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Unsteady Simulations of Flow Around a Smooth Circular Cylinder at Very High Reynolds Numbers Using OpenFOAM

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Abstract

The purpose of this study is to determine if unsteady formulations of RANS turbulence models lead to an improved description of incompressible turbulent flows. Wind tunnel experiments for a smooth circular cylinder at very high Reynolds numbers with an incompressible fluid are expensive. The use of Computational Fluid Dynamics, to predict flow around and behind a smooth circular cylinder, is growing in the scientific community and provides an alternative to traditional wind tunnel experiments. One method for predicting flow characteristics is the open-source toolbox OpenFOAM. OpenFOAM is a robust code used for accurately capturing and predicting incompressible turbulent flow with separation. In this study OpenFOAM is used to implement standardized turbulence models and predict the complex flow physics associated with a smooth circular cylinder. The complex flow physics is predicted with steady and unsteady formulations of the Wilcox 2006 k-ω turbulence model and Menter's 1993 SST turbulence model. A grid convergence study is done to determine the effect that mesh refinement has on simulation results. Results obtained are in agreement with experimental data and with simulations conducted by other research groups.

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Nomenclature

a	=	*speed of sound*
A	=	*frontal area*
C_D	=	*drag coefficient,* $F_D/0.5\rho U_\infty^2\, A$
C_f	=	*friction coefficient,* $\tau_w/0.5\rho U_\infty^2$
C_L	=	*lift coefficient,* $F_L/0.5\rho U_\infty^2\, A$
C_p	=	*pressure coefficient,* $(P-P_\infty)/0.5\rho U_\infty^2$
C_{pb}	=	*base pressure coefficient at* $\theta = 180°$
Cr	=	*Courant-Friedrichs-Lewy condition,* $Cr = U_\infty \Delta t/y$
D	=	*diameter*
F_D	=	*drag force*
F_L	=	*lift force*
h	=	*characteristic mesh length for the constant domain size,* $1/\sqrt{N}$
I	=	*turbulence intensity,* u/U_∞
k	=	*turbulent kinetic energy* $k = 1/2\, \rho\langle u_i u_j\rangle$
ℓ	=	*turbulent length scale*
L_r	=	*recirculation length*
M	=	*Mach number,* U_∞/a
N	=	*total number of cells in the computational domain*
p	=	*pressure fluctuation*
P	=	*mean pressure*
Re	=	*Reynolds number,* $U_\infty\rho/\nu$
S_{ij}	=	*strain-rate tensor,* $S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$
St	=	*Strouhal number,* $St \equiv fd/U_\infty$
t	=	*time*
t^*	=	*non-dimensional time-step,* $t^* = \Delta t\, U_\infty/D$
u	=	*velocity fluctuation*
u_τ	=	*friction velocity,* $\sqrt{\tau_w/\rho}$
U	=	*mean streamwise velocity component*
U_∞	=	*free stream velocity*
$U_\parallel$	=	*mean velocity parallel to surface*
$\langle u_i u_j\rangle$	=	*Reynolds stress tensor*
V	=	*mean vertical velocity component*
W_{ij}	=	*vorticity,* $W_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}\right)$
x	=	*streamwise flow direction*
y	=	*normal-to-wall direction*
y^+	=	*dimensionless distance from the wall based on fluid properties,* yu_τ/ν
y_w	=	*distance between a wall and the first grid node in the y-direction*
β_1	=	*blending constant,* $\beta_1 = 0.075$
β^*	=	*model coefficient,* $\beta^* = 0.07 - 0.09$
δ_{ij}	=	*Kronecker delta*

ε	=	*turbulent scalar dissipation,* $\varepsilon \equiv \nu \ \langle \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j} \rangle = \beta^* \ k^{3/2}/\ell$
θ	=	*azimuth angle measured clockwise from the stagnation point*
μ	=	*dynamic viscosity*
μ_t	=	*dynamic turbulent viscosity*
ν	=	*kinematic viscosity,* $\nu = \mu/\rho$
ν_t	=	*kinematic turbulent viscosity,* $\nu_t = \mu_t/\rho$
ρ	=	*density*
σ_k	=	*model coefficient*
τ_w	=	*wall shear stress,* $\mu \left(\frac{\partial U_\parallel}{\partial y}\right)_{y=0}$
τ_{ij}	=	*Boussinesq approximation,* $-\langle u_i u_j \rangle \equiv \tau_{ij} = 2\nu_t S_{ij} - \frac{2}{3} k \delta_{ij}$
ϕ	=	*separation angle measured clockwise from the stagnation point*
ω	=	*turbulent specific dissipation,* ε/ k
Ω	=	*vorticity magnitude,* $\Omega = \sqrt{2W_{ij}W_{ij}}$

Chapter 1

Introduction

1.1 Overview

Current computational power has increased the accessibility and accuracy of simulation-based analysis of turbulent fluid flow around and behind streamlined and blunt bodies. The advancement of computational power enables the use of Navier-Stokes equations to describe the behavior of fluid motion. However, current computers are not able to predict the exact turbulent motion that interacts with streamlined and blunt bodies. The random fluctuations associated with turbulent flow require that a broad range of time and space scales be resolved, which is a computationally demanding task.[1,2] In order to reduce the required computational power most methods decompose the turbulent field into mean and fluctuating parts.

The first person to decompose a turbulent field into mean and fluctuating parts was sir Osbourne Reynolds.[3] The Reynolds-Averaged Navier-Stokes (RANS) equations are derived when the decomposed quantities are substituted into the Navier-Stokes equations, where RANS equations are an unclosed system of equations.[2,4] Turbulence models can be derived from the RANS equations by modeling the unknown terms with closure coefficients and approximations. These types of models are commonly known as RANS turbulence models.

RANS turbulence models provide a computationally affordable method for solving computer based simulations, which enables researchers and industry to produce fast and reliable results. However, to this date there is no turbulence model that can predict all features for any type of flow. In practice, turbulence models are tailored to a specific type of flow regime (i.e. internal flows, external flows, jets, wakes, etc.). Turbulence models require some kind of standardization in order to obtain the same results, for a specific type of flow situation, on different software packages. However, there are reports that the same turbulence model implemented in two different software packages produced slightly different results.[5-7] The correct implementation of a given turbulence model can be confirmed by comparing results with published experimental and simulation data.

The primary goal of this work is to examine the effect that turbulence model selection has on simulation results for a smooth circular cylinder. This study uses the Wilcox 2006 k-ω turbulence model and Menter's 1993 SST turbulence model (implemented in a previously study: Ref. 8) using the Open Field Operation and Manipulation (OpenFOAM) computational toolbox.[9] Additional goals consist of producing a database for the cross-flow over a smooth circular cylinder and determining the effect that steady RANS and Unsteady RANS (URANS) has on simulation results.

This thesis will first examine and provide an overview of some different turbulence modeling techniques. It will then examine published experimental and computational simulation results relevant to the flow situation of interest. Chapter 2 will discuss the initial and boundary conditions used for the respective two-dimensional (2-D) computational simulations. In Chapter 3 the converged results are then analyzed and compared to published experimental and simulation data. Results for cross-flow over a smooth circular cylinder are compared to experimental[10-15] results, Large Eddy Simulations[16] (LES), Detached Eddy Simulations[17,18] (DES), steady RANS,[16] and unsteady RANS[7,16,19-20] (URANS). The final conclusions are drawn in Chapter 4.

1.2 Turbulence Modeling

Almost every flow occurring from a mechanical device or in nature is turbulent. Some types of turbulent flows include the wake produced by a moving body, i.e. planes, boats, cars, etc., atmospheric turbulence (the weather), the earth's liquid core, a cup of coffee with the dissolution of cream and sugar, etc. All turbulent flows have a large enough Reynolds number, $Re = U_\infty D/\nu$, that the flow can exist in turbulent conditions. The Reynolds number is a non-dimensional quantity that relates inertial forces to viscous forces. The kinematic viscosity, $\nu = \mu/\rho$, is a measure of the fluid's resistance to gradual deformation by shear stress or tensile stress. μ and ρ are defined as dynamic viscosity and fluid density, respectively.[21]

By far the most numerically accurate and computationally demanding turbulence modeling approach is to directly discretize the Navier-Stokes equations. This approach is known as Direct Numerical Simulation (DNS), where no modeling assumptions are made. Due to the computational cost, current computing power has made DNS applicable to only simple flow domains. The computational mesh requires an unrealistically fine grid in order to accurately capture the smallest eddies. When the geometry is complex or the Reynolds number becomes very large the computing demand exceeds resources available, which has led to the creation of other turbulence modeling approaches, i.e., Large Eddy Simulation (LES), Detached Eddy Simulation (DES), Reynolds-Averaged Navier-Stokes (RANS), etc.

RANS turbulence models are derived by decomposing the Navier-Stokes equations into mean and fluctuating parts and time-averaging the turbulent fields, also known as Reynolds decomposition. Applying Reynolds decomposition to the Navier-Stokes equations produces a set of unclosed Partial Differential Equations (PDE). At this point various turbulence models are derived with approximations and closure coefficients. RANS turbulence models require less spatial and temporal refinement when compared to DNS, LES, and DES, therefore making RANS turbulence models economically and scientifically attractive. Utilizing this technique essentially eliminates turbulent fluctuations and causes detail in the complex flow physics to be lost, which is a major drawback of is method. However, this method also accurately produces important flow physics (i.e. lift and drag coefficient) associated with highly separated flow situations.[8,22,23]

Large Eddy Simulations (LES) directly calculate the mean flow and unsteady large-scale eddies while modeling the small-scale eddies with spatial filtering. Spatial filtering of the Navier Stokes equations introduces subgrid-scale (SGS) stresses. SGS stresses are modeled in the same way that the Reynolds Stresses are, where this is commonly known as an SGS model. This spatial filtering is more accurate than RANS turbulence models.[21]

A hybrid option to LES is Detached Eddy Simulation (DES), where LES and RANS are blended together in order to increase computational affordability while capturing the large eddy structures. In DES the near wall model uses RANS, which is significantly less computationally expensive, especially within the boundary layer, and LES away from the wall. It should be noted that the switch between LES and DES is dependent on the turbulence length scale, which is dependent on the local cell length or volume and distance from the wall.[21] This produces a turbulence modeling method that is more accurate than RANS and less computationally expensive than LES.[22]

1.3 Literature Review

1.3.1 Generalized Flow Regimes and the Drag Crisis

A classical problem in fluid mechanics is turbulent flow around a circular cylinder. Flow around a circular cylinder is applicable to many different engineering applications, such as the landing gear on airplanes, offshore platform support legs, risers, bridges, etc. These engineering applications often see very high Reynolds numbers flows with typical values of O(10^6)–O(10^7), where this range of *Re* corresponds to the supercritical regime.[20] The various flow regimes are represented in Table 1.3.1 and are pulled from Stringer et al.[7] and Raghavan and Bernitsas.[24]

Table 1.3.1 Flow regimes around a circular cylinder.[7]

Reynolds Number Range	Flow Regime
$Re < 1$	Creeping flow
$3\text{–}5 < Re < 30\text{–}40$	Steady separation (Foppl vortices)
$30 - 40 < Re < 150 - 300$	Laminar periodic shedding
$150 - 200 < Re < 1.4 \times 10^5$	Subcritical
$1.4 \times 10^5 < Re < 1 \times 10^6$	Critical
$1 \times 10^6 < Re < 5 \times 10^6$	Supercritical
$5 \times 10^6 < Re < 8 \times 10^6$	Transcritical
$8 \times 10^6 < Re$	Postcritical

A full understanding for this type of flow has been a huge fundamental challenge for both experimental and computational simulation-based research due to the complex transient nature of the wake. Experimentally, the supercritical flow regime requires that the cylinders have a large diameter and a large wind/water tunnel in order to accurately capture transition in the boundary layers. Facilities of this magnitude are expensive and forced most research to use medium-sized wind tunnels. This implies that experiments conducted in medium-sized test sections are significantly affected by high blockage (the amount of cross sectional area that is blocked by the testing surface) and low aspect ratio (length of the cylinder divided by the diameter). These two parameters along with turbulence intensity (ratio of velocity fluctuations, u_i, to the freestream velocity, U_∞), $I \approx u_i/U_\infty$, play a key role in reproducing ideal two-dimensional (2D) and disturbance-free flow.[25] The cylinder surface roughness has one of the biggest effects on experimental data. A study done by Shih et al.[15] suggested that the drag coefficient, C_D, is independent of the Reynolds number and is purely a function of surface roughness. The lift, C_L, and drag, C_D, coefficient definition are taken from Schlichting (1955):[26]

$$C_L = \frac{F_L}{1/2\,\rho U_\infty^2 A}, \qquad C_D = \frac{F_D}{1/2\,\rho U_\infty^2 A}. \tag{1.3.1}$$

The lift force, F_L, is oriented orthogonally to the drag force, F_D, where F_D is parallel to the freestream velocity, U_∞. When the Reynolds numbers are $1 < Re < 1 \times 10^6$ the drag coefficient is a function of Re and surface roughness.[25,26]

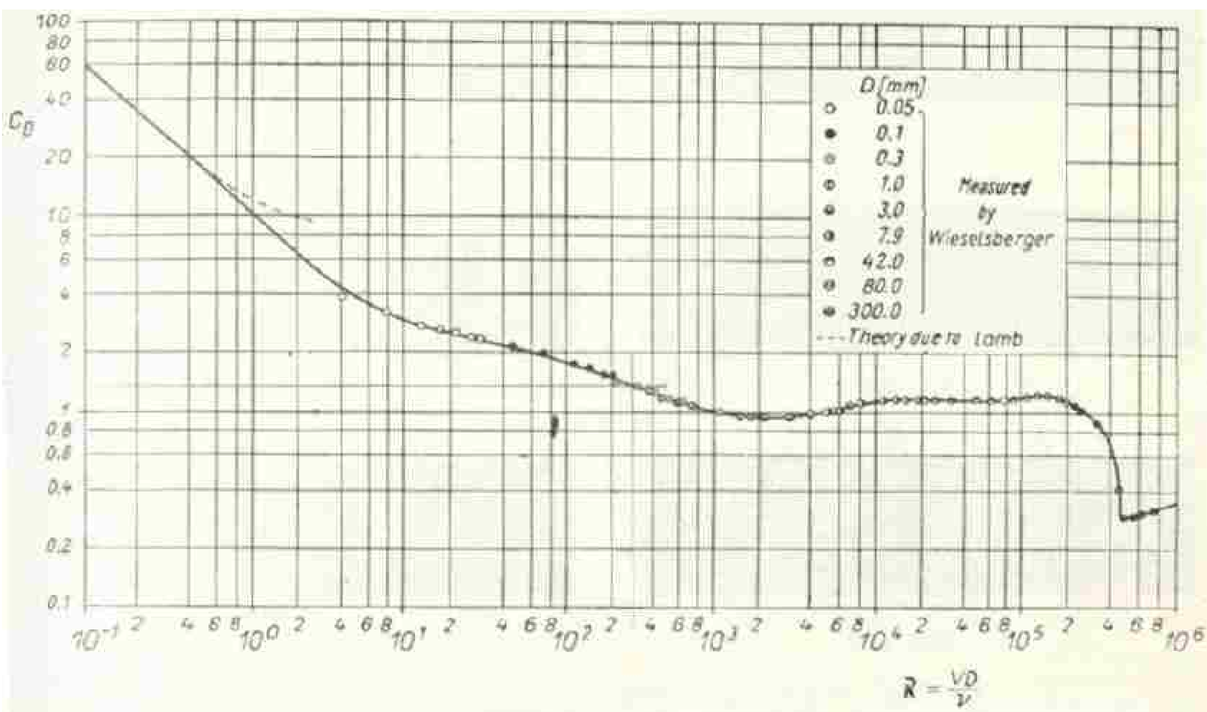


Figure 1.3.1 Drag coefficient for circular cylinders as a function of the Reynolds number.[26]

Figure 1.3.1 represents how the drag coefficient is affected by Reynolds numbers (extracted from Ref. 26). This plot also shows that C_D is independent of the diameter size when comparing the experimental data for this range of Reynolds numbers. There is also a sharp decrease in Reynolds numbers near $Re = 5 \times 10^5$, commonly known as the drag crisis. The drag crisis starts around $Re = 1.4 \times 10^5$ then slowly recovers after $Re = 5 \times 10^5$ and is considered to be in the critical flow regime. This sharp decrease in C_D is a consequence of boundary layer transition to turbulence. Turbulent boundary layer mixing and the accelerating influence of external flow causes the point of separation (separation angle, ϕ, measured clockwise from the stagnation point in the azimuth direction) to move downstream, therefore the turbulent wake region becomes narrow (Fig. 1.3.2 is taken from Ref. 27).[17,21,26,27]

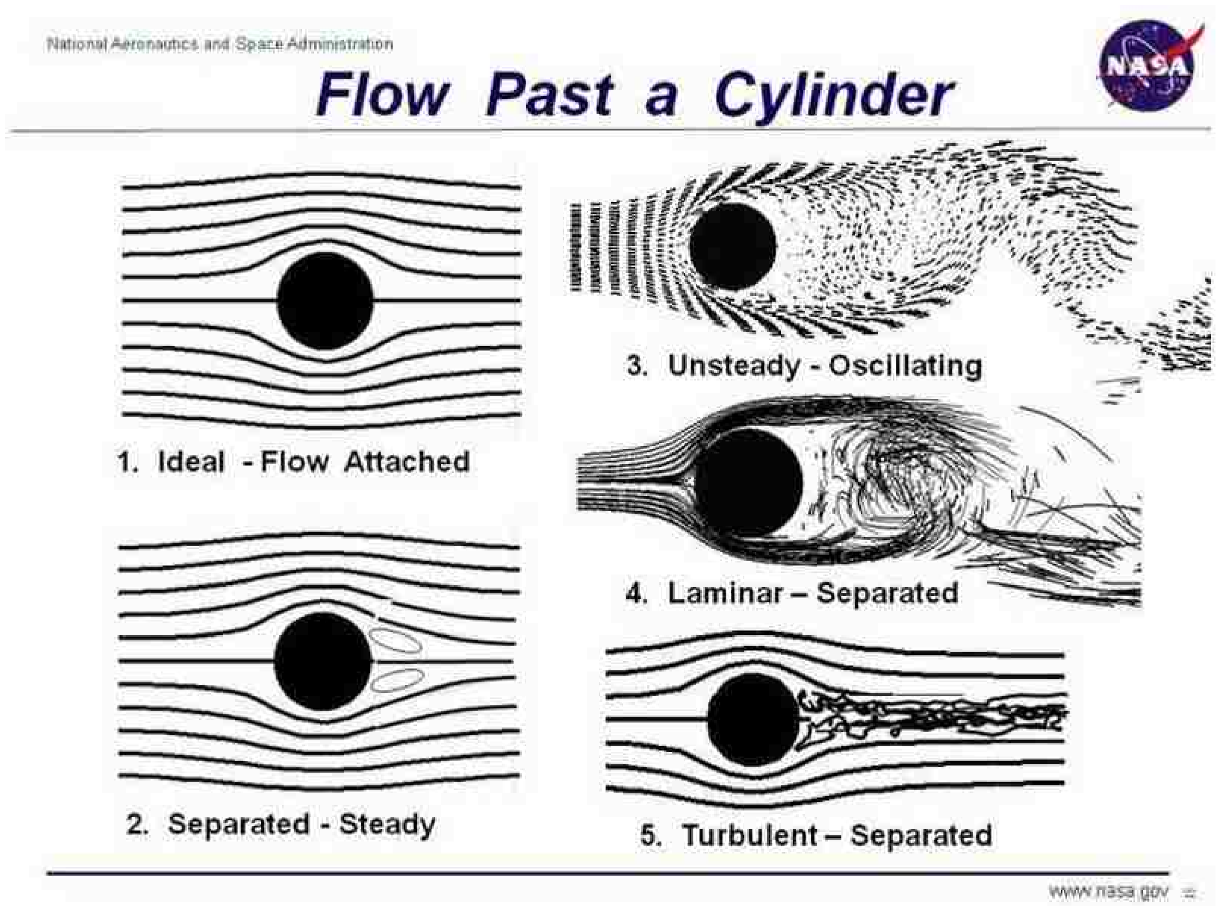


Figure 1.3.2 Transitional flow states with Reynolds number.[27]

In Fig. 1.3.1 the drag coefficient reaches a minimum of $C_D \approx 0.3$ when $0.5 \times 10^6 < Re < 10^6$. In this range of Reynolds numbers a regular vortex street does not exist. When the Reynolds numbers are increased further, $Re > 10^6$, the drag coefficient increases to an almost constant value of $C_D \approx 0.55$ and a regular vortex street is established when $Re > 3.5 \times 10^6$.[10,13,14,25,26] Key features of the turbulent separated flow around and behind a circular cylinder is that the adverse pressure gradient on the top and bottom of the cylinder causes the separation angle to increase and the turbulent wake becomes narrow (Fig. 1.3.2).[28] This is where the drag crisis starts to recover after $Re = 0.5 \times 10^6$.

Before analyzing the complex flow physics around and behind a circular cylinder, some flow properties must be defined. The Strouhal number is defined[14] as the frequency of vortex shedding, f, multiplied by diameter, d, and divided by the freestream velocity, U_∞. This dimensionless quantity is represented below in Eq. 1.3.2.

$$St \equiv \frac{fd}{U_\infty}. \tag{1.3.2}$$

The pressure coefficient is defined[12] as the ratio of difference in local and freestream pressure, $P - P_\infty$, and the dynamic pressure, $q = \rho U_\infty^2/2$. This relationship is defined below in Eq. 1.3.3.

$$C_p \equiv \frac{P - P_\infty}{1/2\,\rho U_\infty^2}. \tag{1.3.3}$$

The surface friction coefficient is the ratio of wall shear stress, τ_w, and dynamic pressure, $q = \rho U_\infty^2/2$, (Eq. 1.3.4).[29]

$$C_f \equiv \frac{\tau_w}{1/2\,\rho U_\infty^2}. \tag{1.3.4}$$

Wall shear stress is defined as the dynamic viscosity multiplied by the wall normal gradient of the velocity parallel to the surface, $U_\parallel$, (Eq. 1.3.5).[29]

$$\tau_w = \mu \left(\frac{\partial U_\parallel}{\partial y}\right)_{y=0}. \tag{1.3.5}$$

1.3.2 Wind Tunnel Experiments

To date, the amount of experimental data is limited because of the high cost to operate very large wind tunnels suitable for capturing important flow physics associated with the supercritical flow regime. Some researchers that examined flow at very high Reynolds numbers are Roshko (1961),[10] Schmidt (1966),[11] Achenbach (1968),[12] Jones et al. (1969),[13] Schewe (1983),[14] and Shih et al. (1993).[15]

Roshko (1961)[10] used a cylinder diameter of 1.5 feet, length of 8.5 feet, and a 11 inch wide wind tunnel, resulting in a blockage ratio of 14% and an aspect ratio of 5.7. There is also a 2 inch thick splitter plate that extruded 4 feet behind the cylinder and spanned the entire 8.5 foot length of the cylinder. A hot wire was placed far downstream: $x/D = 7.3$, $y/D = 0.77$. The cylinder was made of "black steel" pipe that was sand blasted to remove the protective paint. The resulting surface roughness was about 200 μ-in, which was considered to be rough by more recent experiments.[14,15,25,30] The wind tunnel could be pressurized to 4 atm. and was operated below a Mach number $M = 0.25$ to avoid compressibility effects. He found that C_D increases from 0.3-0.7 in the range $10^6 < Re < 3.5 \times 10^6$ and no regular vortex shedding occurred in this range. After $Re = 3.5 \times 10^6$, the base pressure coefficient, C_{pb}, (pressure coefficient, C_p, at 180° measured clockwise from the stagnation point in the azimuth direction, Eq. 1.3.3) is reported to decrease and vortex shedding, also known as the Strouhal number, St, (Eq. 1.3.2) reaches an almost constant value of 0.27. The addition of the splitter plate appeared to change C_{pb} from -0.76 to -0.86, and changed C_D from 0.63 to 0.70.

Schmidt (1966)[11] examined cross-flow around a cantilevered cylinder installed with a steel base plate at the NASA Ames 12-foot wind tunnel facility. This experiment measured $C_D = 0.18$ at $Re = 1 \times 10^6$ with a gradual raise to $C_D = 0.53$ with increasing the Reynolds number to $Re =$

5×10^6. The C_{pb} values are in Reynolds numbers that range $10^6 < Re < 5 \times 10^6$. The 3D flow around the free end of the cylinder relieves the base pressure coefficient, which causes the C_{pb} values to be measured lower than other experiments[25] conducted by Roshko (1961),[10] Achenbach (1968),[12] and Jones et al. (1969).[13]

Achenbach (1968)[12] used a high pressure wind tunnel for Reynolds numbers in the range of $6 \times 10^4 < Re < 5 \times 10^6$. The cylinder was made out of brass with a length of 500mm and a diameter of 150mm, producing an aspect ratio of 3.3. The wind tunnel had a rectangular cross-section of 500 × 900mm, causing a 16% blockage in the test section. The Mach number is $M < 0.05$ with a maximum freestream velocity, U_∞, of 15ms^{-1} and a measured turbulence intensity, I, of 0.7%. Achenbach reported C_f and C_p values on the cylinder surface at $Re = 2.6 \times 10^5$, 8.5×10^6, and 3.6×10^6. The experiment determined that the separation occurs in the range of $115° < \phi < 120°$ for $Re > 1.5 \times 10^6$ (supercritical flow regime). The measured drag coefficient slightly captured the drag crisis and recovered to and average value of approximately $C_D = 0.7$. This experiment has a small cylinder diameter, wind tunnel, aspect ratio, and a large blockage ratio compared to other experiments.[25] The surface roughness was not reported, but the drag coefficient has the same characteristics of a rough cylinder.[30]

Jones et al. (1969)[13] conducted experiments with a 3 foot diameter cylinder and a wind tunnel that had a 16 foot tall test section, producing an aspect ratio of 5.3. This experiment examined a flow range of $0.36 \times 10^6 < Re < 18.70 \times 10^6$ on stationary and oscillating circular cylinders along with compressibility affects. Static-pressure distributions were placed 1.14 diameters above the floor, by using 48 static-pressure orifices spaced around the perimeter of the cylinder. They found that if the Mach number is $M \leq 0.2$ the static-pressure distributions, mean drag coefficients, and St follows the same trends as previous investigators. In other words compressibility effects are negligible if $a < 0.2$. The mean drag coefficient was measured to be $C_D = 0.15$ at $Re \approx 0.5 \times 10^6$ then increases to $C_D = 0.54$ as the Reynolds number reaches $Re \approx 3 \times 10^6$ and then slightly decreases to $C_D = 0.52$ when the Reynolds number is increased to $Re = 10 \times 10^6$. Comparing the C_D values to previous experiments[10,11] postulated that the increased C_D values in Roshko's experiment is attributed to the surface roughness.[11,13,26] C_{pb} follows the same general trend that drag experiences with changing Re. Between $0.5 \times 10^6 < Re < 3 \times 10^6$ the data exhibited no distinct vortex shedding frequency. When the Reynolds numbers are increased to $8 \times 10^6 < Re < 17 \times 10^6$ the Strouhal number is an approximately constant value at $St = 0.3$. The root-mean-square unsteady lift coefficient, C_{Lrms}, at $a < 0.3$ is found to have a large range of measured values in the supercritical regime. They proposed that one possibility for this variation is the variations in symmetry of the flow. After $Re = 8 \times 10^6$ the variation in C_{Lrms} values merge into a single-valued function that decreases with increasing Reynolds number.

Schewe (1983)[14] used a square test section (0.6×0.6 meters) with a fully polished cylinder that has a diameter of $d = 0.06$ meters and a length of 0.6 meters, resulting in a blockage ratio of 10% and an aspect ratio of 10. The range of Reynolds numbers was mainly focused in the range $2.3 \times 10^4 \leq Re \leq 7.1 \times 10^6$ with $4ms^{-1} \leq U_\infty \leq 38ms^{-1}$ and $1\text{bar} \leq P \leq 51\text{bar}$. At this range of Reynolds numbers the turbulence intensity is less than $I = 0.4\%$. Schewe[14] measured a drag coefficient that is nearly constant, $C_D = 0.22$, from $Re = 3.5 \times 10^6$ to approximately $Re \approx 10^6$. After this Reynolds number the drag coefficient experiences the same trend as in previous experiments,[10-13] where the drag coefficient recovers when $10^6 \leq Re \leq 5 \times 10^6$. The mean drag coefficient leveled out at around $C_D = 0.52$, where this value closely matches experiments conducted by Jones et al.[13] One would postulate that the discrepancies in Roshko's[10] C_D data was from surface roughness.[30] Schewe[14] found when the drag crisis starts at $Re \approx 1.4 \times 10^5$, that the

Strouhal number increases from $St = 0.2$ to a maximum of $St = 0.48$ at roughly the peak of the drag crisis $Re \approx 0.5 \times 10^6$. Increasing the Reynolds number further slightly decreases the Strouhal number to $St \approx 0.4$ at $Re \approx 2 \times 10^6$. It should be noted that in the range $0.5 \times 10^6 < Re < 2 \times 10^6$ the Strouhal number was measured to be approximately $St \approx 0.1$. Schewe[14] proposed that a regular vortex street does not exist in this range of Reynolds numbers, $10^6 < Re < 2 \times 10^6$, because the peaks in the frequency spectrum are too broad. After $Re \approx 2 \times 10^6$ the Strouhal number jumps to approximately $St \approx 0.18$ and then slowly increases to a maximum value of $St = 0.27$ at $Re = 7.1 \times 10^6$. Therefore, the Strouhal numbers measured by Jones et al.[13] and Schewe[14] are in close agreement at $Re > 5 \times 10^6$ (transcritical flow regime).

One of the most recent wind tunnel experiments was done by Shih et al. (1993).[15] These tests were conducted at the 12-foot pressurized wind tunnel at NASA Ames Research Center. The Reynolds numbers ranged from $Re = 3 \times 10^5$ to $Re = 8 \times 10^6$, with a Mach number $M < 0.3$ and a turbulence intensity range of $I = 0.04\% - 0.08\%$. The cylinder diameter was $d = 12.46$ inches with an aspect ratio of 8.0 and an overall blockage of 11%. One main difference in this experiment was 91 cm diameter, 2 cm thick end plates used to minimize the boundary layer interaction between the wind tunnel walls and the smooth circular cylinder. Shih et al.[15] found that the base pressure coefficient, C_{pb}, on the smooth cylinder decreases from -0.1 to -0.6 when the Reynolds number is increased from $Re = 7 \times 10^5$ to $Re = 8 \times 10^6$. However, as the surface roughness increases the base pressure coefficient, C_{pb}, becomes independent of the Reynolds number after $Re \approx 2 \times 10^6$. For the smooth circular cylinder, the drag coefficient is in very close agreement with Jones et. al.[13] and Schewe,[14] where the drag crisis occurs at $Re \approx 1.4 \times 10^6$ and starts to recover after $Re \approx 0.5 \times 10^6$. When the surface roughness is increased, measured C_D values are increased to the match experiments by Roshko[10] and Achenbach.[12] If surface roughness is increased further, C_D values are increased and the drag crisis/recovery becomes less prominent. Therefore, one can postulate that when the flow around a circular cylinder is in the supercritical regime, C_D values are no longer dependent on Re and only depend on the relative surface roughness.[15] Beyond $Re = 4 \times 10^5$, coherent vortex shedding disappeared and there was no increase in the Strouhal number to $St \approx 0.4$ (reported by Schewe[14]). It should be noted that the Strouhal number, St, for the smooth cylinder was not reported after $Re \approx 4 \times 10^5$. However, vortex shedding from rough cylinders persisted in the flow regime tested, with the roughest cylinder producing the lowest Strouhal number. The Strouhal number increased as a linear function from $St \approx 0.2$ to $St \approx 0.25$ with increasing Reynolds numbers.

Table 1.3.2 Measured experimental values. Note: *Re* range is based on the focus of the respective paper. ("~" denotes unavailable data), †(Re=3.6×10^6), ‡(*Re*>3.5×10^6), §(Rough cylinder).

Experiment	$Re \times 10^{-6}$	a	I %	C_D	$-C_{pb}$	St
Roshko[10] §	1-3.5	<0.25	~	0.3-0.7	0.62-0.85	0.27 ‡
Schmidt[11]	1-5	~	~	0.18-0.53	0.35-0.60	~
Achenbach[12] §	0.5-5	<0.05	0.7	0.6-0.76	0.85 †	~
Jones et al.[13]	0.5-8	<0.2	~	0.15-54	0.53-0.63	0.3 ‡
Schewe[14]	1-5	~	0.4	0.22-0.52	~	0.2-0.27 ‡
Shih et al.[15]	0.3-8	<0.3	<0.08	0.16-0.50	0.1-0.6	0.2-0.25

From the discussion above and Table 1.3.2 the experimentally measured C_D and C_{pb} values follow the same general trend, where the drag coefficient, C_D, increases with increasing Reynolds numbers and the base pressure coefficient, C_{pb}, becomes more negative with increasing Reynolds numbers. In the range $10^6 \leq Re \leq 3.5 \times 10^6$, a regular vortex street was not present.[10-15] However, Schewe[14] reported a "jump" in the measured Strouhal numbers with a maximum at $St \approx 0.48$ around the drag crisis, $Re \approx 0.5 \times 10^6$. At the same time Schewe[14] reported St values as low as 0.1 in the range $0.5 \times 10^6 < Re < 2 \times 10^6$, then increased from 0.2 to 0.27 after $Re \approx 2 \times 10^6$. Shih et al.[15] reported St values for a rough cylinder that increased from 0.2-0.25 and that the roughest cylinder produced the lowest St values. All of the measured experimental values have a large range in the supercritical flow regime. Slight differences in blockage ratio, aspect ratio, turbulence intensity, and surface roughness have a large impact on the complex flow physics in the supercritical flow regime. Comparing the different experimental systems, it can be postulated that surface roughness has the largest effect on measured values,[15] i.e. C_D, C_f, C_{pb}, etc.

1.3.3 Computational Simulations

An attractive alternative for determining flow characteristics around a smooth circular cylinder is Computational Fluid Dynamics (CFD). In the supercritical flow regime, the amount of published numerical simulations are limited due to the complexity and transient nature of the turbulent wake. Direct Numerical Simulations (DES) are currently not possible in the supercritical flow regime due to the high computational demand required to resolve the grid scales.[20]

The amount of simulation data available is limited at very high Reynolds numbers. For most of the data available, the main focus of the report is on $Re \leq 10^6$ and some of the aerodynamic characteristics in the supercritical flow regime are not available. This next section will examine some of the turbulence modeling methods and simulation parameters used on cross-flow over a smooth circular cylinder.

Large Eddy Simulations conducted at higher Reynolds include Catalano et al. (2003)[16] and Shingh and Mittal (2005).[31] Catalano et al.[16] used 3D LES with wall modeling as well as steady RANS and unsteady RANS (URANS) using the standard high Reynolds number k-ε model of Launder and Spalding[32] with wall functions, where the main focus was on $Re = 10^6$, 2×10^6, 4×10^6. Time-averaged drag coefficients for $10^6 < Re < 4 \times 10^6$ along with the Strouhal number, mean pressure distribution, and velocity profiles at $Re = 10^6$ are presented. When compared to Shih et al.,[15] LES proved to be more accurate at lower Reynolds numbers, between

$Re = 0.5 \times 10^6$ and $Re = 10^6$, where the drag crisis is recovering. The LES case at $Re = 2 \times 10^6$ was less accurate due to the grid resolution.

Shingh et al.[31] performed simulations with a 2D LES method in the range $100 < Re < 10^7$. The main objective of this study was to analyze the instabilities in the separated shear layer during the drag crisis. The primary focus of this study was in the range $100 < Re < 3 \times 10^5$, with some results presented for $Re \geq 10^6$. This study was able to capture the sudden reduction in drag coefficient during the drag crisis, however C_D was overpredicted in comparison to experiments with smooth cylinders.[11,13-15]

Three-dimensional Detached Eddy Simulations (DES) conducted by Travin et al. (1999)[17] and Lo et al. (2005)[18] examined turbulent flow in the range of $1.4 \times 10^5 \leq Re \leq 3.6 \times 10^6$. The DES formulation that Travin et al.[17] used applied a one-equation RANS turbulence model by Spalart-Allmaras[33] near the wall that transitions to a subgrid-scale (SGS) model based on the relative dissipation rate of the eddy viscosity scales. The main Reynolds number examined was $Re = 1.4 \times 10^5$ where the results indicated that the drag coefficient, base pressure coefficient, and Strouhal number are captured at higher accuracy, when compared to experimental data, with the rotation/curvature (RC) suggested by Stalart et al.[33] In the range $Re \geq 3 \times 10^6$, it is assumed that the boundary layer is turbulent well ahead of separation. Travin et al.[17] reported $C_D = 0.51$, $C_{pb} = -0.64$, $\phi = 106°$, and $St = 0.33$, with the RC term at $Re = 3 \times 10^6$. Surface friction and the pressure coefficient are also presented.

The commercial CFD code Cobalt was used by Lo et al. (2005),[18] which is a cell-centered, finite volume, unstructured compressible flow solver. The DES formulation contains both the Spalart-Allmaras and Menter's Shear Stress Transport (SST)[35-37] for modeling the near wall and transitions to the SGS model where the eddy scales are small. This report examined flow around and behind square and circular cylinders. For flow around a circular cylinder at $Re = 3.6 \times 10^6$, a fully turbulent simulation was compared to a transitional formulation with a trip function. They concluded that the trip function had little effect on aerodynamic parameters. A non-dimensional time-step of $t^* = \Delta t U_\infty / D = 0.01$ was used with a Mach number of $M = 0.1$. Time-averages are taken after 100 non-dimensional time-steps. The pressure coefficient is compared to Achenbach[12] with close agreement before $\theta = 90°$. This report also presented values for the drag coefficient, base pressure coefficient, Strouhal number, separation angle, and recirculation length.

Steady and unsteady RANS simulations are carried out by Catalano et al. (2002),[16] Ong et al. (2009),[20] Stringer et al. (2014),[7] and Karabelas et al. (2012).[19] Catalano et al.[16] used the top half of the domain (same 3D grid as in their LES simulations) for steady RANS and the full domain for URANS with the standard k-ε turbulence model (Launder and Spalding 1972)[46] with wall functions using the commercial code FLUENT. They presented time-averaged drag coefficients for $Re = 10^6$, 2×10^6, and 4×10^6, as well as the Strouhal number, base pressure coefficient and drag coefficient at $Re = 10^6$.

Ong et al. (2009)[20] examined 2D simulations at $Re = 10^6$, 2×10^6, and 3.6×10^6 using a standard high Reynolds number k-ε turbulence model[32,38] with wall functions, where simulations were solved using a Galerkin finite element method with a Segregated Implicit Projection (SIP) algorithm[39] for the time-step solution. The turbulence intensity used was $I = 0.008$. A non-dimensional time-step of $t^* = 0.001\, U_\infty / D$ was used with time-averaging to 250 non-dimensional time-steps. They reported the drag coefficient with respect to Reynolds numbers as well as pressure coefficient and surface friction with respect to the azimuth angle, θ, at $Re = 10^6$, and 3.6×10^6. The Strouhal number and separation location is also presented. This report stated that the maximum surface friction coefficient decreases with increasing Reynolds numbers which agrees qualitatively with 3D LES data.[16]

Karabelas et al. (2012)[19] used FLUENT 6.3 to examine 2D stationary and oscillating smooth circular cylinders using the standard k-ε turbulence model with wall functions at $Re = 200, 5 \times 10^5, 10^6$, and 5×10^6. The majority of presented aerodynamic properties for a stationary cylinder in the supercritical flow regime are at $Re = 10^6$.

Stringer et al. (2014)[7] used ANSYS[40] CFX-13.0 and OpenFOAM[9] 1.7.1 to conduct 2D simulations with Menter's SST turbulence model in the range $40 < Re < 10^6$. The majority of the research done was for $Re < 10^5$. The simulations used a non-dimensional time-step based on the Courant-Friedrichs-Lewy condition ($Cr < 1$), $Cr = U_\infty \Delta t / y$ (y is the smallest cell height from the wall), where all simulations are solved to 150 non-dimensional time units. Some information about the drag coefficient and Strouhal number is reported. At $Re = 10^6$ the Strouhal number determined by Stringer et al.[7] with OpenFOAM is approximately zero and Stringer et al.[7] stated that OpenFOAM fails to shed vortices. It should be noted that the Stringer et al.[7] did not mention the implementation of the standard Menter SST turbulence model[41,42] in OpenFOAM. The original implementation of the SST turbulence model in OpenFOAM is different from the standard turbulence model[8] (see Gomez[8] for the standard implementation of the SST turbulence model in OpenFOAM).

Within the supercritical flow regime all the measured simulation values vary for a given Reynolds number. At $Re = 10^6$ the measured drag coefficient between LES simulations conducted by Singh et al.[31] and Catalano et al.[16] are very different. One can postulate that changing the simulations from 3D to 2D effects the accuracy of the drag coefficient when using LES at higher Reynolds numbers. Differences in simulation results lie in the formulation and implementation of a specific turbulence model, the method used, the overall domain shape and size, the type of computational mesh and total number of cells, the non-dimensional time-step, and the initial and boundary conditions. From Table 1.3.3 it is clear that Eddy Viscosity Models (EVM's) provide a satisfactory alternative for determining important aerodynamic information and are less computationally demanding, in the supercritical regime ($Re > 10^6$), than LES and DES. It is clear that values in the supercritical flow regime have discrepancies and the random shedding of vortices produces difficulties in accurately capturing the complex aerodynamic properties associated with smooth circular cylinders.

Table 1.3.3 Published computational simulation results ("~" denotes unavailable data).

Turbulence modeling approach	$Re(10^{-6})$	C_D	St	ϕ	L_R/D	$-C\_pb$
3D RANS/URANS k-ε[16]	1	0.39/.0.40	~/0.31	~/~	~/1.37	0.41/0.33
3D LES[16]	1	0.31	0.35	103˚	1.04	0.32
2D LES[45]	1	0.591	~	~	~	~
2D k-ε[20]	1	0.5174	0.2823	~	~	~
2D k-ε[19]	1	0.34	0.2	~	~	0.3
2D SST CFX/OpenFOAM[7]	1	0.54/0.15	0.3/ ≈ 0	~	~	~
3D DES/DES with RC[17]	3	0.41/0.51	0.35/0.33	111˚/106˚	1.0/1.0	0.53/0.64
2D k-ε[20]	3.6	0.4573	0.3052	114˚	~	~
DES/DES with 65˚ trip[18]	3.6	0.576/0.535	0.305/0.311	118˚/119˚	0.35/0.32	0.796/0.748

Chapter 2

Simulation Parameters

2.1 OpenFOAM

Open Field Operation and Manipulation (OpenFOAM) is a free, object-oriented open-source toolbox. This CFD software package is licensed and distributed by the OpenFOAM Foundation[43] and developed by OpenCFD Ltd.[44] OpenFOAM is based on a C++ library and provides the user with precompiled utilities and solvers useful for problems ranging from complex fluid dynamics involving heat transfer, chemical reactions and turbulence, to electrodynamics and solid dynamics.

When comparing this software to other CDF codes, the open-source nature allows both commercial and academic organizations the ability to completely customize and extend the existing functionality, therefore providing both an economic and technological benefit. From an economic stand point, having a General Public License (GPL) provides the opportunity for free distribution and modification of the software. Technologically, OpenFOAM is equipped with a tool for meshing, pre-and post-processing capabilities, and parallel processing abilities. The open-source nature of the code also provides the possibility for the implementation of standard and new turbulence models. Parallelization of the computational code allows users the ability to take advantage of supercomputer facilities, which decreases the computational time required to accurately capture complex physics associated with a particular engineering application.[45] This study uses the Repository Release OpenFOAM (2.3.x) with NASA's Pleiades Supercomputers.[46] See Ref. 47 or Ref. 48 for information on where to download OpenFOAM (2.3.x).

Simulations in OpenFOAM are conducted with a Finite Volume Method[2,49] that uses a co-located grid. This type of grid stores fluid dynamic quantities at a single node. In order to avoid unphysical behavior, from storing both pressure and velocity at the same point, the code applies interpolation schemes to separate these values between cell centers and face centers.[22] There is no graphical interface for OpenFOAM, instead the CFD-code uses a group of subdirectories to define a simulation. A general overview of the file structure is represented in Fig. 2.1.1.[50]

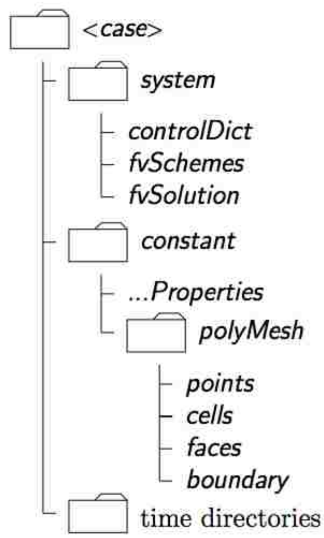


Figure 2.1.1: Case directory structure for OpenFOAM[50]

A case directory in OpenFOAM consists of *system*, *constant*, and *time directories* that allows the user to define data for a particular simulation (Fig. 2.1.1). The *system* directory defines parameters associated with the numerical schemes, solution methods, run-control, and write-control for the simulation process. The *polyMesh* directory that defines the computational mesh, all of the physical properties, and turbulence model specification (if regarding CFD) are stored in the *constant* directory. The *time* directory defines the boundary and initial conditions for a given computational domain and physics situation. *Time* directories are named according the respective time-step and the initial conditions are named based on the parameters need to solve the respective turbulence model, e.g. P, U, ν_t, ε, etc.

2.2 Implementation of Turbulence Models in OpenFOAM

2.2.1 Standard Formulations of Turbulence Models in OpenFOAM

Prior to defining and running simulations, OpenFOAM's implementation of turbulence models required an examination to determine if "standard" implementations of a respective turbulence model was prepared. Previous studies,[8] done by our research group,[51] found that the implementations done by OpenFOAM did not match the *standard* implementations of turbulence models defined by the Turbulence Model Benchmarking Working Group (TMBWG) Turbulence Modeling Resource.[41] This study uses *standard* formulations[41] of the Wilcox 2006 *k*-*ω* turbulence model[52] and the Menter Shear Stress Transport (SST)[42] turbulence model to examine turbulent flow around and behind a 2D smooth circular cylinder. Previous work[8] has been done to implement and test the *standard* formulations of the *k*-*ω* and SST models in OpenFOAM. The applicability of OpenFOAM and the *Standard* formulations of these turbulence models were compared and verified[8,53] on benchmark flows produced[54-56] by NASA's TMBWG Turbulence Modeling Resource.[41]

2.2.2 Wilcox's 2006 *k*-*ω* Turbulence Model

One of the turbulence models used in this study is the Wilcox 2006 *k*-*ω* Turbulence Model. This is a two-equation turbulence model that solves a closed formulation of the turbulent kinetic energy, k, and specific dissipation rate, ω, PDE. In this closed form mean velocities, U_i, mean pressure, P, turbulent kinetic energy, k, specific dissipation rate, ω, and turbulent viscosity, ν_t, fields are all used to discretize and computationally solve the complex flow physics in a particular simulation. The *standard* incompressible formulation[41] of the transport equations for k and ω are presented in Eq. 2.2.1 and Eq. 2.2.2, respectively.

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P - \beta^* \omega k + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma_k \frac{k}{\omega}\right)\frac{\partial k}{\partial x_j}\right]. \quad (2.2.1)$$

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \frac{\gamma\omega}{k} P - \beta\omega^2 + \frac{\partial}{\partial x_j}\left[\left(\nu + \sigma_\omega \frac{k}{\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + \frac{\sigma_d}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}. \quad (2.2.2)$$

In this case *P* denotes the production term (Eq. 2.2.3) and uses τ_{ij} as the Boussinesq approximation (Eq. 2.2.4, 2.2.5).

$$P = \tau_{ij}\frac{\partial U_i}{\partial x_j}. \quad (2.2.3)$$

$$\tau_{ij} = 2\nu_t S_{ij} - \frac{2}{3} k \delta_{ij}. \quad (2.2.4)$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right). \quad (2.2.5)$$

Turbulent kinematic viscosity, ν_t, (Eq. 2.2.6) is defined with a limiting term (Eq. 2.2.7).

$$\nu_t = \frac{k}{\tilde{\omega}}. \quad (2.2.6)$$

$$\tilde{\omega} = \max\left[\omega, C_{\mathrm{lim}}\sqrt{\frac{2S_{ij}S_{ij}}{\beta^*}}\right]. \quad (2.2.7)$$

The auxiliary functions and constants are defined in Eq. 2.2.8-.9 and in Table 2.2.1, respectively.

$$f_\beta = \frac{1 + 85\chi_\omega}{1 + 100\chi_\omega}, \qquad \chi_\omega = \left|\frac{\Omega_{ij}\Omega_{jk}S_{ki}}{(\beta^*\omega)^3}\right|, \qquad \Omega_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}\right). \quad (2.2.8)$$

$$\sigma_d = \begin{cases} 0, & \frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \le 0 \\ \frac{1}{8}, & \frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} > 0 \end{cases}. \quad (2.2.9)$$

Table 2.2.1 *Standard* Wilcox 2006 *k-ω* turbulence model coefficients.

σ_k	σ_ω	β^*	γ	C_{lim}	β	β_0
0.6	0.5	0.09	13/25	7/8	$\beta_0 f_\beta$	0.0708

The auxiliary function χ_ω in Eq. 2.2.8 is denoted as known as "Popes's correction" and is equal to zero in the case of 2D simulations.[41] Implementation of this turbulence model in OpenFOAM required changes to the *kOmega* turbulence model directory. The differences between the *standard* formulation and OpenFOAM's implementations are listed below and was originally found by Ref. 8.

Original *kOmega* directory.

- ❖ β defined as function.
- ❖ $\sigma_k = 0.5$
- ❖ f_β, χ_ω, and σ_d not defined.
- ❖ $\widetilde{\omega}$ doesn't have the limiting term.
- ❖ $CD_{k\omega}$ is missing in the ω PDE.

Changed for *standard* implementation.

- ❖ β now defined as a constant.
- ❖ $\sigma_k = 0.6$
- ❖ f_β, χ_ω, and σ_d are added.
- ❖ ν_t is modified to include $\widetilde{\omega}$ from.
- ❖ $CD_{k\omega}$ is added to the ω PDE.

2.2.3 Menter's Shear Stress Transport Turbulence Model

Similar to the *k*-*ω* turbulence model, Menter's 1993 SST turbulence model is a two-equation EVM that solves a closed form of the transport equations for turbulent kinetic energy and specific dissipation. The formulation of the SST turbulence model applies the *k*-*ω* turbulence model to the inner parts of the boundary layer enabling the SST to be used as a Low-Re turbulence model without any extra damping functions.[57] A blending function is used to link the *k*-*ω* turbulence model applied to the boundary layer with the *k*-*ε* turbulence model used in the free-stream. This is done due to the fact that the *k*-*ω* turbulence model is better at capturing near wall effects and the *k*-*ε* turbulence model is better at capturing far-field flow physics. The *standard* incompressible formulation[41] of the transport equation for k is represented in Eq. 2.2.9.

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = P^* - \beta^* \omega k + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}\right] \tag{2.2.9}$$

Equation 2.2.10 defines the transport equation for ω.

$$\frac{\partial \omega}{\partial t} + U_j \frac{\partial \omega}{\partial x_j} = \frac{\gamma_\omega}{\nu_t} P - \beta_\omega \omega^2 + \frac{\partial}{\partial x_j}\left[(\nu + \sigma_\omega \nu_t)\frac{\partial \omega}{\partial x_j}\right] + 2(1 - F_1)\frac{\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \tag{2.2.10}$$

The production term, P, (Eq 2.2.12) in this case is similar to the k-ω turbulence model with a slight difference in the k PDE (Eq. 2.2.9) having a limiting production term, P^*, (Eq. 2.2.11)

$$P^* = \min(P, 20\beta^*\omega k) \tag{2.2.11}$$

$$P = \tau_{ij}\frac{\partial U_i}{\partial x_j} \tag{2.2.12}$$

$$\tau_{ij} = 2\nu_t S_{ij} - \frac{2}{3}k\delta_{ij} \tag{2.2.13}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{2.2.14}$$

Turbulent viscosity (Eq. 2.2.15) is dependent on model coefficients (Table 2.2.2), vorticity magnitude (Eq. 2.2.16), vorticity (Eq. 2.2.17), and auxiliary relations (Eq. 2.2.18-2.2.19). The variable y is the distance from the wall to the nearest field point.

$$\nu_t = \frac{a_1 k}{\max(a_1\omega, \Omega F_2)} \tag{2.2.15}$$

$$\Omega = \sqrt{2W_{ij}W_{ij}} \tag{2.2.16}$$

$$W_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}\right) \tag{2.2.17}$$

$$F_2 = \tanh(arg_2^2) \tag{2.2.18}$$

$$arg_2 = \max\left(2\frac{\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right) \tag{2.2.19}$$

$$F_1 = \tanh(arg_1^4) \tag{2.2.20}$$

$$arg_1 = \min\left[\max\left(2\frac{\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right), \frac{4\sigma_{\omega 2}k}{CD_{k\omega}d^2}\right] \tag{2.2.21}$$

$$CD_{k\omega} = \max\left(2\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}, 10^{-20}\right) \tag{2.2.22}$$

The blending function (2.2.23) uses Eq. 2.2.18-2.2.22 based on the fluid dynamic properties and computational mesh to determine the blending boundary of the *k-ω* and *k-ε* turbulence models.

$$\phi = F_1\phi_1 + (1 - F_1)\phi_2. \tag{2.2.23}$$

In Eq. 2.2.23, the blending function uses the turbulence model coefficients to ultimately alter the transport equations. ϕ defines the corresponding blended function, where ϕ_1 and ϕ_2 are the corresponding turbulence model coefficients.

The model coefficients are represented in Eq. 2.2.24 and Table 2.2.2.

$$\gamma_1 = \frac{\beta_1}{\beta^*} - \frac{\sigma_{\omega 1}\kappa^2}{\sqrt{\beta^*}}, \qquad \gamma_2 = \frac{\beta_2}{\beta^*} - \frac{\sigma_{\omega 2}\kappa^2}{\sqrt{\beta^*}}. \tag{2.2.24}$$

Table 2.2.2 *Standard* SST turbulence model coefficients.

σ_{k1}	σ_{k2}	$\sigma_{\omega 1}$	$\sigma_{\omega 2}$	β_1	β_2	β^*	κ	a_1
0.85	1	0.5	0.856	0.075	0.0828	0.09	0.41	0.31

Changes to the *kOmegaSST* model in OpenFOAM are listed below.

Original *kOmegaSST* directory.

- ❖ $CD_{k\omega}, arg1$ and $arg2$ have different implementations.
- ❖ Extra functions F_3 and F_{23}.
- ❖ Different implementation of ν_t.
- ❖ Production and sign of last term in the *ω* PDE different.
- ❖ *P* in the *k* PDE doesn't have the limiting term P^*.

Changed for *standard* implementation.

- ❖ Modified $CD_{k\omega}, arg_1$ and arg_2 to match Eq. 2.2.22, 2.2.21, and 2.2.19.
- ❖ Remove F_3 and F_{23} functions.
- ❖ Changed ν_t to match NASA definition.
- ❖ *Standard* definition of $\gamma_\omega P/\nu_t$ and sign change of the last term is applied.
- ❖ Limiting production term, P^*, is implemented in the *k* PDE

A previous study[53] conducted by our research group has shown that the SST turbulence model captures the separation region, behind a 2D NACA 4412 airfoil at maximum lift, with higher accuracy than the *k-ω* turbulence model. Implementation of this model requires more computational effort due to the complex blending function. All source code for the turbulence models can be found in Ref. 8.

2.3 Numerical Methods

As mentioned in Chapter 2.1, OpenFOAM can be applied to a large range of engineering applications. For the case of turbulence modeling, OpenFOAM captures the complex flow physics by representing the fluid with continuum equations, which is representative of discrete particles. The continuum equations, or turbulence models in this case, are discretized with a Finite Volume Method (FVM).[2,21] The FVM discretizes, or subdivides, the integral form of the computational domain into a finite number of control volumes and the surface and volume integrals of the governing equations are approximated using quadrature. This constructs a system of matrix equations that can be applied to arbitrary shaped cells with any number of faces and edges.

Discretization of the continua equations into finite, or discrete, quantities is generally composed of temporal, spatial, and equation schemes. Temporal discretization is used for transient simulations and is based on dividing the total time, used to describe a problem, into uniform or non-uniform time-steps. All simulations conducted in this study will be using uniform time-steps to describe the solution space. Spatial discretization is used to describe a defined region, or control volume, with a computational mesh that describes the solution space under examination. Equation discretization defines the computational methods used on the conservation laws for a specific time-step and location, described by the temporal and spatial discretization.

Once the conservation laws, used to describe a solution space, are fully discretized in space and time, a solution can be obtained. For the case of turbulence models, the discretization methods described above generally generate a finite set of non-linear equations. These non-linear equations can only be solved for with an iterative method. This paper will only discuss the discretization and solution algorithms used in this study. All of the discretization and solution algorithms available in OpenFOAM can be found in Chapter 2 from Ref. 49 and Chapter 4 from Ref. 50.

2.3.1 Temporal Discretization

From Chapter 1.3 Literature Review it is clear that the supercritical flow regime for a circular cylinder is statistically unstable. In this study, both steady and unsteady RANS are implemented to determine if it is necessary to use a transient solver for a highly separated flow. OpenFOAM manages the temporal discretization with the *controlDict* dictionary, which can be found in the *system* directory. It should be noted that the *controlDict* can also be used to measure force coefficients and average the solution in time (see Appendix for the source code). For the case of a steady solver, a pseudo-time step is implemented to execute the iterative process, control the total number of iterations needed for a converged solution, and control the output of iterations. Unsteady RANS uses a specified time-step to march the solution forward in time during the iterative process. The time-step, Δt, has upper limits based on the requirements of accuracy and numerical stability.[21]

2.3.2 Spatial Discretization

OpenFOAM has the ability to discretize structured and unstructured grids, with any number of faces and edges, into smaller control volumes that define the governing equations. In this study four structured grids are used with increasing grid refinement. Due to the relatively simple geometry, the computational mesh was generated with OpenFOAM's *blockMesh* utility (see Appendix for source code). The computational mesh is an O-Grid in the near wake that transitions to a C-Grid in the farfield. This hybrid O-Grid/C-Grid mesh was implemented to reduce the total number of computational nodes in the farfield while utilizing the appropriate near wall flow conditions. Each increasing mesh refinement is done by doubling the local nodes, based on the coarsest grid. Essentially each cell is split in half. See Chapter 2.4 Computational Mesh for more details on the computational mesh used in this study.

2.3.3 Equation Discretization

OpenFOAM has a large variety of schemes used to approximate the governing equations. The type of schemes utilized are controlled through the *fvSchemes* dictionary, where the order of accuracy in the method used to solve temporal, spatial, gradient, divergence, Laplacian, interpolation, surface normal gradient, and flux schemes are defined. Specification of these schemes determines the accuracy and numerical stability for a particular problem.

The *default* setting in the *fvSchemes* specifies a specific numerical scheme to a category of equations, i.e. temporal. In this study both steady and unsteady solvers are used to conduct flow studies for a smooth circular cylinder. For steady RANS, the *ddtSchemes* are set to *steadyState*, therefore using a pseudo-time step in the iteration process. In the URANS case, *ddtSchemes* are specified as *backward*, which is a second order temporal discretization scheme.

OpenFOAM provides the ability to apply a specific type of scheme to each variable, therefore providing complete control over the numerical stability and accuracy of the solution. Second order Gaussian integration is used for all terms in the governing equations that contain a derivative. The solution variables for each matrix equation are co-located variables defined at the cell centers. Unphysical behavior can arise from storing the velocity and pressure values at the same location. OpenFOAM uses an appropriate interpolation method to separate the storage location of these values so that unphysical behavior on a co-located grid does not occur.[58] Since OpenFOAM uses a co-located grid (solutions are calculated at cell centers), a central differencing interpolation method (first-order linear) is applied to all gradient terms, upwind approximations (first- and second-order) are applied to the divergence schemes, and a surface normal gradient scheme (corrected unbounded, second order, conservative scheme) is used for the Laplacian scheme.[49,50] All diffusive terms use a central difference interpolation scheme and an non-orthogonal correction method (explicit second-order) for all surface-normal gradients. All terms that require interpolation are specified as *Gauss* in the *fvSchemes*. The convective terms can be defined as either first- or second-order by specifying the respective term with *upwind* and *linearUpwind*, respectively, in the *fvSchemes*. See Appendix for the *fvSchemes* used to conduct simulations in this study.

2.3.4 Solution to Discretization Schemes

OpenFOAM can solve the coupled discretized equations with a large variety of different algorithms. In this case, the flow is incompressible and turbulent with a large separation region in the wake. Commonly used algorithms in CFD for governing equations that are coupled with velocity and pressure are the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm for RANS and the Pressure Implicit with Splitting of Operators (PISO) algorithm for URANS. The SIMPLE and PISO algorithms implemented in OpenFOAM are segregated iterative solvers.[59]

The SIMPLE algorithm solves the coupled system of equations with primarily a momentum predictor and a pressure correcting step. The PISO algorithm implements a momentum predictor with two corrector steps for pressure values. OpenFOAM solves a Poisson pressure equation to correct the pressure field. Convergence of these two algorithms is improved with under-relaxation factors that calculate the value for the next time-step and blend it with the old value.[8,23]

The SIMPLE algorithm was originally designed for finite volume approximation on staggered techniques. This robust algorithm has been found to converge in many cases, but is known to have slower convergence than more sophisticated methods, i.e. PISO.[21] The SIMPLE algorithm is applicable to iteratively solve steady-state problems, where the discretized momentum equation and pressure correction are solved implicitly and the velocity correction is solved explicitly. This is where the "Semi-Implicit Method" part of the name comes from. An initial guess is made for the velocity profile to solve the momentum equations. This makes it so the continuity equation is not satisfied unless the pressure field is corrected. Updating the pressure and velocity fields satisfies continuity but not momentum. The algorithm then recalculates the velocity field based on the corrected pressure in order to satisfy the momentum. This procedure is repeated until both continuity and momentum are satisfied, also known as convergence of the solution space. Details describing the basic steps of the SIMPLE algorithm are listed below and are based off of Ref. 8, 21, and 60.

1. Apply boundary conditions to the system.
2. Velocity and pressure gradients are computed.
3. Compute the intermediate velocity field by solving the discretized momentum equations.
4. Mass fluxes at cell faces are computed.
5. Correct the pressure field by solving the pressure correction equation.
6. Update the pressure field with the under-relaxation factor.
7. Update the boundaries with the pressure correction.
8. Correct the mass flux at the cell faces.
9. Correct the cell velocities with the pressure gradient form the corrected pressure.

The PISO algorithm is an extension of the SIMPLE algorithm and was first proposed by Issa[61] in 1986. This algorithm is applicable to transient problems that have pressure and velocity coupled governing equations. The first part of the PISO algorithm works in the same way that the SIMPLE algorithm does, where the momentum equation solves for the velocity then uses the Poisson pressure equation to correct the pressure. The general steps of the PISO algorithm can be found in the list below.[61,62] It should be noted that the PISO algorithm can be used for steady-state solutions.[21,62]

1. Implement boundary conditions.
2. Compute an intermediate velocity field by solving the discretized momentum equation.
3. Compute the mass flux at the cell faces.
4. Solve Poisson pressure equation.
5. Correct the mass flux at the cell faces.
6. Correct the cell velocities from the corrected pressure field.
7. Update the boundary conditions from the corrected values.
8. User defines the number of times the process from step 3 to 7 are repeated.
9. Move to next time-step and repeat the process from step 1.

In OpenFOAM, the type of algorithms used to obtain the solution to a defined computational domain are controlled through the *fvSolution* dictionary, which is located in the *system* directory. The SIMPLE algorithm is set up by applying *simpleFOAM* to the *application* specification in the *controlDict* dictionary and *SIMPLE* as the algorithm specification in the *fvSolution* dictionary. The PISO algorithm is set up with the *pisoFOAM* specification in the *controlDict* dictionary and *PISO* as the algorithm specification in the *fvSolution* dictionary. Both SIMPLE and PISO foam can use the *nNonOrthogonalCorrectors* setting, which accounts for the mesh orthogonality. If the mesh is completely orthogonal, the *nNonOrthogonalCorrectors* should be set to 0. For this study the mesh is slightly non-orthogonal, around 1.6 in the O-Grid section, so two non-orthogonal correctors were applied to the iterative process. For only the PISO algorithm, the *nCorrectors* specification in the *fvSolution* dictionary corresponds to number 8 in the general steps for the PISO algorithm. For all unsteady simulations in this study, the *nCorrectors* specification is set to two.

In this study the system is closed and incompressible, where the pressure is relative to the range of *p* values and not the absolute values of *p*. The name of the solution variable is *p* and in this case the solver sets a reference level with *pRefValue* in the cell with *pRefCell*. In this case, both *pRefValue* and *pRefCell* are set to zero. It should be noted that if *pRefValue* and *pRefCell* are not used in the PISO algorithm the solution accumulates a large amount of numerical error and the Strouhal number, St, is not accurately captured.

Both the SIMPLE and PISO algorithms have an under-relaxation factor imbedded in the equations. This under-relaxation factor can range from 0 to 1, where 1 corresponds to no under-relaxation factor and 0 corresponds to a solution that does not change with successive iterations. To specify the under-relaxation factors for the required variables, i.e. pressure, velocity, one must set a value to the *relaxationFactors* in the *fvSolution* dictionary. Pressure field values for the under-relaxation factors can range from 0 to 0.3 for numerical stability. The velocity and turbulence equations can have the under-relaxation factors in the range of 0.3-0.7. These ranges are based on mesh quality, accuracy of the numerical schemes, turbulence model and numerical accuracy.[8,49,50]

Specific variables within the solution space can be assigned a variety of different linear solvers, which can be used to solve each matrix equation generated. Suggested from previous studies done by our research group,[8,53] the preconditioned bi-conjugate gradient (PBiCG) solver for asymmetric matrices and the preconditioned conjugate gradient (PCG) solver for symmetric matrices are used in this study. Since this study is using the *k*-*ω* and SST turbulence models the required linear solvers in the SIMPLE/PISO algorithm are U, P, k, and ω. Note that the PISO algorithm requires a *pFinal* specification as one of the linear solvers to complete the iterative process. Each linear solver requires a preconditioner. The Diagonal Incomplete-Cholesky (DIC) and Faster DIC (FDIC) preconditioner are used for all respective flow variables.

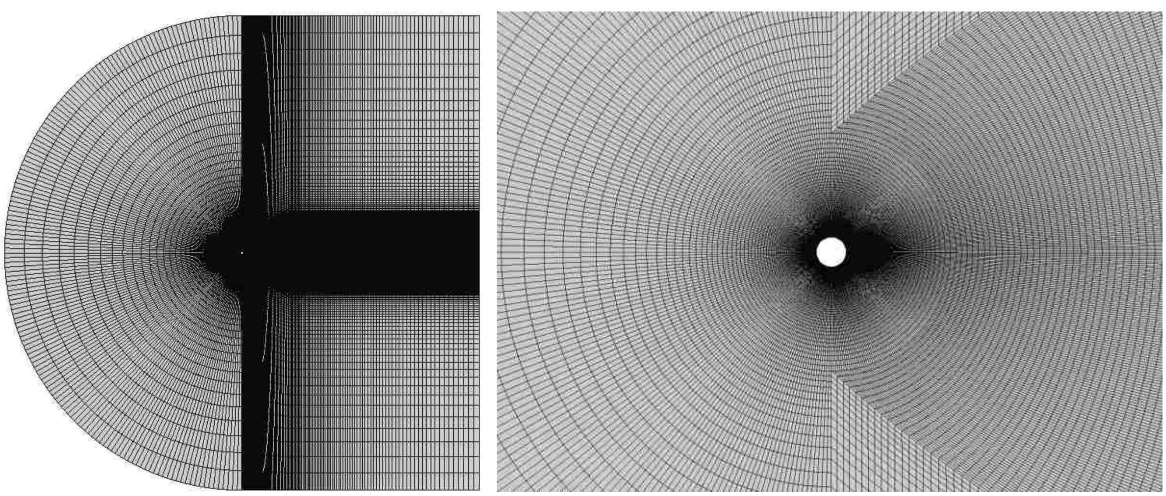
These iterative processes require some kind of measure in the error that is accumulated in the solution space during the iterative process. OpenFOAM provides control over the residuals (also known as a measure of the solution error) for each linear solver used during the iterative process. The linear solver will stop if the imposed residual limit is reached for a specific variable. The linear solver stops if any one of the following conditions are satisfied. Note that the words in *italic* are the specification for each residual control in the *fvSolution* dictionary under the *solvers* application.

- *tolerance*: Solver stops if the residual drops below a specified solver tolerance.
- *relTol*: Solver stops if the ratio of current to initial residuals falls below the solver relative tolerance.
- *maxIter*: Solver stops if the maximum number of iterations exceeds the specified maximum number of iterations.

The solver tolerance, *tolerance*, specifies the residual level (solution space) deemed sufficiently accurate. The *tolerance* value in this study was set to 10^{-15} to ensure that the final solution converged for each linear solver used on a respective variable. In transient solutions it is common to disable the relative tolerance so the solution is forced to converge to the solver tolerance during the iterative process, which is done by setting the *relTol* to 0. It should be noted that the *relTol* is 0 for the steady RANS simulation done in this study. The *maxIter* option in the *fvSolution* dictionary was not used in this study. See Appendix for the *fvSolution* dictionary.

2.4 Computational Mesh

In this study a hybrid O-Grid/C-Grid is used to numerically capture the complex flow physics around and behind a smooth circular cylinder (Fig. 2.4.1). This type of mesh was utilized in order to reduce the total number of cells in the farfield while producing the appropriate refinement near the cylinder surface and in the turbulent wake. The cylinder is located in the center of the computational domain with a diameter of $d = 1m$. The grid transition from the O-Grid to the C-Grid occurs at four diameters away from the center of the computational domain. The farfield boundaries are located 100 diameters away from the origin. There is one cell in the spanwise direction that measures 1 diameter long. This essentially makes the computational mesh 2D. Four grids with increasing refinement are used in this study, where the refinement is done by doubling the local nodes (based on the coarsest mesh). In this study a maximum Reynolds number of $Re = 3.6 \times 10^6$ is used, which produced y^+ values that are less than 2 when using the coarsest grid, G1, and are less than 0.65 when using the finest grid, G4.



a) b)

Figure 2.4.1 Computational domain and grid (G3): a) complete computational domain b) zoomed view of the grid near the cylinder surface.

The y^+ value (Eq. 1.2.1) is the non-dimensional distance measured from the wall and is based on fluid properties, where a y^+ value (Eq. 2.4.1) less than 5 is considered to be within the viscous sublayer.[4,21,23]

$$y^+ = \frac{y u_\tau}{\nu}, \qquad u_\tau = \sqrt{\frac{\tau_w}{\rho}}. \tag{2.4.1}$$

From Eq. 1.2.1, y is the distance from the wall, u_τ is the friction velocity or shear velocity, and τ_w is the wall shear stress.

Table 2.4.1 describes the number of nodes and cells within the computational domain.

Table 2.4.1 Details of the hybrid O-Grid/C-Grid.

Grid	Number of elements	Total number of nodes	Nodes on the cylinder surface	O-Grid: nodes in radial direction (0.5D ≤ x ≤ 4D)	C-Grid: number of nodes at the grid symmetry axis	
					-100D ≤ x ≤ -4D	4D ≤ x ≤100D
G1	14310	29004	132	65	15	45
G2	57240	115248	264	130	30	90
G3	128790	258732	396	195	45	135
G4	228960	459456	448	260	60	180

2.5 Initial and Boundary Conditions

The initial and boundary conditions are based on the experiments discussed in Chapter 1.3 Literature Review. A velocity inlet defines the inlet condition and is located on the left side of the computational domain. The outlet boundary condition is located on the right side of the computational domain and is defined as a zero gradient outlet condition. The cylinder surface is prescribed as a no-slip condition, where the velocity and turbulent kinetic energy are zero. The front and back faces in the spanwise direction used the *empty* boundary condition so the solver performs an effective 2D calculation between cell centers. A study done by Stringer et al.[7] to compare the *empty* boundary condition to the *symmetryPlane* boundary condition on the front and back face found that the difference in converged solutions is negligible.

The inlet velocity and initial freestream velocity correspond to a Mach number of $M = 0.04$ with a turbulence intensity of $I = 0.007$. The viscosity is based on the Reynolds numbers that correspond to $Re = 10^6$, 2×10^6, 3×10^6, and 3.6×10^6. A zero gage pressure is set as the initial pressure field. Initial and boundary conditions for turbulent kinetic energy and specific dissipation can be found in Eq. 2.5.1 and Eq. 2.5.2, respectively. These boundary and initial conditions are adopted from the TMBWG[41] and Ref. 7.

$$k_{wall} = 0, \qquad k_{farfield} = \frac{3}{2}(U_\infty I)^2. \tag{2.5.1}$$

$$\omega_{wall} = 10\frac{6\nu}{\beta_1 y^2}, \qquad \omega_{farfield} = 1 \times 10^{-6}\frac{a^2}{\nu}. \tag{2.5.2}$$

From Eq. 2.5.1 and 2.5.2, $\beta_1 = 0.075$ is the same constant used in the SST turbulence model, y is the smallest cell height from the wall, and a is the speed of sound.

URANS simulations have the same boundary and initial conditions as steady RANS simulations. A non-dimensional time step of $t^* = \Delta t U_\infty / d = 0.005$ is used for all URANS simulations, which is recommended by Iaccarino.[63] It should be noted that this time-step corresponds to half of that used by Catalano et al.[16] Once a converged solution is obtained the data can be post-processed to visualize and assess the accuracy of the numerical results by comparing to experimental[10-15] and simulation[7,16-20] results.

Chapter 3

Results and Discussion

3.1 Grid Sensitivity Study

A sensitivity study on the grid must be done in order to determine the effect that grid refinement has on simulation results. RANS and URANS are used in this study at a Reynolds number of $Re = 3.6 \times 10^6$ for both the k-ω and SST turbulence models. In URANS simulations, the drag coefficient was the last term to converge. Once the drag coefficient was oscillating between a constant maximum and minimum value the solution was considered to be converged. At this point the simulation variables were time-averaged to $t^* = \Delta t U_\infty / D = 300$.

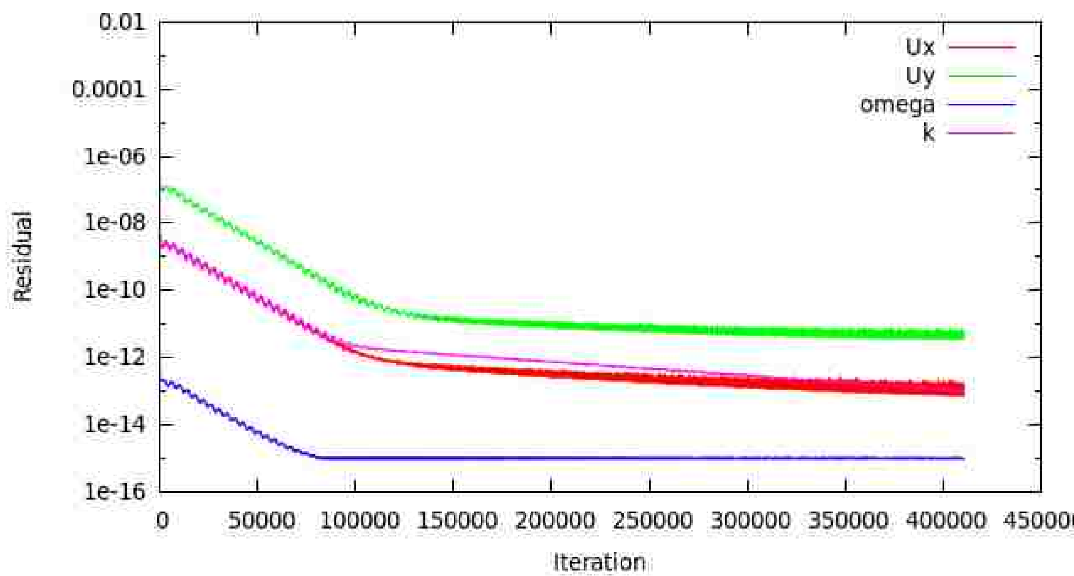


Figure 3.1.1 Residuals for RANS SST at $Re = 10^6$.

Figure 3.1.1 and 3.1.2 represents the residuals at $Re = 10^6$ for RANS SST and URANS SST, respectively. It should be noted that URANS SST was time-averaged from the point that the drag coefficient was oscillating between a constant maximum and minimum value. RANS SST reaches a converged solution around 400,000 iterations. In the case of RANS simulations, the large number of required iterations could be due to the fact that the simulation is imposing symmetry in an asymmetric flow. All turbulent fields in the URANS case are oscillating between a maximum and minimum value for the entire time-averaging simulation. However, the vertical velocity component has a surprisingly high residual value. One could postulate that the high residual value for the vertical velocity component could be due to a large variety of factors, i.e. large time-step, solver algorithm (PISO), mesh shape (aspect ratio, skewness), mesh density, etc.

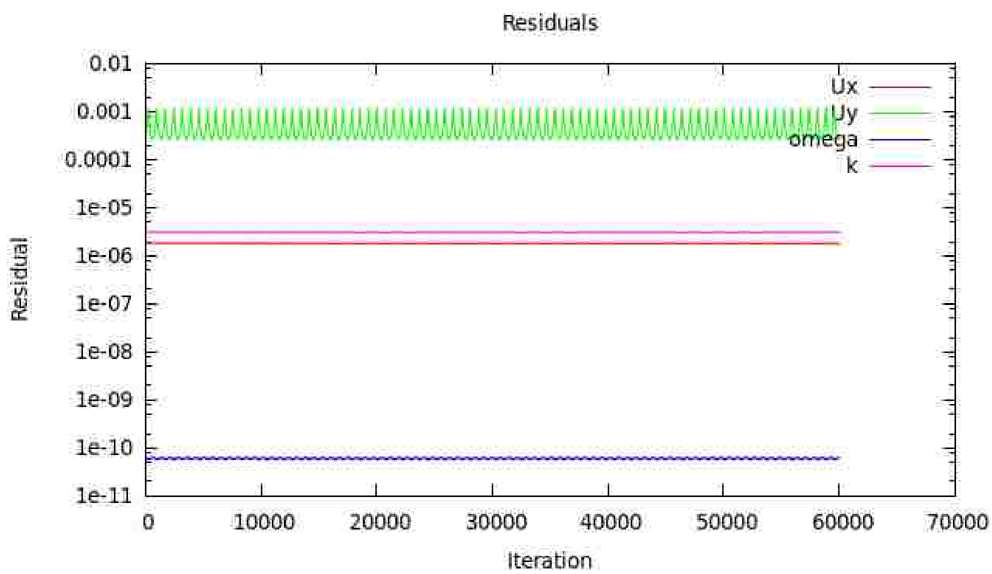


Figure 3.1.2 Residuals for URANS SST at $Re = 10^6$.

All RANS and time-averaged URANS values for the grid sensitivity study are presented in Table 3.1.1. Four different grids were used in this sensitivity study, where the parameters are given in Table 2.4.1. From Table 3.1.1, the drag coefficient, C_D, Strouhal number, St, separation angle, ϕ, and base pressure coefficient, C_{pb}, decrease with increasing grid refinement. The recirculation length behind the circular cylinder, L_r/D, is the most sensitive variable to grid refinement, where the length grows with increasing grid refinement. L_r is measured from the back of the cylinder at $\theta = 180°$.

Table 3.1.1 Grid sensitivity study at $Re = 3.6 \times 10^6$.

Turbulence model approach	C_D	St	ϕ	L_r/d	$-C_{pb}$
G1 RANS k-ω	0.4567	~	117.6°	0.82	0.271
G2 RANS k-ω	0.3527	~	115.5°	1.08	0.299
G3 RANS k-ω	0.3197	~	114.4°	1.26	0.308
G4 RANS k-ω	0.3029	~	113.8°	1.37	0.308
G1 URANS k-ω	0.5012	0.196	120.8°	0.31	0.737
G2 URANS k-ω	0.5075	0.187	122.8°	0.19	0.672
G3 URANS k-ω	0.4369	0.180	120.3°	0.34	0.551
G4 URANS k-ω	0.4107	0.171	118.9°	0.42	0.513
G1 RANS SST	0.5411	~	110.0°	1.02	0.373
G2 RANS SST	0.4605	~	107.6°	1.29	0.411
G3 RANS SST	0.4335	~	106.9°	1.41	0.411
G4 RANS SST	0.4181	~	106.6°	1.49	0.411
G1 URANS SST	0.5524	0.178	112.0°	0.49	0.681
G2 URANS SST	0.5736	0.167	115.0°	0.33	0.719
G3 URANS SST	0.4392	0.157	108.8°	0.99	0.532
G4 URANS SST	0.4206	0.148	107.8°	1.23	0.495

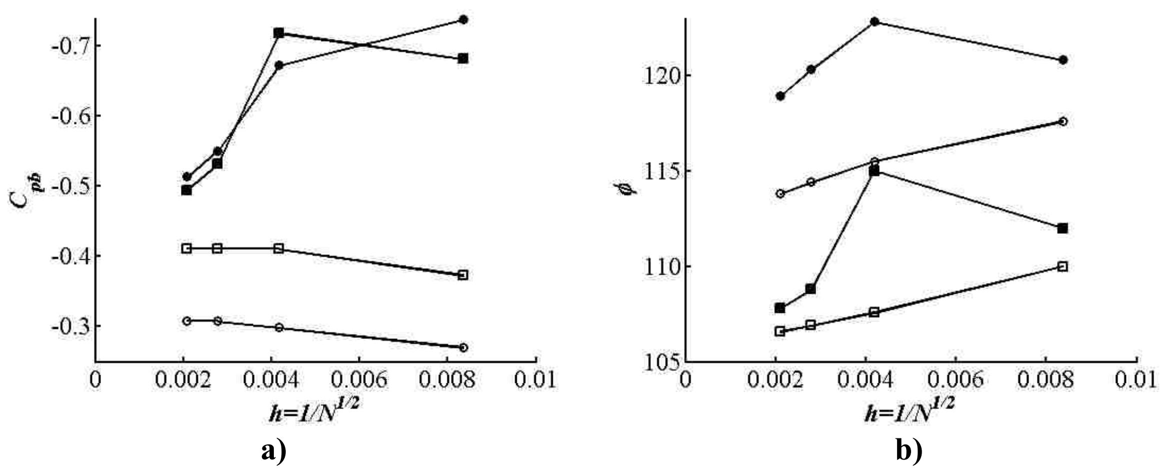


Figure 3.1.3 Results of the grid sensitivity study at $Re = 3.6 \times 10^6$. a) base pressure coefficient, C_{pb}, b) separation angle, ϕ. Notations: ─ ○ ─ RANS k-ω model, ─ ● ─ URANS k-ω model, ─ □ ─ RANS SST model, ─ ■ ─ URANS SST model.

Figure 3.1.3 presents the base pressure coefficient and separation angle with respect to the characteristic mesh length, $h = 1/\sqrt{N}$. For the base pressure coefficient RANS k-ω and RANS

SST have all converged to approximately the same value between the G3 and G4 computational mesh. In all cases the separation angle is decreasing with increasing grid refinement. The percent difference of the drag coefficients between the G3 and G4 mesh are approximately: RANS k-ω 5.4%, URANS k-ω 6.2%, RANS SST 3.6%, and URANS SST 4.1%. The Strouhal number, St, decreases with increasing grid refinement. In all cases, URANS SST is extremely sensitive to grid changes. One could postulate that the blending of the k-ω model near the wall and the k-ε model in the farfield is the primary reason for this sensitivity.

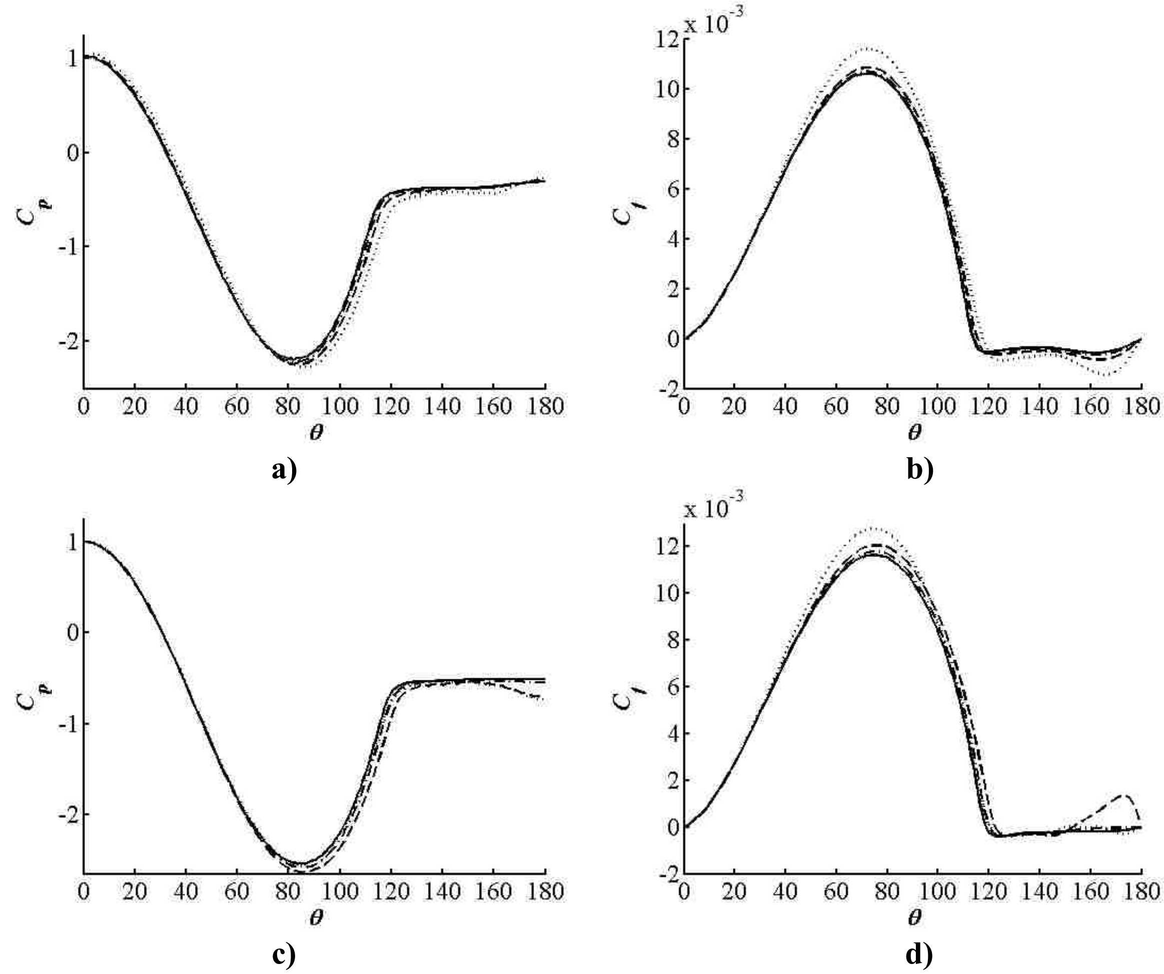


Figure 3.1.4 Grid sensitivity study at $Re = 3.6 \times 10^6$ using the Wilcox 2006 k-ω turbulence model with respect to the azimuth angle, θ, measured clockwise from the stagnation point. a) pressure coefficient RANS b) friction coefficient RANS, c) pressure coefficient URANS d) friction coefficient URANS. Legend: · · · G1, — — G2, — · — G3, —— G4.

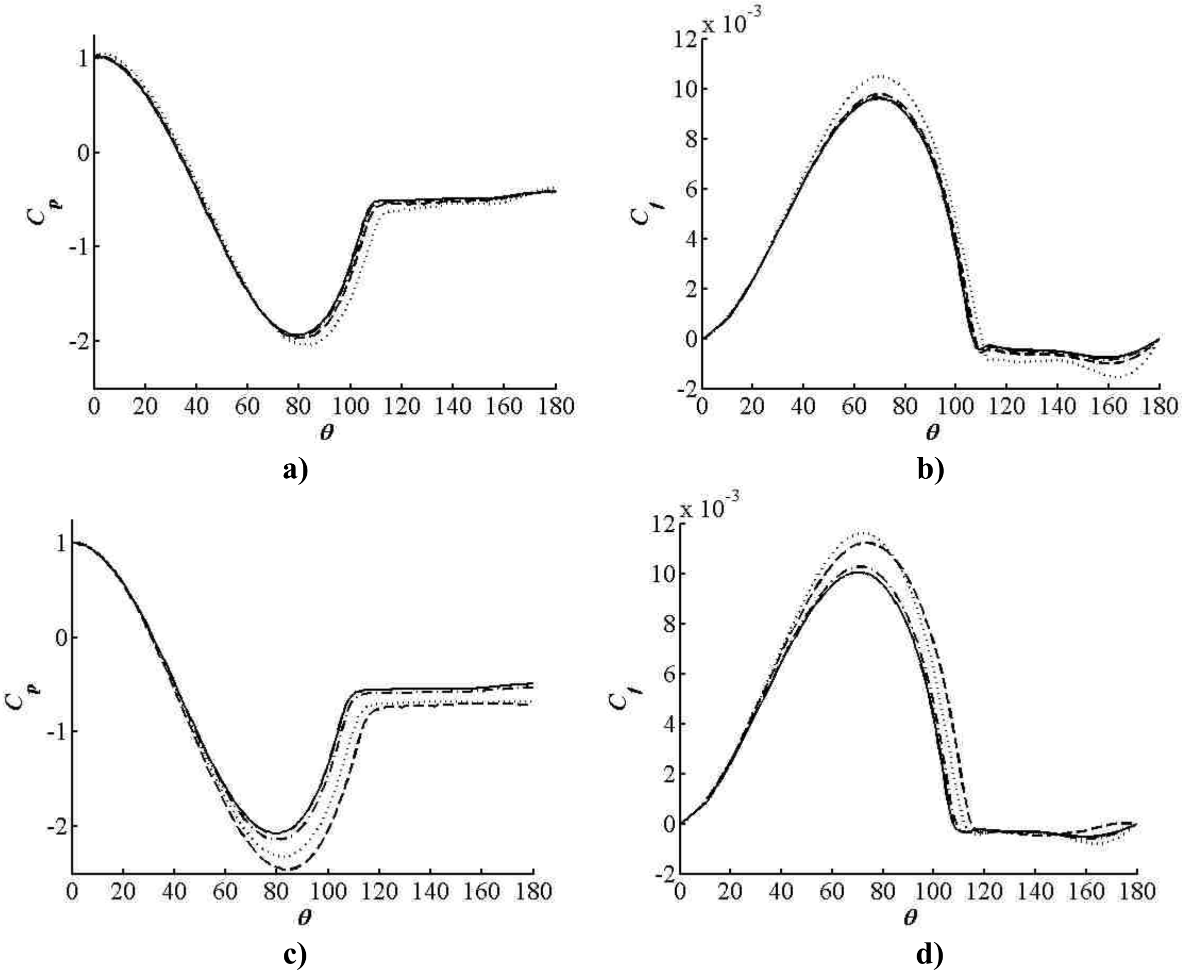


Figure 3.1.5 Grid sensitivity study at $Re = 3.6 \times 10^6$ using the SST turbulence model with respect to the azimuth angle, θ, measured clockwise from the stagnation point. a) coefficient of pressure RANS b) coefficient of friction RANS, c) coefficient of pressure URANS d) coefficient of friction URANS. Legend: · · · G1, — — G2, — · — G3, —— G4.

Figure 3.1.4 and 3.1.5 present the pressure coefficient on the surface of the cylinder and surface friction with respect to the azimuth angle, θ, measured clockwise from the stagnation point. From Fig. 3.1.2 the difference in pressure coefficient, C_p, and surface friction coefficient, C_f, from the G3 to the G4 mesh with RANS *k-ω* is almost negligible. URANS *k-ω* has a bigger difference between the G3 and G4 mesh for both C_p and C_f. However, the difference is small, therefore producing close base pressure coefficients, C_{pb}, and separation angles, ϕ.

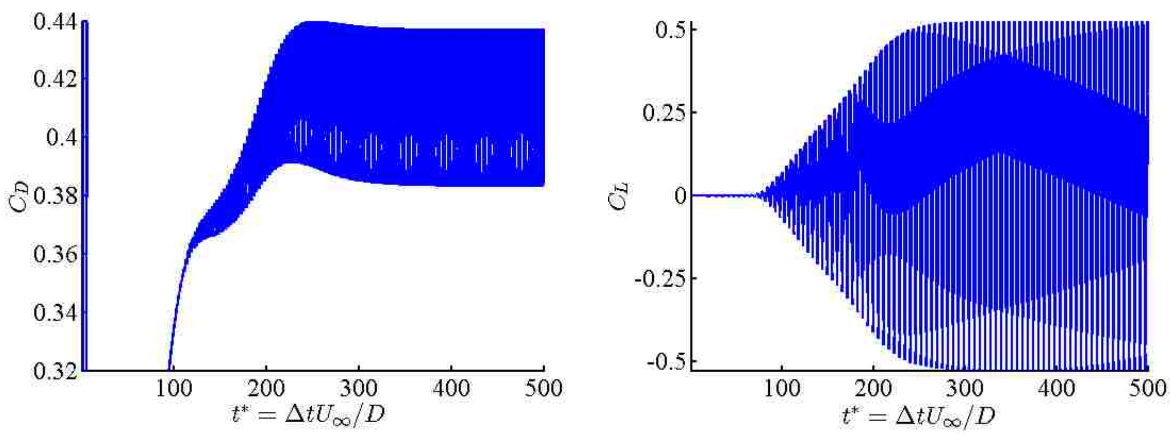
In Fig. 3.1.5, RANS SST simulations are almost the same from the G3 to the G4 mesh for both C_p and C_f. URANS SST produced C_p and C_f values between the G3 and G4 mesh that have a more pronounced difference than the other cases. The average percent differences between the G3 and G4 mesh for both C_p and C_f curves are represented in Table 3.1.2. Due to the computational cost and time, simulations with a finer grid were not performed. The G4 mesh will be used for the remainder of simulations conducted around a smooth circular cylinder.

Table 3.1.2 Average percent difference between the G3 and G4 mesh at $Re = 3.6 \times 10^6$.

Turbulence model approach	% Diff. C_p	% Diff. C_f
k-ω RANS	2.50	9.55
k-ω URANS	3.79	15.62
SST RANS	2.13	11.35
SST URANS	5.51	13.13

3.2 Supercritical Flow Regime

Simulations in the supercritical flow regime are conducted at $Re = 10^6$, 2×10^6, 3×10^6, 3.6×10^6, where the flow is considered to be completely turbulent prior to separation.[16] As stated above, the G4 mesh is used for the remaining part of this study. Due to the limited amount of data available in the supercritical flow regime, this flow regime was chosen to increase the amount of aerodynamic information available for circular cylinders. The effect of Reynold number, RANS vs URANS, and turbulence models will be examined in this section.



a) **b)**

Figure 3.2.1 Transient loads with respect to $t^* = \Delta t U_\infty / D$ on the G4 mesh with the *k*-ω turbulence model at $Re = 3.6 \times 10^6$. a) drag coefficient b) lift coefficient.

At $Re = 3.6 \times 10^6$ with URANS k-ω the transient force coefficients are represented with respect to the non-dimensional time (Fig. 3.2.1). This simulation was started from the initial conditions and boundary conditions stated in Chapter 2.5 Initial and Boundary Conditions. After roughly $t^* = 50$ the solution starts to converge to a symmetric recirculation field in the wake of the cylinder. Around $t^* = 125$ the turbulent wake starts to become asymmetric causing a lift force due to this oscillatory behavior in the turbulent wake. The drag coefficient reaches oscillations between constant maximum and minimum values around $t^* = 400$. At this point the simulation is time averaged for $t^* = 300$. To save computational time, URANS simulations were started from the respective converged RANS simulations, essentially starting the URANS simulation from $t^* = 600$. It should be noted that both SIMPLE and PISO algorithms produce the same result if the temporal discretization scheme is specified as *steadyState* in the *fvSolution* dictionary.

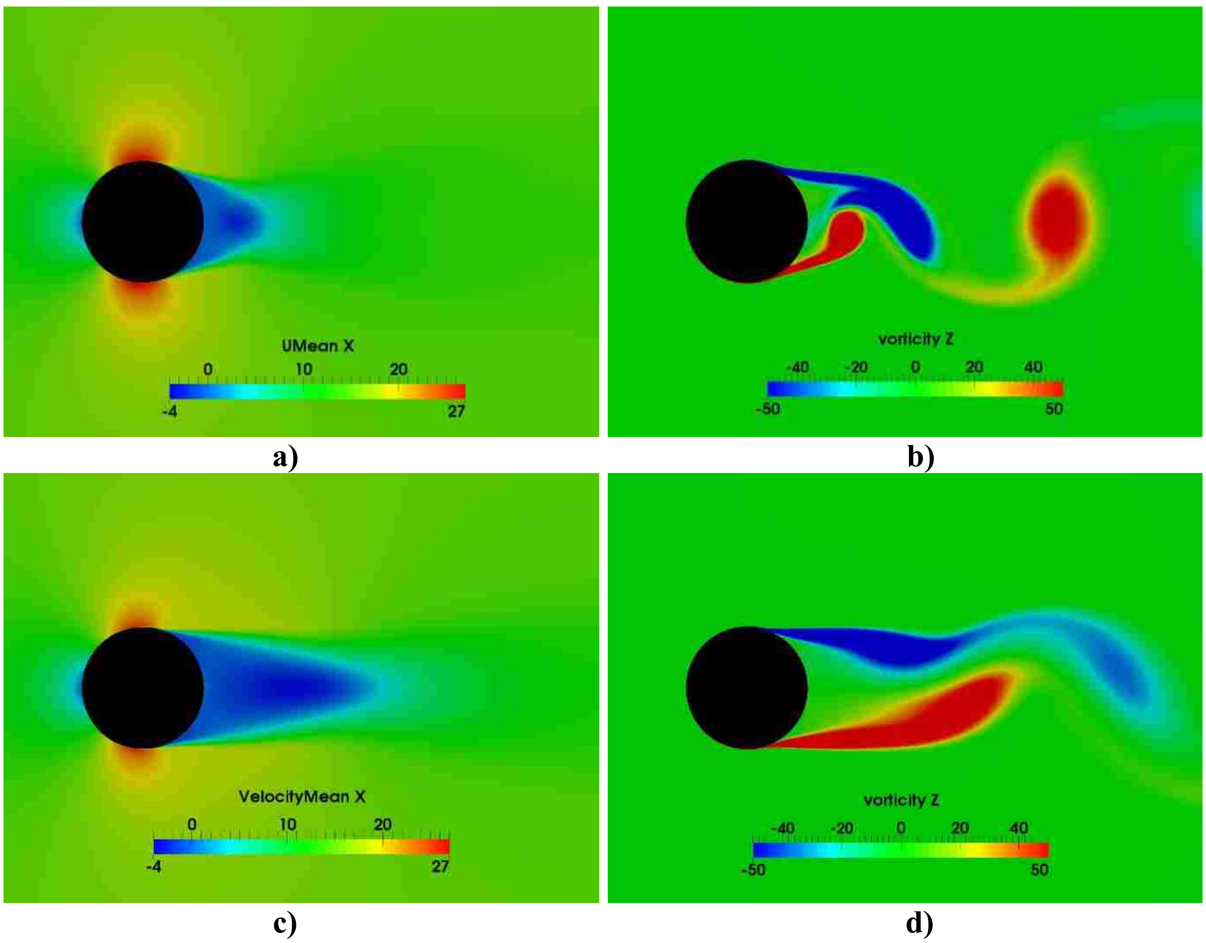


Figure 3.2.2 URANS contour plots at $Re = 3.6 \times 10^6$ with $U_\infty = 14.64\,m/s$ (G4). a) time-averaged streamwise velocity *k-ω*, b) instantaneous spanwise vorticity *k-ω*, c) time-averaged streamwise velocity SST, d) instantaneous spanwise vorticity SST.

URANS results for the time-averaged streamwise velocity and instantaneous spanwise vorticity fields are represented in Fig. 3.2.2. It is clear that the *k-ω* turbulence model has a much smaller turbulent wake than the SST turbulence model. One could postulate that the overdissipative properties in EVM's are enhanced for the URANS k-ω. The instantaneous vorticity contour plots show how vortices are being shed in the turbulent wake.

At $Re = 10^6$, the minimum and maximum drag coefficient with respect to time varies between 0.4598-0.5332 for the k-ω turbulence model and 0.5054-0.5087 for the SST turbulence model. When $Re = 3.6 \times 10^6$, the minimum and maximum drag coefficient with respect to time varies between 0.3778-0.4387 (Fig.3.2.1) and 0.4197-0.4217 for the k-ω and SST turbulence models, respectively. The drag coefficient for the k-ω turbulence model oscillates between a range that is around seven times larger than the SST turbulence model even though the difference in average drag coefficients are less than 1% for both Reynolds numbers. This could be partly due to the large separation angle produced by the k-ω turbulence model, which would correlate to a larger oscillatory load range.

The Strouhal number is calculated by using a Fast Fourier Transform (FFT) on the lift coefficient. The Strouhal numbers range from approximately 0.14-0.17. As stated in Chapter 1.3 Literature Review, regular vortex shedding does not occur in the range $10^6 \leq Re \leq 3.5 \times 10^6$. Stringer et al.[7] found that OpenFOAM underpredicted the St value in the supercritical flow regime. They stated that OpenFOAM failed to periodically shed in this flow regime. One could postulate that a main contributing factor to the incorrect St values is the difference between 2D vs. 3D effects.[17] Another possible factor could be the assumption that the boundary layer is completely turbulent. It is clear that the rate of vortex shedding is not accurately captured with OpenFOAM in 2D. More investigation is needed to address this situation. On the other hand, the time-averaged base pressure coefficient and drag coefficient fall within the measured experimental results, and the wake is clearly turbulent due to the delayed separation angle and narrow wake.

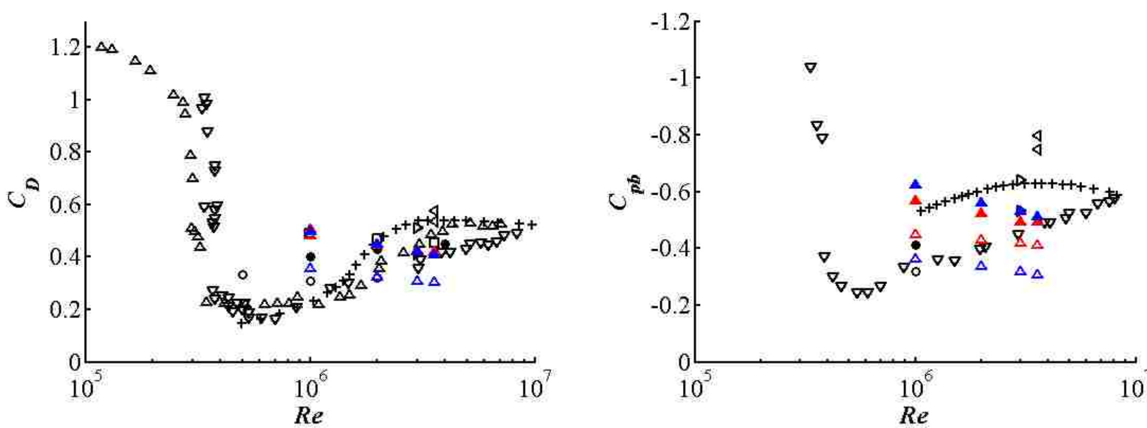
Table 3.2.1 Computed and measured parameters of a flow around a circular cylinder ("~" denotes unavailable data), ("†" denotes Re=3.6×10^6), ("§" denotes rough cylinder).

Turbulence modeling approach	$Re(10)^{-6}$	C_D	St	ϕ	L_r/D	$-C_{pb}$
2D RANS k-ω	1	0.3588	~	108.4˚	1.61	0.364
2D URANS k-ω	1	0.4987	0.161	114.1˚	0.44	0.625
2D RANS SST	1	0.4808	~	101.3˚	1.68	0.448
2D URANS SST	1	0.5070	0.137	102.7˚	1.25	0.569
3D RANS k-ε[16]	1	0.39	~	~	~	0.33
3D URANS k-ε[16]	1	0.40	0.31	~	1.37	0.41
3D LES[16]	1	0.31	0.35	103˚	1.04	0.32
2D URANS k-ε[19]	1	0.34	0.2	~	~	0.30
2D URANS k-ε[20]	1	0.5174	0.2823	~	~	~
2D RANS k-ω	2	0.3268	~	111.5˚	1.47	0.336
2D URANS k-ω	2	0.4467	0.166	116.9˚	0.43	0.560
2D RANS SST	2	0.4458	~	104.3˚	1.57	0.429
2D URANS SST	2	0.4513	0.113	105.3˚	1.32	0.523
2D RANS k-ω	3	0.3100	~	113.1˚	1.40	0.317
2D URANS k-ω	3	0.4220	0.170	118.3˚	0.42	0.532
2D RANS SST	3	0.4265	~	105.9˚	1.51	0.420
2D URANS SST	3	0.4257	0.116	106.8˚	1.30	0.495
3D DES/DES with RC[17]	3	0.41/0.51	0.35/0.33	111˚/106˚	1.0/1.0	0.53/0.64
2D RANS k-ω	3.6	0.3029	~	113.8˚	1.37	0.308
2D URANS k-ω	3.6	0.4107	0.171	118.9˚	0.42	0.513
2D RANS SST	3.6	0.4181	~	106.6˚	1.49	0.411
2D URANS SST	3.6	0.4206	0.148	107.8˚	1.23	0.495
2D URANS k-ε[20]	3.6	0.4703	0.3052	114˚	~	~
3D DES/DES with 65˚ trip[18]	3.6	0.576/0.535	0.305/0.311	118˚/119˚	0.35/0.32	0.796/0.748
Experimental data						
Roshko[10] §	1-3.5	0.3−0.7	0.27	~	~	0.62-0.85
Schmidt[11]	1-5	0.18−0.53	~	~	~	0.35−0.60
Achenbach[12] §	0.5-5	0.6−0.76	~	115˚-120˚	~	0.85 †
Jones et al.[13]	0.5-8	0.15−0.54	0.3	~	~	0.53−0.63
Schewe[14]	1-5	0.22−0.52	0.2-0.27	~	~	~
Shih et al.[15]	0.3-8	0.16-0.50	0.2-0.25	~	~	0.10−0.60

Table 3.2.1 presents the available data produced by this study and other published work, where the drag coefficient, C_D, separation angle, ϕ, recirculation length, L_r/D, and base pressure coefficient, C_{pb} are compared at different Reynolds numbers. The recirculation length L_r/D has a large variety of values, where RANS turbulence models overpredict the bubble length in all simulations. URANS SST produces a bubble length that is close to LES[16] and DES[17] simulations at $Re = 10^6$ and 3×10^6, respectively. The recirculation length, L_r/D, and separation angle, ϕ, at $Re = 3.6 \times 10^6$ for the k-ω turbulence model are close to DES simulations conducted by Lo et al.[18] The recirculation length is visually represented in Fig. 3.2.2 for both the k-ω and SST

turbulence models. In general, the recirculation length decreases with increasing Reynolds numbers.

A graphical representation of the drag coefficient and base pressure coefficient is presented in Fig. 3.2.3. These plots compere simulation and experimental data with respect to the Reynolds number. With the exception of LES,[16] at $Re = 10^6$ the drag coefficient is overpredicted in all simulations when compared to experiments.[11,13-15] If the Reynolds number is increased to $Re \geq 2 \times 10^6$, the drag and base pressure coefficient for URANS k-ω, RANS SST and URANS SST simulations fall within the measured experimental data range for smooth circular cylinders.[11,13-15] Represented in Fig. 3.2.3, URANS simulations for both the k-ω and SST turbulence models cause the drag and base pressure coefficients to increase, therefore quantitatively increasing the accuracy of simulations. It should be noted that the SST turbulence model is closer to the experimental data than the k-ω turbulence model.

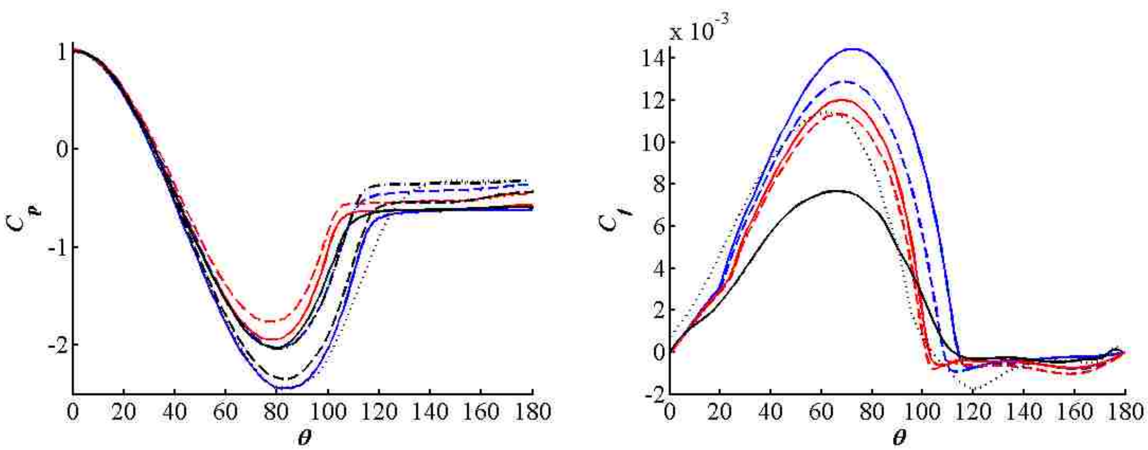


a) **b)**

Figure 3.2.3 Variation of flow parameters with the Reynolds number: a) drag coefficient and b) base pressure coefficient. Computations: △ RANS k-ω (RANS), ▲ URANS k-ω, △ RANS SST, ▲ URANS SST, ○ LES[16], ● URANS[16], □ URANS[20], ▷ DES[17], ◁ DES[18]. Experiments: + Jones et al.[13], △ Schewe[14], ▽ Shih[15].

URANS simulations with both the k-ω and SST turbulence models produce drag coefficient values that are close to DES[17] data at $Re = 3 \times 10^6$. This is not the case for other flow parameters, particularly data produced by the k-ω turbulence model. At $Re = 3.6 \times 10^6$, it is interesting to see that this turbulence model produces a separation angle and recirculation length similar to DES[18] and not for other parameters.

At $Re = 3 \times 10^6$, the surface friction and pressure coefficient on the surface of the cylinder with respect to the azimuth angle are represented in Fig. 3.2.4. On the front side of the cylinder, the pressure coefficients in all simulations are in close agreement with Ref. 16 and 20. After $\theta = 50°$, all reported values differ with a maximum at roughly the top of the cylinder, where the favorable pressure gradient occurs. RANS k-ω and RANS/URANS SST pressure coefficient values closely follow RANS k-ε and URANS k-ε data from Refs. 16 and 20, respectively. URANS k-ω closely follow LES and URANS k-ε results produced by Ref. 16. The adverse pressure gradient is increased for URANS simulations causing the separation angle to increase and providing a more accurate solution than RANS simulations. For all values (Table 3.2.1), the unsteady solver has the largest influence on the k-ω turbulence model, where the favorable



a) b)

Figure 3.2.4 Surface parameters with respect to the azimuth angle measured clockwise from the stagnation point at $Re = 10^6$: a) pressure coefficient, b) friction coefficient. Notations: — — RANS k-ω, —— URANS k-ω, — — RANS SST, —— URANS SST, — · — RANS k-ε[16], — — URANS k-ε[16], · · · LES[16], —— URANS k-ε[20].

pressure gradient is greatly increased, therefore causing the C_p curve for URANS k-ω to closely match LES and URANS k-ε results produced by Ref. 16.

At $Re = 10^6$, the surface friction coefficient has a much larger discrepancy than the pressure coefficient (Fig. 3.2.4). The separation angle and surface friction coefficient profile from RANS/URANS SST are close to those from LES.[16] The large variance in surface friction coefficient curves explains the difference in reported drag coefficient values.

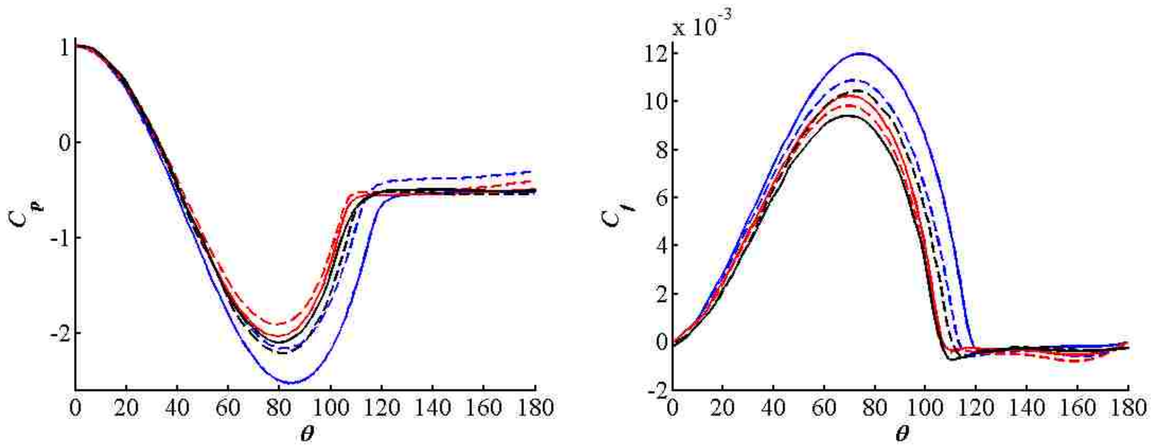


Figure 3.2.5 Surface parameters with respect to the azimuth angle measured clockwise from the stagnation point at $Re = 3 \times 10^6$: a) pressure coefficient, b) friction coefficient. Notations: – – RANS k-ω, —— URANS k-ω, – – RANS SST, —— URANS SST, – – DES,[17] —— DES with RC.[17]

In Fig. 3.2.5, C_p and C_f are compared to DES results produced by Travin et al,[17] at $Re = 3 \times 10^6$. The DES with RC refers to a rotation/curvature term that improved simulations results. Therefore, two sets of DES simulation data are available at this Reynolds number. Results obtained with RANS/URANS SST turbulence models closely match DES data[17] and produce the same separation angle $\phi = 106°$. The k-ω turbulence model overpredicts the C_f curves for both RANS and URANS but follows the same general trend, when compared to DES data.

Pressure coefficient and surface friction coefficient at $Re = 3.6 \times 10^6$ are shown in Fig. 3.2.6. After roughly $\theta > 50°$ none of the turbulence models are consistent with experimental data produced by Achenbach.[12] The surface friction coefficient produces a separation angle that is in good agreement with the experiment. Predictions of the pressure coefficient conducted with URANS k-ω closely follow DES data,[18] and URANS SST is in good agreement with URANS k-ε data.[20] The surface friction is overpredicted in both the RANS/URANS k-ω and RANS/URANS SST when compared to data from Ref. 12 and 18. In Fig. 3.2.4, Ref. 20 underpredicted the surface friction coefficient when compared to LES data.[16] This same trend applies directly to $Re = 3.6 \times 10^6$ and explains why the C_f is so different. If a linear relationship for the surface friction coefficient is derived between LES and DES data for $Re = 10^6$ and $Re = 3 \times 10^6$, then results produced in this study at $Re = 3.6 \times 10^6$ correlate well with this relationship. It should be noted that the experimental results produced by Achenbach[12] used a rough cylinder with a low aspect ratio, small cylinder diameter, and high blockage, which can help explain the significant error between C_f values.

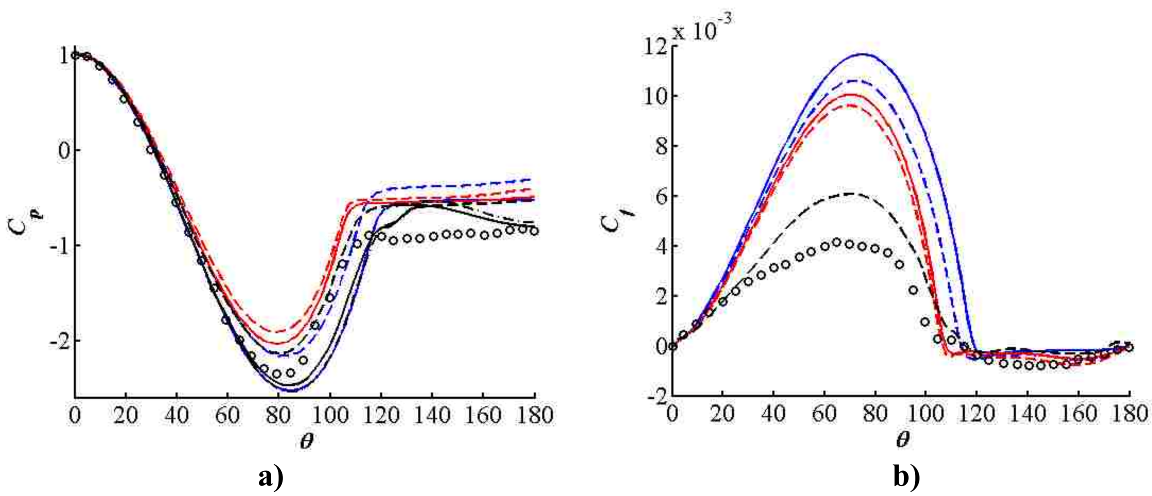


Figure 3.2.6 Surface parameters with respect to the azimuth angle measured clockwise from the stagnation point at $Re = 3.6 \times 10^6$: a) pressure coefficient, b) friction coefficient. Notations: — — RANS k-ω, —— URANS k-ω, — — RANS SST, —— URANS SST, — — URANS k-ε,[20] — · — DES,[18] —— DES with 65° trip,[18] ○ experimental data.[12]

From Fig. 3.2.4b-3.2.6b, unsteady solvers increased the favorable pressure gradient zone on the top of the cylinder causing the separation angle to increase, therefore producing a more accurate solution than steady solvers. However URANS *k-ω* overpredicts the surface friction coefficient in all simulations. This is caused by the delayed separation angle (Table 3.2.1). URANS SST captures surface friction with the highest accuracy.

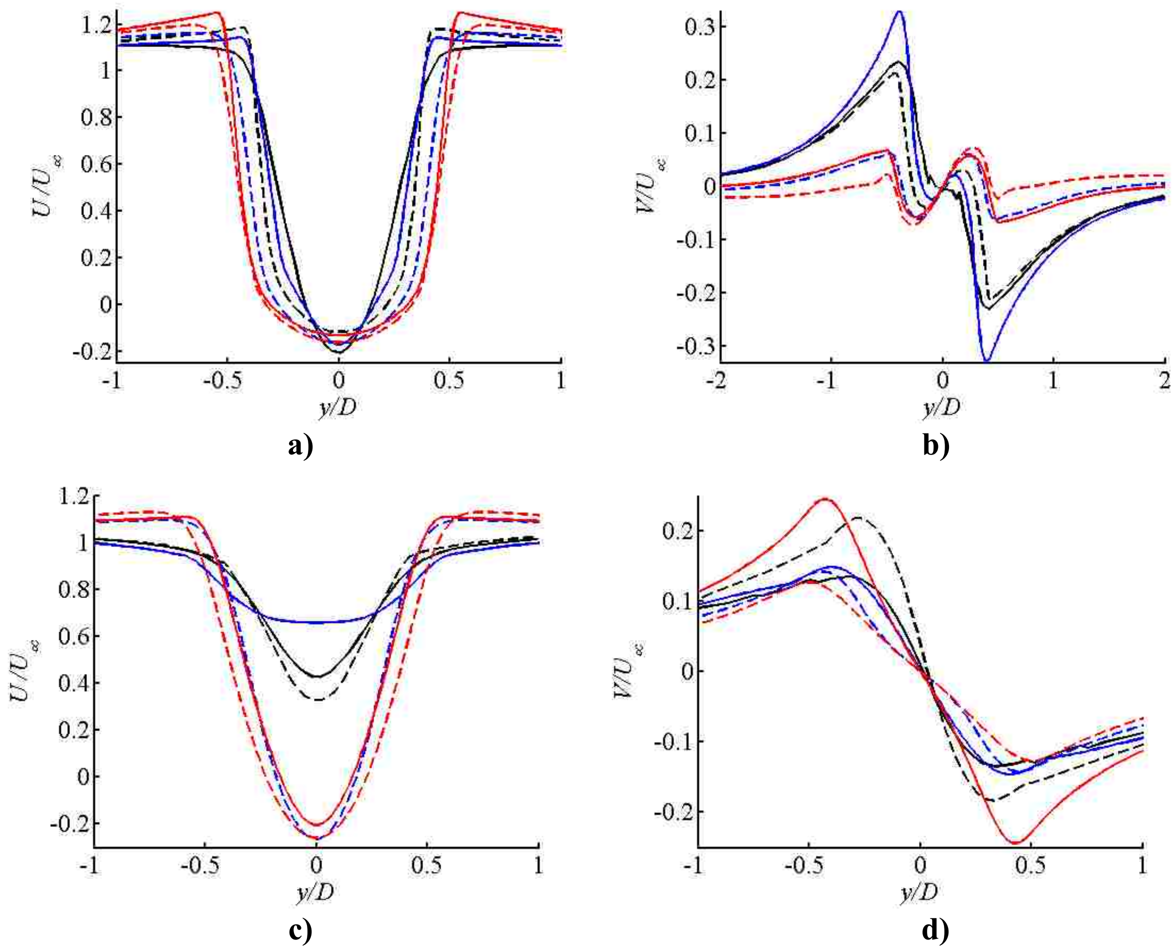


Figure 3.2.7 Wake results at $Re = 10^6$. a) streamwise velocity component, U/U_∞, at $x/D = 0.75$ b) vertical velocity component, V/U_∞, at $x/D = 0.75$ c) streamwise velocity component, U/U_∞, at $x/D = 1.5$ d) vertical velocity component, V/U_∞, at $x/D = 1.5$. Notations: – – RANS k-ω, —— URANS k-ω, – – RANS SST, —— URANS SST, – – URANS k-ε[16], —— LES[16].

In Fig. 3.2.7, the velocity profiles at $Re = 10^6$ are compared to results presented by Catalano et al.[16] RANS simulations with both the *k-ω* and SST turbulence models closely follow the same general trend in the near, $x/D = 0.75$, and far, $x/D = 1.5$, wake. The streamwise velocity profile generated by URANS *k-ω* closely follows LES data[16] in the near wake $x/D =$

0.75. However, in the far wake, $x/D = 1.5$, URANS *k*-*ω* underpredicts the maximum value of the streamwise velocity when compared to other turbulence models. One can postulate that the dissipation is enhanced when using an unsteady formulation of the *k*-*ω* turbulence model. The SST turbulence model is less sensitive to changing the formulation to unsteady. Therefore, the SST turbulence model is better suited at capturing the complex flow physics.

Chapter 4

Conclusion

CFD simulations were conducted and analyzed for high Reynolds number flow around and behind a smooth circular cylinder. The effect of Reynolds number with respect to the drag coefficient and base pressure coefficient is not accurately captured. The drag coefficient and base pressure coefficient decreases with increasing Reynolds numbers, where experimental[10-15] data shows that the drag coefficient and base pressure coefficient should be displaying the opposite behavior. However, Ong et al.[20] reported a decreasing drag coefficient with increasing Reynolds numbers. One may postulate that this effect is due to the EVM's inability to accurately capture the favorable pressure gradient before separation, therefore leading to inaccuracies in the separation angle and ultimately in the drag and base pressure coefficient.

In all cases the pressure coefficient curves on the surface of the cylinder vary after $\theta \approx 50°$. However, the pressure coefficient in the turbulent wake levels out around the same value, therefore producing relatively close base pressure coefficients. Simulation results are less sensitive to the type of turbulence model used at low and high azimuth angles.

For all Reynolds numbers, the surface friction coefficient produces curves that all vary in magnitude between simulation data, but follow the same general trend. Coincidently, the surface friction values cross the zero axis around the same general location causing the flow to separate at nearly the same azimuth angle. It is clear that the friction coefficient is a more sensitive parameter to predict than the pressure coefficient.

URANS simulations are able to capture the complex flow characteristics with higher accuracy than RANS simulations. URANS SST produced results that were closer to experimental results[10-15] than URANS k-ω. This is due to the fact that the SST turbulence model uses a complex blending function to link the k-ω model near the wall and the k-ε in the farfield, therefore producing a more physical turbulence model.

Possible simulation improvements could include increasing the grid refinement, where the solution is relatively grid independent for all measured values. Another improvement could be to determine the culprit for the highly underpredicted vortex shedding rate. Rather than assuming that the suggested time step is suitable,[63] a time-step sensitivity study could be done to determine if the solution is time-step independent.

Overall URANS simulations produced results with higher accuracy than RANS simulations. The SST turbulence model proved to be the superior model; however, its implementation is more difficult to achieve.

The computational time required to reach converged solutions in OpenFOAM on the G4 mesh was roughly 3 days for RANS and 3 days and 18 hours for URANS on 32 processors. OpenFOAM provided a robust platform for implementing standardized turbulence models and accurately capturing the general flow physics at $Re \geq 2 \times 10^6$ for a smooth circular cylinder. The unsteady simulation results produced in this study are in close agreement with DES and LES data.

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Appendix

A.1 Simulation Parameters

controlDict

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/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  2.1.1                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.org                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "system";
    object      controlDict;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

//application     simpleFoam;      //RANS
application     pisoFoam;           //URANS
startFrom       latestTime;
stopAt          endTime;
endTime         20.4964;
deltaT          3.4159e-4;
writeControl    timeStep;
writeInterval   20000;
purgeWrite      0;
writeFormat     ascii;
writePrecision  6;
writeCompression off;
timeFormat      general;
timePrecision   6;
runTimeModifiable true;
libs ("libmyIncompressibleRASModels.so");

functions
{
    #include "forceCoeffs"
    fieldAverage1
    {
        type            fieldAverage;
```

```
        functionObjectLibs ( "libfieldFunctionObjects.so" );
        enabled         true;
        outputControl   outputTime;

        fields
        (
            U
            {
                mean        on;
                prime2Mean  off;
                base        time;
            }

            p
            {
                mean        on;
                prime2Mean  off;
                base        time;
            }
        );
    }
}
// ************************************************************************* //
```

forceCoeffs

```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  2.1.1                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.org                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "system";
    object      forceCoeffs;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

forceCoeffs
{
    type                forceCoeffs;
    functionObjectLibs  ( "libforces.so" );
    outputControl       timeStep;
    outputInterval      1;

    patches             ( "cylinder" );
    pName               p;
    UName               U;
    rhoName             rhoInf;
    log                 true;

    liftDir             (0 1 0);
    dragDir             (1 0 0);
    CofR                (0 0 0);
    pitchAxis           (0 0 1);

    magUInf             14.637;
    rhoInf              1;
    lRef                1;
    Aref                1;
}
// ************************************************************************* //
```

fvSchemes

```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  2.1.1                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.org                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "system";
    object      fvSchemes;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

ddtSchemes
{
    default         backward;
}

gradSchemes
{
    default         Gauss linear;
    grad(p)         Gauss linear;
    grad(U)         Gauss linear;
}

divSchemes
{
    default         none;
    div(phi,U)      bounded Gauss linearUpwind Grad(U);
    div(phi,k)      bounded Gauss upwind;
    div(phi,omega) bounded Gauss upwind;
    div(phi,R)      Gauss upwind;
    div(R)          Gauss linear;
    div(phi,nuTilda) Gauss upwind;
    div((nuEff*dev(T(grad(U))))) Gauss linear;
}

laplacianSchemes
{
    default         none;
    laplacian(nuEff,U) Gauss linear corrected;
    laplacian((1|A(U)),p) Gauss linear corrected;
    laplacian(DkEff,k) Gauss linear corrected;
    laplacian(DomegaEff,omega) Gauss linear corrected;
    laplacian(DREff,R) Gauss linear corrected;
```

```
    laplacian(DnuTildaEff,nuTilda) Gauss linear corrected;
}

interpolationSchemes
{
    default         linear;
    interpolate(U)  linear;
}

snGradSchemes
{
    default         corrected;
}

fluxRequired
{
    default         no;
    p               ;
}


// ************************************************************************* //
```

fvSolution

```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  2.1.1                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.org                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "system";
    object      fvSolution;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

solvers
{
    p
    {
        solver          PCG;
        preconditioner  FDIC;
        tolerance       1e-15;
        relTol          0;
    }

    pFinal
    {
        solver          PCG;
        preconditioner  DIC;
        tolerance       1e-15;
        relTol          0;
    }

    U
    {
        solver          PBiCG;
        preconditioner  DILU;
        tolerance       1e-15;
        relTol          0;
    }

    k
    {
        solver          PBiCG;
        preconditioner  DILU;
        tolerance       1e-15;
        relTol          0;
```

```
    }

    omega
    {
        solver          PBiCG;
        preconditioner  DILU;
        tolerance       1e-15;
        relTol          0;
    }

    epsilon
    {
        solver          PBiCG;
        preconditioner  DILU;
        tolerance       1e-15;
        relTol          0;
    }

    R
    {
        solver          PBiCG;
        preconditioner  DILU;
        tolerance       1e-15;
        relTol          0;
    }

    nuTilda
    {
        solver          PBiCG;
        preconditioner  DILU;
        tolerance       1e-15;
        relTol          0;
    }

}
//SIMPLE //RANS
PISO      //URANS
{
    nCorrectors     2;
    nNonOrthogonalCorrectors 2;
    pRefCell        0;
    pRefValue       0;

    residualControl
    {

    }
}

relaxationFactors
{
```

```
    fields
    {
        p               0.3;
    }
    equations
    {
        U               0.7;
        k              0.7;
        epsilon         0.7;
        R               0.7;
        nuTilda         0.7;
           omega            0.7;
    }
}


// ************************************************************************* //
```

blockMeshDict

G4 Computational Mesh:

```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  2.3.0                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.org                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    object      blockMeshDict;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

convertToMeters 1;

vertices
(
//Quadrant 1
 //0-90 arc
  //Back Face
    (0.5 0 0)               //0
    (4 0 0)                 //1
    (0 4 0)                 //2
    (0 0.5 0)               //3
  //Front Face
    (0.5 0 1)               //4
    (4 0 1)                 //5
    (0 4 1)                 //6
    (0 0.5 1)               //7

 //0-90 Near Wake
  //Back Face
    (20 0 0)                //8
    (20 15 0)               //9
  //Front Face
    (20 0 1)                //10
    (20 15 1)               //11

 //0-90 Far Wake
  //Back Face
    (100 0 0)               //12
    (100 15 0)              //13
  //Front Face
```

```
    (100 0 1)              //14
    (100 15 1)             //15

  //0-90 Top near wake
   //Back Face
    (20 100 0)             //16
    (0 100 0)              //17
   //Front Face
    (20 100 1)             //18
    (0 100 1)              //19

  //0-90 Top far wake
   //Back Face
    (100 100 0)          //20
   //Front Face
    (100 100 1)          //21

 //Quadrant 2
  //90-180 inner arc
   //Back Face
    (-0.5 0 0)             //22
    (-4 0 0)               //23
   //Front Face
    (-0.5 0 1)             //24
    (-4 0 1)               //25

  //90-180 outer arc
   //Back Face
    (-100 0 0)             //26
   //Front Face
    (-100 0 1)             //27

 //Quadrant 3
  // 180-270 inner arc
   //Back Face
    (0 -0.5 0)             //28
    (0 -4 0)               //29
   //Front Face
    (0 -0.5 1)             //30
    (0 -4 1)               //31

  // 180-270 outer arc
   //Back Face
    (0 -100 0)             //32
   //Front Face
    (0 -100 1)             //33

 //Quadrant 4
  //270-360 arc
    // Given by created points
```

```
 //270-360 near wake
  //Back Face
    (20 -15 0)          //34
  //Front Face
    (20 -15 1)          //35

 //270-360 far wake
  //Back Face
    (100 -15 0)         //36
  //Front Face
    (100 -15 1)         //37

 //Bottom near wake
  //Front Face
    (20 -100 0)         //38
  //Back Face
    (20 -100 1)         //39

 //Bottom far wake
  //Front Face
    (100 -100 0)        //40
  //Back Face
    (100 -100 1)        //41

);

blocks
(
//Volume
 //Quadrant 1
    hex (0  1  2  3  4  5  6  7 ) (260 160 1) simpleGrading (27000 2 1)  //0-90 arc
    hex (1  8  9  2  5  10 11 6 ) (80 160 1) simpleGrading (2 2 1)      //0-90 Near Wake
    hex (8  12 13 9  10 14 15 11) (100 160 1) simpleGrading (6 2 1)   //0-90 Far Wake
    hex (2  9  16 17 6  11 18 19) (80 60 1) simpleGrading (2 50 1)   //0-90 Top near wake
    hex (9  13 20 16 11 15 21 18) (100 60 1) simpleGrading (6 50 1)  //0-90 Top far wake

 //Quadrant 2
    hex (23 22 3  2  25 24 7  6 ) (260 104 1) simpleGrading (0.000037037 1 1)  //90-180 inner arc
    hex (26 23 2  17 27 25 6  19) (60 104 1) simpleGrading (0.02 1 1)    //90-180 outer arc

 //Quadrant 3
    hex (29 28 22 23 31 30 24 25) (260 104 1) simpleGrading (0.000037037 1 1)  //180-270 inner
arc
    hex (32 29 23 26 33 31 25 27) (60 104 1) simpleGrading (0.02 1 1)  //180-270 outer arc

 //Quadrant 4
    hex (29 1  0  28 31 5  4  30) (160 260 1) simpleGrading (0.5 0.000037037 1)  //270-360 arc
    hex (34 8  1  29 35 10 5  31) (160 80 1) simpleGrading (0.5 0.5 1)  //270-360 near wake
    hex (34 36 12 8  35 37 14 10) (100 160 1) simpleGrading (6 0.5 1)  //270-360 far wake
    hex (32 38 34 29 33 39 35 31) (80 60 1) simpleGrading (2 0.02 1)  //Bottom near wake
    hex (38 40 36 34 39 41 37 35) (100 60 1) simpleGrading (6 0.02 1)  //Bottom far wake
```

```
);

edges
(
//Quadrant 1
  //0-95 arc
    arc 0 3 (0.353553 0.353553 0)
    arc 1 2 (2.828427 2.828427 0)
    arc 4 7 (0.353553 0.353553 1)
    arc 5 6 (2.828427 2.828427 1)

  //0-90 near wake arc
    arc 2 9 (3 6.5 0)
    arc 6 11 (3 6.5 1)

//Quadrant 2
  //90-180 inner arc
    arc 22 3 (-0.353553 0.353553 0)
    arc 23 2 (-2.828427 2.828427 0)
    arc 24 7 (-0.353553 0.353553 1)
    arc 25 6 (-2.828427 2.828427 1)

  //90-180 outer arc
    arc 26 17 (-70.7107 70.7107 0)
    arc 27 19 (-70.7107 70.7107 1)

//Quadrant 3
  //180-270 inner arc
    arc 28 22 (-0.353553 -0.353553 0)
    arc 29 23 (-2.828427 -2.828427 0)
    arc 30 24 (-0.353553 -0.353553 1)
    arc 31 25 (-2.828427 -2.828427 1)

  //90-180 outer arc
    arc 32 26 (-70.7107 -70.7107 0)
    arc 33 27 (-70.7107 -70.7107 1)

//Quadrant 4
  //270-315 arc
    arc 28 0 (0.353553 -0.353553 0)
    arc 29 1 (2.828427 -2.828427 0)
    arc 30 4 (0.353553 -0.353553 1)
    arc 31 5 (2.828427 -2.828427 1)

  //270-315 near wake arc
    arc 29 34 (3 -6.5 0)
    arc 31 35 (3 -6.5 1)
);

boundary
(
```

```
inlet
{
   type patch;
   faces
   (
      (26 17 19 27)
         (17 16 18 19)
         (16 20 21 18)
         (26 32 33 27)
         (32 38 39 33)
         (38 40 41 39)
   );
}

outlet
{
   type patch;
   faces
   (
      (13 20 21 15)
      (12 13 15 14)
      (36 12 14 37)
      (40 36 37 41)
   );
}

cylinder
{
   type wall;
   faces
   (
      (0 3 7 4)
      (3 22 24 7)
      (22 28 30 24)
      (28 0 4 30)
   );
}

back
{
   type empty;
   faces
   (
      (0 1 2 3)
      (1 8 9 2)
      (8 12 13 9)
      (2 9 16 17)
      (9 13 20 16)
      (22 3 2 23)
      (26 23 2 17)
```

```
        (29 28 22 23)
        (26 23 29 32)
        (28 0 1 29)
        (29 1 8 34)
        (32 29 34 38)
        (34 8 12 36)
        (38 34 36 40)

    );
  }
  front
  {
    type empty;
    faces
    (
          (4 5 6 7)
        (5 10 11 6)
        (10 14 15 11)
        (6 11 18 19)
        (11 15 21 18)
        (24 7 6 25)
        (25 6 19 27)
        (31 30 24 25)
        (27 33 31 25)
        (31 5 4 30)
        (31 35 10 5)
        (35 37 14 10)
        (33 39 35 31)
        (39 41 37 35)
    );
  }
);

mergePatchPairs
(
);

// ************************************************************************* //
```

A.2 Source Data

Table A.2.1 C_p at $Re = 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	1.00820	1.01750	0.99882	0.99882
1.3703	1.00820	1.01750	0.99882	0.99882
2.2073	1.00820	1.00820	0.99882	0.99882
3.0602	1.00820	1.00820	0.98948	0.98948
3.9187	0.99882	0.99882	0.98948	0.98948
4.7800	0.98948	0.98948	0.98015	0.98015
5.6418	0.98015	0.98948	0.96148	0.97081
6.5050	0.97081	0.97081	0.95214	0.96148
7.3684	0.96148	0.96148	0.94281	0.94281
8.2330	0.94281	0.95214	0.92414	0.93347
9.0970	0.93347	0.93347	0.90547	0.91480
9.9616	0.91480	0.91480	0.88680	0.89613
10.8260	0.89613	0.90547	0.86813	0.87746
11.6910	0.87746	0.87746	0.84946	0.85879
12.5550	0.85879	0.85879	0.82146	0.83079
13.4200	0.83079	0.84013	0.79345	0.81212
14.2860	0.80279	0.81212	0.77478	0.78412
15.1500	0.78412	0.79345	0.74678	0.75611
16.0150	0.75611	0.76545	0.70944	0.72811
16.8810	0.72811	0.73744	0.68143	0.70010
17.7450	0.69077	0.70944	0.65343	0.67210
18.6110	0.66277	0.68143	0.61609	0.63476
19.4760	0.63476	0.64410	0.57875	0.60676
20.3410	0.59742	0.61609	0.54141	0.56942
21.2060	0.56008	0.57875	0.50408	0.53208
22.0710	0.52274	0.54141	0.46674	0.49474
22.9370	0.48541	0.50408	0.42940	0.45740
23.8020	0.44807	0.46674	0.38272	0.42006
24.6670	0.41073	0.42940	0.34538	0.38272
25.5320	0.37339	0.39206	0.29871	0.34538
26.3980	0.32672	0.35472	0.25204	0.29871
27.2630	0.28938	0.31738	0.20536	0.25204
28.1280	0.24270	0.27071	0.15869	0.21470
28.9930	0.19603	0.23337	0.11202	0.16803
29.8590	0.14936	0.18669	0.06534	0.12135
30.7240	0.11202	0.14002	0.01867	0.07468
31.5890	0.06534	0.09335	-0.03734	0.02800

32.4540	0.01867	0.05601	-0.08401	-0.01867
33.3200	-0.03734	0.00933	-0.14002	-0.06534
34.1850	-0.08401	-0.03734	-0.18669	-0.11202
35.0510	-0.13069	-0.08401	-0.24270	-0.15869
35.9160	-0.17736	-0.13069	-0.29871	-0.21470
36.7810	-0.23337	-0.17736	-0.35472	-0.26137
37.6470	-0.28004	-0.22403	-0.40139	-0.30805
38.5120	-0.32672	-0.28004	-0.45740	-0.36405
39.3770	-0.38272	-0.32672	-0.51341	-0.41073
40.2420	-0.42940	-0.37339	-0.56942	-0.45740
41.1080	-0.48541	-0.42006	-0.62543	-0.51341
41.9730	-0.53208	-0.46674	-0.68143	-0.56008
42.8380	-0.58809	-0.51341	-0.73744	-0.61609
43.7040	-0.63476	-0.56942	-0.79345	-0.66277
44.5690	-0.69077	-0.61609	-0.84946	-0.71877
45.4340	-0.73744	-0.66277	-0.90547	-0.76545
46.3000	-0.78412	-0.70944	-0.96148	-0.81212
47.1650	-0.84013	-0.75611	-1.00820	-0.86813
48.0300	-0.88680	-0.80279	-1.06420	-0.91480
48.8960	-0.94281	-0.84946	-1.12020	-0.96148
49.7610	-0.98948	-0.89613	-1.17620	-1.00820
50.6260	-1.03620	-0.94281	-1.23220	-1.05480
51.4920	-1.08280	-0.98948	-1.27890	-1.10150
52.3570	-1.12950	-1.02680	-1.33490	-1.14820
53.2220	-1.17620	-1.07350	-1.39090	-1.19480
54.0880	-1.22280	-1.12020	-1.43750	-1.24150
54.9530	-1.26950	-1.15750	-1.49360	-1.28820
55.8190	-1.31620	-1.19480	-1.54020	-1.32550
56.6840	-1.36290	-1.24150	-1.58690	-1.37220
57.5490	-1.40020	-1.27890	-1.64290	-1.40950
58.4150	-1.44690	-1.31620	-1.68960	-1.44690
59.2800	-1.48420	-1.35350	-1.73630	-1.48420
60.1450	-1.52160	-1.39090	-1.77360	-1.52160
61.0110	-1.55890	-1.41890	-1.82030	-1.55890
61.8760	-1.59620	-1.45620	-1.86690	-1.59620
62.7410	-1.63360	-1.48420	-1.90430	-1.63360
63.6070	-1.67090	-1.51220	-1.95100	-1.66160
64.4720	-1.69890	-1.54020	-1.98830	-1.68960
65.3370	-1.73630	-1.56820	-2.02560	-1.72690
66.2030	-1.76430	-1.59620	-2.06300	-1.75490
67.0680	-1.79230	-1.62420	-2.10030	-1.77360

67.9330	-1.82030	-1.64290	-2.12830	-1.80160
68.7990	-1.84830	-1.66160	-2.16570	-1.82030
69.6640	-1.87630	-1.68030	-2.19370	-1.84830
70.5290	-1.89490	-1.69890	-2.22170	-1.86690
71.3950	-1.91360	-1.71760	-2.24970	-1.88560
72.2600	-1.93230	-1.72690	-2.27770	-1.89490
73.1260	-1.95100	-1.73630	-2.30570	-1.91360
73.9910	-1.96960	-1.75490	-2.32430	-1.92300
74.8560	-1.97900	-1.75490	-2.34300	-1.93230
75.7220	-1.99760	-1.76430	-2.37100	-1.94160
76.5870	-2.00700	-1.76430	-2.38040	-1.94160
77.4520	-2.01630	-1.76430	-2.39900	-1.94160
78.3180	-2.01630	-1.76430	-2.40840	-1.94160
79.1830	-2.02560	-1.76430	-2.42700	-1.94160
80.0480	-2.02560	-1.75490	-2.43640	-1.94160
80.9140	-2.02560	-1.74560	-2.43640	-1.93230
81.7790	-2.02560	-1.73630	-2.44570	-1.92300
82.6440	-2.01630	-1.72690	-2.44570	-1.91360
83.5100	-2.00700	-1.70830	-2.44570	-1.89490
84.3750	-1.99760	-1.68960	-2.44570	-1.88560
85.2410	-1.98830	-1.67090	-2.44570	-1.85760
86.1060	-1.97900	-1.65220	-2.43640	-1.83890
86.9710	-1.96030	-1.62420	-2.42700	-1.81090
87.8370	-1.94160	-1.59620	-2.41770	-1.78290
88.7020	-1.92300	-1.55890	-2.40840	-1.75490
89.5670	-1.89490	-1.52160	-2.39900	-1.71760
90.3900	-1.87630	-1.49360	-2.38040	-1.68030
91.1680	-1.84830	-1.44690	-2.36170	-1.64290
91.9420	-1.82030	-1.40950	-2.34300	-1.60560
92.7130	-1.78290	-1.36290	-2.32430	-1.55890
93.4810	-1.75490	-1.31620	-2.29630	-1.52160
94.2460	-1.71760	-1.26950	-2.26830	-1.46560
95.0070	-1.68030	-1.21350	-2.24970	-1.41890
95.7640	-1.64290	-1.15750	-2.22170	-1.36290
96.5190	-1.60560	-1.10150	-2.18430	-1.30690
97.2700	-1.56820	-1.04550	-2.15630	-1.25090
98.0180	-1.52160	-0.98015	-2.11900	-1.18550
98.7630	-1.47490	-0.92414	-2.08160	-1.12020
99.5040	-1.42820	-0.85879	-2.04430	-1.05480
100.2400	-1.37220	-0.80279	-2.00700	-0.98948
100.9800	-1.31620	-0.75611	-1.96030	-0.93347

101.7100	-1.26950	-0.70944	-1.92300	-0.86813
102.4400	-1.21350	-0.66277	-1.87630	-0.82146
103.1600	-1.14820	-0.63476	-1.82030	-0.78412
103.8900	-1.09220	-0.60676	-1.77360	-0.74678
104.6100	-1.02680	-0.59742	-1.71760	-0.71877
105.3200	-0.97081	-0.57875	-1.67090	-0.70010
106.0300	-0.91480	-0.56942	-1.61490	-0.69077
106.7400	-0.84946	-0.56942	-1.54960	-0.67210
107.4500	-0.79345	-0.56008	-1.49360	-0.66277
108.1500	-0.74678	-0.56008	-1.42820	-0.66277
108.8500	-0.70010	-0.56008	-1.36290	-0.65343
109.5500	-0.65343	-0.56008	-1.29750	-0.64410
110.2500	-0.61609	-0.56008	-1.23220	-0.64410
110.9400	-0.58809	-0.56008	-1.16680	-0.64410
111.6300	-0.56942	-0.56008	-1.10150	-0.63476
112.3100	-0.55075	-0.56008	-1.04550	-0.63476
112.9900	-0.53208	-0.56008	-0.98948	-0.63476
113.6700	-0.52274	-0.56008	-0.93347	-0.63476
114.3500	-0.51341	-0.56008	-0.88680	-0.63476
115.0200	-0.50408	-0.56008	-0.84013	-0.63476
115.7000	-0.49474	-0.55075	-0.81212	-0.63476
116.3600	-0.48541	-0.55075	-0.78412	-0.63476
117.0300	-0.48541	-0.55075	-0.75611	-0.63476
117.6900	-0.47607	-0.55075	-0.73744	-0.63476
118.3500	-0.47607	-0.55075	-0.72811	-0.63476
119.0100	-0.46674	-0.55075	-0.70944	-0.63476
119.6600	-0.46674	-0.55075	-0.70010	-0.63476
120.3100	-0.46674	-0.55075	-0.70010	-0.63476
120.9600	-0.45740	-0.55075	-0.69077	-0.63476
121.6000	-0.45740	-0.55075	-0.68143	-0.63476
122.2400	-0.45740	-0.55075	-0.68143	-0.63476
122.8800	-0.45740	-0.55075	-0.67210	-0.63476
123.5200	-0.44807	-0.55075	-0.67210	-0.63476
124.1500	-0.44807	-0.55075	-0.66277	-0.63476
124.7900	-0.44807	-0.55075	-0.66277	-0.63476
125.4100	-0.44807	-0.54141	-0.66277	-0.62543
126.0400	-0.44807	-0.54141	-0.65343	-0.62543
126.6600	-0.44807	-0.54141	-0.65343	-0.62543
127.2800	-0.43873	-0.54141	-0.65343	-0.62543
127.9000	-0.43873	-0.54141	-0.65343	-0.62543
128.5100	-0.43873	-0.54141	-0.65343	-0.62543

129.1300	-0.43873	-0.54141	-0.64410	-0.62543
129.7400	-0.43873	-0.54141	-0.64410	-0.62543
130.3400	-0.43873	-0.54141	-0.64410	-0.62543
130.9500	-0.43873	-0.54141	-0.64410	-0.62543
131.5500	-0.43873	-0.54141	-0.64410	-0.62543
132.1500	-0.43873	-0.54141	-0.64410	-0.62543
132.7400	-0.42940	-0.54141	-0.64410	-0.62543
133.3400	-0.42940	-0.54141	-0.64410	-0.62543
133.9300	-0.42940	-0.54141	-0.64410	-0.62543
134.5200	-0.42940	-0.54141	-0.64410	-0.62543
135.1000	-0.42940	-0.54141	-0.63476	-0.62543
135.6900	-0.42940	-0.54141	-0.63476	-0.62543
136.2700	-0.42940	-0.53208	-0.63476	-0.62543
136.8400	-0.42940	-0.53208	-0.63476	-0.62543
137.4200	-0.42940	-0.53208	-0.63476	-0.62543
137.9900	-0.42940	-0.53208	-0.63476	-0.62543
138.5600	-0.42940	-0.53208	-0.63476	-0.62543
139.1300	-0.42940	-0.53208	-0.63476	-0.62543
139.7000	-0.42940	-0.53208	-0.63476	-0.62543
140.2600	-0.42940	-0.53208	-0.63476	-0.62543
140.8200	-0.42940	-0.53208	-0.63476	-0.62543
141.3800	-0.42940	-0.53208	-0.63476	-0.62543
141.9400	-0.42940	-0.53208	-0.63476	-0.62543
142.4900	-0.42940	-0.53208	-0.63476	-0.62543
143.0400	-0.42940	-0.53208	-0.63476	-0.62543
143.5900	-0.42940	-0.53208	-0.63476	-0.61609
144.1400	-0.42940	-0.53208	-0.62543	-0.61609
144.6800	-0.42940	-0.53208	-0.62543	-0.61609
145.2200	-0.42006	-0.53208	-0.62543	-0.61609
145.7600	-0.42006	-0.53208	-0.62543	-0.61609
146.3000	-0.42006	-0.53208	-0.62543	-0.61609
146.8300	-0.42006	-0.53208	-0.62543	-0.61609
147.3700	-0.42006	-0.53208	-0.62543	-0.61609
147.9000	-0.42006	-0.53208	-0.62543	-0.61609
148.4200	-0.42006	-0.53208	-0.62543	-0.61609
148.9500	-0.42006	-0.53208	-0.62543	-0.61609
149.4700	-0.42006	-0.52274	-0.62543	-0.61609
149.9900	-0.42006	-0.52274	-0.62543	-0.61609
150.5100	-0.42006	-0.52274	-0.62543	-0.61609
151.0300	-0.42006	-0.52274	-0.62543	-0.61609
151.5400	-0.42006	-0.52274	-0.62543	-0.61609

152.0600	-0.42006	-0.52274	-0.62543	-0.61609
152.5600	-0.42006	-0.52274	-0.62543	-0.61609
153.0700	-0.42006	-0.52274	-0.62543	-0.61609
153.5800	-0.42006	-0.52274	-0.62543	-0.61609
154.0800	-0.42006	-0.52274	-0.62543	-0.61609
154.5800	-0.42006	-0.51341	-0.62543	-0.61609
155.0800	-0.42006	-0.51341	-0.62543	-0.61609
155.5800	-0.41073	-0.51341	-0.62543	-0.60676
156.0700	-0.41073	-0.51341	-0.62543	-0.60676
156.5600	-0.41073	-0.51341	-0.62543	-0.60676
157.0500	-0.41073	-0.51341	-0.62543	-0.60676
157.5400	-0.41073	-0.51341	-0.62543	-0.60676
158.0300	-0.41073	-0.51341	-0.62543	-0.60676
158.5100	-0.41073	-0.50408	-0.62543	-0.60676
158.9900	-0.41073	-0.50408	-0.62543	-0.60676
159.4700	-0.41073	-0.50408	-0.62543	-0.60676
159.9500	-0.40139	-0.50408	-0.62543	-0.60676
160.4200	-0.40139	-0.50408	-0.62543	-0.60676
160.9000	-0.40139	-0.50408	-0.62543	-0.59742
161.3700	-0.40139	-0.49474	-0.62543	-0.59742
161.8400	-0.40139	-0.49474	-0.62543	-0.59742
162.3000	-0.40139	-0.49474	-0.62543	-0.59742
162.7700	-0.40139	-0.49474	-0.62543	-0.59742
163.2300	-0.39206	-0.49474	-0.62543	-0.59742
163.6900	-0.39206	-0.48541	-0.62543	-0.59742
164.1500	-0.39206	-0.48541	-0.62543	-0.59742
164.6100	-0.39206	-0.48541	-0.62543	-0.58809
165.0600	-0.39206	-0.48541	-0.62543	-0.58809
165.5200	-0.39206	-0.48541	-0.62543	-0.58809
165.9700	-0.39206	-0.48541	-0.62543	-0.58809
166.4200	-0.38272	-0.47607	-0.62543	-0.58809
166.8600	-0.38272	-0.47607	-0.62543	-0.58809
167.3100	-0.38272	-0.47607	-0.62543	-0.58809
167.7500	-0.38272	-0.47607	-0.62543	-0.58809
168.1900	-0.38272	-0.47607	-0.62543	-0.58809
168.6300	-0.38272	-0.47607	-0.62543	-0.57875
169.0700	-0.38272	-0.46674	-0.62543	-0.57875
169.5100	-0.37339	-0.46674	-0.62543	-0.57875
169.9400	-0.37339	-0.46674	-0.62543	-0.57875
170.3700	-0.37339	-0.46674	-0.62543	-0.57875
170.8000	-0.37339	-0.46674	-0.62543	-0.57875

171.2300	-0.37339	-0.46674	-0.62543	-0.57875
171.6600	-0.37339	-0.46674	-0.62543	-0.57875
172.0800	-0.37339	-0.46674	-0.62543	-0.57875
172.5000	-0.36405	-0.45740	-0.62543	-0.57875
172.9200	-0.36405	-0.45740	-0.62543	-0.57875
173.3400	-0.36405	-0.45740	-0.62543	-0.56942
173.7600	-0.36405	-0.45740	-0.62543	-0.56942
174.1700	-0.36405	-0.45740	-0.62543	-0.56942
174.5900	-0.36405	-0.45740	-0.62543	-0.56942
175.0000	-0.36405	-0.45740	-0.62543	-0.56942
175.4100	-0.36405	-0.45740	-0.62543	-0.56942
175.8200	-0.36405	-0.45740	-0.62543	-0.56942
176.2200	-0.36405	-0.45740	-0.62543	-0.56942
176.6300	-0.36405	-0.45740	-0.62543	-0.56942
177.0300	-0.36405	-0.45740	-0.62543	-0.56942
177.4300	-0.36405	-0.44807	-0.62543	-0.56942
177.8300	-0.36405	-0.44807	-0.62543	-0.56942
178.2200	-0.36405	-0.44807	-0.62543	-0.56942
178.6200	-0.36405	-0.44807	-0.62543	-0.56942
179.0000	-0.36405	-0.44807	-0.62543	-0.56942
179.3800	-0.36405	-0.44807	-0.62543	-0.56942
179.7200	-0.36405	-0.44807	-0.62543	-0.56942

Table A.2.2 C_f at $Re = 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	0.00004044	0.00003842	0.00007169	0.00006886
1.3703	0.00017549	0.00017256	0.00021518	0.00020645
2.2073	0.00031999	0.00031035	0.00035856	0.00034392
3.0602	0.00044920	0.00043849	0.00050173	0.00048117
3.9187	0.00059032	0.00057540	0.00064461	0.00061814
4.7800	0.00072328	0.00070487	0.00078713	0.00075473
5.6418	0.00086088	0.00083978	0.00092919	0.00089087
6.5050	0.00099542	0.00097009	0.00107070	0.00102650
7.3684	0.00113080	0.00110290	0.00121170	0.00116140
8.2330	0.00126500	0.00123300	0.00135190	0.00129570
9.0970	0.00139880	0.00136380	0.00149140	0.00142920
9.9616	0.00153160	0.00149290	0.00163000	0.00156180
10.8260	0.00166360	0.00162170	0.00176770	0.00169340
11.6910	0.00179470	0.00174920	0.00190440	0.00182410
12.5550	0.00192470	0.00187580	0.00204000	0.00195360
13.4200	0.00205350	0.00200110	0.00217450	0.00208200

14.2860	0.00218130	0.00212540	0.00230790	0.00220910
15.1500	0.00230790	0.00224840	0.00244010	0.00233500
16.0150	0.00243360	0.00237010	0.00257150	0.00245950
16.8810	0.00255930	0.00249050	0.00270310	0.00258280
17.7450	0.00268760	0.00260980	0.00283820	0.00270480
18.6110	0.00282630	0.00272820	0.00298840	0.00282590
19.4760	0.00299340	0.00284620	0.00318160	0.00294650
20.3410	0.00321150	0.00296520	0.00344350	0.00306790
21.2060	0.00348440	0.00308770	0.00376280	0.00319260
22.0710	0.00378870	0.00321860	0.00410050	0.00332600
22.9370	0.00409610	0.00336680	0.00442750	0.00347890
23.8020	0.00439280	0.00354480	0.00473540	0.00366790
24.6670	0.00467570	0.00376370	0.00502610	0.00390840
25.5320	0.00494620	0.00402600	0.00530390	0.00420400
26.3980	0.00520650	0.00431960	0.00557260	0.00453050
27.2630	0.00545910	0.00461610	0.00583480	0.00484880
28.1280	0.00570580	0.00489590	0.00609230	0.00513890
28.9930	0.00594790	0.00515570	0.00634630	0.00540250
29.8590	0.00618630	0.00540030	0.00659760	0.00564880
30.7240	0.00642190	0.00563420	0.00684690	0.00588540
31.5890	0.00665490	0.00586080	0.00709450	0.00611660
32.4540	0.00688560	0.00608240	0.00734060	0.00634410
33.3200	0.00711430	0.00630020	0.00758520	0.00656860
34.1850	0.00734090	0.00651480	0.00782830	0.00678980
35.0510	0.00756550	0.00672580	0.00807000	0.00700810
35.9160	0.00778800	0.00693350	0.00831000	0.00722360
36.7810	0.00800820	0.00713790	0.00854840	0.00743630
37.6470	0.00822610	0.00733920	0.00878490	0.00764610
38.5120	0.00844160	0.00753760	0.00901930	0.00785320
39.3770	0.00865440	0.00773290	0.00925140	0.00805700
40.2420	0.00886440	0.00792510	0.00948120	0.00825780
41.1080	0.00907140	0.00811370	0.00970840	0.00845560
41.9730	0.00927510	0.00829880	0.00993280	0.00865040
42.8380	0.00947540	0.00848060	0.01015400	0.00884200
43.7040	0.00967210	0.00865890	0.01037200	0.00903030
44.5690	0.00986510	0.00883340	0.01058700	0.00921510
45.4340	0.01005400	0.00900410	0.01079800	0.00939610
46.3000	0.01023900	0.00917060	0.01100500	0.00957290
47.1650	0.01041900	0.00933280	0.01120800	0.00974500
48.0300	0.01059400	0.00949040	0.01140700	0.00991270
48.8960	0.01076500	0.00964310	0.01160100	0.01007600

49.7610	0.01093100	0.00979050	0.01179100	0.01023400
50.6260	0.01109100	0.00993260	0.01197500	0.01038700
51.4920	0.01124600	0.01006900	0.01215500	0.01053400
52.3570	0.01139500	0.01020000	0.01232900	0.01067600
53.2220	0.01153800	0.01032500	0.01249800	0.01081200
54.0880	0.01167600	0.01044500	0.01266100	0.01094300
54.9530	0.01180700	0.01055700	0.01281900	0.01106600
55.8190	0.01193200	0.01066400	0.01297000	0.01118400
56.6840	0.01204900	0.01076300	0.01311500	0.01129500
57.5490	0.01216100	0.01085600	0.01325400	0.01139900
58.4150	0.01226500	0.01094100	0.01338600	0.01149600
59.2800	0.01236200	0.01101900	0.01351100	0.01158500
60.1450	0.01245200	0.01109000	0.01363000	0.01166700
61.0110	0.01253400	0.01115200	0.01374100	0.01174200
61.8760	0.01260900	0.01120700	0.01384500	0.01180800
62.7410	0.01267500	0.01125400	0.01394200	0.01186700
63.6070	0.01273400	0.01129300	0.01403100	0.01191700
64.4720	0.01278500	0.01132300	0.01411200	0.01195900
65.3370	0.01282700	0.01134400	0.01418500	0.01199200
66.2030	0.01286100	0.01135700	0.01425100	0.01201700
67.0680	0.01288600	0.01136000	0.01430800	0.01203200
67.9330	0.01290300	0.01135500	0.01435700	0.01203800
68.7990	0.01291000	0.01134000	0.01439800	0.01203500
69.6640	0.01290900	0.01131600	0.01443000	0.01202200
70.5290	0.01289900	0.01128200	0.01445400	0.01199900
71.3950	0.01287900	0.01123800	0.01446800	0.01196700
72.2600	0.01285000	0.01118400	0.01447400	0.01192400
73.1260	0.01281100	0.01111900	0.01447000	0.01187000
73.9910	0.01276200	0.01104400	0.01445800	0.01180600
74.8560	0.01270400	0.01095800	0.01443600	0.01173200
75.7220	0.01263600	0.01086200	0.01440500	0.01164600
76.5870	0.01255800	0.01075300	0.01436400	0.01154900
77.4520	0.01246900	0.01063300	0.01431300	0.01144000
78.3180	0.01237000	0.01050200	0.01425300	0.01131900
79.1830	0.01226100	0.01035800	0.01418300	0.01118600
80.0480	0.01214100	0.01020100	0.01410300	0.01104100
80.9140	0.01201000	0.01003200	0.01401200	0.01088200
81.7790	0.01186800	0.00985000	0.01391200	0.01071000
82.6440	0.01171500	0.00965350	0.01380100	0.01052400
83.5100	0.01155100	0.00944250	0.01368000	0.01032400
84.3750	0.01137600	0.00921640	0.01354800	0.01010900

85.2410	0.01118800	0.00897450	0.01340500	0.00987760
86.1060	0.01099000	0.00871430	0.01325100	0.00962880
86.9710	0.01077900	0.00843580	0.01308600	0.00936200
87.8370	0.01055800	0.00813710	0.01291000	0.00907520
88.7020	0.01032200	0.00781730	0.01272300	0.00876790
89.5670	0.01008700	0.00747990	0.01252300	0.00843620
90.3900	0.00980410	0.00708630	0.01232100	0.00809790
91.1680	0.00952590	0.00670730	0.01212100	0.00775550
91.9420	0.00928060	0.00634150	0.01191300	0.00739040
92.7130	0.00899640	0.00591850	0.01169400	0.00699920
93.4810	0.00871200	0.00548770	0.01146700	0.00658370
94.2460	0.00840960	0.00502070	0.01122900	0.00614210
95.0070	0.00809680	0.00453210	0.01098200	0.00567250
95.7640	0.00776930	0.00401320	0.01072500	0.00517330
96.5190	0.00742820	0.00347070	0.01045800	0.00464340
97.2700	0.00707180	0.00290570	0.01018100	0.00408270
98.0180	0.00669990	0.00232720	0.00989190	0.00349370
98.7630	0.00631140	0.00174600	0.00959190	0.00288250
99.5040	0.00590550	0.00117980	0.00928010	0.00226020
100.2400	0.00548160	0.00064996	0.00895610	0.00164510
100.9800	0.00503910	0.00018166	0.00861910	0.00106320
101.7100	0.00457770	-0.00020296	0.00826850	0.00054583
102.4400	0.00409780	-0.00049144	0.00790360	0.00012319
103.1600	0.00360050	-0.00067650	0.00752360	-0.00018675
103.8900	0.00308820	-0.00076320	0.00712740	-0.00038704
104.6100	0.00256510	-0.00078670	0.00671440	-0.00050060
105.3200	0.00203770	-0.00077831	0.00628340	-0.00055766
106.0300	0.00151530	-0.00074605	0.00583380	-0.00058343
106.7400	0.00101050	-0.00068520	0.00536480	-0.00059347
107.4500	0.00053896	-0.00060183	0.00487620	-0.00059567
108.1500	0.00011849	-0.00052522	0.00436820	-0.00059336
108.8500	-0.00023484	-0.00047599	0.00384210	-0.00058731
109.5500	-0.00051111	-0.00045309	0.00330070	-0.00057531
110.2500	-0.00070348	-0.00044612	0.00274870	-0.00055127
110.9400	-0.00081616	-0.00045070	0.00219380	-0.00051188
111.6300	-0.00087230	-0.00046138	0.00164730	-0.00046338
112.3100	-0.00090055	-0.00047557	0.00112430	-0.00041814
112.9900	-0.00091297	-0.00049132	0.00064366	-0.00038508
113.6700	-0.00091307	-0.00050734	0.00022549	-0.00036523
114.3500	-0.00090463	-0.00052276	-0.00011338	-0.00035528
115.0200	-0.00089111	-0.00053711	-0.00036498	-0.00035174

115.7000	-0.00087485	-0.00055027	-0.00053401	-0.00035229
116.3600	-0.00085705	-0.00056211	-0.00063632	-0.00035553
117.0300	-0.00083814	-0.00057268	-0.00069199	-0.00036063
117.6900	-0.00081864	-0.00058211	-0.00071862	-0.00036708
118.3500	-0.00079861	-0.00059027	-0.00072802	-0.00037445
119.0100	-0.00077847	-0.00059746	-0.00072687	-0.00038240
119.6600	-0.00075849	-0.00060378	-0.00071876	-0.00039058
120.3100	-0.00073862	-0.00060912	-0.00070585	-0.00039863
120.9600	-0.00071933	-0.00061380	-0.00068958	-0.00040622
121.6000	-0.00070067	-0.00061763	-0.00067099	-0.00041308
122.2400	-0.00068295	-0.00062080	-0.00065083	-0.00041902
122.8800	-0.00066627	-0.00062329	-0.00062968	-0.00042392
123.5200	-0.00065071	-0.00062517	-0.00060801	-0.00042775
124.1500	-0.00063636	-0.00062646	-0.00058622	-0.00043053
124.7900	-0.00062318	-0.00062727	-0.00056465	-0.00043234
125.4100	-0.00061112	-0.00062762	-0.00054356	-0.00043328
126.0400	-0.00060007	-0.00062762	-0.00052319	-0.00043347
126.6600	-0.00058987	-0.00062732	-0.00050370	-0.00043303
127.2800	-0.00058044	-0.00062685	-0.00048524	-0.00043208
127.9000	-0.00057159	-0.00062626	-0.00046791	-0.00043076
128.5100	-0.00056325	-0.00062567	-0.00045179	-0.00042917
129.1300	-0.00055532	-0.00062514	-0.00043695	-0.00042745
129.7400	-0.00054772	-0.00062480	-0.00042341	-0.00042569
130.3400	-0.00054042	-0.00062470	-0.00041119	-0.00042401
130.9500	-0.00053339	-0.00062495	-0.00040030	-0.00042248
131.5500	-0.00052667	-0.00062560	-0.00039069	-0.00042121
132.1500	-0.00052025	-0.00062672	-0.00038235	-0.00042026
132.7400	-0.00051420	-0.00062835	-0.00037521	-0.00041969
133.3400	-0.00050854	-0.00063055	-0.00036919	-0.00041957
133.9300	-0.00050336	-0.00063333	-0.00036422	-0.00041994
134.5200	-0.00049867	-0.00063674	-0.00036020	-0.00042083
135.1000	-0.00049456	-0.00064079	-0.00035701	-0.00042227
135.6900	-0.00049106	-0.00064549	-0.00035454	-0.00042428
136.2700	-0.00048823	-0.00065084	-0.00035265	-0.00042687
136.8400	-0.00048609	-0.00065684	-0.00035122	-0.00043004
137.4200	-0.00048468	-0.00066349	-0.00035011	-0.00043380
137.9900	-0.00048404	-0.00067077	-0.00034921	-0.00043813
138.5600	-0.00048416	-0.00067866	-0.00034839	-0.00044303
139.1300	-0.00048506	-0.00068713	-0.00034753	-0.00044849
139.7000	-0.00048674	-0.00069617	-0.00034654	-0.00045448
140.2600	-0.00048918	-0.00070573	-0.00034533	-0.00046098

140.8200	-0.00049239	-0.00071578	-0.00034382	-0.00046797
141.3800	-0.00049634	-0.00072628	-0.00034196	-0.00047541
141.9400	-0.00050101	-0.00073720	-0.00033971	-0.00048329
142.4900	-0.00050637	-0.00074848	-0.00033703	-0.00049156
143.0400	-0.00051241	-0.00076008	-0.00033391	-0.00050019
143.5900	-0.00051907	-0.00077196	-0.00033037	-0.00050914
144.1400	-0.00052633	-0.00078405	-0.00032641	-0.00051837
144.6800	-0.00053414	-0.00079633	-0.00032206	-0.00052785
145.2200	-0.00054247	-0.00080872	-0.00031736	-0.00053753
145.7600	-0.00055125	-0.00082119	-0.00031235	-0.00054737
146.3000	-0.00056045	-0.00083368	-0.00030708	-0.00055732
146.8300	-0.00057002	-0.00084613	-0.00030160	-0.00056735
147.3700	-0.00057990	-0.00085851	-0.00029597	-0.00057741
147.9000	-0.00059004	-0.00087074	-0.00029025	-0.00058746
148.4200	-0.00060038	-0.00088279	-0.00028448	-0.00059744
148.9500	-0.00061088	-0.00089461	-0.00027872	-0.00060733
149.4700	-0.00062147	-0.00090614	-0.00027302	-0.00061708
149.9900	-0.00063211	-0.00091734	-0.00026741	-0.00062664
150.5100	-0.00064273	-0.00092816	-0.00026194	-0.00063598
151.0300	-0.00065329	-0.00093855	-0.00025665	-0.00064505
151.5400	-0.00066373	-0.00094848	-0.00025156	-0.00065381
152.0600	-0.00067400	-0.00095789	-0.00024669	-0.00066224
152.5600	-0.00068405	-0.00096675	-0.00024207	-0.00067028
153.0700	-0.00069382	-0.00097501	-0.00023770	-0.00067791
153.5800	-0.00070327	-0.00098264	-0.00023360	-0.00068508
154.0800	-0.00071236	-0.00098959	-0.00022977	-0.00069179
154.5800	-0.00072103	-0.00099583	-0.00022621	-0.00069797
155.0800	-0.00072923	-0.00100130	-0.00022292	-0.00070361
155.5800	-0.00073693	-0.00100610	-0.00021988	-0.00070868
156.0700	-0.00074409	-0.00101000	-0.00021710	-0.00071316
156.5600	-0.00075065	-0.00101310	-0.00021456	-0.00071701
157.0500	-0.00075659	-0.00101540	-0.00021225	-0.00072022
157.5400	-0.00076187	-0.00101680	-0.00021014	-0.00072277
158.0300	-0.00076645	-0.00101730	-0.00020823	-0.00072464
158.5100	-0.00077031	-0.00101690	-0.00020649	-0.00072580
158.9900	-0.00077342	-0.00101560	-0.00020490	-0.00072626
159.4700	-0.00077575	-0.00101330	-0.00020344	-0.00072599
159.9500	-0.00077727	-0.00101010	-0.00020209	-0.00072497
160.4200	-0.00077797	-0.00100590	-0.00020083	-0.00072322
160.9000	-0.00077782	-0.00100080	-0.00019963	-0.00072071
161.3700	-0.00077681	-0.00099471	-0.00019847	-0.00071744

161.8400	-0.00077492	-0.00098763	-0.00019732	-0.00071340
162.3000	-0.00077214	-0.00097957	-0.00019617	-0.00070860
162.7700	-0.00076844	-0.00097054	-0.00019499	-0.00070304
163.2300	-0.00076383	-0.00096054	-0.00019376	-0.00069671
163.6900	-0.00075830	-0.00094957	-0.00019246	-0.00068961
164.1500	-0.00075184	-0.00093763	-0.00019106	-0.00068176
164.6100	-0.00074445	-0.00092475	-0.00018956	-0.00067317
165.0600	-0.00073613	-0.00091092	-0.00018793	-0.00066382
165.5200	-0.00072688	-0.00089616	-0.00018615	-0.00065374
165.9700	-0.00071671	-0.00088048	-0.00018421	-0.00064293
166.4200	-0.00070561	-0.00086390	-0.00018210	-0.00063142
166.8600	-0.00069360	-0.00084644	-0.00017980	-0.00061920
167.3100	-0.00068068	-0.00082811	-0.00017729	-0.00060630
167.7500	-0.00066687	-0.00080893	-0.00017457	-0.00059273
168.1900	-0.00065219	-0.00078894	-0.00017163	-0.00057852
168.6300	-0.00063663	-0.00076813	-0.00016846	-0.00056367
169.0700	-0.00062024	-0.00074657	-0.00016505	-0.00054820
169.5100	-0.00060301	-0.00072423	-0.00016140	-0.00053215
169.9400	-0.00058499	-0.00070119	-0.00015750	-0.00051552
170.3700	-0.00056618	-0.00067744	-0.00015335	-0.00049835
170.8000	-0.00054664	-0.00065303	-0.00014895	-0.00048064
171.2300	-0.00052636	-0.00062797	-0.00014430	-0.00046244
171.6600	-0.00050540	-0.00060233	-0.00013940	-0.00044376
172.0800	-0.00048378	-0.00057609	-0.00013426	-0.00042463
172.5000	-0.00046156	-0.00054934	-0.00012888	-0.00040507
172.9200	-0.00043876	-0.00052205	-0.00012326	-0.00038511
173.3400	-0.00041545	-0.00049432	-0.00011742	-0.00036478
173.7600	-0.00039164	-0.00046612	-0.00011137	-0.00034411
174.1700	-0.00036743	-0.00043755	-0.00010511	-0.00032311
174.5900	-0.00034282	-0.00040857	-0.00009866	-0.00030183
175.0000	-0.00031793	-0.00037930	-0.00009203	-0.00028028
175.4100	-0.00029273	-0.00034968	-0.00008522	-0.00025850
175.8200	-0.00026739	-0.00031986	-0.00007827	-0.00023651
176.2200	-0.00024182	-0.00028974	-0.00007117	-0.00021434
176.6300	-0.00021623	-0.00025951	-0.00006396	-0.00019202
177.0300	-0.00019049	-0.00022903	-0.00005663	-0.00016957
177.4300	-0.00016485	-0.00019853	-0.00004921	-0.00014703
177.8300	-0.00013911	-0.00016783	-0.00004171	-0.00012442
178.2200	-0.00011356	-0.00013720	-0.00003415	-0.00010176
178.6200	-0.00008791	-0.00010643	-0.00002655	-0.00007909
179.0000	-0.00006255	-0.00007581	-0.00001893	-0.00005643

179.3800	-0.00003711	-0.00004513	-0.00001129	-0.00003381
179.7200	-0.00001200	-0.00001469	-0.00000366	-0.00001124

Table A.2.3 C_p at $Re = 2 \times 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	1.00820	1.01750	0.99882	0.99882
1.3703	1.00820	1.01750	0.99882	0.99882
2.2073	1.00820	1.00820	0.99882	0.99882
3.0602	1.00820	1.00820	0.98948	0.98948
3.9187	0.99882	0.99882	0.98948	0.98948
4.7800	0.98948	0.98948	0.98015	0.98015
5.6418	0.98015	0.98015	0.96148	0.97081
6.5050	0.97081	0.97081	0.95214	0.96148
7.3684	0.96148	0.96148	0.94281	0.94281
8.2330	0.94281	0.95214	0.92414	0.93347
9.0970	0.93347	0.93347	0.90547	0.91480
9.9616	0.91480	0.91480	0.88680	0.89613
10.8260	0.89613	0.89613	0.86813	0.87746
11.6910	0.87746	0.87746	0.84946	0.85879
12.5550	0.84946	0.85879	0.82146	0.83079
13.4200	0.83079	0.84013	0.79345	0.81212
14.2860	0.80279	0.81212	0.77478	0.78412
15.1500	0.77478	0.78412	0.73744	0.75611
16.0150	0.74678	0.75611	0.70944	0.72811
16.8810	0.71877	0.72811	0.68143	0.70010
17.7450	0.69077	0.70010	0.64410	0.67210
18.6110	0.66277	0.67210	0.61609	0.63476
19.4760	0.62543	0.64410	0.57875	0.60676
20.3410	0.58809	0.60676	0.54141	0.56942
21.2060	0.56008	0.56942	0.50408	0.53208
22.0710	0.52274	0.54141	0.46674	0.49474
22.9370	0.48541	0.50408	0.42006	0.45740
23.8020	0.43873	0.46674	0.38272	0.42006
24.6670	0.40139	0.42940	0.33605	0.38272
25.5320	0.36405	0.38272	0.29871	0.33605
26.3980	0.31738	0.34538	0.25204	0.29871
27.2630	0.28004	0.30805	0.20536	0.25204
28.1280	0.23337	0.26137	0.15869	0.20536
28.9930	0.18669	0.21470	0.11202	0.15869
29.8590	0.14002	0.17736	0.05601	0.12135

30.7240	0.09335	0.13069	0.00933	0.07468
31.5890	0.04667	0.08401	-0.03734	0.02800
32.4540	0.00000	0.03734	-0.09335	-0.02800
33.3200	-0.04667	-0.00933	-0.14002	-0.07468
34.1850	-0.09335	-0.05601	-0.19603	-0.12135
35.0510	-0.14936	-0.10268	-0.25204	-0.16803
35.9160	-0.19603	-0.14936	-0.30805	-0.21470
36.7810	-0.25204	-0.19603	-0.35472	-0.27071
37.6470	-0.29871	-0.25204	-0.41073	-0.31738
38.5120	-0.35472	-0.29871	-0.46674	-0.37339
39.3770	-0.40139	-0.34538	-0.52274	-0.42006
40.2420	-0.45740	-0.39206	-0.57875	-0.47607
41.1080	-0.50408	-0.44807	-0.63476	-0.52274
41.9730	-0.56008	-0.49474	-0.69077	-0.56942
42.8380	-0.60676	-0.54141	-0.74678	-0.62543
43.7040	-0.66277	-0.58809	-0.80279	-0.67210
44.5690	-0.70944	-0.64410	-0.85879	-0.72811
45.4340	-0.76545	-0.69077	-0.91480	-0.77478
46.3000	-0.82146	-0.73744	-0.97081	-0.83079
47.1650	-0.86813	-0.78412	-1.02680	-0.87746
48.0300	-0.92414	-0.83079	-1.08280	-0.92414
48.8960	-0.97081	-0.88680	-1.13880	-0.97081
49.7610	-1.01750	-0.93347	-1.19480	-1.02680
50.6260	-1.07350	-0.98015	-1.24150	-1.07350
51.4920	-1.12020	-1.01750	-1.29750	-1.12020
52.3570	-1.16680	-1.06420	-1.35350	-1.16680
53.2220	-1.21350	-1.11080	-1.40950	-1.21350
54.0880	-1.26020	-1.15750	-1.45620	-1.26020
54.9530	-1.30690	-1.19480	-1.51220	-1.30690
55.8190	-1.35350	-1.24150	-1.55890	-1.34420
56.6840	-1.40020	-1.27890	-1.61490	-1.39090
57.5490	-1.44690	-1.32550	-1.66160	-1.42820
58.4150	-1.49360	-1.36290	-1.70830	-1.47490
59.2800	-1.53090	-1.40020	-1.75490	-1.51220
60.1450	-1.56820	-1.43750	-1.80160	-1.54960
61.0110	-1.61490	-1.47490	-1.84830	-1.58690
61.8760	-1.65220	-1.50290	-1.88560	-1.62420
62.7410	-1.68960	-1.54020	-1.93230	-1.65220
63.6070	-1.72690	-1.56820	-1.97900	-1.68960
64.4720	-1.76430	-1.60560	-2.01630	-1.71760
65.3370	-1.79230	-1.63360	-2.05360	-1.75490

66.2030	-1.82960	-1.66160	-2.09100	-1.78290
67.0680	-1.85760	-1.68960	-2.12830	-1.81090
67.9330	-1.88560	-1.70830	-2.16570	-1.82960
68.7990	-1.91360	-1.73630	-2.19370	-1.85760
69.6640	-1.94160	-1.75490	-2.23100	-1.87630
70.5290	-1.96030	-1.77360	-2.25900	-1.89490
71.3950	-1.98830	-1.79230	-2.28700	-1.91360
72.2600	-2.00700	-1.80160	-2.31500	-1.93230
73.1260	-2.02560	-1.82030	-2.34300	-1.95100
73.9910	-2.04430	-1.82960	-2.36170	-1.96030
74.8560	-2.06300	-1.83890	-2.38970	-1.96960
75.7220	-2.07230	-1.84830	-2.40840	-1.97900
76.5870	-2.09100	-1.85760	-2.42700	-1.98830
77.4520	-2.10030	-1.85760	-2.44570	-1.98830
78.3180	-2.10960	-1.85760	-2.45500	-1.99760
79.1830	-2.10960	-1.85760	-2.46440	-1.99760
80.0480	-2.11900	-1.85760	-2.48300	-1.98830
80.9140	-2.11900	-1.84830	-2.48300	-1.98830
81.7790	-2.11900	-1.83890	-2.49240	-1.97900
82.6440	-2.11900	-1.82960	-2.50170	-1.96960
83.5100	-2.10960	-1.82030	-2.50170	-1.96030
84.3750	-2.10030	-1.80160	-2.50170	-1.94160
85.2410	-2.10030	-1.79230	-2.50170	-1.92300
86.1060	-2.08160	-1.77360	-2.49240	-1.90430
86.9710	-2.07230	-1.74560	-2.49240	-1.88560
87.8370	-2.05360	-1.71760	-2.48300	-1.85760
88.7020	-2.03500	-1.68960	-2.47370	-1.82960
89.5670	-2.01630	-1.66160	-2.45500	-1.80160
90.3900	-1.99760	-1.63360	-2.44570	-1.76430
91.1680	-1.96960	-1.59620	-2.42700	-1.73630
91.9420	-1.95100	-1.55890	-2.40840	-1.69890
92.7130	-1.92300	-1.52160	-2.38970	-1.66160
93.4810	-1.89490	-1.48420	-2.37100	-1.62420
94.2460	-1.86690	-1.43750	-2.35240	-1.57760
95.0070	-1.82960	-1.39090	-2.32430	-1.53090
95.7640	-1.79230	-1.34420	-2.29630	-1.48420
96.5190	-1.76430	-1.28820	-2.26830	-1.42820
97.2700	-1.71760	-1.23220	-2.24030	-1.37220
98.0180	-1.68030	-1.17620	-2.21230	-1.31620
98.7630	-1.64290	-1.12020	-2.17500	-1.26020
99.5040	-1.59620	-1.05480	-2.13770	-1.19480

100.2400	-1.54960	-0.99882	-2.10030	-1.12950
100.9800	-1.50290	-0.93347	-2.06300	-1.06420
101.7100	-1.45620	-0.86813	-2.02560	-0.98948
102.4400	-1.40020	-0.80279	-1.97900	-0.92414
103.1600	-1.34420	-0.74678	-1.94160	-0.85879
103.8900	-1.28820	-0.69077	-1.89490	-0.80279
104.6100	-1.23220	-0.64410	-1.84830	-0.74678
105.3200	-1.17620	-0.61609	-1.79230	-0.70944
106.0300	-1.11080	-0.58809	-1.74560	-0.67210
106.7400	-1.04550	-0.56942	-1.68960	-0.65343
107.4500	-0.98948	-0.55075	-1.63360	-0.63476
108.1500	-0.92414	-0.54141	-1.57760	-0.61609
108.8500	-0.85879	-0.54141	-1.51220	-0.60676
109.5500	-0.80279	-0.53208	-1.45620	-0.60676
110.2500	-0.73744	-0.53208	-1.39090	-0.59742
110.9400	-0.69077	-0.53208	-1.32550	-0.58809
111.6300	-0.64410	-0.53208	-1.26020	-0.58809
112.3100	-0.59742	-0.53208	-1.19480	-0.58809
112.9900	-0.56942	-0.53208	-1.12020	-0.57875
113.6700	-0.54141	-0.53208	-1.05480	-0.57875
114.3500	-0.52274	-0.53208	-0.98948	-0.57875
115.0200	-0.50408	-0.53208	-0.93347	-0.57875
115.7000	-0.49474	-0.53208	-0.87746	-0.57875
116.3600	-0.48541	-0.53208	-0.82146	-0.57875
117.0300	-0.47607	-0.53208	-0.77478	-0.57875
117.6900	-0.46674	-0.53208	-0.73744	-0.57875
118.3500	-0.45740	-0.53208	-0.70944	-0.57875
119.0100	-0.44807	-0.53208	-0.69077	-0.57875
119.6600	-0.44807	-0.53208	-0.67210	-0.57875
120.3100	-0.44807	-0.53208	-0.65343	-0.57875
120.9600	-0.43873	-0.53208	-0.64410	-0.57875
121.6000	-0.43873	-0.53208	-0.63476	-0.57875
122.2400	-0.42940	-0.53208	-0.62543	-0.57875
122.8800	-0.42940	-0.53208	-0.62543	-0.57875
123.5200	-0.42940	-0.53208	-0.61609	-0.57875
124.1500	-0.42940	-0.52274	-0.60676	-0.57875
124.7900	-0.42006	-0.52274	-0.60676	-0.57875
125.4100	-0.42006	-0.52274	-0.60676	-0.57875
126.0400	-0.42006	-0.52274	-0.59742	-0.57875
126.6600	-0.42006	-0.52274	-0.59742	-0.57875
127.2800	-0.42006	-0.52274	-0.59742	-0.57875

127.9000	-0.42006	-0.52274	-0.59742	-0.57875
128.5100	-0.41073	-0.52274	-0.58809	-0.56942
129.1300	-0.41073	-0.52274	-0.58809	-0.56942
129.7400	-0.41073	-0.52274	-0.58809	-0.56942
130.3400	-0.41073	-0.52274	-0.58809	-0.56942
130.9500	-0.41073	-0.52274	-0.58809	-0.56942
131.5500	-0.41073	-0.52274	-0.58809	-0.56942
132.1500	-0.41073	-0.52274	-0.57875	-0.56942
132.7400	-0.41073	-0.52274	-0.57875	-0.56942
133.3400	-0.41073	-0.52274	-0.57875	-0.56942
133.9300	-0.40139	-0.51341	-0.57875	-0.56942
134.5200	-0.40139	-0.51341	-0.57875	-0.56942
135.1000	-0.40139	-0.51341	-0.57875	-0.56942
135.6900	-0.40139	-0.51341	-0.57875	-0.56942
136.2700	-0.40139	-0.51341	-0.57875	-0.56942
136.8400	-0.40139	-0.51341	-0.57875	-0.56942
137.4200	-0.40139	-0.51341	-0.57875	-0.56942
137.9900	-0.40139	-0.51341	-0.57875	-0.56942
138.5600	-0.40139	-0.51341	-0.57875	-0.56942
139.1300	-0.40139	-0.51341	-0.57875	-0.56942
139.7000	-0.40139	-0.51341	-0.56942	-0.56942
140.2600	-0.40139	-0.51341	-0.56942	-0.56942
140.8200	-0.40139	-0.51341	-0.56942	-0.56942
141.3800	-0.40139	-0.51341	-0.56942	-0.56942
141.9400	-0.40139	-0.51341	-0.56942	-0.56942
142.4900	-0.40139	-0.51341	-0.56942	-0.56942
143.0400	-0.40139	-0.51341	-0.56942	-0.56942
143.5900	-0.40139	-0.51341	-0.56942	-0.56942
144.1400	-0.40139	-0.51341	-0.56942	-0.56942
144.6800	-0.40139	-0.51341	-0.56942	-0.56942
145.2200	-0.40139	-0.51341	-0.56942	-0.56942
145.7600	-0.40139	-0.51341	-0.56942	-0.56942
146.3000	-0.40139	-0.51341	-0.56942	-0.56942
146.8300	-0.40139	-0.51341	-0.56942	-0.56942
147.3700	-0.39206	-0.51341	-0.56942	-0.56942
147.9000	-0.39206	-0.51341	-0.56942	-0.56942
148.4200	-0.39206	-0.51341	-0.56942	-0.56942
148.9500	-0.39206	-0.51341	-0.56942	-0.56942
149.4700	-0.39206	-0.50408	-0.56942	-0.56942
149.9900	-0.39206	-0.50408	-0.56942	-0.56942
150.5100	-0.39206	-0.50408	-0.56942	-0.56942

151.0300	-0.39206	-0.50408	-0.56942	-0.56008
151.5400	-0.39206	-0.50408	-0.56008	-0.56008
152.0600	-0.39206	-0.50408	-0.56008	-0.56008
152.5600	-0.39206	-0.50408	-0.56008	-0.56008
153.0700	-0.39206	-0.50408	-0.56008	-0.56008
153.5800	-0.39206	-0.50408	-0.56008	-0.56008
154.0800	-0.39206	-0.50408	-0.56008	-0.56008
154.5800	-0.39206	-0.50408	-0.56008	-0.56008
155.0800	-0.39206	-0.49474	-0.56008	-0.56008
155.5800	-0.39206	-0.49474	-0.56008	-0.56008
156.0700	-0.39206	-0.49474	-0.56008	-0.56008
156.5600	-0.39206	-0.49474	-0.56008	-0.56008
157.0500	-0.38272	-0.49474	-0.56008	-0.56008
157.5400	-0.38272	-0.49474	-0.56008	-0.56008
158.0300	-0.38272	-0.49474	-0.56008	-0.56008
158.5100	-0.38272	-0.48541	-0.56008	-0.55075
158.9900	-0.38272	-0.48541	-0.56008	-0.55075
159.4700	-0.38272	-0.48541	-0.56008	-0.55075
159.9500	-0.38272	-0.48541	-0.56008	-0.55075
160.4200	-0.38272	-0.48541	-0.56008	-0.55075
160.9000	-0.38272	-0.48541	-0.56008	-0.55075
161.3700	-0.37339	-0.47607	-0.56008	-0.55075
161.8400	-0.37339	-0.47607	-0.56008	-0.55075
162.3000	-0.37339	-0.47607	-0.56008	-0.55075
162.7700	-0.37339	-0.47607	-0.56008	-0.55075
163.2300	-0.37339	-0.47607	-0.56008	-0.54141
163.6900	-0.37339	-0.47607	-0.56008	-0.54141
164.1500	-0.37339	-0.46674	-0.56008	-0.54141
164.6100	-0.36405	-0.46674	-0.56008	-0.54141
165.0600	-0.36405	-0.46674	-0.56008	-0.54141
165.5200	-0.36405	-0.46674	-0.56008	-0.54141
165.9700	-0.36405	-0.46674	-0.56008	-0.54141
166.4200	-0.36405	-0.46674	-0.56008	-0.54141
166.8600	-0.36405	-0.45740	-0.56008	-0.54141
167.3100	-0.35472	-0.45740	-0.56008	-0.53208
167.7500	-0.35472	-0.45740	-0.56008	-0.53208
168.1900	-0.35472	-0.45740	-0.56008	-0.53208
168.6300	-0.35472	-0.45740	-0.56008	-0.53208
169.0700	-0.35472	-0.45740	-0.56008	-0.53208
169.5100	-0.35472	-0.44807	-0.56008	-0.53208
169.9400	-0.35472	-0.44807	-0.56008	-0.53208

170.3700	-0.34538	-0.44807	-0.56008	-0.53208
170.8000	-0.34538	-0.44807	-0.56008	-0.53208
171.2300	-0.34538	-0.44807	-0.56008	-0.53208
171.6600	-0.34538	-0.44807	-0.56008	-0.52274
172.0800	-0.34538	-0.44807	-0.56008	-0.52274
172.5000	-0.34538	-0.43873	-0.56008	-0.52274
172.9200	-0.34538	-0.43873	-0.56008	-0.52274
173.3400	-0.34538	-0.43873	-0.56008	-0.52274
173.7600	-0.33605	-0.43873	-0.56008	-0.52274
174.1700	-0.33605	-0.43873	-0.56008	-0.52274
174.5900	-0.33605	-0.43873	-0.56008	-0.52274
175.0000	-0.33605	-0.43873	-0.56008	-0.52274
175.4100	-0.33605	-0.43873	-0.56008	-0.52274
175.8200	-0.33605	-0.43873	-0.56008	-0.52274
176.2200	-0.33605	-0.43873	-0.56008	-0.52274
176.6300	-0.33605	-0.43873	-0.56008	-0.52274
177.0300	-0.33605	-0.42940	-0.56008	-0.52274
177.4300	-0.33605	-0.42940	-0.56008	-0.52274
177.8300	-0.33605	-0.42940	-0.56008	-0.52274
178.2200	-0.33605	-0.42940	-0.56008	-0.52274
178.6200	-0.33605	-0.42940	-0.56008	-0.52274
179.0000	-0.33605	-0.42940	-0.56008	-0.52274
179.3800	-0.33605	-0.42940	-0.56008	-0.52274
179.7200	-0.33605	-0.42940	-0.56008	-0.52274

Table A.2.4 C_f at $Re = 2 \times 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	0.000029028	0.000027943	0.000051032	0.000049025
1.3703	0.000125140	0.000122580	0.000152840	0.000146660
2.2073	0.000228540	0.000222480	0.000254570	0.000244200
3.0602	0.000320500	0.000312790	0.000356150	0.000341600
3.9187	0.000421180	0.000410980	0.000457530	0.000438790
4.7800	0.000516100	0.000503390	0.000558650	0.000535720
5.6418	0.000614180	0.000599400	0.000659450	0.000632330
6.5050	0.000710240	0.000692830	0.000759890	0.000728550
7.3684	0.000806810	0.000787250	0.000859890	0.000824350
8.2330	0.000902610	0.000880540	0.000959420	0.000919650
9.0970	0.000998120	0.000973740	0.001058500	0.001014400
9.9616	0.001093300	0.001066300	0.001157100	0.001108700
10.8260	0.001189000	0.001158400	0.001255800	0.001202300

11.6910	0.001289600	0.001250100	0.001360000	0.001295500
12.5550	0.001412500	0.001341900	0.001496000	0.001388600
13.4200	0.001578100	0.001435100	0.001684300	0.001482400
14.2860	0.001776300	0.001532900	0.001902700	0.001579900
15.1500	0.001982100	0.001643500	0.002121600	0.001690000
16.0150	0.002183700	0.001780200	0.002331100	0.001830400
16.8810	0.002379700	0.001952900	0.002533000	0.002015900
17.7450	0.002571600	0.002156700	0.002730600	0.002237500
18.6110	0.002761200	0.002366500	0.002926700	0.002462100
19.4760	0.002950100	0.002567400	0.003122900	0.002670700
20.3410	0.003139300	0.002758700	0.003320100	0.002865500
21.2060	0.003329200	0.002944800	0.003518700	0.003053900
22.0710	0.003520300	0.003128600	0.003719100	0.003240100
22.9370	0.003712800	0.003311600	0.003921400	0.003426500
23.8020	0.003906600	0.003494800	0.004125400	0.003613900
24.6670	0.004101800	0.003678500	0.004331200	0.003802100
25.5320	0.004298200	0.003862700	0.004538600	0.003990400
26.3980	0.004495700	0.004046900	0.004747500	0.004179600
27.2630	0.004694200	0.004231800	0.004957700	0.004369600
28.1280	0.004893500	0.004417400	0.005169000	0.004560600
28.9930	0.005093400	0.004603700	0.005381200	0.004752100
29.8590	0.005293800	0.004790100	0.005594100	0.004943700
30.7240	0.005494400	0.004976500	0.005807600	0.005135800
31.5890	0.005695000	0.005163000	0.006021300	0.005328300
32.4540	0.005895500	0.005349500	0.006235200	0.005520900
33.3200	0.006095600	0.005535900	0.006449000	0.005713500
34.1850	0.006295100	0.005721900	0.006662500	0.005905700
35.0510	0.006493900	0.005907300	0.006875400	0.006096600
35.9160	0.006691700	0.006091000	0.007087700	0.006286600
36.7810	0.006888200	0.006273500	0.007299000	0.006475600
37.6470	0.007083400	0.006454800	0.007509100	0.006663400
38.5120	0.007277000	0.006634500	0.007717900	0.006849800
39.3770	0.007468700	0.006812500	0.007925200	0.007034600
40.2420	0.007658500	0.006988500	0.008130700	0.007217500
41.1080	0.007846000	0.007162400	0.008334300	0.007398300
41.9730	0.008031100	0.007334000	0.008535700	0.007576500
42.8380	0.008213500	0.007502900	0.008734700	0.007751600
43.7040	0.008393200	0.007668500	0.008931200	0.007923900
44.5690	0.008569800	0.007830800	0.009124900	0.008093300

45.4340	0.008743200	0.007989900	0.009315700	0.008259500
46.3000	0.008913200	0.008145500	0.009503300	0.008422300
47.1650	0.009079600	0.008297500	0.009687600	0.008581600
48.0300	0.009242200	0.008445700	0.009868400	0.008737100
48.8960	0.009400800	0.008590000	0.010045000	0.008888700
49.7610	0.009555200	0.008729900	0.010219000	0.009036000
50.6260	0.009705300	0.008865500	0.010388000	0.009179000
51.4920	0.009850900	0.008996600	0.010553000	0.009317400
52.3570	0.009991700	0.009122800	0.010713000	0.009451100
53.2220	0.010128000	0.009244000	0.010869000	0.009579800
54.0880	0.010259000	0.009360100	0.011020000	0.009703300
54.9530	0.010384000	0.009470800	0.011166000	0.009821600
55.8190	0.010505000	0.009576000	0.011307000	0.009934000
56.6840	0.010619000	0.009675400	0.011443000	0.010041000
57.5490	0.010728000	0.009768900	0.011573000	0.010141000
58.4150	0.010832000	0.009856300	0.011698000	0.010236000
59.2800	0.010929000	0.009937400	0.011817000	0.010324000
60.1450	0.011020000	0.010012000	0.011931000	0.010406000
61.0110	0.011104000	0.010080000	0.012038000	0.010482000
61.8760	0.011182000	0.010141000	0.012139000	0.010551000
62.7410	0.011254000	0.010195000	0.012234000	0.010613000
63.6070	0.011319000	0.010242000	0.012322000	0.010668000
64.4720	0.011377000	0.010282000	0.012404000	0.010715000
65.3370	0.011427000	0.010315000	0.012479000	0.010756000
66.2030	0.011471000	0.010340000	0.012547000	0.010789000
67.0680	0.011508000	0.010358000	0.012608000	0.010814000
67.9330	0.011537000	0.010368000	0.012663000	0.010832000
68.7990	0.011558000	0.010370000	0.012710000	0.010841000
69.6640	0.011572000	0.010364000	0.012750000	0.010843000
70.5290	0.011578000	0.010350000	0.012782000	0.010836000
71.3950	0.011576000	0.010327000	0.012807000	0.010821000
72.2600	0.011567000	0.010296000	0.012824000	0.010797000
73.1260	0.011549000	0.010256000	0.012834000	0.010764000
73.9910	0.011523000	0.010207000	0.012836000	0.010722000
74.8560	0.011489000	0.010148000	0.012830000	0.010671000
75.7220	0.011447000	0.010081000	0.012816000	0.010610000
76.5870	0.011396000	0.010003000	0.012794000	0.010540000
77.4520	0.011337000	0.009915900	0.012764000	0.010459000
78.3180	0.011268000	0.009818700	0.012725000	0.010368000

79.1830	0.011192000	0.009711500	0.012678000	0.010266000
80.0480	0.011106000	0.009593800	0.012623000	0.010154000
80.9140	0.011011000	0.009465700	0.012559000	0.010032000
81.7790	0.010908000	0.009326800	0.012487000	0.009898100
82.6440	0.010795000	0.009176900	0.012406000	0.009753400
83.5100	0.010674000	0.009015700	0.012316000	0.009597000
84.3750	0.010543000	0.008842800	0.012218000	0.009429000
85.2410	0.010402000	0.008657200	0.012110000	0.009248700
86.1060	0.010253000	0.008459300	0.011993000	0.009055600
86.9710	0.010093000	0.008248800	0.011868000	0.008848700
87.8370	0.009926300	0.008025500	0.011733000	0.008627600
88.7020	0.009747700	0.007788300	0.011589000	0.008392600
89.5670	0.009571500	0.007541900	0.011434000	0.008141500
90.3900	0.009360700	0.007262300	0.011279000	0.007888000
91.1680	0.009146700	0.006985400	0.011123000	0.007633300
91.9420	0.008957700	0.006722700	0.010962000	0.007365600
92.7130	0.008742800	0.006424100	0.010792000	0.007082200
93.4810	0.008526800	0.006115900	0.010615000	0.006782400
94.2460	0.008298800	0.005786700	0.010431000	0.006463800
95.0070	0.008063300	0.005441100	0.010240000	0.006126800
95.7640	0.007818000	0.005075400	0.010041000	0.005770700
96.5190	0.007563300	0.004689400	0.009833900	0.005393700
97.2700	0.007298600	0.004281700	0.009619300	0.004994500
98.0180	0.007023600	0.003851900	0.009396800	0.004571400
98.7630	0.006737700	0.003400300	0.009166200	0.004123500
99.5040	0.006440500	0.002928900	0.008927300	0.003650500
100.2400	0.006131300	0.002441500	0.008679800	0.003153800
100.9800	0.005809500	0.001945600	0.008423500	0.002637600
101.7100	0.005474600	0.001452400	0.008158100	0.002110200
102.4400	0.005125800	0.000977820	0.007883100	0.001585900
103.1600	0.004762500	0.000541770	0.007598000	0.001085500
103.8900	0.004384400	0.000165720	0.007302600	0.000636110
104.6100	0.003991300	-0.000133430	0.006996100	0.000264760
105.3200	0.003583300	-0.000350580	0.006678000	-0.000011003
106.0300	0.003161500	-0.000483300	0.006347600	-0.000192560
106.7400	0.002727800	-0.000537580	0.006004200	-0.000299550
107.4500	0.002285600	-0.000548580	0.005647000	-0.000357950
108.1500	0.001840100	-0.000532110	0.005275400	-0.000389050
108.8500	0.001399300	-0.000486800	0.004888600	-0.000405760

109.5500	0.000973830	-0.000422700	0.004486200	-0.000414450
110.2500	0.000577290	-0.000370830	0.004068100	-0.000417830
110.9400	0.000225010	-0.000342910	0.003634600	-0.000416030
111.6300	-0.000068389	-0.000334620	0.003187100	-0.000404960
112.3100	-0.000295730	-0.000337120	0.002728200	-0.000379450
112.9900	-0.000455190	-0.000346860	0.002262500	-0.000342410
113.6700	-0.000551020	-0.000360920	0.001797100	-0.000305500
114.3500	-0.000603950	-0.000376170	0.001342700	-0.000278790
115.0200	-0.000635950	-0.000392560	0.000913440	-0.000264060
115.7000	-0.000652980	-0.000407800	0.000526690	-0.000258050
116.3600	-0.000658970	-0.000422470	0.000199850	-0.000257400
117.0300	-0.000657980	-0.000435640	-0.000054698	-0.000259970
117.6900	-0.000652870	-0.000447470	-0.000235220	-0.000264560
118.3500	-0.000644950	-0.000458000	-0.000352260	-0.000270490
119.0100	-0.000635090	-0.000467330	-0.000423290	-0.000277320
119.6600	-0.000623810	-0.000475600	-0.000464910	-0.000284680
120.3100	-0.000611370	-0.000482820	-0.000488450	-0.000292270
120.9600	-0.000598210	-0.000489390	-0.000500150	-0.000299780
121.6000	-0.000584590	-0.000494890	-0.000503520	-0.000306910
122.2400	-0.000570780	-0.000499930	-0.000500870	-0.000313410
122.8800	-0.000557070	-0.000504050	-0.000493890	-0.000319110
123.5200	-0.000543610	-0.000507720	-0.000483790	-0.000323910
124.1500	-0.000530700	-0.000510680	-0.000471520	-0.000327810
124.7900	-0.000518520	-0.000513150	-0.000457760	-0.000330840
125.4100	-0.000507180	-0.000515130	-0.000443070	-0.000333070
126.0400	-0.000496740	-0.000516610	-0.000427880	-0.000334580
126.6600	-0.000487190	-0.000517780	-0.000412570	-0.000335470
127.2800	-0.000478500	-0.000518540	-0.000397420	-0.000335840
127.9000	-0.000470570	-0.000519120	-0.000382700	-0.000335790
128.5100	-0.000463300	-0.000519450	-0.000368590	-0.000335410
129.1300	-0.000456570	-0.000519730	-0.000355270	-0.000334810
129.7400	-0.000450330	-0.000519930	-0.000342870	-0.000334080
130.3400	-0.000444430	-0.000520220	-0.000331460	-0.000333300
130.9500	-0.000438860	-0.000520600	-0.000321100	-0.000332560
131.5500	-0.000433530	-0.000521210	-0.000311800	-0.000331930
132.1500	-0.000428450	-0.000522060	-0.000303560	-0.000331480
132.7400	-0.000423610	-0.000523240	-0.000296360	-0.000331270
133.3400	-0.000419000	-0.000524800	-0.000290150	-0.000331350
133.9300	-0.000414680	-0.000526790	-0.000284870	-0.000331770

134.5200	-0.000410660	-0.000529220	-0.000280450	-0.000332570
135.1000	-0.000407010	-0.000532150	-0.000276830	-0.000333780
135.6900	-0.000403740	-0.000535580	-0.000273910	-0.000335410
136.2700	-0.000400930	-0.000539540	-0.000271600	-0.000337490
136.8400	-0.000398600	-0.000544020	-0.000269800	-0.000340010
137.4200	-0.000396790	-0.000549050	-0.000268420	-0.000343000
137.9900	-0.000395530	-0.000554610	-0.000267350	-0.000346430
138.5600	-0.000394860	-0.000560700	-0.000266490	-0.000350320
139.1300	-0.000394800	-0.000567300	-0.000265750	-0.000354650
139.7000	-0.000395360	-0.000574390	-0.000265040	-0.000359410
140.2600	-0.000396540	-0.000581950	-0.000264280	-0.000364580
140.8200	-0.000398340	-0.000589960	-0.000263400	-0.000370150
141.3800	-0.000400770	-0.000598390	-0.000262340	-0.000376090
141.9400	-0.000403800	-0.000607210	-0.000261050	-0.000382370
142.4900	-0.000407440	-0.000616380	-0.000259500	-0.000388980
143.0400	-0.000411650	-0.000625860	-0.000257660	-0.000395890
143.5900	-0.000416420	-0.000635630	-0.000255520	-0.000403060
144.1400	-0.000421730	-0.000645640	-0.000253080	-0.000410470
144.6800	-0.000427550	-0.000655840	-0.000250360	-0.000418080
145.2200	-0.000433840	-0.000666190	-0.000247360	-0.000425860
145.7600	-0.000440570	-0.000676660	-0.000244110	-0.000433780
146.3000	-0.000447700	-0.000687200	-0.000240650	-0.000441810
146.8300	-0.000455190	-0.000697770	-0.000237020	-0.000449900
147.3700	-0.000463010	-0.000708310	-0.000233250	-0.000458020
147.9000	-0.000471110	-0.000718800	-0.000229390	-0.000466140
148.4200	-0.000479450	-0.000729170	-0.000225470	-0.000474230
148.9500	-0.000487990	-0.000739400	-0.000221550	-0.000482240
149.4700	-0.000496670	-0.000749440	-0.000217650	-0.000490150
149.9900	-0.000505460	-0.000759240	-0.000213820	-0.000497920
150.5100	-0.000514310	-0.000768770	-0.000210090	-0.000505520
151.0300	-0.000523170	-0.000777980	-0.000206480	-0.000512910
151.5400	-0.000532000	-0.000786850	-0.000203030	-0.000520070
152.0600	-0.000540750	-0.000795320	-0.000199760	-0.000526960
152.5600	-0.000549380	-0.000803360	-0.000196680	-0.000533560
153.0700	-0.000557850	-0.000810930	-0.000193800	-0.000539820
153.5800	-0.000566120	-0.000818000	-0.000191150	-0.000545740
154.0800	-0.000574130	-0.000824540	-0.000188710	-0.000551280
154.5800	-0.000581860	-0.000830500	-0.000186510	-0.000556410
155.0800	-0.000589260	-0.000835870	-0.000184520	-0.000561120

155.5800	-0.000596300	-0.000840610	-0.000182760	-0.000565370
156.0700	-0.000602930	-0.000844700	-0.000181220	-0.000569150
156.5600	-0.000609110	-0.000848110	-0.000179880	-0.000572440
157.0500	-0.000614820	-0.000850810	-0.000178750	-0.000575210
157.5400	-0.000620020	-0.000852790	-0.000177790	-0.000577460
158.0300	-0.000624680	-0.000854030	-0.000177010	-0.000579160
158.5100	-0.000628760	-0.000854510	-0.000176380	-0.000580300
158.9900	-0.000632250	-0.000854210	-0.000175890	-0.000580870
159.4700	-0.000635110	-0.000853120	-0.000175520	-0.000580860
159.9500	-0.000637330	-0.000851220	-0.000175240	-0.000580260
160.4200	-0.000638860	-0.000848500	-0.000175040	-0.000579070
160.9000	-0.000639710	-0.000844960	-0.000174900	-0.000577260
161.3700	-0.000639850	-0.000840580	-0.000174790	-0.000574850
161.8400	-0.000639260	-0.000835360	-0.000174690	-0.000571820
162.3000	-0.000637930	-0.000829310	-0.000174570	-0.000568170
162.7700	-0.000635830	-0.000822400	-0.000174430	-0.000563910
163.2300	-0.000632970	-0.000814650	-0.000174220	-0.000559020
163.6900	-0.000629330	-0.000806050	-0.000173930	-0.000553520
164.1500	-0.000624890	-0.000796610	-0.000173550	-0.000547410
164.6100	-0.000619670	-0.000786340	-0.000173030	-0.000540680
165.0600	-0.000613640	-0.000775230	-0.000172380	-0.000533360
165.5200	-0.000606820	-0.000763300	-0.000171560	-0.000525430
165.9700	-0.000599190	-0.000750560	-0.000170560	-0.000516910
166.4200	-0.000590760	-0.000737010	-0.000169360	-0.000507820
166.8600	-0.000581530	-0.000722680	-0.000167940	-0.000498150
167.3100	-0.000571510	-0.000707570	-0.000166300	-0.000487920
167.7500	-0.000560700	-0.000691700	-0.000164410	-0.000477150
168.1900	-0.000549110	-0.000675100	-0.000162270	-0.000465840
168.6300	-0.000536750	-0.000657760	-0.000159870	-0.000454020
169.0700	-0.000523640	-0.000639730	-0.000157200	-0.000441690
169.5100	-0.000509790	-0.000621010	-0.000154250	-0.000428870
169.9400	-0.000495210	-0.000601650	-0.000151020	-0.000415580
170.3700	-0.000479930	-0.000581630	-0.000147510	-0.000401840
170.8000	-0.000463970	-0.000561020	-0.000143710	-0.000387660
171.2300	-0.000447340	-0.000539810	-0.000139630	-0.000373070
171.6600	-0.000430080	-0.000518060	-0.000135260	-0.000358080
172.0800	-0.000412200	-0.000495770	-0.000130620	-0.000342720
172.5000	-0.000393760	-0.000472990	-0.000125710	-0.000327000
172.9200	-0.000374770	-0.000449720	-0.000120540	-0.000310960

173.3400	-0.000355290	-0.000426030	-0.000115100	-0.000294600
173.7600	-0.000335320	-0.000401910	-0.000109430	-0.000277950
174.1700	-0.000314950	-0.000377440	-0.000103520	-0.000261040
174.5900	-0.000294180	-0.000352580	-0.000097385	-0.000243880
175.0000	-0.000273110	-0.000327450	-0.000091046	-0.000226500
175.4100	-0.000251720	-0.000301990	-0.000084514	-0.000208930
175.8200	-0.000230150	-0.000276330	-0.000077804	-0.000191180
176.2200	-0.000208330	-0.000250390	-0.000070934	-0.000173280
176.6300	-0.000186440	-0.000224340	-0.000063919	-0.000155250
177.0300	-0.000164380	-0.000198050	-0.000056777	-0.000137110
177.4300	-0.000142360	-0.000171730	-0.000049527	-0.000118900
177.8300	-0.000120210	-0.000145220	-0.000042185	-0.000100620
178.2200	-0.000098198	-0.000118770	-0.000034772	-0.000082302
178.6200	-0.000076085	-0.000092162	-0.000027304	-0.000063970
179.0000	-0.000054182	-0.000065701	-0.000019803	-0.000045643
179.3800	-0.000032195	-0.000039144	-0.000012285	-0.000027344
179.7200	-0.000010479	-0.000012820	-0.000004770	-0.000009092

Table A.2.5 C_p at $Re = 3 \times 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	1.00820	1.01750	0.99882	0.99882
1.3703	1.00820	1.00820	0.99882	0.99882
2.2073	1.00820	1.00820	0.99882	0.99882
3.0602	1.00820	1.00820	0.98948	0.98948
3.9187	0.99882	0.99882	0.98015	0.98948
4.7800	0.98948	0.98948	0.98015	0.98015
5.6418	0.98015	0.98015	0.96148	0.97081
6.5050	0.97081	0.97081	0.95214	0.95214
7.3684	0.96148	0.96148	0.94281	0.94281
8.2330	0.94281	0.95214	0.92414	0.92414
9.0970	0.93347	0.93347	0.90547	0.91480
9.9616	0.91480	0.91480	0.88680	0.89613
10.8260	0.89613	0.89613	0.86813	0.87746
11.6910	0.87746	0.87746	0.84946	0.84946
12.5550	0.84946	0.85879	0.82146	0.83079
13.4200	0.83079	0.83079	0.79345	0.81212
14.2860	0.80279	0.81212	0.76545	0.78412
15.1500	0.77478	0.78412	0.73744	0.75611
16.0150	0.74678	0.75611	0.70944	0.72811

16.8810	0.71877	0.72811	0.68143	0.70010
17.7450	0.69077	0.70010	0.64410	0.66277
18.6110	0.65343	0.67210	0.61609	0.63476
19.4760	0.62543	0.63476	0.57875	0.59742
20.3410	0.58809	0.60676	0.54141	0.56942
21.2060	0.55075	0.56942	0.50408	0.53208
22.0710	0.51341	0.53208	0.46674	0.49474
22.9370	0.47607	0.49474	0.42006	0.45740
23.8020	0.43873	0.45740	0.38272	0.42006
24.6670	0.40139	0.42006	0.33605	0.37339
25.5320	0.35472	0.38272	0.28938	0.33605
26.3980	0.31738	0.33605	0.24270	0.28938
27.2630	0.27071	0.29871	0.20536	0.25204
28.1280	0.22403	0.25204	0.14936	0.20536
28.9930	0.17736	0.21470	0.10268	0.15869
29.8590	0.14002	0.16803	0.05601	0.11202
30.7240	0.09335	0.12135	0.00933	0.06534
31.5890	0.03734	0.07468	-0.04667	0.01867
32.4540	-0.00933	0.02800	-0.09335	-0.02800
33.3200	-0.05601	-0.01867	-0.14936	-0.07468
34.1850	-0.10268	-0.06534	-0.20536	-0.13069
35.0510	-0.15869	-0.11202	-0.25204	-0.17736
35.9160	-0.20536	-0.15869	-0.30805	-0.22403
36.7810	-0.26137	-0.20536	-0.36405	-0.28004
37.6470	-0.30805	-0.26137	-0.42006	-0.32672
38.5120	-0.36405	-0.30805	-0.47607	-0.37339
39.3770	-0.41073	-0.35472	-0.53208	-0.42940
40.2420	-0.46674	-0.41073	-0.58809	-0.47607
41.1080	-0.51341	-0.45740	-0.64410	-0.53208
41.9730	-0.56942	-0.50408	-0.70010	-0.57875
42.8380	-0.62543	-0.56008	-0.75611	-0.63476
43.7040	-0.67210	-0.60676	-0.81212	-0.68143
44.5690	-0.72811	-0.65343	-0.86813	-0.73744
45.4340	-0.78412	-0.70944	-0.92414	-0.78412
46.3000	-0.83079	-0.75611	-0.98015	-0.84013
47.1650	-0.88680	-0.80279	-1.03620	-0.88680
48.0300	-0.93347	-0.84946	-1.09220	-0.94281
48.8960	-0.98948	-0.89613	-1.14820	-0.98948
49.7610	-1.03620	-0.95214	-1.19480	-1.03620

50.6260	-1.09220	-0.99882	-1.25090	-1.08280
51.4920	-1.13880	-1.04550	-1.30690	-1.12950
52.3570	-1.18550	-1.09220	-1.36290	-1.18550
53.2220	-1.23220	-1.12950	-1.41890	-1.23220
54.0880	-1.28820	-1.17620	-1.46560	-1.26950
54.9530	-1.33490	-1.22280	-1.52160	-1.31620
55.8190	-1.38150	-1.26020	-1.56820	-1.36290
56.6840	-1.42820	-1.30690	-1.62420	-1.40950
57.5490	-1.46560	-1.34420	-1.67090	-1.44690
58.4150	-1.51220	-1.39090	-1.71760	-1.49360
59.2800	-1.55890	-1.42820	-1.76430	-1.53090
60.1450	-1.59620	-1.46560	-1.81090	-1.56820
61.0110	-1.64290	-1.50290	-1.85760	-1.60560
61.8760	-1.68030	-1.54020	-1.90430	-1.64290
62.7410	-1.71760	-1.56820	-1.94160	-1.68030
63.6070	-1.75490	-1.60560	-1.98830	-1.70830
64.4720	-1.79230	-1.63360	-2.02560	-1.74560
65.3370	-1.82030	-1.66160	-2.07230	-1.77360
66.2030	-1.85760	-1.68960	-2.10960	-1.80160
67.0680	-1.88560	-1.71760	-2.14700	-1.82960
67.9330	-1.92300	-1.74560	-2.17500	-1.85760
68.7990	-1.95100	-1.77360	-2.21230	-1.88560
69.6640	-1.97900	-1.79230	-2.24030	-1.90430
70.5290	-1.99760	-1.81090	-2.27770	-1.93230
71.3950	-2.02560	-1.82960	-2.30570	-1.95100
72.2600	-2.04430	-1.84830	-2.33370	-1.96960
73.1260	-2.06300	-1.85760	-2.36170	-1.97900
73.9910	-2.08160	-1.87630	-2.38040	-1.99760
74.8560	-2.10030	-1.88560	-2.40840	-2.00700
75.7220	-2.11900	-1.89490	-2.42700	-2.01630
76.5870	-2.12830	-1.90430	-2.44570	-2.02560
77.4520	-2.13770	-1.90430	-2.46440	-2.02560
78.3180	-2.14700	-1.91360	-2.47370	-2.03500
79.1830	-2.15630	-1.91360	-2.49240	-2.03500
80.0480	-2.16570	-1.90430	-2.50170	-2.03500
80.9140	-2.16570	-1.90430	-2.51100	-2.02560
81.7790	-2.16570	-1.89490	-2.52040	-2.02560
82.6440	-2.16570	-1.89490	-2.52040	-2.01630
83.5100	-2.16570	-1.87630	-2.52970	-2.00700

84.3750	-2.15630	-1.86690	-2.52970	-1.98830
85.2410	-2.14700	-1.84830	-2.52970	-1.97900
86.1060	-2.13770	-1.82960	-2.52040	-1.96030
86.9710	-2.12830	-1.81090	-2.52040	-1.94160
87.8370	-2.11900	-1.79230	-2.51100	-1.91360
88.7020	-2.10030	-1.76430	-2.50170	-1.88560
89.5670	-2.08160	-1.73630	-2.49240	-1.85760
90.3900	-2.06300	-1.70830	-2.47370	-1.82960
91.1680	-2.03500	-1.67090	-2.46440	-1.80160
91.9420	-2.01630	-1.64290	-2.44570	-1.76430
92.7130	-1.98830	-1.60560	-2.42700	-1.72690
93.4810	-1.96960	-1.56820	-2.40840	-1.68960
94.2460	-1.93230	-1.52160	-2.38970	-1.65220
95.0070	-1.90430	-1.48420	-2.36170	-1.60560
95.7640	-1.87630	-1.43750	-2.34300	-1.55890
96.5190	-1.83890	-1.39090	-2.31500	-1.51220
97.2700	-1.80160	-1.33490	-2.28700	-1.46560
98.0180	-1.76430	-1.28820	-2.25900	-1.40950
98.7630	-1.72690	-1.23220	-2.22170	-1.35350
99.5040	-1.68030	-1.16680	-2.19370	-1.28820
100.2400	-1.64290	-1.11080	-2.15630	-1.23220
100.9800	-1.59620	-1.04550	-2.11900	-1.16680
101.7100	-1.54960	-0.98015	-2.08160	-1.09220
102.4400	-1.50290	-0.91480	-2.03500	-1.02680
103.1600	-1.44690	-0.84946	-1.99760	-0.96148
103.8900	-1.39090	-0.78412	-1.95100	-0.88680
104.6100	-1.33490	-0.72811	-1.90430	-0.82146
105.3200	-1.27890	-0.67210	-1.85760	-0.76545
106.0300	-1.22280	-0.62543	-1.81090	-0.70944
106.7400	-1.15750	-0.58809	-1.75490	-0.67210
107.4500	-1.10150	-0.56008	-1.69890	-0.64410
108.1500	-1.03620	-0.55075	-1.65220	-0.61609
108.8500	-0.97081	-0.53208	-1.58690	-0.60676
109.5500	-0.90547	-0.52274	-1.53090	-0.58809
110.2500	-0.84013	-0.52274	-1.47490	-0.57875
110.9400	-0.78412	-0.52274	-1.40950	-0.57875
111.6300	-0.71877	-0.52274	-1.34420	-0.56942
112.3100	-0.67210	-0.52274	-1.27890	-0.56942
112.9900	-0.61609	-0.52274	-1.21350	-0.56008

113.6700	-0.57875	-0.52274	-1.13880	-0.56008
114.3500	-0.54141	-0.52274	-1.07350	-0.56008
115.0200	-0.51341	-0.52274	-1.00820	-0.56008
115.7000	-0.49474	-0.52274	-0.94281	-0.56008
116.3600	-0.48541	-0.52274	-0.87746	-0.56008
117.0300	-0.46674	-0.52274	-0.82146	-0.56008
117.6900	-0.45740	-0.52274	-0.76545	-0.56008
118.3500	-0.44807	-0.52274	-0.72811	-0.56008
119.0100	-0.44807	-0.52274	-0.69077	-0.56008
119.6600	-0.43873	-0.52274	-0.66277	-0.56008
120.3100	-0.42940	-0.52274	-0.64410	-0.56008
120.9600	-0.42940	-0.51341	-0.62543	-0.56008
121.6000	-0.42006	-0.51341	-0.61609	-0.56008
122.2400	-0.42006	-0.51341	-0.60676	-0.56008
122.8800	-0.42006	-0.51341	-0.59742	-0.56008
123.5200	-0.41073	-0.51341	-0.58809	-0.56008
124.1500	-0.41073	-0.51341	-0.57875	-0.56008
124.7900	-0.41073	-0.51341	-0.57875	-0.56008
125.4100	-0.41073	-0.51341	-0.56942	-0.55075
126.0400	-0.40139	-0.51341	-0.56942	-0.55075
126.6600	-0.40139	-0.51341	-0.56942	-0.55075
127.2800	-0.40139	-0.51341	-0.56008	-0.55075
127.9000	-0.40139	-0.51341	-0.56008	-0.55075
128.5100	-0.40139	-0.51341	-0.56008	-0.55075
129.1300	-0.40139	-0.51341	-0.56008	-0.55075
129.7400	-0.40139	-0.51341	-0.56008	-0.55075
130.3400	-0.39206	-0.51341	-0.55075	-0.55075
130.9500	-0.39206	-0.50408	-0.55075	-0.55075
131.5500	-0.39206	-0.50408	-0.55075	-0.55075
132.1500	-0.39206	-0.50408	-0.55075	-0.55075
132.7400	-0.39206	-0.50408	-0.55075	-0.55075
133.3400	-0.39206	-0.50408	-0.55075	-0.55075
133.9300	-0.39206	-0.50408	-0.55075	-0.55075
134.5200	-0.39206	-0.50408	-0.55075	-0.55075
135.1000	-0.39206	-0.50408	-0.54141	-0.55075
135.6900	-0.39206	-0.50408	-0.54141	-0.55075
136.2700	-0.38272	-0.50408	-0.54141	-0.55075
136.8400	-0.38272	-0.50408	-0.54141	-0.55075
137.4200	-0.38272	-0.50408	-0.54141	-0.55075

137.9900	-0.38272	-0.50408	-0.54141	-0.55075
138.5600	-0.38272	-0.50408	-0.54141	-0.55075
139.1300	-0.38272	-0.50408	-0.54141	-0.55075
139.7000	-0.38272	-0.50408	-0.54141	-0.55075
140.2600	-0.38272	-0.50408	-0.54141	-0.55075
140.8200	-0.38272	-0.50408	-0.54141	-0.55075
141.3800	-0.38272	-0.50408	-0.54141	-0.55075
141.9400	-0.38272	-0.50408	-0.54141	-0.55075
142.4900	-0.38272	-0.50408	-0.54141	-0.55075
143.0400	-0.38272	-0.50408	-0.54141	-0.55075
143.5900	-0.38272	-0.50408	-0.54141	-0.55075
144.1400	-0.38272	-0.50408	-0.54141	-0.55075
144.6800	-0.38272	-0.50408	-0.53208	-0.55075
145.2200	-0.38272	-0.50408	-0.53208	-0.55075
145.7600	-0.38272	-0.50408	-0.53208	-0.55075
146.3000	-0.38272	-0.50408	-0.53208	-0.55075
146.8300	-0.38272	-0.49474	-0.53208	-0.55075
147.3700	-0.38272	-0.49474	-0.53208	-0.55075
147.9000	-0.38272	-0.49474	-0.53208	-0.55075
148.4200	-0.38272	-0.49474	-0.53208	-0.54141
148.9500	-0.38272	-0.49474	-0.53208	-0.54141
149.4700	-0.38272	-0.49474	-0.53208	-0.54141
149.9900	-0.38272	-0.49474	-0.53208	-0.54141
150.5100	-0.38272	-0.49474	-0.53208	-0.54141
151.0300	-0.38272	-0.49474	-0.53208	-0.54141
151.5400	-0.38272	-0.49474	-0.53208	-0.54141
152.0600	-0.37339	-0.49474	-0.53208	-0.54141
152.5600	-0.37339	-0.49474	-0.53208	-0.54141
153.0700	-0.37339	-0.49474	-0.53208	-0.54141
153.5800	-0.37339	-0.49474	-0.53208	-0.54141
154.0800	-0.37339	-0.48541	-0.53208	-0.54141
154.5800	-0.37339	-0.48541	-0.53208	-0.54141
155.0800	-0.37339	-0.48541	-0.53208	-0.54141
155.5800	-0.37339	-0.48541	-0.53208	-0.54141
156.0700	-0.37339	-0.48541	-0.53208	-0.54141
156.5600	-0.37339	-0.48541	-0.53208	-0.54141
157.0500	-0.37339	-0.48541	-0.53208	-0.54141
157.5400	-0.37339	-0.48541	-0.53208	-0.54141
158.0300	-0.37339	-0.47607	-0.53208	-0.53208

158.5100	-0.37339	-0.47607	-0.53208	-0.53208
158.9900	-0.36405	-0.47607	-0.53208	-0.53208
159.4700	-0.36405	-0.47607	-0.53208	-0.53208
159.9500	-0.36405	-0.47607	-0.53208	-0.53208
160.4200	-0.36405	-0.47607	-0.53208	-0.53208
160.9000	-0.36405	-0.46674	-0.53208	-0.53208
161.3700	-0.36405	-0.46674	-0.53208	-0.53208
161.8400	-0.36405	-0.46674	-0.53208	-0.53208
162.3000	-0.36405	-0.46674	-0.53208	-0.53208
162.7700	-0.35472	-0.46674	-0.53208	-0.52274
163.2300	-0.35472	-0.46674	-0.53208	-0.52274
163.6900	-0.35472	-0.45740	-0.53208	-0.52274
164.1500	-0.35472	-0.45740	-0.53208	-0.52274
164.6100	-0.35472	-0.45740	-0.53208	-0.52274
165.0600	-0.35472	-0.45740	-0.53208	-0.52274
165.5200	-0.34538	-0.45740	-0.53208	-0.52274
165.9700	-0.34538	-0.45740	-0.53208	-0.52274
166.4200	-0.34538	-0.44807	-0.53208	-0.52274
166.8600	-0.34538	-0.44807	-0.53208	-0.51341
167.3100	-0.34538	-0.44807	-0.53208	-0.51341
167.7500	-0.34538	-0.44807	-0.53208	-0.51341
168.1900	-0.34538	-0.44807	-0.53208	-0.51341
168.6300	-0.33605	-0.44807	-0.53208	-0.51341
169.0700	-0.33605	-0.43873	-0.53208	-0.51341
169.5100	-0.33605	-0.43873	-0.53208	-0.51341
169.9400	-0.33605	-0.43873	-0.53208	-0.51341
170.3700	-0.33605	-0.43873	-0.53208	-0.51341
170.8000	-0.33605	-0.43873	-0.53208	-0.51341
171.2300	-0.33605	-0.43873	-0.53208	-0.50408
171.6600	-0.32672	-0.42940	-0.53208	-0.50408
172.0800	-0.32672	-0.42940	-0.53208	-0.50408
172.5000	-0.32672	-0.42940	-0.53208	-0.50408
172.9200	-0.32672	-0.42940	-0.53208	-0.50408
173.3400	-0.32672	-0.42940	-0.53208	-0.50408
173.7600	-0.32672	-0.42940	-0.53208	-0.50408
174.1700	-0.32672	-0.42940	-0.53208	-0.50408
174.5900	-0.32672	-0.42940	-0.53208	-0.50408
175.0000	-0.32672	-0.42940	-0.53208	-0.50408
175.4100	-0.31738	-0.42940	-0.53208	-0.50408

175.8200	-0.31738	-0.42006	-0.53208	-0.50408
176.2200	-0.31738	-0.42006	-0.53208	-0.50408
176.6300	-0.31738	-0.42006	-0.53208	-0.50408
177.0300	-0.31738	-0.42006	-0.53208	-0.50408
177.4300	-0.31738	-0.42006	-0.53208	-0.50408
177.8300	-0.31738	-0.42006	-0.53208	-0.50408
178.2200	-0.31738	-0.42006	-0.53208	-0.49474
178.6200	-0.31738	-0.42006	-0.53208	-0.49474
179.0000	-0.31738	-0.42006	-0.53208	-0.49474
179.3800	-0.31738	-0.42006	-0.53208	-0.49474
179.7200	-0.31738	-0.42006	-0.53208	-0.49474

Table A.2.6 C_f at $Re = 3 \times 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	0.000023929	0.000023028	0.000041736	0.000039979
1.3703	0.000102640	0.000100600	0.000125000	0.000119950
2.2073	0.000187570	0.000182680	0.000208200	0.000199850
3.0602	0.000262910	0.000256720	0.000291290	0.000279640
3.9187	0.000345490	0.000337320	0.000374200	0.000359250
4.7800	0.000423380	0.000413170	0.000456910	0.000438650
5.6418	0.000503800	0.000491960	0.000539360	0.000517790
6.5050	0.000582670	0.000568700	0.000621540	0.000596640
7.3684	0.000662090	0.000646240	0.000703440	0.000675150
8.2330	0.000742000	0.000722980	0.000785310	0.000753340
9.0970	0.000829580	0.000799910	0.000876620	0.000831280
9.9616	0.000945200	0.000877170	0.001004000	0.000909320
10.8260	0.001091200	0.000956990	0.001163600	0.000988890
11.6910	0.001248300	0.001045600	0.001331000	0.001076200
12.5550	0.001405300	0.001155900	0.001494900	0.001187900
13.4200	0.001560700	0.001296700	0.001655500	0.001337900
14.2860	0.001715600	0.001460400	0.001815600	0.001513800
15.1500	0.001871400	0.001625400	0.001976900	0.001688200
16.0150	0.002028800	0.001784800	0.002140500	0.001852400
16.8810	0.002188600	0.001940900	0.002306900	0.002010800
17.7450	0.002350800	0.002096000	0.002476300	0.002168100
18.6110	0.002515700	0.002252300	0.002648700	0.002327200
19.4760	0.002683200	0.002410400	0.002824100	0.002488500
20.3410	0.002853200	0.002570100	0.003002400	0.002651500

21.2060	0.003025700	0.002731400	0.003183500	0.002816700
22.0710	0.003200500	0.002894900	0.003367100	0.002984300
22.9370	0.003377300	0.003060600	0.003553100	0.003154100
23.8020	0.003556200	0.003227900	0.003741300	0.003325300
24.6670	0.003736800	0.003396700	0.003931600	0.003498400
25.5320	0.003919000	0.003567300	0.004123600	0.003673600
26.3980	0.004102600	0.003739400	0.004317300	0.003850500
27.2630	0.004287400	0.003913100	0.004512500	0.004028900
28.1280	0.004473200	0.004087800	0.004708800	0.004207800
28.9930	0.004659800	0.004262600	0.004906200	0.004387500
29.8590	0.004847000	0.004438100	0.005104400	0.004568200
30.7240	0.005034600	0.004614200	0.005303300	0.004749400
31.5890	0.005222500	0.004790700	0.005502600	0.004931200
32.4540	0.005410400	0.004967400	0.005702200	0.005113200
33.3200	0.005598100	0.005144000	0.005901800	0.005295200
34.1850	0.005785400	0.005320300	0.006101200	0.005476200
35.0510	0.005972200	0.005495400	0.006300300	0.005656400
35.9160	0.006158100	0.005669500	0.006498900	0.005836100
36.7810	0.006343200	0.005842700	0.006696700	0.006014800
37.6470	0.006527100	0.006014700	0.006893500	0.006192600
38.5120	0.006709600	0.006185500	0.007089300	0.006369200
39.3770	0.006890500	0.006354800	0.007283700	0.006544300
40.2420	0.007069800	0.006522400	0.007476600	0.006717800
41.1080	0.007247100	0.006688100	0.007667900	0.006889400
41.9730	0.007422300	0.006851700	0.007857200	0.007059000
42.8380	0.007595200	0.007013000	0.008044500	0.007226400
43.7040	0.007765600	0.007171800	0.008229500	0.007390300
44.5690	0.007933300	0.007327500	0.008412000	0.007551500
45.4340	0.008098200	0.007479800	0.008592000	0.007709800
46.3000	0.008260000	0.007628900	0.008769100	0.007865100
47.1650	0.008418600	0.007774800	0.008943200	0.008017200
48.0300	0.008573800	0.007917200	0.009114200	0.008165900
48.8960	0.008725400	0.008056000	0.009281900	0.008310900
49.7610	0.008873300	0.008191000	0.009446000	0.008452300
50.6260	0.009017200	0.008322000	0.009606500	0.008589600
51.4920	0.009157100	0.008448800	0.009763100	0.008722800
52.3570	0.009292700	0.008571300	0.009915700	0.008851700
53.2220	0.009423900	0.008689200	0.010064000	0.008976000
54.0880	0.009550500	0.008802500	0.010208000	0.009095600

54.9530	0.009672400	0.008910900	0.010348000	0.009210400
55.8190	0.009789300	0.009014200	0.010483000	0.009320200
56.6840	0.009901300	0.009112300	0.010613000	0.009424700
57.5490	0.010008000	0.009204900	0.010738000	0.009523800
58.4150	0.010109000	0.009292000	0.010859000	0.009617400
59.2800	0.010205000	0.009373400	0.010974000	0.009705300
60.1450	0.010295000	0.009448900	0.011083000	0.009787400
61.0110	0.010380000	0.009518300	0.011187000	0.009863400
61.8760	0.010459000	0.009581600	0.011286000	0.009933200
62.7410	0.010531000	0.009638500	0.011378000	0.009996700
63.6070	0.010597000	0.009688900	0.011465000	0.010054000
64.4720	0.010658000	0.009732700	0.011546000	0.010104000
65.3370	0.010711000	0.009769500	0.011621000	0.010147000
66.2030	0.010758000	0.009799200	0.011689000	0.010183000
67.0680	0.010799000	0.009821600	0.011751000	0.010212000
67.9330	0.010832000	0.009836700	0.011807000	0.010234000
68.7990	0.010859000	0.009844200	0.011856000	0.010248000
69.6640	0.010879000	0.009844200	0.011898000	0.010254000
70.5290	0.010892000	0.009836500	0.011934000	0.010252000
71.3950	0.010897000	0.009820900	0.011962000	0.010243000
72.2600	0.010896000	0.009797500	0.011984000	0.010225000
73.1260	0.010887000	0.009765900	0.011999000	0.010199000
73.9910	0.010870000	0.009726000	0.012006000	0.010165000
74.8560	0.010846000	0.009677900	0.012007000	0.010123000
75.7220	0.010815000	0.009621400	0.012000000	0.010072000
76.5870	0.010776000	0.009556300	0.011985000	0.010012000
77.4520	0.010728000	0.009482400	0.011963000	0.009943300
78.3180	0.010673000	0.009399800	0.011934000	0.009865600
79.1830	0.010611000	0.009308200	0.011897000	0.009778800
80.0480	0.010540000	0.009207400	0.011852000	0.009682700
80.9140	0.010461000	0.009097500	0.011799000	0.009577000
81.7790	0.010374000	0.008977900	0.011739000	0.009461600
82.6440	0.010278000	0.008848700	0.011671000	0.009336400
83.5100	0.010175000	0.008709800	0.011594000	0.009201100
84.3750	0.010063000	0.008560800	0.011510000	0.009055400
85.2410	0.009942500	0.008401500	0.011417000	0.008899100
86.1060	0.009814100	0.008231300	0.011317000	0.008731900
86.9710	0.009676900	0.008049700	0.011208000	0.008553400
87.8370	0.009533000	0.007857500	0.011091000	0.008362700

88.7020	0.009378900	0.007653400	0.010965000	0.008159300
89.5670	0.009227400	0.007443900	0.010830000	0.007942500
90.3900	0.009046600	0.007208100	0.010694000	0.007724400
91.1680	0.008860000	0.006971000	0.010558000	0.007506300
91.9420	0.008694900	0.006747100	0.010417000	0.007278000
92.7130	0.008509000	0.006496000	0.010268000	0.007037600
93.4810	0.008321400	0.006239000	0.010113000	0.006784200
94.2460	0.008124200	0.005965500	0.009951700	0.006517900
95.0070	0.007920500	0.005677800	0.009783700	0.006237200
95.7640	0.007708700	0.005373500	0.009609000	0.005940000
96.5190	0.007489200	0.005053400	0.009427700	0.005625900
97.2700	0.007261400	0.004715900	0.009239700	0.005294600
98.0180	0.007025200	0.004360300	0.009044900	0.004944600
98.7630	0.006780300	0.003985500	0.008843200	0.004574700
99.5040	0.006526300	0.003591000	0.008634400	0.004183500
100.2400	0.006262800	0.003177200	0.008418400	0.003770200
100.9800	0.005989400	0.002745700	0.008195100	0.003334500
101.7100	0.005705500	0.002300000	0.007964300	0.002878000
102.4400	0.005410700	0.001846600	0.007725600	0.002404600
103.1600	0.005104400	0.001395700	0.007478700	0.001922300
103.8900	0.004786000	0.000961670	0.007223500	0.001444500
104.6100	0.004454900	0.000562290	0.006959400	0.000990990
105.3200	0.004110900	0.000217480	0.006686200	0.000586920
106.0300	0.003753700	-0.000058138	0.006403100	0.000256870
106.7400	0.003383400	-0.000260040	0.006109900	0.000015025
107.4500	0.003000800	-0.000388780	0.005805700	-0.000142920
108.1500	0.002607400	-0.000440910	0.005490200	-0.000236640
108.8500	0.002206000	-0.000452100	0.005162400	-0.000289170
109.5500	0.001801000	-0.000434430	0.004822000	-0.000318590
110.2500	0.001399000	-0.000388060	0.004468100	-0.000335480
110.9400	0.001009300	-0.000334980	0.004100600	-0.000344890
111.6300	0.000643800	-0.000301000	0.003719100	-0.000348930
112.3100	0.000316340	-0.000288030	0.003324200	-0.000346420
112.9900	0.000040818	-0.000287640	0.002917000	-0.000331970
113.6700	-0.000174920	-0.000295680	0.002500000	-0.000303740
114.3500	-0.000331220	-0.000308050	0.002077200	-0.000270170
115.0200	-0.000430890	-0.000322530	0.001655200	-0.000243130
115.7000	-0.000487910	-0.000338400	0.001243900	-0.000227430
116.3600	-0.000523430	-0.000353270	0.000856420	-0.000220880

117.0300	-0.000543500	-0.000367700	0.000508800	-0.000219980
117.6900	-0.000552670	-0.000380750	0.000217090	-0.000222370
118.3500	-0.000555080	-0.000392570	-0.000007971	-0.000226740
119.0100	-0.000553350	-0.000403140	-0.000166420	-0.000232370
119.6600	-0.000548680	-0.000412550	-0.000269660	-0.000238810
120.3100	-0.000541910	-0.000420910	-0.000333990	-0.000245740
120.9600	-0.000533550	-0.000428290	-0.000373490	-0.000252850
121.6000	-0.000523920	-0.000434780	-0.000397100	-0.000259850
122.2400	-0.000513450	-0.000440420	-0.000409700	-0.000266490
122.8800	-0.000502420	-0.000445470	-0.000414410	-0.000272550
123.5200	-0.000491090	-0.000449730	-0.000413430	-0.000277860
124.1500	-0.000479810	-0.000453520	-0.000408360	-0.000282370
124.7900	-0.000468710	-0.000456660	-0.000400390	-0.000286060
125.4100	-0.000458120	-0.000459350	-0.000390400	-0.000288980
126.0400	-0.000448150	-0.000461560	-0.000379040	-0.000291190
126.6600	-0.000438910	-0.000463320	-0.000366830	-0.000292780
127.2800	-0.000430440	-0.000464760	-0.000354190	-0.000293820
127.9000	-0.000422720	-0.000465850	-0.000341440	-0.000294410
128.5100	-0.000415720	-0.000466730	-0.000328880	-0.000294640
129.1300	-0.000409340	-0.000467390	-0.000316720	-0.000294590
129.7400	-0.000403500	-0.000467960	-0.000305170	-0.000294340
130.3400	-0.000398080	-0.000468470	-0.000294380	-0.000293970
130.9500	-0.000393060	-0.000469020	-0.000284430	-0.000293570
131.5500	-0.000388290	-0.000469650	-0.000275410	-0.000293200
132.1500	-0.000383800	-0.000470460	-0.000267320	-0.000292920
132.7400	-0.000379510	-0.000471480	-0.000260170	-0.000292810
133.3400	-0.000375440	-0.000472780	-0.000253940	-0.000292900
133.9300	-0.000371580	-0.000474420	-0.000248580	-0.000293260
134.5200	-0.000367960	-0.000476420	-0.000244040	-0.000293920
135.1000	-0.000364600	-0.000478820	-0.000240250	-0.000294920
135.6900	-0.000361540	-0.000481660	-0.000237140	-0.000296270
136.2700	-0.000358830	-0.000484950	-0.000234630	-0.000298000
136.8400	-0.000356490	-0.000488700	-0.000232640	-0.000300120
137.4200	-0.000354570	-0.000492930	-0.000231080	-0.000302630
137.9900	-0.000353110	-0.000497640	-0.000229860	-0.000305550
138.5600	-0.000352140	-0.000502830	-0.000228900	-0.000308860
139.1300	-0.000351670	-0.000508490	-0.000228110	-0.000312570
139.7000	-0.000351750	-0.000514610	-0.000227410	-0.000316670
140.2600	-0.000352380	-0.000521170	-0.000226730	-0.000321140

140.8200	-0.000353560	-0.000528160	-0.000226000	-0.000325970
141.3800	-0.000355290	-0.000535540	-0.000225170	-0.000331140
141.9400	-0.000357570	-0.000543300	-0.000224190	-0.000336640
142.4900	-0.000360400	-0.000551410	-0.000223010	-0.000342430
143.0400	-0.000363770	-0.000559820	-0.000221620	-0.000348500
143.5900	-0.000367650	-0.000568520	-0.000220000	-0.000354820
144.1400	-0.000372040	-0.000577470	-0.000218140	-0.000361360
144.6800	-0.000376900	-0.000586620	-0.000216040	-0.000368100
145.2200	-0.000382210	-0.000595950	-0.000213730	-0.000375010
145.7600	-0.000387950	-0.000605410	-0.000211210	-0.000382050
146.3000	-0.000394080	-0.000614970	-0.000208510	-0.000389200
146.8300	-0.000400570	-0.000624570	-0.000205660	-0.000396430
147.3700	-0.000407380	-0.000634190	-0.000202700	-0.000403700
147.9000	-0.000414480	-0.000643790	-0.000199660	-0.000410990
148.4200	-0.000421830	-0.000653320	-0.000196570	-0.000418260
148.9500	-0.000429390	-0.000662740	-0.000193470	-0.000425470
149.4700	-0.000437130	-0.000672010	-0.000190400	-0.000432620
149.9900	-0.000444990	-0.000681100	-0.000187380	-0.000439640
150.5100	-0.000452940	-0.000689970	-0.000184450	-0.000446530
151.0300	-0.000460940	-0.000698580	-0.000181640	-0.000453250
151.5400	-0.000468940	-0.000706890	-0.000178960	-0.000459770
152.0600	-0.000476920	-0.000714860	-0.000176440	-0.000466070
152.5600	-0.000484810	-0.000722480	-0.000174100	-0.000472110
153.0700	-0.000492600	-0.000729690	-0.000171940	-0.000477870
153.5800	-0.000500230	-0.000736460	-0.000169970	-0.000483330
154.0800	-0.000507670	-0.000742770	-0.000168210	-0.000488460
154.5800	-0.000514880	-0.000748570	-0.000166660	-0.000493240
155.0800	-0.000521820	-0.000753850	-0.000165310	-0.000497640
155.5800	-0.000528470	-0.000758570	-0.000164170	-0.000501640
156.0700	-0.000534770	-0.000762710	-0.000163220	-0.000505240
156.5600	-0.000540710	-0.000766250	-0.000162470	-0.000508390
157.0500	-0.000546230	-0.000769150	-0.000161900	-0.000511090
157.5400	-0.000551320	-0.000771410	-0.000161500	-0.000513330
158.0300	-0.000555950	-0.000772990	-0.000161260	-0.000515080
158.5100	-0.000560070	-0.000773880	-0.000161160	-0.000516340
158.9900	-0.000563680	-0.000774080	-0.000161200	-0.000517090
159.4700	-0.000566730	-0.000773550	-0.000161340	-0.000517320
159.9500	-0.000569210	-0.000772290	-0.000161580	-0.000517020
160.4200	-0.000571100	-0.000770280	-0.000161890	-0.000516190

160.9000	-0.000572370	-0.000767520	-0.000162250	-0.000514810
161.3700	-0.000573010	-0.000763990	-0.000162640	-0.000512880
161.8400	-0.000573000	-0.000759690	-0.000163040	-0.000510410
162.3000	-0.000572320	-0.000754620	-0.000163420	-0.000507370
162.7700	-0.000570950	-0.000748770	-0.000163770	-0.000503780
163.2300	-0.000568900	-0.000742130	-0.000164060	-0.000499630
163.6900	-0.000566130	-0.000734710	-0.000164270	-0.000494920
164.1500	-0.000562650	-0.000726510	-0.000164360	-0.000489660
164.6100	-0.000558440	-0.000717530	-0.000164330	-0.000483840
165.0600	-0.000553500	-0.000707780	-0.000164160	-0.000477480
165.5200	-0.000547830	-0.000697260	-0.000163810	-0.000470570
165.9700	-0.000541420	-0.000685980	-0.000163270	-0.000463130
166.4200	-0.000534270	-0.000673950	-0.000162520	-0.000455150
166.8600	-0.000526380	-0.000661180	-0.000161550	-0.000446660
167.3100	-0.000517760	-0.000647680	-0.000160340	-0.000437650
167.7500	-0.000508400	-0.000633460	-0.000158880	-0.000428140
168.1900	-0.000498320	-0.000618550	-0.000157140	-0.000418140
168.6300	-0.000487520	-0.000602950	-0.000155130	-0.000407670
169.0700	-0.000476020	-0.000586690	-0.000152840	-0.000396740
169.5100	-0.000463810	-0.000569770	-0.000150250	-0.000385350
169.9400	-0.000450920	-0.000552240	-0.000147360	-0.000373530
170.3700	-0.000437360	-0.000534090	-0.000144180	-0.000361300
170.8000	-0.000423150	-0.000515370	-0.000140690	-0.000348660
171.2300	-0.000408310	-0.000496080	-0.000136900	-0.000335640
171.6600	-0.000392870	-0.000476270	-0.000132810	-0.000322250
172.0800	-0.000376830	-0.000455940	-0.000128430	-0.000308510
172.5000	-0.000360250	-0.000435140	-0.000123760	-0.000294450
172.9200	-0.000343130	-0.000413870	-0.000118800	-0.000280080
173.3400	-0.000325530	-0.000392190	-0.000113580	-0.000265420
173.7600	-0.000307450	-0.000370090	-0.000108090	-0.000250480
174.1700	-0.000288980	-0.000347660	-0.000102350	-0.000235310
174.5900	-0.000270100	-0.000324850	-0.000096382	-0.000219900
175.0000	-0.000250920	-0.000301770	-0.000090187	-0.000204290
175.4100	-0.000231410	-0.000278380	-0.000083785	-0.000188490
175.8200	-0.000211700	-0.000254780	-0.000077193	-0.000172520
176.2200	-0.000191740	-0.000230910	-0.000070427	-0.000156420
176.6300	-0.000171680	-0.000206930	-0.000063506	-0.000140190
177.0300	-0.000151440	-0.000182720	-0.000056448	-0.000123860
177.4300	-0.000131210	-0.000158460	-0.000049273	-0.000107460

177.8300	-0.000110850	-0.000134030	-0.000041999	-0.000090992
178.2200	-0.000090582	-0.000109630	-0.000034646	-0.000074489
178.6200	-0.000070217	-0.000085096	-0.000027234	-0.000057969
179.0000	-0.000050027	-0.000060683	-0.000019783	-0.000041452
179.3800	-0.000029753	-0.000036178	-0.000012314	-0.000024957
179.7200	-0.000009718	-0.000011880	-0.000004846	-0.000008504

Table A.2.7 C_p at $Re = 3.6 \times 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	1.00820	1.00820	0.99882	0.99882
1.3703	1.00820	1.00820	0.99882	0.99882
2.2073	1.00820	1.00820	0.99882	0.99882
3.0602	1.00820	1.00820	0.98948	0.98948
3.9187	0.99882	0.99882	0.98015	0.98948
4.7800	0.98948	0.98948	0.98015	0.98015
5.6418	0.98015	0.98015	0.96148	0.97081
6.5050	0.97081	0.97081	0.95214	0.95214
7.3684	0.96148	0.96148	0.94281	0.94281
8.2330	0.94281	0.95214	0.92414	0.92414
9.0970	0.93347	0.93347	0.90547	0.91480
9.9616	0.91480	0.91480	0.88680	0.89613
10.8260	0.89613	0.89613	0.86813	0.87746
11.6910	0.86813	0.87746	0.84946	0.84946
12.5550	0.84946	0.85879	0.82146	0.83079
13.4200	0.83079	0.83079	0.79345	0.80279
14.2860	0.80279	0.81212	0.76545	0.78412
15.1500	0.77478	0.78412	0.73744	0.75611
16.0150	0.74678	0.75611	0.70944	0.72811
16.8810	0.71877	0.72811	0.68143	0.70010
17.7450	0.69077	0.70010	0.64410	0.66277
18.6110	0.65343	0.67210	0.61609	0.63476
19.4760	0.62543	0.63476	0.57875	0.59742
20.3410	0.58809	0.60676	0.54141	0.56008
21.2060	0.55075	0.56942	0.50408	0.53208
22.0710	0.51341	0.53208	0.45740	0.49474
22.9370	0.47607	0.49474	0.42006	0.44807
23.8020	0.43873	0.45740	0.38272	0.41073
24.6670	0.40139	0.42006	0.33605	0.37339
25.5320	0.35472	0.38272	0.28938	0.32672

26.3980	0.31738	0.33605	0.24270	0.28938
27.2630	0.27071	0.29871	0.19603	0.24270
28.1280	0.22403	0.25204	0.14936	0.19603
28.9930	0.17736	0.20536	0.10268	0.15869
29.8590	0.13069	0.16803	0.05601	0.11202
30.7240	0.08401	0.12135	0.00933	0.06534
31.5890	0.03734	0.07468	-0.04667	0.00933
32.4540	-0.00933	0.02800	-0.09335	-0.03734
33.3200	-0.05601	-0.01867	-0.14936	-0.08401
34.1850	-0.11202	-0.06534	-0.20536	-0.13069
35.0510	-0.15869	-0.11202	-0.25204	-0.18669
35.9160	-0.21470	-0.16803	-0.30805	-0.23337
36.7810	-0.26137	-0.21470	-0.36405	-0.28004
37.6470	-0.31738	-0.26137	-0.42006	-0.33605
38.5120	-0.36405	-0.30805	-0.47607	-0.38272
39.3770	-0.42006	-0.36405	-0.53208	-0.43873
40.2420	-0.46674	-0.41073	-0.58809	-0.48541
41.1080	-0.52274	-0.45740	-0.64410	-0.54141
41.9730	-0.57875	-0.51341	-0.70010	-0.58809
42.8380	-0.62543	-0.56008	-0.75611	-0.64410
43.7040	-0.68143	-0.61609	-0.81212	-0.70010
44.5690	-0.73744	-0.66277	-0.86813	-0.74678
45.4340	-0.78412	-0.70944	-0.92414	-0.80279
46.3000	-0.84013	-0.76545	-0.98015	-0.84946
47.1650	-0.88680	-0.81212	-1.03620	-0.89613
48.0300	-0.94281	-0.85879	-1.09220	-0.95214
48.8960	-0.98948	-0.90547	-1.14820	-0.99882
49.7610	-1.04550	-0.95214	-1.20420	-1.05480
50.6260	-1.09220	-1.00820	-1.26020	-1.10150
51.4920	-1.14820	-1.05480	-1.30690	-1.14820
52.3570	-1.19480	-1.10150	-1.36290	-1.19480
53.2220	-1.24150	-1.13880	-1.41890	-1.24150
54.0880	-1.29750	-1.18550	-1.47490	-1.28820
54.9530	-1.34420	-1.23220	-1.52160	-1.33490
55.8190	-1.39090	-1.27890	-1.57760	-1.38150
56.6840	-1.43750	-1.31620	-1.62420	-1.42820
57.5490	-1.47490	-1.36290	-1.67090	-1.46560
58.4150	-1.52160	-1.40020	-1.72690	-1.51220
59.2800	-1.56820	-1.43750	-1.77360	-1.54960

60.1450	-1.60560	-1.47490	-1.82030	-1.58690
61.0110	-1.65220	-1.51220	-1.86690	-1.62420
61.8760	-1.68960	-1.54960	-1.90430	-1.66160
62.7410	-1.72690	-1.58690	-1.95100	-1.69890
63.6070	-1.76430	-1.61490	-1.99760	-1.73630
64.4720	-1.80160	-1.65220	-2.03500	-1.76430
65.3370	-1.83890	-1.68030	-2.07230	-1.80160
66.2030	-1.86690	-1.70830	-2.10960	-1.82960
67.0680	-1.90430	-1.73630	-2.14700	-1.85760
67.9330	-1.93230	-1.76430	-2.18430	-1.88560
68.7990	-1.96030	-1.78290	-2.22170	-1.91360
69.6640	-1.98830	-1.81090	-2.24970	-1.93230
70.5290	-2.01630	-1.82960	-2.28700	-1.96030
71.3950	-2.04430	-1.84830	-2.31500	-1.97900
72.2600	-2.06300	-1.86690	-2.34300	-1.99760
73.1260	-2.08160	-1.87630	-2.36170	-2.01630
73.9910	-2.10030	-1.89490	-2.38970	-2.02560
74.8560	-2.11900	-1.90430	-2.41770	-2.03500
75.7220	-2.13770	-1.91360	-2.43640	-2.05360
76.5870	-2.14700	-1.92300	-2.45500	-2.05360
77.4520	-2.15630	-1.93230	-2.47370	-2.06300
78.3180	-2.16570	-1.93230	-2.48300	-2.07230
79.1830	-2.17500	-1.93230	-2.50170	-2.07230
80.0480	-2.18430	-1.93230	-2.51100	-2.07230
80.9140	-2.18430	-1.93230	-2.52040	-2.07230
81.7790	-2.19370	-1.92300	-2.52970	-2.06300
82.6440	-2.18430	-1.91360	-2.52970	-2.05360
83.5100	-2.18430	-1.90430	-2.53900	-2.04430
84.3750	-2.18430	-1.89490	-2.53900	-2.03500
85.2410	-2.17500	-1.87630	-2.53900	-2.02560
86.1060	-2.16570	-1.85760	-2.53900	-2.00700
86.9710	-2.15630	-1.83890	-2.52970	-1.98830
87.8370	-2.13770	-1.82030	-2.52040	-1.96030
88.7020	-2.12830	-1.79230	-2.51100	-1.94160
89.5670	-2.10960	-1.76430	-2.50170	-1.91360
90.3900	-2.09100	-1.74560	-2.49240	-1.88560
91.1680	-2.06300	-1.70830	-2.47370	-1.84830
91.9420	-2.04430	-1.67090	-2.46440	-1.82030
92.7130	-2.02560	-1.64290	-2.44570	-1.78290

93.4810	-1.99760	-1.60560	-2.42700	-1.75490
94.2460	-1.96960	-1.56820	-2.39900	-1.70830
95.0070	-1.94160	-1.52160	-2.38040	-1.67090
95.7640	-1.90430	-1.47490	-2.35240	-1.62420
96.5190	-1.87630	-1.42820	-2.33370	-1.57760
97.2700	-1.83890	-1.38150	-2.30570	-1.53090
98.0180	-1.80160	-1.32550	-2.26830	-1.47490
98.7630	-1.76430	-1.27890	-2.24030	-1.42820
99.5040	-1.71760	-1.21350	-2.21230	-1.36290
100.2400	-1.68030	-1.15750	-2.17500	-1.30690
100.9800	-1.63360	-1.09220	-2.13770	-1.24150
101.7100	-1.58690	-1.02680	-2.10030	-1.17620
102.4400	-1.54020	-0.96148	-2.06300	-1.11080
103.1600	-1.49360	-0.89613	-2.01630	-1.03620
103.8900	-1.43750	-0.83079	-1.96960	-0.97081
104.6100	-1.38150	-0.76545	-1.93230	-0.89613
105.3200	-1.32550	-0.70944	-1.88560	-0.83079
106.0300	-1.26950	-0.65343	-1.82960	-0.77478
106.7400	-1.21350	-0.60676	-1.78290	-0.71877
107.4500	-1.14820	-0.57875	-1.72690	-0.67210
108.1500	-1.08280	-0.55075	-1.68030	-0.64410
108.8500	-1.01750	-0.53208	-1.62420	-0.61609
109.5500	-0.95214	-0.52274	-1.55890	-0.60676
110.2500	-0.89613	-0.52274	-1.50290	-0.58809
110.9400	-0.83079	-0.51341	-1.43750	-0.57875
111.6300	-0.76545	-0.51341	-1.37220	-0.57875
112.3100	-0.70944	-0.51341	-1.30690	-0.56942
112.9900	-0.65343	-0.51341	-1.24150	-0.56942
113.6700	-0.60676	-0.51341	-1.17620	-0.56008
114.3500	-0.56008	-0.51341	-1.11080	-0.56008
115.0200	-0.53208	-0.51341	-1.03620	-0.56008
115.7000	-0.50408	-0.51341	-0.97081	-0.56008
116.3600	-0.48541	-0.51341	-0.90547	-0.56008
117.0300	-0.46674	-0.51341	-0.84013	-0.56008
117.6900	-0.45740	-0.51341	-0.78412	-0.56008
118.3500	-0.44807	-0.51341	-0.73744	-0.56008
119.0100	-0.43873	-0.51341	-0.70010	-0.56008
119.6600	-0.42940	-0.51341	-0.66277	-0.56008
120.3100	-0.42940	-0.51341	-0.63476	-0.56008

120.9600	-0.42006	-0.51341	-0.61609	-0.56008
121.6000	-0.42006	-0.51341	-0.60676	-0.56008
122.2400	-0.41073	-0.51341	-0.58809	-0.56008
122.8800	-0.41073	-0.51341	-0.57875	-0.56008
123.5200	-0.41073	-0.51341	-0.57875	-0.56008
124.1500	-0.40139	-0.51341	-0.56942	-0.56008
124.7900	-0.40139	-0.51341	-0.56008	-0.55075
125.4100	-0.40139	-0.50408	-0.56008	-0.55075
126.0400	-0.40139	-0.50408	-0.55075	-0.55075
126.6600	-0.40139	-0.50408	-0.55075	-0.55075
127.2800	-0.39206	-0.50408	-0.55075	-0.55075
127.9000	-0.39206	-0.50408	-0.55075	-0.55075
128.5100	-0.39206	-0.50408	-0.54141	-0.55075
129.1300	-0.39206	-0.50408	-0.54141	-0.55075
129.7400	-0.39206	-0.50408	-0.54141	-0.55075
130.3400	-0.39206	-0.50408	-0.54141	-0.55075
130.9500	-0.39206	-0.50408	-0.54141	-0.55075
131.5500	-0.38272	-0.50408	-0.53208	-0.55075
132.1500	-0.38272	-0.50408	-0.53208	-0.55075
132.7400	-0.38272	-0.50408	-0.53208	-0.55075
133.3400	-0.38272	-0.50408	-0.53208	-0.55075
133.9300	-0.38272	-0.50408	-0.53208	-0.55075
134.5200	-0.38272	-0.50408	-0.53208	-0.55075
135.1000	-0.38272	-0.50408	-0.53208	-0.55075
135.6900	-0.38272	-0.49474	-0.53208	-0.55075
136.2700	-0.38272	-0.49474	-0.53208	-0.55075
136.8400	-0.38272	-0.49474	-0.53208	-0.55075
137.4200	-0.38272	-0.49474	-0.52274	-0.55075
137.9900	-0.38272	-0.49474	-0.52274	-0.55075
138.5600	-0.37339	-0.49474	-0.52274	-0.55075
139.1300	-0.37339	-0.49474	-0.52274	-0.55075
139.7000	-0.37339	-0.49474	-0.52274	-0.55075
140.2600	-0.37339	-0.49474	-0.52274	-0.55075
140.8200	-0.37339	-0.49474	-0.52274	-0.55075
141.3800	-0.37339	-0.49474	-0.52274	-0.55075
141.9400	-0.37339	-0.49474	-0.52274	-0.55075
142.4900	-0.37339	-0.49474	-0.52274	-0.55075
143.0400	-0.37339	-0.49474	-0.52274	-0.55075
143.5900	-0.37339	-0.49474	-0.52274	-0.55075

144.1400	-0.37339	-0.49474	-0.52274	-0.55075
144.6800	-0.37339	-0.49474	-0.52274	-0.55075
145.2200	-0.37339	-0.49474	-0.52274	-0.55075
145.7600	-0.37339	-0.49474	-0.52274	-0.55075
146.3000	-0.37339	-0.49474	-0.52274	-0.55075
146.8300	-0.37339	-0.49474	-0.52274	-0.55075
147.3700	-0.37339	-0.49474	-0.52274	-0.55075
147.9000	-0.37339	-0.49474	-0.52274	-0.55075
148.4200	-0.37339	-0.49474	-0.51341	-0.54141
148.9500	-0.37339	-0.49474	-0.51341	-0.54141
149.4700	-0.37339	-0.49474	-0.51341	-0.54141
149.9900	-0.37339	-0.49474	-0.51341	-0.54141
150.5100	-0.37339	-0.49474	-0.51341	-0.54141
151.0300	-0.37339	-0.48541	-0.51341	-0.54141
151.5400	-0.37339	-0.48541	-0.51341	-0.54141
152.0600	-0.37339	-0.48541	-0.51341	-0.54141
152.5600	-0.37339	-0.48541	-0.51341	-0.54141
153.0700	-0.37339	-0.48541	-0.51341	-0.54141
153.5800	-0.37339	-0.48541	-0.51341	-0.54141
154.0800	-0.37339	-0.48541	-0.51341	-0.54141
154.5800	-0.36405	-0.48541	-0.51341	-0.54141
155.0800	-0.36405	-0.48541	-0.51341	-0.54141
155.5800	-0.36405	-0.48541	-0.51341	-0.54141
156.0700	-0.36405	-0.47607	-0.51341	-0.54141
156.5600	-0.36405	-0.47607	-0.51341	-0.54141
157.0500	-0.36405	-0.47607	-0.51341	-0.54141
157.5400	-0.36405	-0.47607	-0.51341	-0.54141
158.0300	-0.36405	-0.47607	-0.51341	-0.53208
158.5100	-0.36405	-0.47607	-0.51341	-0.53208
158.9900	-0.36405	-0.47607	-0.51341	-0.53208
159.4700	-0.36405	-0.46674	-0.51341	-0.53208
159.9500	-0.35472	-0.46674	-0.51341	-0.53208
160.4200	-0.35472	-0.46674	-0.51341	-0.53208
160.9000	-0.35472	-0.46674	-0.51341	-0.53208
161.3700	-0.35472	-0.46674	-0.51341	-0.53208
161.8400	-0.35472	-0.46674	-0.51341	-0.53208
162.3000	-0.35472	-0.45740	-0.51341	-0.53208
162.7700	-0.35472	-0.45740	-0.51341	-0.52274
163.2300	-0.35472	-0.45740	-0.51341	-0.52274

163.6900	-0.34538	-0.45740	-0.51341	-0.52274
164.1500	-0.34538	-0.45740	-0.51341	-0.52274
164.6100	-0.34538	-0.45740	-0.51341	-0.52274
165.0600	-0.34538	-0.44807	-0.51341	-0.52274
165.5200	-0.34538	-0.44807	-0.51341	-0.52274
165.9700	-0.34538	-0.44807	-0.51341	-0.52274
166.4200	-0.33605	-0.44807	-0.51341	-0.52274
166.8600	-0.33605	-0.44807	-0.51341	-0.51341
167.3100	-0.33605	-0.43873	-0.51341	-0.51341
167.7500	-0.33605	-0.43873	-0.51341	-0.51341
168.1900	-0.33605	-0.43873	-0.51341	-0.51341
168.6300	-0.33605	-0.43873	-0.51341	-0.51341
169.0700	-0.33605	-0.43873	-0.51341	-0.51341
169.5100	-0.32672	-0.43873	-0.51341	-0.51341
169.9400	-0.32672	-0.42940	-0.51341	-0.51341
170.3700	-0.32672	-0.42940	-0.51341	-0.51341
170.8000	-0.32672	-0.42940	-0.51341	-0.51341
171.2300	-0.32672	-0.42940	-0.51341	-0.50408
171.6600	-0.32672	-0.42940	-0.51341	-0.50408
172.0800	-0.32672	-0.42940	-0.51341	-0.50408
172.5000	-0.31738	-0.42940	-0.51341	-0.50408
172.9200	-0.31738	-0.42940	-0.51341	-0.50408
173.3400	-0.31738	-0.42006	-0.51341	-0.50408
173.7600	-0.31738	-0.42006	-0.51341	-0.50408
174.1700	-0.31738	-0.42006	-0.51341	-0.50408
174.5900	-0.31738	-0.42006	-0.51341	-0.50408
175.0000	-0.31738	-0.42006	-0.51341	-0.50408
175.4100	-0.31738	-0.42006	-0.51341	-0.50408
175.8200	-0.31738	-0.42006	-0.51341	-0.50408
176.2200	-0.31738	-0.42006	-0.51341	-0.50408
176.6300	-0.31738	-0.42006	-0.51341	-0.50408
177.0300	-0.30805	-0.42006	-0.51341	-0.50408
177.4300	-0.30805	-0.42006	-0.51341	-0.50408
177.8300	-0.30805	-0.42006	-0.51341	-0.49474
178.2200	-0.30805	-0.42006	-0.51341	-0.49474
178.6200	-0.30805	-0.42006	-0.51341	-0.49474
179.0000	-0.30805	-0.42006	-0.51341	-0.49474
179.3800	-0.30805	-0.42006	-0.51341	-0.49474
179.7200	-0.30805	-0.41073	-0.51341	-0.49474

Table A.2.8 C_f at $Re = 3.6 \times 10^6$

θ	k-ω RANS	SST RANS	k-ω URANS	SST URANS
0.6171	0.000021940	0.000021417	0.000038298	0.000036505
1.3703	0.000093872	0.000091680	0.000114370	0.000109770
2.2073	0.000171590	0.000167580	0.000190370	0.000182980
3.0602	0.000240480	0.000234860	0.000266260	0.000256070
3.9187	0.000316010	0.000308630	0.000342010	0.000329010
4.7800	0.000387260	0.000378200	0.000417560	0.000401760
5.6418	0.000460840	0.000450040	0.000492910	0.000474280
6.5050	0.000533190	0.000520500	0.000568010	0.000546540
7.3684	0.000607330	0.000591380	0.000643310	0.000618550
8.2330	0.000692690	0.000662050	0.000733240	0.000690400
9.0970	0.000806740	0.000733640	0.000857540	0.000762570
9.9616	0.000941390	0.000809140	0.001002600	0.000837460
10.8260	0.001081000	0.000897870	0.001150100	0.000925660
11.6910	0.001220800	0.001012400	0.001295500	0.001045100
12.5550	0.001360800	0.001153300	0.001440400	0.001197000
13.4200	0.001502300	0.001302100	0.001586900	0.001355700
14.2860	0.001646000	0.001447500	0.001736000	0.001506800
15.1500	0.001792400	0.001590400	0.001888400	0.001652700
16.0150	0.001941900	0.001733200	0.002044200	0.001797700
16.8810	0.002094400	0.001877500	0.002203400	0.001944800
17.7450	0.002250000	0.002024100	0.002366000	0.002094800
18.6110	0.002408500	0.002173200	0.002531900	0.002247200
19.4760	0.002569900	0.002324200	0.002700900	0.002402100
20.3410	0.002733900	0.002477800	0.002872900	0.002559900
21.2060	0.002900500	0.002634100	0.003047600	0.002720500
22.0710	0.003069500	0.002792700	0.003225000	0.002883000
22.9370	0.003240600	0.002952900	0.003404700	0.003047800
23.8020	0.003413800	0.003115300	0.003586700	0.003215000
24.6670	0.003588700	0.003279800	0.003770800	0.003384300
25.5320	0.003765300	0.003446100	0.003956600	0.003555700
26.3980	0.003943200	0.003614100	0.004144100	0.003728100
27.2630	0.004122500	0.003782600	0.004333100	0.003901600
28.1280	0.004302700	0.003952100	0.004523300	0.004076300
28.9930	0.004483900	0.004122700	0.004714500	0.004252200
29.8590	0.004665700	0.004294000	0.004906700	0.004429000
30.7240	0.004847900	0.004466000	0.005099500	0.004606500
31.5890	0.005030500	0.004638400	0.005292800	0.004784500

32.4540	0.005213100	0.004811000	0.005486400	0.004962300
33.3200	0.005395600	0.004983000	0.005680100	0.005139500
34.1850	0.005577900	0.005154200	0.005873700	0.005316400
35.0510	0.005759600	0.005325000	0.006067000	0.005493100
35.9160	0.005940700	0.005495100	0.006259800	0.005669200
36.7810	0.006120800	0.005664500	0.006452000	0.005844600
37.6470	0.006300000	0.005832800	0.006643300	0.006019100
38.5120	0.006477900	0.006000000	0.006833700	0.006192500
39.3770	0.006654300	0.006165800	0.007022700	0.006364500
40.2420	0.006829100	0.006329900	0.007210400	0.006535100
41.1080	0.007002100	0.006492300	0.007396500	0.006703800
41.9730	0.007173200	0.006652700	0.007580800	0.006870200
42.8380	0.007342000	0.006810900	0.007763200	0.007033800
43.7040	0.007508500	0.006965800	0.007943400	0.007194900
44.5690	0.007672500	0.007117900	0.008121300	0.007353600
45.4340	0.007833700	0.007267300	0.008296800	0.007509700
46.3000	0.007992100	0.007413800	0.008469500	0.007662800
47.1650	0.008147400	0.007557100	0.008639400	0.007812900
48.0300	0.008299500	0.007697100	0.008806300	0.007959800
48.8960	0.008448100	0.007833700	0.008970000	0.008103300
49.7610	0.008593200	0.007966600	0.009130400	0.008243100
50.6260	0.008734500	0.008095700	0.009287300	0.008379200
51.4920	0.008871900	0.008220800	0.009440400	0.008511200
52.3570	0.009005200	0.008341600	0.009589800	0.008639100
53.2220	0.009134300	0.008458100	0.009735100	0.008762700
54.0880	0.009259000	0.008570100	0.009876300	0.008881800
54.9530	0.009379200	0.008677400	0.010013000	0.008996200
55.8190	0.009494700	0.008779800	0.010146000	0.009105800
56.6840	0.009605300	0.008877100	0.010273000	0.009210400
57.5490	0.009710900	0.008969300	0.010397000	0.009309800
58.4150	0.009811400	0.009056100	0.010515000	0.009403800
59.2800	0.009906600	0.009137400	0.010628000	0.009492300
60.1450	0.009996400	0.009213100	0.010736000	0.009575000
61.0110	0.010081000	0.009282700	0.010839000	0.009651700
61.8760	0.010159000	0.009346000	0.010936000	0.009722300
62.7410	0.010232000	0.009403100	0.011028000	0.009786600
63.6070	0.010299000	0.009453800	0.011114000	0.009844500
64.4720	0.010359000	0.009497900	0.011194000	0.009895800
65.3370	0.010414000	0.009535300	0.011268000	0.009940400

66.2030	0.010462000	0.009565900	0.011336000	0.009978200
67.0680	0.010504000	0.009589500	0.011399000	0.010009000
67.9330	0.010540000	0.009606200	0.011455000	0.010033000
68.7990	0.010568000	0.009615700	0.011504000	0.010050000
69.6640	0.010590000	0.009617900	0.011547000	0.010059000
70.5290	0.010606000	0.009612700	0.011584000	0.010061000
71.3950	0.010614000	0.009600100	0.011614000	0.010055000
72.2600	0.010615000	0.009579900	0.011637000	0.010042000
73.1260	0.010609000	0.009551900	0.011654000	0.010020000
73.9910	0.010596000	0.009516000	0.011663000	0.009991300
74.8560	0.010576000	0.009472200	0.011666000	0.009954100
75.7220	0.010549000	0.009420200	0.011662000	0.009908700
76.5870	0.010514000	0.009360100	0.011650000	0.009855000
77.4520	0.010471000	0.009291700	0.011631000	0.009792800
78.3180	0.010421000	0.009214900	0.011605000	0.009722000
79.1830	0.010364000	0.009129500	0.011571000	0.009642400
80.0480	0.010298000	0.009035300	0.011530000	0.009554000
80.9140	0.010225000	0.008932200	0.011482000	0.009456600
81.7790	0.010144000	0.008820200	0.011426000	0.009350000
82.6440	0.010056000	0.008699000	0.011363000	0.009234000
83.5100	0.009959100	0.008568500	0.011291000	0.009108500
84.3750	0.009854500	0.008428600	0.011212000	0.008973300
85.2410	0.009741900	0.008278900	0.011126000	0.008828000
86.1060	0.009621500	0.008119500	0.011031000	0.008672500
86.9710	0.009492800	0.007950100	0.010928000	0.008506500
87.8370	0.009357500	0.007770300	0.010818000	0.008329500
88.7020	0.009212600	0.007578900	0.010699000	0.008141600
89.5670	0.009070500	0.007382000	0.010572000	0.007941200
90.3900	0.008901000	0.007162400	0.010443000	0.007738600
91.1680	0.008724900	0.006938900	0.010315000	0.007535900
91.9420	0.008568800	0.006729300	0.010181000	0.007324100
92.7130	0.008393800	0.006496700	0.010040000	0.007101800
93.4810	0.008217000	0.006256700	0.009893500	0.006868800
94.2460	0.008031400	0.006002800	0.009740400	0.006624400
95.0070	0.007839600	0.005737100	0.009581300	0.006366900
95.7640	0.007640400	0.005456500	0.009415900	0.006096100
96.5190	0.007433900	0.005160400	0.009244200	0.005810800
97.2700	0.007219800	0.004848700	0.009066100	0.005509000
98.0180	0.006998100	0.004520700	0.008881700	0.005190800

98.7630	0.006768300	0.004175200	0.008690800	0.004855200
99.5040	0.006530200	0.003811400	0.008493300	0.004500900
100.2400	0.006283500	0.003429000	0.008289200	0.004126700
100.9800	0.006027900	0.003028400	0.008078200	0.003731600
101.7100	0.005762700	0.002611300	0.007860100	0.003315400
102.4400	0.005487700	0.002181400	0.007634900	0.002879000
103.1600	0.005202400	0.001745300	0.007402200	0.002425700
103.8900	0.004906100	0.001313000	0.007161800	0.001962200
104.6100	0.004598300	0.000899130	0.006913400	0.001500300
105.3200	0.004278700	0.000520690	0.006656500	0.001057700
106.0300	0.003946800	0.000196810	0.006390900	0.000657530
106.7400	0.003602400	-0.000060075	0.006115900	0.000324220
107.4500	0.003245700	-0.000247320	0.005831200	0.000073966
108.1500	0.002877500	-0.000364220	0.005536100	-0.000093982
108.8500	0.002499200	-0.000408260	0.005230100	-0.000196300
109.5500	0.002113700	-0.000415230	0.004912500	-0.000254820
110.2500	0.001725200	-0.000393240	0.004582800	-0.000288000
110.9400	0.001340300	-0.000345440	0.004240300	-0.000307340
111.6300	0.000967880	-0.000299870	0.003884900	-0.000318530
112.3100	0.000619580	-0.000275490	0.003516400	-0.000324090
112.9900	0.000308700	-0.000268580	0.003135300	-0.000323380
113.6700	0.000048494	-0.000272440	0.002742900	-0.000311480
114.3500	-0.000154340	-0.000281970	0.002341700	-0.000286160
115.0200	-0.000301420	-0.000295280	0.001936100	-0.000255110
115.7000	-0.000395660	-0.000310290	0.001532900	-0.000229830
116.3600	-0.000450380	-0.000325060	0.001141900	-0.000215210
117.0300	-0.000484730	-0.000339750	0.000776420	-0.000209310
117.6900	-0.000503890	-0.000353210	0.000452160	-0.000208790
118.3500	-0.000512930	-0.000365460	0.000184090	-0.000211390
119.0100	-0.000515790	-0.000376630	-0.000019167	-0.000215860
119.6600	-0.000514770	-0.000386390	-0.000160250	-0.000221490
120.3100	-0.000510960	-0.000395240	-0.000251840	-0.000227870
120.9600	-0.000504990	-0.000402880	-0.000309410	-0.000234670
121.6000	-0.000497400	-0.000409770	-0.000345220	-0.000241610
122.2400	-0.000488690	-0.000415830	-0.000366630	-0.000248430
122.8800	-0.000479040	-0.000421120	-0.000377880	-0.000254880
123.5200	-0.000468920	-0.000425780	-0.000381830	-0.000260740
124.1500	-0.000458530	-0.000429800	-0.000380550	-0.000265900
124.7900	-0.000448180	-0.000433280	-0.000375540	-0.000270280

125.4100	-0.000438080	-0.000436220	-0.000367900	-0.000273890
126.0400	-0.000428460	-0.000438700	-0.000358450	-0.000276770
126.6600	-0.000419420	-0.000440740	-0.000347780	-0.000278980
127.2800	-0.000411080	-0.000442400	-0.000336380	-0.000280610
127.9000	-0.000403450	-0.000443740	-0.000324640	-0.000281720
128.5100	-0.000396520	-0.000444780	-0.000312860	-0.000282410
129.1300	-0.000390220	-0.000445640	-0.000301320	-0.000282760
129.7400	-0.000384490	-0.000446320	-0.000290220	-0.000282840
130.3400	-0.000379240	-0.000446950	-0.000279740	-0.000282740
130.9500	-0.000374380	-0.000447550	-0.000270020	-0.000282540
131.5500	-0.000369830	-0.000448230	-0.000261140	-0.000282300
132.1500	-0.000365550	-0.000449010	-0.000253140	-0.000282100
132.7400	-0.000361480	-0.000449990	-0.000246030	-0.000282000
133.3400	-0.000357620	-0.000451200	-0.000239810	-0.000282050
133.9300	-0.000353950	-0.000452710	-0.000234430	-0.000282310
134.5200	-0.000350490	-0.000454540	-0.000229850	-0.000282830
135.1000	-0.000347270	-0.000456760	-0.000226000	-0.000283640
135.6900	-0.000344310	-0.000459360	-0.000222820	-0.000284780
136.2700	-0.000341660	-0.000462390	-0.000220240	-0.000286260
136.8400	-0.000339340	-0.000465860	-0.000218170	-0.000288110
137.4200	-0.000337400	-0.000469790	-0.000216540	-0.000290340
137.9900	-0.000335880	-0.000474160	-0.000215260	-0.000292950
138.5600	-0.000334810	-0.000479000	-0.000214250	-0.000295950
139.1300	-0.000334200	-0.000484290	-0.000213430	-0.000299340
139.7000	-0.000334100	-0.000490020	-0.000212720	-0.000303100
140.2600	-0.000334510	-0.000496190	-0.000212060	-0.000307240
140.8200	-0.000335450	-0.000502760	-0.000211370	-0.000311750
141.3800	-0.000336920	-0.000509720	-0.000210600	-0.000316590
141.9400	-0.000338910	-0.000517060	-0.000209710	-0.000321770
142.4900	-0.000341420	-0.000524730	-0.000208660	-0.000327250
143.0400	-0.000344450	-0.000532710	-0.000207420	-0.000333030
143.5900	-0.000347980	-0.000540980	-0.000205980	-0.000339060
144.1400	-0.000351990	-0.000549490	-0.000204320	-0.000345340
144.6800	-0.000356470	-0.000558210	-0.000202450	-0.000351820
145.2200	-0.000361390	-0.000567110	-0.000200370	-0.000358490
145.7600	-0.000366730	-0.000576150	-0.000198110	-0.000365320
146.3000	-0.000372450	-0.000585300	-0.000195680	-0.000372280
146.8300	-0.000378530	-0.000594500	-0.000193120	-0.000379330
147.3700	-0.000384930	-0.000603740	-0.000190450	-0.000386440

147.9000	-0.000391620	-0.000612960	-0.000187700	-0.000393600
148.4200	-0.000398560	-0.000622130	-0.000184910	-0.000400750
148.9500	-0.000405720	-0.000631210	-0.000182110	-0.000407880
149.4700	-0.000413060	-0.000640160	-0.000179330	-0.000414960
149.9900	-0.000420540	-0.000648950	-0.000176610	-0.000421940
150.5100	-0.000428110	-0.000657530	-0.000173970	-0.000428810
151.0300	-0.000435750	-0.000665880	-0.000171440	-0.000435540
151.5400	-0.000443410	-0.000673960	-0.000169040	-0.000442080
152.0600	-0.000451060	-0.000681720	-0.000166790	-0.000448430
152.5600	-0.000458640	-0.000689150	-0.000164710	-0.000454540
153.0700	-0.000466130	-0.000696200	-0.000162800	-0.000460400
153.5800	-0.000473490	-0.000702840	-0.000161080	-0.000465970
154.0800	-0.000480680	-0.000709040	-0.000159560	-0.000471230
154.5800	-0.000487660	-0.000714770	-0.000158230	-0.000476170
155.0800	-0.000494400	-0.000720000	-0.000157100	-0.000480750
155.5800	-0.000500870	-0.000724710	-0.000156160	-0.000484950
156.0700	-0.000507030	-0.000728860	-0.000155420	-0.000488750
156.5600	-0.000512840	-0.000732440	-0.000154860	-0.000492130
157.0500	-0.000518270	-0.000735410	-0.000154480	-0.000495080
157.5400	-0.000523300	-0.000737770	-0.000154260	-0.000497580
158.0300	-0.000527890	-0.000739490	-0.000154200	-0.000499610
158.5100	-0.000532020	-0.000740550	-0.000154280	-0.000501150
158.9900	-0.000535650	-0.000740940	-0.000154480	-0.000502200
159.4700	-0.000538760	-0.000740640	-0.000154790	-0.000502740
159.9500	-0.000541330	-0.000739630	-0.000155190	-0.000502770
160.4200	-0.000543350	-0.000737910	-0.000155660	-0.000502270
160.9000	-0.000544770	-0.000735460	-0.000156180	-0.000501230
161.3700	-0.000545600	-0.000732280	-0.000156730	-0.000499650
161.8400	-0.000545800	-0.000728360	-0.000157290	-0.000497520
162.3000	-0.000545370	-0.000723690	-0.000157830	-0.000494850
162.7700	-0.000544300	-0.000718270	-0.000158330	-0.000491620
163.2300	-0.000542550	-0.000712090	-0.000158770	-0.000487840
163.6900	-0.000540130	-0.000705160	-0.000159130	-0.000483500
164.1500	-0.000537020	-0.000697470	-0.000159390	-0.000478610
164.6100	-0.000533220	-0.000689030	-0.000159510	-0.000473160
165.0600	-0.000528720	-0.000679840	-0.000159480	-0.000467170
165.5200	-0.000523510	-0.000669900	-0.000159290	-0.000460630
165.9700	-0.000517590	-0.000659220	-0.000158900	-0.000453550
166.4200	-0.000510960	-0.000647820	-0.000158300	-0.000445940

166.8600	-0.000503620	-0.000635690	-0.000157470	-0.000437810
167.3100	-0.000495560	-0.000622860	-0.000156400	-0.000429160
167.7500	-0.000486800	-0.000609330	-0.000155070	-0.000420010
168.1900	-0.000477330	-0.000595120	-0.000153470	-0.000410360
168.6300	-0.000467170	-0.000580230	-0.000151590	-0.000400240
169.0700	-0.000456320	-0.000564700	-0.000149420	-0.000389640
169.5100	-0.000444780	-0.000548540	-0.000146960	-0.000378590
169.9400	-0.000432590	-0.000531770	-0.000144190	-0.000367090
170.3700	-0.000419740	-0.000514390	-0.000141110	-0.000355180
170.8000	-0.000406250	-0.000496460	-0.000137720	-0.000342860
171.2300	-0.000392150	-0.000477970	-0.000134030	-0.000330140
171.6600	-0.000377450	-0.000458960	-0.000130040	-0.000317050
172.0800	-0.000362170	-0.000439440	-0.000125740	-0.000303610
172.5000	-0.000346360	-0.000419460	-0.000121150	-0.000289830
172.9200	-0.000330010	-0.000399020	-0.000116280	-0.000275730
173.3400	-0.000313190	-0.000378180	-0.000111120	-0.000261340
173.7600	-0.000295900	-0.000356930	-0.000105700	-0.000246670
174.1700	-0.000278210	-0.000335330	-0.000100020	-0.000231750
174.5900	-0.000260120	-0.000313370	-0.000094105	-0.000216590
175.0000	-0.000241720	-0.000291150	-0.000087959	-0.000201230
175.4100	-0.000222980	-0.000268610	-0.000081603	-0.000185660
175.8200	-0.000204050	-0.000245860	-0.000075053	-0.000169930
176.2200	-0.000184850	-0.000222860	-0.000068325	-0.000154060
176.6300	-0.000165550	-0.000199730	-0.000061439	-0.000138050
177.0300	-0.000146070	-0.000176380	-0.000054413	-0.000121940
177.4300	-0.000126580	-0.000152980	-0.000047266	-0.000105750
177.8300	-0.000106950	-0.000129400	-0.000040020	-0.000089491
178.2200	-0.000087414	-0.000105860	-0.000032693	-0.000073195
178.6200	-0.000067774	-0.000082177	-0.000025307	-0.000056879
179.0000	-0.000048296	-0.000058618	-0.000017882	-0.000040563
179.3800	-0.000028735	-0.000034954	-0.000010438	-0.000024269
179.7200	-0.000009399	-0.000011505	-0.000002996	-0.000008014

Table A.2.9 U/U_∞ at $x/D = 0.75$ with $Re = 10^6$

y/D	k-ω RANS	SST RANS	k-ω URANS	SST URANS
-1.9960	1.0730	1.0804	1.0542	1.0789
-1.9526	1.0753	1.0828	1.0560	1.0815
-1.9252	1.0766	1.0844	1.0571	1.0831
-1.8865	1.0787	1.0867	1.0587	1.0856

-1.8590	1.0802	1.0883	1.0599	1.0874
-1.8228	1.0823	1.0906	1.0616	1.0899
-1.7969	1.0838	1.0922	1.0627	1.0917
-1.7612	1.0859	1.0946	1.0645	1.0943
-1.7385	1.0872	1.0961	1.0655	1.0959
-1.7016	1.0895	1.0987	1.0674	1.0987
-1.6834	1.0907	1.1000	1.0683	1.1001
-1.6441	1.0932	1.1029	1.0704	1.1033
-1.6314	1.0941	1.1038	1.0710	1.1043
-1.5884	1.0970	1.1071	1.0734	1.1080
-1.5822	1.0974	1.1076	1.0737	1.1085
-1.5356	1.1006	1.1113	1.0763	1.1127
-1.5346	1.1007	1.1114	1.0764	1.1128
-1.4914	1.1038	1.1149	1.0788	1.1168
-1.4824	1.1045	1.1157	1.0794	1.1177
-1.4493	1.1070	1.1185	1.0813	1.1209
-1.4320	1.1083	1.1201	1.0824	1.1227
-1.4093	1.1100	1.1221	1.0837	1.1249
-1.3831	1.1120	1.1245	1.0854	1.1277
-1.3711	1.1130	1.1256	1.0861	1.1289
-1.3357	1.1157	1.1288	1.0883	1.1327
-1.3346	1.1158	1.1289	1.0883	1.1328
-1.2998	1.1186	1.1323	1.0906	1.1367
-1.2898	1.1194	1.1333	1.0912	1.1379
-1.2664	1.1213	1.1355	1.0927	1.1406
-1.2453	1.1230	1.1377	1.0941	1.1431
-1.2345	1.1239	1.1387	1.0947	1.1443
-1.2038	1.1264	1.1418	1.0967	1.1480
-1.2021	1.1265	1.1420	1.0968	1.1482
-1.1743	1.1288	1.1449	1.0986	1.1517
-1.1601	1.1300	1.1464	1.0995	1.1535
-1.1460	1.1311	1.1478	1.1003	1.1553
-1.1193	1.1333	1.1506	1.1020	1.1587
-1.1187	1.1334	1.1507	1.1020	1.1588
-1.0924	1.1355	1.1535	1.1037	1.1623
-1.0797	1.1365	1.1548	1.1045	1.1640
-1.0671	1.1375	1.1562	1.1052	1.1657
-1.0427	1.1394	1.1588	1.1067	1.1690
-1.0412	1.1395	1.1589	1.1068	1.1692
-1.0191	1.1413	1.1613	1.1081	1.1723
-1.0036	1.1425	1.1630	1.1090	1.1745

-0.9963	1.1430	1.1638	1.1094	1.1755
-0.9742	1.1447	1.1662	1.1107	1.1787
-0.9671	1.1452	1.1670	1.1111	1.1797
-0.9528	1.1462	1.1685	1.1118	1.1818
-0.9321	1.1477	1.1707	1.1129	1.1848
-0.9314	1.1477	1.1708	1.1130	1.1849
-0.9120	1.1491	1.1729	1.1140	1.1878
-0.8966	1.1501	1.1745	1.1148	1.1901
-0.8926	1.1504	1.1750	1.1150	1.1907
-0.8736	1.1516	1.1770	1.1159	1.1936
-0.8627	1.1523	1.1782	1.1165	1.1953
-0.8553	1.1527	1.1789	1.1168	1.1964
-0.8374	1.1538	1.1808	1.1176	1.1992
-0.8295	1.1542	1.1816	1.1180	1.2005
-0.8200	1.1548	1.1826	1.1184	1.2019
-0.8031	1.1556	1.1843	1.1191	1.2046
-0.7970	1.1560	1.1850	1.1194	1.2056
-0.7867	1.1565	1.1860	1.1198	1.2072
-0.7706	1.1573	1.1876	1.1204	1.2098
-0.7651	1.1575	1.1881	1.1207	1.2107
-0.7550	1.1580	1.1892	1.1211	1.2124
-0.7397	1.1586	1.1906	1.1217	1.2148
-0.7339	1.1589	1.1912	1.1219	1.2158
-0.7248	1.1592	1.1920	1.1223	1.2173
-0.7103	1.1597	1.1934	1.1228	1.2197
-0.7032	1.1600	1.1940	1.1232	1.2209
-0.6961	1.1602	1.1946	1.1234	1.2222
-0.6822	1.1606	1.1956	1.1239	1.2245
-0.6730	1.1609	1.1962	1.1243	1.2261
-0.6687	1.1611	1.1965	1.1245	1.2268
-0.6554	1.1614	1.1968	1.1251	1.2291
-0.6433	1.1616	1.1964	1.1256	1.2312
-0.6424	1.1617	1.1966	1.1256	1.2314
-0.6297	1.1619	1.1950	1.1262	1.2337
-0.6173	1.1620	1.1917	1.1268	1.2359
-0.6139	1.1620	1.1904	1.1270	1.2365
-0.6051	1.1619	1.1864	1.1275	1.2381
-0.5931	1.1616	1.1772	1.1281	1.2403
-0.5849	1.1611	1.1683	1.1286	1.2420
-0.5814	1.1609	1.1645	1.1288	1.2427
-0.5699	1.1593	1.1456	1.1296	1.2457

-0.5587	1.1565	1.1201	1.1303	1.2486
-0.5561	1.1557	1.1133	1.1305	1.2492
-0.5476	1.1524	1.0886	1.1312	1.2501
-0.5367	1.1456	1.0481	1.1321	1.2427
-0.5275	1.1374	1.0069	1.1329	1.2249
-0.5261	1.1366	1.0013	1.1330	1.2248
-0.5156	1.1228	0.9452	1.1341	1.1818
-0.5053	1.1044	0.8829	1.1352	1.1166
-0.4989	1.0904	0.8414	1.1360	1.0667
-0.4951	1.0815	0.8163	1.1364	1.0351
-0.4852	1.0514	0.7455	1.1378	0.9375
-0.4754	1.0145	0.6738	1.1393	0.8349
-0.4704	0.9932	0.6366	1.1403	0.7813
-0.4657	0.9721	0.6025	1.1412	0.7322
-0.4562	0.9218	0.5337	1.1429	0.6351
-0.4469	0.8653	0.4690	1.1438	0.5464
-0.4417	0.8317	0.4343	1.1437	0.4995
-0.4376	0.8046	0.4079	1.1434	0.4643
-0.4286	0.7386	0.3526	1.1385	0.3927
-0.4196	0.6699	0.3029	1.1272	0.3304
-0.4128	0.6155	0.2668	1.1128	0.2873
-0.4108	0.5998	0.2567	1.1095	0.2744
-0.4021	0.5294	0.2117	1.0783	0.2275
-0.3936	0.4611	0.1684	1.0371	0.1876
-0.3851	0.3961	0.1289	0.9896	0.1537
-0.3835	0.3834	0.1216	0.9797	0.1475
-0.3768	0.3344	0.0940	0.9405	0.1239
-0.3686	0.2790	0.0687	0.8909	0.0997
-0.3604	0.2305	0.0499	0.8420	0.0794
-0.3535	0.1935	0.0363	0.8000	0.0640
-0.3524	0.1870	0.0339	0.7949	0.0612
-0.3445	0.1522	0.0205	0.7463	0.0463
-0.3367	0.1238	0.0084	0.6977	0.0332
-0.3289	0.1011	-0.0023	0.6485	0.0218
-0.3225	0.0846	-0.0106	0.6063	0.0132
-0.3213	0.0813	-0.0123	0.5997	0.0114
-0.3138	0.0648	-0.0210	0.5479	0.0025
-0.3063	0.0500	-0.0291	0.4954	-0.0056
-0.2989	0.0368	-0.0365	0.4423	-0.0129
-0.2916	0.0248	-0.0434	0.3900	-0.0196
-0.2901	0.0224	-0.0448	0.3793	-0.0209

-0.2844	0.0135	-0.0500	0.3383	-0.0260
-0.2773	0.0032	-0.0561	0.2916	-0.0318
-0.2702	-0.0062	-0.0618	0.2510	-0.0373
-0.2632	-0.0151	-0.0673	0.2175	-0.0425
-0.2563	-0.0234	-0.0725	0.1901	-0.0474
-0.2558	-0.0241	-0.0728	0.1883	-0.0478
-0.2494	-0.0315	-0.0775	0.1666	-0.0522
-0.2426	-0.0389	-0.0822	0.1483	-0.0567
-0.2359	-0.0460	-0.0867	0.1326	-0.0609
-0.2293	-0.0527	-0.0909	0.1186	-0.0650
-0.2227	-0.0591	-0.0951	0.1058	-0.0689
-0.2182	-0.0633	-0.0977	0.0974	-0.0714
-0.2161	-0.0654	-0.0990	0.0933	-0.0727
-0.2096	-0.0712	-0.1028	0.0818	-0.0763
-0.2032	-0.0768	-0.1064	0.0707	-0.0797
-0.1969	-0.0822	-0.1099	0.0599	-0.0830
-0.1905	-0.0874	-0.1132	0.0493	-0.0862
-0.1843	-0.0924	-0.1163	0.0389	-0.0892
-0.1781	-0.0971	-0.1194	0.0287	-0.0921
-0.1754	-0.0991	-0.1206	0.0242	-0.0933
-0.1719	-0.1018	-0.1223	0.0183	-0.0949
-0.1658	-0.1062	-0.1250	0.0084	-0.0975
-0.1597	-0.1104	-0.1277	-0.0015	-0.1001
-0.1537	-0.1144	-0.1302	-0.0112	-0.1025
-0.1478	-0.1183	-0.1326	-0.0207	-0.1048
-0.1418	-0.1220	-0.1349	-0.0300	-0.1070
-0.1359	-0.1255	-0.1371	-0.0392	-0.1091
-0.1301	-0.1289	-0.1392	-0.0482	-0.1111
-0.1243	-0.1321	-0.1412	-0.0570	-0.1130
-0.1216	-0.1336	-0.1420	-0.0610	-0.1138
-0.1185	-0.1352	-0.1430	-0.0658	-0.1148
-0.1128	-0.1381	-0.1448	-0.0742	-0.1165
-0.1071	-0.1409	-0.1465	-0.0823	-0.1181
-0.1015	-0.1435	-0.1480	-0.0902	-0.1196
-0.0959	-0.1460	-0.1495	-0.0978	-0.1210
-0.0903	-0.1483	-0.1509	-0.1051	-0.1223
-0.0847	-0.1505	-0.1522	-0.1121	-0.1235
-0.0792	-0.1525	-0.1534	-0.1188	-0.1247
-0.0737	-0.1544	-0.1545	-0.1251	-0.1258
-0.0683	-0.1562	-0.1555	-0.1311	-0.1268
-0.0629	-0.1578	-0.1565	-0.1368	-0.1277

-0.0575	-0.1593	-0.1574	-0.1420	-0.1285
-0.0521	-0.1607	-0.1581	-0.1469	-0.1292
-0.0468	-0.1619	-0.1589	-0.1514	-0.1299
-0.0415	-0.1630	-0.1595	-0.1554	-0.1305
-0.0362	-0.1640	-0.1600	-0.1591	-0.1310
-0.0310	-0.1648	-0.1605	-0.1622	-0.1315
-0.0257	-0.1655	-0.1609	-0.1650	-0.1319
-0.0205	-0.1660	-0.1612	-0.1672	-0.1322
-0.0154	-0.1665	-0.1615	-0.1690	-0.1324
-0.0102	-0.1668	-0.1616	-0.1703	-0.1326
-0.0051	-0.1670	-0.1618	-0.1710	-0.1327
0.0000	-0.1670	-0.1618	-0.1717	-0.1327
0.0051	-0.1670	-0.1618	-0.1712	-0.1327
0.0102	-0.1668	-0.1617	-0.1705	-0.1326
0.0154	-0.1665	-0.1615	-0.1693	-0.1324
0.0205	-0.1660	-0.1612	-0.1677	-0.1322
0.0257	-0.1655	-0.1609	-0.1656	-0.1319
0.0310	-0.1648	-0.1605	-0.1630	-0.1315
0.0362	-0.1640	-0.1600	-0.1599	-0.1310
0.0415	-0.1630	-0.1595	-0.1564	-0.1305
0.0468	-0.1619	-0.1589	-0.1524	-0.1299
0.0521	-0.1607	-0.1581	-0.1481	-0.1292
0.0575	-0.1593	-0.1574	-0.1433	-0.1285
0.0629	-0.1578	-0.1565	-0.1381	-0.1277
0.0683	-0.1562	-0.1555	-0.1326	-0.1268
0.0737	-0.1544	-0.1545	-0.1267	-0.1258
0.0792	-0.1525	-0.1534	-0.1204	-0.1247
0.0847	-0.1505	-0.1522	-0.1138	-0.1235
0.0903	-0.1483	-0.1509	-0.1068	-0.1223
0.0959	-0.1460	-0.1495	-0.0996	-0.1210
0.1015	-0.1435	-0.1480	-0.0920	-0.1196
0.1071	-0.1409	-0.1465	-0.0841	-0.1181
0.1128	-0.1381	-0.1448	-0.0760	-0.1165
0.1185	-0.1352	-0.1430	-0.0677	-0.1148
0.1216	-0.1336	-0.1420	-0.0631	-0.1138
0.1243	-0.1321	-0.1412	-0.0591	-0.1130
0.1301	-0.1289	-0.1392	-0.0503	-0.1111
0.1359	-0.1255	-0.1371	-0.0413	-0.1091
0.1418	-0.1220	-0.1349	-0.0322	-0.1070
0.1478	-0.1183	-0.1326	-0.0229	-0.1048
0.1537	-0.1144	-0.1302	-0.0134	-0.1025

0.1597	-0.1104	-0.1277	-0.0036	-0.1000
0.1658	-0.1061	-0.1250	0.0062	-0.0975
0.1719	-0.1017	-0.1223	0.0163	-0.0948
0.1754	-0.0991	-0.1206	0.0220	-0.0933
0.1781	-0.0971	-0.1194	0.0264	-0.0921
0.1843	-0.0924	-0.1163	0.0367	-0.0892
0.1905	-0.0874	-0.1132	0.0471	-0.0861
0.1969	-0.0822	-0.1099	0.0577	-0.0830
0.2032	-0.0768	-0.1064	0.0686	-0.0797
0.2096	-0.0712	-0.1028	0.0798	-0.0762
0.2161	-0.0653	-0.0990	0.0915	-0.0726
0.2182	-0.0633	-0.0977	0.0952	-0.0714
0.2227	-0.0591	-0.0951	0.1036	-0.0689
0.2293	-0.0527	-0.0910	0.1165	-0.0650
0.2359	-0.0460	-0.0867	0.1305	-0.0609
0.2426	-0.0389	-0.0822	0.1465	-0.0566
0.2494	-0.0314	-0.0774	0.1654	-0.0521
0.2558	-0.0241	-0.0728	0.1861	-0.0478
0.2563	-0.0234	-0.0725	0.1880	-0.0474
0.2632	-0.0151	-0.0673	0.2153	-0.0425
0.2702	-0.0062	-0.0619	0.2487	-0.0373
0.2773	0.0033	-0.0561	0.2896	-0.0318
0.2844	0.0137	-0.0499	0.3367	-0.0259
0.2901	0.0224	-0.0448	0.3765	-0.0209
0.2916	0.0248	-0.0434	0.3872	-0.0196
0.2989	0.0368	-0.0365	0.4394	-0.0129
0.3063	0.0500	-0.0291	0.4923	-0.0056
0.3138	0.0650	-0.0209	0.5441	0.0026
0.3213	0.0818	-0.0120	0.5952	0.0117
0.3225	0.0842	-0.0107	0.6025	0.0130
0.3289	0.1011	-0.0023	0.6452	0.0218
0.3367	0.1238	0.0084	0.6945	0.0332
0.3445	0.1528	0.0206	0.7428	0.0465
0.3524	0.1885	0.0344	0.7911	0.0618
0.3535	0.1924	0.0359	0.7969	0.0635
0.3604	0.2305	0.0499	0.8397	0.0793
0.3686	0.2790	0.0687	0.8890	0.0996
0.3768	0.3350	0.0952	0.9385	0.1245
0.3835	0.3834	0.1215	0.9785	0.1474
0.3851	0.3961	0.1289	0.9885	0.1537
0.3936	0.4611	0.1684	1.0363	0.1875

0.4021	0.5295	0.2118	1.0770	0.2278
0.4108	0.5998	0.2567	1.1069	0.2757
0.4128	0.6152	0.2663	1.1130	0.2863
0.4196	0.6699	0.3028	1.1267	0.3303
0.4286	0.7386	0.3527	1.1379	0.3928
0.4376	0.8040	0.4086	1.1423	0.4655
0.4417	0.8317	0.4341	1.1433	0.4992
0.4469	0.8653	0.4690	1.1433	0.5463
0.4562	0.9218	0.5336	1.1424	0.6350
0.4657	0.9713	0.6027	1.1406	0.7328
0.4704	0.9932	0.6365	1.1398	0.7811
0.4754	1.0145	0.6738	1.1388	0.8348
0.4852	1.0514	0.7455	1.1373	0.9374
0.4951	1.0807	0.8158	1.1359	1.0333
0.4989	1.0905	0.8413	1.1355	1.0669
0.5053	1.1044	0.8829	1.1347	1.1166
0.5156	1.1227	0.9450	1.1336	1.1811
0.5261	1.1359	1.0001	1.1326	1.2211
0.5275	1.1377	1.0072	1.1325	1.2264
0.5367	1.1456	1.0480	1.1316	1.2427
0.5476	1.1522	1.0880	1.1307	1.2495
0.5561	1.1557	1.1133	1.1301	1.2492
0.5587	1.1565	1.1201	1.1299	1.2486
0.5699	1.1593	1.1455	1.1291	1.2457
0.5814	1.1607	1.1638	1.1284	1.2427
0.5849	1.1611	1.1684	1.1283	1.2420
0.5931	1.1616	1.1772	1.1277	1.2403
0.6051	1.1619	1.1861	1.1271	1.2381
0.6139	1.1620	1.1904	1.1267	1.2366
0.6173	1.1620	1.1917	1.1265	1.2359
0.6297	1.1619	1.1950	1.1259	1.2337
0.6424	1.1617	1.1964	1.1253	1.2314
0.6433	1.1616	1.1965	1.1253	1.2313
0.6554	1.1614	1.1968	1.1248	1.2292
0.6687	1.1610	1.1964	1.1242	1.2268
0.6730	1.1609	1.1962	1.1241	1.2261
0.6822	1.1606	1.1956	1.1237	1.2245
0.6961	1.1602	1.1946	1.1231	1.2222
0.7032	1.1600	1.1940	1.1229	1.2210
0.7103	1.1597	1.1934	1.1226	1.2198
0.7248	1.1592	1.1920	1.1220	1.2173

0.7339	1.1589	1.1912	1.1217	1.2158
0.7397	1.1586	1.1906	1.1214	1.2149
0.7550	1.1580	1.1891	1.1209	1.2124
0.7651	1.1575	1.1881	1.1205	1.2107
0.7706	1.1573	1.1876	1.1202	1.2098
0.7867	1.1565	1.1860	1.1196	1.2072
0.7970	1.1560	1.1850	1.1192	1.2056
0.8031	1.1556	1.1843	1.1189	1.2046
0.8200	1.1547	1.1826	1.1182	1.2019
0.8295	1.1542	1.1816	1.1178	1.2005
0.8374	1.1538	1.1808	1.1174	1.1992
0.8553	1.1527	1.1789	1.1166	1.1964
0.8627	1.1523	1.1782	1.1163	1.1953
0.8736	1.1516	1.1770	1.1158	1.1936
0.8926	1.1504	1.1750	1.1149	1.1907
0.8966	1.1501	1.1746	1.1147	1.1902
0.9120	1.1491	1.1729	1.1139	1.1878
0.9314	1.1477	1.1708	1.1129	1.1849
0.9321	1.1477	1.1707	1.1128	1.1848
0.9528	1.1462	1.1685	1.1118	1.1818
0.9671	1.1452	1.1670	1.1110	1.1797
0.9742	1.1447	1.1662	1.1106	1.1787
0.9963	1.1430	1.1638	1.1094	1.1755
1.0036	1.1425	1.1630	1.1090	1.1745
1.0191	1.1413	1.1613	1.1081	1.1723
1.0412	1.1395	1.1589	1.1068	1.1692
1.0427	1.1394	1.1588	1.1067	1.1690
1.0671	1.1375	1.1562	1.1052	1.1657
1.0797	1.1365	1.1548	1.1045	1.1640
1.0924	1.1355	1.1535	1.1037	1.1623
1.1187	1.1333	1.1506	1.1020	1.1588
1.1193	1.1333	1.1506	1.1021	1.1588
1.1460	1.1311	1.1478	1.1003	1.1553
1.1601	1.1300	1.1464	1.0995	1.1536
1.1743	1.1288	1.1449	1.0986	1.1517
1.2021	1.1265	1.1420	1.0968	1.1483
1.2038	1.1264	1.1418	1.0967	1.1481
1.2345	1.1239	1.1387	1.0947	1.1444
1.2453	1.1230	1.1377	1.0941	1.1431
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1.2998	1.1186	1.1323	1.0906	1.1368
1.3346	1.1158	1.1289	1.0884	1.1329
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1.3711	1.1130	1.1255	1.0861	1.1289
1.3831	1.1121	1.1245	1.0854	1.1277
1.4093	1.1100	1.1221	1.0838	1.1250
1.4320	1.1083	1.1201	1.0825	1.1227
1.4493	1.1070	1.1185	1.0814	1.1209
1.4824	1.1045	1.1157	1.0794	1.1177
1.4914	1.1038	1.1149	1.0789	1.1168
1.5346	1.1007	1.1114	1.0764	1.1128
1.5356	1.1006	1.1113	1.0763	1.1127
1.5822	1.0974	1.1076	1.0737	1.1086
1.5884	1.0970	1.1071	1.0735	1.1081
1.6314	1.0941	1.1038	1.0711	1.1044
1.6441	1.0933	1.1029	1.0705	1.1034
1.6834	1.0907	1.1000	1.0684	1.1002
1.7016	1.0896	1.0987	1.0675	1.0988
1.7385	1.0872	1.0961	1.0656	1.0959
1.7612	1.0859	1.0946	1.0645	1.0943
1.7969	1.0838	1.0922	1.0628	1.0917
1.8228	1.0823	1.0906	1.0617	1.0899
1.8590	1.0802	1.0883	1.0600	1.0874
1.8865	1.0787	1.0867	1.0588	1.0856
1.9252	1.0767	1.0844	1.0571	1.0832
1.9526	1.0753	1.0828	1.0560	1.0815
1.9960	1.0731	1.0804	1.0543	1.0789

Table A.2.10 V/U_∞ at $x/D = 0.75$ with $Re = 10^6$

y/D	k-ω RANS	SST RANS	k-ω URANS	SST URANS
-1.9960	-0.00580	-0.02023	0.02323	0.00055
-1.9526	-0.00536	-0.02026	0.02489	0.00111
-1.9252	-0.00505	-0.02025	0.02597	0.00151
-1.8865	-0.00459	-0.02024	0.02762	0.00208
-1.8590	-0.00422	-0.02020	0.02884	0.00253
-1.8228	-0.00371	-0.02015	0.03057	0.00314
-1.7969	-0.00332	-0.02008	0.03184	0.00362
-1.7612	-0.00274	-0.01999	0.03373	0.00430
-1.7385	-0.00234	-0.01990	0.03497	0.00478
-1.7016	-0.00166	-0.01975	0.03713	0.00556

-1.6834	-0.00129	-0.01966	0.03822	0.00599
-1.6441	-0.00047	-0.01944	0.04076	0.00693
-1.6314	-0.00018	-0.01935	0.04160	0.00726
-1.5884	0.00084	-0.01905	0.04464	0.00839
-1.5822	0.00099	-0.01899	0.04508	0.00858
-1.5356	0.00223	-0.01859	0.04869	0.00993
-1.5346	0.00226	-0.01858	0.04877	0.00996
-1.4914	0.00352	-0.01813	0.05240	0.01134
-1.4824	0.00379	-0.01803	0.05319	0.01164
-1.4493	0.00485	-0.01762	0.05621	0.01279
-1.4320	0.00544	-0.01740	0.05789	0.01342
-1.4093	0.00624	-0.01707	0.06012	0.01428
-1.3831	0.00721	-0.01668	0.06284	0.01530
-1.3711	0.00767	-0.01648	0.06411	0.01580
-1.3357	0.00909	-0.01588	0.06806	0.01729
-1.3346	0.00913	-0.01586	0.06818	0.01735
-1.2998	0.01063	-0.01521	0.07235	0.01891
-1.2898	0.01107	-0.01501	0.07361	0.01937
-1.2664	0.01215	-0.01452	0.07659	0.02050
-1.2453	0.01317	-0.01406	0.07943	0.02154
-1.2345	0.01369	-0.01381	0.08090	0.02210
-1.2038	0.01526	-0.01308	0.08526	0.02371
-1.2021	0.01535	-0.01304	0.08551	0.02380
-1.1743	0.01684	-0.01233	0.08970	0.02533
-1.1601	0.01763	-0.01197	0.09195	0.02613
-1.1460	0.01842	-0.01158	0.09418	0.02696
-1.1193	0.01998	-0.01082	0.09859	0.02854
-1.1187	0.02001	-0.01080	0.09870	0.02858
-1.0924	0.02161	-0.01003	0.10328	0.03019
-1.0797	0.02240	-0.00965	0.10561	0.03099
-1.0671	0.02319	-0.00925	0.10790	0.03180
-1.0427	0.02477	-0.00846	0.11253	0.03340
-1.0412	0.02487	-0.00842	0.11283	0.03350
-1.0191	0.02633	-0.00769	0.11722	0.03498
-1.0036	0.02738	-0.00718	0.12039	0.03603
-0.9963	0.02788	-0.00693	0.12191	0.03654
-0.9742	0.02941	-0.00616	0.12663	0.03808
-0.9671	0.02991	-0.00592	0.12821	0.03858
-0.9528	0.03091	-0.00542	0.13138	0.03960

-0.9321	0.03239	-0.00468	0.13610	0.04109
-0.9314	0.03244	-0.00466	0.13626	0.04114
-0.9120	0.03383	-0.00397	0.14088	0.04255
-0.8966	0.03495	-0.00342	0.14463	0.04367
-0.8926	0.03524	-0.00328	0.14565	0.04398
-0.8736	0.03662	-0.00260	0.15042	0.04537
-0.8627	0.03742	-0.00221	0.15327	0.04617
-0.8553	0.03795	-0.00195	0.15519	0.04673
-0.8374	0.03925	-0.00132	0.15995	0.04805
-0.8295	0.03983	-0.00106	0.16215	0.04863
-0.8200	0.04050	-0.00073	0.16474	0.04933
-0.8031	0.04172	-0.00016	0.16948	0.05057
-0.7970	0.04215	0.00004	0.17127	0.05102
-0.7867	0.04287	0.00037	0.17426	0.05177
-0.7706	0.04399	0.00088	0.17899	0.05293
-0.7651	0.04437	0.00105	0.18067	0.05332
-0.7550	0.04505	0.00135	0.18376	0.05404
-0.7397	0.04607	0.00180	0.18847	0.05511
-0.7339	0.04645	0.00195	0.19034	0.05551
-0.7248	0.04703	0.00220	0.19323	0.05614
-0.7103	0.04794	0.00258	0.19793	0.05712
-0.7032	0.04838	0.00275	0.20030	0.05758
-0.6961	0.04880	0.00293	0.20267	0.05804
-0.6822	0.04961	0.00328	0.20735	0.05893
-0.6730	0.05013	0.00351	0.21054	0.05950
-0.6687	0.05035	0.00361	0.21208	0.05977
-0.6554	0.05106	0.00401	0.21676	0.06056
-0.6433	0.05168	0.00444	0.22111	0.06126
-0.6424	0.05171	0.00443	0.22147	0.06130
-0.6297	0.05232	0.00502	0.22615	0.06198
-0.6173	0.05289	0.00581	0.23080	0.06264
-0.6139	0.05304	0.00605	0.23210	0.06280
-0.6051	0.05342	0.00675	0.23553	0.06323
-0.5931	0.05396	0.00805	0.24019	0.06378
-0.5849	0.05433	0.00913	0.24349	0.06413
-0.5814	0.05447	0.00957	0.24493	0.06426
-0.5699	0.05505	0.01146	0.24962	0.06464
-0.5587	0.05569	0.01358	0.25428	0.06494
-0.5561	0.05584	0.01409	0.25538	0.06500

-0.5476	0.05638	0.01577	0.25906	0.06523
-0.5367	0.05721	0.01797	0.26377	0.06582
-0.5275	0.05800	0.01968	0.26786	0.06657
-0.5261	0.05809	0.01995	0.26858	0.06665
-0.5156	0.05909	0.02144	0.27333	0.06760
-0.5053	0.06010	0.02223	0.27808	0.06802
-0.4989	0.06070	0.02233	0.28108	0.06780
-0.4951	0.06103	0.02228	0.28298	0.06752
-0.4852	0.06174	0.02117	0.28781	0.06522
-0.4754	0.06208	0.01896	0.29263	0.06116
-0.4704	0.06209	0.01747	0.29514	0.05852
-0.4657	0.06197	0.01586	0.29763	0.05571
-0.4562	0.06105	0.01161	0.30256	0.04880
-0.4469	0.05923	0.00653	0.30749	0.04104
-0.4417	0.05784	0.00342	0.31026	0.03645
-0.4376	0.05659	0.00091	0.31261	0.03276
-0.4286	0.05268	-0.00527	0.31743	0.02424
-0.4196	0.04763	-0.01178	0.32178	0.01581
-0.4128	0.04303	-0.01704	0.32469	0.00940
-0.4108	0.04174	-0.01851	0.32585	0.00749
-0.4021	0.03465	-0.02582	0.32820	-0.00036
-0.3936	0.02681	-0.03333	0.32894	-0.00767
-0.3851	0.01848	-0.04058	0.32796	-0.01438
-0.3835	0.01676	-0.04197	0.32756	-0.01568
-0.3768	0.00985	-0.04726	0.32572	-0.02066
-0.3686	0.00121	-0.05239	0.32126	-0.02617
-0.3604	-0.00707	-0.05624	0.31495	-0.03100
-0.3535	-0.01381	-0.05896	0.30817	-0.03478
-0.3524	-0.01492	-0.05940	0.30765	-0.03543
-0.3445	-0.02181	-0.06197	0.29767	-0.03919
-0.3367	-0.02777	-0.06418	0.28593	-0.04247
-0.3289	-0.03280	-0.06604	0.27217	-0.04529
-0.3225	-0.03651	-0.06738	0.25910	-0.04738
-0.3213	-0.03724	-0.06764	0.25709	-0.04782
-0.3138	-0.04099	-0.06891	0.23920	-0.04988
-0.3063	-0.04428	-0.06994	0.21965	-0.05162
-0.2989	-0.04714	-0.07072	0.19857	-0.05306
-0.2916	-0.04964	-0.07131	0.17664	-0.05425
-0.2901	-0.05013	-0.07141	0.17196	-0.05447

-0.2844	-0.05189	-0.07173	0.15374	-0.05526
-0.2773	-0.05378	-0.07196	0.13209	-0.05602
-0.2702	-0.05540	-0.07204	0.11230	-0.05659
-0.2632	-0.05676	-0.07197	0.09504	-0.05700
-0.2563	-0.05789	-0.07177	0.08015	-0.05725
-0.2558	-0.05797	-0.07175	0.07910	-0.05726
-0.2494	-0.05886	-0.07145	0.06658	-0.05738
-0.2426	-0.05958	-0.07100	0.05583	-0.05736
-0.2359	-0.06013	-0.07045	0.04646	-0.05721
-0.2293	-0.06049	-0.06978	0.03831	-0.05695
-0.2227	-0.06069	-0.06903	0.03097	-0.05658
-0.2182	-0.06076	-0.06847	0.02627	-0.05628
-0.2161	-0.06076	-0.06817	0.02380	-0.05611
-0.2096	-0.06067	-0.06723	0.01783	-0.05555
-0.2032	-0.06044	-0.06620	0.01240	-0.05489
-0.1969	-0.06008	-0.06510	0.00750	-0.05414
-0.1905	-0.05958	-0.06392	0.00318	-0.05332
-0.1843	-0.05897	-0.06267	-0.00074	-0.05242
-0.1781	-0.05825	-0.06135	-0.00428	-0.05144
-0.1754	-0.05792	-0.06077	-0.00586	-0.05101
-0.1719	-0.05742	-0.05996	-0.00794	-0.05040
-0.1658	-0.05648	-0.05851	-0.01078	-0.04929
-0.1597	-0.05544	-0.05701	-0.01332	-0.04812
-0.1537	-0.05431	-0.05545	-0.01558	-0.04690
-0.1478	-0.05308	-0.05384	-0.01752	-0.04562
-0.1418	-0.05177	-0.05218	-0.01915	-0.04428
-0.1359	-0.05038	-0.05048	-0.02054	-0.04290
-0.1301	-0.04891	-0.04873	-0.02169	-0.04148
-0.1243	-0.04736	-0.04694	-0.02261	-0.04001
-0.1216	-0.04663	-0.04611	-0.02310	-0.03932
-0.1185	-0.04574	-0.04511	-0.02377	-0.03849
-0.1128	-0.04406	-0.04325	-0.02423	-0.03694
-0.1071	-0.04231	-0.04135	-0.02449	-0.03536
-0.1015	-0.04051	-0.03943	-0.02456	-0.03375
-0.0959	-0.03865	-0.03748	-0.02446	-0.03210
-0.0903	-0.03674	-0.03550	-0.02418	-0.03043
-0.0847	-0.03479	-0.03350	-0.02375	-0.02874
-0.0792	-0.03279	-0.03147	-0.02311	-0.02702
-0.0737	-0.03075	-0.02943	-0.02233	-0.02528

-0.0683	-0.02867	-0.02737	-0.02143	-0.02352
-0.0629	-0.02656	-0.02530	-0.02040	-0.02175
-0.0575	-0.02443	-0.02322	-0.01927	-0.01997
-0.0521	-0.02227	-0.02112	-0.01803	-0.01817
-0.0468	-0.02008	-0.01902	-0.01670	-0.01636
-0.0415	-0.01788	-0.01691	-0.01528	-0.01454
-0.0362	-0.01567	-0.01479	-0.01379	-0.01272
-0.0310	-0.01344	-0.01267	-0.01223	-0.01090
-0.0257	-0.01120	-0.01055	-0.01061	-0.00907
-0.0205	-0.00896	-0.00843	-0.00895	-0.00724
-0.0154	-0.00672	-0.00632	-0.00724	-0.00542
-0.0102	-0.00447	-0.00421	-0.00551	-0.00359
-0.0051	-0.00223	-0.00210	-0.00376	-0.00177
0.0000	0.00000	0.00000	-0.00201	0.00004
0.0051	0.00223	0.00210	-0.00025	0.00185
0.0102	0.00447	0.00420	0.00151	0.00367
0.0154	0.00672	0.00632	0.00325	0.00550
0.0205	0.00896	0.00843	0.00498	0.00732
0.0257	0.01120	0.01055	0.00667	0.00915
0.0310	0.01344	0.01267	0.00831	0.01098
0.0362	0.01567	0.01479	0.00990	0.01280
0.0415	0.01788	0.01690	0.01144	0.01462
0.0468	0.02008	0.01901	0.01290	0.01644
0.0521	0.02227	0.02112	0.01428	0.01825
0.0575	0.02443	0.02321	0.01557	0.02004
0.0629	0.02656	0.02530	0.01676	0.02183
0.0683	0.02867	0.02737	0.01785	0.02360
0.0737	0.03075	0.02943	0.01882	0.02536
0.0792	0.03279	0.03147	0.01966	0.02709
0.0847	0.03479	0.03349	0.02038	0.02881
0.0903	0.03674	0.03550	0.02084	0.03051
0.0959	0.03865	0.03748	0.02113	0.03218
0.1015	0.04051	0.03943	0.02125	0.03382
0.1071	0.04231	0.04136	0.02119	0.03544
0.1128	0.04406	0.04325	0.02094	0.03702
0.1185	0.04574	0.04511	0.02049	0.03857
0.1216	0.04663	0.04611	0.02030	0.03939
0.1243	0.04736	0.04694	0.01986	0.04008
0.1301	0.04891	0.04873	0.01903	0.04155

0.1359	0.05038	0.05048	0.01797	0.04297
0.1418	0.05177	0.05218	0.01668	0.04435
0.1478	0.05308	0.05384	0.01515	0.04568
0.1537	0.05431	0.05545	0.01326	0.04696
0.1597	0.05544	0.05701	0.01099	0.04819
0.1658	0.05648	0.05852	0.00843	0.04936
0.1719	0.05741	0.05996	0.00557	0.05047
0.1754	0.05792	0.06077	0.00396	0.05108
0.1781	0.05825	0.06135	0.00243	0.05151
0.1843	0.05897	0.06267	-0.00101	0.05248
0.1905	0.05958	0.06392	-0.00482	0.05338
0.1969	0.06008	0.06510	-0.00904	0.05420
0.2032	0.06044	0.06620	-0.01397	0.05495
0.2096	0.06066	0.06723	-0.01946	0.05560
0.2161	0.06075	0.06817	-0.02551	0.05616
0.2182	0.06078	0.06848	-0.02734	0.05634
0.2227	0.06069	0.06902	-0.03208	0.05663
0.2293	0.06049	0.06978	-0.03931	0.05700
0.2359	0.06013	0.07045	-0.04736	0.05726
0.2426	0.05958	0.07100	-0.05685	0.05740
0.2494	0.05883	0.07144	-0.06789	0.05742
0.2558	0.05797	0.07175	-0.07966	0.05731
0.2563	0.05789	0.07177	-0.08069	0.05730
0.2632	0.05676	0.07197	-0.09545	0.05704
0.2702	0.05540	0.07204	-0.11257	0.05664
0.2773	0.05377	0.07196	-0.13243	0.05606
0.2844	0.05185	0.07172	-0.15417	0.05527
0.2901	0.05013	0.07141	-0.17180	0.05451
0.2916	0.04964	0.07131	-0.17644	0.05429
0.2989	0.04714	0.07072	-0.19824	0.05310
0.3063	0.04428	0.06994	-0.21919	0.05166
0.3138	0.04094	0.06890	-0.23843	0.04988
0.3213	0.03713	0.06760	-0.25595	0.04777
0.3225	0.03661	0.06743	-0.25841	0.04748
0.3289	0.03280	0.06604	-0.27149	0.04533
0.3367	0.02777	0.06418	-0.28524	0.04251
0.3445	0.02173	0.06194	-0.29674	0.03917
0.3524	0.01476	0.05932	-0.30643	0.03534
0.3535	0.01395	0.05905	-0.30756	0.03491

0.3604	0.00707	0.05624	-0.31437	0.03104
0.3686	-0.00121	0.05240	-0.32073	0.02621
0.3768	-0.00985	0.04707	-0.32488	0.02061
0.3835	-0.01676	0.04198	-0.32710	0.01572
0.3851	-0.01848	0.04058	-0.32750	0.01443
0.3936	-0.02681	0.03334	-0.32850	0.00771
0.4021	-0.03460	0.02584	-0.32762	0.00037
0.4108	-0.04158	0.01860	-0.32499	-0.00755
0.4128	-0.04307	0.01706	-0.32429	-0.00928
0.4196	-0.04763	0.01178	-0.32132	-0.01576
0.4286	-0.05266	0.00528	-0.31694	-0.02420
0.4376	-0.05646	-0.00085	-0.31198	-0.03273
0.4417	-0.05786	-0.00342	-0.30976	-0.03640
0.4469	-0.05923	-0.00653	-0.30698	-0.04099
0.4562	-0.06105	-0.01161	-0.30204	-0.04875
0.4657	-0.06190	-0.01575	-0.29700	-0.05555
0.4704	-0.06209	-0.01747	-0.29460	-0.05847
0.4754	-0.06208	-0.01896	-0.29208	-0.06111
0.4852	-0.06174	-0.02116	-0.28725	-0.06517
0.4951	-0.06102	-0.02217	-0.28233	-0.06731
0.4989	-0.06070	-0.02235	-0.28051	-0.06779
0.5053	-0.06010	-0.02222	-0.27751	-0.06798
0.5156	-0.05910	-0.02143	-0.27273	-0.06755
0.5261	-0.05812	-0.01991	-0.26790	-0.06665
0.5275	-0.05799	-0.01972	-0.26728	-0.06649
0.5367	-0.05721	-0.01796	-0.26317	-0.06577
0.5476	-0.05639	-0.01579	-0.25843	-0.06521
0.5561	-0.05584	-0.01409	-0.25478	-0.06495
0.5587	-0.05569	-0.01358	-0.25367	-0.06489
0.5699	-0.05505	-0.01145	-0.24901	-0.06459
0.5814	-0.05449	-0.00963	-0.24426	-0.06422
0.5849	-0.05433	-0.00911	-0.24289	-0.06407
0.5931	-0.05396	-0.00805	-0.23958	-0.06373
0.6051	-0.05343	-0.00678	-0.23489	-0.06318
0.6139	-0.05304	-0.00604	-0.23148	-0.06275
0.6173	-0.05289	-0.00580	-0.23018	-0.06259
0.6297	-0.05232	-0.00502	-0.22554	-0.06194
0.6424	-0.05172	-0.00447	-0.22080	-0.06126
0.6433	-0.05168	-0.00441	-0.22053	-0.06120

0.6554	-0.05106	-0.00400	-0.21615	-0.06051
0.6687	-0.05036	-0.00363	-0.21143	-0.05973
0.6730	-0.05013	-0.00350	-0.20995	-0.05945
0.6822	-0.04961	-0.00328	-0.20675	-0.05889
0.6961	-0.04880	-0.00293	-0.20204	-0.05800
0.7032	-0.04838	-0.00275	-0.19970	-0.05753
0.7103	-0.04794	-0.00258	-0.19733	-0.05707
0.7248	-0.04703	-0.00220	-0.19262	-0.05610
0.7339	-0.04645	-0.00195	-0.18975	-0.05547
0.7397	-0.04607	-0.00179	-0.18789	-0.05508
0.7550	-0.04505	-0.00135	-0.18317	-0.05401
0.7651	-0.04437	-0.00104	-0.18009	-0.05328
0.7706	-0.04399	-0.00088	-0.17842	-0.05290
0.7867	-0.04288	-0.00037	-0.17369	-0.05174
0.7970	-0.04215	-0.00004	-0.17071	-0.05098
0.8031	-0.04172	0.00016	-0.16892	-0.05054
0.8200	-0.04051	0.00073	-0.16418	-0.04930
0.8295	-0.03983	0.00106	-0.16160	-0.04860
0.8374	-0.03925	0.00133	-0.15941	-0.04802
0.8553	-0.03796	0.00195	-0.15465	-0.04670
0.8627	-0.03742	0.00222	-0.15275	-0.04614
0.8736	-0.03662	0.00260	-0.14989	-0.04534
0.8926	-0.03525	0.00327	-0.14512	-0.04395
0.8966	-0.03495	0.00343	-0.14415	-0.04364
0.9120	-0.03383	0.00397	-0.14038	-0.04252
0.9314	-0.03244	0.00466	-0.13577	-0.04111
0.9321	-0.03239	0.00468	-0.13561	-0.04106
0.9528	-0.03091	0.00542	-0.13089	-0.03957
0.9671	-0.02991	0.00592	-0.12774	-0.03856
0.9742	-0.02941	0.00617	-0.12616	-0.03806
0.9963	-0.02788	0.00693	-0.12145	-0.03652
1.0036	-0.02739	0.00718	-0.11996	-0.03601
1.0191	-0.02633	0.00770	-0.11678	-0.03496
1.0412	-0.02487	0.00842	-0.11240	-0.03348
1.0427	-0.02477	0.00847	-0.11210	-0.03338
1.0671	-0.02319	0.00925	-0.10748	-0.03179
1.0797	-0.02240	0.00965	-0.10520	-0.03097
1.0924	-0.02161	0.01003	-0.10288	-0.03018
1.1187	-0.02002	0.01080	-0.09831	-0.02856

1.1193	-0.01998	0.01083	-0.09825	-0.02852
1.1460	-0.01843	0.01158	-0.09381	-0.02694
1.1601	-0.01763	0.01197	-0.09158	-0.02612
1.1743	-0.01684	0.01234	-0.08934	-0.02532
1.2021	-0.01535	0.01304	-0.08516	-0.02380
1.2038	-0.01526	0.01308	-0.08491	-0.02370
1.2345	-0.01370	0.01381	-0.08057	-0.02209
1.2453	-0.01317	0.01407	-0.07911	-0.02154
1.2664	-0.01215	0.01452	-0.07627	-0.02050
1.2898	-0.01107	0.01501	-0.07330	-0.01937
1.2998	-0.01063	0.01521	-0.07205	-0.01891
1.3346	-0.00913	0.01586	-0.06789	-0.01734
1.3357	-0.00909	0.01589	-0.06781	-0.01728
1.3711	-0.00767	0.01649	-0.06384	-0.01580
1.3831	-0.00721	0.01669	-0.06258	-0.01530
1.4093	-0.00624	0.01708	-0.05986	-0.01428
1.4320	-0.00544	0.01740	-0.05764	-0.01342
1.4493	-0.00485	0.01763	-0.05596	-0.01280
1.4824	-0.00379	0.01803	-0.05296	-0.01164
1.4914	-0.00352	0.01813	-0.05217	-0.01135
1.5346	-0.00226	0.01858	-0.04856	-0.00997
1.5356	-0.00223	0.01859	-0.04847	-0.00994
1.5822	-0.00099	0.01900	-0.04489	-0.00857
1.5884	-0.00084	0.01906	-0.04446	-0.00839
1.6314	0.00018	0.01936	-0.04141	-0.00726
1.6441	0.00047	0.01945	-0.04059	-0.00693
1.6834	0.00130	0.01966	-0.03805	-0.00599
1.7016	0.00166	0.01976	-0.03696	-0.00557
1.7385	0.00234	0.01990	-0.03481	-0.00478
1.7612	0.00274	0.01999	-0.03358	-0.00431
1.7969	0.00332	0.02008	-0.03169	-0.00363
1.8228	0.00372	0.02015	-0.03043	-0.00315
1.8590	0.00422	0.02020	-0.02870	-0.00254
1.8865	0.00459	0.02024	-0.02749	-0.00209
1.9252	0.00505	0.02025	-0.02585	-0.00152
1.9526	0.00536	0.02027	-0.02477	-0.00112
1.9960	0.00580	0.02023	-0.02312	-0.00056

Table A.2.11 U/U_∞ at $x/D = 1.5$ with $Re = 10^6$

y/D	k-ω RANS	SST RANS	k-ω URANS	SST URANS
-1.99250	1.05690	1.06950	1.02390	1.05730
-1.94840	1.05810	1.07110	1.02390	1.05860
-1.92220	1.05880	1.07210	1.02380	1.05940
-1.90560	1.05920	1.07270	1.02380	1.05980
-1.86420	1.06030	1.07430	1.02360	1.06110
-1.82630	1.06140	1.07580	1.02350	1.06220
-1.82400	1.06140	1.07580	1.02340	1.06220
-1.78510	1.06250	1.07740	1.02320	1.06350
-1.74730	1.06360	1.07890	1.02290	1.06460
-1.73220	1.06410	1.07960	1.02280	1.06520
-1.71050	1.06470	1.08050	1.02260	1.06580
-1.67480	1.06570	1.08200	1.02220	1.06690
-1.64010	1.06670	1.08350	1.02180	1.06810
-1.63960	1.06680	1.08350	1.02180	1.06810
-1.60630	1.06770	1.08490	1.02130	1.06920
-1.57330	1.06870	1.08640	1.02080	1.07030
-1.54810	1.06950	1.08760	1.02030	1.07110
-1.54120	1.06970	1.08790	1.02020	1.07130
-1.51000	1.07070	1.08930	1.01950	1.07240
-1.47950	1.07160	1.09080	1.01890	1.07350
-1.45780	1.07230	1.09180	1.01840	1.07420
-1.44970	1.07250	1.09220	1.01810	1.07450
-1.42060	1.07340	1.09360	1.01740	1.07550
-1.39220	1.07430	1.09500	1.01660	1.07650
-1.36810	1.07500	1.09620	1.01580	1.07740
-1.36450	1.07510	1.09630	1.01570	1.07740
-1.33740	1.07600	1.09770	1.01480	1.07840
-1.31080	1.07680	1.09910	1.01380	1.07940
-1.28490	1.07760	1.10040	1.01280	1.08030
-1.27870	1.07780	1.10070	1.01260	1.08060
-1.25950	1.07840	1.10170	1.01170	1.08120
-1.23460	1.07920	1.10310	1.01060	1.08220
-1.21020	1.08000	1.10440	1.00950	1.08310
-1.18920	1.08060	1.10550	1.00840	1.08390
-1.18630	1.08070	1.10560	1.00820	1.08390
-1.16280	1.08150	1.10690	1.00700	1.08480
-1.13990	1.08220	1.10820	1.00570	1.08570

-1.11730	1.08290	1.10940	1.00430	1.08650
-1.09910	1.08350	1.11040	1.00320	1.08720
-1.09520	1.08360	1.11060	1.00290	1.08730
-1.07340	1.08430	1.11190	1.00150	1.08820
-1.05210	1.08490	1.11310	0.99997	1.08900
-1.03110	1.08560	1.11430	0.99843	1.08980
-1.01050	1.08620	1.11540	0.99684	1.09050
-1.00770	1.08630	1.11560	0.99662	1.09070
-0.99024	1.08680	1.11660	0.99518	1.09130
-0.97030	1.08750	1.11780	0.99350	1.09210
-0.95069	1.08810	1.11890	0.99177	1.09280
-0.93140	1.08860	1.12000	0.99000	1.09360
-0.91410	1.08920	1.12100	0.98834	1.09420
-0.91241	1.08920	1.12110	0.98813	1.09420
-0.89370	1.08980	1.12220	0.98627	1.09500
-0.87528	1.09030	1.12330	0.98435	1.09570
-0.85714	1.09090	1.12430	0.98239	1.09640
-0.83926	1.09140	1.12530	0.98038	1.09710
-0.82164	1.09190	1.12620	0.97832	1.09780
-0.81692	1.09200	1.12650	0.97775	1.09800
-0.80426	1.09240	1.12710	0.97617	1.09840
-0.78713	1.09290	1.12780	0.97402	1.09910
-0.77023	1.09330	1.12840	0.97182	1.09980
-0.75355	1.09370	1.12870	0.96958	1.10050
-0.73709	1.09410	1.12870	0.96729	1.10110
-0.72085	1.09450	1.12820	0.96494	1.10170
-0.71421	1.09460	1.12790	0.96395	1.10210
-0.70481	1.09480	1.12730	0.96251	1.10230
-0.68897	1.09490	1.12530	0.96007	1.10300
-0.67333	1.09500	1.12220	0.95759	1.10360
-0.65787	1.09480	1.11780	0.95507	1.10420
-0.64260	1.09420	1.11140	0.95254	1.10490
-0.62750	1.09320	1.10300	0.95000	1.10570
-0.61258	1.09160	1.09210	0.94731	1.10660
-0.60252	1.09020	1.08320	0.94519	1.10730
-0.59782	1.08960	1.07950	0.94395	1.10750
-0.58323	1.08640	1.06240	0.93938	1.10780
-0.56880	1.08190	1.04180	0.93329	1.10660
-0.55451	1.07590	1.01740	0.92566	1.10280

-0.54038	1.06830	0.98918	0.91659	1.09540
-0.52639	1.05840	0.95682	0.90631	1.08350
-0.51255	1.04630	0.92078	0.89508	1.06680
-0.49884	1.03150	0.88140	0.88319	1.04550
-0.48527	1.01380	0.83912	0.87089	1.01980
-0.47482	0.99802	0.80443	0.86116	0.99702
-0.47182	0.99427	0.79509	0.85845	0.99233
-0.45851	0.97008	0.74825	0.84584	0.95857
-0.44531	0.94257	0.70036	0.83322	0.92152
-0.43224	0.91181	0.65203	0.82062	0.88160
-0.41928	0.87784	0.60376	0.80814	0.83927
-0.40644	0.84076	0.55599	0.79595	0.79501
-0.39370	0.80063	0.50909	0.78424	0.74914
-0.38108	0.75774	0.46332	0.77316	0.70227
-0.36856	0.71250	0.41886	0.76272	0.65512
-0.35614	0.66531	0.37582	0.75292	0.60815
-0.34382	0.61660	0.33428	0.74372	0.56176
-0.33160	0.56682	0.29427	0.73512	0.51627
-0.31948	0.51642	0.25580	0.72710	0.47191
-0.31093	0.48016	0.22911	0.72163	0.44076
-0.30745	0.46576	0.21832	0.71983	0.42858
-0.29550	0.41521	0.18286	0.71289	0.38666
-0.28365	0.36536	0.14888	0.70650	0.34624
-0.27188	0.31660	0.11636	0.70068	0.30732
-0.26019	0.26933	0.08524	0.69538	0.26987
-0.24858	0.22399	0.05549	0.69059	0.23384
-0.23706	0.18106	0.02709	0.68628	0.19920
-0.22561	0.14086	0.00006	0.68242	0.16590
-0.21423	0.10321	-0.02550	0.67899	0.13392
-0.20293	0.06757	-0.04958	0.67595	0.10322
-0.19170	0.03365	-0.07219	0.67327	0.07380
-0.18055	0.00148	-0.09334	0.67092	0.04571
-0.16945	-0.02882	-0.11307	0.66886	0.01890
-0.15843	-0.05722	-0.13144	0.66708	-0.00660
-0.14747	-0.08376	-0.14846	0.66554	-0.03079
-0.13657	-0.10848	-0.16416	0.66421	-0.05363
-0.12574	-0.13141	-0.17857	0.66308	-0.07507
-0.11496	-0.15256	-0.19171	0.66212	-0.09505
-0.10425	-0.17193	-0.20361	0.66130	-0.11352

-0.09359	-0.18953	-0.21429	0.66061	-0.13040
-0.08298	-0.20532	-0.22377	0.66004	-0.14564
-0.07243	-0.21930	-0.23206	0.65955	-0.15918
-0.06194	-0.23146	-0.23919	0.65915	-0.17096
-0.05149	-0.24176	-0.24517	0.65883	-0.18095
-0.04110	-0.25020	-0.25003	0.65857	-0.18913
-0.03075	-0.25676	-0.25379	0.65837	-0.19548
-0.02046	-0.26144	-0.25645	0.65824	-0.20000
-0.01021	-0.26424	-0.25803	0.65815	-0.20270
0.00000	-0.26546	-0.25881	0.65827	-0.20432
0.01021	-0.26424	-0.25804	0.65813	-0.20268
0.02046	-0.26144	-0.25645	0.65819	-0.19996
0.03075	-0.25676	-0.25379	0.65831	-0.19541
0.04110	-0.25020	-0.25004	0.65849	-0.18904
0.05149	-0.24176	-0.24518	0.65872	-0.18084
0.06194	-0.23146	-0.23919	0.65903	-0.17083
0.07243	-0.21930	-0.23206	0.65941	-0.15902
0.08298	-0.20532	-0.22377	0.65987	-0.14547
0.09359	-0.18953	-0.21430	0.66043	-0.13020
0.10425	-0.17193	-0.20362	0.66110	-0.11329
0.11496	-0.15256	-0.19172	0.66191	-0.09480
0.12574	-0.13141	-0.17858	0.66286	-0.07480
0.13657	-0.10848	-0.16417	0.66398	-0.05334
0.14747	-0.08376	-0.14847	0.66529	-0.03048
0.15843	-0.05722	-0.13145	0.66683	-0.00627
0.16945	-0.02882	-0.11309	0.66861	0.01925
0.18055	0.00148	-0.09335	0.67066	0.04607
0.19170	0.03365	-0.07220	0.67302	0.07419
0.20293	0.06762	-0.04956	0.67568	0.10370
0.21423	0.10333	-0.02544	0.67871	0.13448
0.22561	0.14108	0.00017	0.68214	0.16654
0.23706	0.18137	0.02723	0.68600	0.19991
0.24858	0.22435	0.05568	0.69031	0.23461
0.26019	0.26969	0.08548	0.69512	0.27068
0.27188	0.31692	0.11666	0.70043	0.30815
0.28365	0.36562	0.14925	0.70629	0.34706
0.29550	0.41538	0.18328	0.71269	0.38743
0.30745	0.46581	0.21881	0.71967	0.42923
0.31093	0.47990	0.22877	0.72153	0.44077

0.31948	0.51642	0.25578	0.72718	0.47232
0.33160	0.56681	0.29425	0.73527	0.51667
0.34382	0.61660	0.33426	0.74396	0.56214
0.35614	0.66531	0.37580	0.75323	0.60852
0.36856	0.71250	0.41884	0.76313	0.65548
0.38108	0.75774	0.46330	0.77366	0.70262
0.39370	0.80063	0.50906	0.78487	0.74948
0.40644	0.84068	0.55597	0.79668	0.79517
0.41928	0.87756	0.60374	0.80898	0.83897
0.43224	0.91131	0.65195	0.82156	0.88083
0.44531	0.94185	0.70016	0.83426	0.92029
0.45851	0.96914	0.74786	0.84698	0.95695
0.47182	0.99313	0.79442	0.85969	0.99040
0.47482	0.99827	0.80435	0.86245	0.99769
0.48527	1.01380	0.83910	0.87231	1.02020
0.49884	1.03150	0.88138	0.88470	1.04590
0.51255	1.04630	0.92076	0.89666	1.06720
0.52639	1.05840	0.95679	0.90794	1.08380
0.54038	1.06830	0.98917	0.91825	1.09580
0.55451	1.07580	1.01710	0.92731	1.10300
0.56880	1.08170	1.04120	0.93492	1.10660
0.58323	1.08610	1.06160	0.94099	1.10790
0.59782	1.08930	1.07840	0.94552	1.10770
0.60252	1.09030	1.08340	0.94679	1.10760
0.61258	1.09160	1.09210	0.94879	1.10690
0.62750	1.09320	1.10300	0.95143	1.10600
0.64260	1.09420	1.11140	0.95393	1.10520
0.65787	1.09480	1.11780	0.95643	1.10450
0.67333	1.09490	1.12210	0.95893	1.10380
0.68897	1.09490	1.12510	0.96139	1.10320
0.70481	1.09470	1.12710	0.96379	1.10260
0.71421	1.09460	1.12790	0.96518	1.10230
0.72085	1.09450	1.12820	0.96615	1.10190
0.73709	1.09410	1.12870	0.96846	1.10130
0.75355	1.09370	1.12870	0.97072	1.10060
0.77023	1.09330	1.12840	0.97293	1.10000
0.78713	1.09290	1.12780	0.97512	1.09930
0.80426	1.09240	1.12710	0.97725	1.09870
0.81692	1.09200	1.12650	0.97877	1.09820

0.82164	1.09190	1.12620	0.97933	1.09800
0.83926	1.09140	1.12530	0.98136	1.09730
0.85714	1.09090	1.12430	0.98334	1.09660
0.87528	1.09030	1.12330	0.98528	1.09590
0.89370	1.08980	1.12220	0.98718	1.09520
0.91241	1.08920	1.12110	0.98903	1.09440
0.91410	1.08920	1.12110	0.98921	1.09450
0.93140	1.08860	1.12000	0.99084	1.09370
0.95069	1.08810	1.11890	0.99259	1.09300
0.97030	1.08750	1.11780	0.99429	1.09220
0.99024	1.08680	1.11660	0.99596	1.09140
1.00770	1.08630	1.11560	0.99736	1.09080
1.01050	1.08620	1.11540	0.99758	1.09060
1.03110	1.08560	1.11430	0.99915	1.08990
1.05210	1.08490	1.11310	1.00070	1.08910
1.07340	1.08430	1.11190	1.00210	1.08830
1.09520	1.08360	1.11060	1.00360	1.08740
1.09910	1.08350	1.11050	1.00380	1.08740
1.11730	1.08290	1.10940	1.00500	1.08660
1.13990	1.08220	1.10820	1.00630	1.08570
1.16280	1.08150	1.10690	1.00760	1.08490
1.18630	1.08070	1.10560	1.00880	1.08400
1.18920	1.08070	1.10550	1.00900	1.08400
1.21020	1.08000	1.10430	1.01000	1.08310
1.23460	1.07920	1.10310	1.01110	1.08220
1.25950	1.07840	1.10170	1.01220	1.08130
1.27870	1.07780	1.10070	1.01300	1.08060
1.28490	1.07760	1.10040	1.01330	1.08040
1.31080	1.07680	1.09910	1.01430	1.07950
1.33740	1.07600	1.09770	1.01520	1.07850
1.36450	1.07510	1.09630	1.01610	1.07750
1.36810	1.07510	1.09620	1.01630	1.07750
1.39220	1.07430	1.09500	1.01700	1.07650
1.42060	1.07340	1.09360	1.01780	1.07550
1.44970	1.07250	1.09220	1.01850	1.07450
1.45780	1.07230	1.09180	1.01870	1.07430
1.47950	1.07160	1.09080	1.01920	1.07350
1.51000	1.07070	1.08930	1.01990	1.07240
1.54120	1.06970	1.08790	1.02050	1.07140

1.54810	1.06950	1.08760	1.02060	1.07120
1.57330	1.06870	1.08640	1.02110	1.07030
1.60630	1.06780	1.08500	1.02160	1.06920
1.63960	1.06680	1.08350	1.02200	1.06810
1.64010	1.06670	1.08350	1.02200	1.06810
1.67480	1.06570	1.08200	1.02250	1.06700
1.71050	1.06470	1.08050	1.02280	1.06580
1.73220	1.06410	1.07960	1.02300	1.06520
1.74730	1.06360	1.07890	1.02320	1.06470
1.78510	1.06250	1.07740	1.02340	1.06350
1.82400	1.06140	1.07580	1.02370	1.06230
1.82630	1.06140	1.07580	1.02370	1.06230
1.86420	1.06030	1.07430	1.02380	1.06110
1.90560	1.05920	1.07270	1.02400	1.05980
1.92220	1.05880	1.07210	1.02400	1.05940
1.94840	1.05810	1.07110	1.02410	1.05860
1.99250	1.05690	1.06950	1.02410	1.05730

Table A.2.12 V/U_∞ at $x/D = 1.5$ with $Re = 10^6$

y/D	k-ω RANS	SST RANS	k-ω URANS	SST URANS
-1.99250	0.0232970	0.0147320	0.0366900	0.0340410
-1.94840	0.0246420	0.0159300	0.0383760	0.0358370
-1.92220	0.0254760	0.0166740	0.0394220	0.0369550
-1.90560	0.0260210	0.0171770	0.0400510	0.0376830
-1.86420	0.0274120	0.0184290	0.0417770	0.0395540
-1.82630	0.0287370	0.0196330	0.0434000	0.0413420
-1.82400	0.0288320	0.0197290	0.0434710	0.0414690
-1.78510	0.0302650	0.0210310	0.0452340	0.0434120
-1.74730	0.0317110	0.0223560	0.0469920	0.0453790
-1.73220	0.0323150	0.0229070	0.0477340	0.0462050
-1.71050	0.0331940	0.0237310	0.0487380	0.0474050
-1.67480	0.0346800	0.0251050	0.0505240	0.0494440
-1.64010	0.0361780	0.0265030	0.0522970	0.0515090
-1.63960	0.0362010	0.0265240	0.0523240	0.0515410
-1.60630	0.0377150	0.0279460	0.0540800	0.0536410
-1.57330	0.0392470	0.0293840	0.0558820	0.0557730
-1.54810	0.0404590	0.0305280	0.0572950	0.0574710
-1.54120	0.0408120	0.0308760	0.0576440	0.0579650
-1.51000	0.0423770	0.0323570	0.0594650	0.0601690

-1.47950	0.0439500	0.0338560	0.0612740	0.0623940
-1.45780	0.0451070	0.0349620	0.0625960	0.0640410
-1.44970	0.0455600	0.0354110	0.0630400	0.0646860
-1.42060	0.0471640	0.0369520	0.0648610	0.0669840
-1.39220	0.0487740	0.0385080	0.0666670	0.0693030
-1.36810	0.0501870	0.0398830	0.0682270	0.0713500
-1.36450	0.0504240	0.0401260	0.0684180	0.0716940
-1.33740	0.0520620	0.0417200	0.0702340	0.0740840
-1.31080	0.0537090	0.0433350	0.0720260	0.0765010
-1.28490	0.0553640	0.0449690	0.0737960	0.0789440
-1.27870	0.0557710	0.0453670	0.0742430	0.0795500
-1.25950	0.0570640	0.0466590	0.0755450	0.0814740
-1.23460	0.0587480	0.0483340	0.0773150	0.0839960
-1.21020	0.0604310	0.0500140	0.0790700	0.0865310
-1.18920	0.0619190	0.0515090	0.0805890	0.0887900
-1.18630	0.0621650	0.0517690	0.0807550	0.0891650
-1.16280	0.0638750	0.0534880	0.0825080	0.0917790
-1.13990	0.0655960	0.0552310	0.0842260	0.0944300
-1.11730	0.0673200	0.0569850	0.0859240	0.0971010
-1.09910	0.0687490	0.0584440	0.0873080	0.0993330
-1.09520	0.0691010	0.0588170	0.0875490	0.0998850
-1.07340	0.0708490	0.0606070	0.0892380	0.1026400
-1.05210	0.0726120	0.0624240	0.0908890	0.1054300
-1.03110	0.0743740	0.0642480	0.0925190	0.1082500
-1.01050	0.0761530	0.0661010	0.0941070	0.1111100
-1.00770	0.0763990	0.0663550	0.0943380	0.1115100
-0.99024	0.0779910	0.0680250	0.0956640	0.1140900
-0.97030	0.0797950	0.0699140	0.0972390	0.1170400
-0.95069	0.0816040	0.0718180	0.0987810	0.1200200
-0.93140	0.0834220	0.0737420	0.1002900	0.1230400
-0.91410	0.0850950	0.0755190	0.1016400	0.1258400
-0.91241	0.0853180	0.0757640	0.1017100	0.1262200
-0.89370	0.0871600	0.0777230	0.1031900	0.1293300
-0.87528	0.0890210	0.0797160	0.1046400	0.1325000
-0.85714	0.0908900	0.0817270	0.1060400	0.1357100
-0.83926	0.0927680	0.0837590	0.1074100	0.1389500
-0.82164	0.0946680	0.0858270	0.1087400	0.1422600
-0.81692	0.0951900	0.0863890	0.1091300	0.1431800
-0.80426	0.0966500	0.0879920	0.1100000	0.1457500

-0.78713	0.0985750	0.0901100	0.1112900	0.1491700
-0.77023	0.1005300	0.0922720	0.1125300	0.1526500
-0.75355	0.1024800	0.0944580	0.1137400	0.1561700
-0.73709	0.1044500	0.0966880	0.1149100	0.1597500
-0.72085	0.1064500	0.0989690	0.1160200	0.1634000
-0.71421	0.1072900	0.0999170	0.1165400	0.1649600
-0.70481	0.1085600	0.1013700	0.1170500	0.1672900
-0.68897	0.1105900	0.1037300	0.1181200	0.1710700
-0.67333	0.1126700	0.1061300	0.1191400	0.1749400
-0.65787	0.1147700	0.1085600	0.1201100	0.1788800
-0.64260	0.1168800	0.1109800	0.1210300	0.1828500
-0.62750	0.1190300	0.1133900	0.1218800	0.1869200
-0.61258	0.1212000	0.1157500	0.1227100	0.1910700
-0.60252	0.1227000	0.1173200	0.1233800	0.1939900
-0.59782	0.1235100	0.1181700	0.1236000	0.1955800
-0.58323	0.1257000	0.1202900	0.1249400	0.1999500
-0.56880	0.1279000	0.1222200	0.1266700	0.2045100
-0.55451	0.1300700	0.1238900	0.1287400	0.2092700
-0.54038	0.1321800	0.1252600	0.1310500	0.2142100
-0.52639	0.1341900	0.1262200	0.1335200	0.2192100
-0.51255	0.1360600	0.1267700	0.1360000	0.2242000
-0.49884	0.1377500	0.1268800	0.1383900	0.2290100
-0.48527	0.1392200	0.1265200	0.1405900	0.2334800
-0.47482	0.1401600	0.1259100	0.1422000	0.2365900
-0.47182	0.1406200	0.1259300	0.1424600	0.2382700
-0.45851	0.1414200	0.1246000	0.1442200	0.2413500
-0.44531	0.1418100	0.1228500	0.1456900	0.2434500
-0.43224	0.1417300	0.1207200	0.1468800	0.2444500
-0.41928	0.1411400	0.1182700	0.1477500	0.2442500
-0.40644	0.1400100	0.1155300	0.1482500	0.2428000
-0.39370	0.1383000	0.1125300	0.1483200	0.2400100
-0.38108	0.1359900	0.1093400	0.1479400	0.2359700
-0.36856	0.1331100	0.1060100	0.1471200	0.2308900
-0.35614	0.1296900	0.1025600	0.1458800	0.2249100
-0.34382	0.1257400	0.0990440	0.1442400	0.2181700
-0.33160	0.1213300	0.0954740	0.1422500	0.2108300
-0.31948	0.1165000	0.0918760	0.1399000	0.2030300
-0.31093	0.1128100	0.0892620	0.1381100	0.1971500
-0.30745	0.1114900	0.0883350	0.1371600	0.1951800

-0.29550	0.1059800	0.0847010	0.1342300	0.1866600
-0.28365	0.1002800	0.0810820	0.1310100	0.1780400
-0.27188	0.0944690	0.0774790	0.1275200	0.1694000
-0.26019	0.0886470	0.0738940	0.1237900	0.1607900
-0.24858	0.0829120	0.0703290	0.1198500	0.1522600
-0.23706	0.0773640	0.0667740	0.1157000	0.1438400
-0.22561	0.0720780	0.0632200	0.1113700	0.1355600
-0.21423	0.0670560	0.0596670	0.1068700	0.1274200
-0.20293	0.0622400	0.0561240	0.1022400	0.1194600
-0.19170	0.0575980	0.0526050	0.0974730	0.1116600
-0.18055	0.0531310	0.0491250	0.0925980	0.1040600
-0.16945	0.0488600	0.0457040	0.0876230	0.0966450
-0.15843	0.0447960	0.0423520	0.0825630	0.0894130
-0.14747	0.0409260	0.0390760	0.0774280	0.0823600
-0.13657	0.0372370	0.0358780	0.0722270	0.0754830
-0.12574	0.0337170	0.0327580	0.0669710	0.0687800
-0.11496	0.0303510	0.0297150	0.0616690	0.0622470
-0.10425	0.0271280	0.0267450	0.0563290	0.0558830
-0.09359	0.0240340	0.0238460	0.0509570	0.0496870
-0.08298	0.0210570	0.0210120	0.0455610	0.0436570
-0.07243	0.0181850	0.0182380	0.0401460	0.0377890
-0.06194	0.0154050	0.0155180	0.0347180	0.0320770
-0.05149	0.0127050	0.0128470	0.0292830	0.0265110
-0.04110	0.0100740	0.0102190	0.0238460	0.0210790
-0.03075	0.0074998	0.0076261	0.0184130	0.0157630
-0.02046	0.0049706	0.0050635	0.0129880	0.0105430
-0.01021	0.0024750	0.0025244	0.0075755	0.0053937
0.00000	0.0000000	0.0000008	0.0021777	0.0002895
0.01021	-0.0024750	-0.0025228	-0.0032236	-0.0048171
0.02046	-0.0049706	-0.0050619	-0.0086417	-0.0099669
0.03075	-0.0074998	-0.0076246	-0.0140760	-0.0151890
0.04110	-0.0100740	-0.0102170	-0.0195230	-0.0205070
0.05149	-0.0127050	-0.0128460	-0.0249780	-0.0259420
0.06194	-0.0154050	-0.0155170	-0.0304350	-0.0315110
0.07243	-0.0181850	-0.0182360	-0.0358880	-0.0372270
0.08298	-0.0210570	-0.0210100	-0.0413320	-0.0431000
0.09359	-0.0240340	-0.0238440	-0.0467610	-0.0491350
0.10425	-0.0271280	-0.0267430	-0.0521700	-0.0553370
0.11496	-0.0303510	-0.0297130	-0.0575520	-0.0617080

0.12574	-0.0337170	-0.0327560	-0.0628990	-0.0682480
0.13657	-0.0372370	-0.0358760	-0.0682030	-0.0749600
0.14747	-0.0409260	-0.0390740	-0.0734540	-0.0818440
0.15843	-0.0447960	-0.0423500	-0.0786460	-0.0889050
0.16945	-0.0488600	-0.0457010	-0.0837660	-0.0961460
0.18055	-0.0531310	-0.0491230	-0.0888020	-0.1035700
0.19170	-0.0575990	-0.0526010	-0.0937430	-0.1111800
0.20293	-0.0622410	-0.0561130	-0.0985820	-0.1190000
0.21423	-0.0670580	-0.0596520	-0.1033000	-0.1269900
0.22561	-0.0720830	-0.0632020	-0.1078700	-0.1351400
0.23706	-0.0773690	-0.0667550	-0.1122800	-0.1434300
0.24858	-0.0829060	-0.0703070	-0.1165200	-0.1518600
0.26019	-0.0886210	-0.0738650	-0.1205600	-0.1603800
0.27188	-0.0944140	-0.0774370	-0.1243800	-0.1689600
0.28365	-0.1001900	-0.0810280	-0.1279600	-0.1775500
0.29550	-0.1058500	-0.0846370	-0.1312800	-0.1861000
0.30745	-0.1113200	-0.0882590	-0.1343100	-0.1945300
0.31093	-0.1127900	-0.0892220	-0.1352800	-0.1967300
0.31948	-0.1165000	-0.0918730	-0.1370600	-0.2027000
0.33160	-0.1213300	-0.0954700	-0.1394900	-0.2105200
0.34382	-0.1257400	-0.0990410	-0.1415800	-0.2178800
0.35614	-0.1296900	-0.1025600	-0.1433000	-0.2246400
0.36856	-0.1331100	-0.1060100	-0.1446400	-0.2306500
0.38108	-0.1359900	-0.1093400	-0.1455500	-0.2357500
0.39370	-0.1383000	-0.1125300	-0.1460100	-0.2398100
0.40644	-0.1399900	-0.1155100	-0.1460400	-0.2425400
0.41928	-0.1410700	-0.1182200	-0.1456500	-0.2438000
0.43224	-0.1416100	-0.1206400	-0.1448800	-0.2438300
0.44531	-0.1416500	-0.1227200	-0.1437900	-0.2426900
0.45851	-0.1412300	-0.1244200	-0.1424200	-0.2404700
0.47182	-0.1404000	-0.1257000	-0.1407600	-0.2373300
0.47482	-0.1401900	-0.1259300	-0.1405000	-0.2366100
0.48527	-0.1392200	-0.1265200	-0.1388500	-0.2334300
0.49884	-0.1377500	-0.1268700	-0.1367100	-0.2289800
0.51255	-0.1360600	-0.1267700	-0.1343800	-0.2241700
0.52639	-0.1341900	-0.1262200	-0.1319600	-0.2191900
0.54038	-0.1321800	-0.1252600	-0.1295400	-0.2142100
0.55451	-0.1300400	-0.1238600	-0.1273100	-0.2092100
0.56880	-0.1278400	-0.1221400	-0.1253200	-0.2044000

0.58323	-0.1256200	-0.1201800	-0.1236800	-0.1998000
0.59782	-0.1234000	-0.1180300	-0.1224100	-0.1953700
0.60252	-0.1227000	-0.1173200	-0.1221400	-0.1940100
0.61258	-0.1212000	-0.1157500	-0.1214900	-0.1911000
0.62750	-0.1190300	-0.1133900	-0.1207200	-0.1869400
0.64260	-0.1168800	-0.1109800	-0.1199200	-0.1828800
0.65787	-0.1147700	-0.1085600	-0.1190400	-0.1789100
0.67333	-0.1126400	-0.1061100	-0.1181400	-0.1749300
0.68897	-0.1105500	-0.1036800	-0.1171900	-0.1710100
0.70481	-0.1084800	-0.1013000	-0.1161900	-0.1671900
0.71421	-0.1072900	-0.0999160	-0.1156400	-0.1650000
0.72085	-0.1064500	-0.0989680	-0.1151400	-0.1634500
0.73709	-0.1044500	-0.0966870	-0.1140700	-0.1598000
0.75355	-0.1024800	-0.0944570	-0.1129400	-0.1562200
0.77023	-0.1005200	-0.0922650	-0.1117700	-0.1527000
0.78713	-0.0985450	-0.0900750	-0.1105900	-0.1491700
0.80426	-0.0965940	-0.0879300	-0.1093500	-0.1457100
0.81692	-0.0951900	-0.0863870	-0.1084600	-0.1432400
0.82164	-0.0946680	-0.0858250	-0.1080800	-0.1423200
0.83926	-0.0927680	-0.0837570	-0.1067900	-0.1390100
0.85714	-0.0908900	-0.0817260	-0.1054500	-0.1357700
0.87528	-0.0890100	-0.0797010	-0.1040800	-0.1325400
0.89370	-0.0871240	-0.0776810	-0.1026900	-0.1293300
0.91241	-0.0852600	-0.0756950	-0.1012500	-0.1261800
0.91410	-0.0850990	-0.0755100	-0.1012000	-0.1259200
0.93140	-0.0834220	-0.0737410	-0.0998130	-0.1231100
0.95069	-0.0816040	-0.0718170	-0.0983300	-0.1200900
0.97030	-0.0797850	-0.0699000	-0.0968220	-0.1170900
0.99024	-0.0779590	-0.0679850	-0.0952940	-0.1141000
1.00770	-0.0763990	-0.0663540	-0.0939560	-0.1115700
1.01050	-0.0761530	-0.0661000	-0.0937280	-0.1111700
1.03110	-0.0743740	-0.0642460	-0.0921620	-0.1083100
1.05210	-0.0726120	-0.0624230	-0.0905530	-0.1055000
1.07340	-0.0708300	-0.0605820	-0.0889430	-0.1026700
1.09520	-0.0690620	-0.0587670	-0.0872950	-0.0998840
1.09910	-0.0687540	-0.0584390	-0.0870580	-0.0994120
1.11730	-0.0673200	-0.0569830	-0.0856460	-0.0971640
1.13990	-0.0655970	-0.0552300	-0.0839660	-0.0944930
1.16280	-0.0638590	-0.0534670	-0.0822820	-0.0918170

1.18630	-0.0621310	-0.0517240	-0.0805680	-0.0891720
1.18920	-0.0619260	-0.0515050	-0.0804120	-0.0888680
1.21020	-0.0604310	-0.0500130	-0.0788590	-0.0865920
1.23460	-0.0587480	-0.0483320	-0.0771180	-0.0840570
1.25950	-0.0570460	-0.0466340	-0.0753850	-0.0815060
1.27870	-0.0557710	-0.0453660	-0.0740690	-0.0796080
1.28490	-0.0553640	-0.0449680	-0.0736260	-0.0790020
1.31080	-0.0537090	-0.0433340	-0.0718690	-0.0765580
1.33740	-0.0520540	-0.0417070	-0.0701000	-0.0741280
1.36450	-0.0504000	-0.0400900	-0.0683180	-0.0717110
1.36810	-0.0501950	-0.0398800	-0.0681350	-0.0714200
1.39220	-0.0487740	-0.0385070	-0.0665440	-0.0693560
1.42060	-0.0471600	-0.0369450	-0.0647540	-0.0670300
1.44970	-0.0455410	-0.0353820	-0.0629660	-0.0647090
1.45780	-0.0451110	-0.0349600	-0.0625180	-0.0641010
1.47950	-0.0439500	-0.0338540	-0.0611790	-0.0624430
1.51000	-0.0423740	-0.0323510	-0.0593840	-0.0602130
1.54120	-0.0407950	-0.0308490	-0.0575940	-0.0579870
1.54810	-0.0404650	-0.0305260	-0.0572460	-0.0575280
1.57330	-0.0392470	-0.0293830	-0.0558110	-0.0558180
1.60630	-0.0377100	-0.0279370	-0.0540250	-0.0536780
1.63960	-0.0362010	-0.0265230	-0.0522670	-0.0515830
1.64010	-0.0361780	-0.0265010	-0.0522400	-0.0515510
1.67480	-0.0346800	-0.0251040	-0.0504730	-0.0494850
1.71050	-0.0331860	-0.0237170	-0.0487090	-0.0474330
1.73220	-0.0323150	-0.0229060	-0.0476910	-0.0462430
1.74730	-0.0317110	-0.0223550	-0.0469520	-0.0454160
1.78510	-0.0302630	-0.0210270	-0.0452020	-0.0434460
1.82400	-0.0288190	-0.0197070	-0.0434670	-0.0414870
1.82630	-0.0287450	-0.0196300	-0.0434030	-0.0413910
1.86420	-0.0274120	-0.0184280	-0.0417500	-0.0395870
1.90560	-0.0260130	-0.0171620	-0.0400450	-0.0377050
1.92220	-0.0254770	-0.0166730	-0.0394070	-0.0369890
1.94840	-0.0246420	-0.0159290	-0.0383560	-0.0358670
1.99250	-0.0232930	-0.0147230	-0.0366840	-0.0340640