Development of a One-Equation Eddy Viscosity Turbulence Model for Application to Complex Turbulent Flows

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UMich/NASA Symposium on Advanced Turbulence Modeling

University of Michigan, 11-13 July 2017

Wray-Agarwal (WA) Model

Beginning with Wilcox's 2006 k-ω model:

$$\frac{Dk}{Dt} = \frac{\partial}{\partial y}\left(\sigma_k \frac{k}{\omega}\frac{\partial k}{\partial y}\right) + \nu_t\left(\frac{\partial u}{\partial y}\right)^2 - \beta^* k\omega$$

$$\frac{D\omega}{Dt} = \frac{\partial}{\partial y}\left(\sigma_\omega \frac{k}{\omega}\frac{\partial \omega}{\partial y}\right) + \alpha\frac{\omega}{k}\nu_t\left(\frac{\partial u}{\partial y}\right)^2 - \beta\omega^2 + \frac{\sigma_d}{\omega}\frac{\partial k}{\partial y}\frac{\partial \omega}{\partial y}$$

With R defined as k/ω, the material derivative of R can be obtained as:

$$\frac{DR}{Dt} = \frac{1}{\omega}\frac{Dk}{Dt} - \frac{k}{\omega^2}\frac{D\omega}{Dt}$$

To finish the closure one additional equation is needed. With Bradshaw's relation, the system is complete:

$$|-\overline{u'v'}| = \nu_t\left|\frac{\partial u}{\partial y}\right| = a_1 k$$

Wray-Agarwal (WA) Model (Contd.)

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After substitution the R transport equation can be obtained as:

$$\frac{DR}{Dt} = \frac{\partial}{\partial y}\left(\sigma_R R \frac{\partial R}{\partial y}\right) + C_1 R \left|\frac{\partial u}{\partial y}\right| + C_2 \frac{R}{\left|\frac{\partial u}{\partial y}\right|} \frac{\partial R}{\partial y} \frac{\partial \left|\frac{\partial u}{\partial y}\right|}{\partial y} - C_3 R^2 \left(\frac{\frac{\partial \left|\frac{\partial u}{\partial y}\right|}{\partial y} \frac{\partial \left|\frac{\partial u}{\partial y}\right|}{\partial y}}{\left|\frac{\partial u}{\partial y}\right|^2} \right)$$

C_2 term is identical to the destruction term in one-equation k-ω models

- Shown to have free stream sensitivity
- Does well in adverse pressure gradient flows

C_3 term is identical to the destruction term in one-equation k-ε models

- Poor near wall behavior
- Accurate in free shear flows

Design a switch to control the C_2/C_3 behavior.

Wray-Agarwal Model (Contd.)

$$\frac{\partial R}{\partial t}+\frac{\partial u_j R}{\partial x_j}=\frac{\partial}{\partial x_j}\left[(\sigma_R R+\nu)\frac{\partial R}{\partial x_j}\right]+C_1 RS+f_1 C_{2k\omega}\frac{R}{S}\frac{\partial R}{\partial x_j}\frac{\partial S}{\partial x_j}-(1-f_1)C_{2k\varepsilon}R^2\left(\frac{\frac{\partial S}{\partial x_j}\frac{\partial S}{\partial x_j}}{S^2}\right)$$

$$\nu_T = f_\mu R$$

$$f_\mu = \frac{\chi^3}{\chi^3 + C_w^3}, \qquad \chi = \frac{R}{\nu}$$

$$f_1 = \tanh(arg_1^4)$$

$$S = \sqrt{2S_{ij}S_{ij}}, \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)$$

$$C_{1k\omega} = 0.0833 \quad C_{1k\varepsilon} = 0.1127$$

$$C_1 = f_1(C_{1k\omega} - C_{1k\varepsilon}) + C_{1k\varepsilon}$$

$$\sigma_{k\omega} = 0.72 \quad \sigma_{k\varepsilon} = 1.0$$

$$\sigma_R = f_1(\sigma_{k\omega} - \sigma_{k\varepsilon}) + \sigma_{k\varepsilon}$$

$$\kappa = 0.41$$

$$C_{2k\omega} = \frac{C_{1k\omega}}{\kappa^2} + \sigma_{k\omega} \quad C_{2k\varepsilon} = \frac{C_{1k\varepsilon}}{\kappa^2} + \sigma_{k\varepsilon}$$

$$C_w = 8.54$$

$$C_\mu = 0.09$$

Wray-Agarwal (WA) (Contd.)

- Desire a switch that smoothly transitions from 1 near solid boundaries to zero at the boundary layer edge. Analogous to the SST *k-ω* model

$$arg_1 = \min\left(\frac{C_b R}{S\kappa^2 d^2}, \left(\frac{R+\nu}{\nu}\right)^2\right) \text{ or } arg_1 = \frac{1+\frac{d\sqrt{RS}}{\nu}}{1+\left[\frac{d\, max(\sqrt{RS}, 1.5)}{20\nu}\right]^2}$$

- **Wall-Distance Free WA Model:** $arg_1 = \frac{\nu+R}{2}\frac{\eta^2}{C_\mu k\omega}$

$$k = \frac{\nu_T S}{\sqrt{C_\mu}}\ ,\ \omega = \frac{S}{\sqrt{C_\mu}}, \eta = S max\left(1, \left|\frac{W}{S}\right|\right), W = \sqrt{2W_{ij}W_{ij}}\ ,\ W_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i}\right)$$

arg_1 is one in the near one in the viscous sublayer, equal to one in the log layer, decays approaching the outer edge of the boundary layer.

- To ensure smoothness and boundedness, arg_1 is wrapped in hyperbolic tangent:

$$f_1 = \tanh(arg_1^4)$$

Extensions to Wray-Agarwal Model

- WA-QCR: incorporation of Quadratic Constitutive Relation in WA model (Spalart)
- Compressibility Correction (Wilcox, Sarkar)
- $\frac{\mathrm{D}R}{\mathrm{D}t} =$

$$\boxed{\left(a_1 + \frac{\beta^* f_\mu}{a_1} + \frac{\beta f_\mu}{a_1} - \alpha a_1\right)} RS + \frac{\partial}{\partial y}\left(\sigma_R R \frac{\partial R}{\partial y}\right) + f_1 C_{2k\omega} \frac{R}{S} \frac{\partial R}{\partial x_j} \frac{\partial S}{\partial x_j} - (1 - f_1) C_{2k\varepsilon} R^2 \left(\frac{\frac{\partial S}{\partial x_j} \frac{\partial S}{\partial x_j}}{S^2}\right)$$

- $\left(a_1 + \frac{\beta^* f_\mu}{a_1} + \frac{\beta f_\mu}{a_1} - \alpha a_1\right) = -C_{comp} F(M_t) RS$
- $\beta = \beta_0 - \beta_0^* F(M_t),\ \beta^* = \beta_0^* [1 + \xi^* F(M_t)$, Sarkar: $\xi^* = 1,\ F(M_t) = M_t^2, M_t = \frac{\sqrt{2k}}{a}$
- Wilcox: $\xi^* = \frac{3}{2}\ , M_{t0} = \frac{1}{4},\ F(M_t) = [M_t^2 - M_{t0}^2] H(M_t - M_{t0})$
- High Temperature Correction (Abdol-Hamid)
- $T_g = (\frac{\sigma_R R}{S})^{1/2} \frac{|\nabla T_t|}{T_t},\ \nu_t = 0.09 \left[1 + \frac{{T_g}^3}{0.041 + F(M_\tau)}\right] \frac{k}{\omega},\ \nu_t = f_\mu R(1 + 18.0 \times {T_g}^3)$
- Rotation & Curvature (RC) Correction (Spalart-Shur)
- Rough Wall Flows
- WA-γ Transition Model

DES & IDDES Versions of WA Model

$$\frac{\partial R}{\partial t} + \frac{\partial u_j R}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\sigma_R R + \nu)\frac{\partial R}{\partial x_j}\right] + C_1 RS + f_1 C_{2k\omega}\frac{R}{F_{DES}^2 S}\frac{\partial R}{\partial x_j}\frac{\partial S}{\partial x_j} - (1 - f_1)C_{2k\varepsilon}\frac{R^2}{F_{DES}^2}\left(\frac{\frac{\partial S}{\partial x_j}\frac{\partial S}{\partial x_j}}{S^2}\right)$$

$$F_{DES} = \max\left(\frac{l_{RANS}}{l_{LES}}, 1\right), \quad l_{RANS} = \sqrt{\frac{R}{S}}, \quad l_{LES} = C_{DES}\Delta_{DES}, \quad \Delta_{DES} = max(\Delta_x, \Delta_y, \Delta_z)$$

- The calibrated value of C_{DES} = 0.41 using the DIT test case.
- WA-IDDES model redefines the characteristic length scale ratio F_{DES} in WA-DES model as F_{IDDES}
- IDDES equations and constants are the same as in the SA-IDDES and SST-IDDES models.

Coefficients of IDDES WA Model

$$F_{IDDES} = \max\left(\frac{l_{RANS}}{l_{HYB}}, 1\right), \quad l_{HYB} = \tilde{f}_d(1+f_e)l_{RANS} + \left(1-\tilde{f}_d\right)l_{LES}, \quad l_{LES} = C_{DES}\Delta_{IDDES}$$

$$\Delta_{IDDES} = min\{max[C_w d, C_w\Delta_{DES}, \Delta_{WN}], \Delta_{DES}\}$$

Δ_{WN} is wall normal grid spacing

$$\tilde{f}_d = max(1 - f_{dt}, f_B)$$
$$f_{dt} = 1 - tanh[(C_{d1} r_{dt})^3]$$
$$f_B = \min\left(2e^{-9\alpha^2}, 1\right)$$
$$\alpha = 0.25 - d/max\left(\Delta_x, \Delta_y, \Delta_z\right)$$

C_{d1} = 4

$$f_e = \max(f_{e1} - 1, 0) f_{e2}$$
$$f_{e1} = \begin{cases} 2e^{-11.09\alpha^2} & if\ \alpha \geq 0 \\ 2e^{-9.0\alpha^2} & if\ \alpha < 0 \end{cases}$$
$$f_{e2} = 1.0 - max(f_t, f_l)$$
$$\begin{cases} f_t = tanh[(c_t{}^2 r_{dt})^3] \\ f_l = tanh[(c_l{}^2 r_{dl})^{10}] \end{cases}$$

$$\begin{cases} r_{dt} = \dfrac{\nu_t}{\kappa^2 d^2 max\left\{\left[\sum_{i,j}\left(\dfrac{\partial u_i}{\partial x_j}\right)^2\right]^{1/2}, 10^{-10}\right\}} \\ r_{dl} = \dfrac{\nu}{\kappa^2 d^2 max\left\{\left[\sum_{i,j}\left(\dfrac{\partial u_i}{\partial x_j}\right)^2\right]^{1/2}, 10^{-10}\right\}} \end{cases}$$

Implementation of WA Model

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- Implemented in OpenFOAM
- UDF for Fluent
- Being implemented in NASA FUN3D by Missouri University of Science & Technology
- Code modules available
- 40+ benchmark cases computed
- Contact Ramesh Agarwal; Email: rka@wustl.edu, Phone: 314-935-6091

Turbulence Model Validation Cases and Grids

- **Basic Cases:**
  - ✓ **2DZP:** 2D Zero pressure gradient flat plate
  - ✓ **2DML:** 2D Mixing Layer
  - ✓ **2DANW:** 2D Airfoil near-wake
  - ✓ **2DN00:** 2D NACA 0012 airfoil
  - **ASJ:** Axisymmetric Subsonic jet
  - **AHSJ:** Axisymmetric Hot subsonic jet
  - **ANSJ:** Axisymmetric Near-sonic jet
  - ✓ **ASBL:** Axisymmetric Separated boundary layer
  - ✓ **ATB:** Axisymmetric Transonic Bump
- **Extended Cases:**
  - ✓ **2DZPH:** 2D Zero pressure gradient high Mach number flat plate
  - ✓ **2DBFS:** 2D Backward facing step
  - ✓ **2DN44:** 2D NACA 4412 airfoil trailing edge separation
  - ✓ **2DCC:** 2D Convex curvature boundary layer
  - ✓ **2DWMH:** 2D NASA wall-mounted hump separated flow
  - ✓ **ASWBLI:** Axisymmetric Shock Wave Boundary Layer Interaction near M=7
  - **ACSSJ:** Axisymmetric Cold Supersonic Jet
  - **AHSSJ:** Axisymmetric Hot Supersonic Jet
  - ✓ **3DSSD:** 3D Supersonic square duct

Each case has a family of grids, boundary conditions, and expected results for at least the SA and SST models.

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	Mach	Description
	0.00	Sod's Shock Tube
✓	0.05	Incompressible Driven Cavity
	0.10	Blasius Incompressible Laminar Flat Plate
✓	0.13	Driver-Seegmiller Incompressible Backward-Facing Step
	0.15	Fraser Subsonic Conical Diffuser
✓	0.20	Incompressible, Buice Axisymmetric Diffuser
	0.20	NLR Airfoil with Flap
✓	0.20	Incompressible, Turbulent Flat Plate
	0.20	Laminar Flow over a Circular Cylinder
✓	0.20	Ejector Nozzle
✓	0.21	Low-Subsonic S-Duct
	0.30	Steady, Inviscid Flow in a Converging-Diverging Verfication (CDV) Nozzle
	0.30	Subsonic Annular Duct
	0.40	Square Jet Injection
	0.46	Sajben Transonic Converging-Diverging Diffuser
✓	0.73	RAE 2822 Transonic Airfoil
	0.80	MADIC 2D Axisymmetric CD Boattail Nozzle
	0.80	MADIC 3D CD Boattail Nozzle
✓	0.84	Transonic, ONERA M6 Wing
	0.97	Acoustic Reference Nozzle with Mach 0.97, Unheated Jet Flow
	1.30	Normal shock at Mach 1.3
	1.82	Hydrogen-Air Combustion in a Channel
	2.00	Mach 2.0 Flow over a 15-Degree Wedge
✓	2.00	Seiner Nozzle with Mach 2.0, Heated Jet Flow
	2.22	Supersonic Axisymmetric "submerged" Jet Flow
	2.35	Conical shock on a 10 degree cone at Mach 2.35
	2.44	Burrows and Kurkov Supersonic Mixing/Combustion
	2.50	Oblique shock on a 15 degree wedge at Mach 2.5
	2.50	Prandtl-Meyer 15 Degree Expansion Corner at Mach 2.5
✓	4.50	Mach 4.5 Flow over a Flat Plate
	5.00	Mach 5.0 Shock Boundary Layer Interaction
	7.00	Mach 7, Laminar 15-degree Ramp
	15.00	Hypersonic Cylinder

Broad CFD cases, not all are applicable to turbulence modeling.

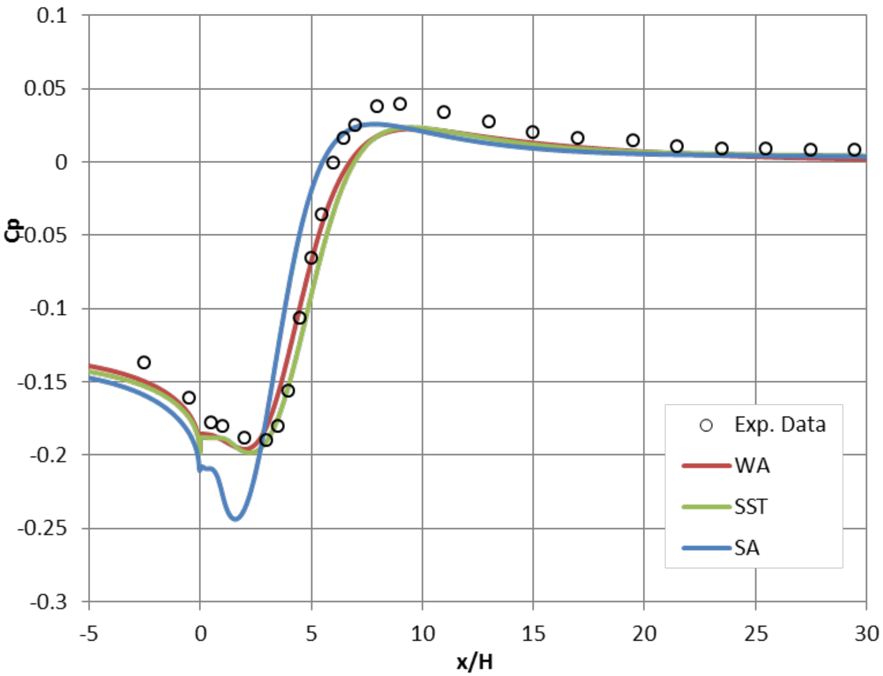
Free Shear Layer Spreading Rates

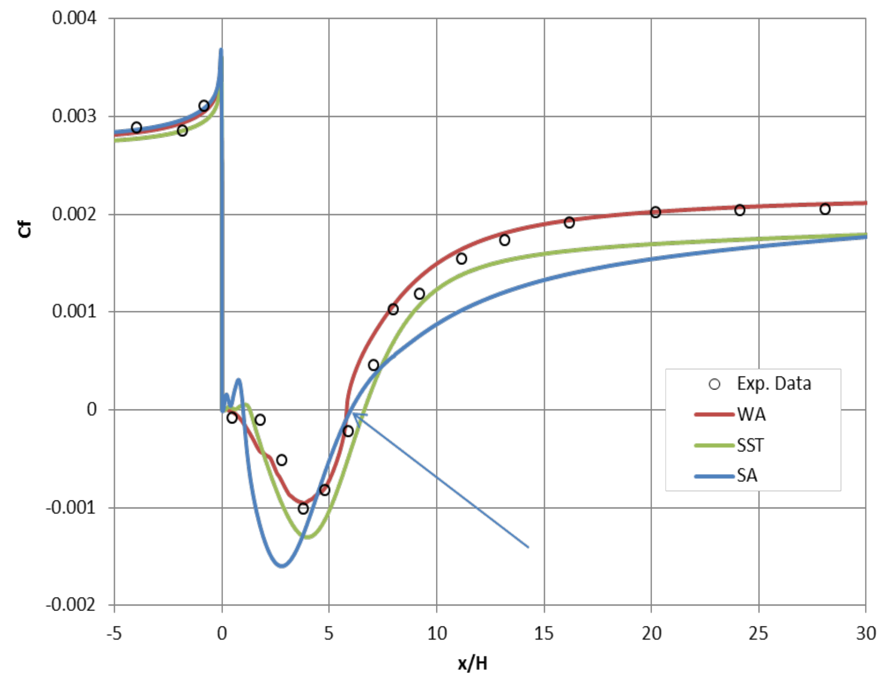
Flow	WA	SA	SST *k*-*ω*	Experiment
Far Wake	0.305	0.341	0.258	0.32-0.40 [Fage & Falkner]
Plane Jet	0.108	0.157	0.112	0.10-0.11 [Bradbury]
Round Jet	0.119	0.248	0.127	0.086-0.096 [Wygnanski & Fiedler]
Radial Jet	0.093	0.166	---	0.096-0.110 [Witze & Dwyer]

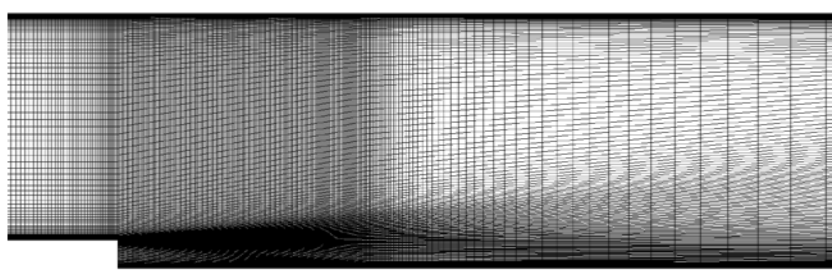
2D Backward Facing Step

$Re_H = 36{,}000$, $M_{ref} = 0.128$, Reattachment point varies from x/H = 6.16 to 6.36

Experiment reattachment at x/H = 6.26±0.1







2D Asymmetric Diffuser

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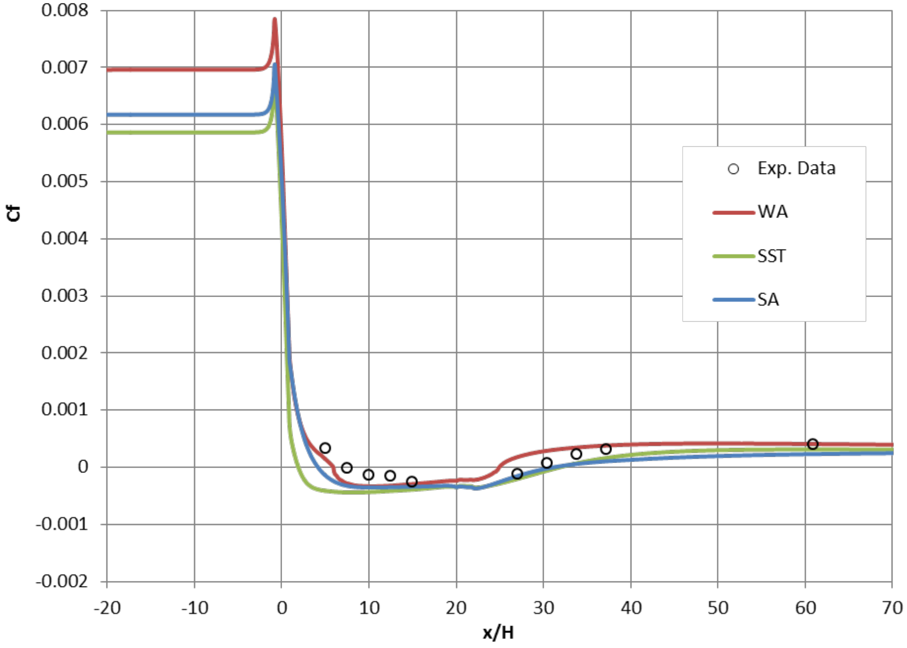
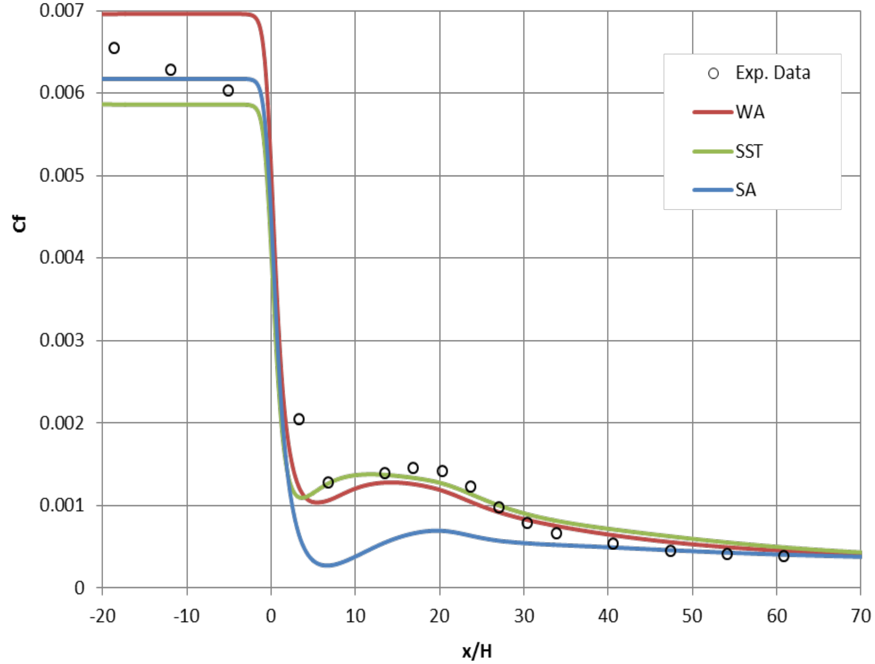
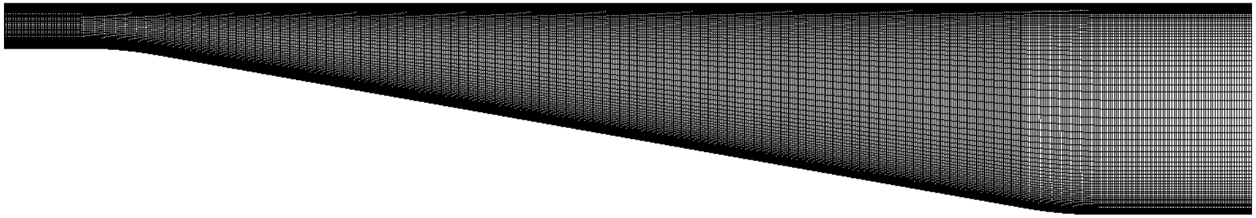
Re_H = 20,000, M_{ref} = 0.06, Opening angle α=10°, Separation region x/H = 7.03 to 30.97

Skin-friction along bottom wall



Skin-friction along top wall





2D Wall-Mounted Hump

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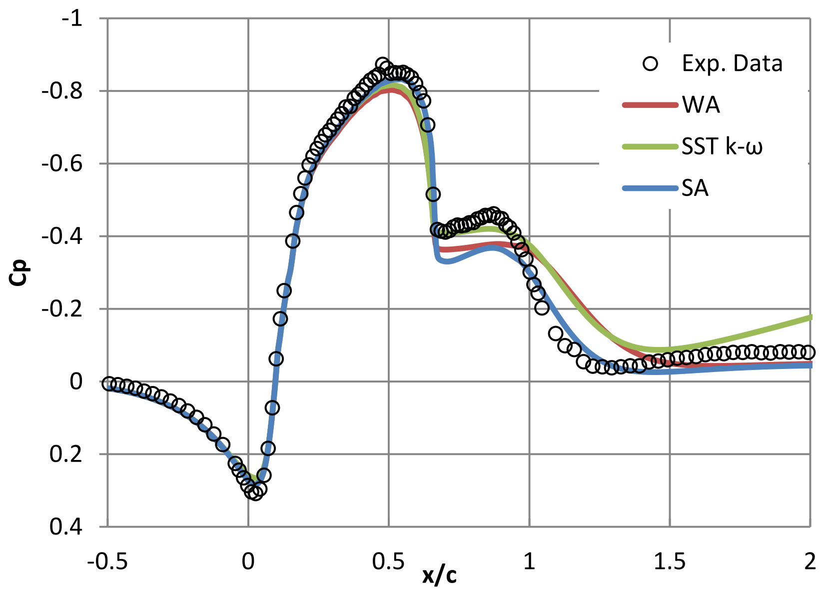
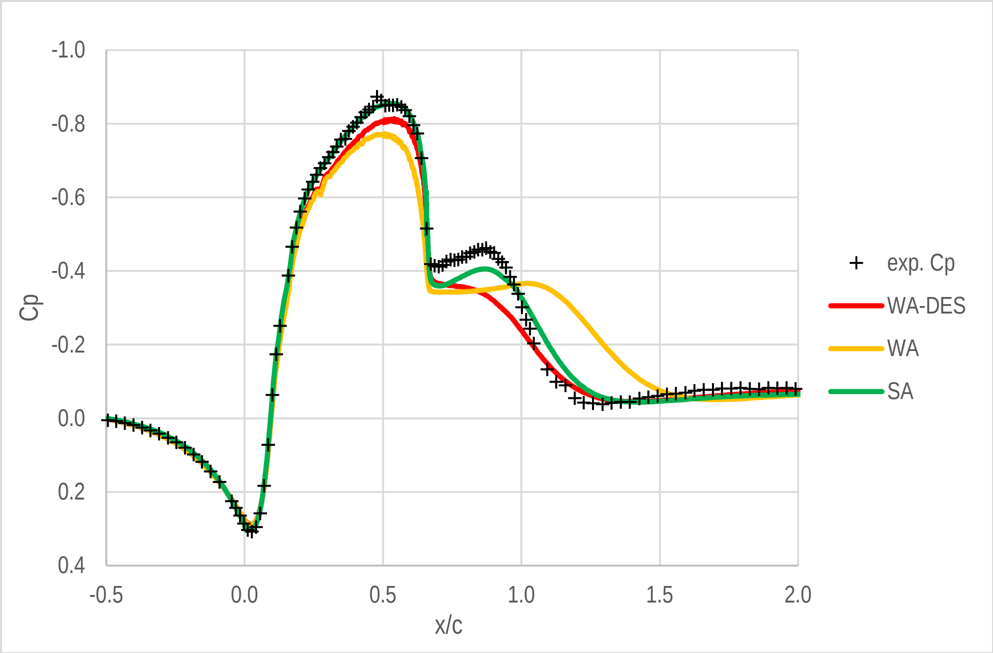
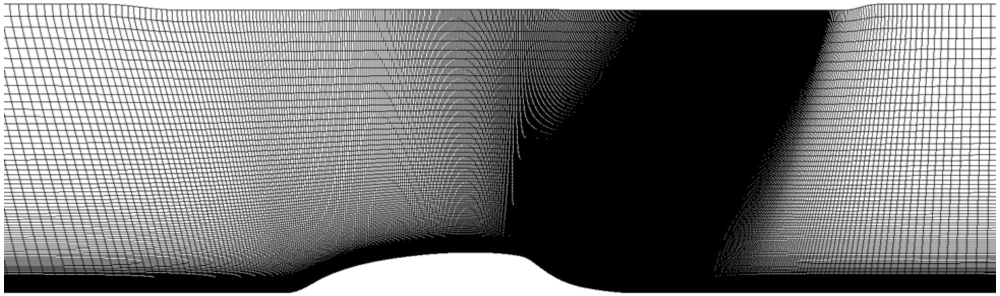
Re_C = 936,000, M_{ref} = 0.1, Surface Pressure Coefficient







2D Wall-Mounted Hump

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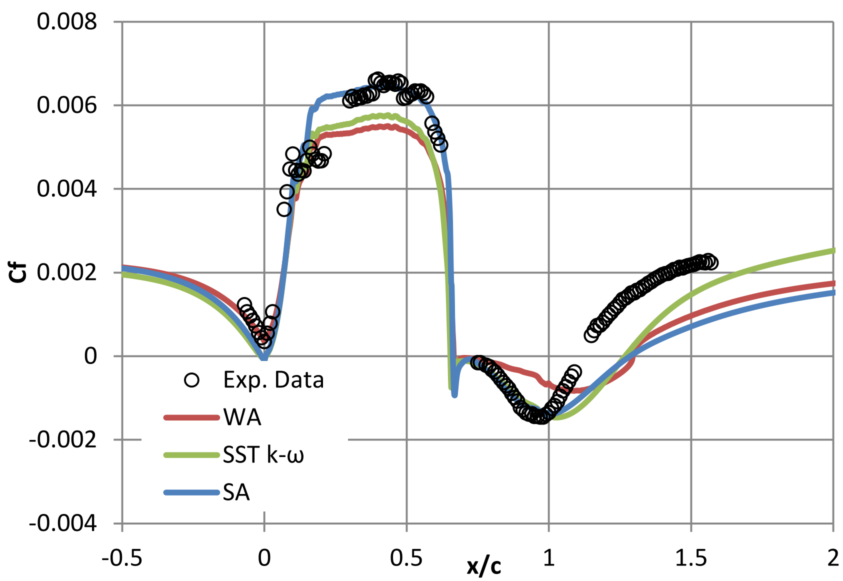
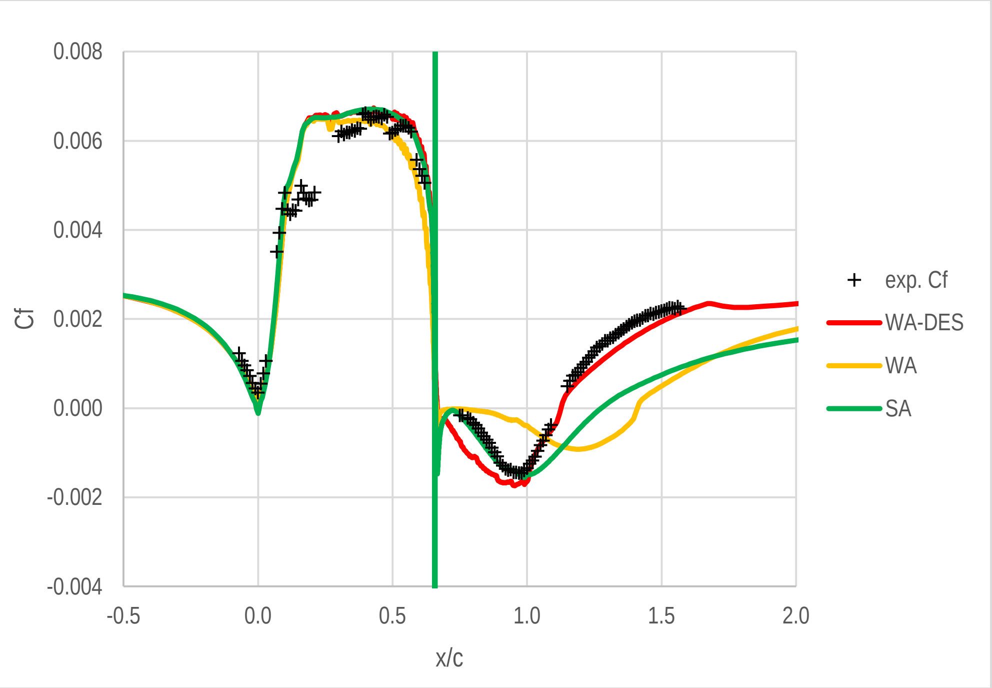
Re_C = 936,000, Mref = 0.1, Surface skin friction coefficient



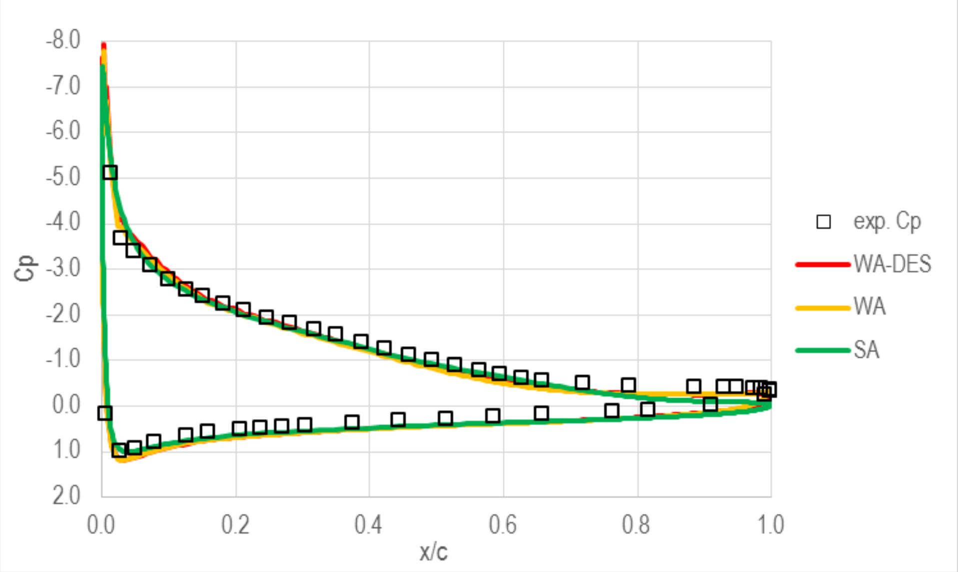


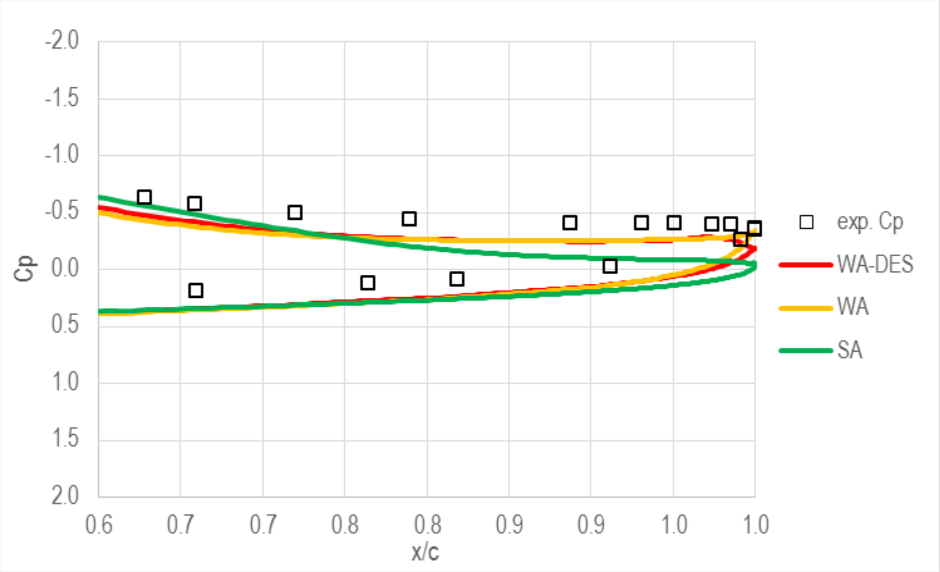
Experiment reattachment at x/c = 1.10±0.03

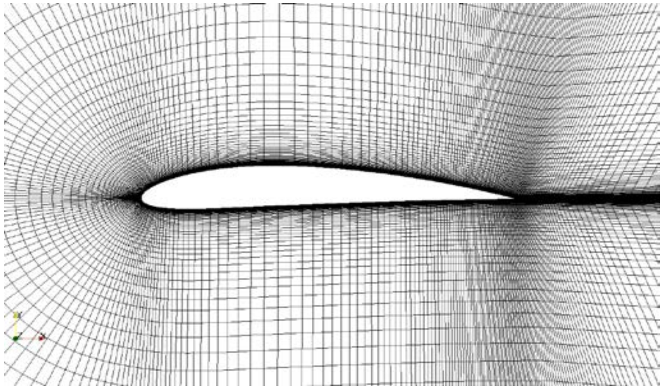
All models reattach in the range of x/c = 1.26-1.29 except WA-DES (x/c = 1.10)

2D NACA4412

Re$_c$ = 1.52x10^6, M$_{ref}$ = 0.09, α = 13.9°, Separation point varies from x/c = 0.6 to 0.7



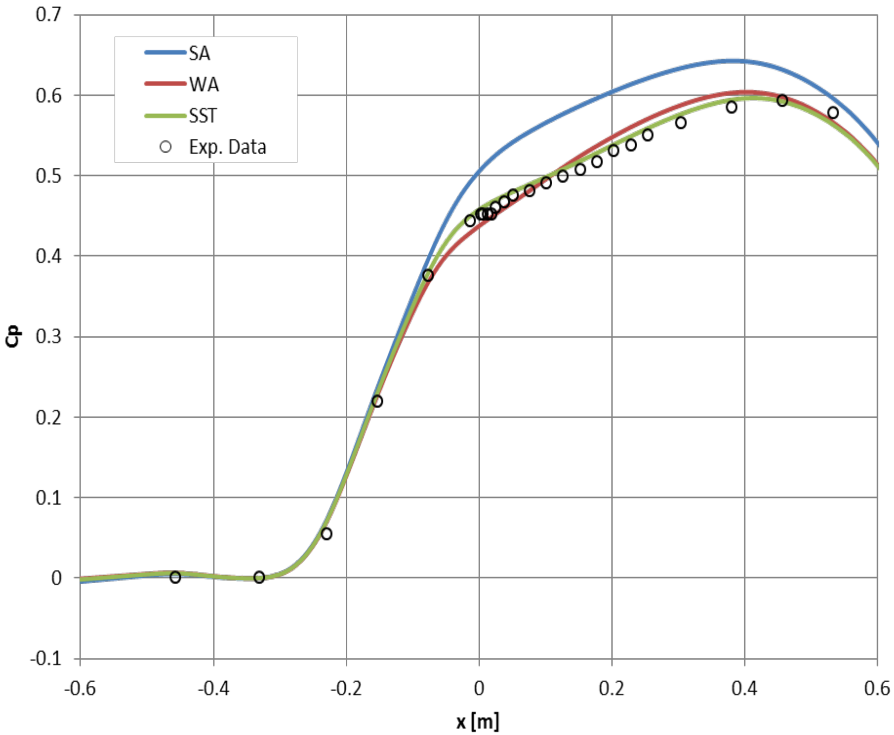




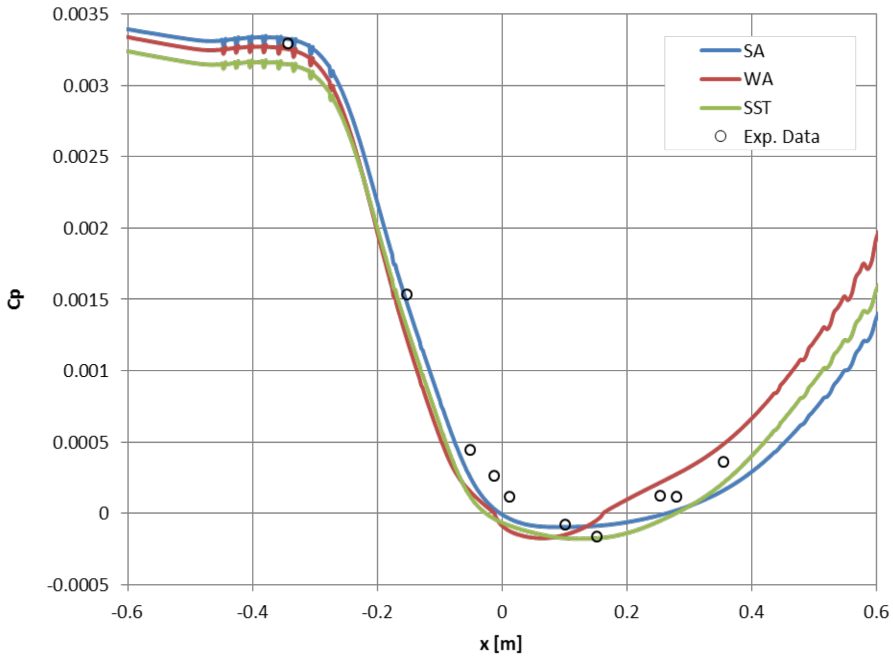
2D Axisymmetric Separated Boundary Layer

$Re_H = 2x10^6, M_{ref} = 0.08812$

Surface pressure coefficient



Surface skin friction coefficient



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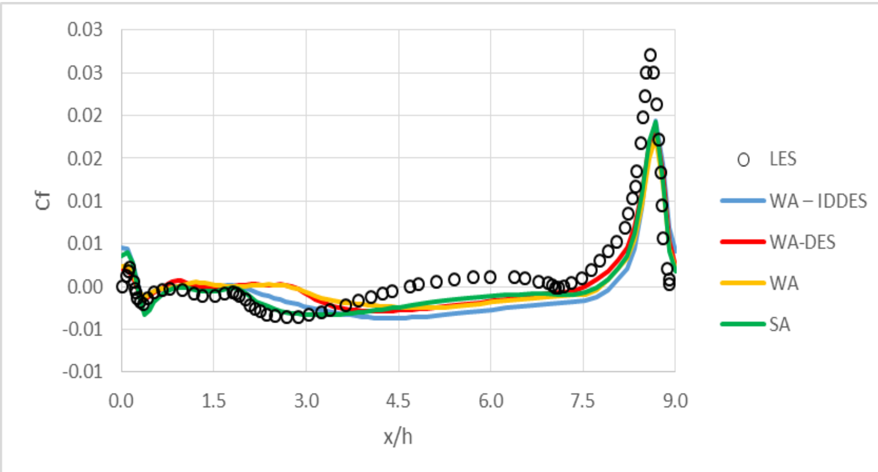
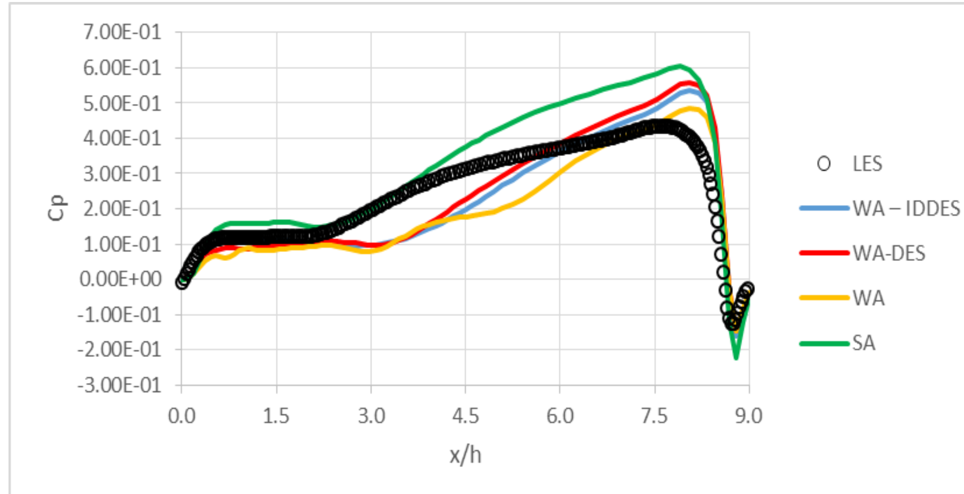
Periodic Hill

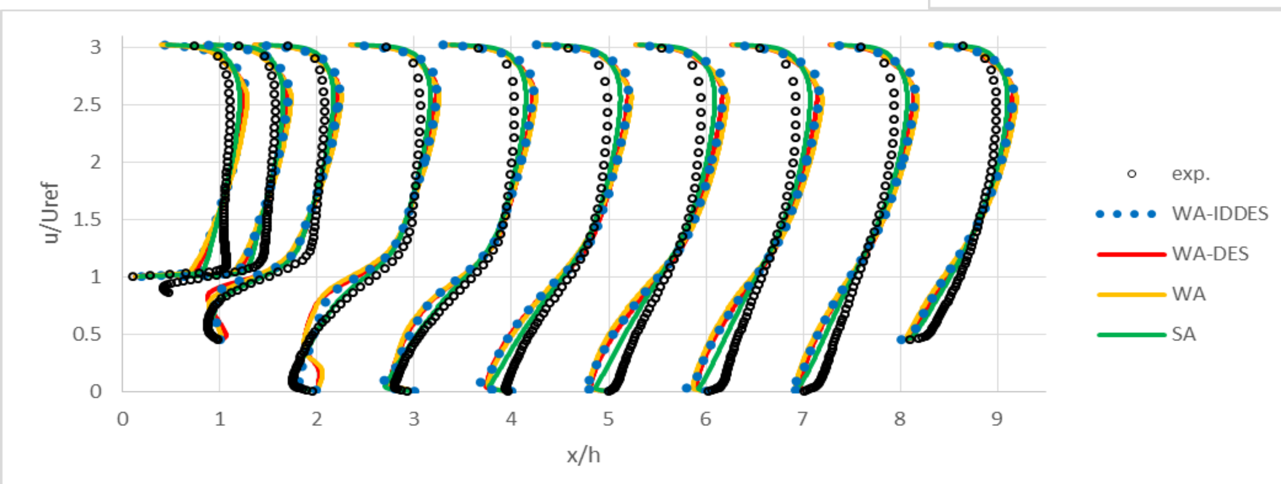
- Re =10,595 based on hill height h and bulk velocity U_b at the crest of first hill.

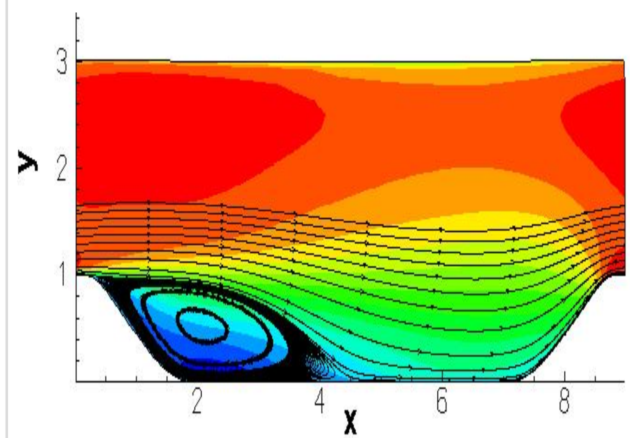
Skin friction coefficient



Cp distribution

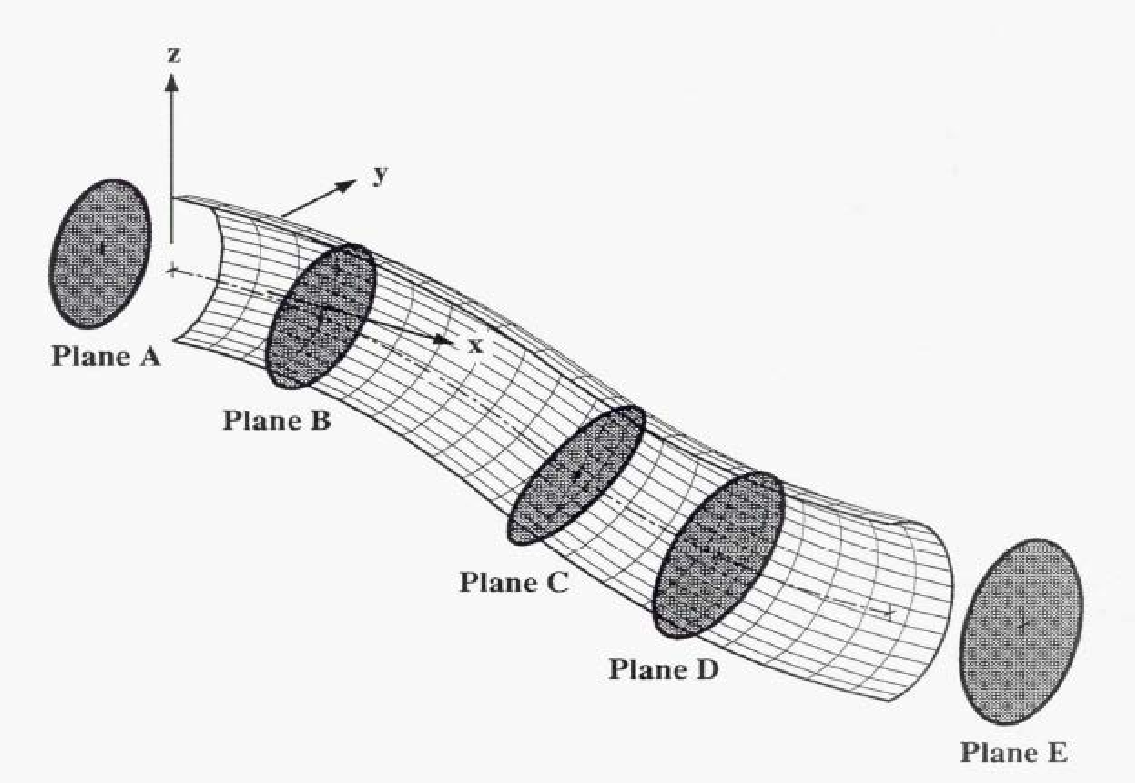




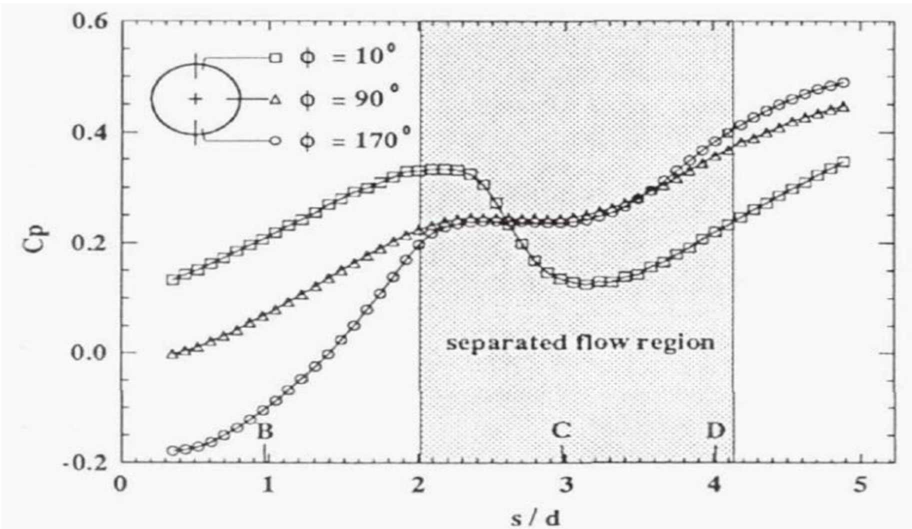


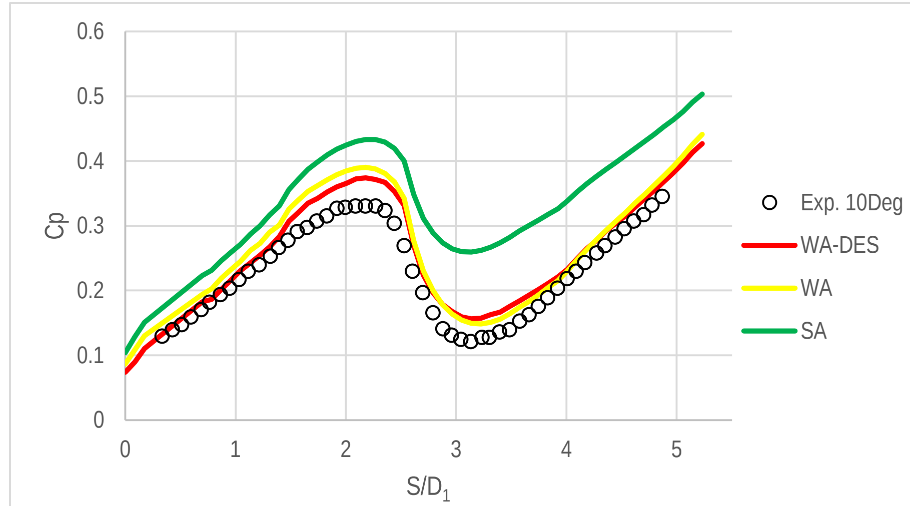
NASA Glenn S-Duct

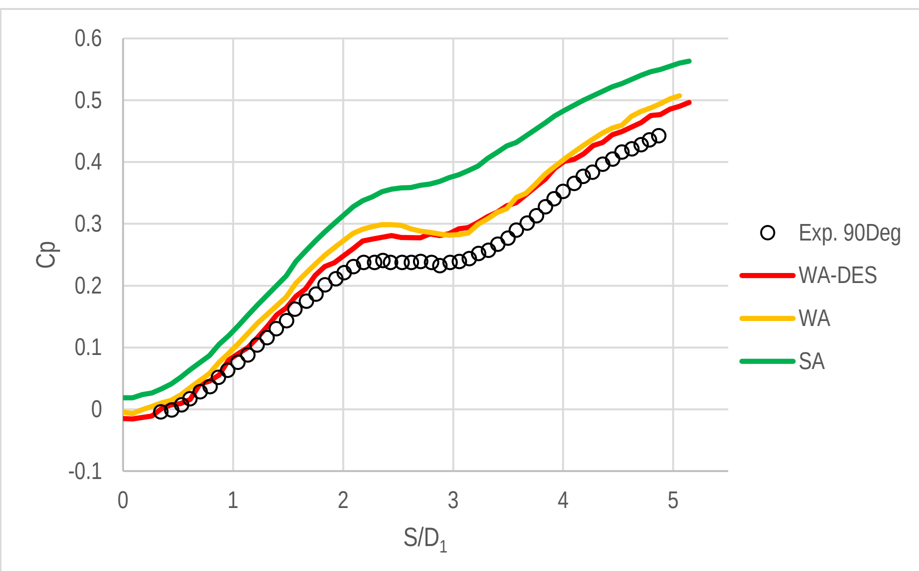
- M = 0.6, Re = 2,600,000 at s/D_1 = -0.5 (Plane A)
- The Aerodynamic Interface Plane (AIP), where the turbine face is located, is at s/D_1 = 5.73 (Plane E)

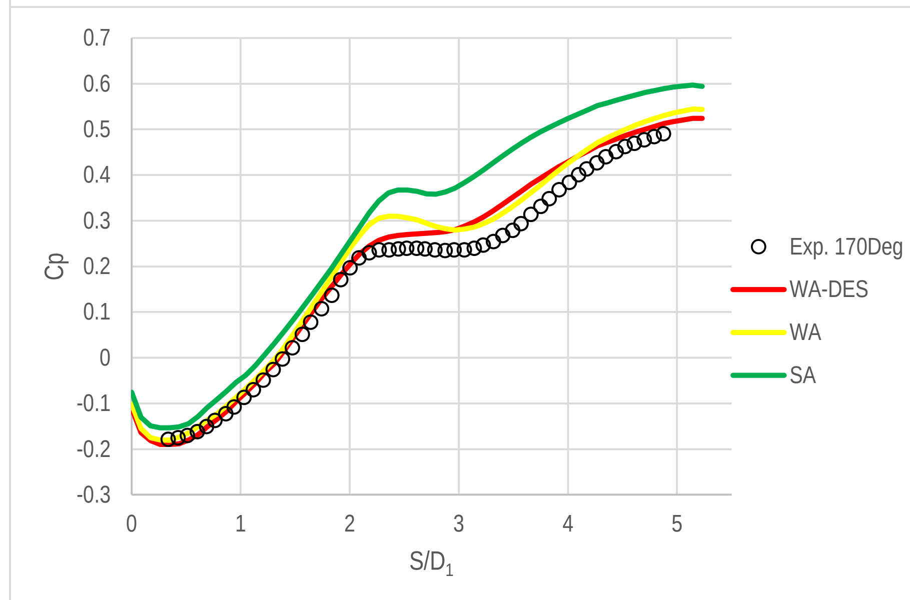


NASA Glenn S-Duct









Axisymmetric Transonic Bump

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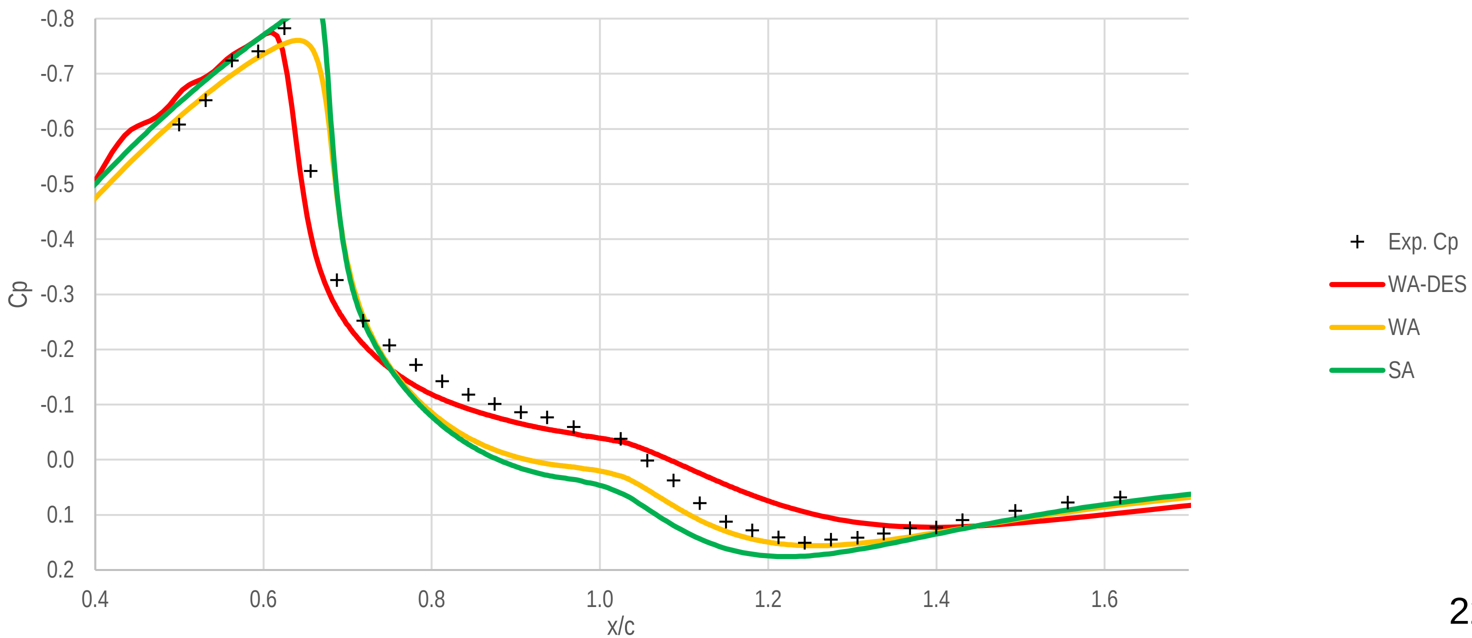
- Freestream Mach number M = 0.875, Reynolds number Re_c=2,763,000
- Separation region varies from x/c = 0.7 to 1.1

	Experiment	WA-DES	% Error	WA	% Error	SA	% Error
Separation	0.7	0.696	0.571	0.817	16.714	0.688	1.714
Reattachment	1.1	1.106	0.6	1.123	2.091	1.160	5.455



2D Slot Nozzle Ejector

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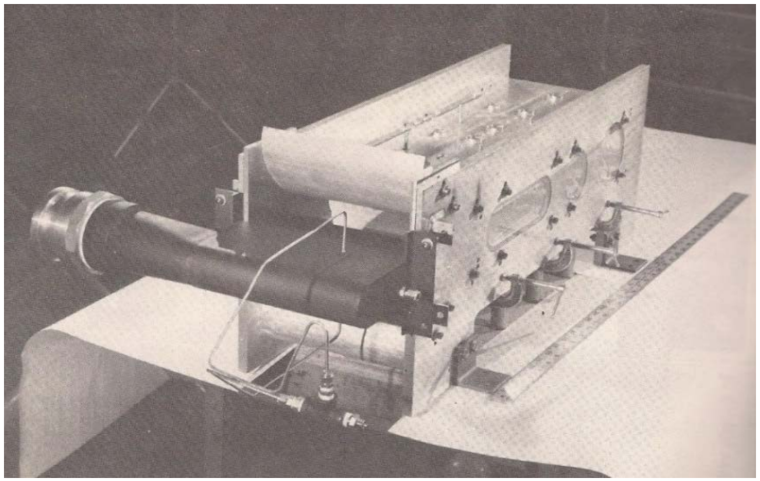
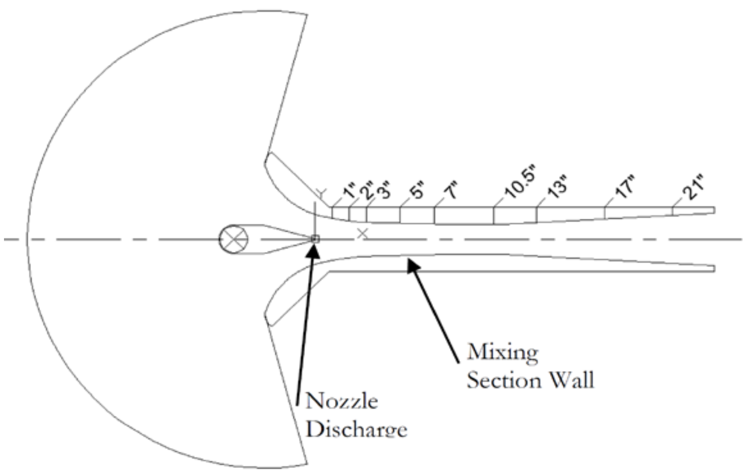
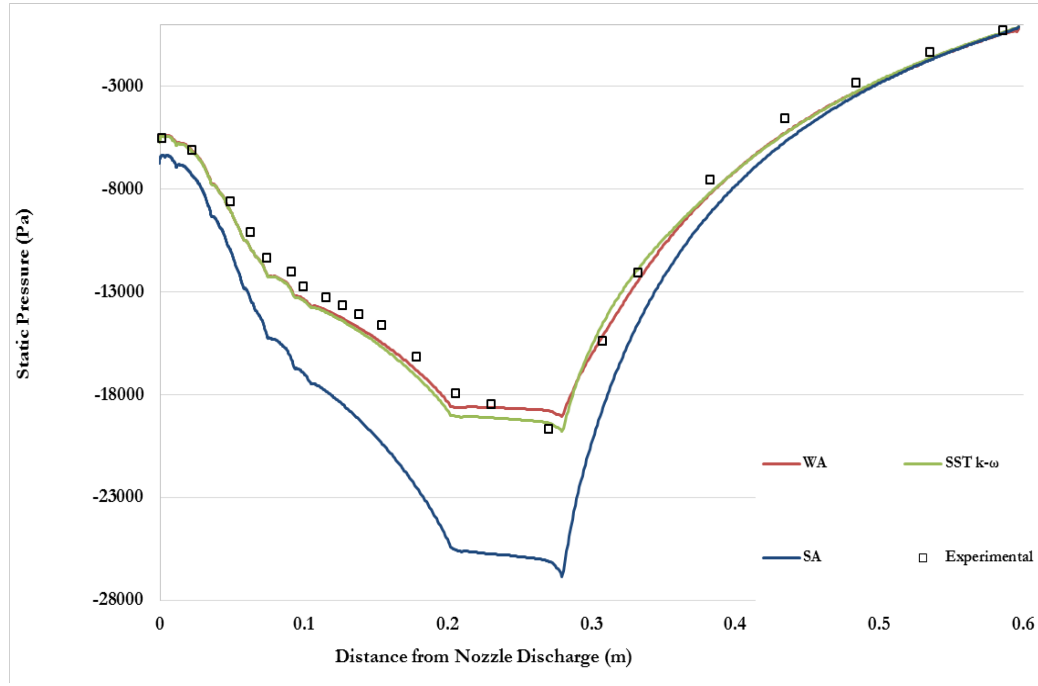
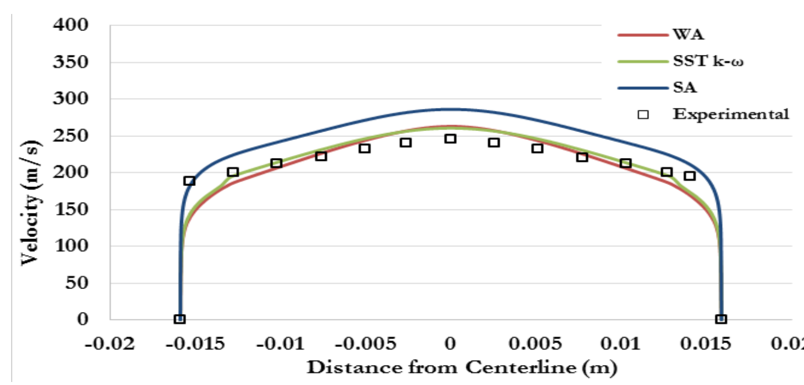
"Run5", P_{nozzle} = 31.71 Psia, T_{nozzle} = 648 R, Mixing Section Throat = 1.25", $\dot{m}_{nozzle}$ = 0.0787



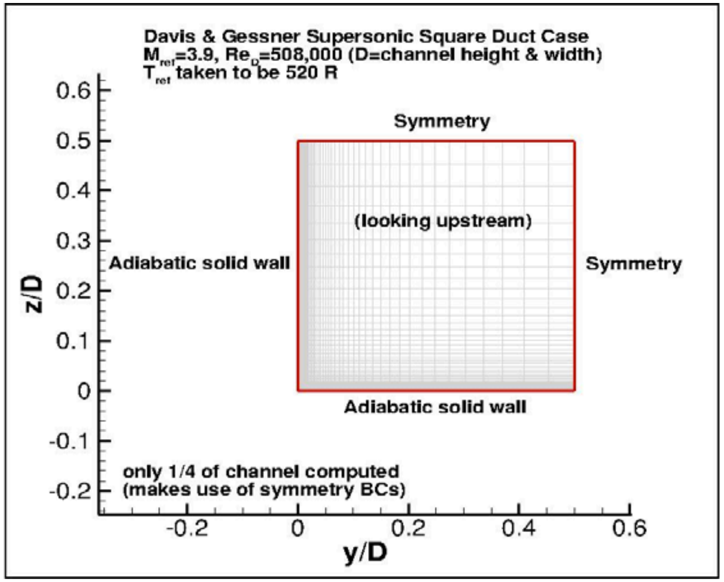


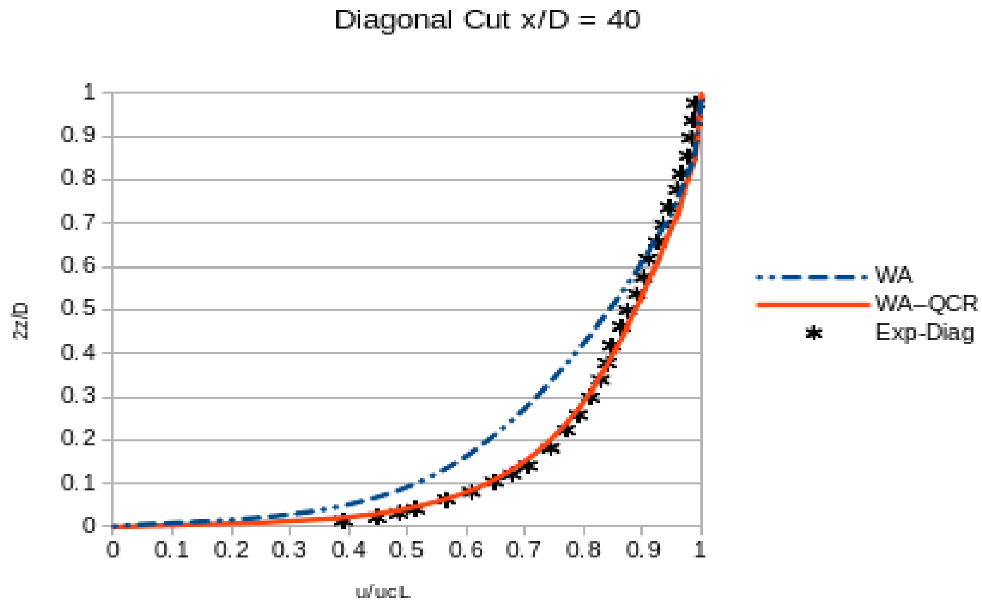


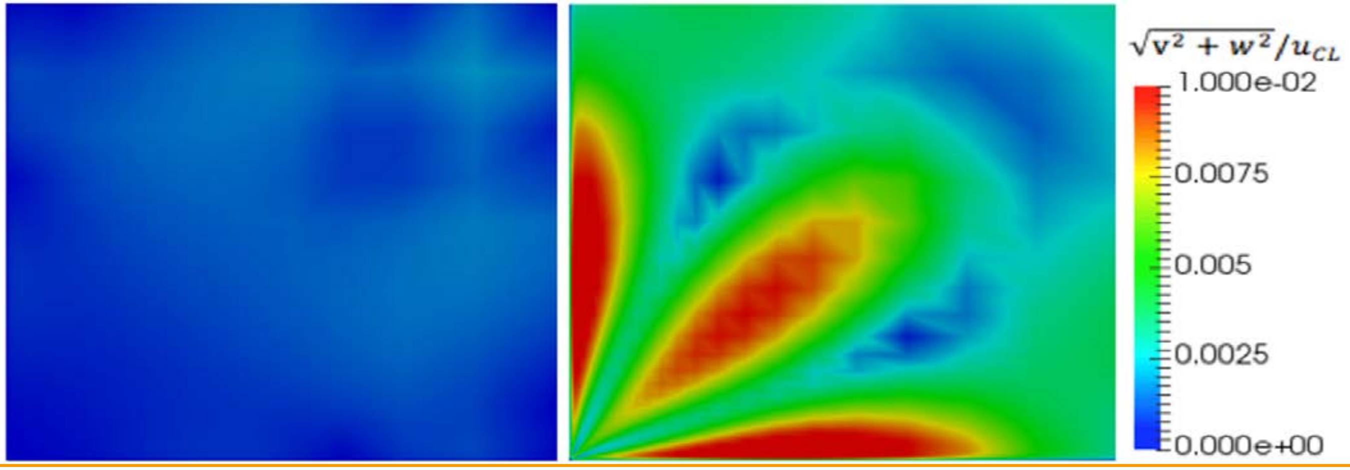


3D Supersonic Flow in a Square Duct

Experiment of Davis and Gessner, M = 3.9, Re_D = 508,000, D = 25.4mm, x/D = 50







System Rotation and Curvature

- The main characteristic of system rotation and large curvature flows is the additional turbulent production experienced in these flows.
- For this reason, corrections to turbulence models aim to increase the production term or decrease the destruction term in the transport equations.
- The Spalart-Shur correction multiplies the production term by a rotation function $f_{r1}(r^*, \tilde{r}) = (1 + c_{r1})\frac{2r^*}{1+r^*}[1 - c_{r3}\tan^{-1}(c_{r2}\tilde{r})] - c_{r1}, \quad r^* = \frac{S}{W}$
- Modification of coefficients in Spalart-Shur RC correction using UQ:

Turbulence model	C_{r1}	C_{r2}	C_{r3}
Original WA-RC	1.0	12.0	1.0
Modified WA-RC	1.0	0.1	0.1

- Zhang and Yang RC correction
- Durbin-Arrola correction

Rotation & Curvature Benchmark Cases

- 2D Curved Duct
- 2D U-turn Duct
- 2D Rotating Channel
- 2D Rotating Backward-facing Step
- Rotating Cavity – Radial Inflow
- Rotating Cavity – Axial Inflow
- Serpentine Channel
- Rotating Serpentine Channel
- Rotor-Stator Cavity
- Hydrocyclone
- Supersonic Jet in Crossflow

Rotating Serpentine Channel

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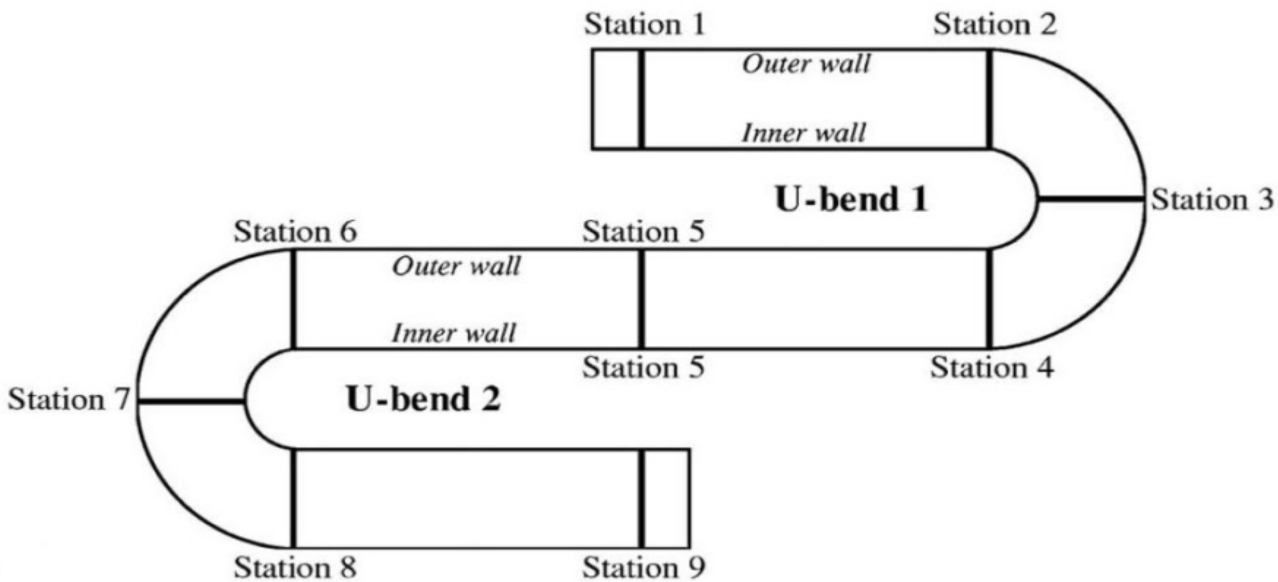
School of Engineering & Applied Science

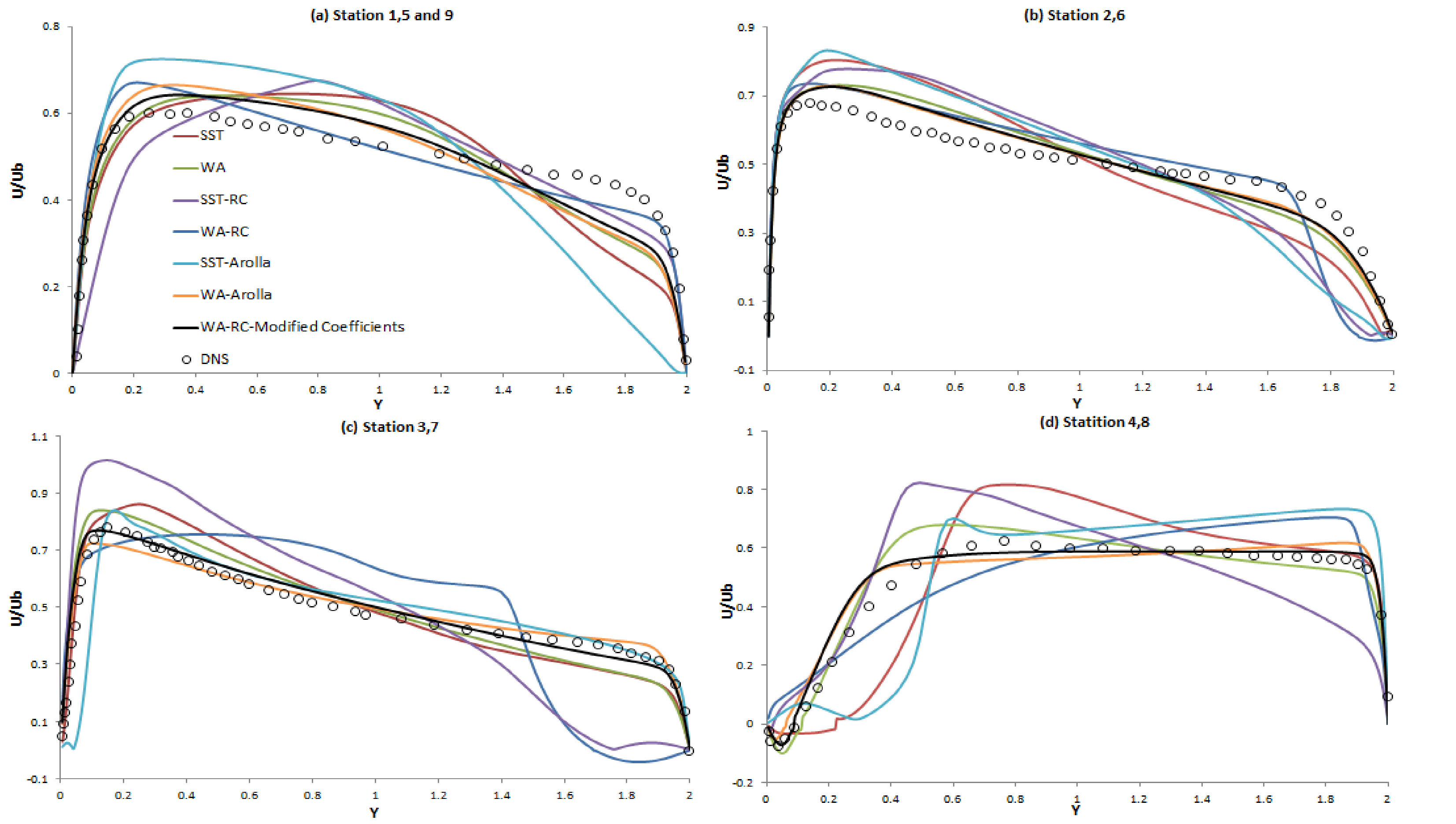
Geometry and Input

- The geometry is $12\pi\delta \times 2\delta$ with a curvature ratio $R_c/\delta = 2$ based on the channel half-width δ.
- Reynolds number: $Re \equiv 2\delta U_b/\nu = 5600$
- Rotation number: $R_o \equiv 2\delta\Omega/U_b = 0.32$



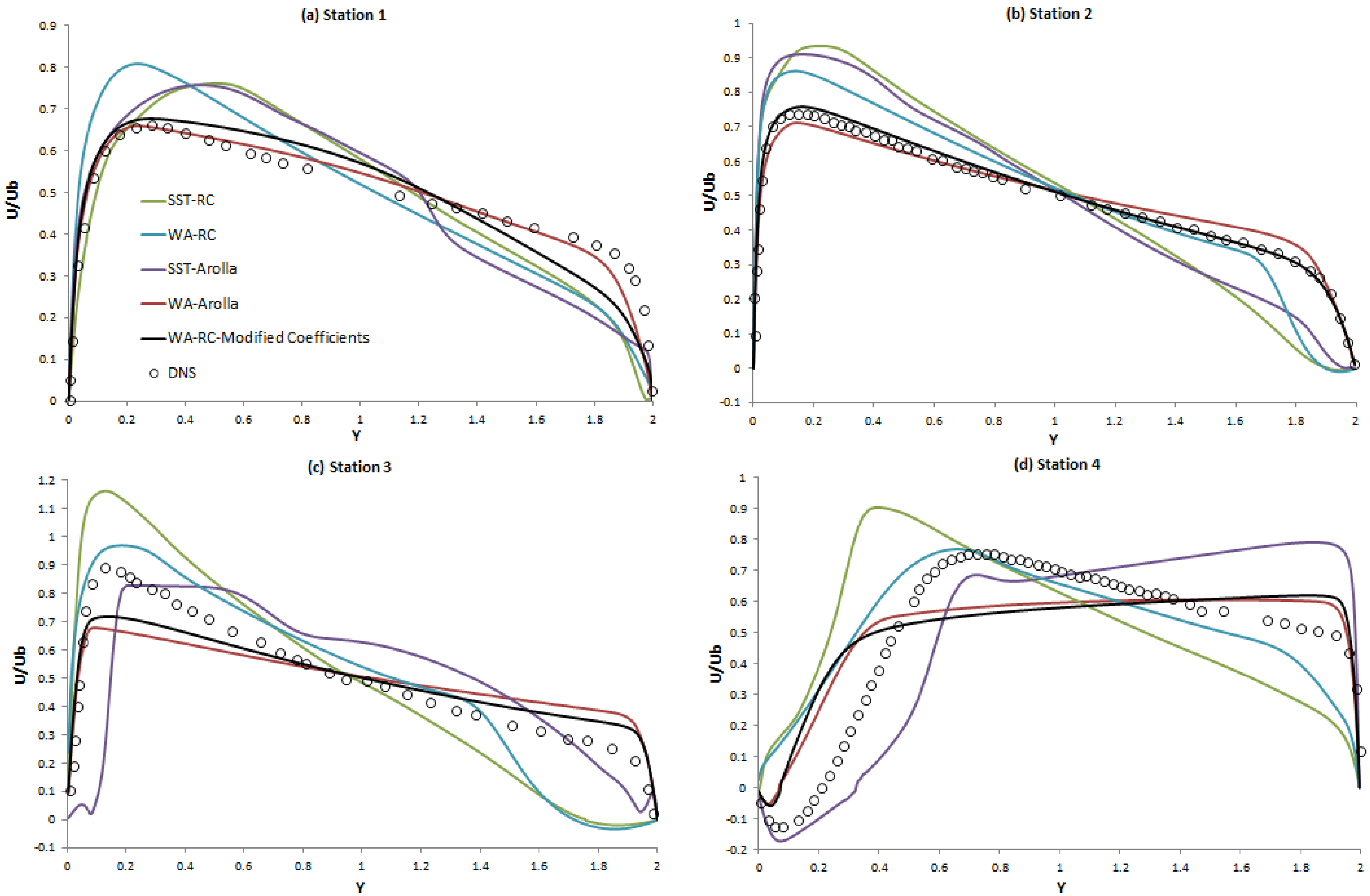
Serpentine Channel

Mean Velocity Profile



Rotating Serpentine Channel

Mean Velocity Profile



WA-Rough

- Follows the procedure of the SA-Rough model.

$$d_{new} = d + 0.03k_s$$

$$f_\mu = \frac{\chi^3}{\chi^3 + C_w^3}, \qquad \chi = \frac{R}{\nu} + C_{r1}\frac{k_s}{d}$$

- Wall boundary condition for *R* becomes:

$$\frac{\partial R}{\partial n} = \frac{R}{d_{new}}$$

- To further increase the eddy-viscosity near the wall

$$(C_{2k\omega})_r = C_{2k\omega}\left(\frac{1}{1 + \frac{C_{r2}k_s}{d_{new}}}\right)$$

Smooth and Rough S809 Airfoil

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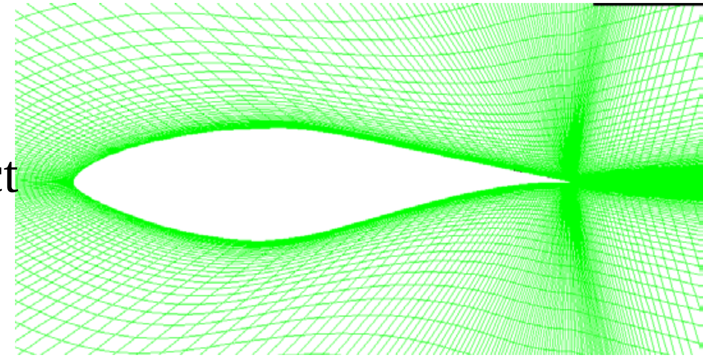
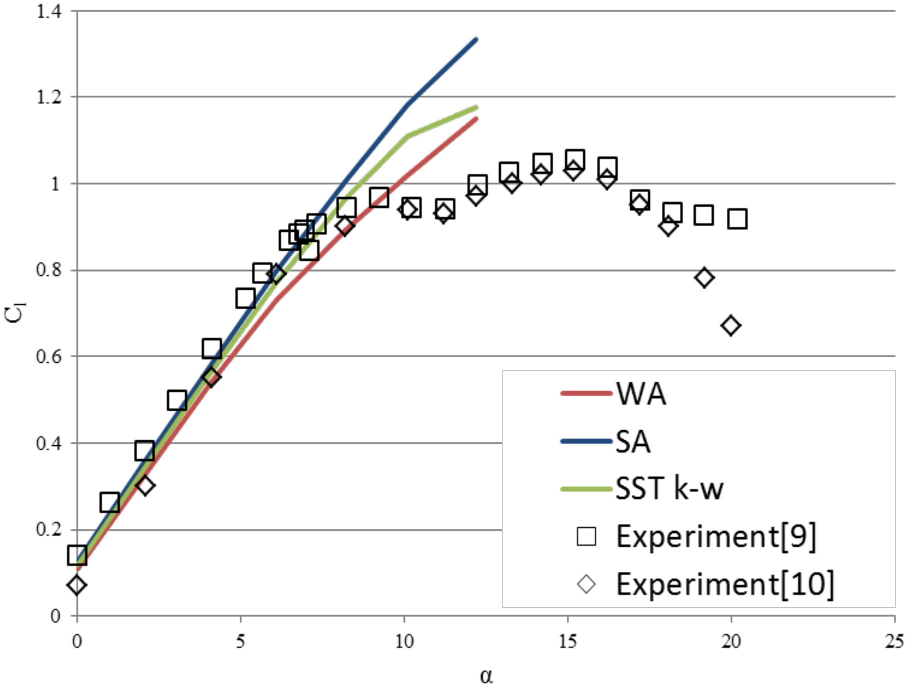
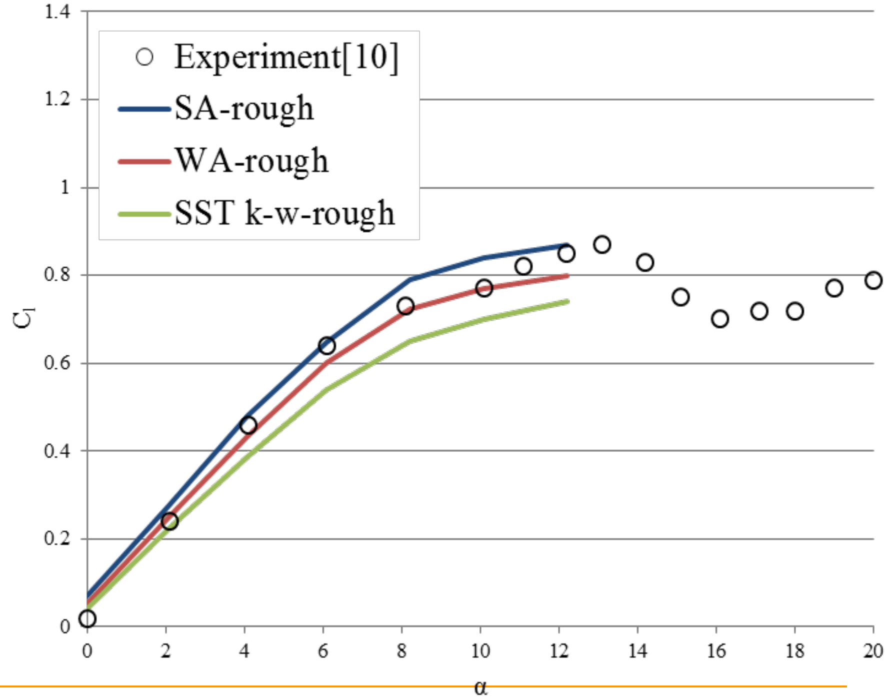
NREL's S809 Airfoil commonly used in HAWT

$Re_c = 1x10^6$, $U = 12.8\ m/s$, $\alpha = 0°, 2°, 4°, 6°, 8°, 10°, 12°$

Roughness pattern was developed using a molded insect pattern taken from a field wind turbine. $k_s/c = 0.0019$







WA-γ Transition Model

$$\frac{\partial \rho R}{\partial t} + \frac{\partial \rho u_j R}{\partial x_j} = \frac{\partial}{\partial x_j}\left[(\mu + \sigma_R \mu_T)\frac{\partial R}{\partial x_j}\right] + \gamma\rho C_1 RS + \gamma\rho f_1 C_{2k\omega}\frac{\partial R}{\partial x_j}\frac{\partial S}{\partial x_j}\frac{R}{S} + P_R^{lim} - \max(\gamma, 0.1)(1 - f_1)\rho C_{2k\epsilon}\left(\frac{R\frac{\partial S}{\partial x_j}}{S}\right)^2$$

$$\frac{\partial \rho\gamma}{\partial t} + \frac{\partial \rho u_j \gamma}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_T}{\sigma_\gamma}\right)\frac{\partial \gamma}{\partial x_j}\right] + F_{length}\rho S\gamma(1-\gamma)F_{onset} - \rho c_{a2}\Omega\gamma F_{turb}(c_{e2}\gamma - 1)$$

γ = intermittency parameter, $P_R{}^{lim}$ ensure proper R generation for very low Tu values

F_{onset} triggers the intermittency production, it is a function of R_T, Re_v, and $Re_{\theta c}$

Local TurbulenceIntensity: $Tu_L = \min\left(100\,\frac{\sqrt{\frac{2R}{3}}}{\sqrt{\frac{S}{0.3}*d_w}}, 100\right)$, d_w~distance from wall

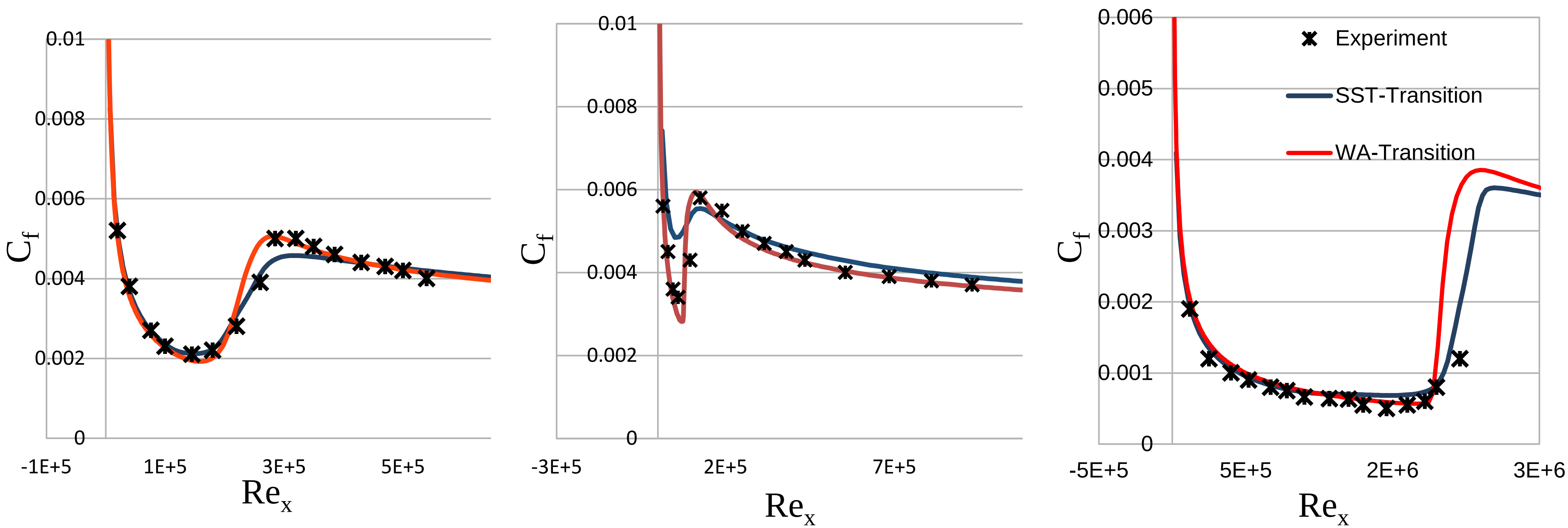
Pressure gradient parameter: $\lambda_{\theta L} = -7.57 \cdot 10^{-3}\,\frac{dV}{dy}\frac{d_w^2}{\nu} + 0.0128$

$Re_{\theta c}$ correlation: $Re_{\theta c} = 100.0 + 1000.0\exp[-1.0 * Tu_L * F_{PG}]$
where F_{PG} is a correlation function of $\lambda_{\theta L}$

WA-γ Transition Model

- Three zero pressure gradient flat plate cases : T3A, T3B, T3A-

	U_∞ (m/s)	Tu_∞(%)	μ_T/μ	ρ (kg/m³)	μ (kg/ms)	Re
T3A	5.4	3.5	13.3	1.2	1.8e-5	9e+5
T3B	9.4	6.5	100	1.2	1.8e-5	1.57e+6
T3A-	19.8	0.874	8.72	1.2	1.8e-5	3.3e+6



T3A T3B T3A-

Summary

- A new one-equation turbulence model has been developed to have desirable characteristics of one-equation k-ω and one equation k-ε models.
- The new one-equation WA model has been used to simulate a number of wide-ranging canonical turbulent flow cases.
- The behavior of the WA model is very similar to the two-equation SST k-ω model.
- A clear advantage of the WA model's predictive capability over the SA model has been shown for a number of cases from subsonic to transonic to hypersonic wall bounded flows with small regions of separation and subsonic/supersonic free shear layer flows.
- Spalart-Shur R/C correction has been implemented and verified for all three models.
- Surface roughness corrections have been implemented and verified for all three models.
- The DES and IDDES versions of WA model have been developed which show improvement in accuracy over the WA model.

Acknowledgements

- This research has been partially supported by NASA EPSCoR Program.
- PI is very grateful to Dr. Mujeeb Malik for his support and help.
- The presentation is based on the work of many graduate students: Tim Wray, Xu Han, Hakop Nagapetyan, Xiao Zhang, Francis Acquaye, Colin Graham and Isaac Witte
- The research has been presented at AIAA and ASME conferences .
- The conference papers and journal papers are available.
- Code modules for OpenFOAM and Fluent UDFs are available upon request.