of 20.55 ohms. Based on the total ribbon length, this gave a resistance per unit length of 0.92 ohm/meter (vs. manufacture specified resistance of 0.837 ohms/meter). To measure the surface temperature of the ribbon, 74 Omega Engineering E type thermocouples were placed under the ribbon at the center of the cylinder. The thermocouples were placed in drilled holes in the polyvinylchloride (PVC) cylinder and super glued in place. The holes were placed in a helix and were drilled every 10° for one complete wrap. There were two sets of holes placed 12.7 mm apart. The second set of holes were there for redundancy, in case a thermocouple was broken during assembly. The ribbon was wrapped on the cylinder so that the thermocouple holes were 6.35 mm from the edge of the ribbon. Thermal grease was used to improve contact with the ribbon. Heat transfer coefficients were effectively acquired every 2° around the cylinder, so at each wind tunnel speed, the cylinder was rotated a total of 180° in 2° increments. At each of these rotations, the cylinder was allowed to reach what was believed to be a steady state that could take as long as 15 minutes to obtain. A similar procedure was used with the mast, differing in terms of the total ribbon linear length of 16.37 m, resulting in an end-to-end resistance of 15.47 ohms.

Since the ribbon had a current flowing through it, each set of thermocouples had a different common mode voltage. None of the data acquisition systems available for this project that were capable of reading thermocouples had provisions for a varying common mode voltage between thermocouples and therefore could not be used. The thermocouples were processed with each leg connected to a copper wire using an isolated terminal strip. The terminal strips were placed in an ice bath with crushed ice and distilled water. The temperature of the ice bath was monitored using a type T thermocouple and an Omega thermocouple meter that provided internal cold junction compensation. During the entire test performed, the ice bath remained at 0 °C. The copper wires from the terminal strip were then connected to a rotary switch that was housed in an electrically isolated box. The switch provided output from two thermocouples at a time and these outputs were connected to two Fluke 8840A voltmeters. The voltage from the meters was recorded in a notebook. Before the testing began, a check was made to ensure that there was not any cross talk between thermocouples and that the common mode voltages did not influence the thermocouple readings.

The heat transfer coefficient from the geometry (cylinder or mast) was obtained by heating the external surface of the test geometry and measuring the temperature difference between the surface and the ambient air. The amount of heat produced per unit length of ribbon is a constant and the local heat transfer coefficient is determined from

$$\frac{q}{A} = h\Delta T, \quad (1)$$

where q/A is the local heat flux, h is the local heat transfer coefficient and ΔT is the temperature difference between the ribbon and the ambient airflow. The local heat flux is proportional to the resistance heating $\frac{I^2 R}{wL}$, where I is the current, R is the local resistance of the ribbon, w is the width of the ribbon, and L is the length of the ribbon over which R is measured. The wind tunnel velocity varied between 11 meters per second (m/s) and 42.6 m/s for cylinder measurements.

Power was supplied to the ribbon by a Sorensen DCR 600-8T direct current (DC) power supply. The current supplied was between 5 amperes at 11 m/s to 6.2 amperes at 42.6 m/s. The resulting heat flux varied from 926–1423 Watts per square meter (W/m^2) yielding maximum differential temperatures between 40 °C and 54 °C relative to ambient. For the mast measurements, the wind tunnel velocity varied between 10 m/s and 50 m/s. The current supplied was between 7.75 amps at 10 m/s, 8 amps at 20 m/s and 8.33 amps at the higher velocities. The resulting heat flux varied from 2207–2532 W/m^2 yielding maximum differential temperatures between 16 °C and 71 °C relative to ambient.

2.3 ERROR ANALYSIS SUMMARY

An error analysis was conducted by Roberts¹⁹ and this reference is recommended for the complete details regarding the experimental error. A summary of the analysis applied to the current tests is presented. There are two distinct areas of uncertainty. First is the uncertainty due to temperature and current measurements and associated spatial resolution limits. Second is the uncertainty due to losses derived from other physical mechanisms that could not be measured. The heat transfer due to external convection was by far the greatest (with on average on the order of 93% occurring at 10 m/s and 97% occurring at 40 m/s) and represents the quantity that was actually measured. Heat transfer also occurs due to convection to the cylinder interior, convection along the ribbon and the radiation exchange between the ribbon and the ambient. The amount of heat transfer to the inside of the cylinder peaked at 3.2% for the 10 m/s velocity with typical values on the order of 2% and decreasing for the higher velocities. The heat transfer along the ribbon was on the order of 0.1%. Accordingly, the heat transfer contributions due to convection inside the cylinder and along the ribbon can be neglected. Radiation to the environment was greatest for the 10 m/s case peaking at 7% but diminished rapidly as velocity was increased so peak radiation losses at 50 m/s was 2.5%.

Sources of error were quantified with uncertainties of various natural constants assumed at 10% due to variability with temperature and humidity. The largest uncertainties were the ribbon thickness (10%) and ribbon thermal conductivity (20%). Ribbon and ambient temperature uncertainty was 2.5%. These factors affected the uncertainty of the actual measurements. Table 1 summarizes the uncertainties in the Nusselt Number over the range of flow velocities and for minimum and maximum Nusselt numbers that occurred along the surface of the ribbon at each free stream speed. These uncertainties include the losses due to the various physical processes described in the preceding paragraph. As can be seen, the highest uncertainties are associated with the lowest flow velocities. These uncertainties can be applied to both cylinder and mast test geometries.

Table 1. Nusselt Number Values and Uncertainty

Flow Speed (m/s)	Minimum Nu		Maximum Nu	
	Value	% Uncertainty	Value	% Uncertainty
10	206	24.9	463	20.1
20	301	21.9	1404	20.5
30	388	17.5	1534	16.6
40	523	16.2	1691	16.3
50	603	15.3	1922	15.8

2.4 URANS/LES FORMULATION

The commercial CFD code Fluent[®] was used for all computations with full summary provided in the Analysis System (ANSYS)/Fluent[®] User's Guide.²⁰ A 3-D implicit flow solver was used to compute the unsteady flow past the cylinder. The solution methodology employs a finite volume formulation with a mixture of tetrahedral and brick elements as defined by the grid generator, Gambit[®]. Due to the high Reynolds numbers examined, it was necessary to increase grid resolution near the wall to implement wall models properly. This boundary layer resolution was maintained with the first layer of grid points. The first layer was limited to 0.001 mm geometrically increasing from the surface by a factor of 1.2. The value of y^+ varied from an average value of 0.07 (maximum value 0.175) at a flow velocity of 11 m/s to 0.31 (maximum value 0.8) at 42.6 m/s. The number of boundary layers varied between 20 and 25, depending on the grid resolution. It was necessary to maintain this resolution in order to properly model the boundary layer flow as well as employ the transition turbulence model (described below). At the edge of the boundary layer, the elements had approximately equal dimensions. For proper application of large eddy simulations, it is necessary to form brick elements (vs. tetrahedra). 3-D geometries were studied, making construction of fully structured grids impractical everywhere. To ensure compatibility with large eddy simulations, brick elements were formed based on quadrilateral elements using a pave algorithm in conjunction with the Cooper tool. In order to minimize the artificial numerical diffusion associated with tetrahedral elements, their use was limited to grid transition regions away from the boundary layer and separated region. Computations utilized second order upwind schemes for the advection term, dissipation and turbulent kinetic energy. A standard semi-implicit method for pressure linked equations (SIMPLE) algorithm solved the pressure-velocity coupling term. Bounded, second order time stepping was used for both unsteady RANS and large eddy simulations.

2.4.1 Transition Shear Stress Transport (SST) Turbulence Model

In order to better model the boundary layer transition phenomena, a transition SST turbulence model was used. According to the ANSYS/Fluent[®] User's Guide,¹⁹ the transition SST model is based on the coupling of the SST $k-\omega$ transport equations with two other transport equations, one for the intermittency and one for the transition onset criteria, in terms of

momentum-thickness Reynolds number. The SST model developed by Menter²¹ takes advantage of the more accurate k- ω model (originally developed by Wilcox²²) in the near wall region and blends the model with the k- ϵ formulation in the outer boundary layer and farfield. Important aspects of the SST model include the use of blending functions to add the effects of the separate k- ω and k- ϵ models, the SST model incorporates a damped cross-diffusion derivative term in the ω equation and the definition of turbulent viscosity is modified to account for the turbulent shear stress. In the transition model, an ANSYS empirical correlation developed by researchers Langtry and Menter, has been developed to cover standard bypass transition as well as flows in low free-stream turbulence environments. The full transport equations can be found in the Fluent[®] User's Guide,²⁰ but will be summarized here.

The transport equation for intermittency (γ) is:

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_{\gamma 1} - E_{\gamma 1} + P_{\gamma 2} - E_{\gamma 2} + \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\gamma} \right) \frac{\partial \gamma}{\partial x_j} \right]. \quad (2)$$

The transport equation for intermittency includes transition sources ($P_{\gamma 1}, E_{\gamma 1}$), as well as destruction/relaminarization ($P_{\gamma 2}, E_{\gamma 2}$) sources. The transition sources are defined as:

$$P_{\gamma 1} = C_{a1} F_{length} \rho S [\gamma F_{onset}]^{C_{\gamma 3}}, E_{\gamma 1} = C_{e1} P_{\gamma 1} \gamma, \quad (3)$$

where S is the strain rate magnitude and F_{length} is an empirical correlation that controls the length of the transition region, the C 's are constants. The destruction/relaminarization sources are:

$$P_{\gamma 2} = C_{a2} \rho \Omega \gamma F_{turb}, E_{\gamma 2} = C_{e2} P_{\gamma 2} \gamma, \quad (4)$$

where Ω is the vorticity magnitude. Transition onset is controlled by the following functions:

$$Re_V = \frac{\rho y^2 S}{\mu}, R_T = \frac{\rho k}{\mu \omega}, \quad (5)$$

$$F_{onset1} = \frac{Re_V}{2.193 Re_{\theta c}}, F_{onset2} = \min(\max(F_{onset1}, F_{onset1}^4), 2.0), \quad (6)$$

$$F_{onset3} = \max\left(1 - \left(\frac{R_T}{2.5}\right)^3, 0\right), F_{onset} = \max(F_{onset2} - F_{onset3}, 0), \text{ and} \quad (7)$$

$$F_{turb} = e^{-\left(\frac{R_T}{4}\right)^4}. \quad (8)$$

The transition sources account for the effects of the local strain rate as well as empirical terms incorporating the transition length and transition onset. The destruction/relaminarization sources are influenced by the vorticity magnitude as well as an empirical factor based on the turbulent Reynolds number. All these terms are a linear function of the intermittency, which varies in value from 0 to 1. In addition, there is a separation induced transition correction:

$$\gamma_{sep} = \min \left(C_{s1} \max \left[\left(\frac{Re_V}{3.235 Re_{\theta c}} \right) - 1, 0 \right] F_{reattach}, 2 \right) F_{\theta t}, F_{reattach} = e^{-\left(\frac{R_T}{20}\right)^4} \quad (9)$$

and

$$\gamma_{eff} = \max(\gamma, \gamma_{sep}). \quad (10)$$

Constants for the above equations are $C_{a1}=2$, $C_{e1}=1$, $C_{a2}=0.06$, $C_{e2}=50$, $C_{s1}=2$, $c_{\gamma3}=0.5$, and $\sigma_\gamma=1.0$, and are independent of the experimental conditions. A transport equation describing the transition momentum thickness Reynolds number ($Re_{\theta t}$) is:

$$\frac{\partial(\rho Re_{\theta t})}{\partial t} + \frac{\partial(\rho U_j Re_{\theta t})}{\partial x_j} = P_{\theta t} + \frac{\partial}{\partial x_j} \left[\sigma_{\theta t} \left(\mu + \frac{\mu_t}{\sigma_\gamma} \right) \frac{\partial Re_{\theta t}}{\partial x_j} \right] \quad (11)$$

The source term is modeled based on empirical factors that are based on a critical momentum thickness Reynolds number where transition was found to occur experimentally:

$$P_{\theta t} = c_{\theta t} \frac{\rho}{t} (Re_{\theta t exp} - Re_{\theta t}) (1.0 - F_{\theta t}), t = \frac{500\mu}{\rho U^2}, \quad (12)$$

$$F_{\theta t} = \min \left(\max \left(F_{wake} e^{-\left(\frac{y}{\delta}\right)^4}, 1.0 - \left(\frac{\gamma - 1/50}{1.0 - 1/50} \right) \right), 1.0 \right), \text{ and} \quad (13)$$

$$\theta_{BL} = \frac{Re_{\theta t} \mu}{\rho U}, \delta_{BL} = \frac{15}{2} \theta_{BL}, \delta = \frac{50 \Omega y}{U} \delta_{BL}, Re_\omega = \frac{\rho \omega y^2}{\mu}, F_{wake} = e^{-\left(\frac{Re_\omega}{1E+5}\right)^2}. \quad (14)$$

The source terms are affected primarily by the vorticity magnitude, as well as the local distance from the wall. The model constants are $c_{\theta t}=0.03$, and $\sigma_{\theta t}=2.0$. The three empirical correlations, $Re_{\theta t}$, F_{length} , and $Re_{\theta c}$ are proprietary and were not provided in the ANSYS/Fluent® User's Guide. The intermittency and transition thickness Reynolds number are coupled with the k- ω SST transport equations by modification of the k-equation:

$$\begin{aligned} \frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} &= \frac{\partial}{\partial x_j} \left[\Gamma_k \frac{\partial k}{\partial x_j} \right] + G_k^* - Y_k^* + S_k \\ G_k^* &= \gamma_{eff} G_k \\ Y_k^* &= \min(\max(\gamma_{eff}, 0.1), 1.0) Y_k \end{aligned} \quad (15)$$

where G_k and Y_k are the original production and destruction terms for the SST turbulence model.

The equation for ω is not modified and remains the same:

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right] + G_\omega - Y_\omega + D_\omega + S_\omega. \quad (16)$$

In the $k-\omega$ equations, G represents the production terms, Y the dissipation terms, S user defined source terms and D the cross-diffusion term. Γ represents the effective diffusion. Additional methodology and rationale can be found in Menter et al.²³ As can be seen in the equations, the intermittency effectively attenuates the turbulent kinetic energy, k , as it varies from 0.0 to 1.0 in the production term with a minimum of 0.1 in the destruction term.

2.4.2 Large Eddy Simulation

The ability of a LES methodology was investigated to determine the potential to predict the surface heat transfer characteristics for cylinder and mast applications more accurately. The specific mathematical formulation will not be repeated as the theory has been extensively published (e.g., references 11-17 and 19). The governing concept is the observation that turbulent flows are comprised of a variety of eddies with differing length and time scales. The largest eddies are governed primarily by the mean flow velocities and the smaller scales are mainly responsible for the dissipation of turbulent energy. Since it is impractical to resolve all the length and time scales for realistic flow problems, the idea of LES is to directly resolve the largest eddies and model the smallest ones. LES can be considered a way to bridge the gap between direct numerical simulation and unsteady RANS.

In order for LES to be implemented adequately, the smallest eddies must be isotropic and minimally problem dependent in order that the largest eddies transport the majority of mass, momentum and energy. For wall-bounded flows, this can become increasingly problematic due to the thin boundary layer associated with high Reynolds number flows. Consequently, wall models must still be implemented in order to examine complex flows – including flow past a cylinder and mast. Finally, the flow must be averaged over a sufficient time so that the statistics are replicated.

In LES problems, the filtered equations are solved in the normal fashion and subgrid scale stresses resulting from the filtering operation require modeling. Fluent® User's Guide¹⁹ employs the Boussinesq hypothesis computing the subgrid scale stresses from

$$\tau_{ij} = -\frac{1}{3}\tau_{kk}\delta_{ij} = -2\mu_t\overline{S_{ij}}, \quad (17)$$

where μ_t is the subgrid-scale turbulent viscosity. $\overline{S_{ij}}$ is the rate-of-strain tensor defined as:

$$\overline{S_{ij}} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right). \quad (18)$$

Various models can be used to determine μ_t . In order to model the heat transfer from solid surfaces, the Wall-Adapting Local Eddy-Viscosity (WALE) model was employed in the current problem. In the WALE model, developed by Nicoud and Ducros,²⁴ the eddy viscosity is modeled by:

$$\mu_t = \rho L_s^2 \frac{(s_{ij}^d s_{ij}^d)^{3/2}}{(\bar{s}_{ij} \bar{s}_{ij})^{5/2} + (s_{ij}^d s_{ij}^d)^{5/4}}, \quad (19)$$

$$L_s^2 = \min \left(\kappa d, C_w V_{cell}^{\frac{1}{3}} \right), \text{ and} \quad (20)$$

$$S_{ij}^d = \frac{1}{2} (\bar{g}_{ij}^2 + \bar{g}_{ji}^2) - \frac{1}{3} \delta_{ij} \bar{g}_{kk}^2, \quad \bar{g}_{ij} = \frac{\partial \bar{u}_i}{\partial x_j}. \quad (21)$$

The WALE constant, C_w , is 0.325, κ is the von Kármán constant=0.41, d is the distance to the closest wall, and V_{cell} is the cell volume, so $V_{cell}^{1/3}$ is effectively the local grid scale.

2.5 PROBLEM SET-UP

For both mast and cylinder simulations, both 3-D and effectively two-dimensional (2-D) calculations were conducted. For the full 3-D calculations, Symmetrical boundary conditions were used to effectively split the wind tunnel and model in half. The overall CFD geometrical set-up is shown in figure 2 for the cylinder and for the Symmetrical boundary condition cases. Figure 3 shows close-up views of the tunnel and cylinder surface meshes. The geometrical CFD set-up for periodic boundary conditions is shown in figure 4. For these cases, a short middle section, 0.3 m (11.8 inch) in width was bounded. The advantage of the periodic boundary condition cases is increased effects of grid resolution could be examined for large eddy simulations. In addition, information was gained regarding the full three-dimensionality of the flow. An identical methodology was implemented for the Symmetrical and periodic mast calculations. Surface geometry meshes for the Symmetrical and periodic boundary condition cases can be seen in figures 5 and 6 respectively. Finally, the global volume mesh can be seen in figure 7 and is applied to cylinder and mast calculations. Figures 8 and 9 show the close-up meshes for the cylinder and mast calculations respectively.

In all cases, a steady state solution was used to initialize the problem. After the steady state solution converged, URANS calculations were conducted at a time step corresponding to the flow moving 1 mm per time step. For flows of 10 m/s, this corresponded to a time step of 0.0001 sec and at 40 m/s this corresponded to 0.000025 sec. Unsteady flow and wall statistics were compiled so mean and root-mean-square (RMS) velocities and wall quantities were gathered. Typically, data were averaged over 3000 time steps. LES calculations used identical time step parameters so direct comparisons could be made in the solution. All runs were conducted on Department of Defense (DoD) high-performance supercomputer systems on parallel SGI® ICE™ XA and Cray XC40/50 computer systems. Typical runs utilized 440 processors over 8 hours of run time.

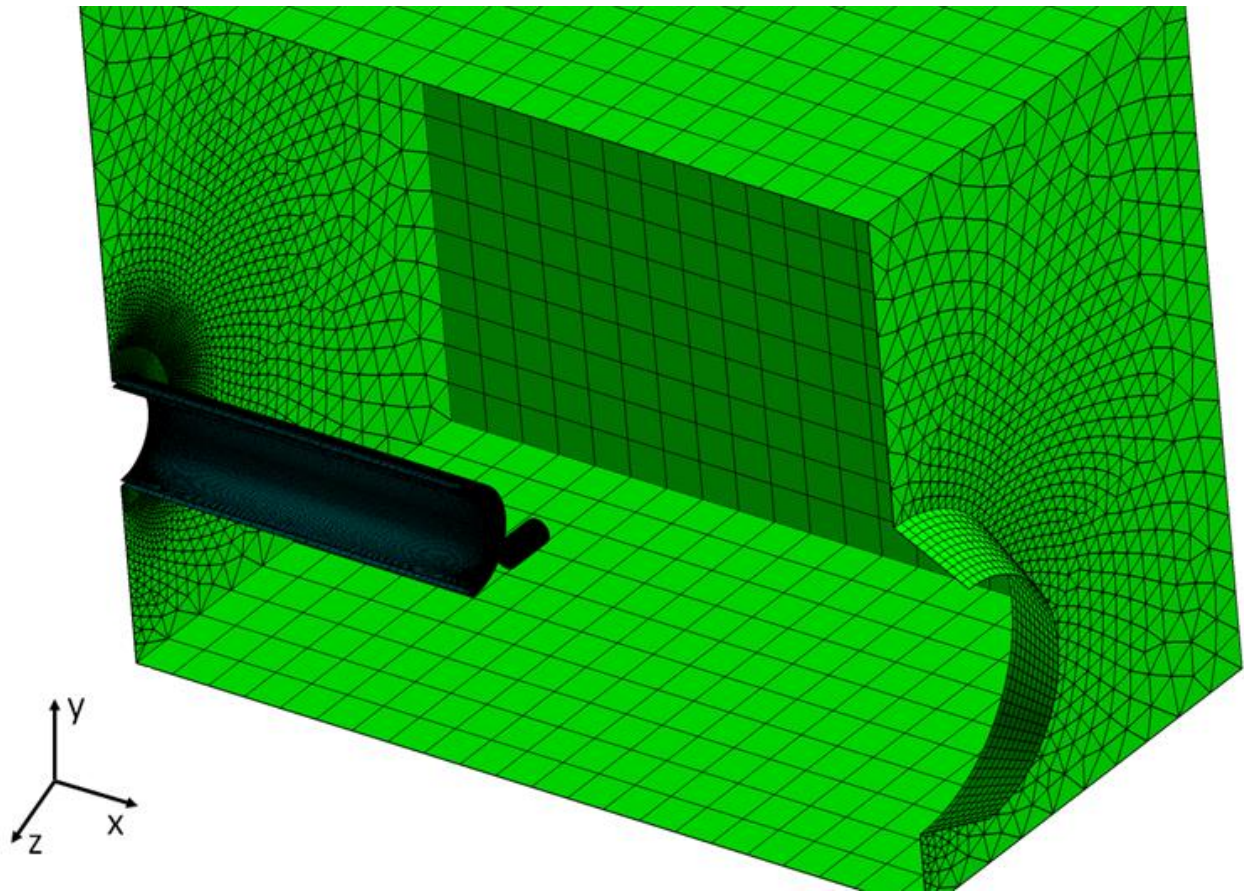


Figure 2. Cylinder CFD Symmetrical Boundary Condition Geometry Set-Up

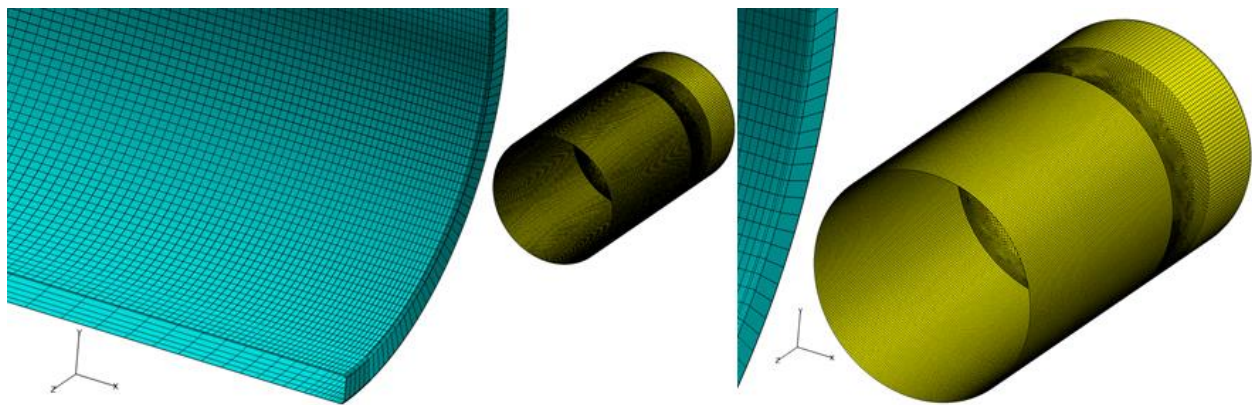


Figure 3. Close-Up View of Cylinder CFD Symmetrical Condition Geometry Set-Up

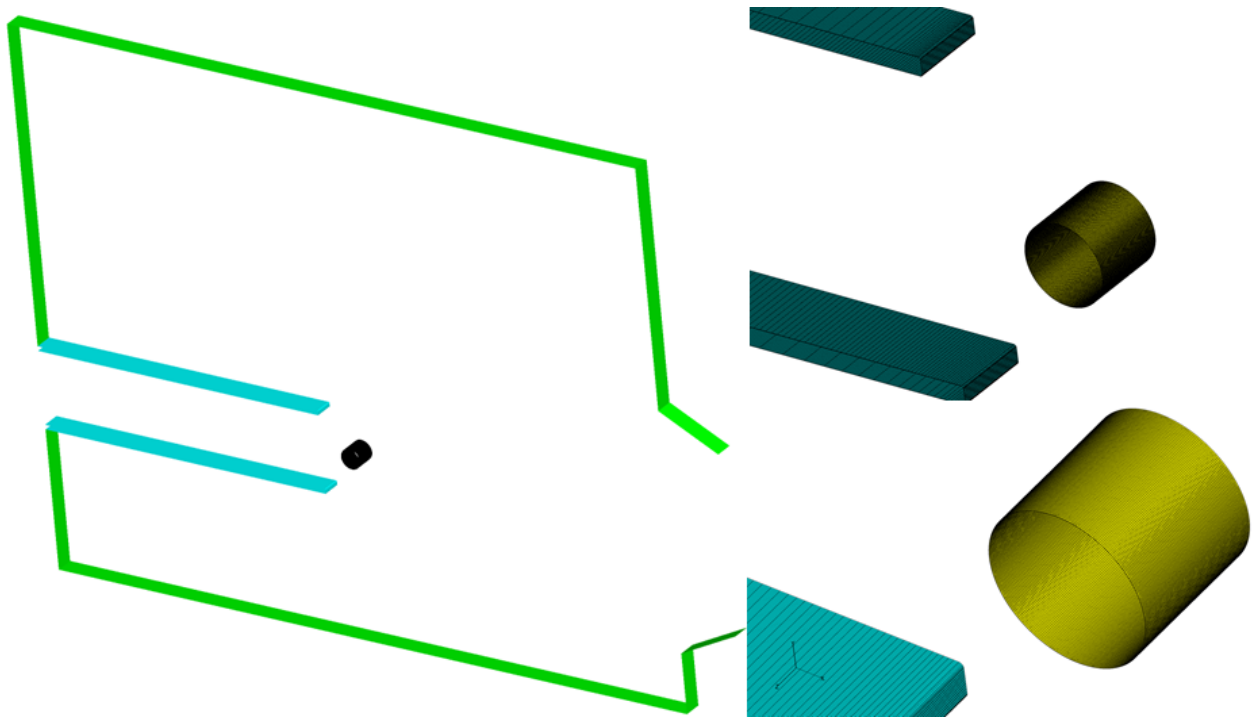


Figure 4. Cylinder CFD Periodic Boundary Condition Geometry Set-Up

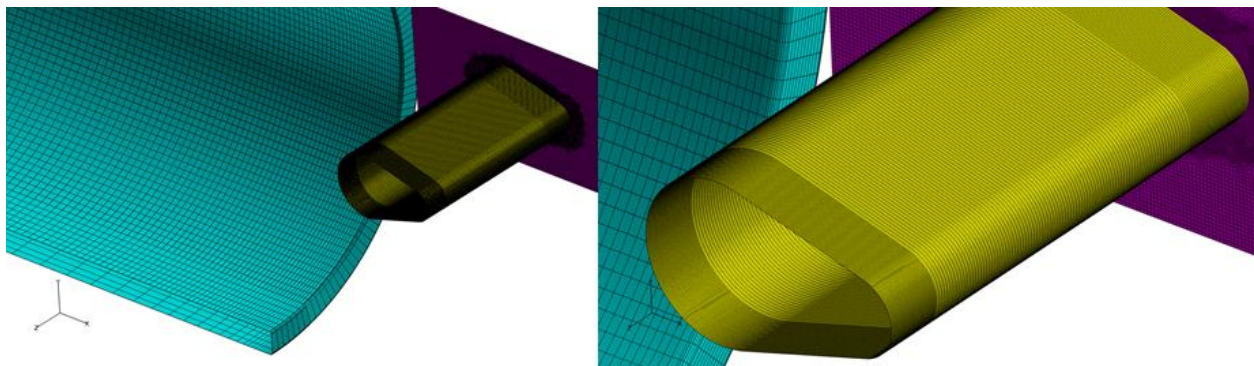


Figure 5. Close-Up View of Mast CFD Symmetrical Boundary Condition Geometry Set-Up

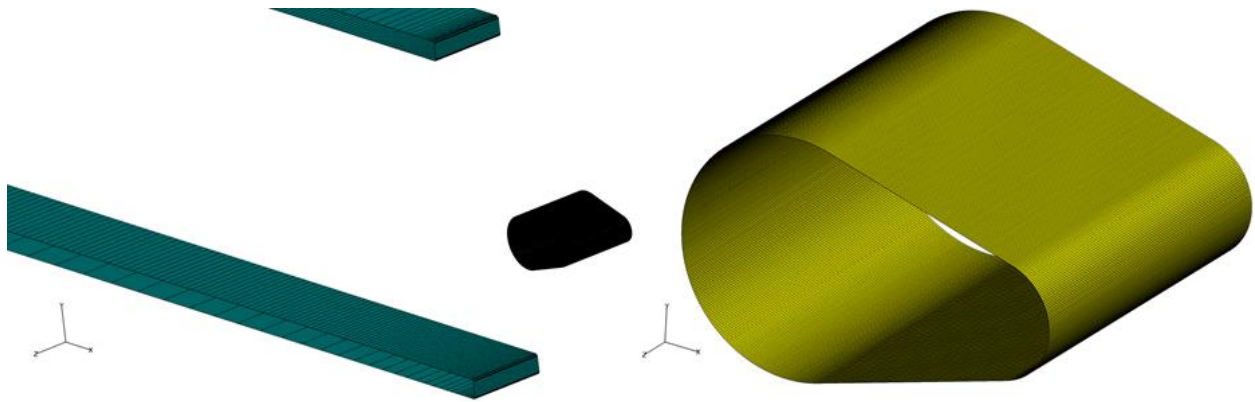


Figure 6. Close-Up View of Mast CFD Periodic Boundary Condition Geometry Set-Up

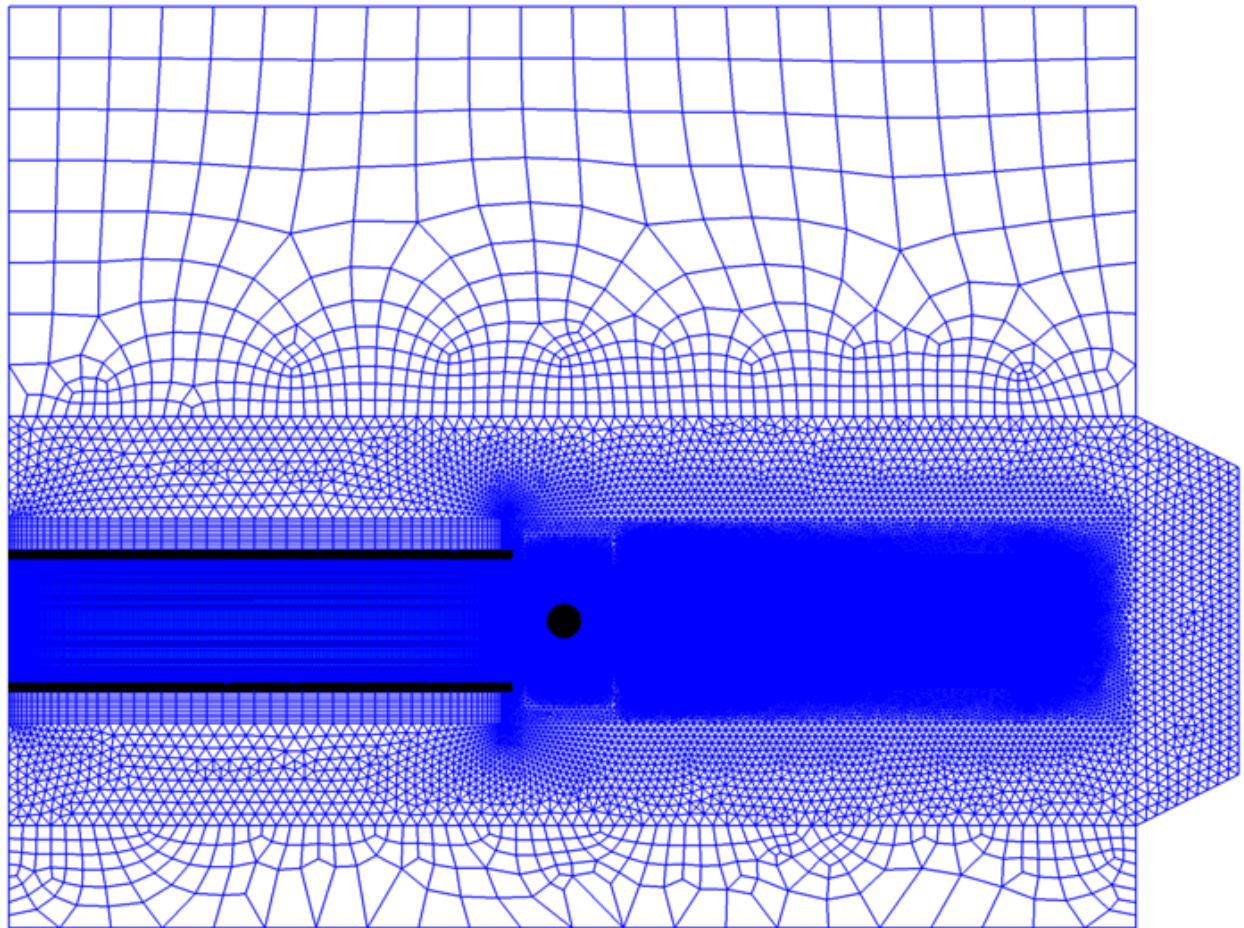


Figure 7. Cylinder CFD Symmetrical Boundary Condition Global Mesh

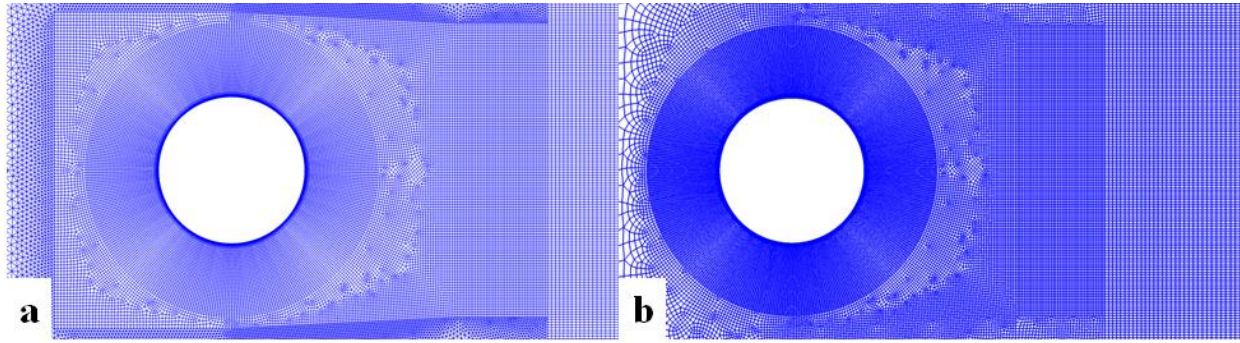


Figure 8. Cylinder CFD Symmetrical (a) and Periodic (b) Boundary Condition Local Mesh

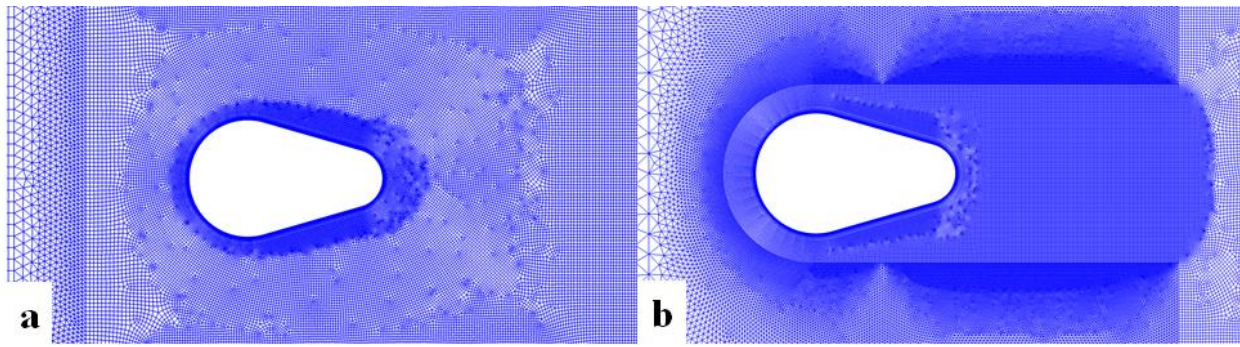


Figure 9. Mast CFD Symmetrical (a) and Periodic (b) Boundary Condition Local Mesh

2.6 COORDINATE SYSTEM

A right-handed coordinate system was used and illustrated in figure 2. X is positive in the direction of the flow, y is positive vertical, and z is positive along the cylinder/mast span. For cylinder data presentations, the circumferential angle is zero at the forward stagnation point and increases clockwise to be consistent with historical data presentations.

3. RESULTS

3.1 GRID CONVERGENCE STUDIES

The effects of grid resolution were examined for cylinder and mast computations for unsteady RANS and LES calculations. Figures 10 and 11 present the effect of grid resolution on time-averaged surface pressure and Nusselt Number for cylinder unsteady RANS and LES simulations. The very low resolution (VLR) consists of 90 circumferential points, the low resolution consists of 180 circumferential points, the medium resolution (MR) consists of 270 circumferential points, the high resolution (HR) consists of 360 points and the very high resolution (VHR) consists of 720 points. When forming the grid, the spanwise grid dimension was kept the same as the circumferential one. The boundary layer grid then increased the surface normal distance until the outer grid was the same size as the circumferential and spanwise length so the resultant volume was as close to a cube as possible. As a result, the base grid cell dimension for the VLR case are 11.3 mm (0.445 inch), 5.65 mm (0.223 inch) for the low resolution (LR) case, 3.77 mm (0.148 inch) for the MR case, 2.83 mm (0.111 inch) for the HR case, and 1.41 mm (0.056 inch) for the VHR case.

It is clear that the URANS surface pressure predictions are significantly less, compared with the LES ones, with negative pressure peaks of -1.5 vs. -2.25 respectively. Increased grid resolution results in a decrease in the negative pressure peak, but is minimal. The VHR simulations predicts a 'jog' in the surface pressure for the LES at approximately $\theta = 105^\circ$. Overall, the ability of URANS and LES to predict the surface pressure distributions even for low resolutions is impressive.

The differences in time-averaged Nusselt Number are more pronounced among the various grid resolutions. The differences for the URANS predictions are minimal at the forward part of the cylinder where the flow is attached. As the flow separates near $\theta = 110^\circ$, a rise in Nusselt Number is seen with the various grid resolutions capturing the peak. In the wake, the differences in grid resolution can be seen more clearly with the HR and VHR simulations similar. In contrast, the differences in grid resolution are more pronounced for the LES simulations. The VLR, LR, and MR exhibit continued improvements in predicting the decrease in Nusselt number near the separation point followed by a peak. The HR and VHR resolutions are similar, with the VHR predicting a deeper decline near the point of separation. Finally, the URANS and LES predictions are different, with URANS predicting higher Nusselt Numbers in the wake.

Similarly, the effects of grid resolution were examined for the Mast case for four cases (figures 12 and 13). The procedure was kept the same as for the cylinder case, with slight differences in grid dimensions. The base grid cell dimension for the LR case is 3.55 mm (0.14 inch), 2.36 mm (0.093 inch) for the MR case, 1.77 mm (0.07 inch) for the HR case, and 0.887 mm (0.035 inch) for the VHR case. Surface pressure and Nusselt number were used as metrics with comparisons to experiments. The grid at the outer boundary layer was kept as cubic as possible.

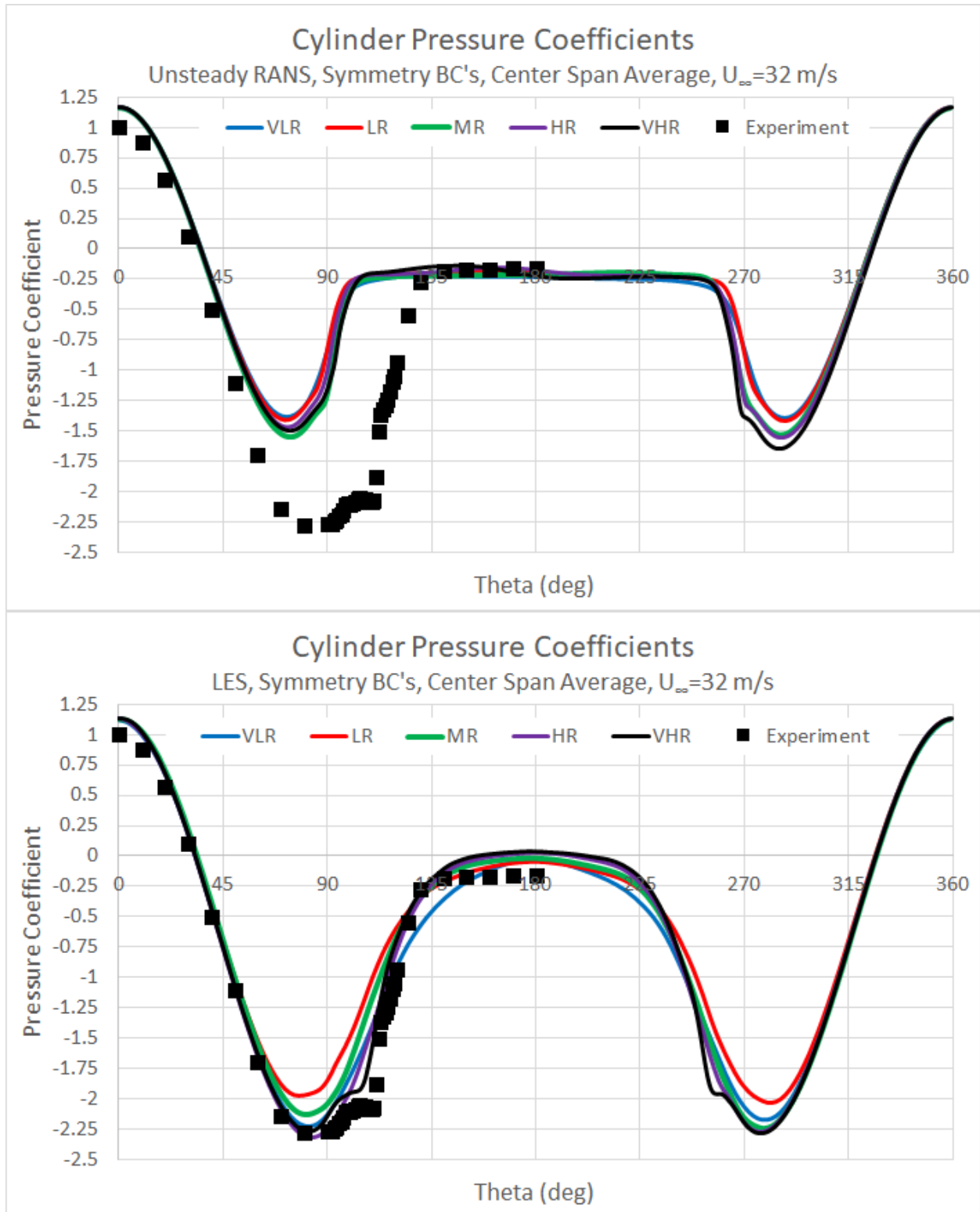


Figure 10. Comparison of Cylinder Surface Pressure Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Symmetry Boundary Conditions at the Center-Span Average for $U_\infty = 32$ m/s, $Re = 710,000$.

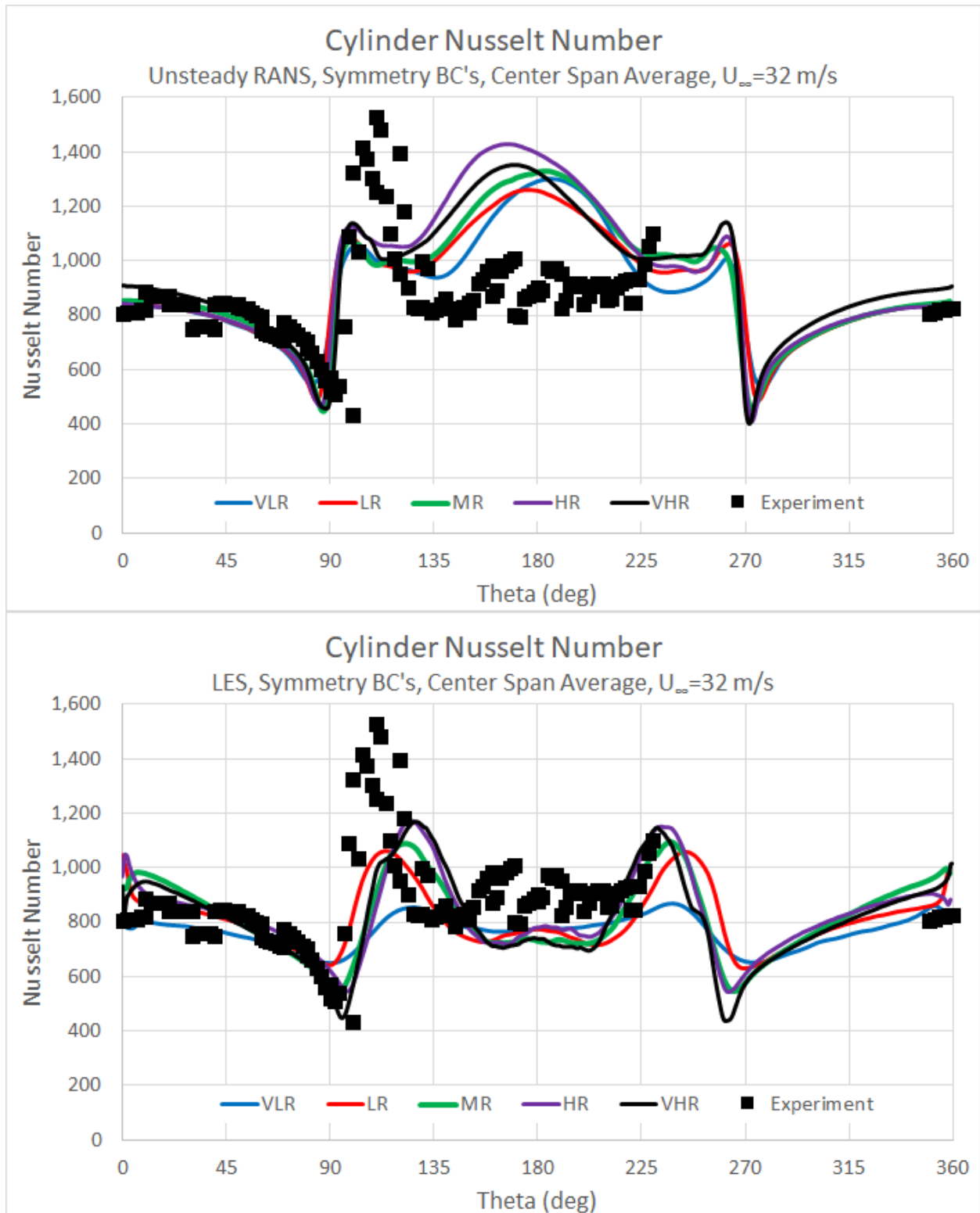


Figure 11. Comparison of Cylinder Nusselt Number Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Symmetry Boundary Conditions at the Center-Span Average for $U_\infty = 32$ m/s, $Re = 710,000$.

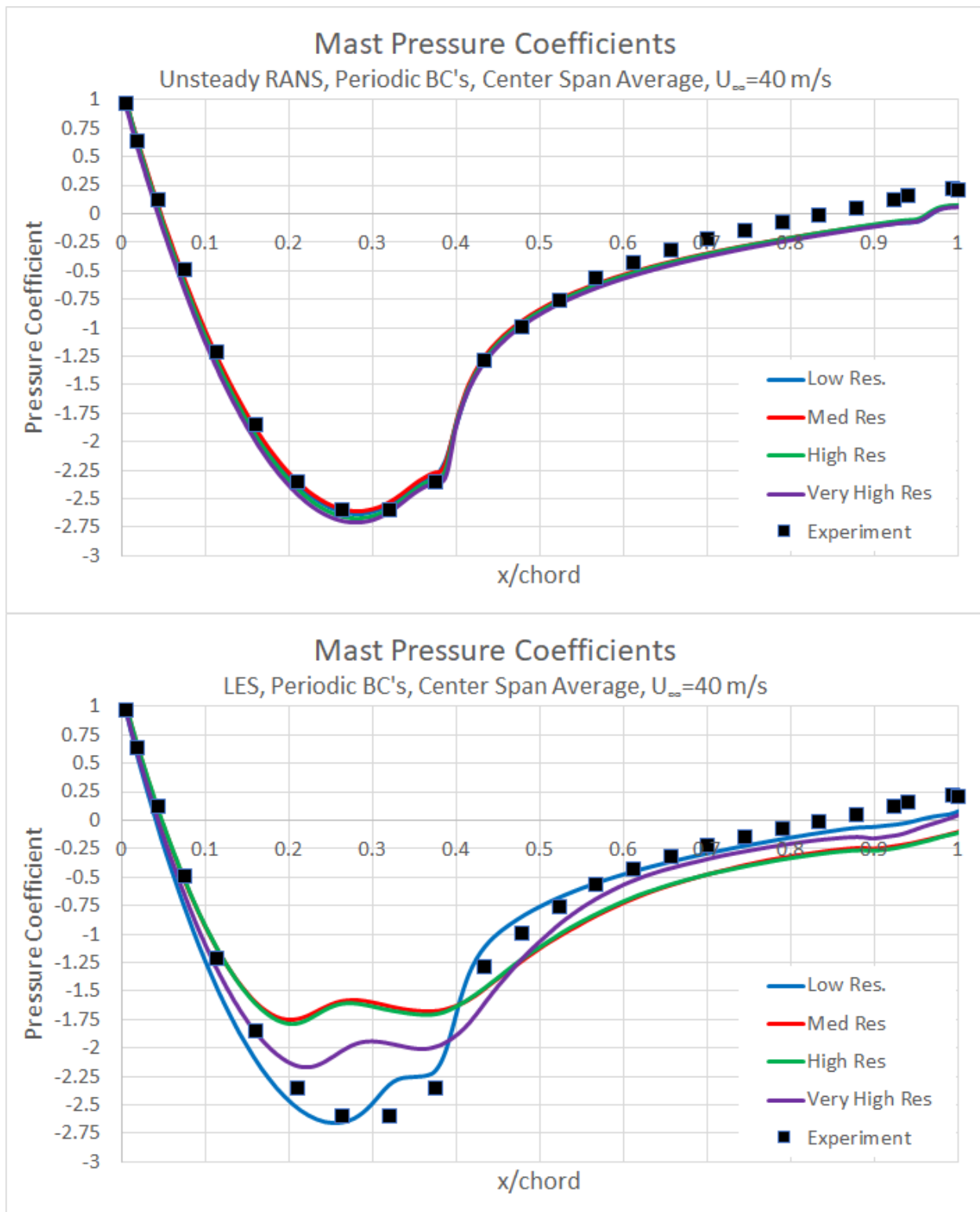


Figure 12. Comparison of Mast Surface Pressure Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Periodic Boundary Conditions at the Center-Span Average for $U_{\infty} = 40$ m/s, $Re = 870,000$.

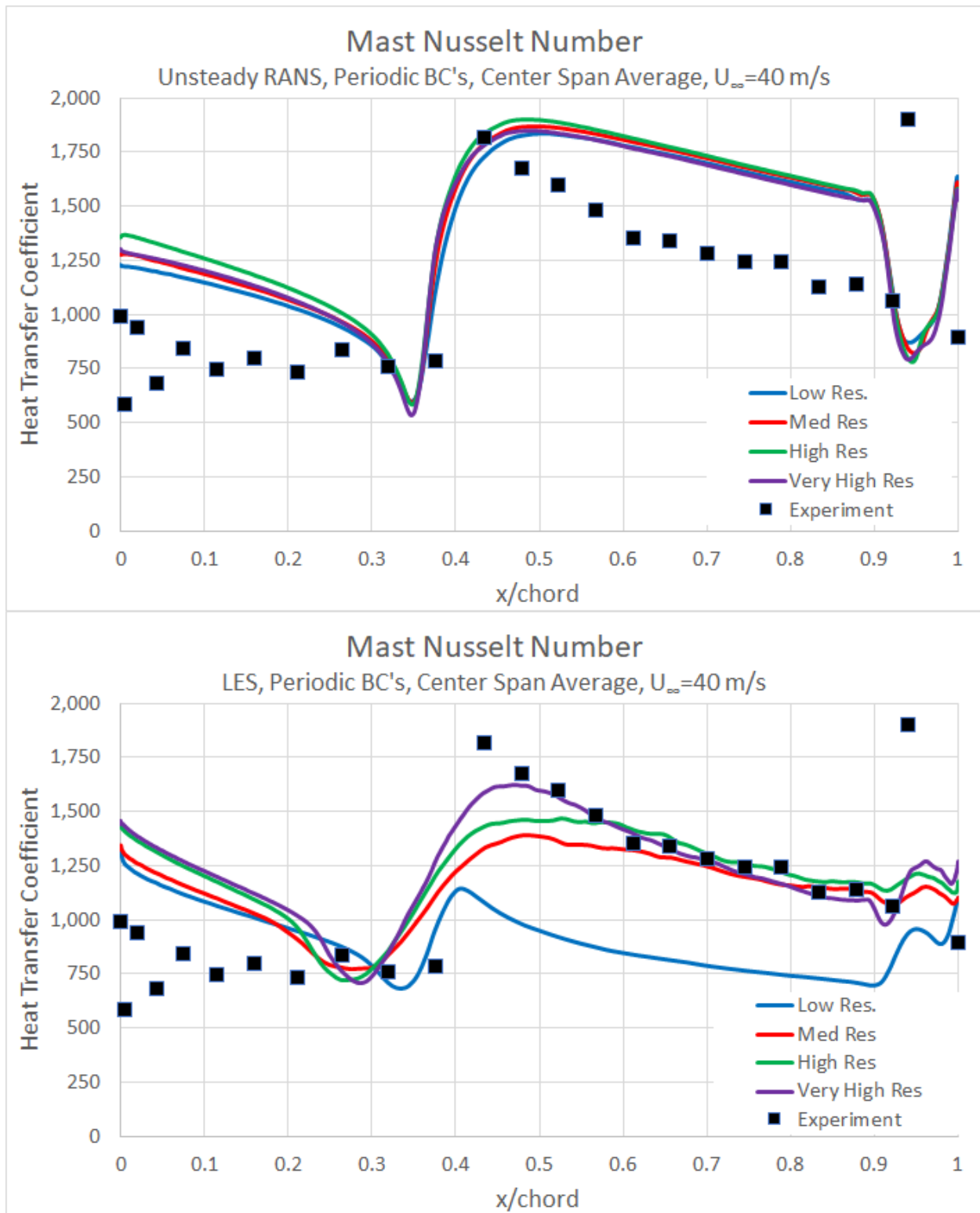


Figure 13. Comparison of Mast Nusselt Number Distributions for the Full Range of Grid Resolution Cases. Both URANS and LES Simulations Are Displayed for Periodic Boundary Conditions at the Center-Span Average for $U_\infty = 40$ m/s, $Re = 870,000$.

In contrast with the cylinder simulations, the surface pressure distributions indicate improved agreement utilizing the URANS methodology. The VHR case captures the jog in the surface pressure, but even the LR simulation demonstrates excellent overall agreement. At 40 m/s, this may be due to the fact that the flow is attached over the mast upper surface. In contrast, the LES simulations generally under-predicted the surface pressure distributions. Interestingly, the LR simulation best captures the depth of the suction pressure peak, indicating the influence of the wall models for the lower grid resolutions.

The effectiveness of LES can be seen primarily in the heat transfer characteristics. While both URANS and LES over-predict the surface Nusselt number over the forward portion of the mast (similar to the cylinder simulations), URANS consistently over-predicts the surface Nusselt number over the remainder of the upper surface followed by a precipitous decrease over the mast trailing edge. In contrast, LES under-predicts the surface heat transfer for lower resolution simulations with the VHR simulation showing excellent agreement. However, experimental data indicate a sharp rise in Nusselt number at $x/c_{\text{mast}} = 0.4$. LES predicts a more gradual rise in Nusselt number, whereas URANS captures the sudden rise much better.

3.2 CYLINDER SURFACE PRESSURE DISTRIBUTIONS

The URANS and LES simulations were evaluated by comparing the surface pressure predictions with experiments. The HR grid was used for all simulations. During the experiments, the presence of strong spanwise flow was qualitatively observed for lower velocity test cases, indicating strong 3-D behavior. For this reason, both periodic and symmetry boundary conditions were evaluated where the periodic boundary conditions would more readily simulate 2-D flow behavior. Figures 14 through 18 show the comparisons for flow velocities between 11 m/s ($Re = 244,000$) and 42.6 m/s ($Re = 945,000$). This velocity range was intentionally chosen for the flow to transition from laminar to turbulent flow separation. At 11 m/s, figure 14 shows the pressure distribution is indicative of laminar flow separation. Experimental data show the absence of a suction pressure peak with minimum pressures in the cylinder wake on the order of -0.5. It is clear that the periodic boundary condition (PBC) simulations significantly over-predict the wake suction pressures strongly indicating highly 3-D flow. Both URANS and LES Symmetrical boundary condition (SBC) predictions fare better. The URANS predicts a suction pressure peak of approximately -1.25 with aft pressures on the order of -0.25. In contrast, LES does not predict a significant pressure peak with aft pressures fairly constant on the order of -0.75.

At 18.7 m/s, experimental data observations indicated the flow was just below the point of critical transition, making this a challenging case to simulate. The absence of a suction pressure peak continued. PBC simulations significantly over predict the pressure. However, the SBC simulations also over-predicted the suction pressures with suction pressure peaks with the profiles suggesting turbulent transition already occurred.

Turbulent transition occurs by 21.2 m/s as is demonstrated clearly by the experimental surface pressure distribution. For this test case the LES SBC case accurately predicts the surface pressure distribution even predicting the jog in surface pressure at $\theta = 100^\circ$ - 108° . URANS SBC

simulations significantly under-predict the suction pressure peak but is more closely predicted using PBC. LES PBC simulations fail to capture the surface pressure characteristics.

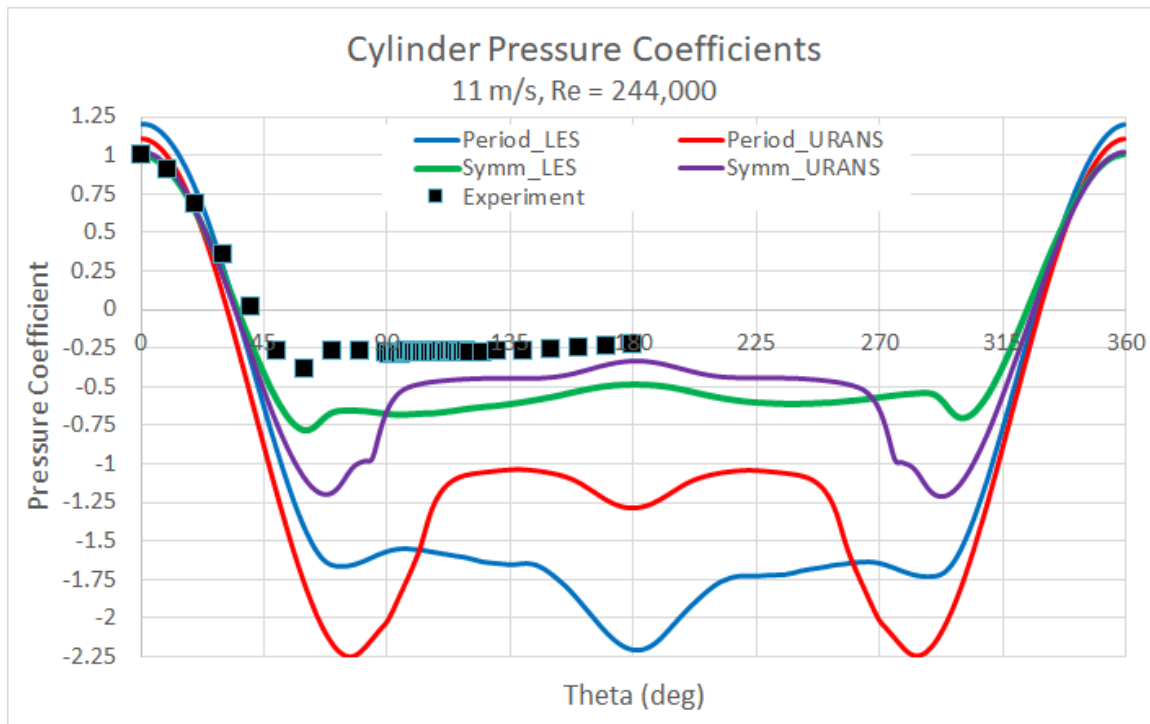


Figure 14. Cylinder Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 11$ m/s, $Re = 244,000$

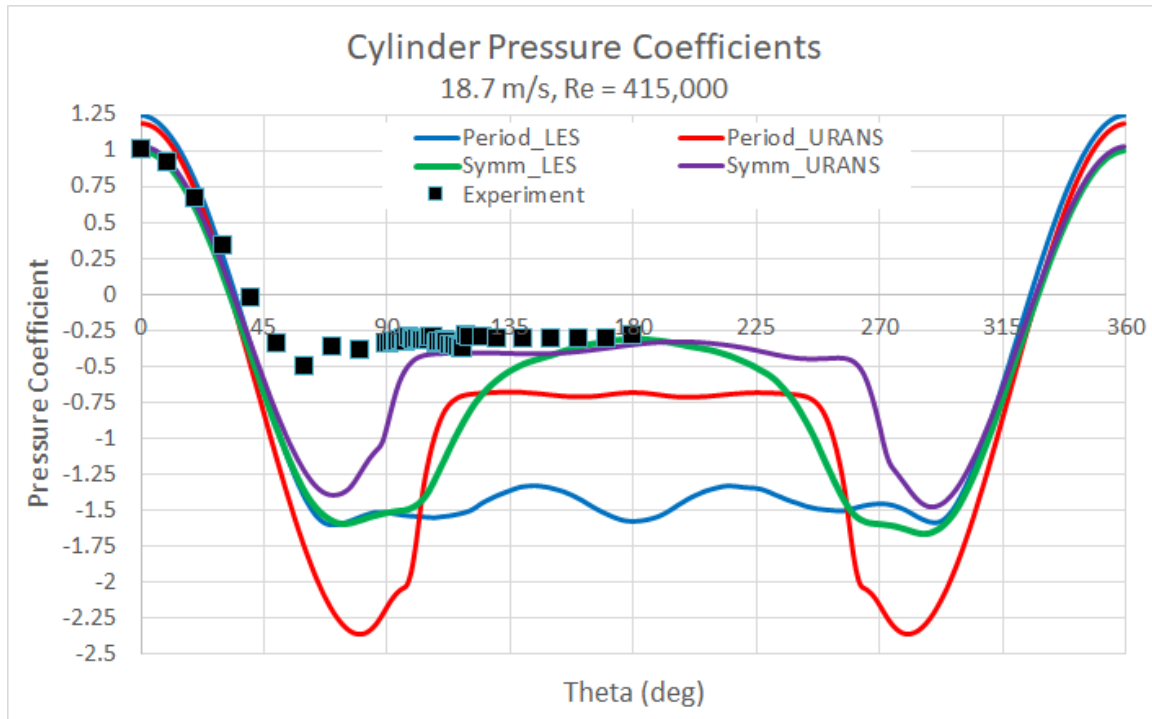


Figure 15. Cylinder Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 18.7$ m/s, $Re = 415,000$

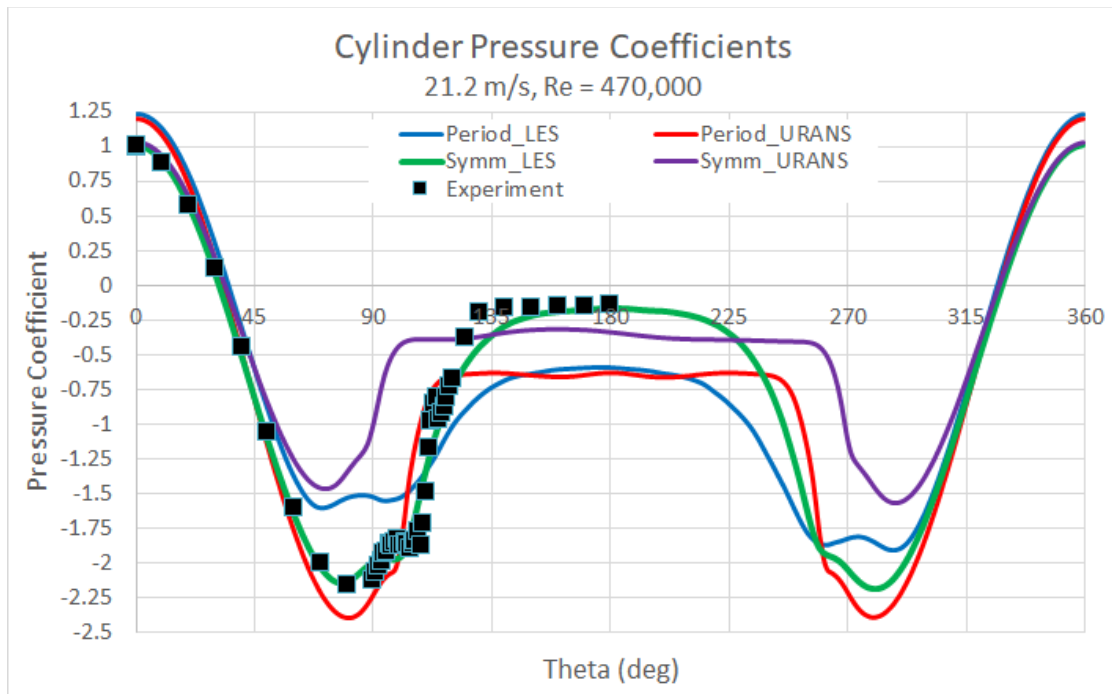


Figure 16. Cylinder Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 21.2$ m/s, $Re = 470,000$

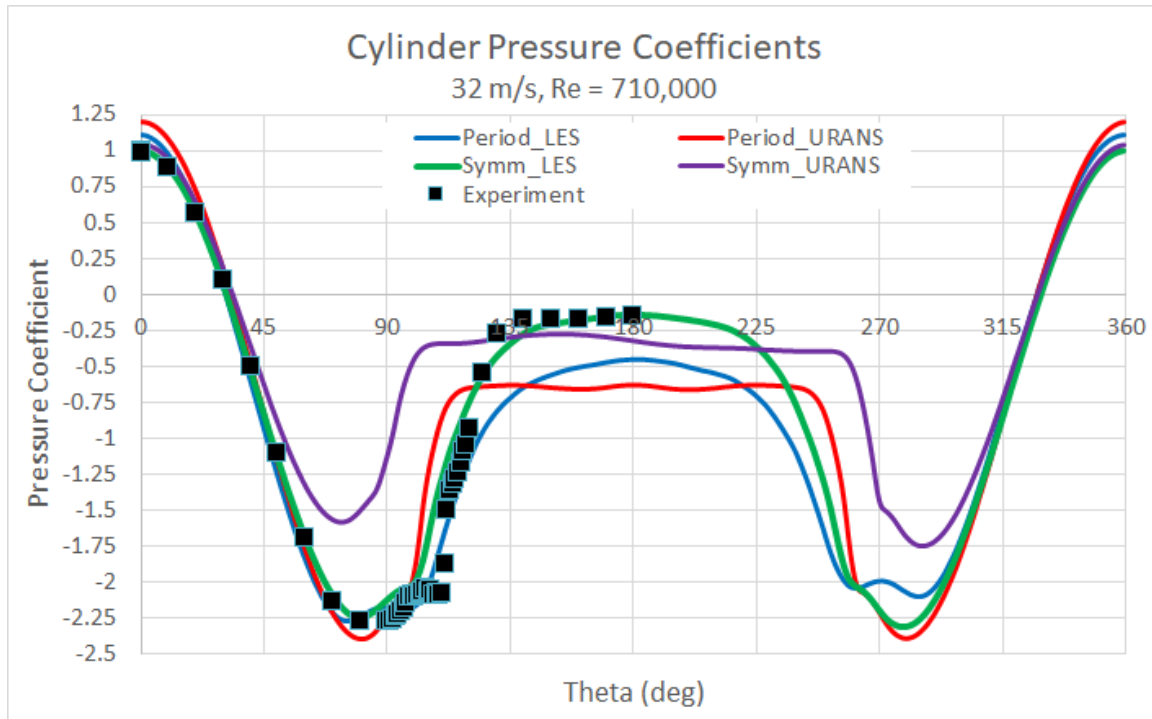


Figure 17. Cylinder Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 32$ m/s, $Re = 710,000$

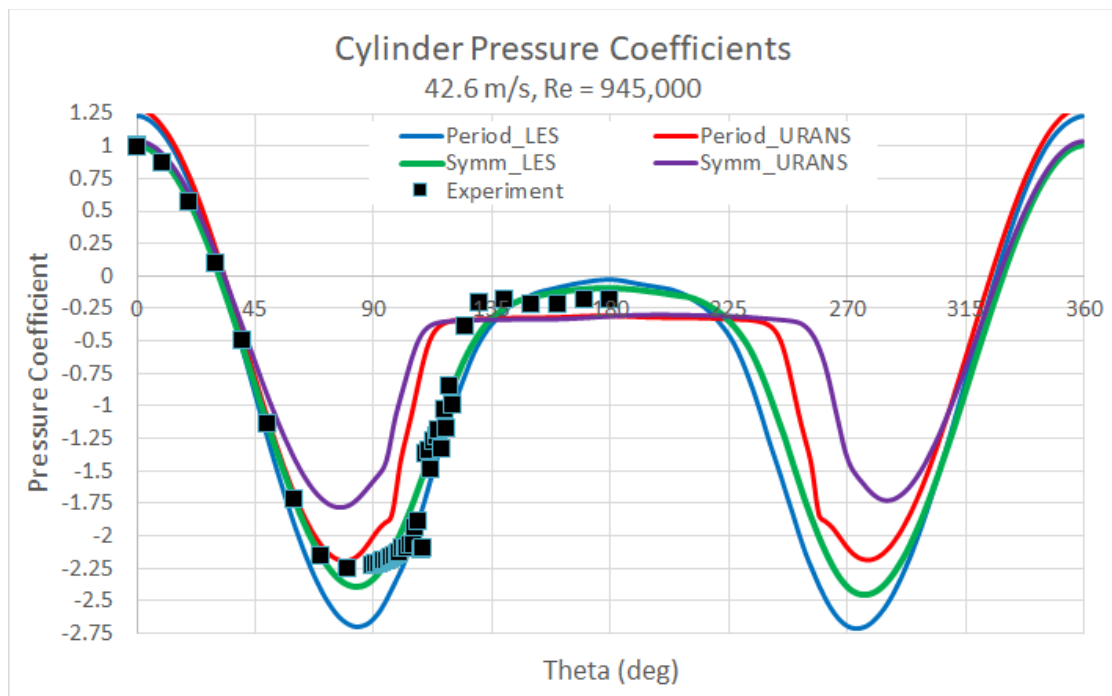


Figure 18. Cylinder Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 42.6$ m/s, $Re = 945,000$

As the flow velocity is increased to 32 m/s and 42.6 m/s, there is minimal change in the experimental surface pressure coefficients. Similarly, the changes in URANS and LES simulations for both PBC and SBC cases are minimal as well. The LES SBC continues to predict the surface pressure distribution very well. Improvement is seen for the LES PBC simulation indicating the flow is more two-dimensional at the center span location. At 32 m/s, the LES and URANS PBC simulations predict lower pressures on the aft portion of the cylinder compared with experiment. At 42.6 m/s, these predictions are much more representative of the data further indicating two-dimensional flow characteristics. The URANS, SBC simulations continue to significantly under-predict the suction pressure peak.

3.3 CYLINDER NUSSELT NUMBER RESULTS

Prediction of the cylinder heat transfer characteristics is best exemplified by comparisons of the Nusselt number (Nu). In similar fashion as the surface pressure distributions, predictions of experimental Nu are compared with URANS and LES simulations for Symmetrical and periodic boundary conditions. These results are presented in figures 19 through 23. At 11 m/s, all simulations predict the heat transfer in the forward portion of the cylinder. As the flow separates, a gradual drop in Nu was measured and simulated. In the wake, however, both URANS PBC and SBC simulations greatly over-predict the heat transfer. The LES simulations perform much better with the SBC and PBC predictions being similar. There is an increase from $\theta = 135^\circ$ - 225° where the LES over-predicts the Nu peaking at 600, compared to constant values of 400 in the wake.

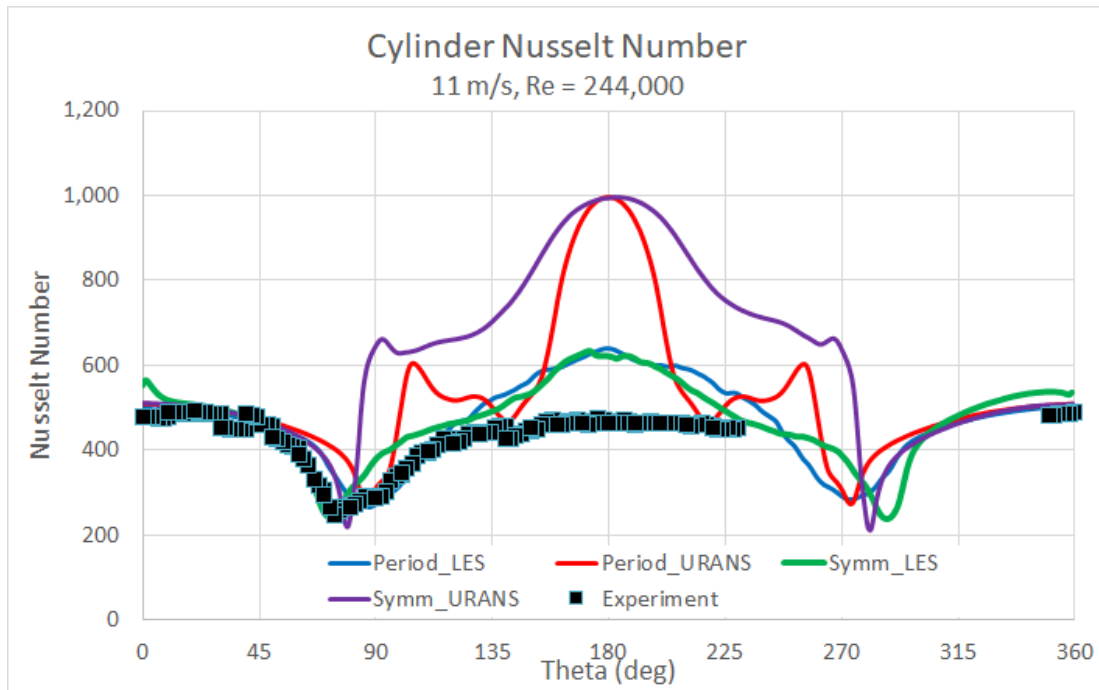


Figure 19. Cylinder Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_\infty = 11$ m/s, $Re = 244,000$

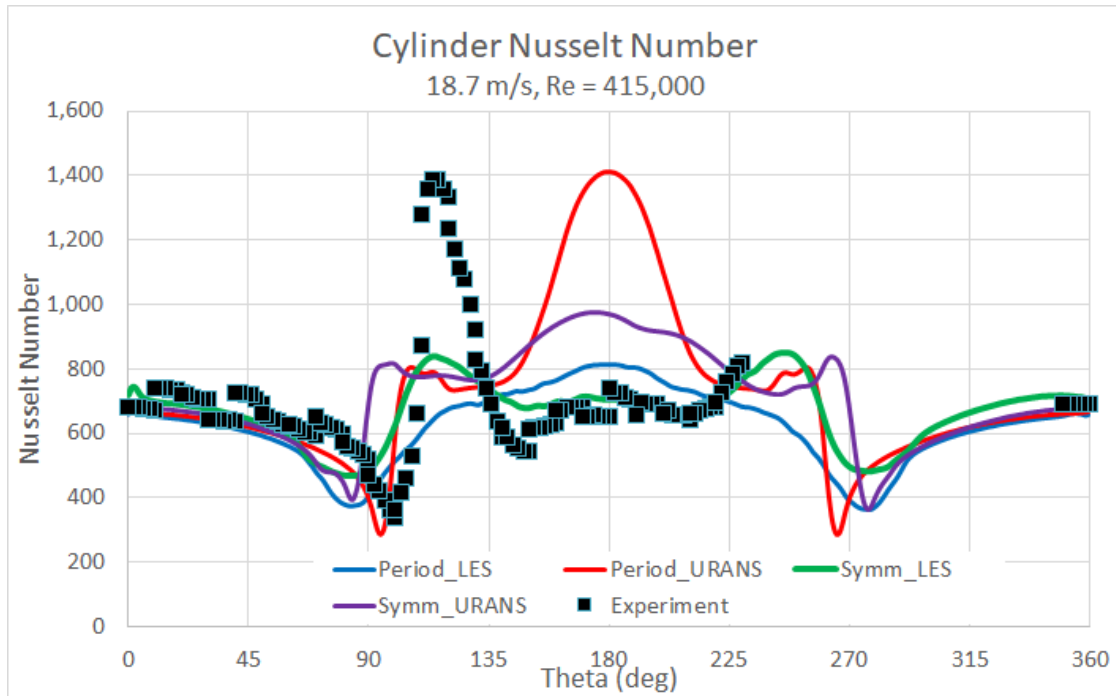


Figure 20. Cylinder Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 18.7$ m/s, $Re = 415,000$

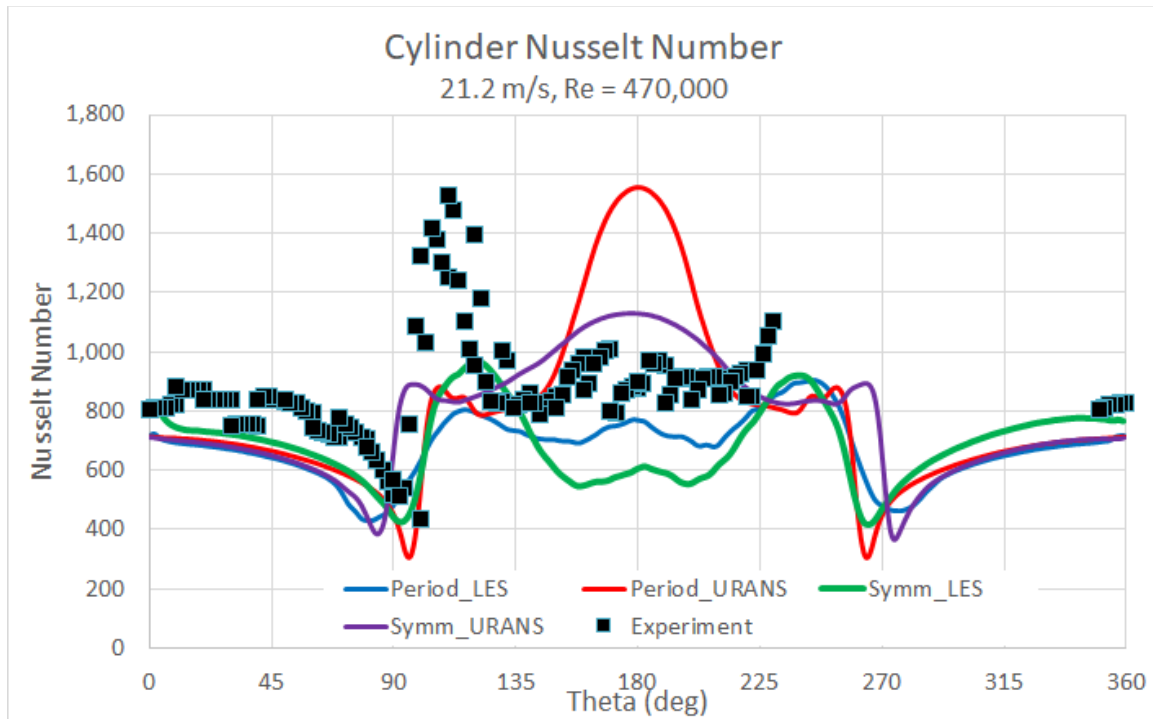


Figure 21. Cylinder Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 21.2$ m/s, $Re = 470,000$

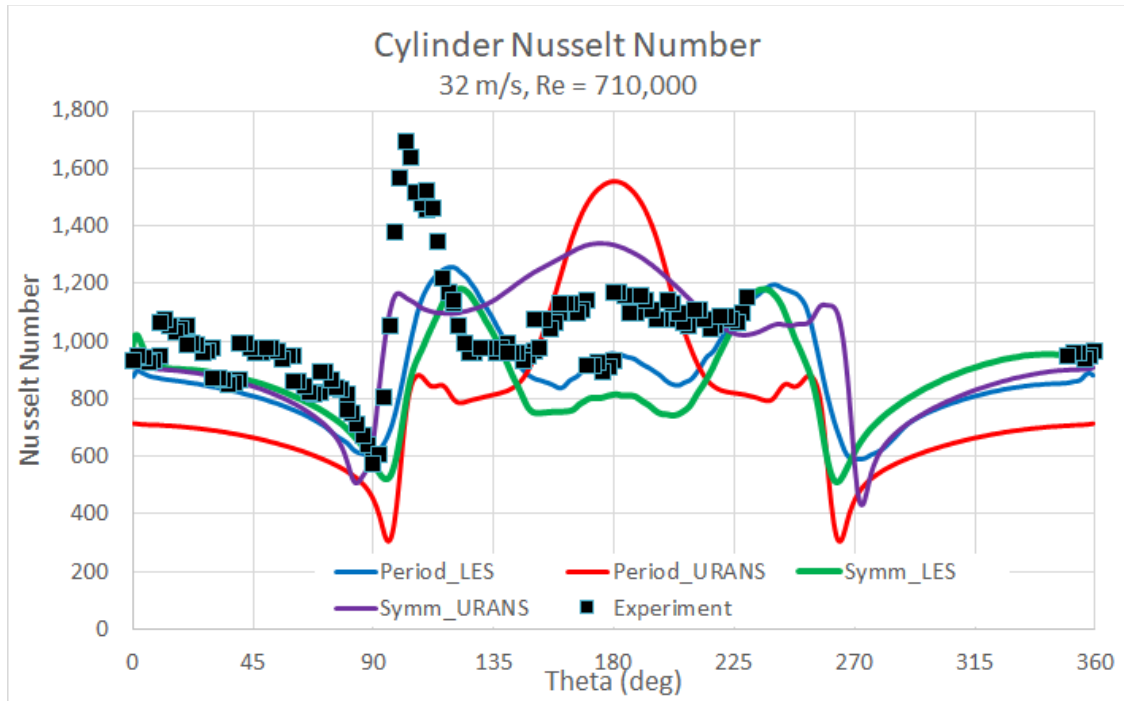


Figure 22. Cylinder Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_\infty = 32$ m/s, $Re = 710,000$

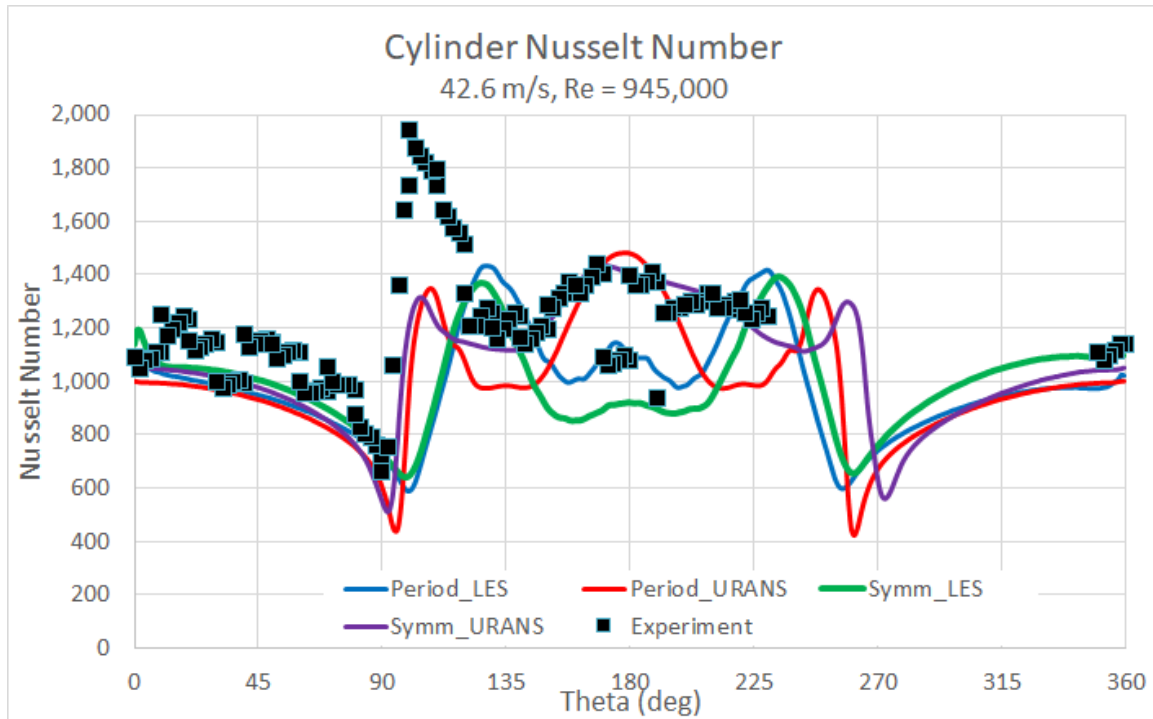


Figure 23. Cylinder Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_\infty = 42.6$ m/s, $Re = 945,000$

Beginning at 18.7 m/s, the surface Nu were measured and were qualitatively similar, representing turbulent flow separation. Just after $\theta = 90^\circ$, experiments measure a sharp rise in heat transfer followed by a decline, reaching a local minimum at $\theta = 135^\circ$. All four of the solution methodologies perform similarly in the forward portion of the cylinder where the flow is attached. As the flow separates, URANS (both PBC and SBC) replicate the sharp increase in heat transfer better. LES predicts a much more gradual rise in Nusselt number. All four methods, however, fail to capture the peak Nu. URANS predicts a rise in Nu that levels off in the wake. For PBC, URANS predicts an additional peak at the aft end of the cylinder that is not seen in the experiments. LES predicts a rise, followed by a drop in Nu. As a result, LES predicts the trends in the experimental data, but tend to under-predict the actual values.

3.4 CYLINDER VELOCITY PREDICTIONS:

Experiments acquired mean and RMS axial and vertical velocity data to provide comparisons with computational simulations. Color contour plots of the mean axial velocities are shown in figure 24 for the Symmetrical and periodic URANS and LES simulations. As can be seen, the SBC URANS simulations predict an expanding wake and explain the reduced surface suction pressure when compared with LES and PBC URANS. In contrast, the PBC URANS simulations predict a converging wake. The LES simulations are similar for SBC and PBC and exhibit a wake that remains relatively flat with slight expansion. Finally, the PBC cases indicate increased reverse flows compared with the SBC cases.

Instantaneously, the velocity field is composed of several small scale eddies. In order to illustrate the differences between URANS and LES, the instantaneous z-vorticity color contour plots are presented in figure 25. As can be seen, the URANS simulations predict a shear layer of concentrated z-vorticity resulting in the formation of stronger, discrete vortices. In contrast, LES correctly predicts the experimentally observed smaller eddies, which coalesce into vortex structures downstream.

Hot-wire anemometry was used to measure the mean and RMS velocity profiles for the range of velocities between 11 and 42.6 m/s. The complete results are presented in appendix A. Profiles normal to the surface were taken at several cylinder circumferential locations. At the forward portion of the cylinder, good agreement was seen with both URANS and LES simulations. The challenging region is aft of the point of separation and the wake.

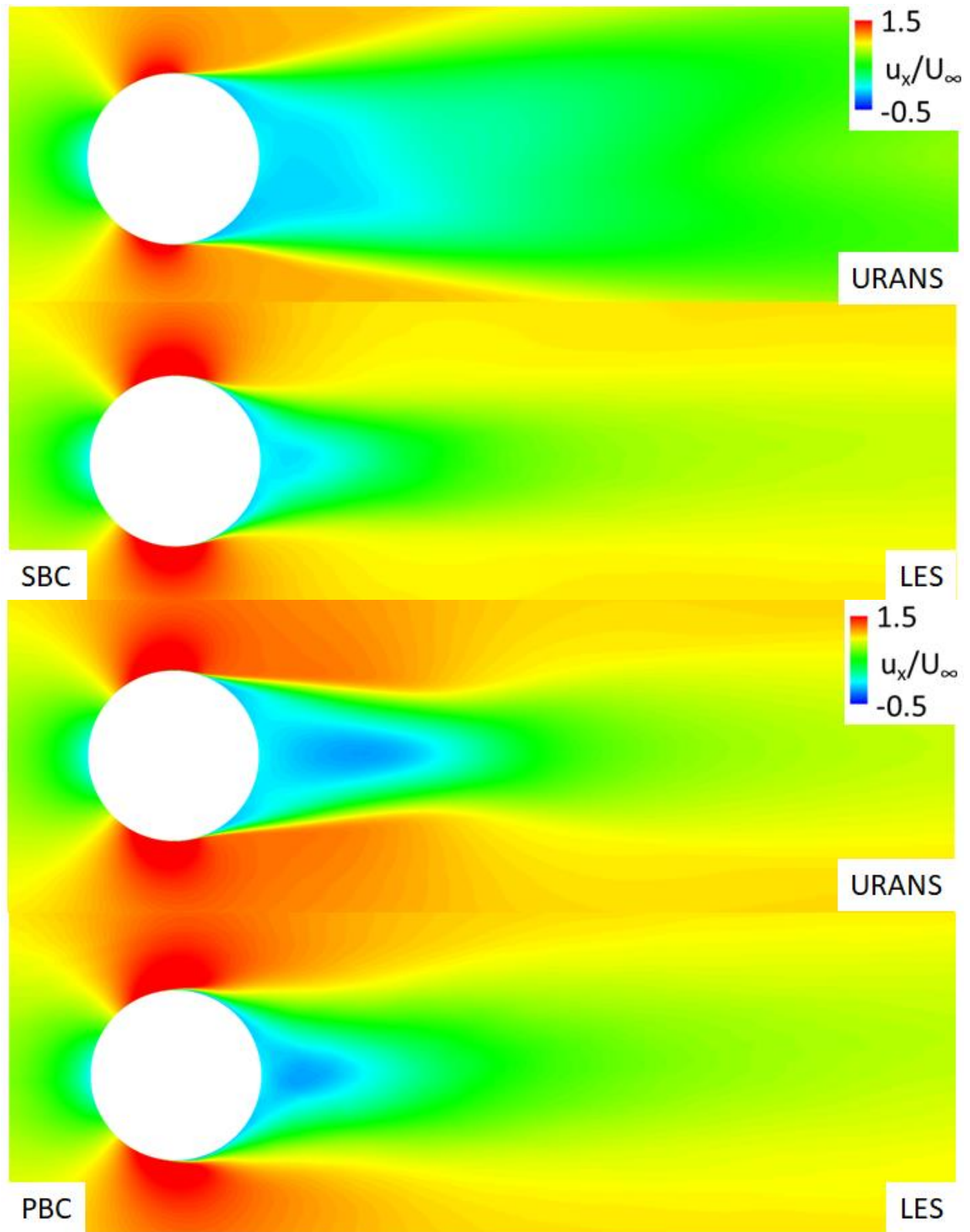


Figure 24. Color Velocity Contours of the Mean Axial Velocity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_\infty = 32$ m/s, $Re = 710,000$

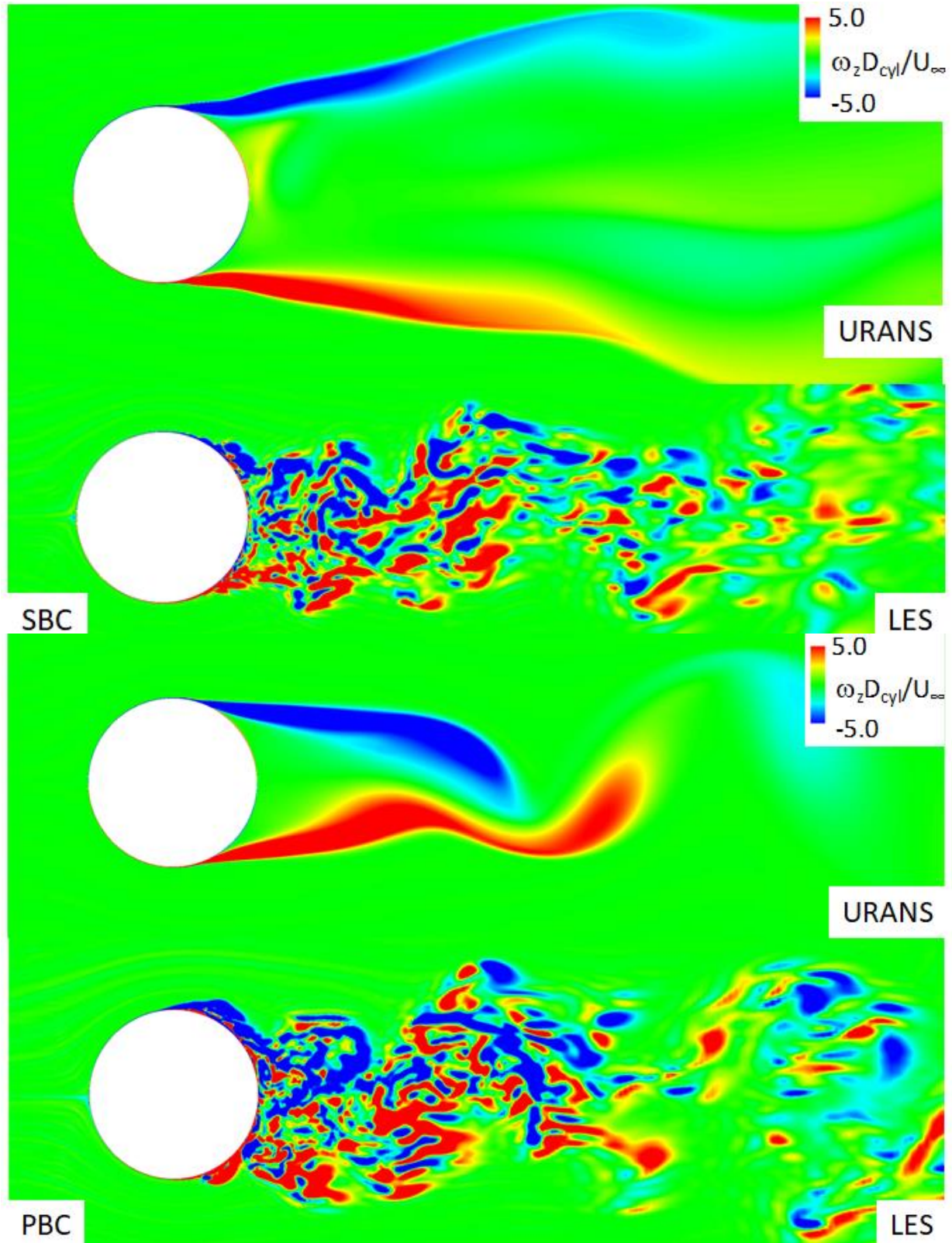


Figure 25. Color Velocity Contours of Instantaneous Z-Vorticity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_\infty = 32$ m/s, $Re = 710,000$

Figure 26 presents axial and vertical velocity distributions in the wake for 11 m/s comparing URANS and LES for Symmetrical boundary conditions. For this case, laminar flow separation occurred experimentally. URANS fared poorly due to the prediction of wake expansion resulting in a significantly under-predicting the axial velocities. LES performs much better at $\theta = 120^\circ$ for both axial and vertical velocities. At $\theta = 150^\circ$ and 180° , axial velocities are under-predicted and vertical velocities over-predicted.

Figure 27 presents the RMS axial and vertical velocities for the 11 m/s test case. As can be seen, URANS predicts minimal RMS velocities. LES significantly over-predicts RMS axial and vertical velocities. The exception is along the wake centerline ($\theta = 180^\circ$) where the axial RMS velocities are consistent with experiment.

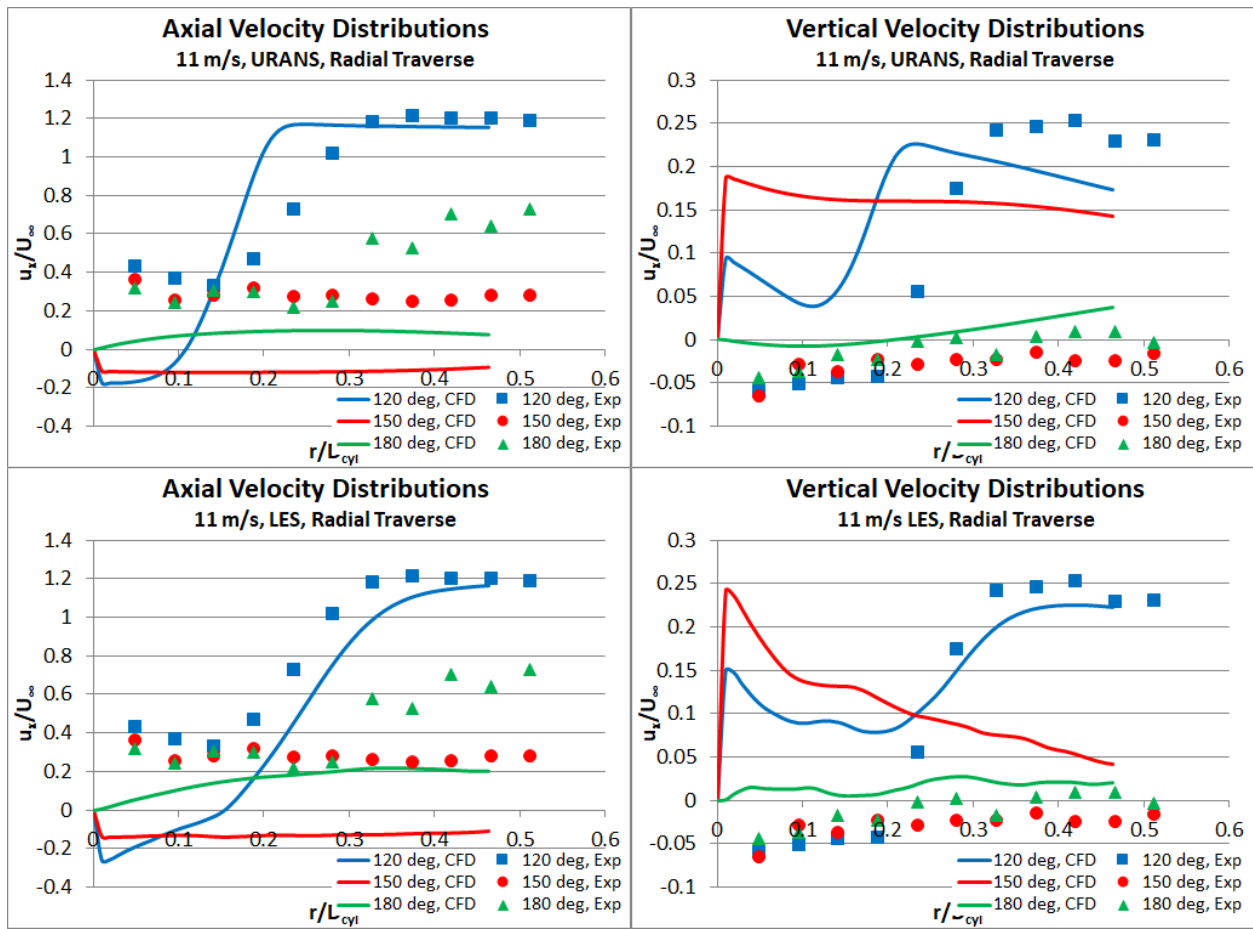


Figure 26. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 120^\circ$, 150° and 180° for $U_\infty = 11$ m/s, $Re = 244,000$. URANS and LES Simulation with SBC.

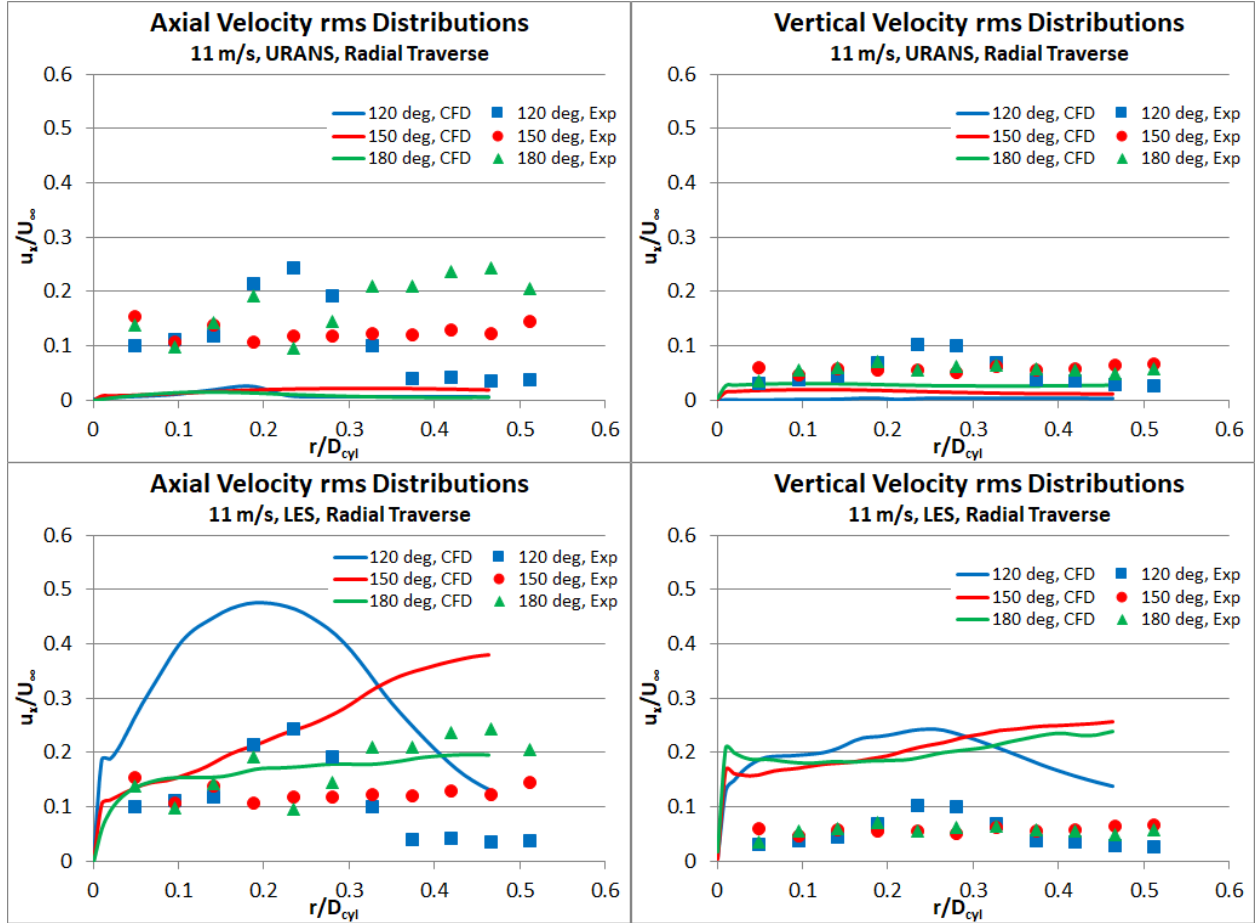


Figure 27. Cylinder Axial and Vertical RMS Velocity Profiles for $\theta = 120^\circ$, 150° and 180° for $U_\infty = 11$ m/s, $Re = 244,000$. URANS and LES Simulation with SBC.

For the 42.6 m/s flow velocity the flow is characterized by turbulent flow separation. Figure 28 highlights comparisons of axial and vertical mean flow velocities for URANS and LES using Symmetrical boundary conditions. Again, URANS fails to properly capture the velocity profiles in the inner wake with vertical velocities predicting wake expansion (positive velocities) as opposed to the experimentally observed negative vertical velocities. Alternatively, LES is able to mostly capture the axial and vertical flow velocities at each of the circumferential profiles. At $\theta = 120^\circ$, LES profiles overlay the axial and vertical velocity experimental data points. At $\theta = 150^\circ$, the axial profile is more gradual compared with the experimental data but still capture the trend in increased velocity. Vertical velocities are closely predicted. Along the wake centerline, mean axial and vertical velocities are expected to be near zero.

Figure 29 highlights the RMS velocity predictions for the 42.6 m/s test case. URANS over-predicts the RMS velocities and predicts a peak in RMS axial velocity at $\theta = 120^\circ$ due to the prediction of wake expansion. LES performs ably and captures the RMS axial and vertical velocities at $\theta = 120^\circ$. For $\theta = 150^\circ$, LES over-predicts the RMS axial and vertical velocities.

Along the centerline, the RMS axial velocities follow closely with the experimental data with vertical RMS velocities over-predicted.

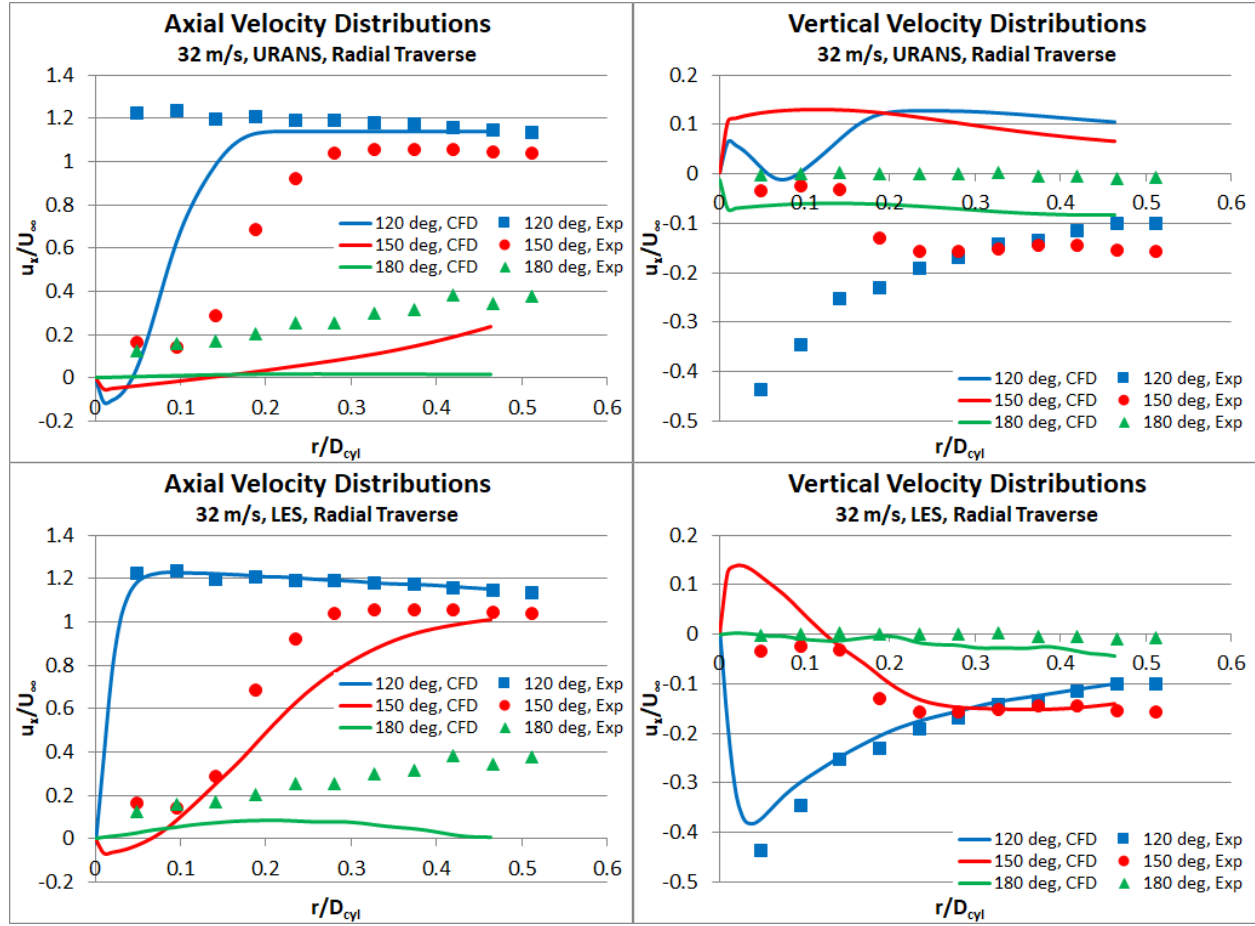


Figure 28. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 120^\circ$, 150° and 180° for $U_\infty = 32 \text{ m/s}$, $Re = 710,000$. URANS and LES Simulation with SBC.

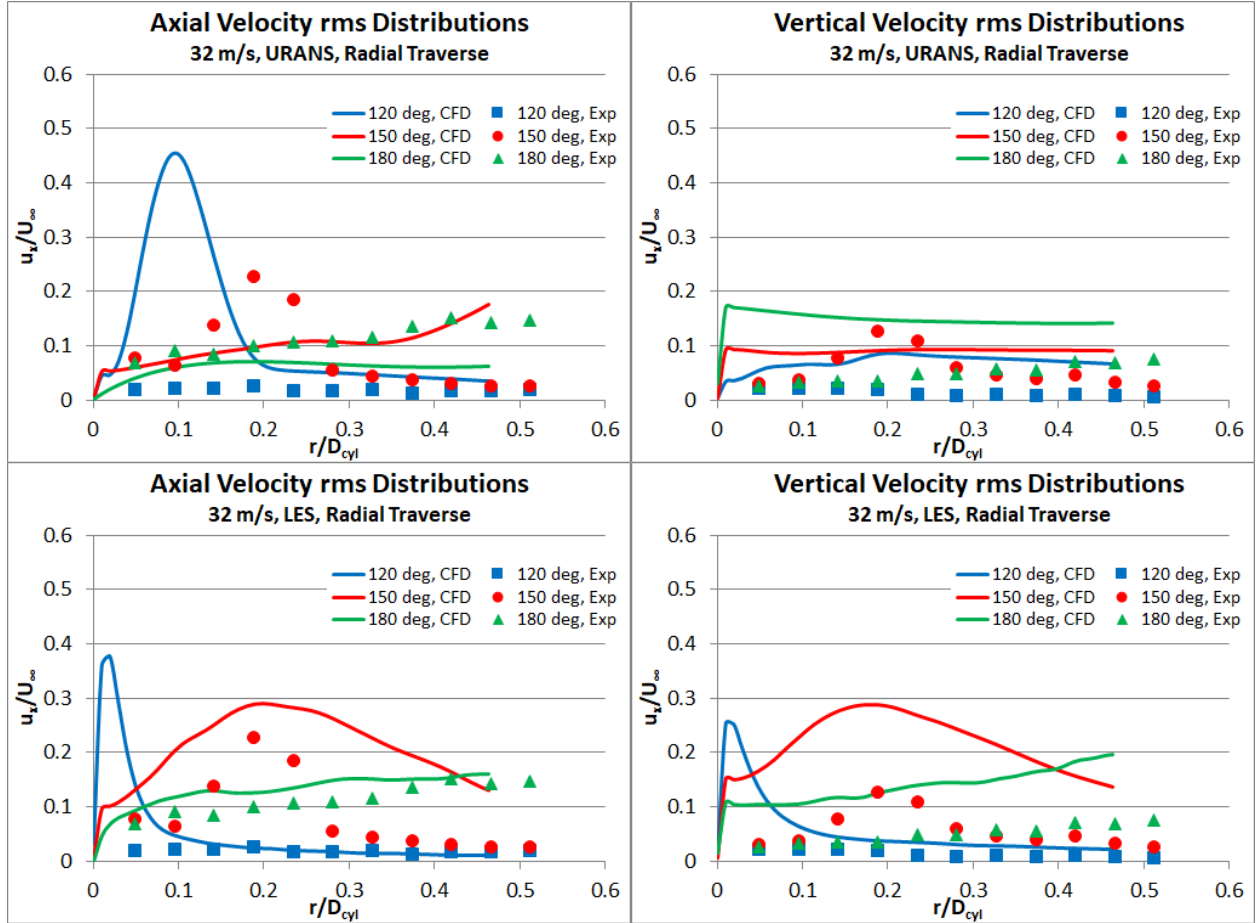


Figure 29. Cylinder Axial and Vertical RMS Velocity Profiles for $\theta = 120^\circ$, 150° and 180° for $U_\infty = 32 \text{ m/s}$, $Re = 710,000$. URANS and LES Simulation with SBC.

3.5 MAST SURFACE PRESSURE DISTRIBUTIONS:

Similar to the cylinder test cases, an examination of URANS and LES for PBC and SBC was conducted for flow past a mast. Unlike the cylinder, experiments used fences to bound the flow over the mast in order to replicate two-dimensional flow conditions. Velocities of 10, 20, 30, 40 and 50 m/s were simulated to encompass flow separation at the lower velocities and flow attachment at the higher velocities. The 20 m/s case was experimentally found to be a transition case. Surface pressure distributions were consistent with leading edge flow separation but surface heat transfer was consistent with attached flow. In the data presented, the HR grid was used for all SBC and URANS cases. The PBC LES simulation used the HR grid at 10 and 20 m/s, and the VHR grid for the higher velocities.

Mast surface pressure distributions are presented in figure 30 at $U_\infty = 10 \text{ m/s}$ for the solution methodologies examined. Experimental measurements show a modest suction pressure peak of -0.75 followed by pressure coefficients of -0.5 in the aft region of the wake. All methodologies over-predict the suction pressure peak the LES SBC and URANS PBC

performing poorest. LES PBC and URANS SBC perform somewhat better with suction pressure peaks of -1.0. URANS SBC performs best in terms of predicting the aft pressures whereas LES PBC over-predicts the negative wake pressures with values on the order of -0.75.

As the velocity is increased to 20 m/s (figure 31), the experimental data showed little change in surface pressure coefficients indicating continued separated flow. LES SBC predictions are consistent with attached flow and thus substantially over-predict the suction pressure peak. In contrast, the other solution methodologies are consistent with separated flow. LES SBC pressure coefficient predictions are similar to those computed for 10 m/s with slightly higher (-0.95 vs. -0.75) suction pressures in the aft region. Both URANS (SBC and PBC) computations produced similar results with suction pressure peaks on the order of -1.5 but correctly predicting the surface pressures in the aft region.

At 30 m/s (figure 32), experimental results clearly show attached flow. A substantial suction pressure peak of -2.75 was measured followed by a “jog” in the surface pressure profile at $x/c_{\text{mast}} = 0.37$. After this, a consistent decline in suction pressure was measured with some pressure recovery in the trailing edge region ($x/c_{\text{mast}} = 0.9$). Both URANS simulations (SBC and PBC) are nearly identical and perform the best overall in terms of predicting the suction pressure peak, the “jog” in pressure and subsequent pressure recovery. LES SBC method correctly predicts the magnitude of the suction pressure peak, but fails to predict the jog. The LES PBC method under-predicts the suction pressure peak but does predict a jog. Both LES methods predict the pressure recovery similar to the URANS simulations.

At the highest velocities (figures 33 and 34), the surface pressure coefficients are little changed. The solution methodologies also perform in similar fashion. The URANS simulations perform best in terms of predicting the surface pressure distribution including the jog. The LES SBC method again predicts the suction pressure peak for both velocities. There is a difference between 40 m/s and 50 m/s with respect to the LES PBC methodology. At 40 m/s, LES PBC performs worse in terms of predicting the suction pressure peak with minimum values on the order of -2.05. At 50 m/s, this method performs better predicting minimum values of -2.5. All methodologies adequately predict the pressure recovery.

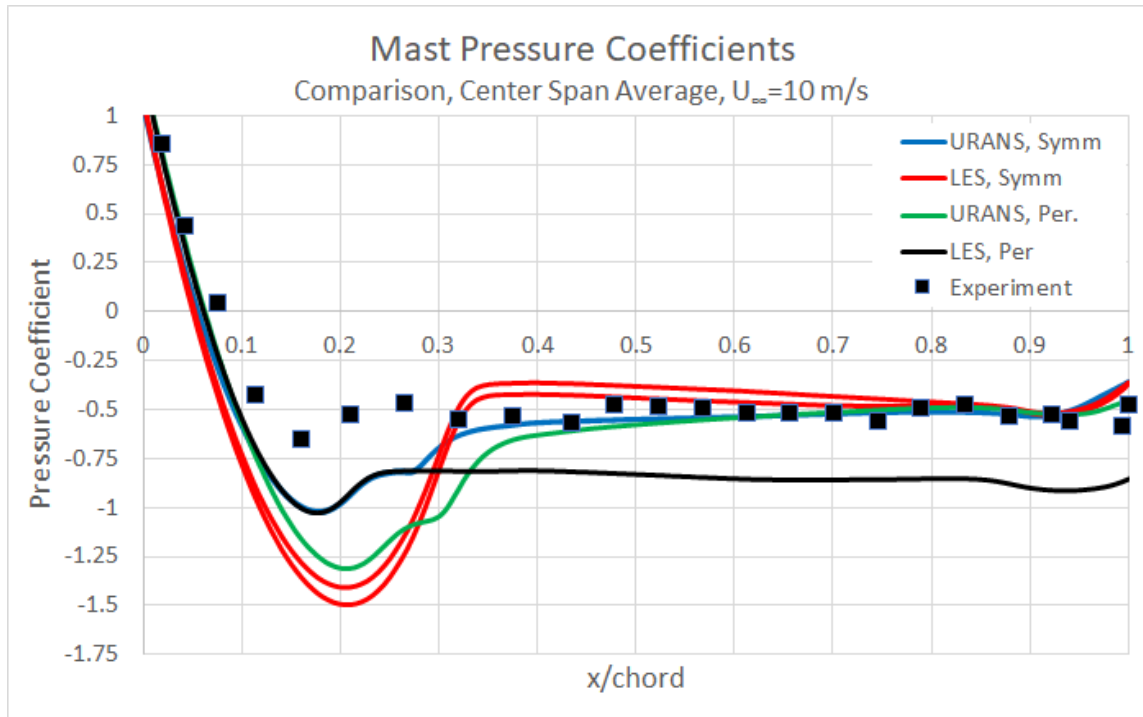


Figure 30. Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_\infty = 10$ m/s, $Re = 230,000$

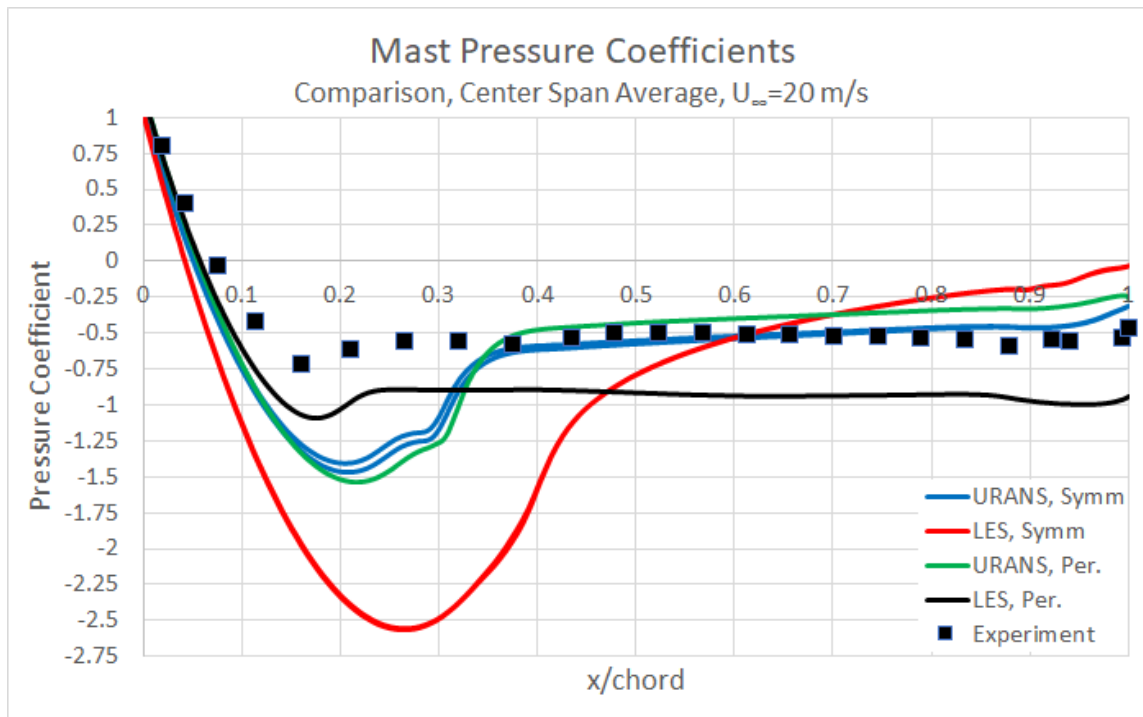


Figure 31. Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_\infty = 20$ m/s, $Re = 461,000$

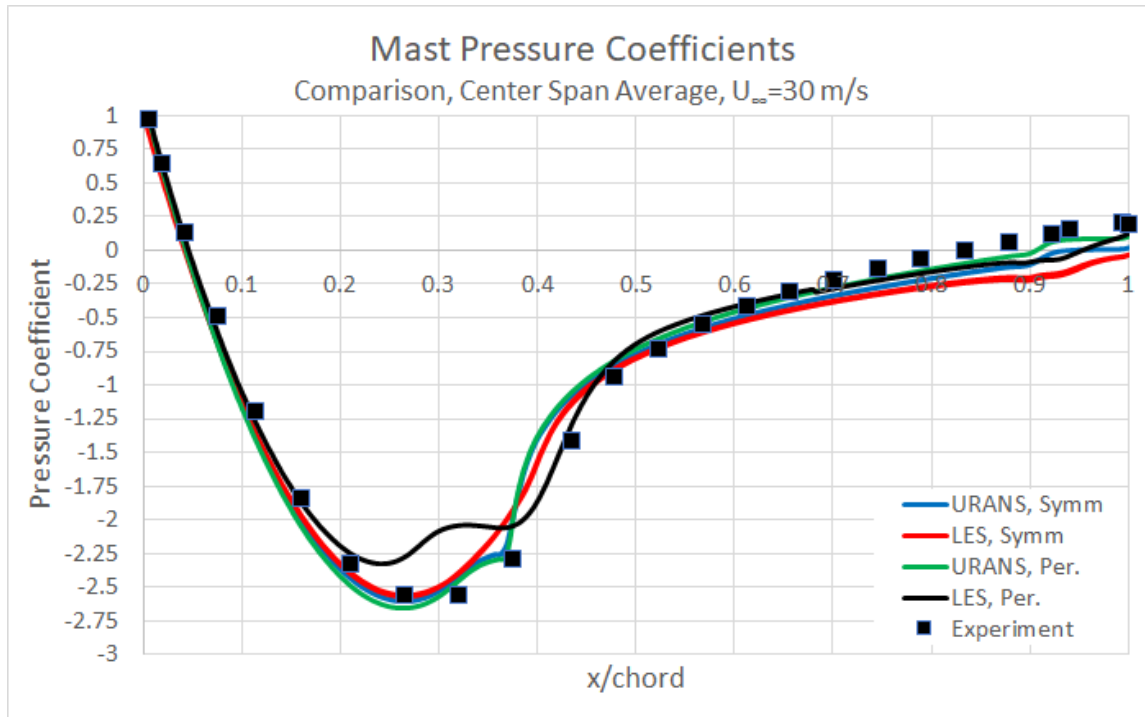


Figure 32. Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_\infty = 30$ m/s, $Re = 691,000$

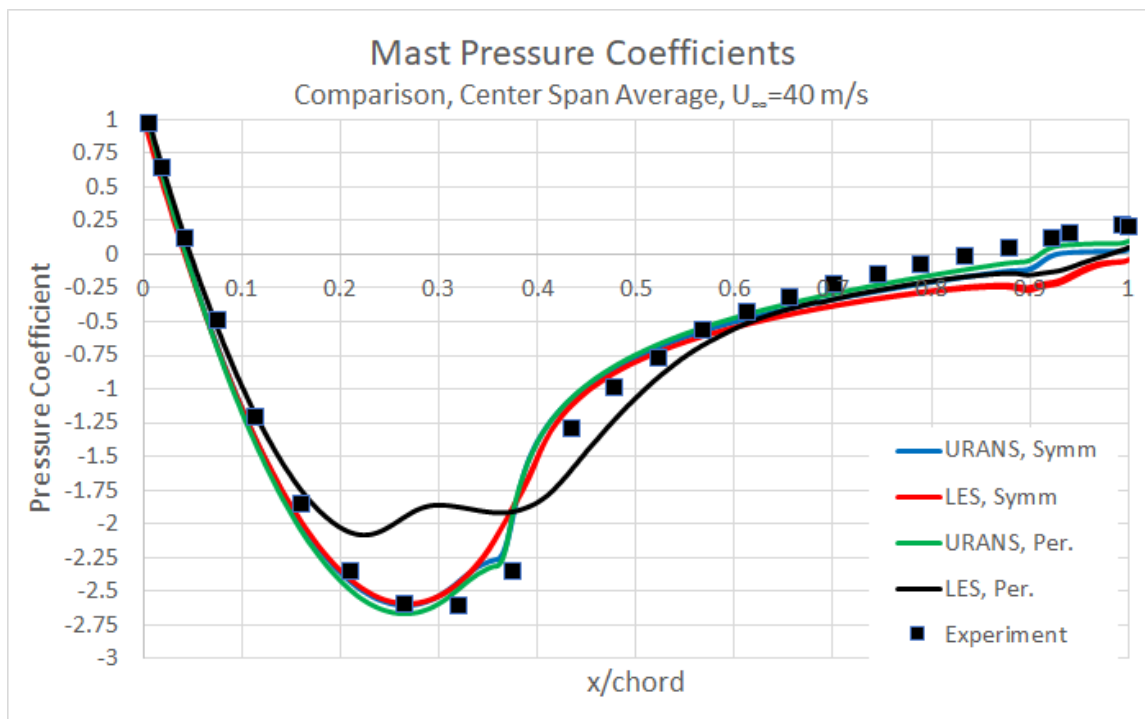


Figure 33. Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_\infty = 40$ m/s, $Re = 921,000$

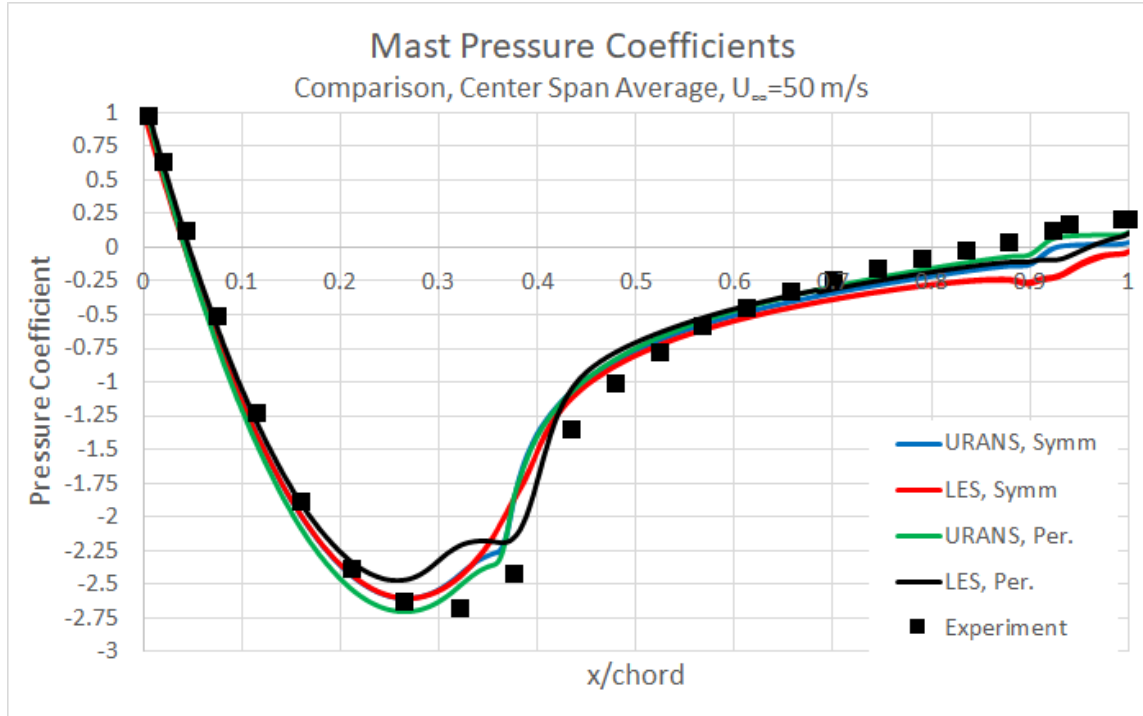


Figure 34. Mast Surface Pressure Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 50$ m/s, $Re = 1,152,000$

3.6 MAST NUSSELT NUMBER RESULTS

Figures 35 through 39 present the LES and URANS, PBC and SBC predictions of surface Nusselt number (Nu) and highlight the heat transfer characteristics with experimental results. At 10 m/s (figure 35), experiments measured a peak leading edge Nu of 500 and exhibit a gradual decline to 250 at $x/c_{\text{mast}} = 0.26$. Nu values in the wake region gradually rise in linear fashion to 400 at $x/c_{\text{mast}} = 0.9$ at the mast trailing edge. Nu values then increase in this region to 600. Both URANS simulations (SBC and PBC) predict qualitatively similar results with a rise in Nu at $x/c_{\text{mast}} = 0.25$. This peak is shifted downstream for URANS PBC. The LES SBC simulation substantially over-predicts Nu in the leading edge region. URANS and the LES PBC method slightly over-predict Nu in the leading edge region (600 vs. 500). The LES PBC method predicts the decline in Nu at $x/c_{\text{mast}} = 0.2$ and correctly predicts Nu over the aft region of the mast. LES SBC also predicts Nu in the aft region but LES PBC performs best overall.

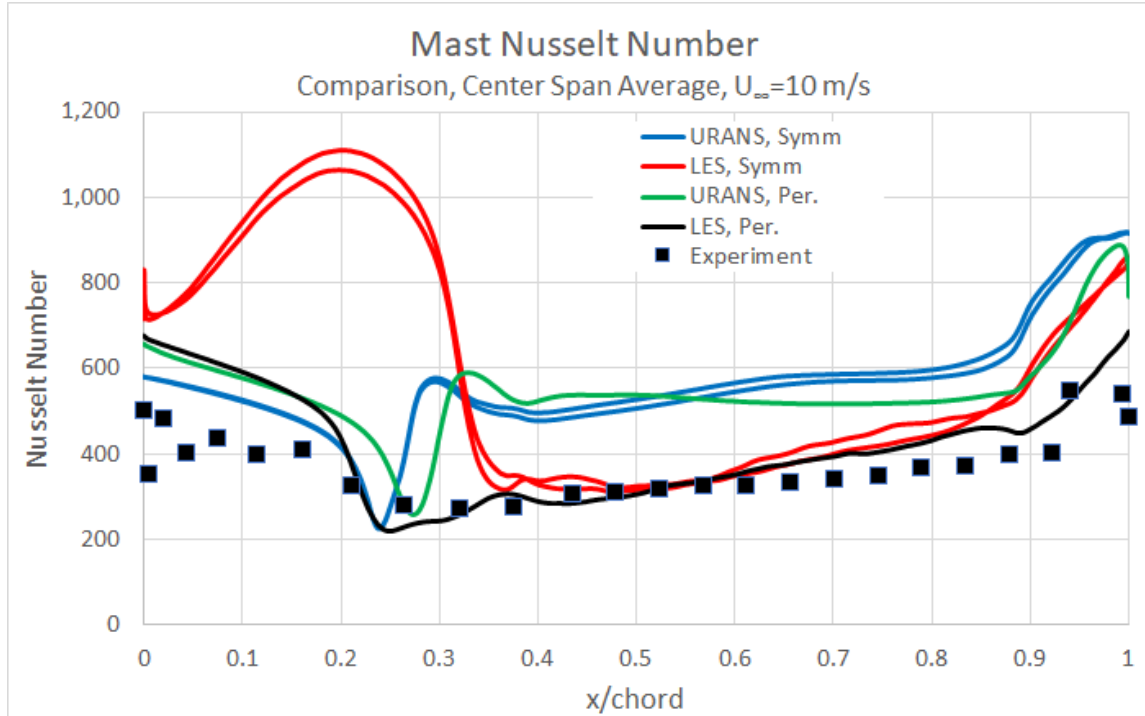


Figure 35. Mast Surface Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 10$ m/s, $Re = 230,000$

As the flow velocity is increased to 20 m/s (figure 36), experimental data suggest attached vs separated flow. This is indicated by a gradual decline in Nu from 700 at the leading edge pushed further downstream to $x/c_{mast} = 0.32$ with $Nu = 490$. This is followed by a sharper increase in Nu to 1,050 forming a peak at $x/c_{mast} = 0.45$ followed by a non-linear decrease to $Nu = 750$ at $x/c_{mast} = 0.85$. In the trailing edge region a sharp peak was measured with $Nu = 1,150$. Overall, the LES SBC performs best in terms of predicting this behavior. The heat transfer in the leading edge region is over-predicted, but the location of the rise is predicted with the peak values slightly under-predicted (950 vs. 1,050). Both URANS simulations are qualitatively similar and predict a sharper rise compared with experimental data. In addition, the wake Nu values are constant with a peak in the trailing edge region. The URANS predictions are qualitatively consistent with the 10 m/s case and predict separated flow. The LES PBC simulation is wholly consistent with separated flow.

At 30 m/s (figure 37), the flow is attached with all simulations predicting attached flow. Experimental data exhibit a modest decline in Nu in the leading edge region from 800 to 600 at $x/c_{mast} = 0.38$. This is followed by a sharp increase in Nu with peak values of 1,400 at $x/c_{mast} = 0.45$. A non-linear decline was then measured followed by a sharp increase in the trailing edge region. Measured Nu values approached 2,000 in this region. All methodologies over-predict Nu in the leading edge region. Both URANS simulations produce nearly identical results. Nu values decline in the leading edge region reaching a local minima of $Nu = 480$ at $x/c_{mast} = 0.35$ followed by a sharp increase matching experimental values at $x/c_{mast} = 0.45$. In the aft region, Nu decreases only modestly and over-predict experimental values as a result. At the trailing

edge, URANS predicts a precipitous decrease in Nu. Both LES method perform better in terms of predicting the characteristics of the experimental Nu, however, the SBC method substantially under-predicts the measured values. The PBC method performs much better. However, the rise in Nu begins at $x/c_{\text{mast}} = 0.32$ (vs. 0.38) making the peak less sharp. Peak values are similar with a slightly greater decline in Nu using LES PBC. At the trailing edge, there is a sharp increase in Nu to 1,100 although the peak experimental value of 2,000 was not reached.

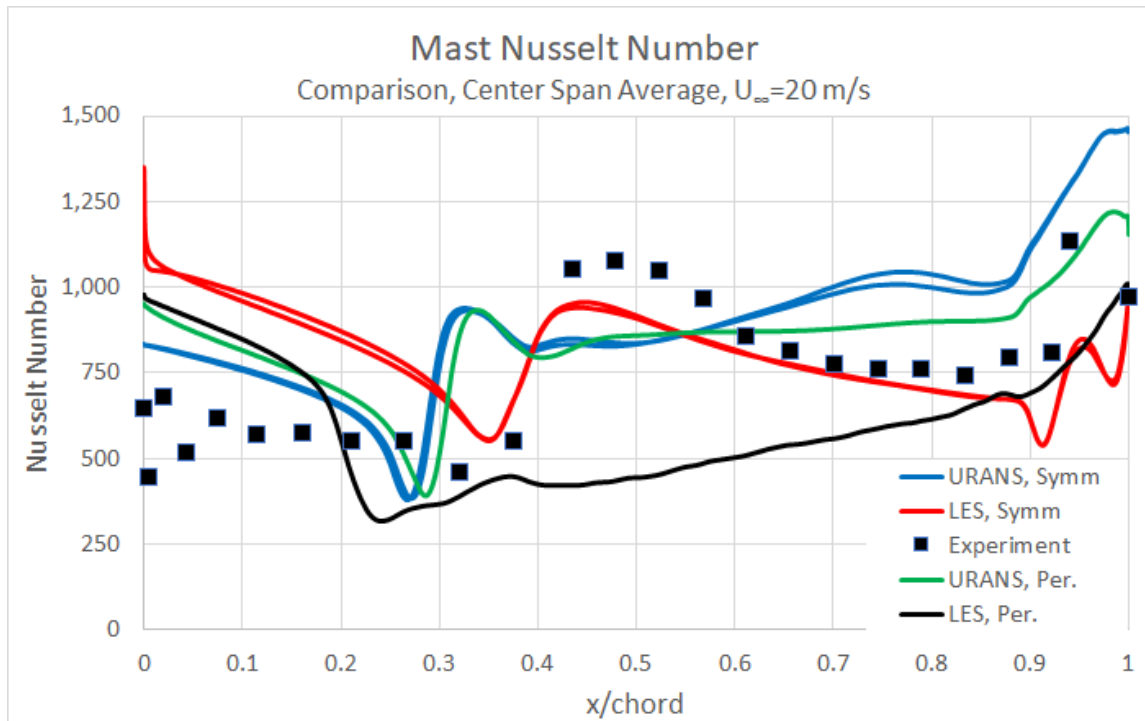


Figure 36. Mast Surface Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 20$ m/s, $Re = 461,000$

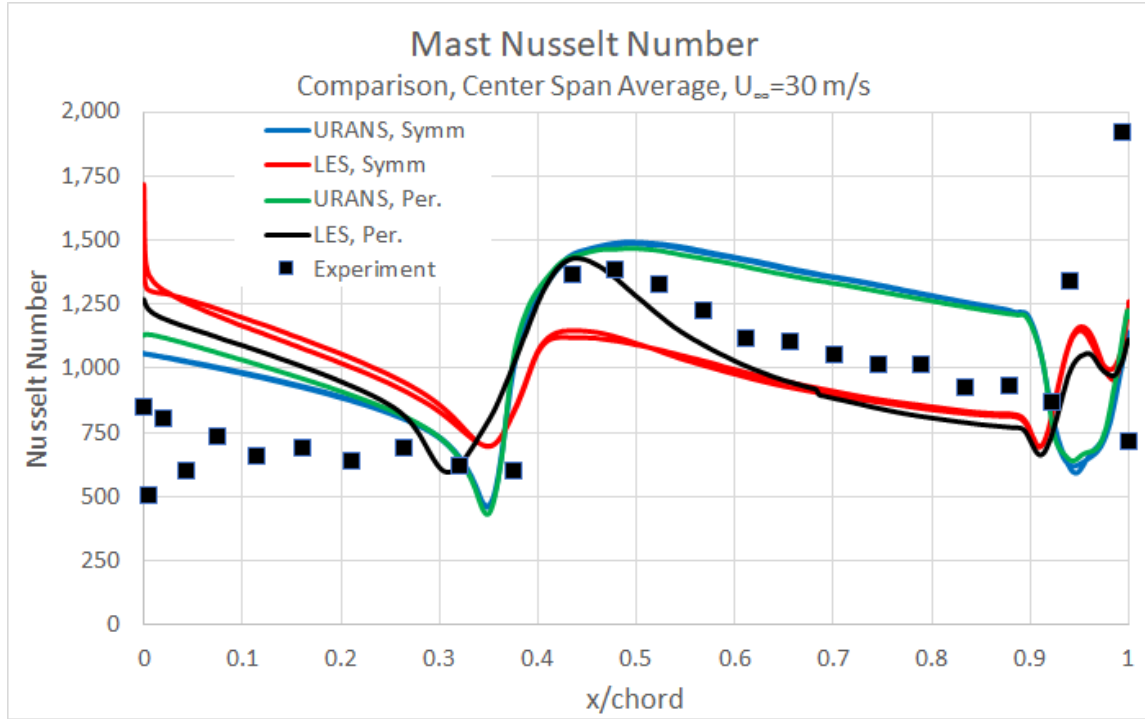


Figure 37. Mast Surface Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 30$ m/s, $Re = 691,000$

Results for the 40 m/s case are presented in figure 38. Experimental data are qualitatively similar with increased Nu. Nu values in the leading edge region decrease from 1000 to 750 with a sharp peak of 1,800 at $x/C_{mast} = 0.45$. Both URANS simulations are nearly identical and are able to predict the sharp increase in Nu with agreeing with experiment in terms of peak values. Similar to the 30 m/s results, Nu values in the aft region are over-predicted as is the sharp decline in the TE region. The LES SBC significantly under-predicts the heat transfer in the aft region. Again, the LES PBC method performs best overall. However, the Nu gradient is not nearly as sharp with the rise in Nu beginning at $x/C_{mast} = 0.29$. In addition, the peak experimental value of 1,800 is not reached (1,600) but the heat transfer in the aft region is predicted. A modest rise in Nu was predicted at the trailing edge and did not match the sharp increase measured.

At maximum flow velocities of 50 m/s (figure 39), experimental data qualitatively remain unchanged except for corresponding increases in Nu. Peak values of 2,000 were measured at $x/C_{mast} = 0.45$. For this test condition, URANS results are nearly identical except for a reduced peak Nu for the PBC compared with the SBC simulations (2,200 vs. 1,850). The sharp decline predicted in the trailing edge region are nearly identical. Both LES simulations significantly under-predict the heat transfer characteristics measured. While the PBC method does predict higher peak and aft region values (1,600 vs. 1,200), both are inadequate. The sharp rise in Nu in the trailing edge region is predicted and at least mimics the experimental behavior.

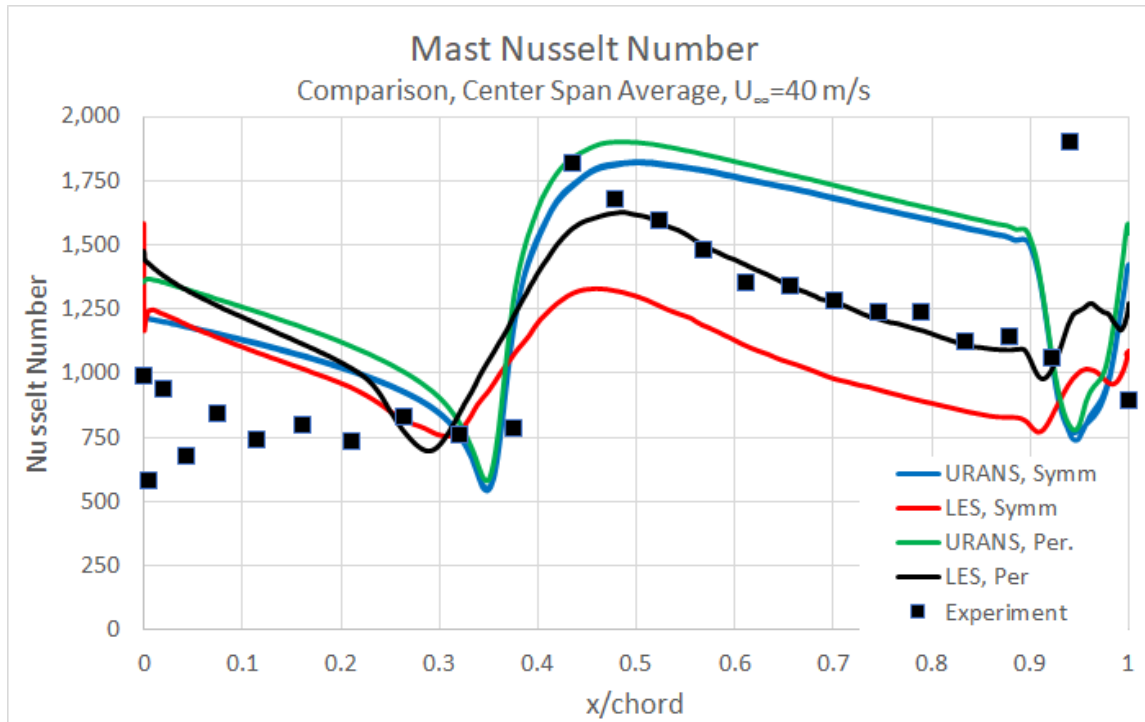


Figure 38. Mast Surface Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 40$ m/s, $Re = 921,000$

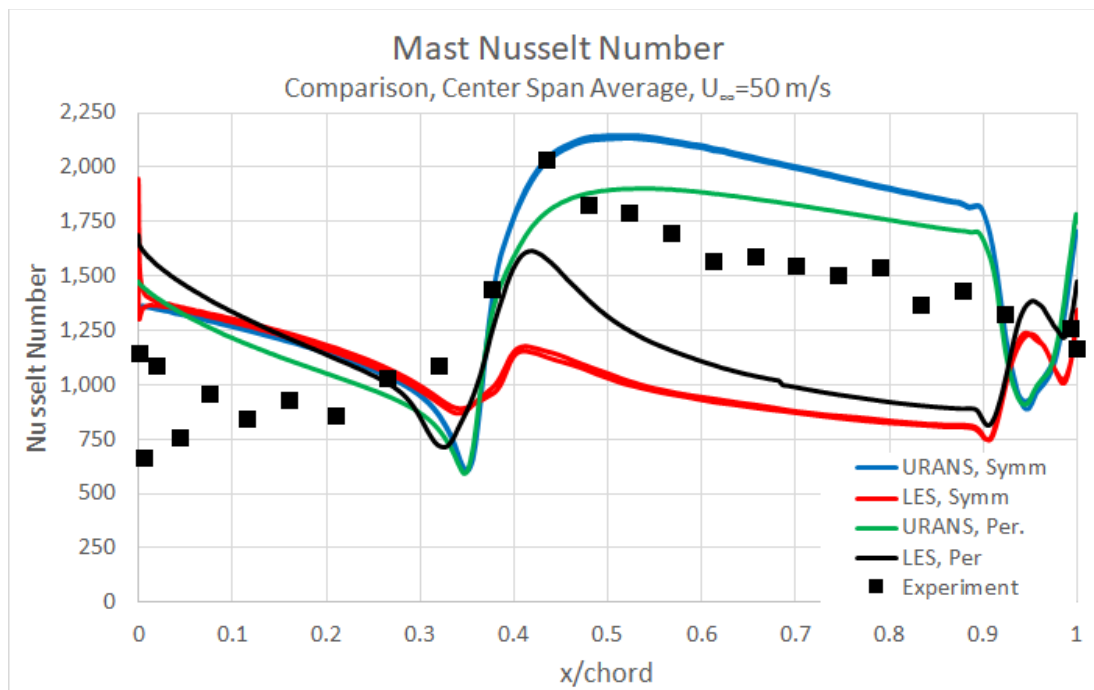


Figure 39. Mast Surface Nusselt Number Distributions for Periodic and Symmetrical URANS and LES Simulations for $U_{\infty} = 50$ m/s, $Re = 1,152,000$

3.7 MAST VELOCITY PREDICTIONS:

Experiments acquired mean and RMS axial and vertical velocity data to provide comparisons with computational simulations. Color contour plots of the mean axial velocities are shown in figure 40 for Symmetrical and periodic URANS and LES simulations. Instantaneous z-vorticity are shown in figure 40 and highlight the formed eddies.

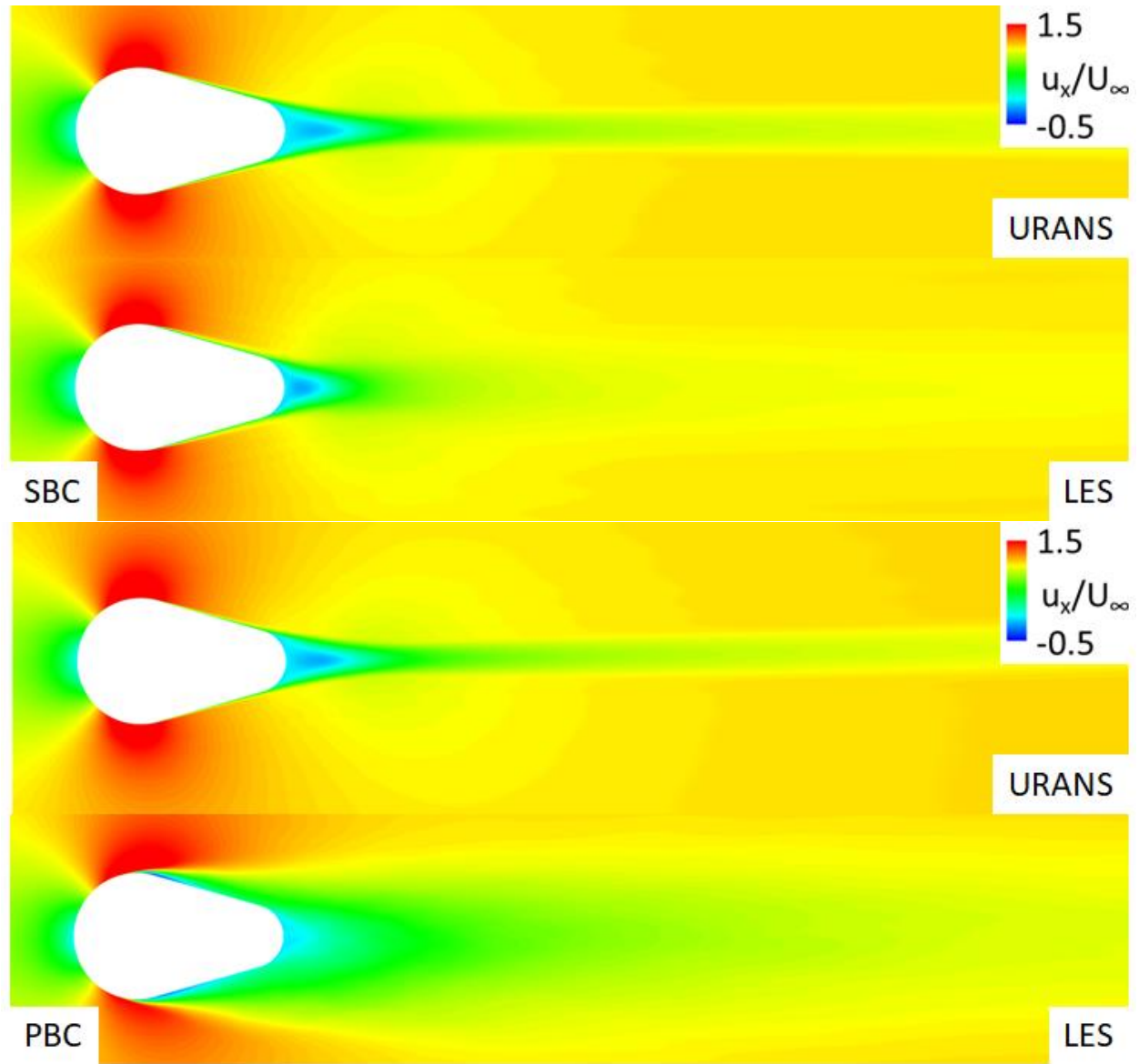


Figure 40. Color Velocity Contours of the Mean Mast Axial Velocity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_\infty = 40$ m/s, $Re = 921,000$

For this test condition, the flow is attached so the contour plots highlight the thickening boundary layer and differences in the flow computations. As can be seen, the SBC and PBC URANS simulations predict fully attached flow and a relatively thin boundary layer. The LES SBC simulations are similar to the URANS simulations and likewise predict a thin boundary layer. However, the wake deficit, especially downstream, appears less compared with the URANS simulations. The LES PBC simulations predict attached flow with a significantly thicker boundary layer and exhibit a wake that is significantly wider.

Figure 41 highlights the instantaneous z-vorticity color contours provide a better understanding regarding the flow predictions. For both URANS simulations, the vorticity remains confined to a thin region in the boundary layer and wake with no roll-up into defined coherent vortices. In contrast, the LES simulations model the small eddies in the wake. For the SBC simulations, small eddies form in the boundary layer but the boundary layer remains relatively thin. For the PBC simulations, eddies begin to form over the upper surface resulting in a thicker boundary layer while the mean flow appears attached. The wake then appears thicker due to the small eddies shed.

Streamwise and normal velocity components were measured normal to the surface at various locations over the mast. Velocities at these rake locations were computed as well for direct comparison with experiment. Rakes 1-4 correspond to mast cylindrical leading edge locations of $\theta = 0^\circ, 30^\circ, 60^\circ$ and 90° . Rake 5 is located at the transition between the cylinder and flat section ($\theta = 110^\circ$). Rakes 6-10 were evenly spaced between $x/c_{\text{mast}} = 0.51 - 0.95$ (corresponding to the transition from the flat section to trailing edge cylindrical section. Rakes 11 and 12 are located on the cylindrical trailing edge at $\theta = 145^\circ$ and 180° respectively. All computational rakes correspond to the experimentally measured ones (designated by “Exp” in the plots).

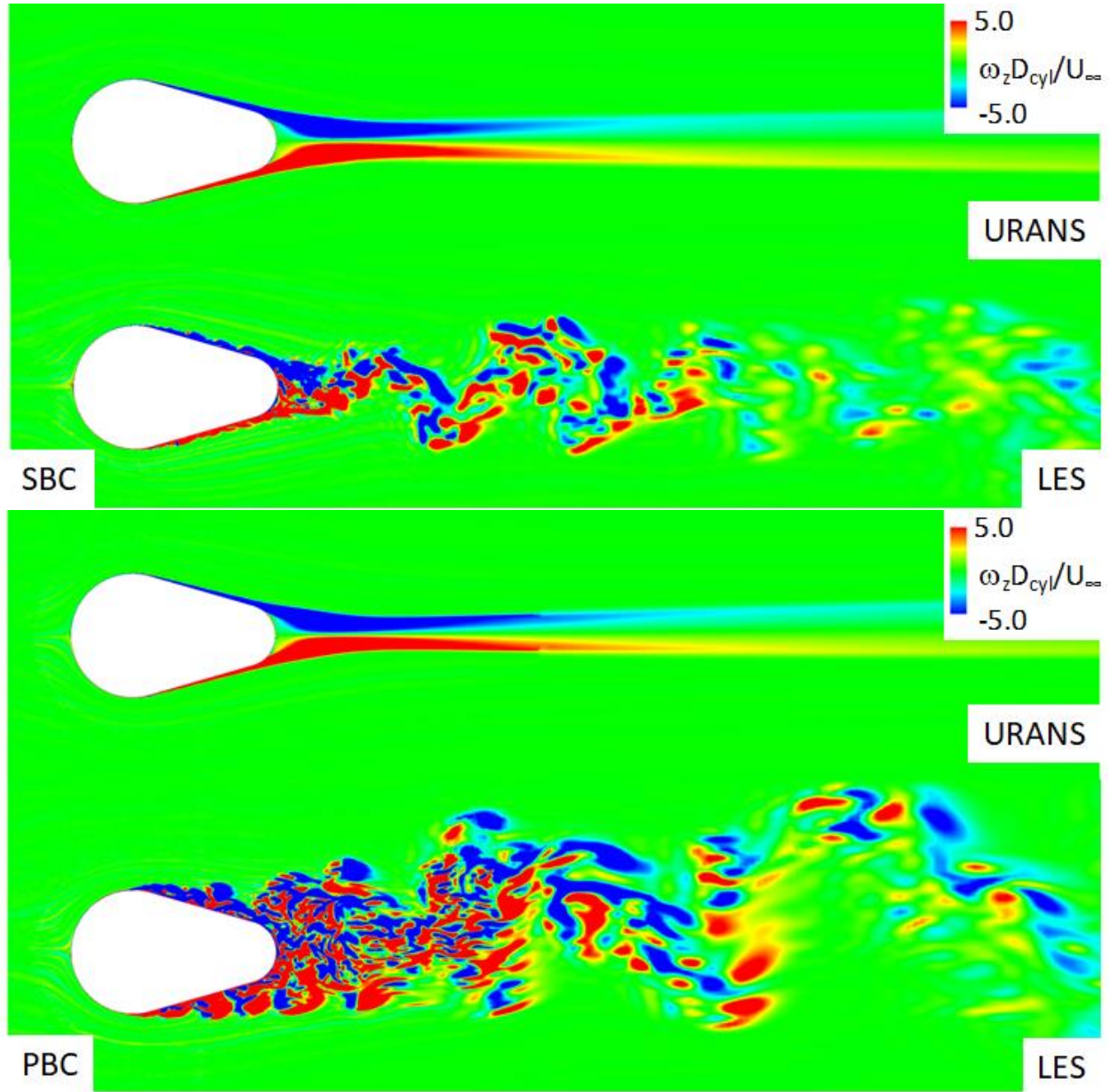


Figure 41. Color Velocity Contours of the Mast Z-Vorticity for Symmetrical (SBC) and Periodic (PBC) URANS and LES Simulations for $U_\infty = 40$ m/s, $Re = 921,000$

Figure 42 highlights the mast cylindrical leading edge mean streamwise and vertical velocity profiles (Rakes 1-4) for the 30 m/s flow velocity. Both URANS (SBC) and LES (PBC) are compared with experimental data. These profiles were found to be qualitatively similar for all flow velocities due to the fact the flow is attached in this region. As can be seen, streamwise velocity profiles are in excellent agreement with experiment. The vertical velocity profiles are mixed with Rake 2 computations over-predicting the experimental results. Better agreement is seen with Rake 3 and Rake 4 (located at $\theta = 90^\circ$) exhibiting near zero vertical velocities. In addition, there is minimal difference between the URANS and LES velocity results in this region.

Figure 43 highlights the streamwise and vertical velocity profiles located on the aft straight section of the mast for $U_\infty = 20$ m/s. URANS and LES profiles are significantly different as the URANS profiles are more representative of mild or transitional flow separation whereas LES predicts complete flow separation consistent with experimental results. URANS predicts attached flow at Rake 5 with x-velocities substantially greater than experiment. The flow separates beginning at Rake 6 as indicated by the reverse flow velocities. Conversely, LES predicts the correct separated flow characteristics matching the experimental velocity profiles at all Rake locations at least for the outer flow. In the separated region, as indicated experimentally by reduced constant but positive mean x-velocities LES predicts reversed mean x-velocities. URANS also under-predicts the mean y-velocities and does not match the shape of the experimental profile at any of the rake locations. In contrast, LES performs much better in terms of matching the profile shapes and values at Rakes 5 and 6. At the downstream rake locations, experimental vertical velocities remain near zero but continue to be positive for the LES simulations.

RMS streamwise and vertical velocity profiles are presented in figure 44 for the same test condition presented in figure 43 for the LES flow simulation. As can be seen in appendix B, URANS predicts very small RMS velocity values with the flow predictions being quasi-steady. URANS RMS velocities are therefore not presented. As can be seen, LES tends to over-predict the RMS velocity components in the separated flow region significantly. The actual shape of the RMS x-velocities does follow the experimental data, however, for Rakes 5-7. Similarly, RMS y-velocities over-predict experiments and the Rake 5 RMS y-velocity profile follows the experimental data. The Rake 6 data appears spatially shifted.

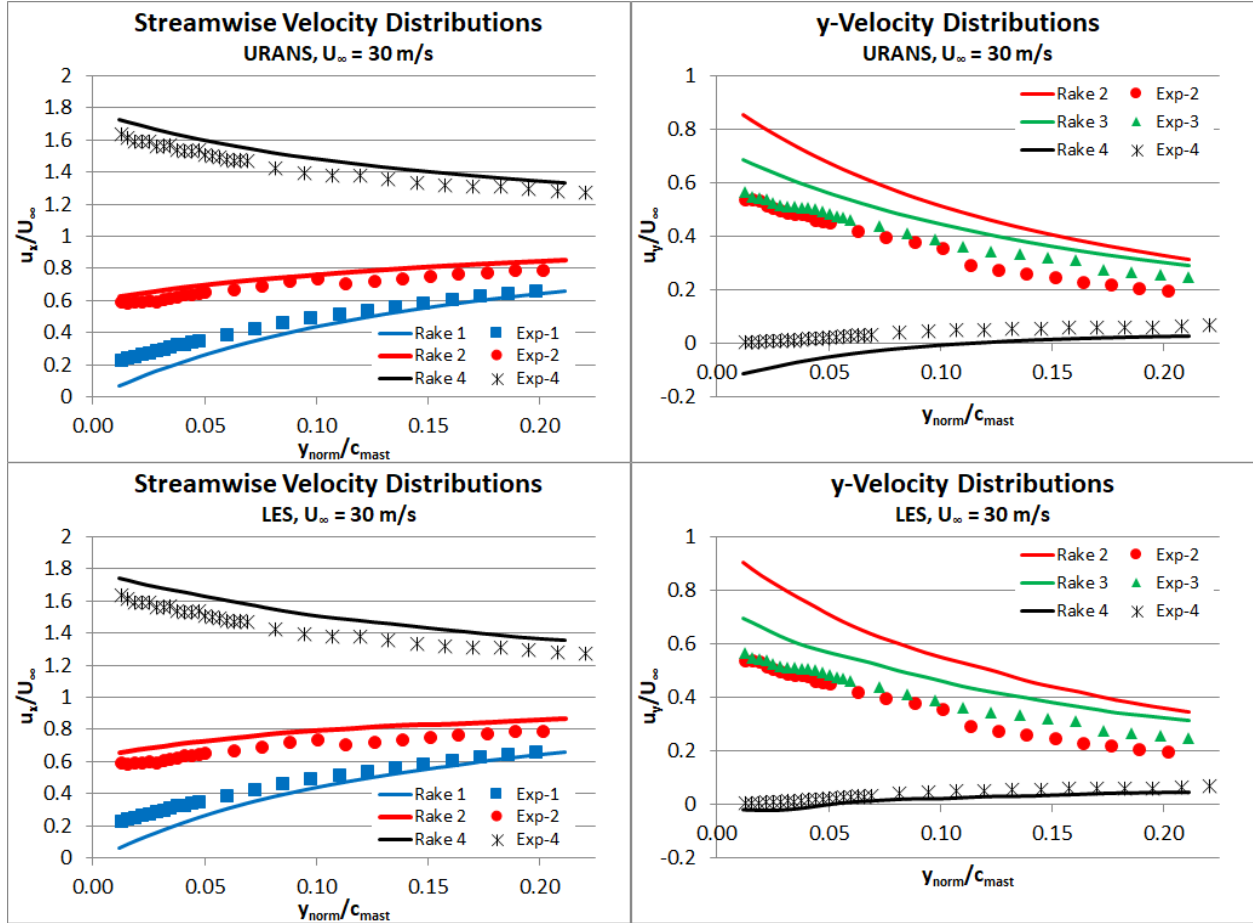


Figure 42. Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 1-4 for $U_\infty = 30$ m/s and $Re = 691,000$. URANS SBC and LES PBC.

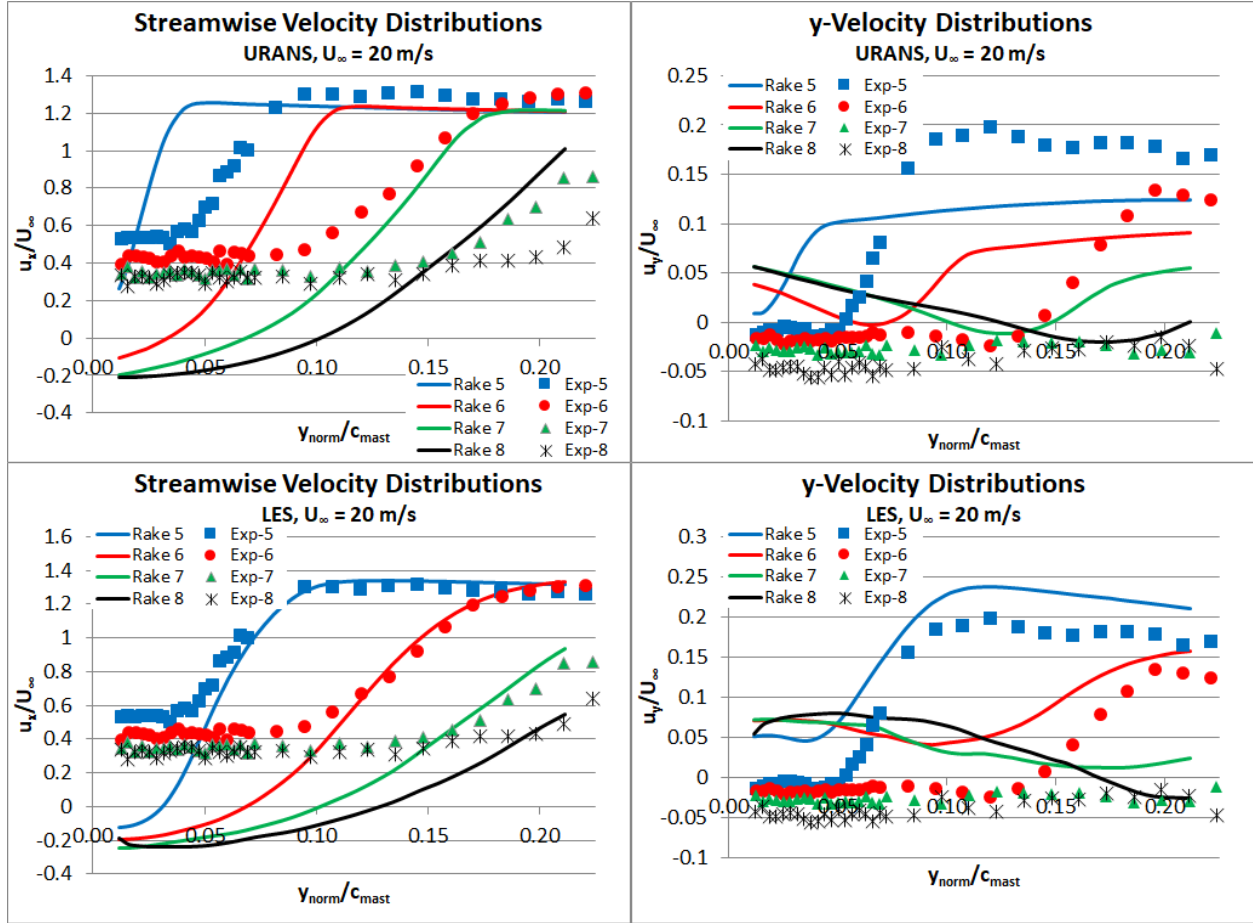


Figure 43. Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 5-8 for $U_\infty = 20$ m/s and $Re = 461,000$. URANS SBC and LES PBC.

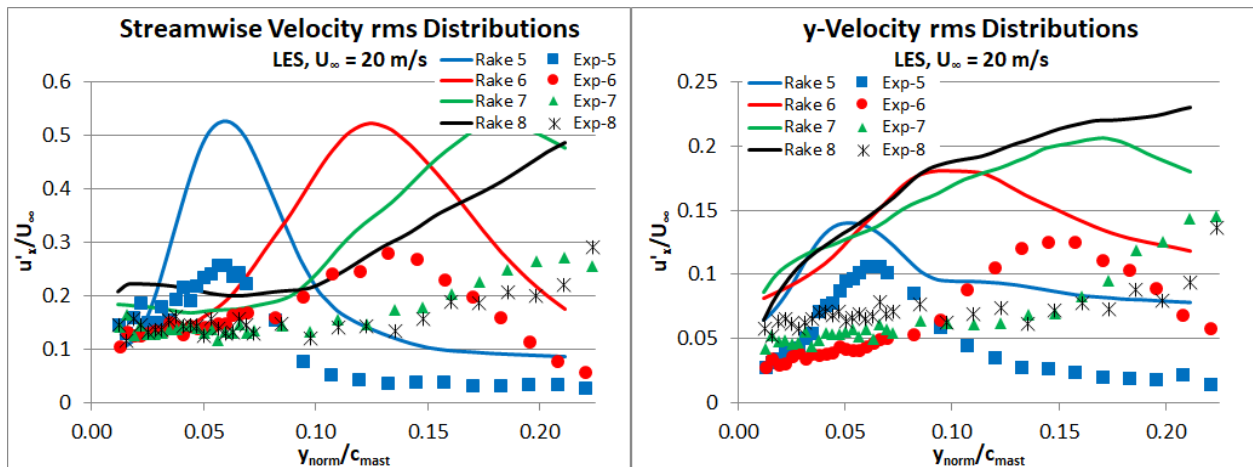


Figure 44. Mast Streamwise and Vertical RMS Velocity Profiles for Rakes 5-8 for $U_\infty = 20$ m/s and $Re = 461,000$. LES PBC.

Figure 45 highlights the streamwise and vertical velocity profiles located on the aft straight section of the mast for $U_\infty = 30$ m/s. For this particular case, experimental data indicated the flow was characterized by a thick but attached boundary layer. The LES PBC method best simulated this particular flow condition whereas URANS predicted for this and higher velocities fully attached thin boundary layer flow. Both mean and RMS streamwise and vertical velocities are presented at Rakes 5-8. Computed streamwise data agree with experiment at Rakes 5-7. At Rake 8, experimental data indicated lower flow velocities and significant increase in boundary layer thickness. The negative vertical velocities indicated attached flow at all locations. However, streamwise and vertical velocity data indicates significant boundary layer growth beginning at Rakes 7 and 8. Overall, the computed vertical velocities are more negative compared with experiment but follow the shape of the profile. RMS velocity data also indicate increased boundary layer thickness. At rakes 5 and 6, the data agree well. Minimal experimental RMS values outside the boundary layer are due to the freestream turbulence not having been modelled using LES. At Rakes 7 and 8, both streamwise and vertical RMS profiles indicate increased boundary layer thickness. While LES does predict increased RMS at these rake locations, they are significantly less than the experimental values.

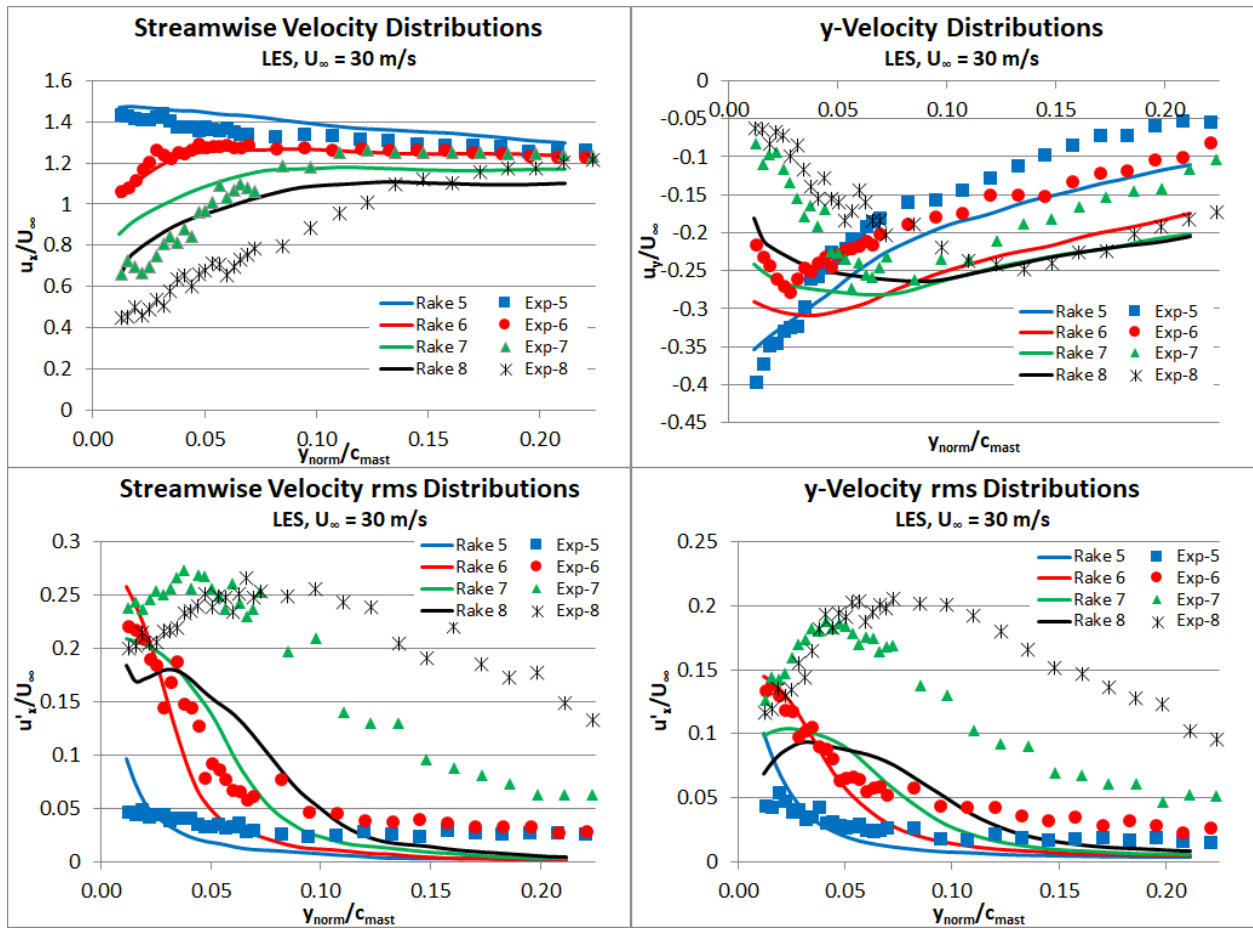


Figure 45. Mast Streamwise and Vertical Mean and RMS Velocity Profiles for Rakes 5-8 for $U_\infty = 30$ m/s and $Re = 681,000$. LES PBC.

At flow velocities of 40 m/s and higher, the flow over the mast is fully attached with characteristic thin boundary layers. Figure 46 presents the streamwise and vertical velocity profiles for URANS and LES simulations. Both methodologies are in excellent agreement with experiment at all rake locations. Both do slightly under-predict the x-velocities at Rake 5. In addition, the simulations predict slightly thicker boundary layers as indicated by the reduced velocities closer to the surface – especially at Rakes 7 and 8. The LES appears to perform better in terms of predicting the correct velocities at Rake 8. The negative vertical velocities, however, are significantly under-predicted by both URANS and LES. Minimum experimental velocities are on the order of -0.45 freestream, but URANS and LES only predict -0.3 freestream.

RMS velocities for the 40 m/s test case are presented in figure 47. Both streamwise and vertical experimental RMS velocities can be attributed mostly to the freestream turbulence component. Rake 8 x- and y- RMS velocity experimental values exhibit a rise closer to the surface indicating measurements near the edge of the boundary layer. RMS velocities associated with URANS and LES simulations show a significant rise at Rakes 7 and 8 predicting a thicker boundary layer at those locations.

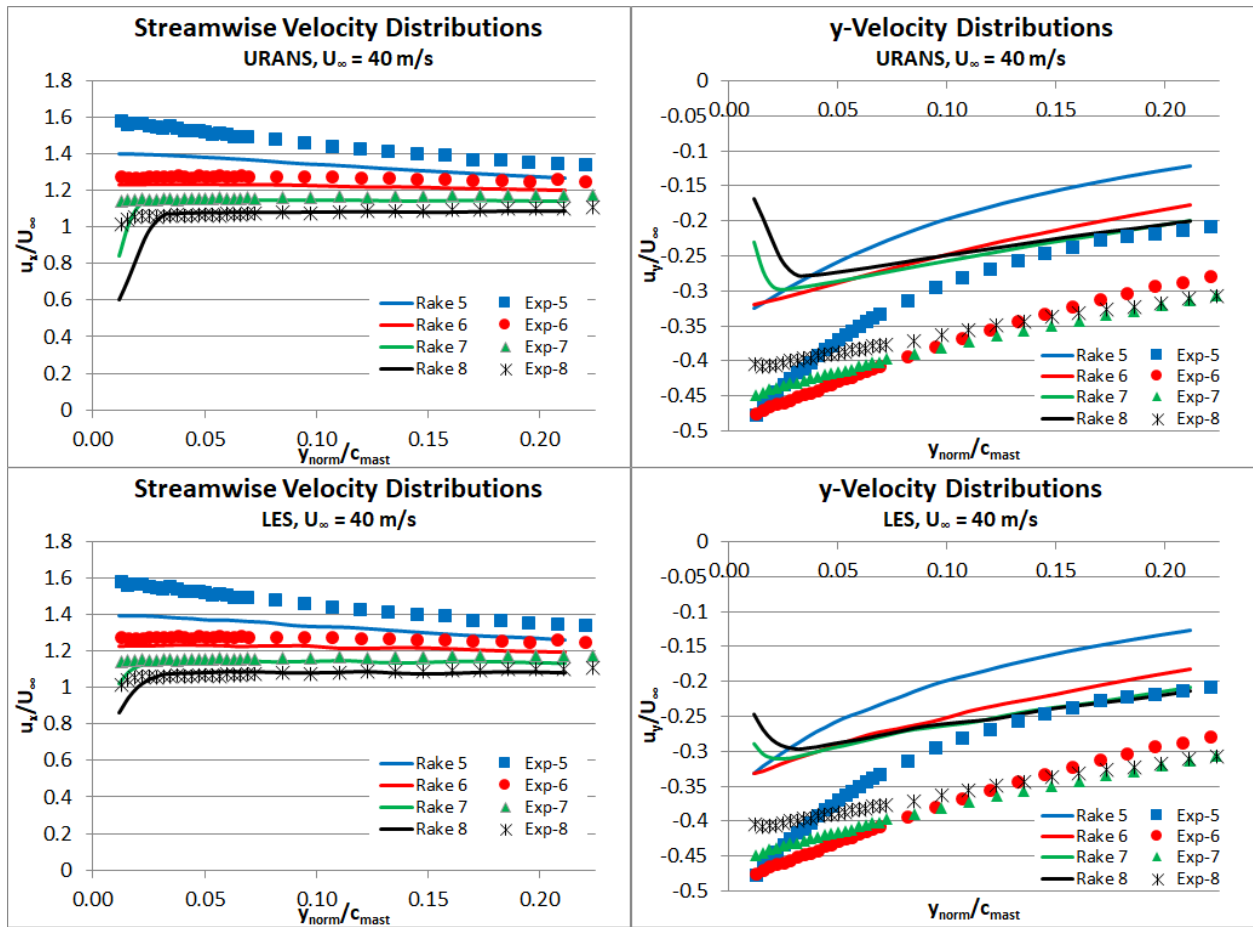


Figure 46. Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 5-8 for $U_{\infty} = 40$ m/s and $Re = 921,000$. URANS SBC and LES PBC.

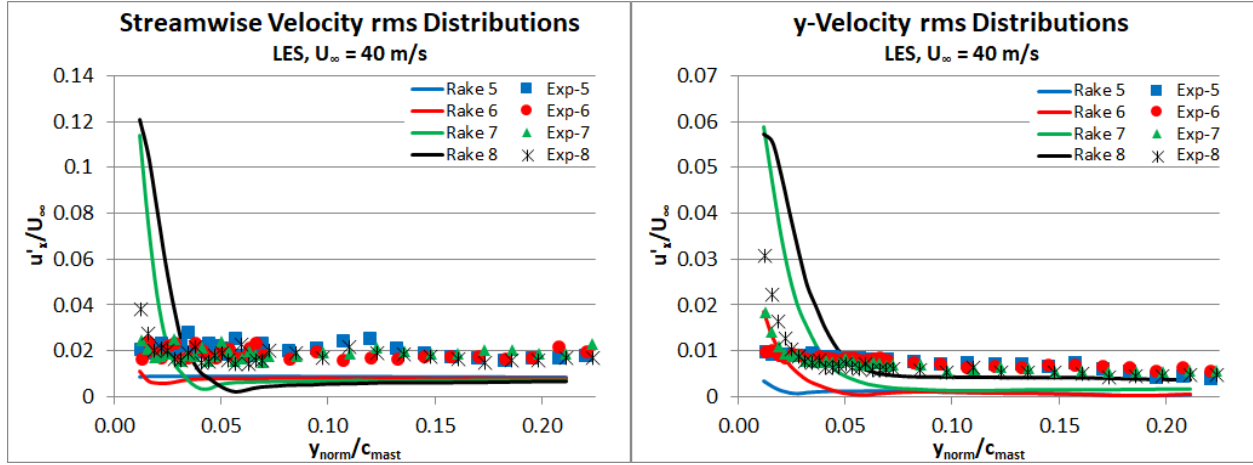


Figure 47. Mast Streamwise and Vertical RMS Velocity Profiles for Rakes 5-8 for $U_{\infty} = 40$ m/s and $Re = 921,000$. LES PBC.

The thick wake flow in the aft region of the mast was measured and simulated with streamwise and normal velocity profiles presented in figure 48 for $U_{\infty} = 40$ m/s. Rakes 9 and 10 are located on the upper surface and project into the main flow. At these rake locations, URANS and LES agree well with experiment in the outer region. Consistent with the upstream wakes, a thicker boundary layer is predicted as indicated by the reduced streamwise velocities closer to the surface. Rakes 11 and 12 are located in the wake. Rake 11 values are consistent with experiment but are just spatially shifted due to thicker wake predictions. Consistently positive streamwise velocities of 0.2 freestream were measured along the wake centerline. Conversely, a region of reversed flow is predicted by both URANS and LES. For URANS, the reversed flow region extends along the entire profile. LES predicts a reversed flow region to $x/c_{mast} = 0.15$ followed by positive streamwise velocities that match experiment at the end of the profile. The vertical velocity predictions show that URANS continues to under-predict the experimental values significantly. Conversely, LES performs much better in this region. Although Rake 9 vertical velocities are greater by 0.1 freestream, Rake 10 values are quite close within 0.03 freestream. Rake 11 values also follow the experimental profile, but are shifted spatially.

The corresponding RMS velocity profiles for the LES simulations are presented in figure 49. The RMS velocities at Rakes 9 and 10 are consistent with experiment aside from the increased boundary layer thickness prediction. At Rake 11, the RMS x- and y-velocities are both over-predicted, but follow the overall shape of the experimental profile. Centerline RMS x- and y-velocities are significantly over-predicted and both increase at downstream locations.

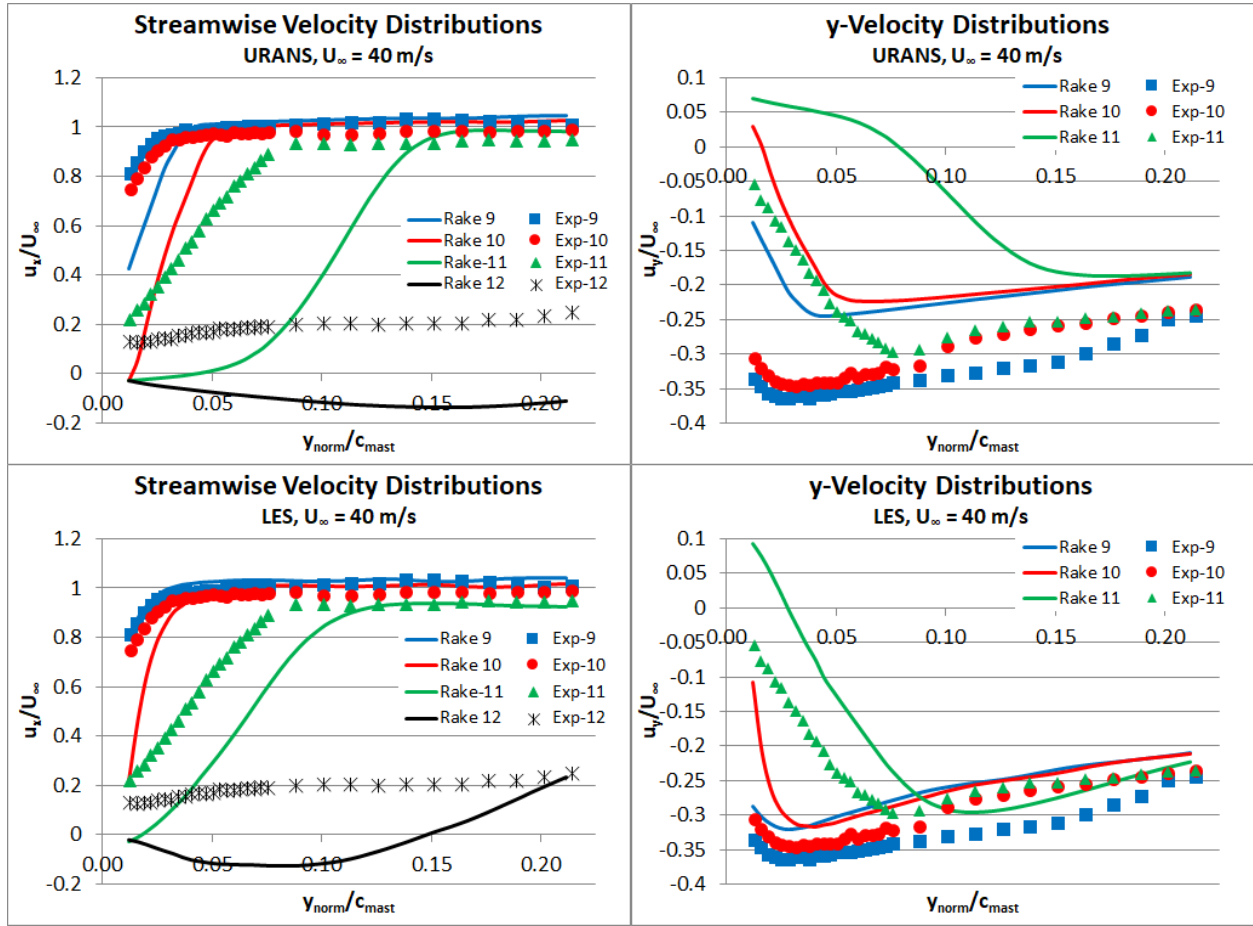


Figure 48. Mast Streamwise and Vertical Mean Velocity Profiles for Rakes 9-12 for $U_\infty = 40$ m/s and $Re = 921,000$. URANS SBC and LES PBC.

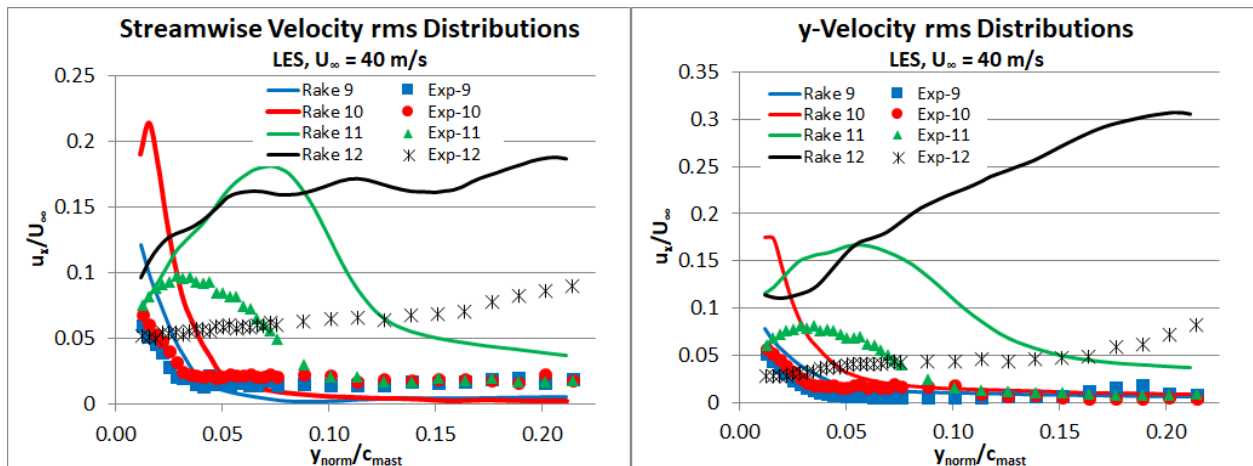


Figure 49. Mast Streamwise and Vertical RMS Velocity Profiles for Rakes 9-12 for $U_\infty = 40$ m/s and $Re = 921,000$. LES PBC.

4. DISCUSSION

The comparisons between URANS and LES highlight the relevant physics that must be captured in order to predict flow and heat transfer phenomena sufficiently. Comparison of these methodologies also indicate which is sufficient to provide the information that is required to scientists and engineers. It is known the URANS only captures the large-scale flow features that are on the order of the body being modelled. LES on the other hand is used to predict very small flow features that affect a body. The idea behind LES as applied to walls is that the boundary layer is sufficiently resolved by the grid to capture the small-scale flows of interest. URANS wall models are vital to properly predicting the large-scale flows. Wall models become necessary, as the boundary layer becomes thinner and the grid anisotropic. Ideally, LES would forego wall models, but the thin boundary layers associated with high Reynolds number attached to flow make them necessary to treat problems of engineering interest. With that in mind, two simple geometries eliciting complex flow fields over a wide range of Reynolds numbers to best examine the effectiveness of URANS and LES in computing the surface pressure and heat transfer characteristics for laminar and turbulent, attached and separated flow fields.

The problem of a circular cylinder in cross-flow is one of the most extensively studied problems due to the simple geometry, yet complexity of the elicited flow fields, that change greatly depending on laminar or turbulent flow separation. Experiments measured the surface pressure and heat transfer over this range. At the lower velocities, laminar flow separation was evident resulting in surface pressure distributions that were flat beginning at the point of separation. The observation that URANS with transition SST wall models substantially over-predicted the surface pressures (with pressure peaks) indicates the inability of the wall models to capture the complex laminar-turbulent transition physics. Alternatively, LES was much more effective at predicting surface pressure. Even though the values were over-predicted, the profiles did not exhibit a significant pressure peak and the SBC better captured the three-dimensionality of the problem. This was also indicated in the ability LES SBC to capture the heat transfer characteristics, replicating the experimental results very well. URANS predicted sharp increases in heat transfer near the point of separation that were not measured experimentally. The formation of small eddies near the point of separation properly modeled the flow phenomena at this point and downstream in the separated flow region. URANS models the flow as large vortices shed into the wake, whereas LES properly captures the small eddies and resultant impact on the wall.

Experiments measured the surface pressure and heat transfer over a wide range of Reynolds numbers. It is readily apparent that 3-D URANS simulations using SBC were unable to capture the true 3-D aspects of the flow. This is visually illustrated by the color contour plots of the axial velocity and y-vorticity displayed in figure 50. As can be seen, there is excessive flow around the end for URANS resulting in decreased near wake velocities and increased far wake velocities at the cylinder centerline. The vorticity plot highlights a two secondary large vortex structures at mid-span with opposite y-vorticity. This has the effect of reducing the suction pressure peak on the top of the cylinder with increased 3-D variation. The LES, however, reduces the flow to smaller eddies, as can be seen by the y-vorticity contour plots. As

a result, the surface pressure is even away from the cylinder end and the wake structure is much more even with 2-D characteristics.

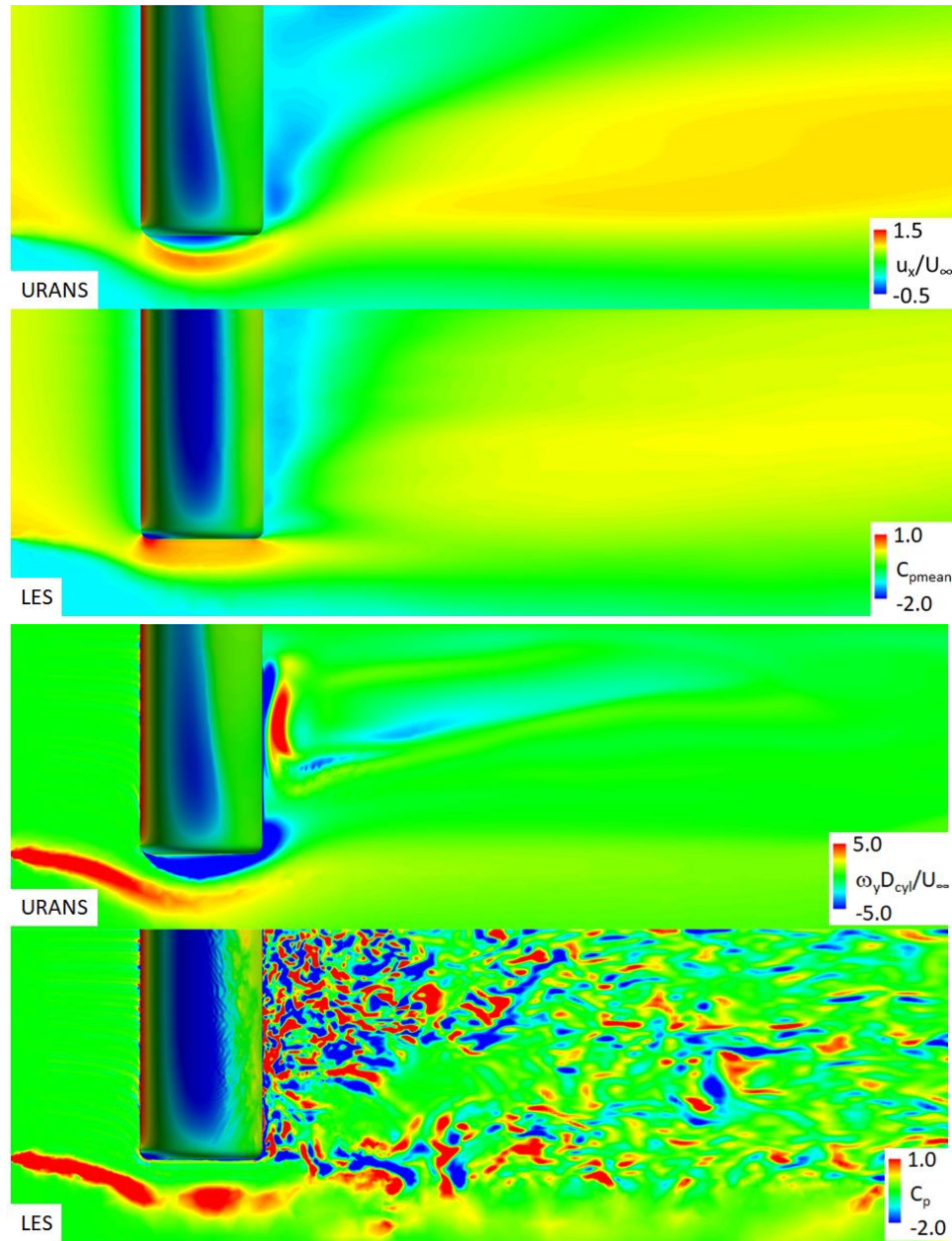


Figure 50. Cylinder Axial Velocity and Y-Vorticity Color Contour Plots in the X-Z Plane with Surface Pressure Coefficients at the Cylinder Centerline for URANS and LES Using SBC. $U_\infty = 32$ m/s, $Re = 710,000$

As the cylinder flow regime is transitioned to turbulent separation, URANS is better suited to capture a larger portion of the relevant flow physics. In addition, the turbulent wall models are more applicable. In addition, the flow effectively becomes more two-dimensional.

As a result, the surface pressure distributions were properly modelled with URANS using PBC. The three-dimensionality associated with the problem resulted in the prediction of large-scale vortices around the cylinder ends using SBC. This effectively reduced the overall surface pressures. LES continued to predict the formation of smaller eddies even around the end of the cylinder. As a result, the surface pressures predicted using PBC and SBC were similar. It is clear that the relevant physics require the cascade of energy to smaller scales vs. modeling large-scale vortices. This includes the formation of smaller vortices around the cylinder end. For this reason, LES with SBD was extremely effective in capturing the mean surface pressure distributions over the full turbulent flow range from $U_\infty = 21 - 22$ m/s.

The problem of flow past a cylinder with turbulent separation illustrates the difficulty correctly predicting the heat transfer characteristics. It is vital to compute the thermal boundary layer in the region of interest properly. The relevant equations indicate that the heat transfer is related to the temperature gradient at the wall so that properly computing the temperature distribution is vital toward getting the heat transfer correct. In all cases, the wall models perform sufficiently to capture the heat transfer on the forward part of the cylinder. For turbulent flow, a sharp increase in heat transfer was measured at the point of separation. None of the models was able to capture this peak. URANS performed best in terms of predicting a sharp gradient at the point of separation but proceeded to over-predict the heat transfer at the rear of the cylinder significantly. This is due to the prediction of large-scale vortices. Alternatively, LES predicted a much more gradual rise in surface heat transfer proximal to the separation point but under-predicted the heat transfer in the aft region of the cylinder. The formation of the smaller wake eddies did not properly model the heat transfer characteristics.

The velocity and vorticity contour plots and the subsequent axial and vertical velocity mean and RMS plots ably illustrate the differences between URANS and LES. The vorticity contour plots especially highlight the ability of LES to cascade flow energy to smaller spatial scales. As a result, the mean streamwise and normal velocities were better predicted using LES for both the laminar (11 m/s) and turbulent (32 m/s) flow cases. The RMS velocities also highlight the limitations of both methods. URANS significantly under-predicted the RMS velocities whereas LES significantly over-predicted them. As URANS modelled the flow using larger scale vortices, the energy was kept at larger scales resulting in relatively small variations in streamwise and normal velocity. LES modelled the flow as much smaller eddies. However, it is clear that these eddies were still too large compared with the axial flow. Significantly smaller eddies and associated lower velocities would produce smaller RMS velocities. While the scale of eddies modelled was sufficient for the surface pressure calculations, the scale of eddies was still too large to fully capture the heat transfer characteristics.

The simple mast geometry poses another complex flow problem. At low velocities (and Re) the flow separates near the point where the cylindrical leading edge intersects with the straight section. As the freestream velocity is increased, the flow became attached and separated near the trailing edge forming a thick wake region. In addition, the measured boundary layer characteristics can vary over this velocity range. At 30 m/s, the boundary layer was substantially thicker even though the flow was attached. At the higher velocities, thin boundary layers were found experimentally. The 20 m/s produced an interesting test case. Velocity measurements and surface pressure distributions were consistent with separated flow. However, heat transfer

measurements were consistent with attached flow. For air, the kinematic viscosity is known to increase with temperature resulting in lower Re . Intuitively, this should result in more pronounced separation, not flow attachment. It is therefore possible the ribbon used to generate the surface heat had uneven regions tripping the boundary layer resulting in attached flow. Regardless, the comparison of experimental data with URANS and LES simulations provided great insight into the flow physics captured.

Unlike the cylinder, the mast end was bounded using a fence to maintain two-dimensional flow conditions. The relative two-dimensionality was confirmed as SBC and PBC data were very consistent. The two-dimensionality of the flow allowed for an expanded examination of grid size pushing the limits of the computational capability. As a result, very high-resolution grids could be used to examine the effectiveness of LES. As shown by the grid convergence study, URANS results were changed minimally with reduced grid size. This actually highlights one of the main advantages of URANS. If, for example, it is important to model the surface pressure only, then this can be accomplished for attached turbulent flow using minimal grid resolution. However, if the physics dictate replication of surface heat transfer, then the high-resolution grids and LES need to be used.

The grid convergence study also highlighted the limitations of the LES wall models in terms of predicting the surface pressure for this particular problem. The low-resolution grid actually performed best in terms of predicting the surface pressure for the attached flow case. This is because the wall models were dominant as the grid size dictated LES would be used only away from the body. As resolution was increased, LES was applied closer to the wall and subsequent limitations of grid size exposed. Only the very high grid resolution produced improved correlation with experimental surface pressure. However, LES was necessary to predict the surface heat transfer properly. The low-resolution grid performed poorly. As resolution was increased, the peak in heat transfer was modelled, as was the heat transfer over the aft portion of the mast.

The low velocity case (10 m/s) illustrates the difficulty both methods had in terms of predicting the surface pressure and the advantages of LES in predicting heat transfer for laminar separation. Experimental data show a minimal surface pressure peak with flat constant pressures downstream. URANS and LES predicted a surface pressure peak with separation aft. LES with PBC and URANS with SBC did best in terms of matching the surface pressure. However, LES with PBC performed best in predicting the heat transfer in the separated region. URANS predicted a significant peak at the point of separation and over-predicted the heat transfer aft.

At 20 m/s, LES with PBC predicted separated flow and LES with SBC predicted attached flow. The discrepancy was likely due to differing grid resolutions (by necessity, SBC had decreased grid resolution). URANS also predicted flow separation. In this case, the heat transfer was best modelled by LES with SBC but the surface pressure was best modelled by LES with PBC. This further demonstrates the observation that the experiments measured separated flow for surface pressure and velocity but attached flow for the heat transfer.

At velocities of 30 m/s and higher, the flow is definitely attached. URANS and LES using SBC show excellent agreement in all cases with experimental data. These test cases

demonstrate the strengths of URANS in predicting these specific flow quantities. Due to the limited grid resolution, LES defaults to using the wall models. For LES, PBC, the surface pressure peaks are under-predicted further demonstrating that even though the very high grid resolution was used, the mixture of wall models and LES resulted in not capturing the pressure. However, the surface heat transfer results were in much better agreement using LES PBC compared with the other methods. URANS SBC and PBC were nearly identical and did better predict the sharp rise in heat transfer seen as the flow enters the mast straight section. The heat transfer was significantly over-predicted in the aft region and unrealistically drops off near the trailing edge. LES PBC smooths the peak over a larger region likely due to limits imposed on the grid resolution and wall modelling. However, in the aft region, the heat transfer is predicted very well at 30 and 40 m/s. At the highest velocity, LES PBC surface pressure predictions are greatly improved but the heat transfer is under-predicted. This again suggests the dominance of the wall models coupled with limits regarding the grid (and subsequent small eddies) that are modelled. In all cases, LES does somewhat capture the increase in heat transfer at the trailing edge. The peak is significantly less than that measured experimentally and this peak substantially increases with flow velocity. This finding further demonstrates the necessity of modelling even smaller eddies in order to capture the heat transfer in this region fully.

Comparison of URANS and LES with the measured mean and RMS velocities further demonstrate the advantages and limitations of each methodology in modelling these complex flows. The RMS velocities associated with the URANS calculations were near zero indicating the flow was effectively modelled as quasi-steady. In contrast, the RMS velocities associated with the LES simulations tended to over-predict the experimental values. This further makes it clear that while the smaller eddies modelled by LES resulted in much better prediction of the mean streamwise and vertical velocities compared with URANS, the eddies were still larger than those found in the actual flow. Smaller eddies would produce lower velocities resulting in reduced RMS values. It is further likely that the larger eddies modelled in the attached flow region resulted in the formation of thicker boundary layers at the higher flow velocities of 40 m/s. The fact that LES under-predicted the boundary layer thickness at 30 m/s may be attributed to not correctly modelling this particular flow regime.

5. CONCLUSIONS

URANS and large eddy simulation computational fluid dynamic solution methodologies were evaluated against experimental data to understand the range of applicability in terms of predicting surface heat transfer, pressure and near surface flow quantities. The simple cylinder and mast geometries elicit complex flow fields over a wide range of flow regimes providing a significant challenge in terms of the ability to predict these flows. Experimental data were collected in an open-jet facility that was geometrically replicated via CFD. Both periodic and Symmetrical boundary conditions were examined. Symmetrical boundary conditions better reflected the actual flow conditions but inherently was limited to larger mesh sizes. Periodic boundary conditions allowed for the examination of more resolved meshes.

For cases of flow past a cylinder, experiments left the ends open, resulting in inherently three-dimensional flow problems at lower Reynolds numbers. Significant differences were found at these flow velocities suggesting additional vertical flow produced around the ends. At these low flow velocities, URANS performed poorly overall. LES performed very well in terms of predicting the surface pressure and heat transfer. As the flow velocity was increased, resulting in turbulent separation, URANS performed much better using periodic boundary conditions. Symmetrical boundary conditions resulted in significantly under-predicting the surface pressure and over-predicting the heat transfer. Conversely, LES performed best in terms of predicting the surface pressure with the use of Symmetrical boundary conditions. At these higher velocities, both URANS and LES failed to predict the sharp rise in heat transfer at the separation point. URANS did predict a sharper increase whereas LES predicted a more gradual one near the separation point. Overall, URANS tended to over-predict the heat transfer in the aft region of the cylinder. LES tended more closely match the heat transfer, but still tended to under-predict the actual values.

Comparison of the flow velocity profiles also provided an understanding of the effectiveness and limitations of the URANS and LES methodologies. Both methods accurately predicted the velocity profiles in the forward part of the cylinder where the flow was attached. In the separated region, URANS velocity profiles showed this method under-predicted the thickness of the separated region and significantly under-predicted the RMS velocities. LES accurately predicted the shape of the profiles. However, reversed flow velocities were predicted in the separated region that were not measured experimentally. In addition, LES over-predicted the RMS velocities but did match the shape of the profiles. For the turbulent separation case, URANS performed poorly and was unable to match the profiles shapes or magnitudes. The RMS predictions did increase but did not match the experimental values. LES performed substantially better in terms of matching the shape of the velocity profiles for both axial and vertical flow velocities. Again, RMS values were over-predicted overall with the profile shapes matched. The centerline RMS axial velocities followed closely the experimental values.

The mast geometry was unique with a complex set of flow physics elicited. At low velocities, the flow separates aft of the cylindrical leading edge apex. At sufficiently high velocities, the flow becomes attached due to the turbulent boundary layer physics. Experimentally, a complex transition from fully attached to fully separated was measured in the

20-30 m/s range. At 20 m/s, surface pressure and velocity profiles indicated separated flow whereas surface heat transfer measurements predicted attached flow. At 30 m/s, the flow was attached with a thicker boundary layer region compared with the higher flow velocities. For the most experiments, the use of fences on the mast ends was used to ensure better two-dimensional flow conditions. This was confirmed computationally as there was minimal difference using Symmetrical and periodic boundary conditions. The differences in the methodologies was attributed to differences in grid resolution in the case of LES. URANS grid resolution examinations demonstrated little difference in surface pressure or heat transfer highlighting this methods effectiveness in modelling desired flow phenomena with relatively low grid resolution.

For the low velocity case where flow separation was clear, URANS best modelled the surface pressure and LES accurately modelled the surface heat transfer. For this case, the differences in Symmetrical vs. periodic boundary conditions was largest. At 20 m/s, these differences were minimal with the exception that the use of higher resolution periodic boundary conditions resulted in separated flow predictions using LES. LES with Symmetrical boundary conditions predicted attached flow and URANS predicted separated flow. LES periodic performed best in predicting the surface pressure and Symmetrical performed best predicting the heat transfer. For cases of clear flow attachment, URANS performed best predicting the surface pressure. Predicting attached, turbulent boundary layer flow is the strength of this methodology. However, it did not predict the overall heat transfer. The initial sharp rise was predicted with the aft region heat transfer significantly over-predicted. LES predicted a more gradual rise in heat transfer but did accurately predict the heat transfer in the aft region. The exception was the highest velocity case exposing the limits of LES. Finally, in the trailing edge region, URANS significantly under-predicted the heat transfer with a precipitous decline. Alternatively, LES predicted a modest increase but still failed to predict sharp rise measured experimentally.

The velocity profiles demonstrate URANS predicted the flow in a quasi-steady manner as indicated by the near zero RMS velocity predictions across the entire flow regime. LES was better able to predict the velocity profiles for both separated and attached flow cases. Generally, LES over-predicted the RMS velocities but tended to match the RMS profile shapes. This indicates that the actual flow was composed of smaller eddies that generate smaller local velocity variations. Even the mean LES streamwise profiles showed reversed flow predictions for separated flow whereas experiments indicated positive streamwise flow. Breakdown of the flow scales to smaller eddies would account for this.

This research highlights the applicability, usefulness and limitations of URANS and LES in terms of predicting desired surface pressure, heat transfer and flow velocities. URANS is best for attached turbulent flow with the ability to predict surface pressures correctly, even with relatively low grid resolutions. This makes it an effective tool if a quick turnaround is desired. Surface heat transfer requires properly resolving the temperature gradient and thermal boundary layer. As such higher resolution is required. LES is most effective in this regard but requires significantly more grid resolution to resolve the small eddies. As such, its usefulness is still limited to the lower velocities. The velocity profiles further highlighted the effectiveness of LES in predicting the correct flow velocities. Both methods have their uses for engineering level problems.

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APPENDIX A CYLINDER VELOCITY PROFILES

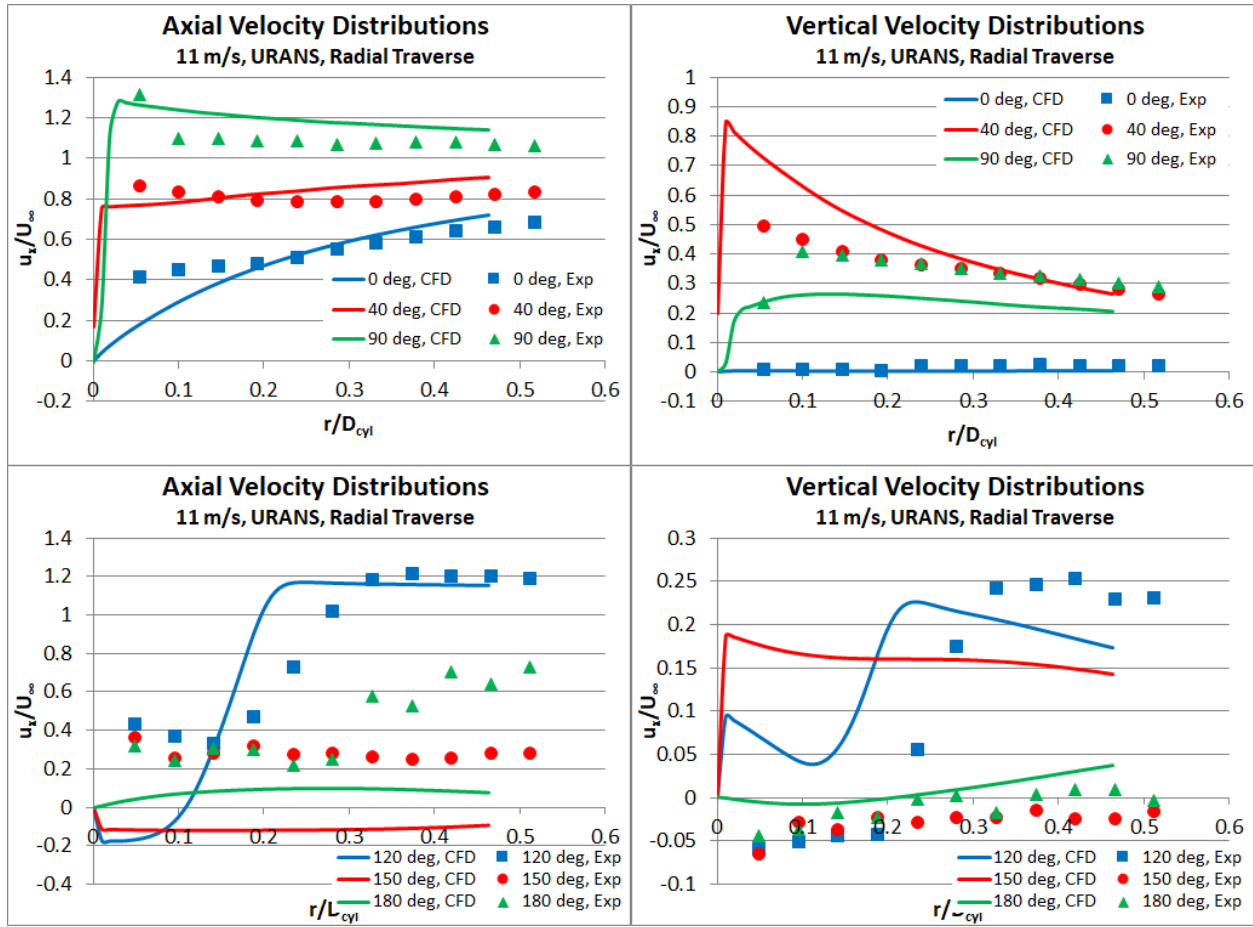


Figure A-1. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 11$ m/s, $Re = 244,000$. URANS Simulation with Symmetrical Boundary Conditions.

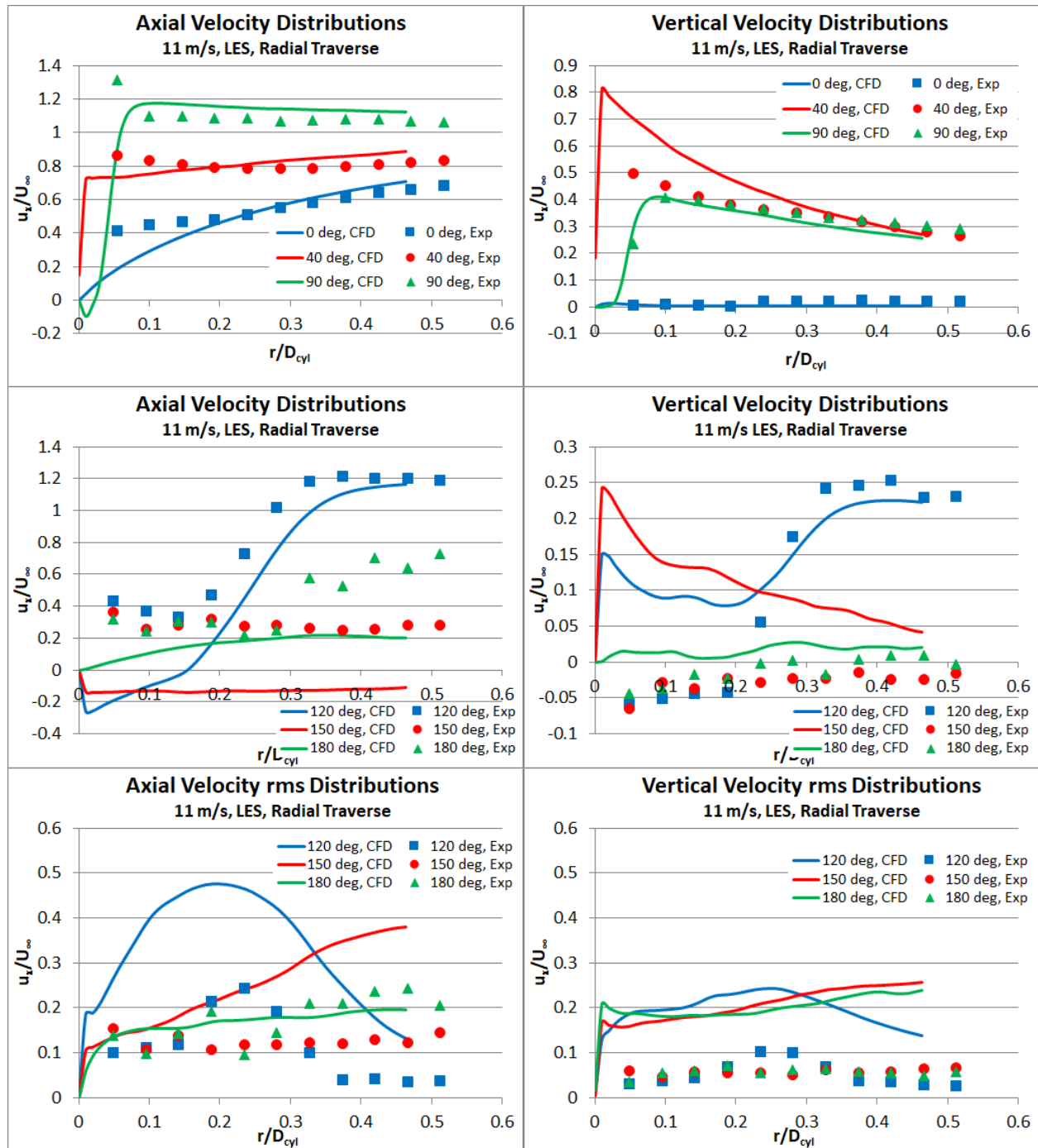


Figure A-2. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 11$ m/s, $Re = 244,000$. LES Simulation with Symmetrical Boundary Conditions.

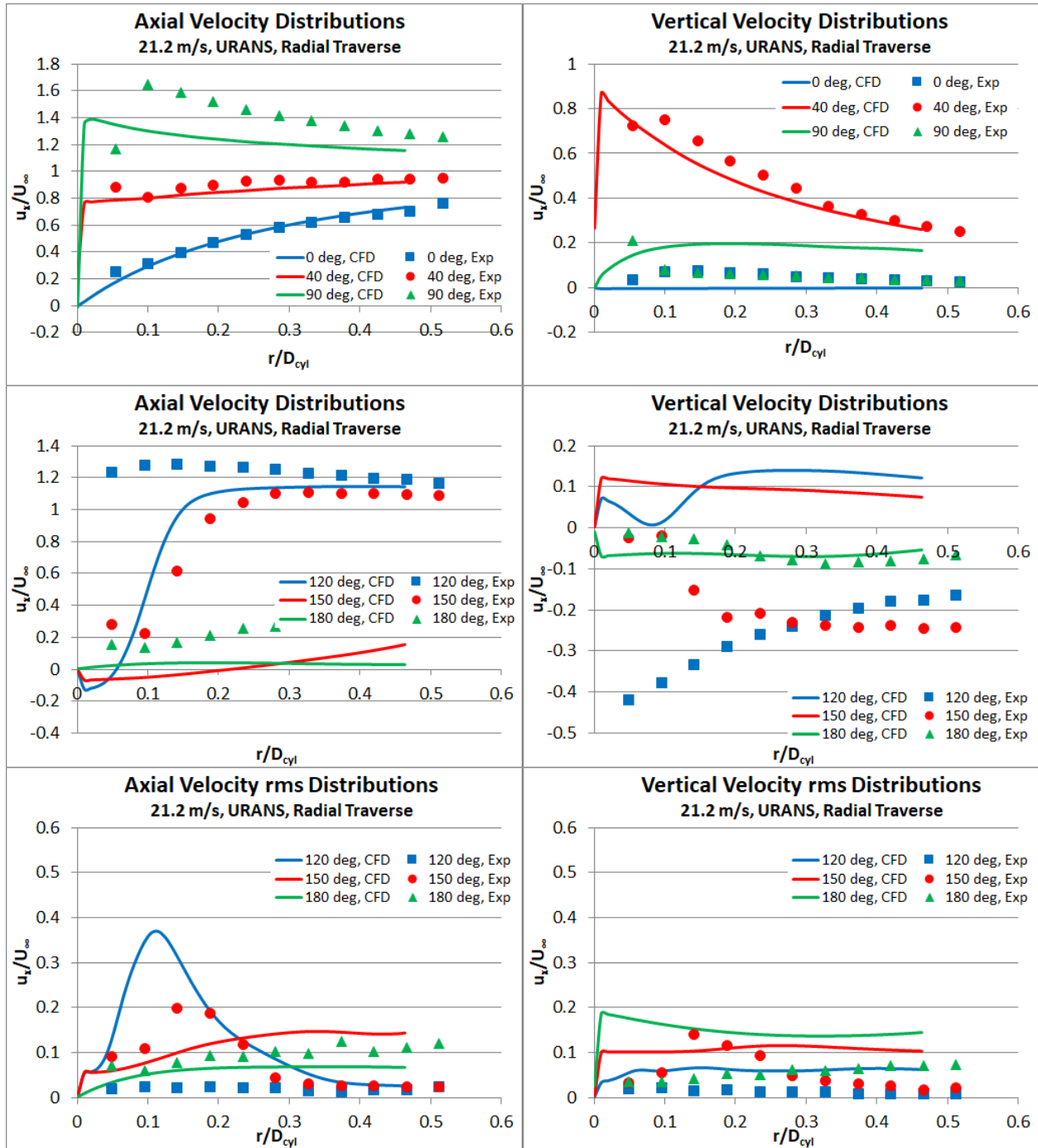


Figure A-3. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 21.2$ m/s, $Re = 470,000$. URANS Simulation with Symmetrical Boundary Conditions.

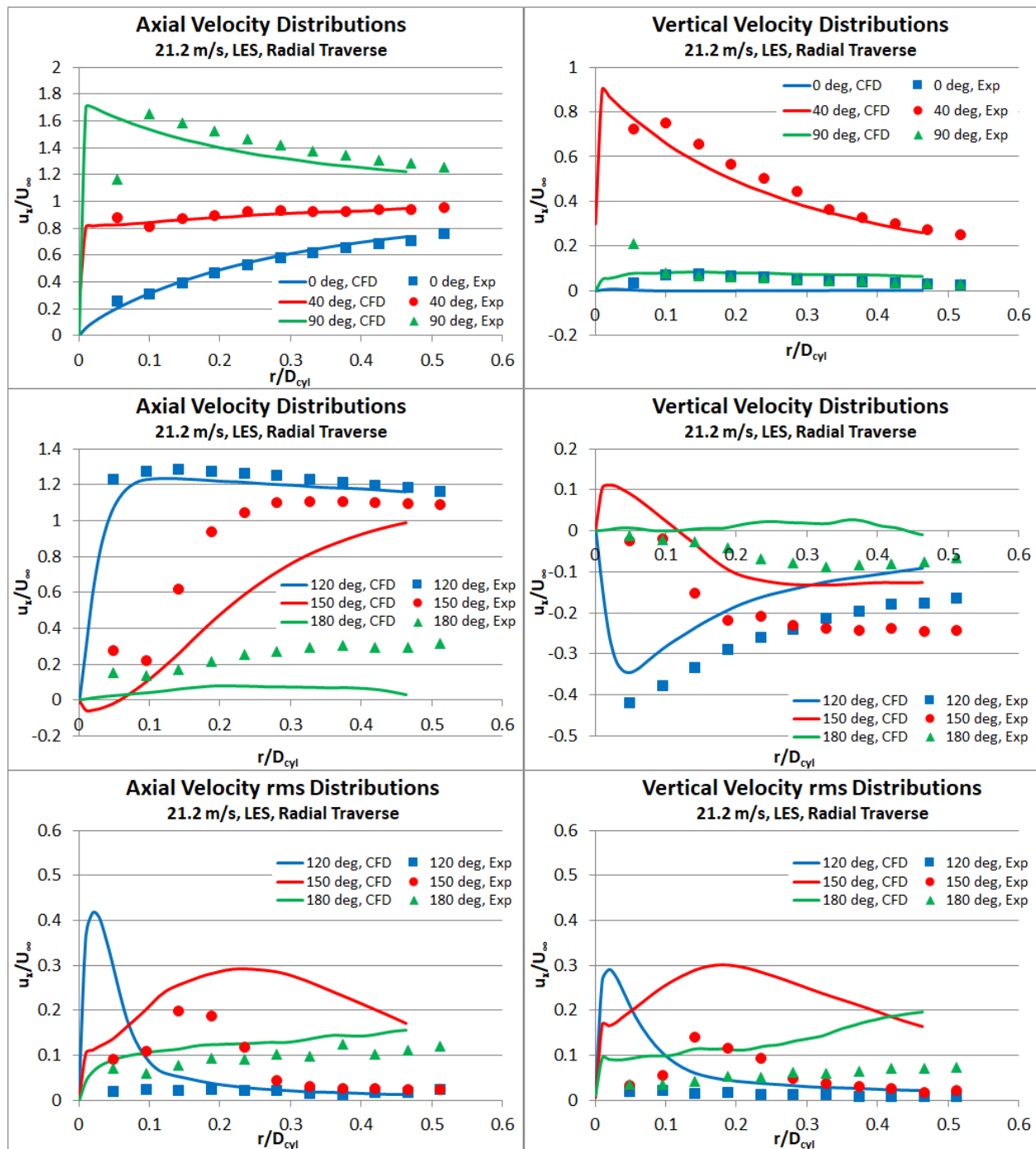


Figure A-4. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 21.2$ m/s, $Re = 470,000$. LES Simulation with Symmetrical Boundary Conditions.

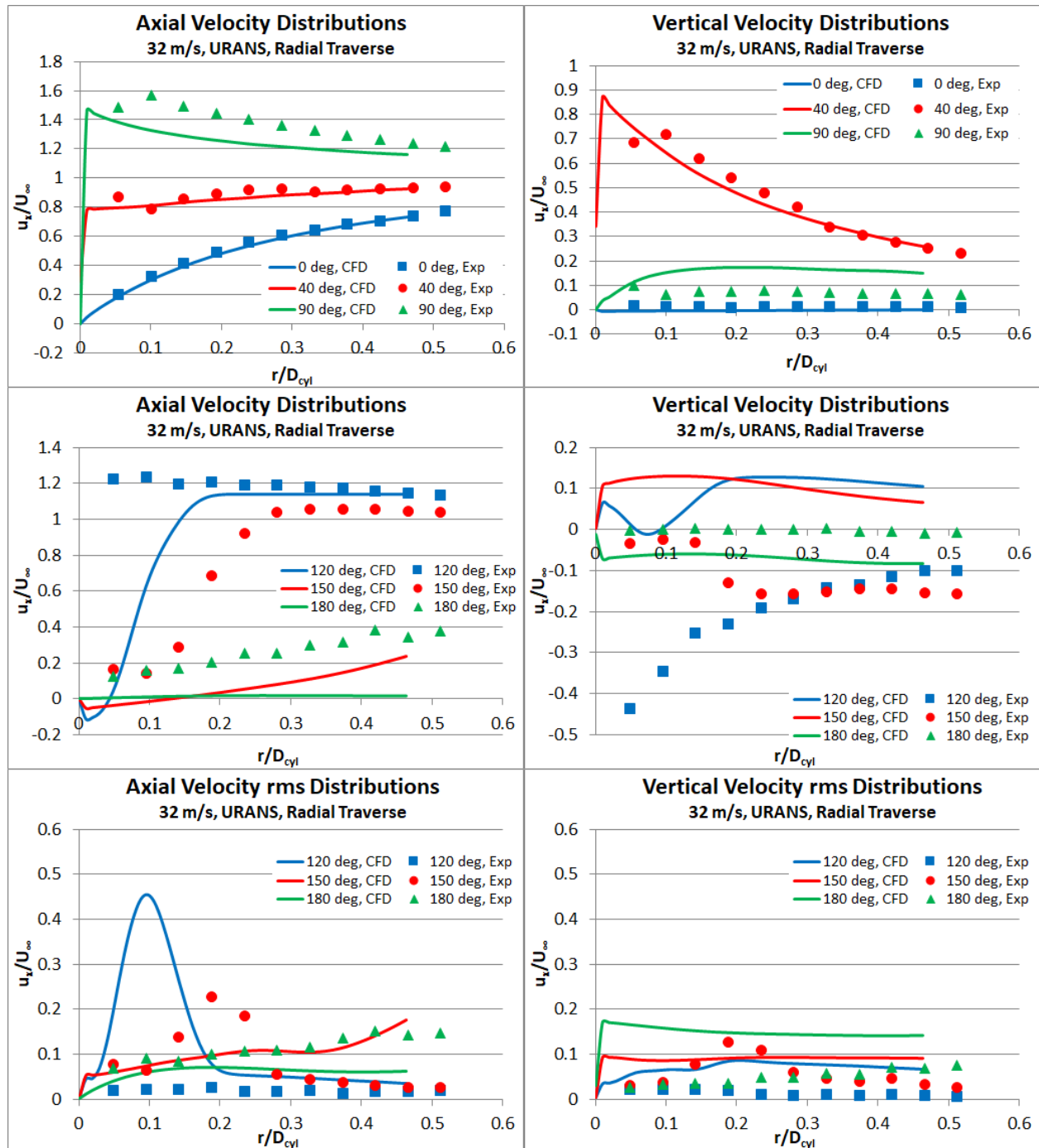


Figure A-5. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 32$ m/s, $Re = 710,000$. URANS Simulation with Symmetrical Boundary Conditions.

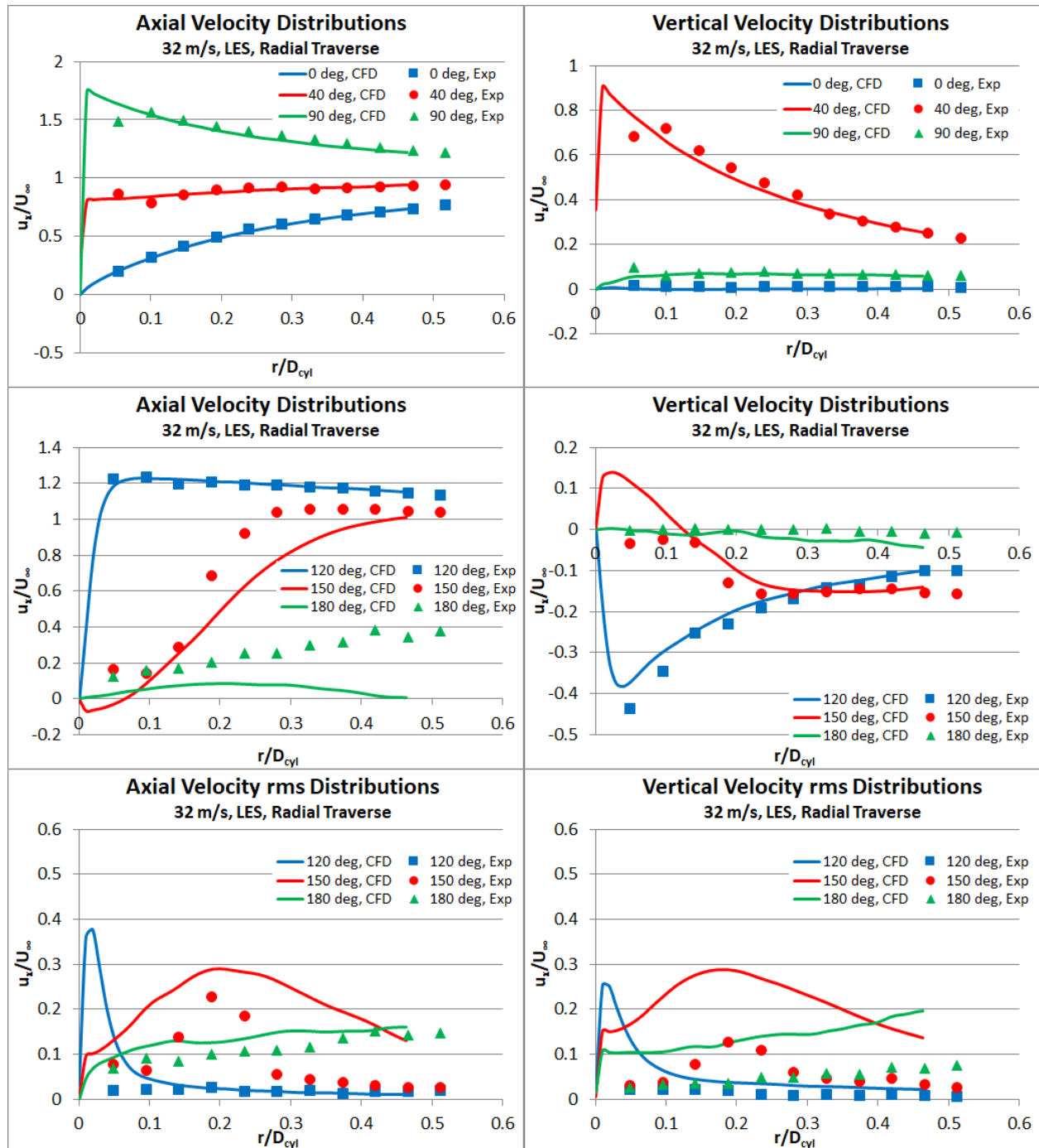


Figure A-6. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 32 \text{ m/s}$, $Re = 710,000$. LES Simulation with Symmetrical Boundary Conditions.

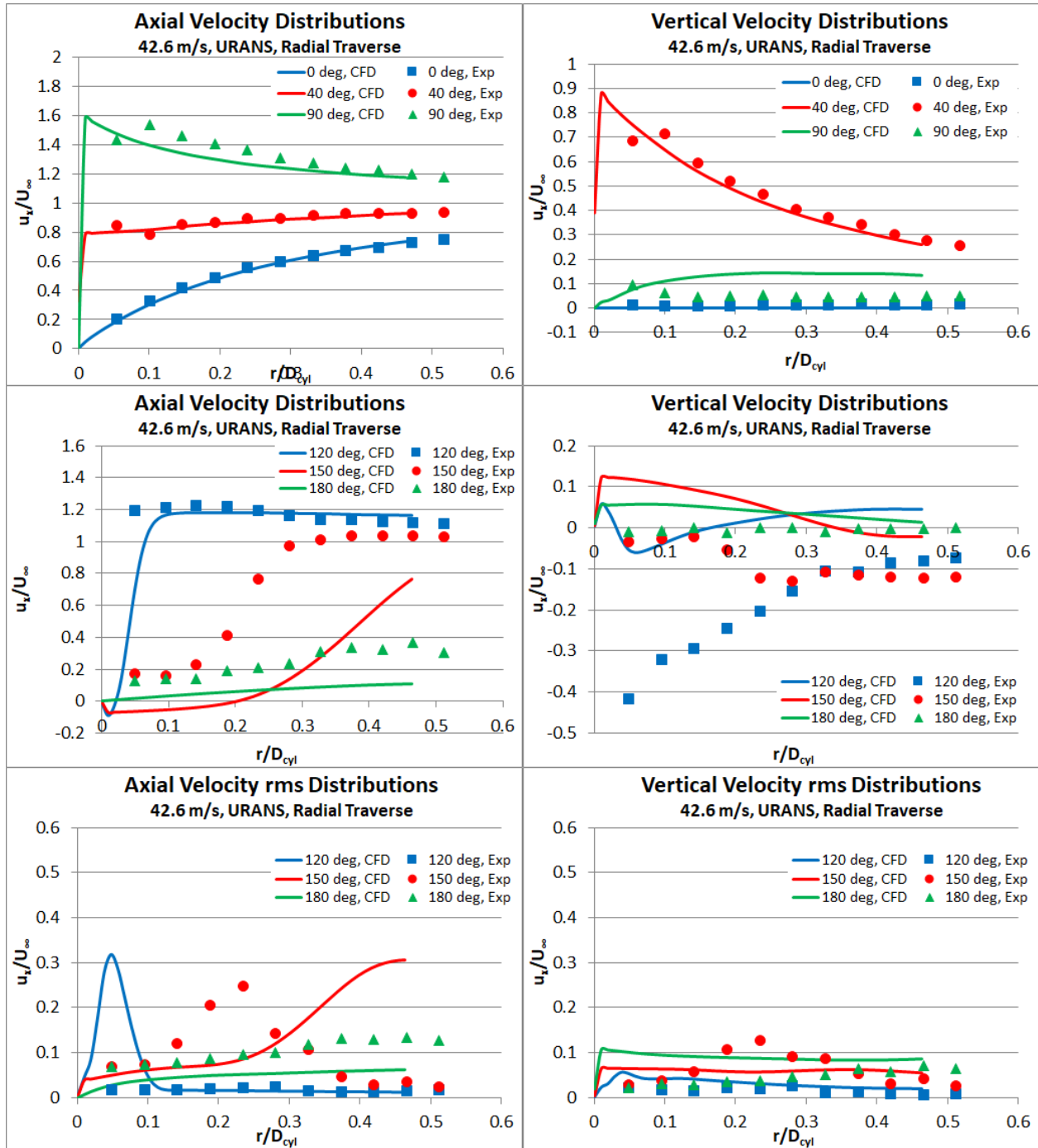


Figure A-7. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 42.6$ m/s, $Re = 945,000$. URANS Simulation with Symmetrical Boundary Conditions.

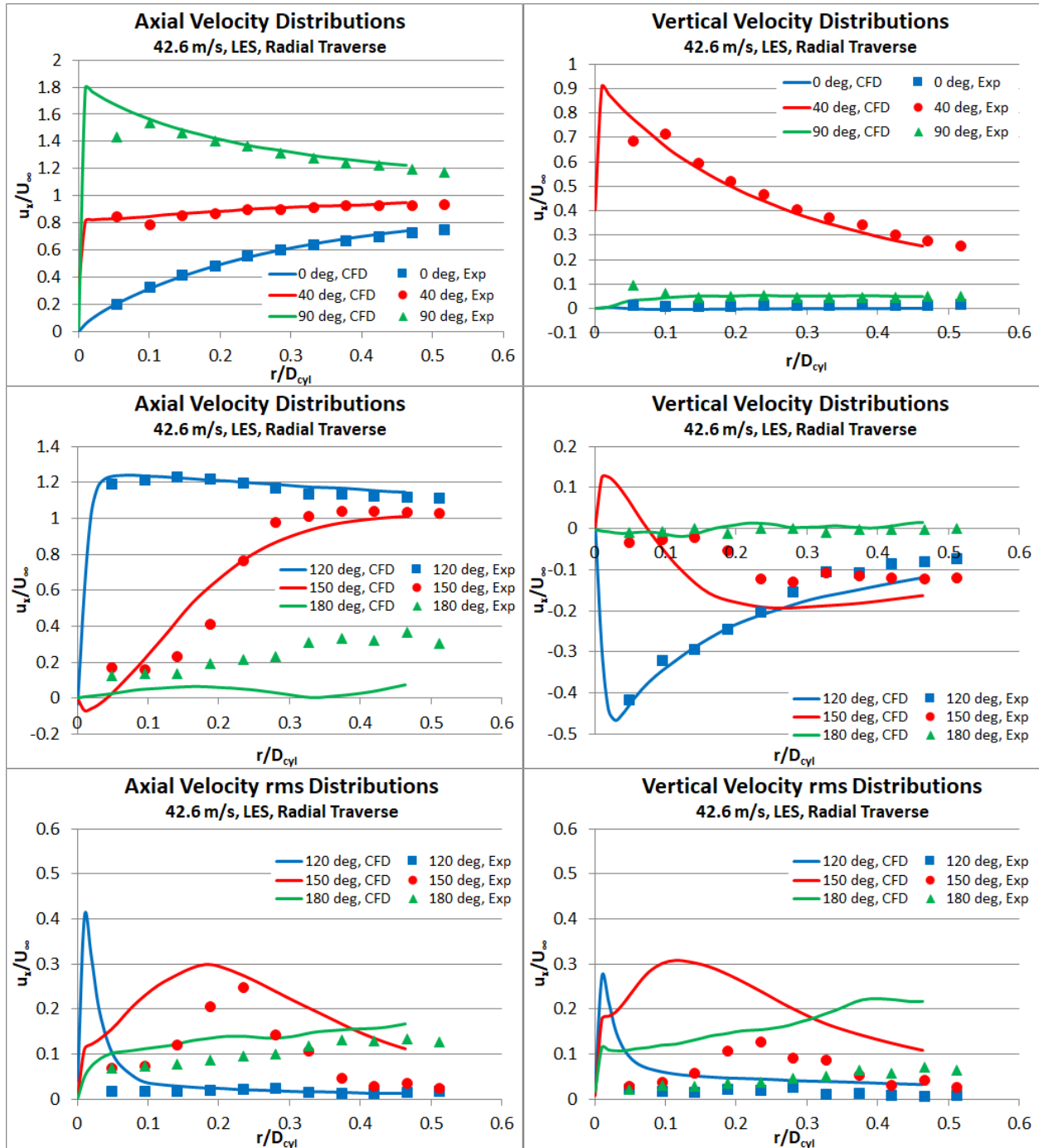


Figure A-8. Cylinder Axial and Vertical Mean Velocity Profiles for $\theta = 0^\circ, 40^\circ, 90^\circ, 120^\circ, 150^\circ$ and 180° and RMS Velocities for $\theta = 120^\circ, 150^\circ$ and 180° for $U_\infty = 42.6$ m/s, $Re = 945,000$. LES Simulation with Symmetrical Boundary Conditions.

APPENDIX B MAST VELOCITY PROFILES

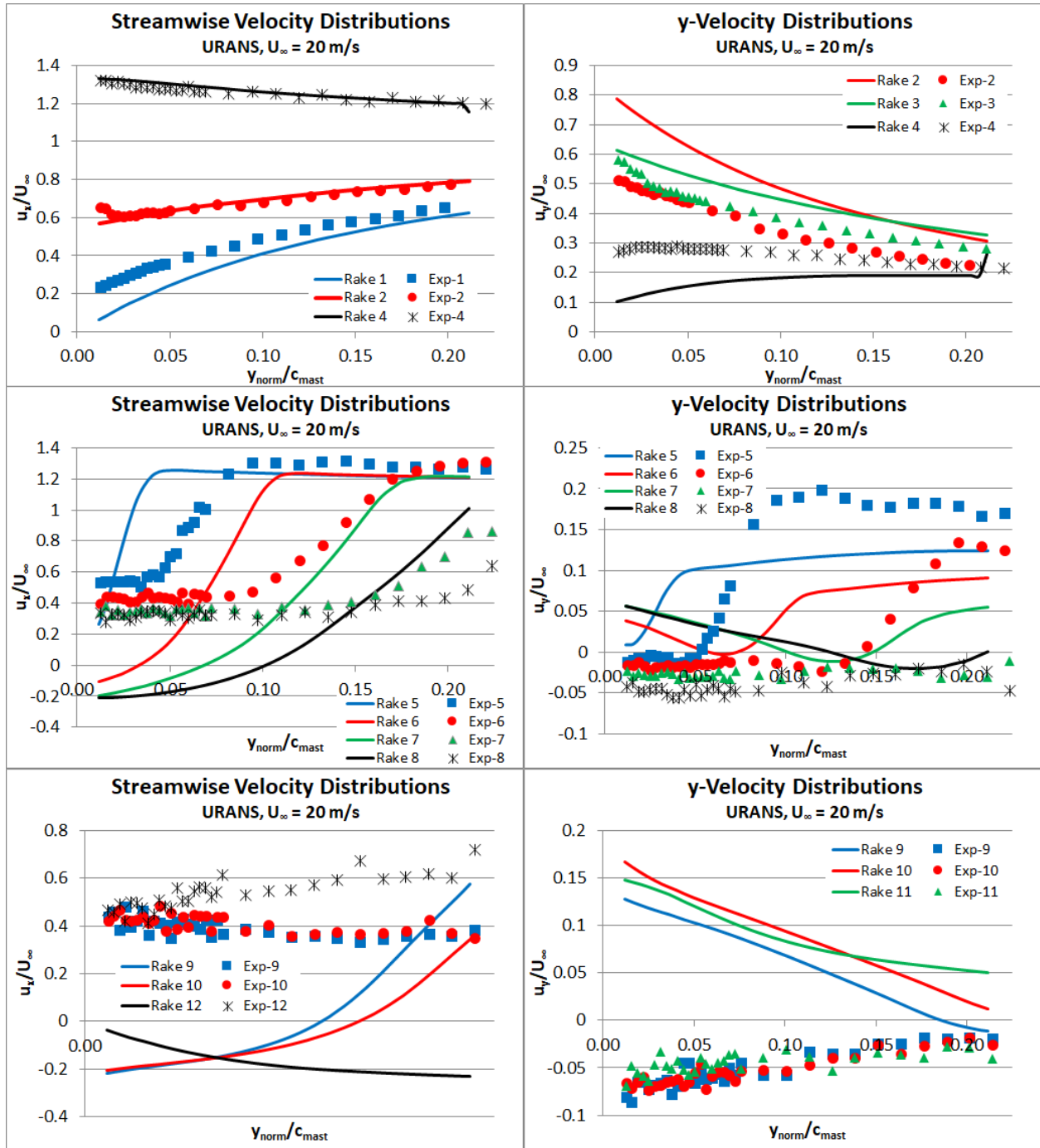


Figure B-1. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 20$ m/s, $Re = 461,000$. URANS Simulation with Symmetrical Boundary Conditions.

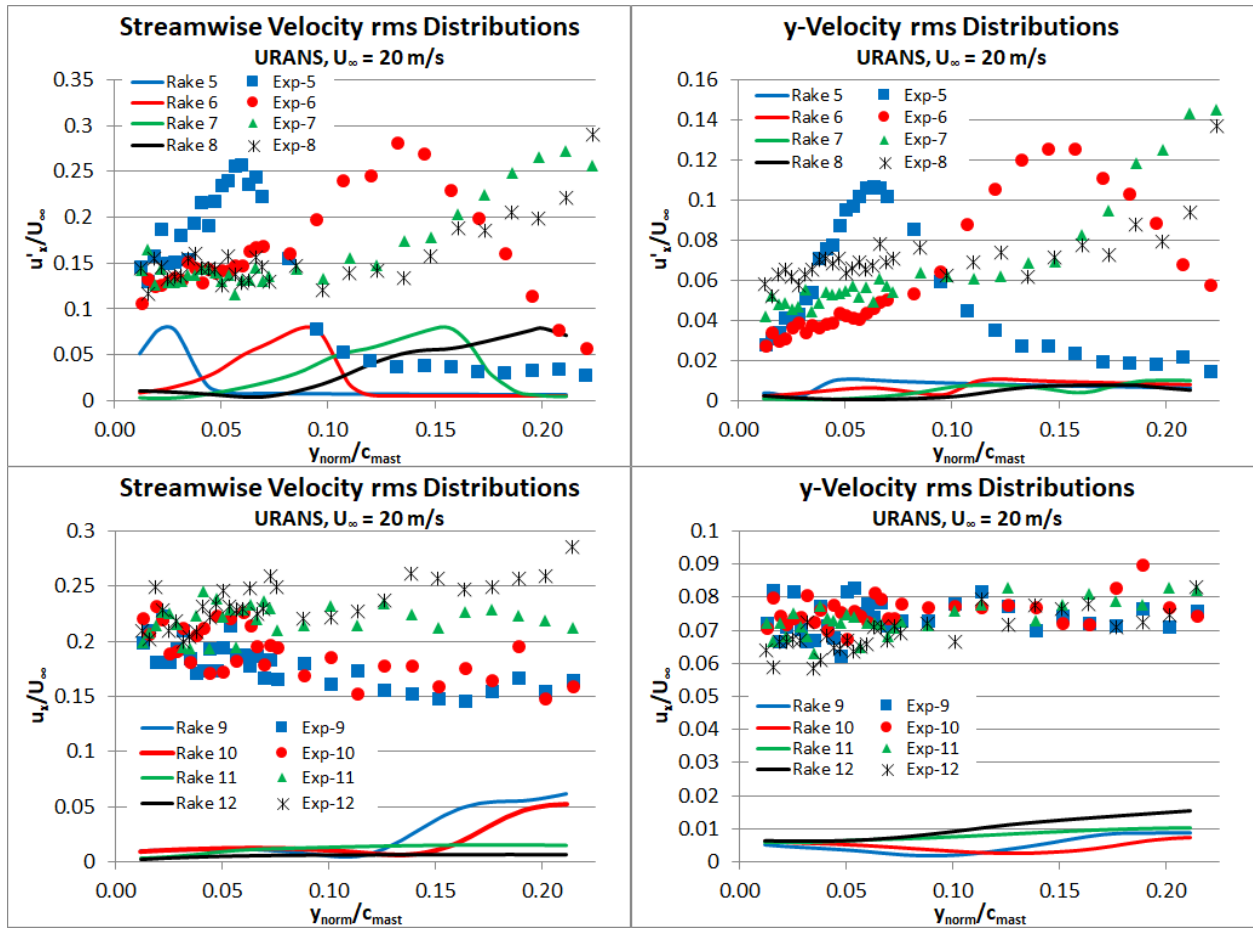


Figure B-2. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 20$ m/s, $Re = 461,000$. URANS Simulation with Symmetrical Boundary Conditions.

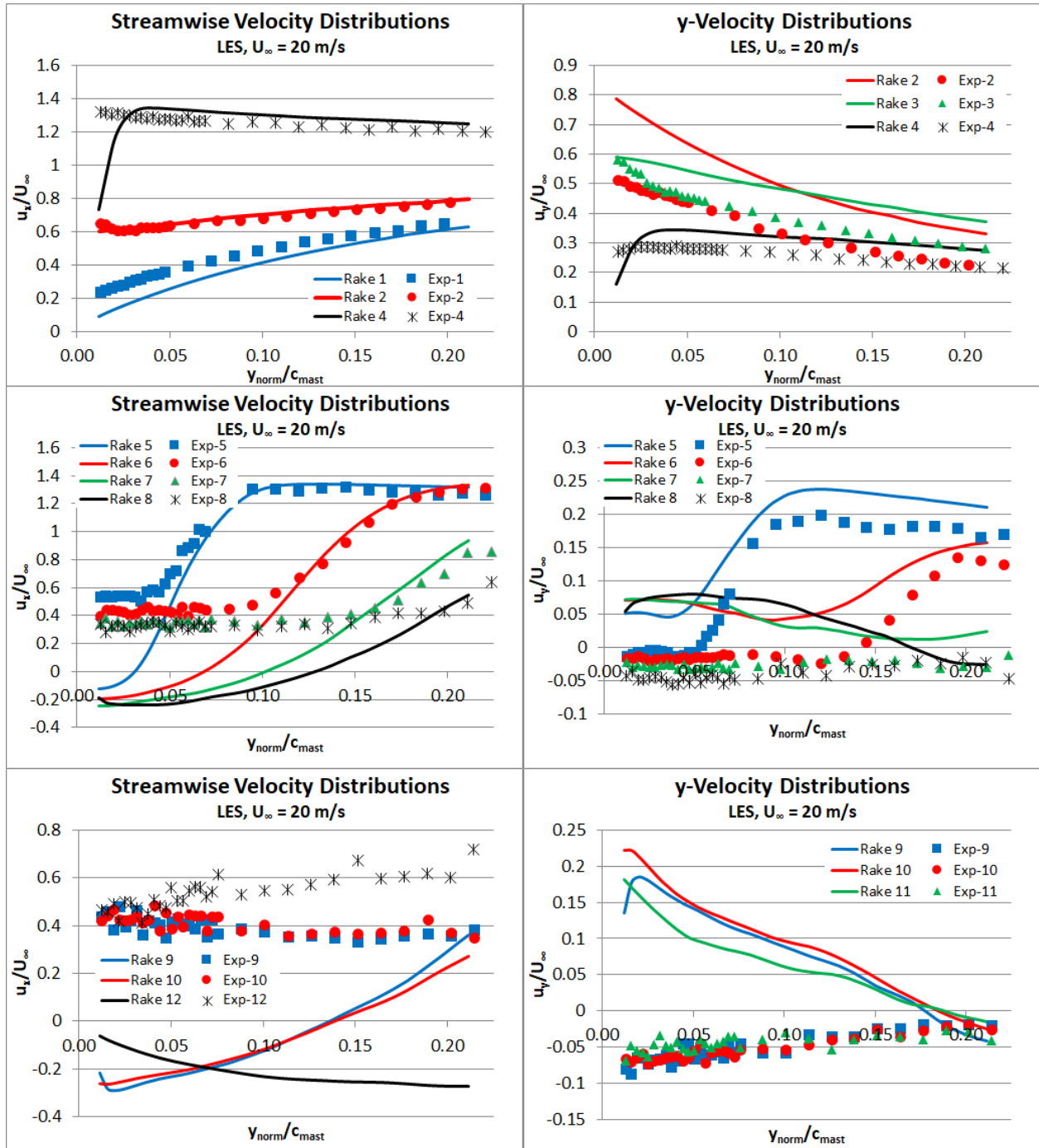


Figure B-3. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 20$ m/s, $Re = 461,000$. LES Simulation with Periodic Boundary Conditions.

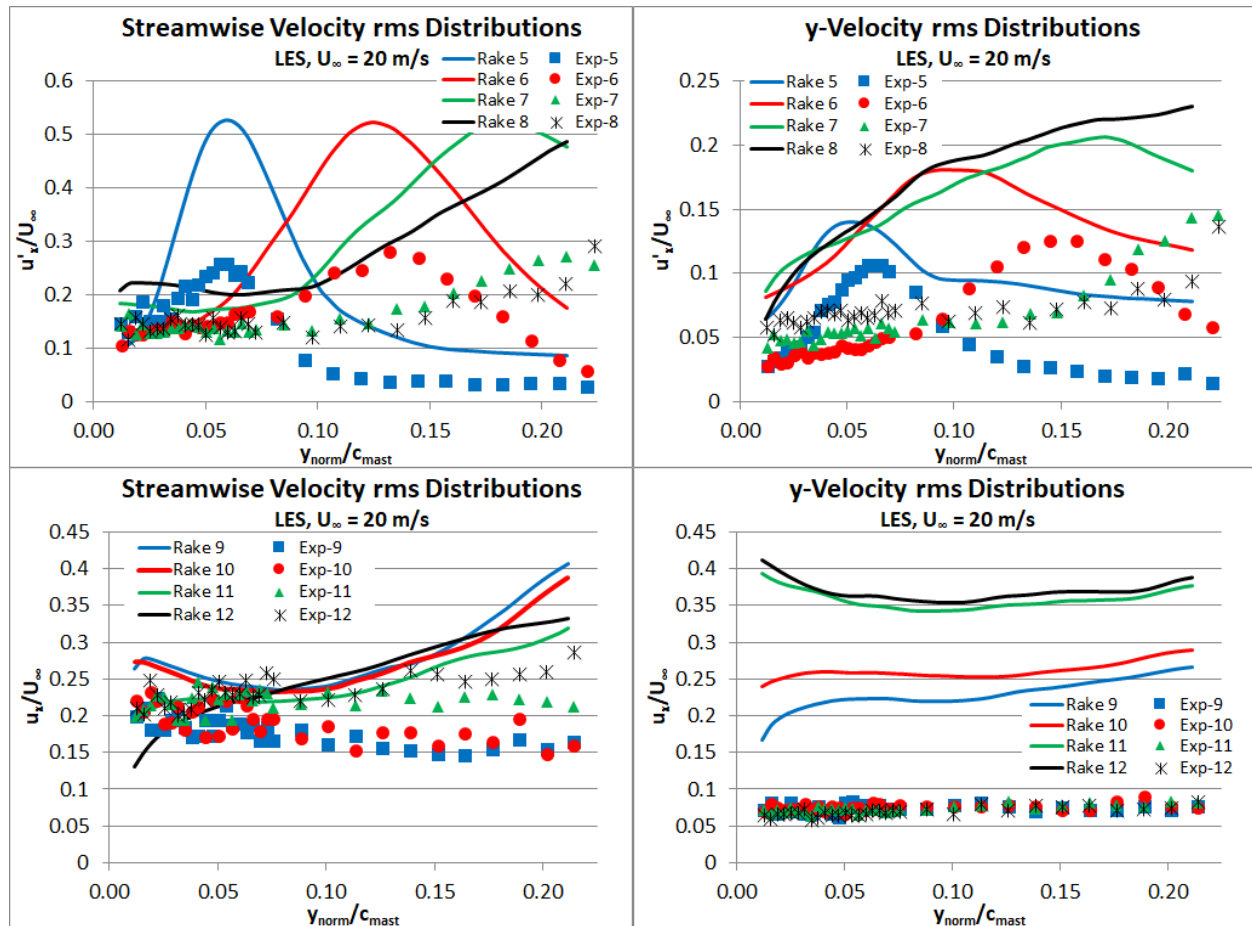


Figure B-4. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 20$ m/s, $Re = 461,000$. LES Simulation with Periodic Boundary Conditions.

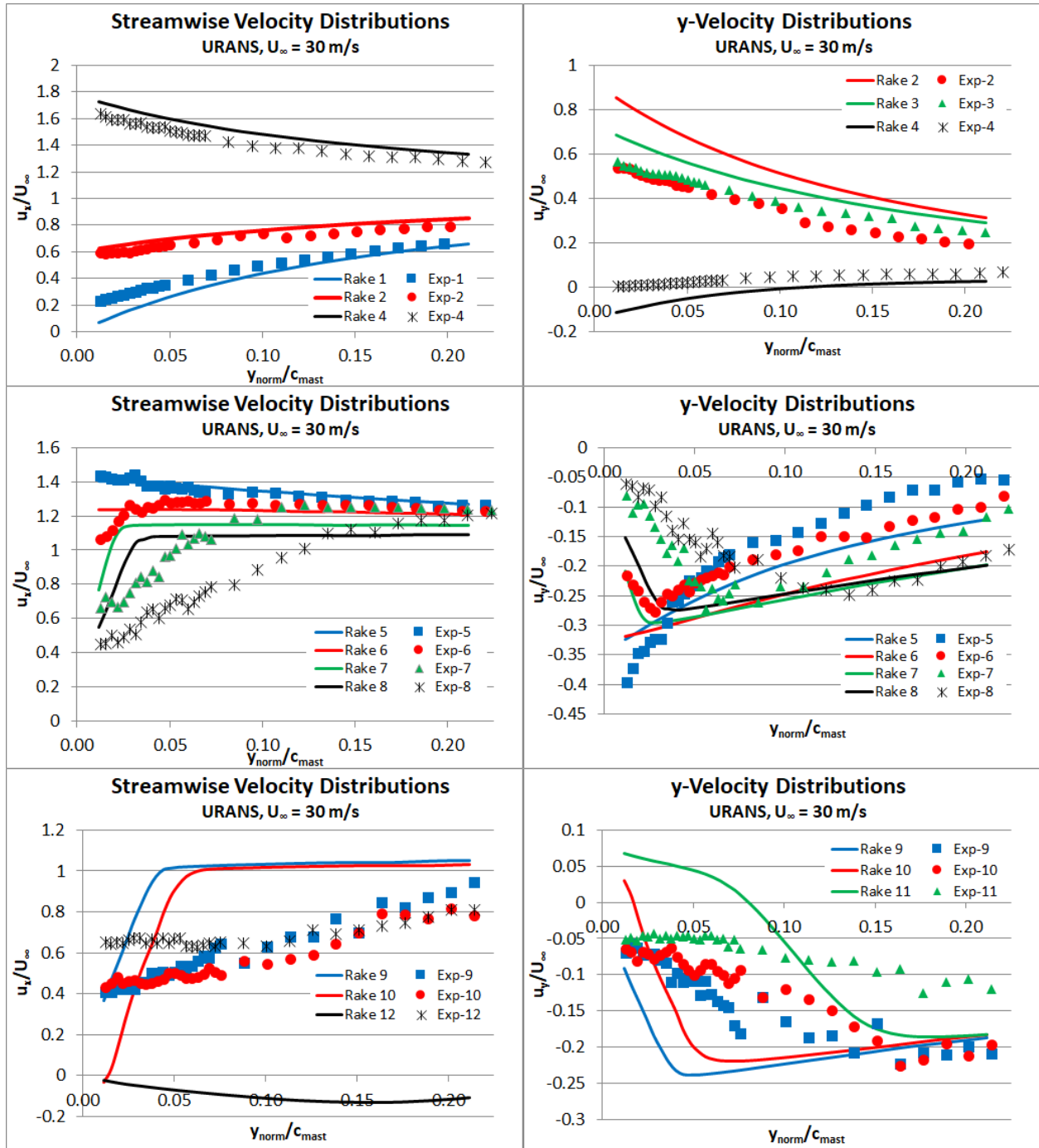


Figure B-5. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 30$ m/s, $Re = 691,000$. URANS Simulation with Symmetrical Boundary Conditions.

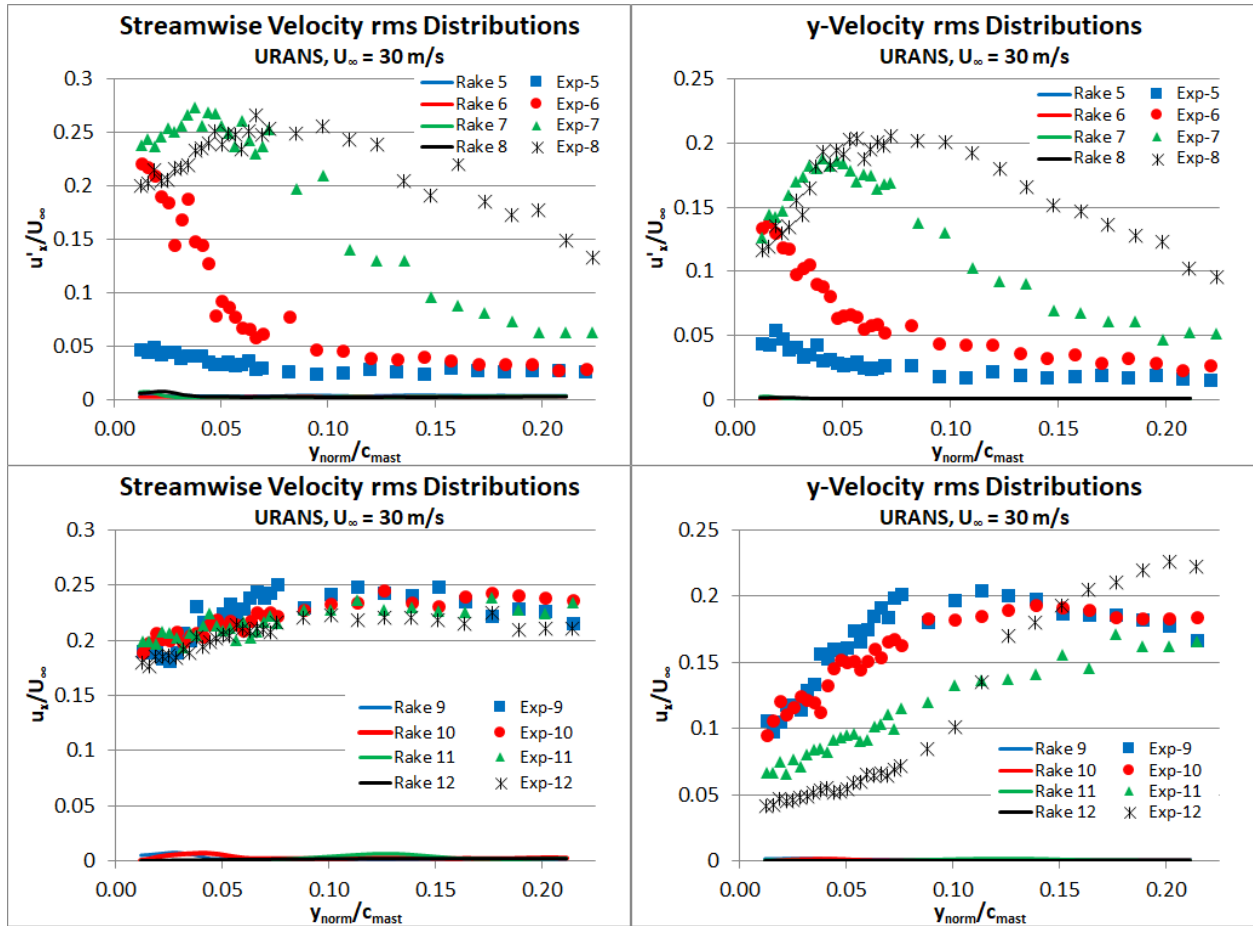


Figure B-6. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 30$ m/s, $Re = 691,000$. URANS Simulation with Symmetrical Boundary Conditions.

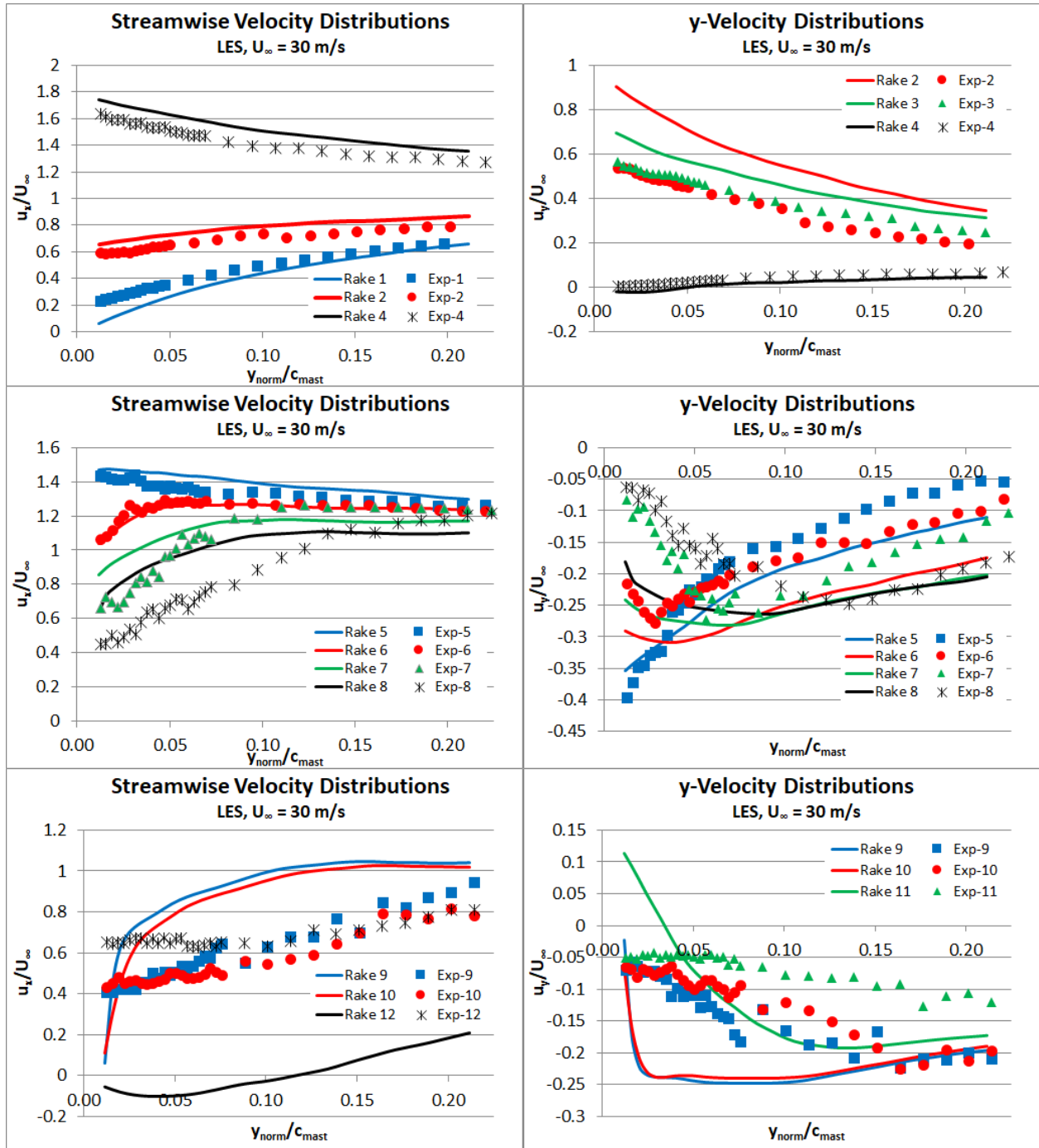


Figure B-7. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 30$ m/s, $Re = 691,000$. LES Simulation with Periodic Boundary Conditions.

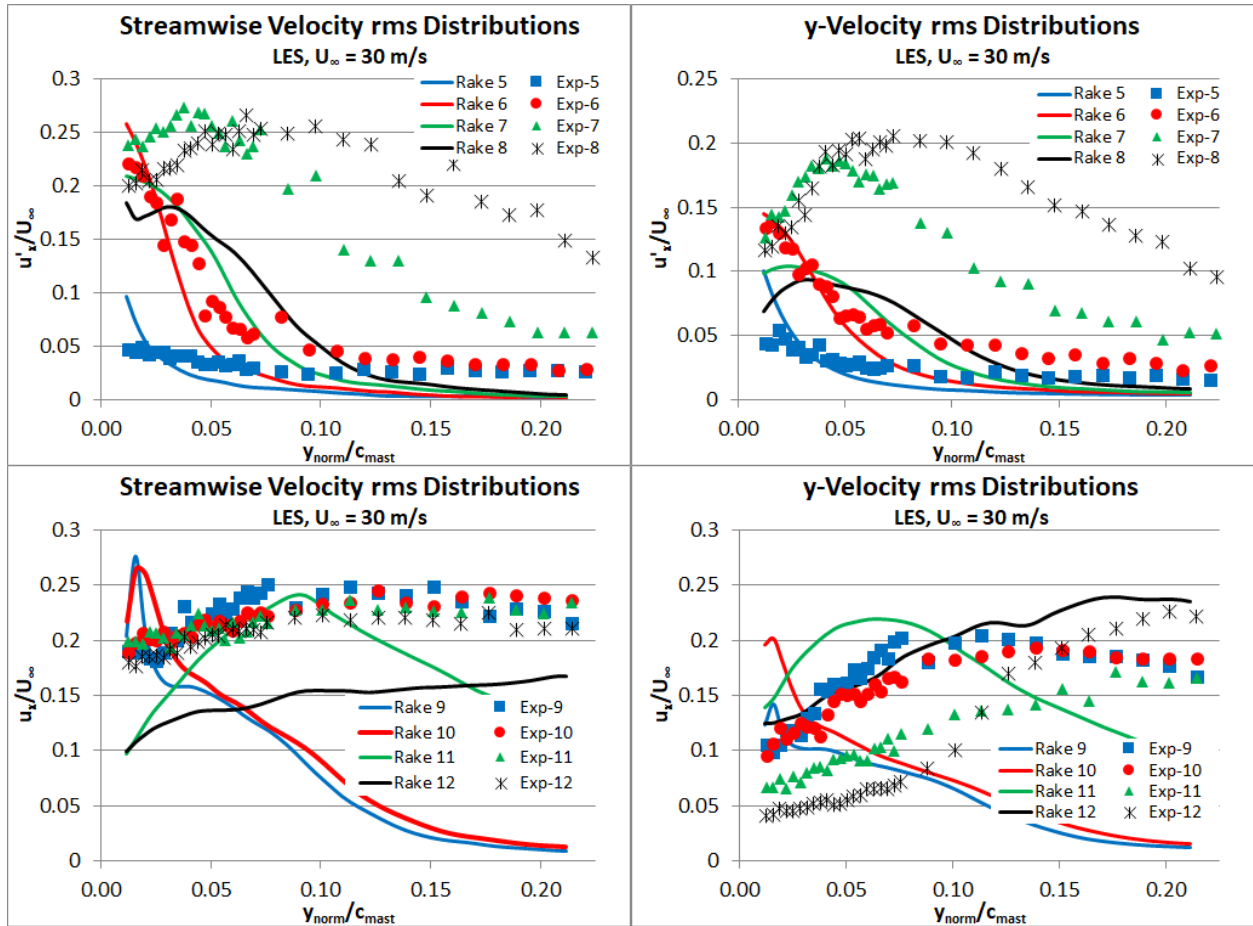


Figure B-8. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 30$ m/s, $Re = 691,000$. LES Simulation with Periodic Boundary Conditions.

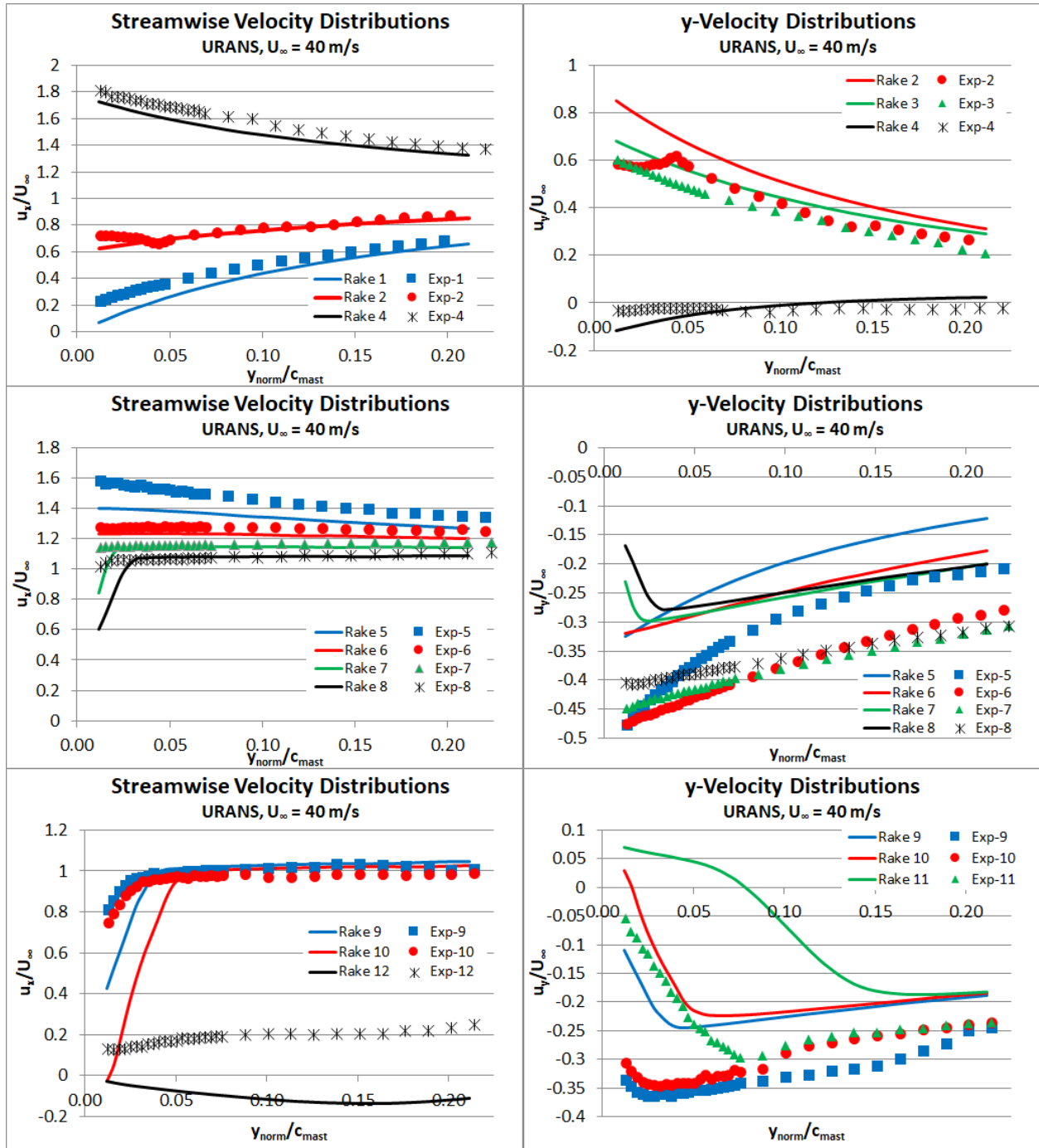


Figure B-9. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 40$ m/s, $Re = 921,000$. URANS simulation with Symmetrical boundary conditions.

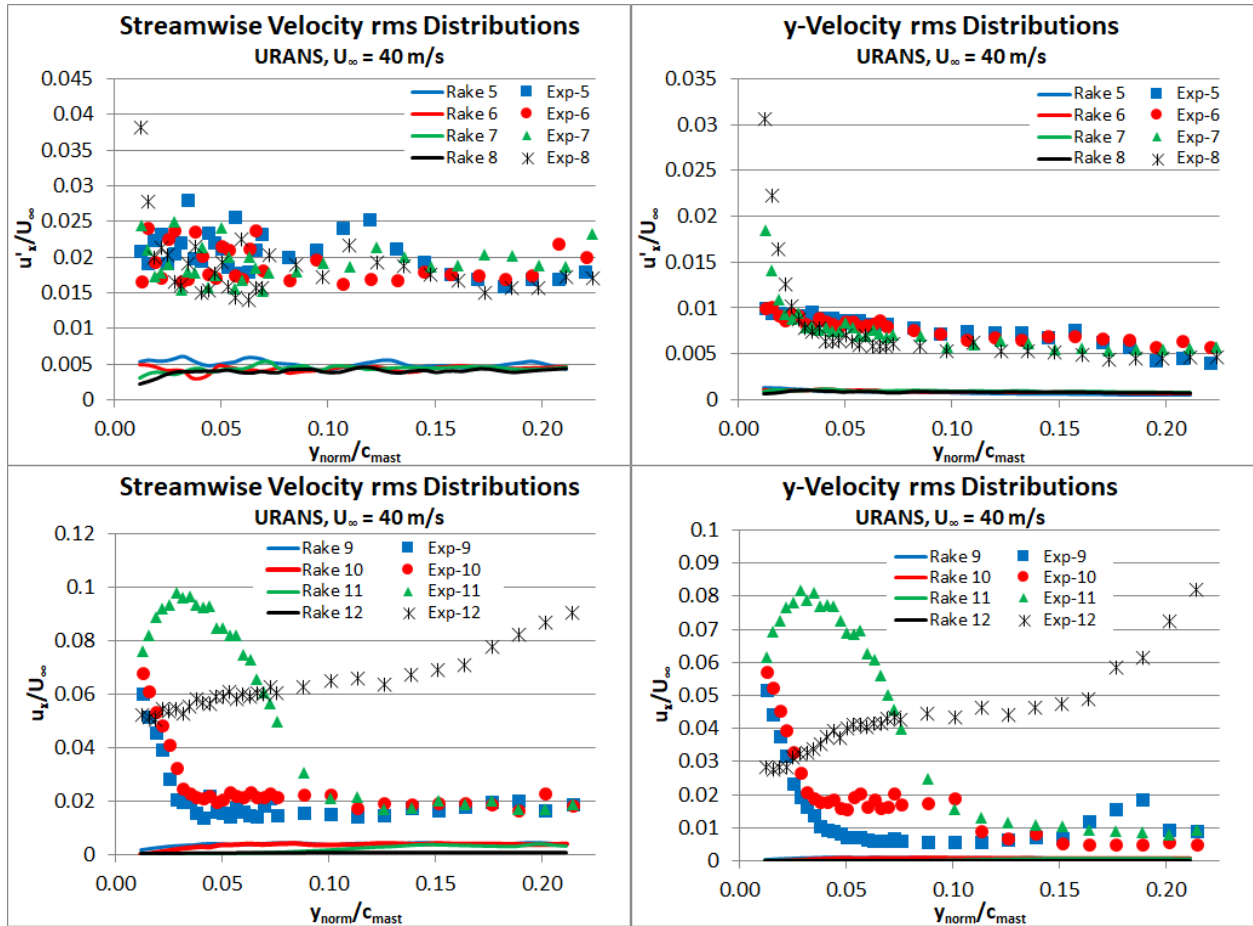


Figure B-10. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 40$ m/s, $Re = 921,000$. URANS Simulation with Symmetrical Boundary Conditions.

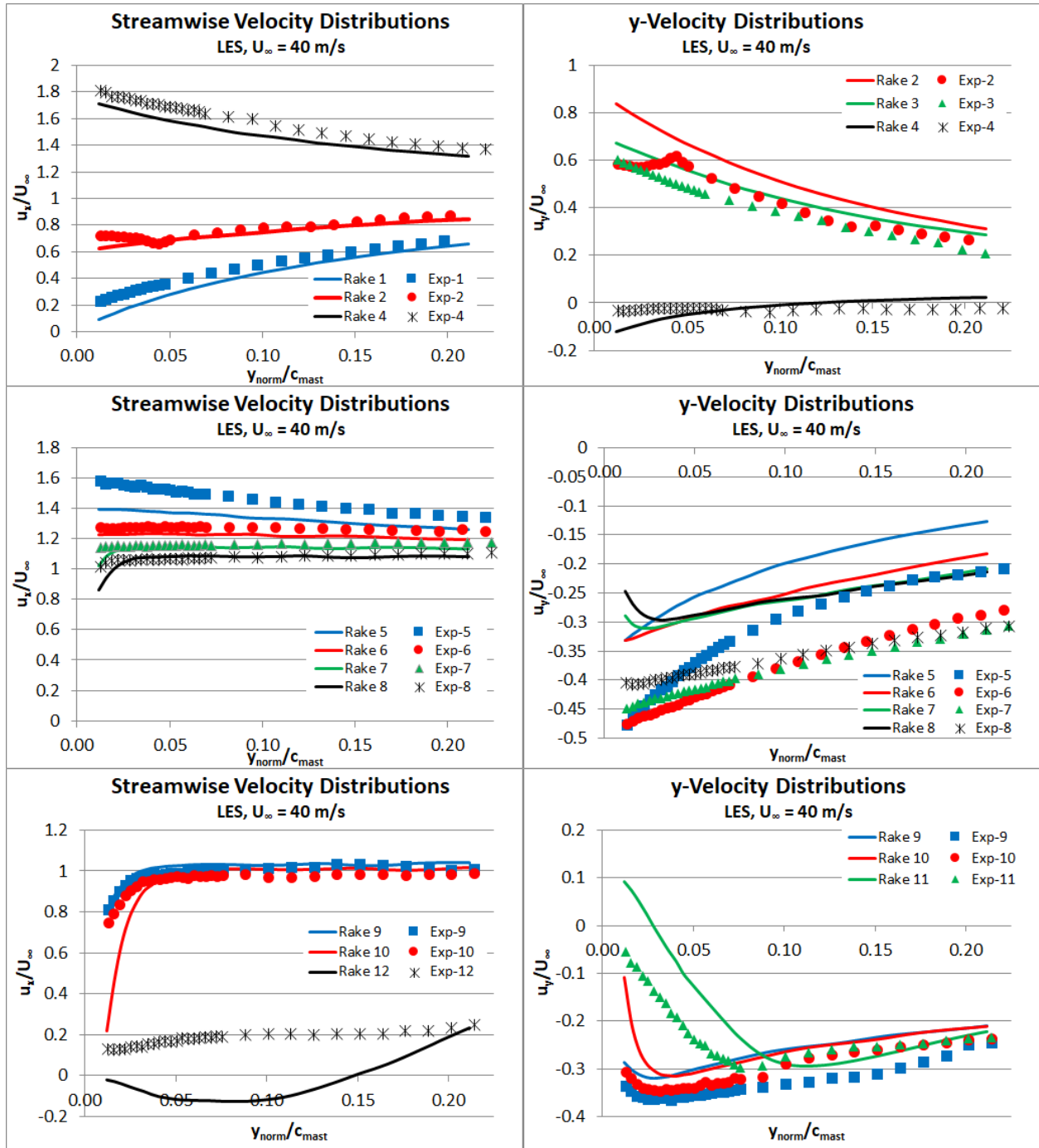


Figure B-11. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 40$ m/s, $Re = 921,000$. LES Simulation with Symmetrical Boundary Conditions.

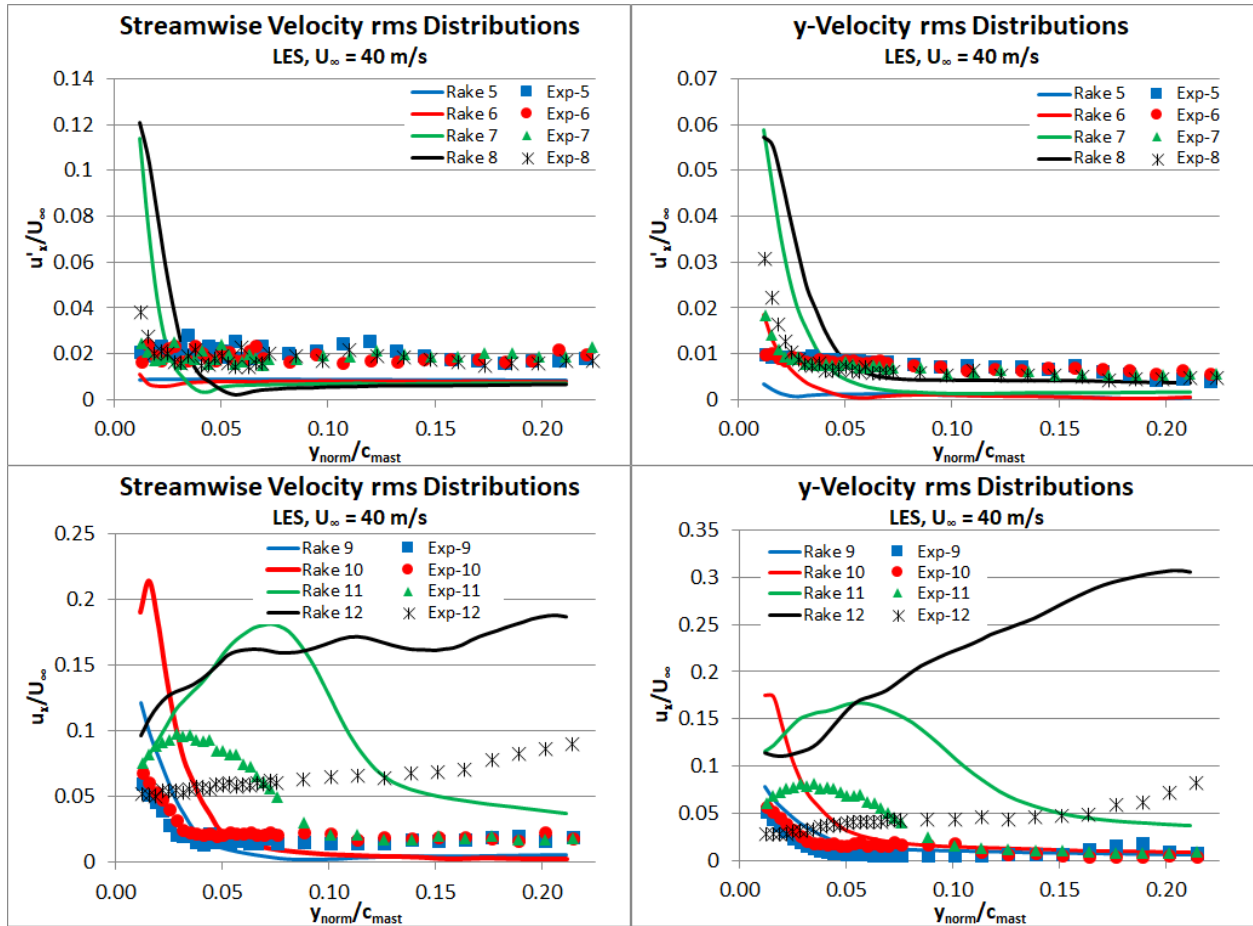


Figure B-12. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 40$ m/s, $Re = 921,000$. LES Simulation with Symmetrical Boundary Conditions.

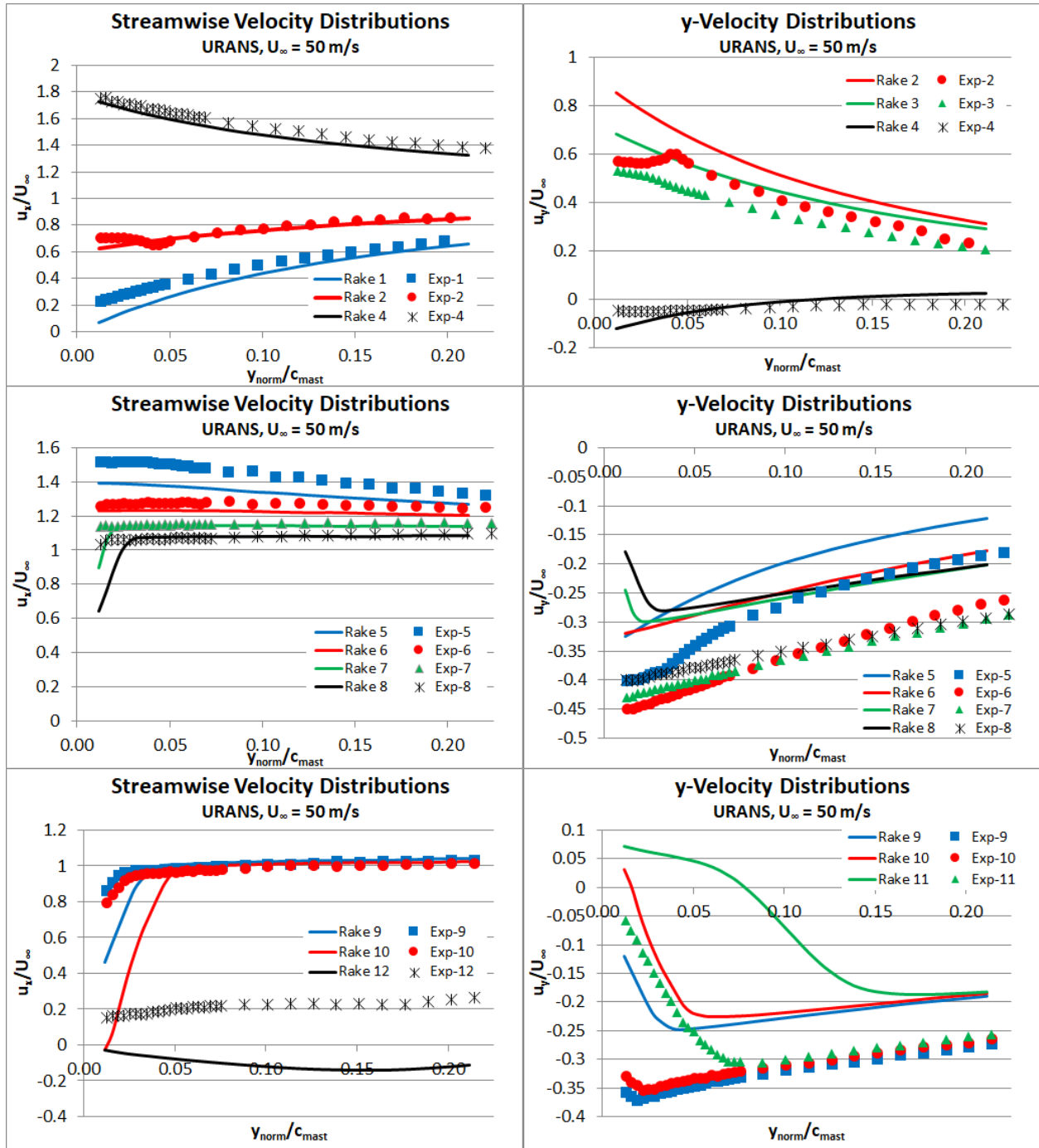


Figure B-13. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 50$ m/s, $Re = 1,151,000$. URANS Simulation with Symmetrical Boundary Conditions.

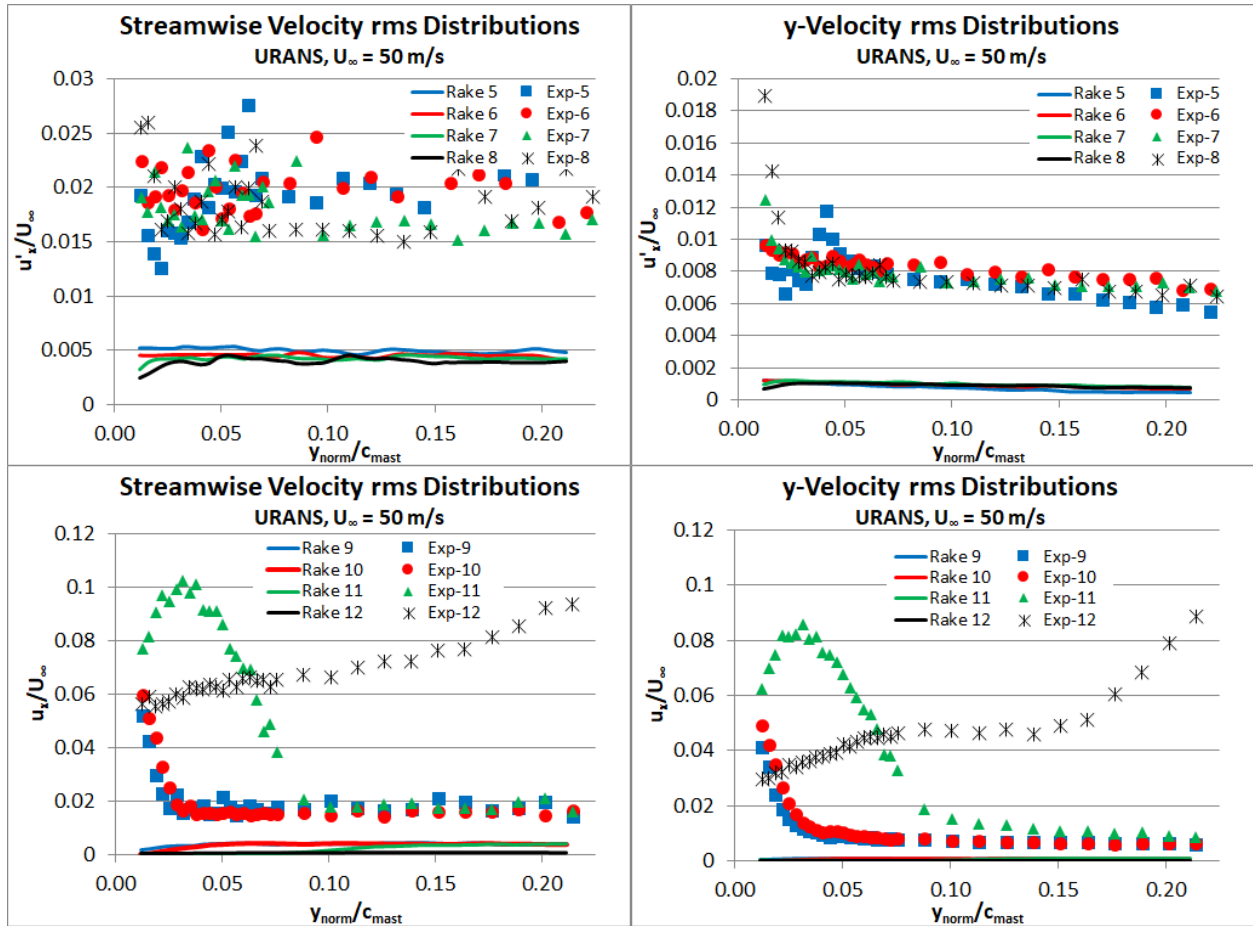


Figure B-14. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 50$ m/s, $Re = 1,151,000$. URANS Simulation with Symmetrical Boundary Conditions.

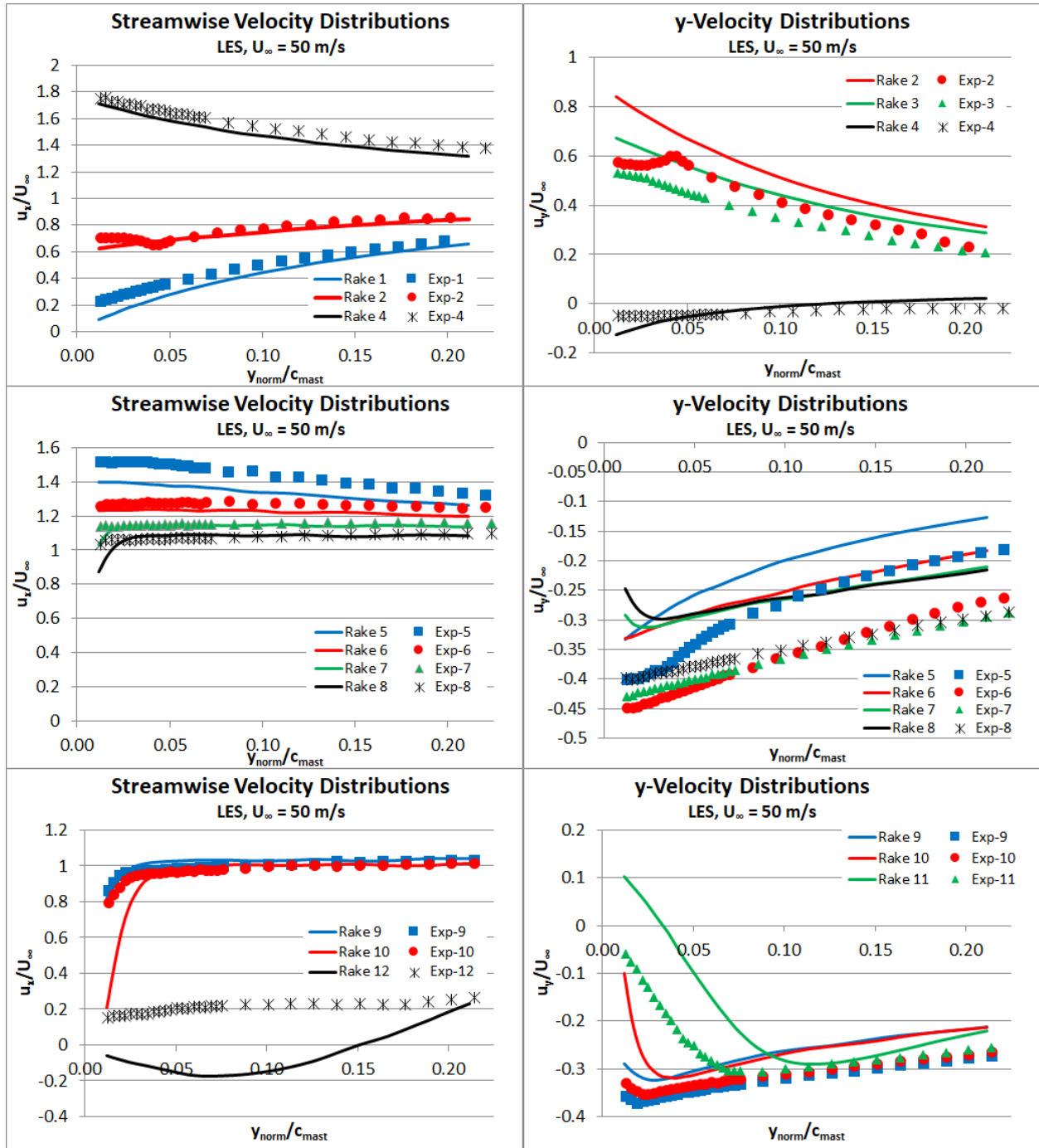


Figure B-15. Mast Axial and Vertical Mean Velocity Profiles with Comparisons to Experimental Data for $U_\infty = 50$ m/s, $Re = 1,151,000$. LES Simulation with Symmetrical Boundary Conditions.

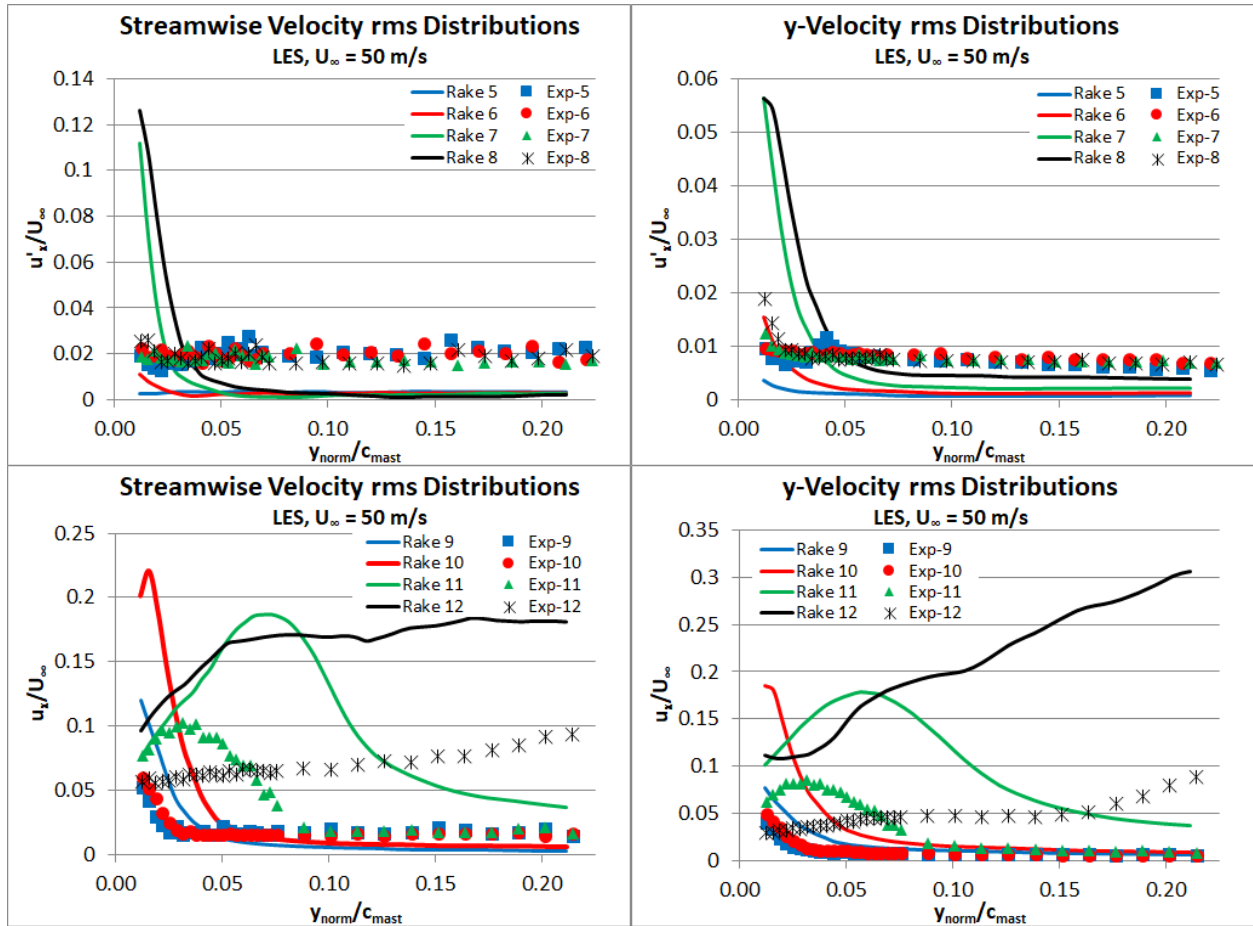


Figure B-16. Mast Axial and Vertical RMS Velocity Profiles with Comparisons to Experimental Data for $U_{\infty} = 50$ m/s, $Re = 1,151,000$. LES Simulation with Symmetrical Boundary Conditions.

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