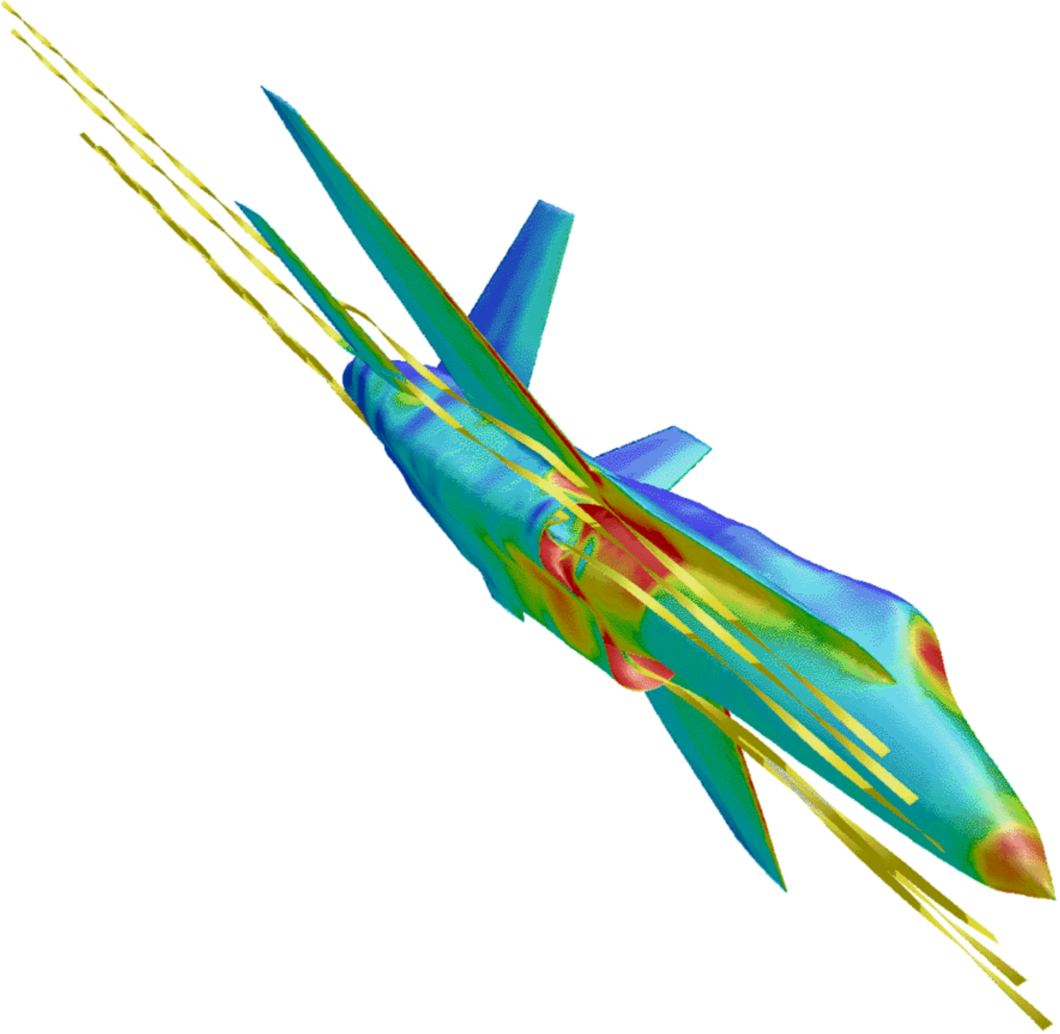
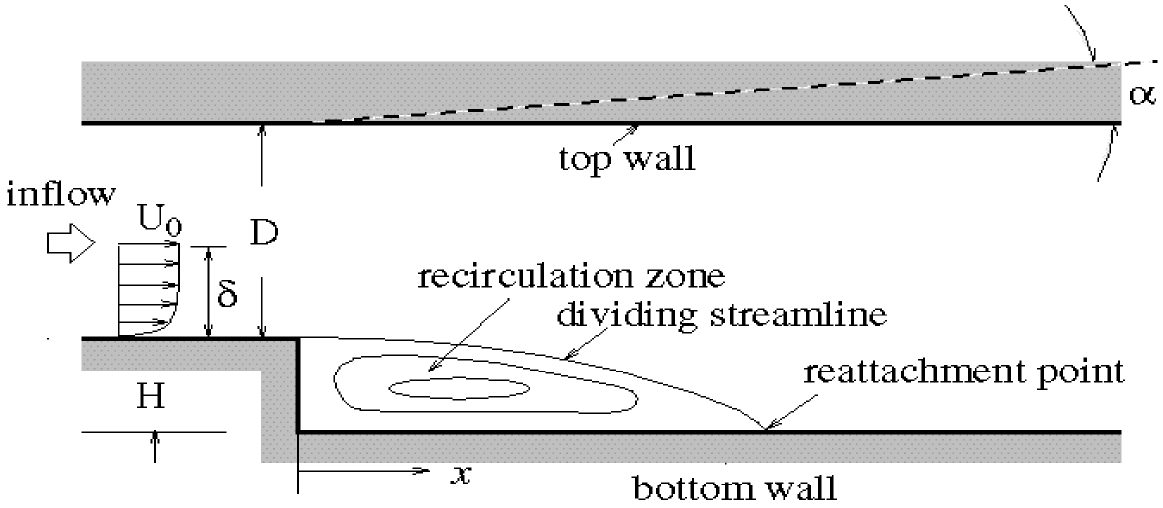
Turbulent Flow Examples



2d Backstep

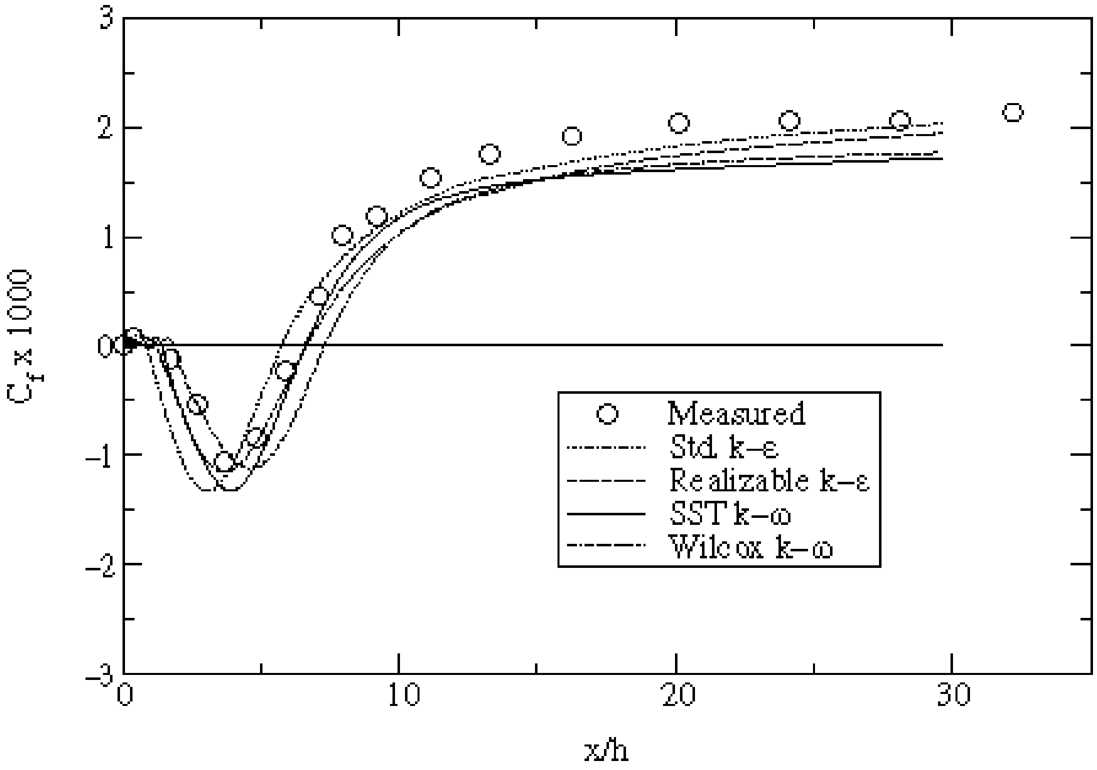
- Experiments conducted at NASA Ames (Driver and Seegmiller, 1985)
- $Re_H = 3.74 \times 10^4$, $\alpha = 0$ deg.
- The flow features re-circulation, reattachment, and re-developing BL
- Computed using SKE, RNG, RKE, and k-ω models on a fine mesh



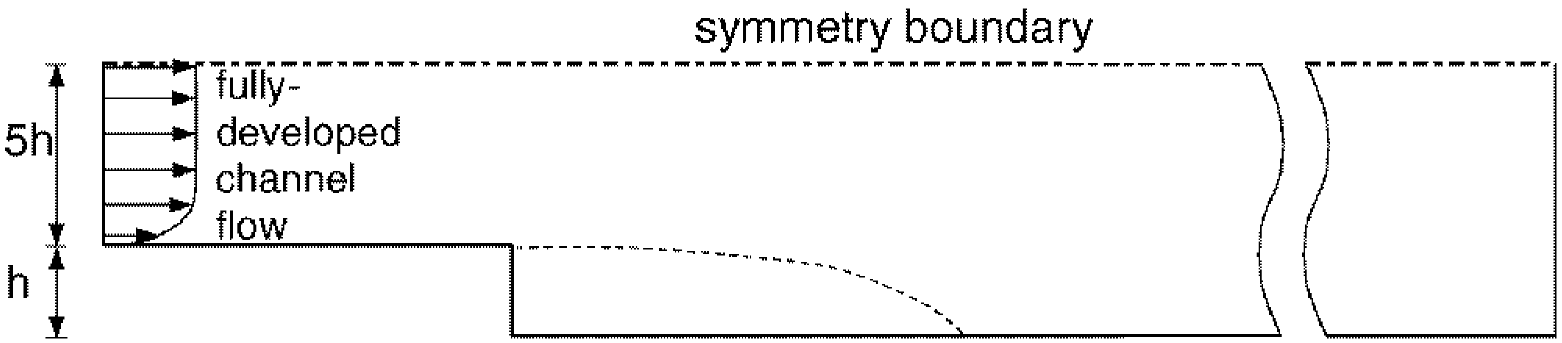
2D Backstep - Skin Friction Coefficient

Predicted reattachment lengths

	Std. k-ε	Real. k-ε	SST k-ω	Wilcox k-ω	Measured
x_r/H	5.8	6.6	6.6	7.3	6.4

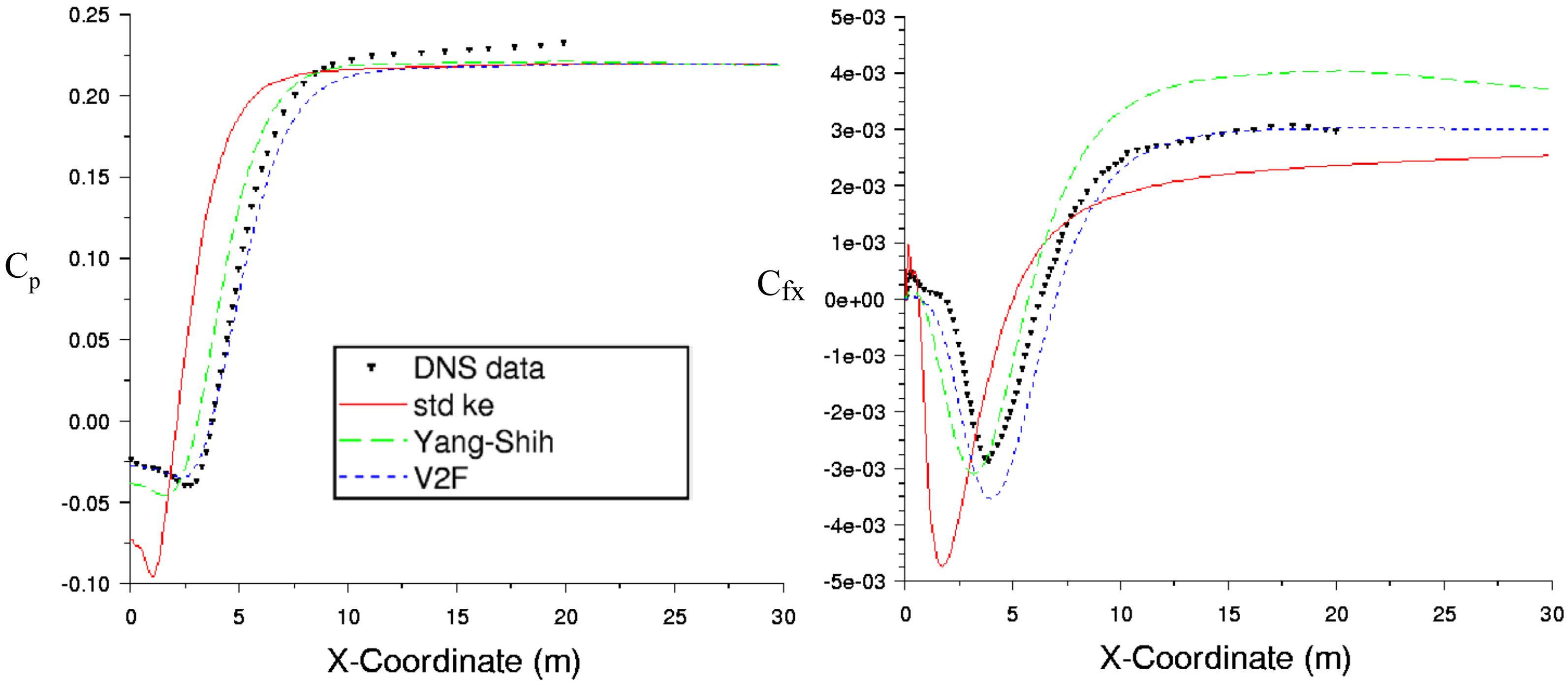


Low-Re Backstep



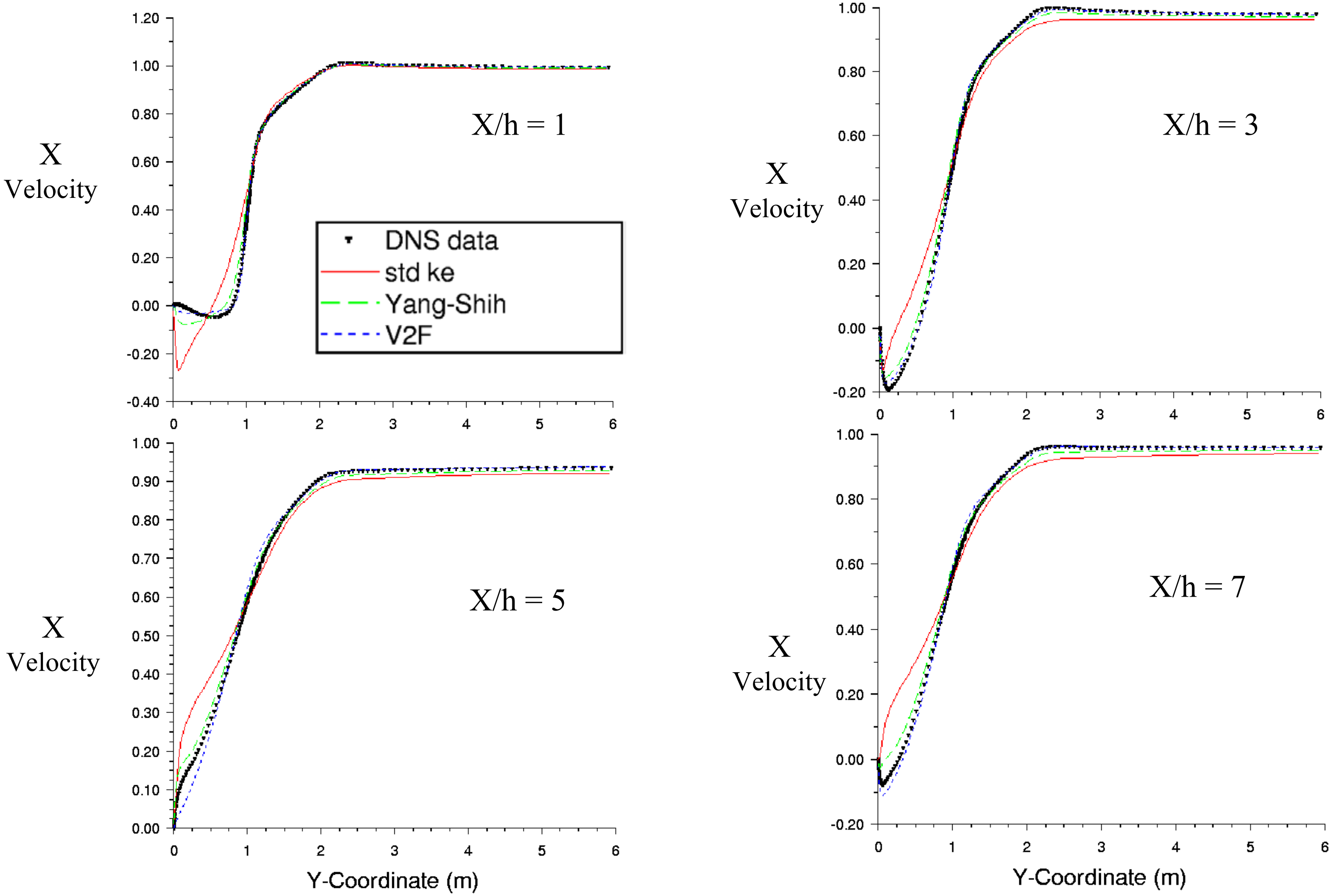
- Re = 5,100
- Comparison with DNS data of Le and Moin (1994)
- Comparison of Standard *k*-ε + 2-layer, Yang-Shih low-Re model and V2F low-Re model

Low-Re Backstep

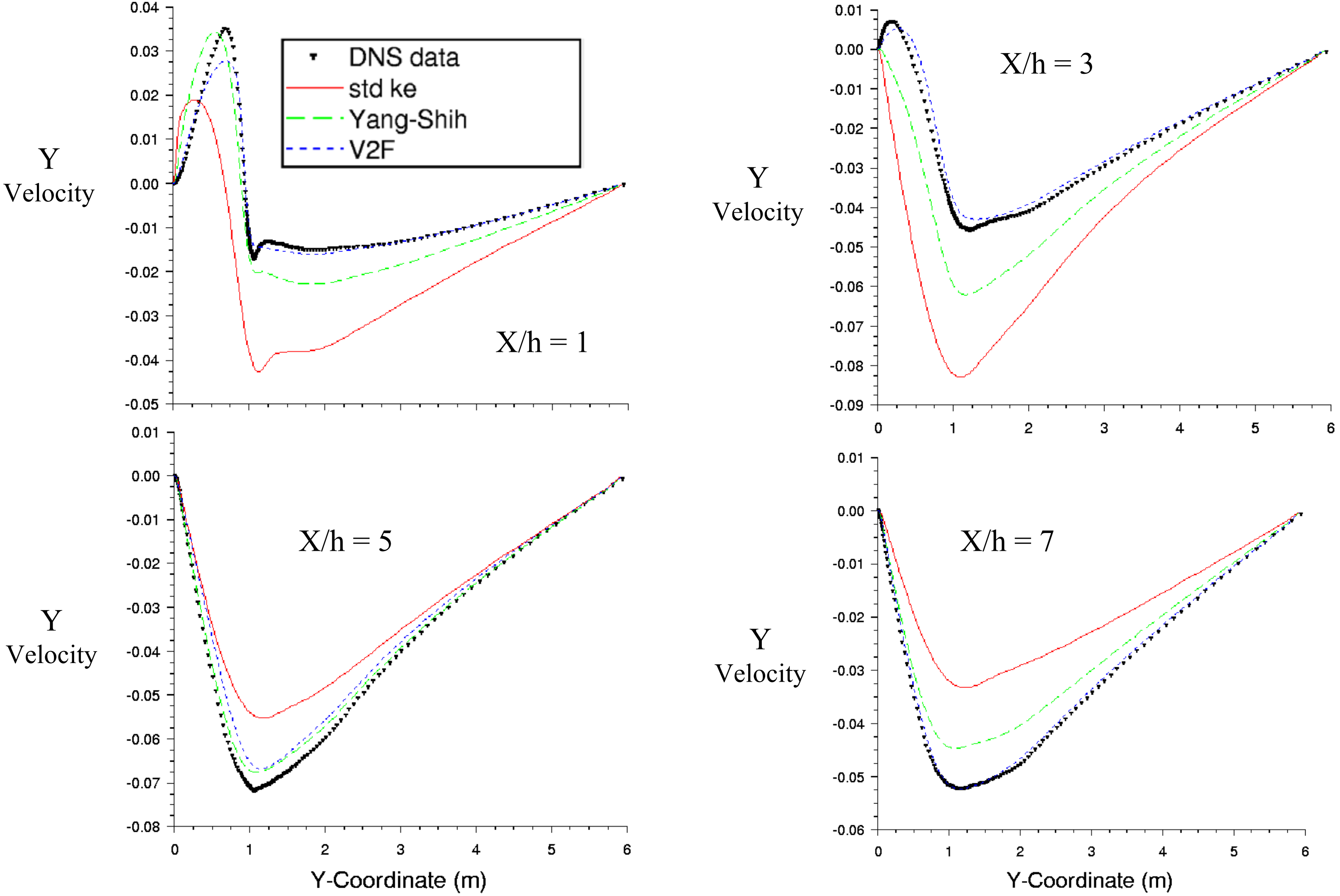


- Pressure coefficient and x-component of skin friction
- 2-layer model less accurate than V2F and Yang-Shih

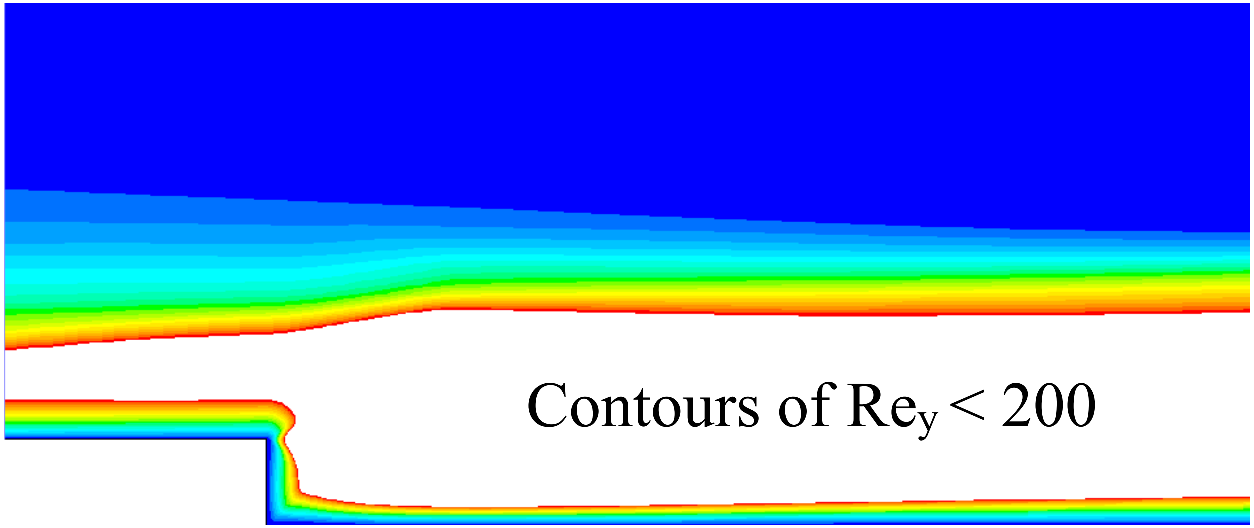
Low-Re Backstep



Low-Re Backstep

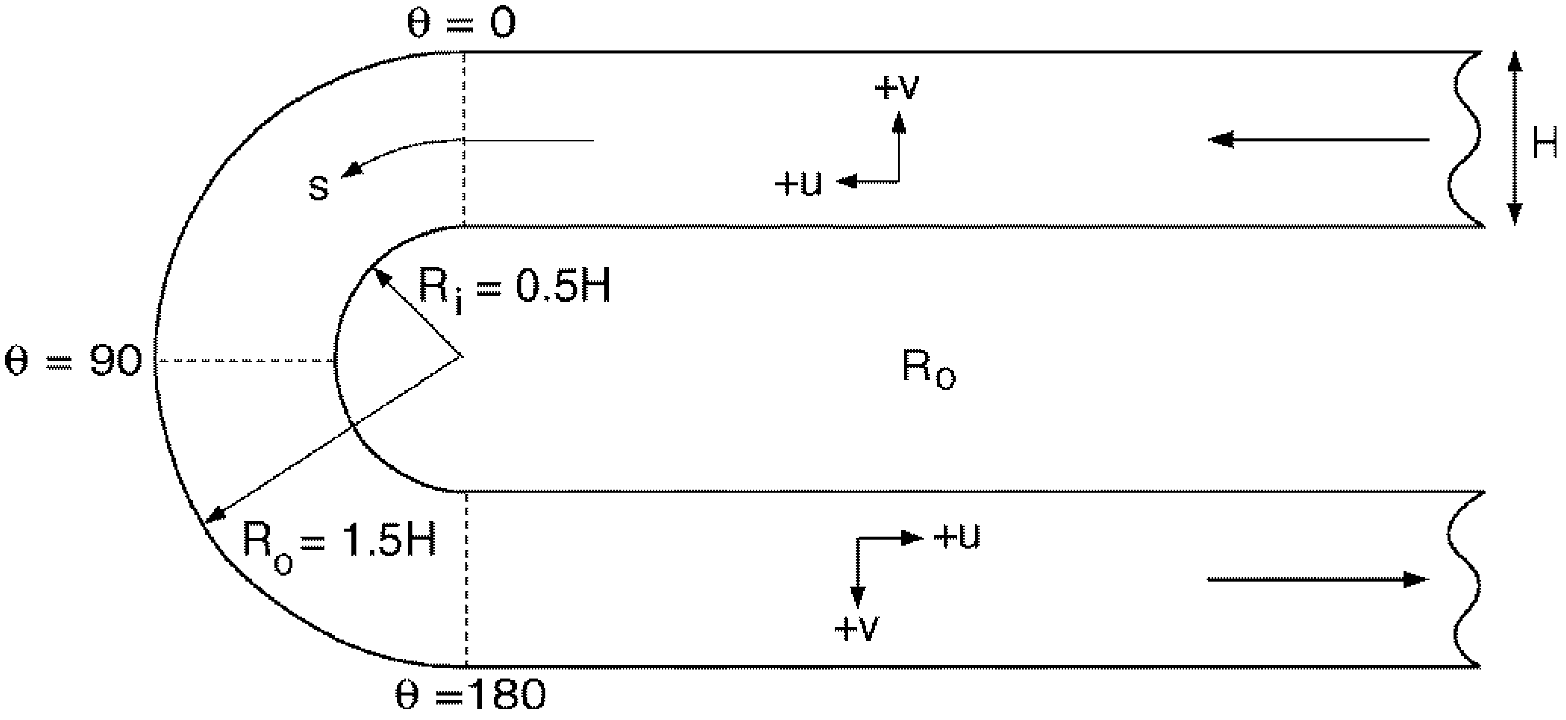


Low-Re Backstep


Contours of $Re_y < 200$

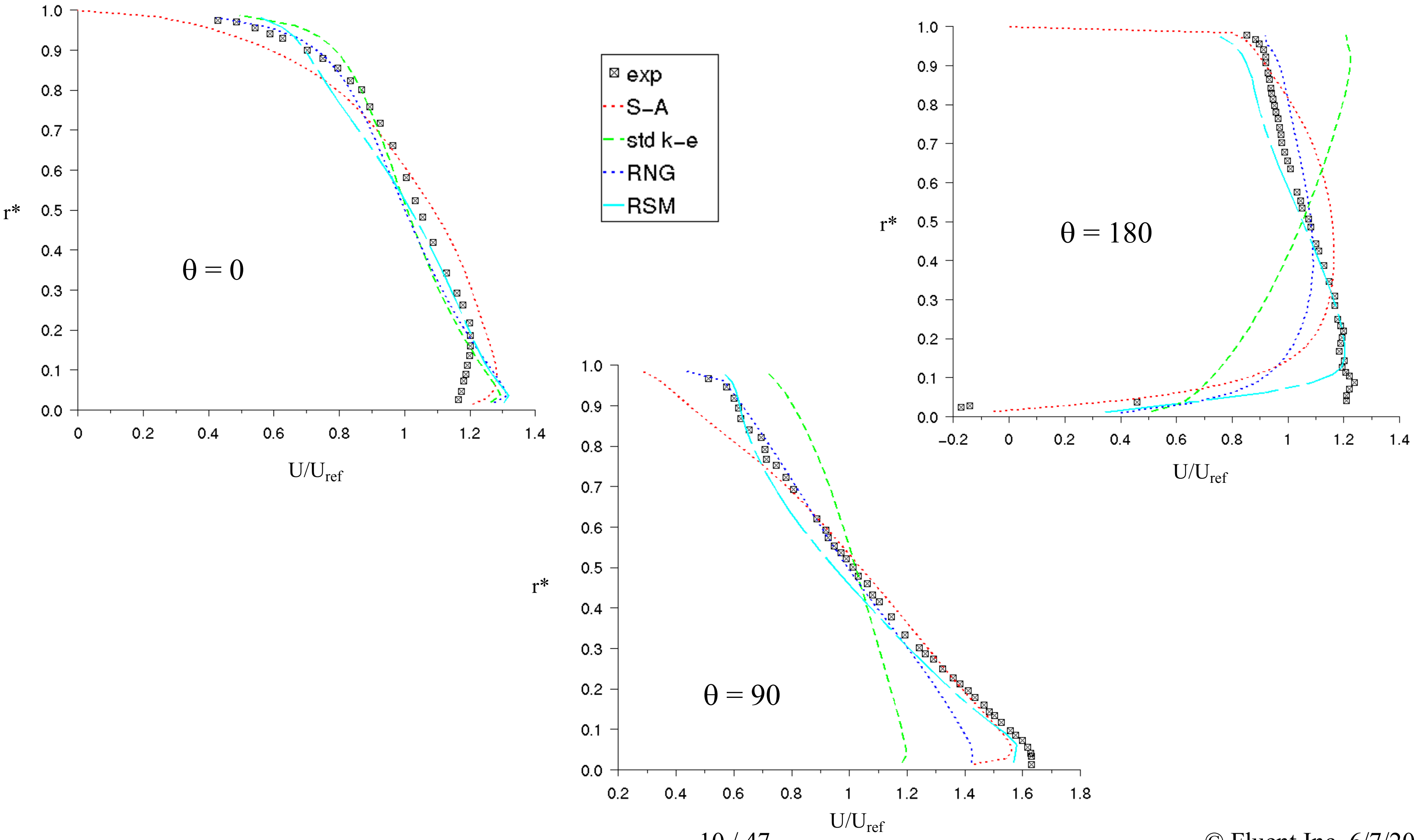
- ε and ν_t prescribed algebraically for 2-layer model in region where $Re_y < 200$
- For low Re, much of the flow is in this region
- 2-layer model is not always a good substitute for a low-Re model

2D U-Bend

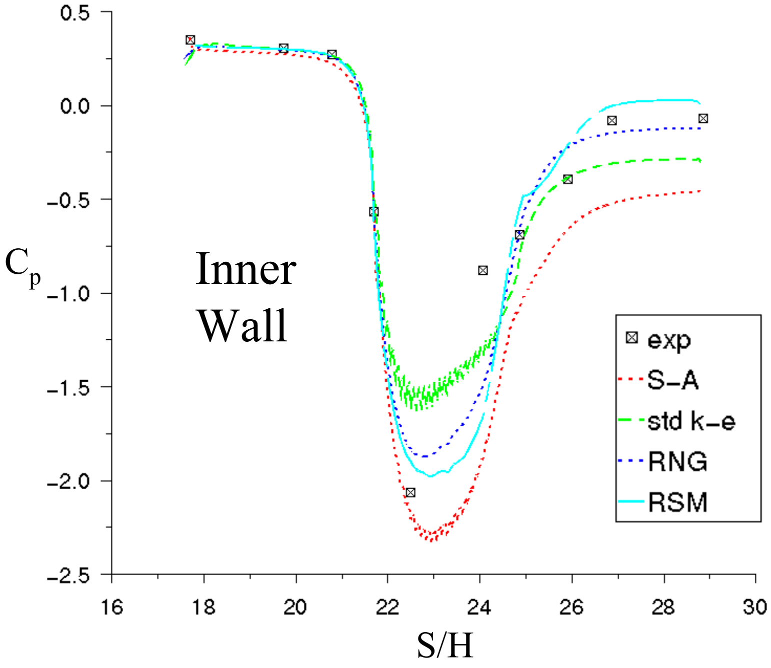


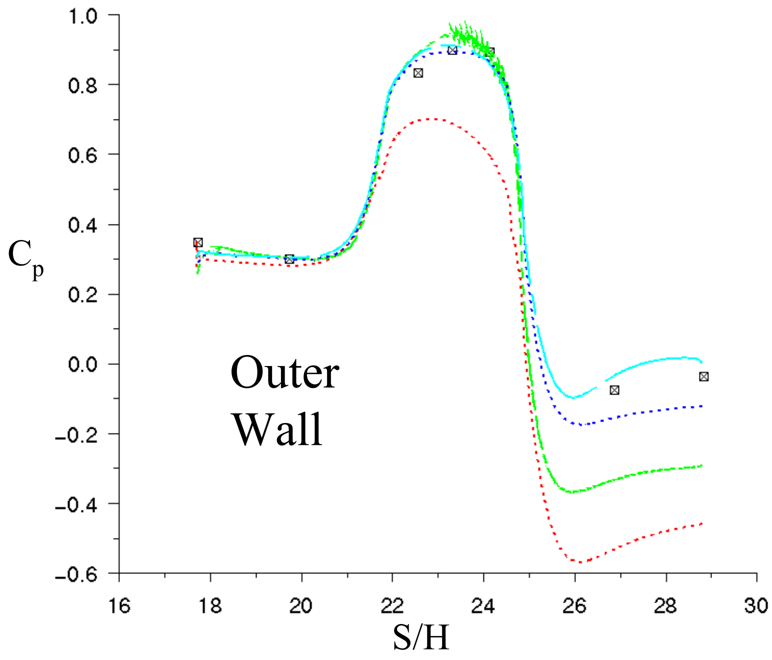
Comparison with experimental data of Monson *et al.* (1990)

Streamwise Velocity Comparisons

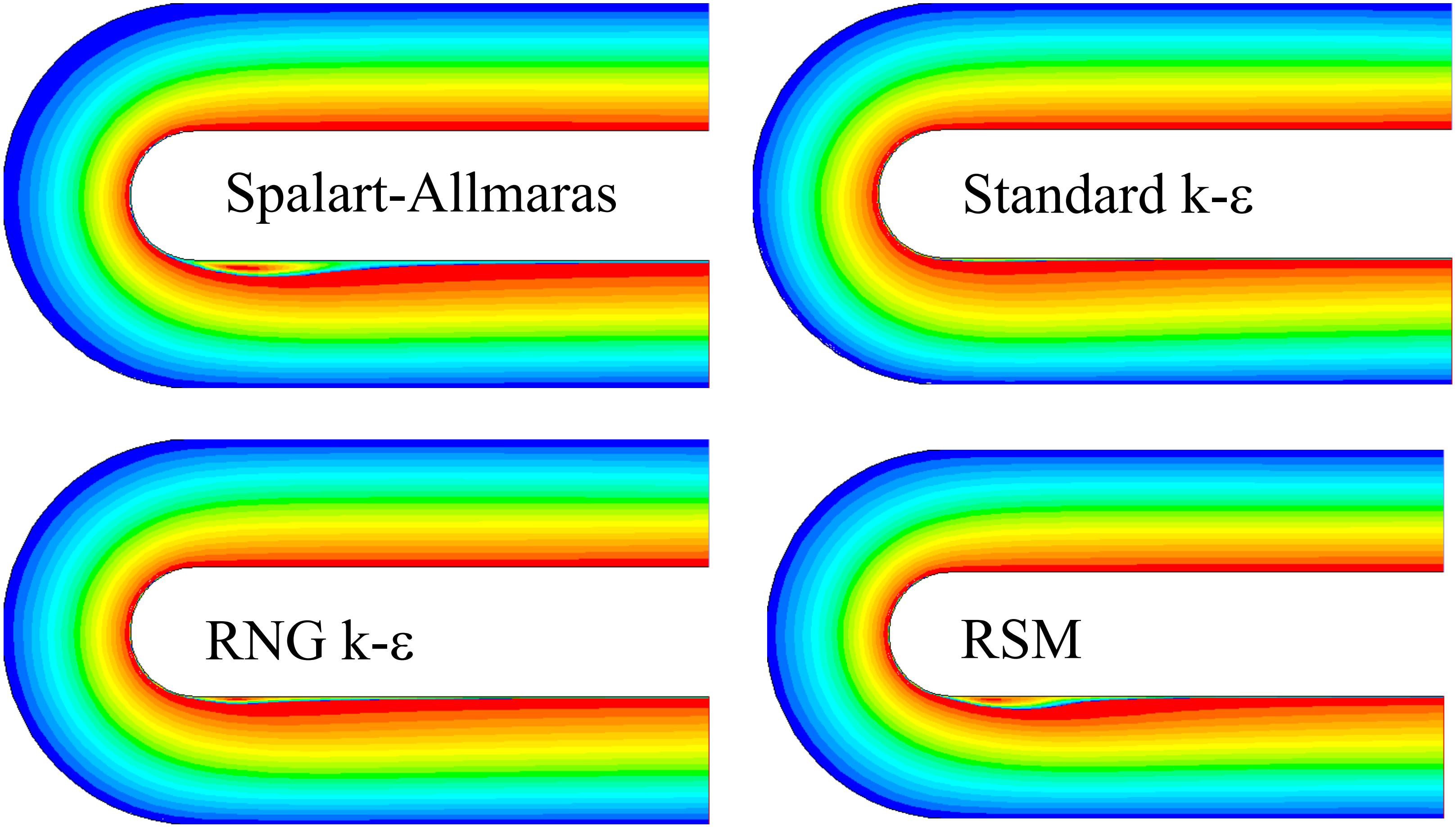


Pressure Coefficients





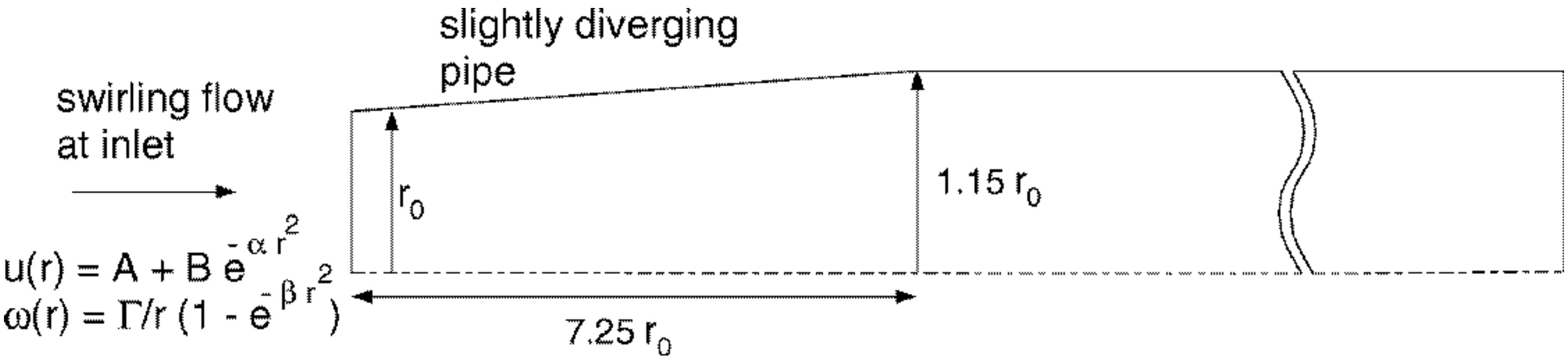
Stream Function Contours



Lessons from 2-D U-Bend

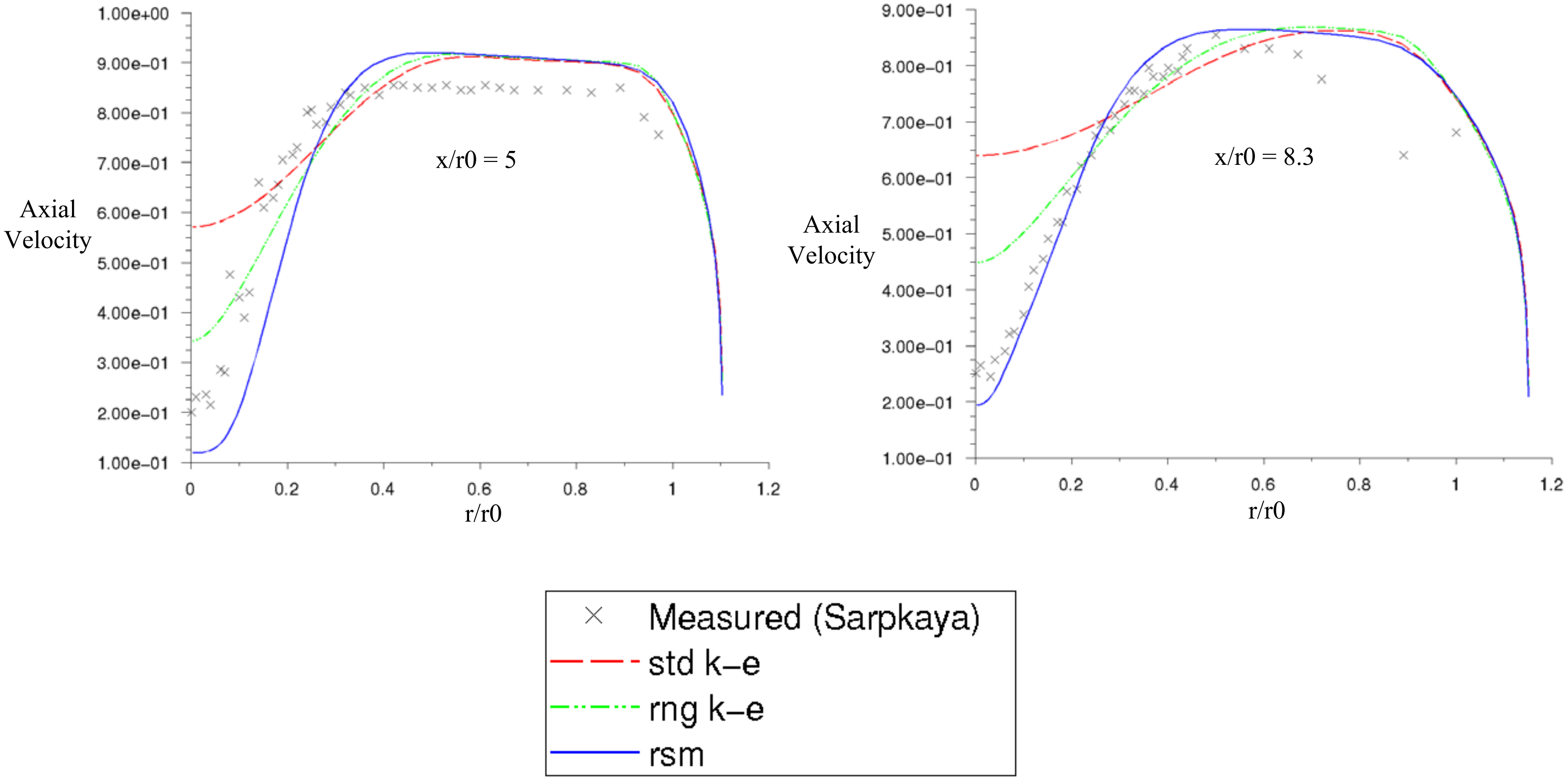
- Only the RSM correctly predicts the effects of streamline curvature
- Standard *k*-ε does not predict any separation
- RNG *k*-ε predicts slight separation
- Both RSM and Spalart-Allmaras predict significant separation

Turbulent Vortex Breakdown

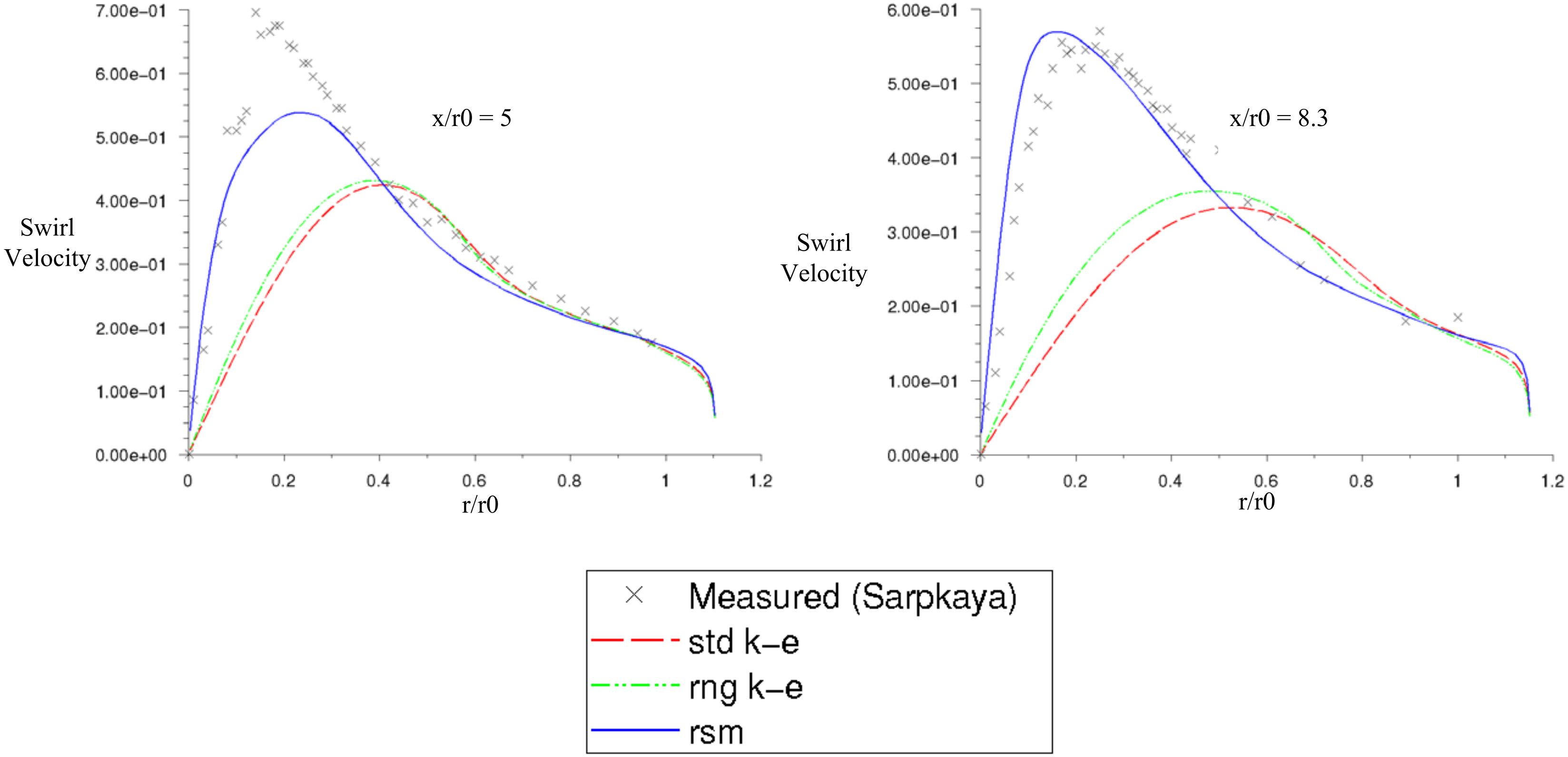


- Comparison with experimental data of Sarpkaya (1999)
- 2D axisymmetric calculation
- Simulation courtesy of R. Spall, Utah State University

Comparisons of Axial Velocity Profiles



Comparisons of Swirl Velocity Profiles

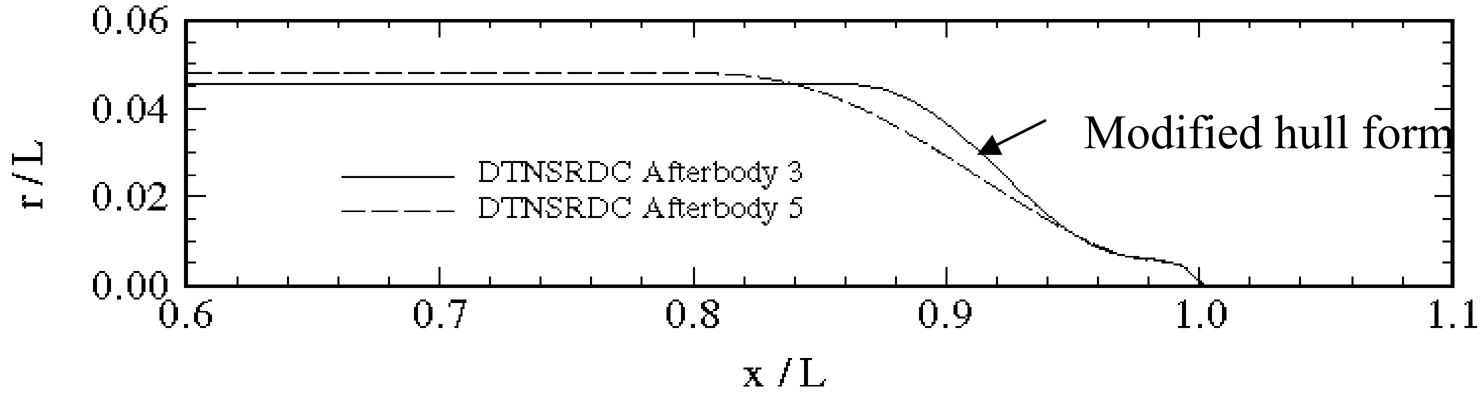


Lessons from Turbulent Vortex Breakdown

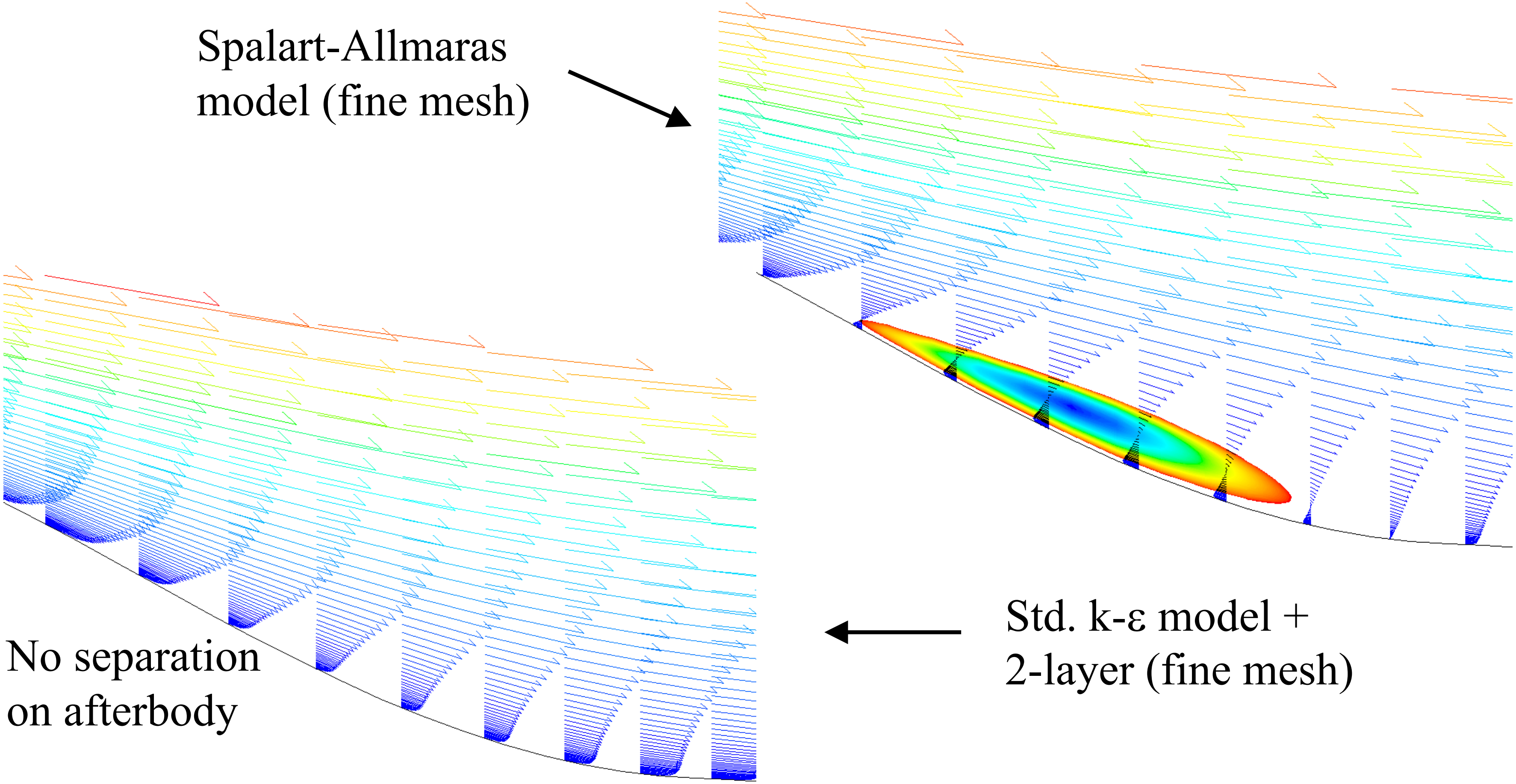
- *k*-ε model cannot predict vortex breakdown
  - in high strain rates, turbulent kinetic energy increases and increases turbulent viscosity
  - RNG *k*-ε model is better (additional strain-rate term, and an ad hoc swirl correction, reduce the turbulent viscosity) but not acceptable
- RSM results show significant improvement for this and many other swirling flow cases

Axisymmetric Underwater-Body

- Experiments conducted (Huang *et al.*, 1976) at DTNSRDC
- High-Re (Re_L= 5.9 x 10^6), incompressible BL flow with a separation at around x/L = 0.92, and reattachment at x/L = 0.97
- SKE, RNG, RKE, SA, SKO, SST, RSM and Low Re models tried
  - Different near-wall treatments tried



Axisymmetric Afterbody

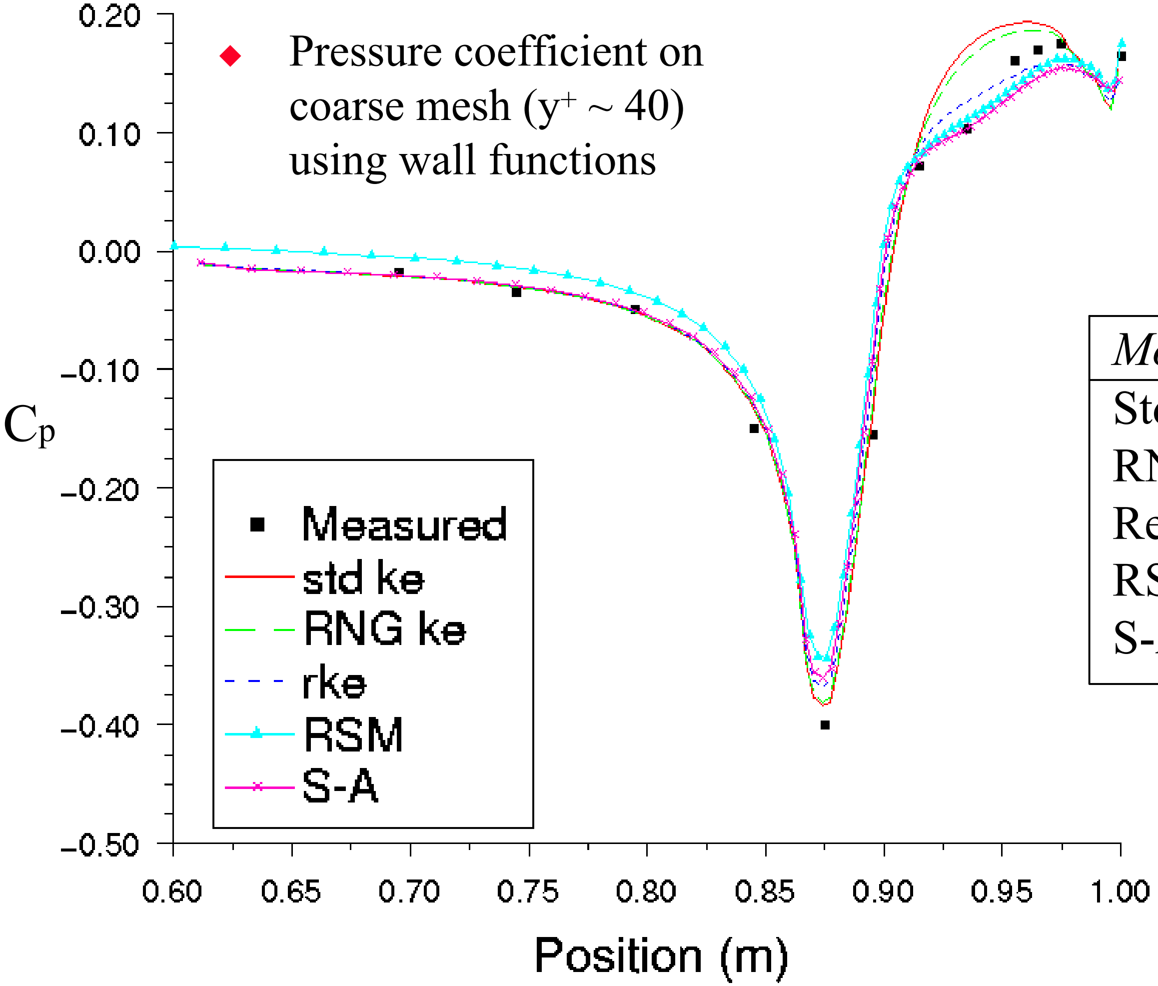


Spalart-Allmaras model (fine mesh)

Std. k-ε model + 2-layer (fine mesh)

No separation on afterbody

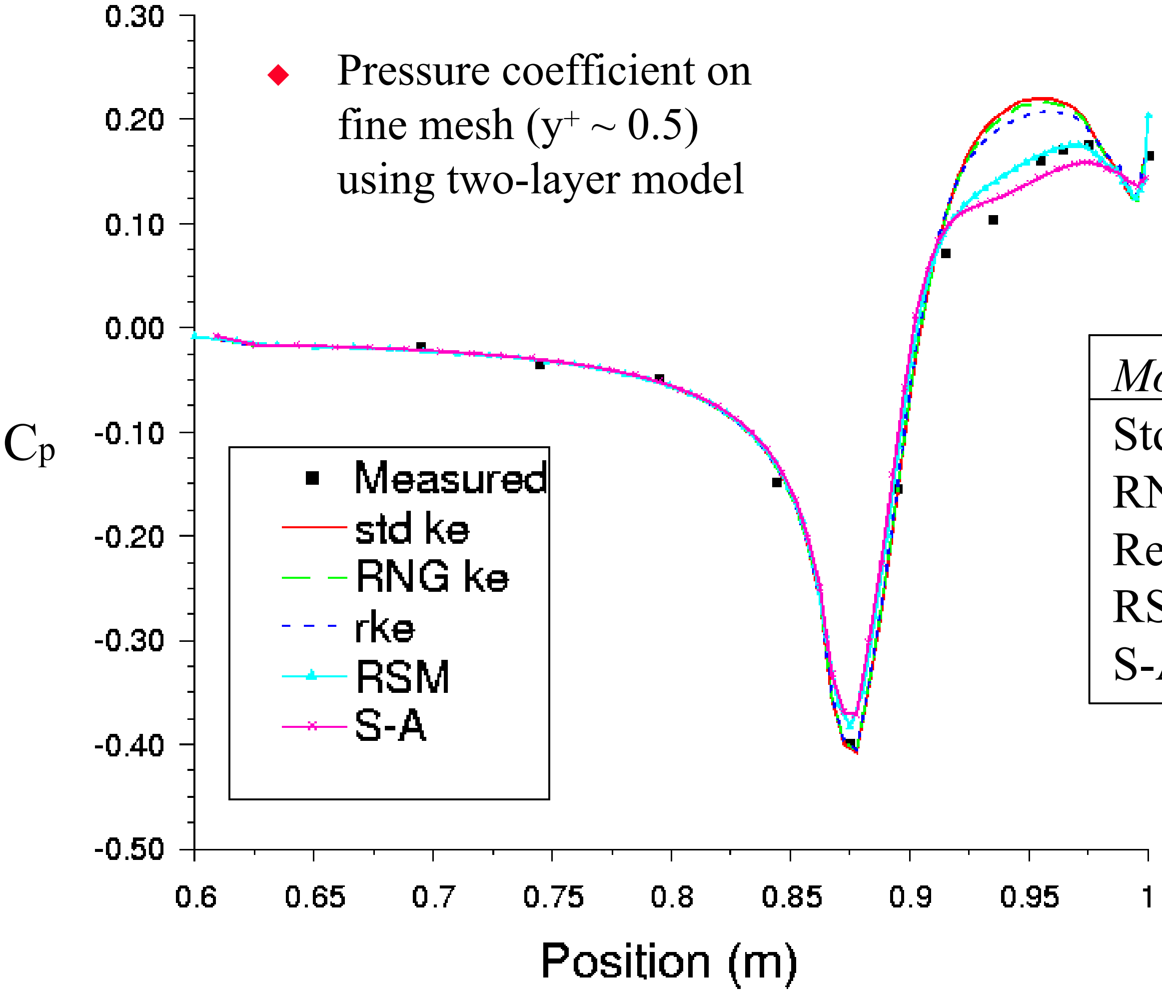
Axisymmetric Afterbody



- Pressure coefficient on coarse mesh ($y^+ \sim 40$) using wall functions

Model	*Separates?*
Std k-ε	n
RNG k-ε	n
Real. k-ε	y
RSM	y
S-A	y

Axisymmetric Afterbody

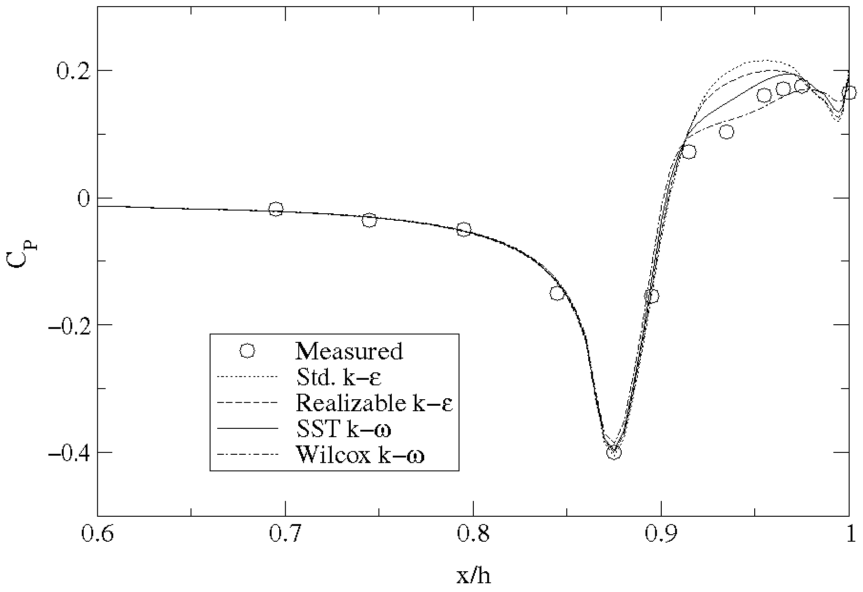


◆ Pressure coefficient on fine mesh ($y^+ \sim 0.5$) using two-layer model

Model	*Separates?*
Std k-ε	n
RNG k-ε	n
Real. k-ε	y?
RSM	y
S-A	y

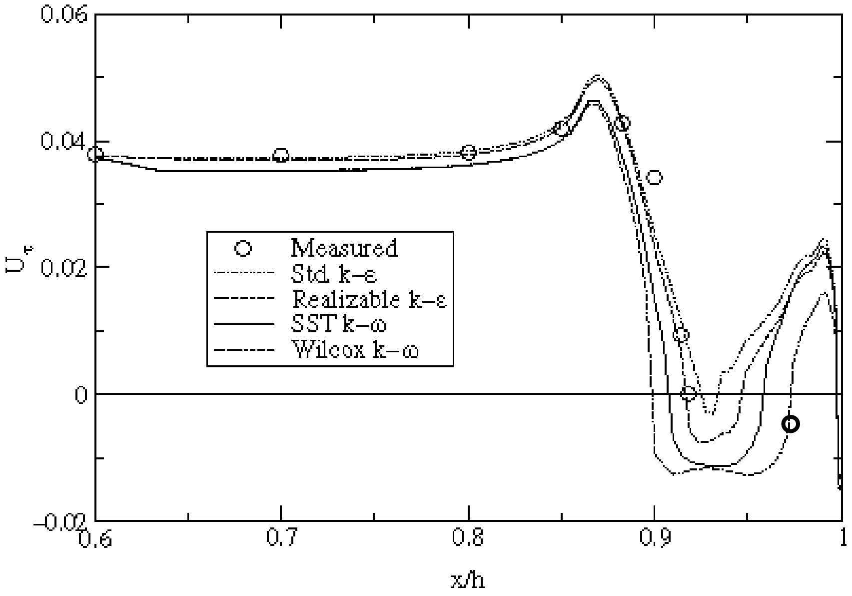
Axisymmetric Underwater-Body (2)

- Pressure (C_p) predictions



- Static pressure in the separated region is over-predicted by *k-ε* models

- Skin-friction predictions



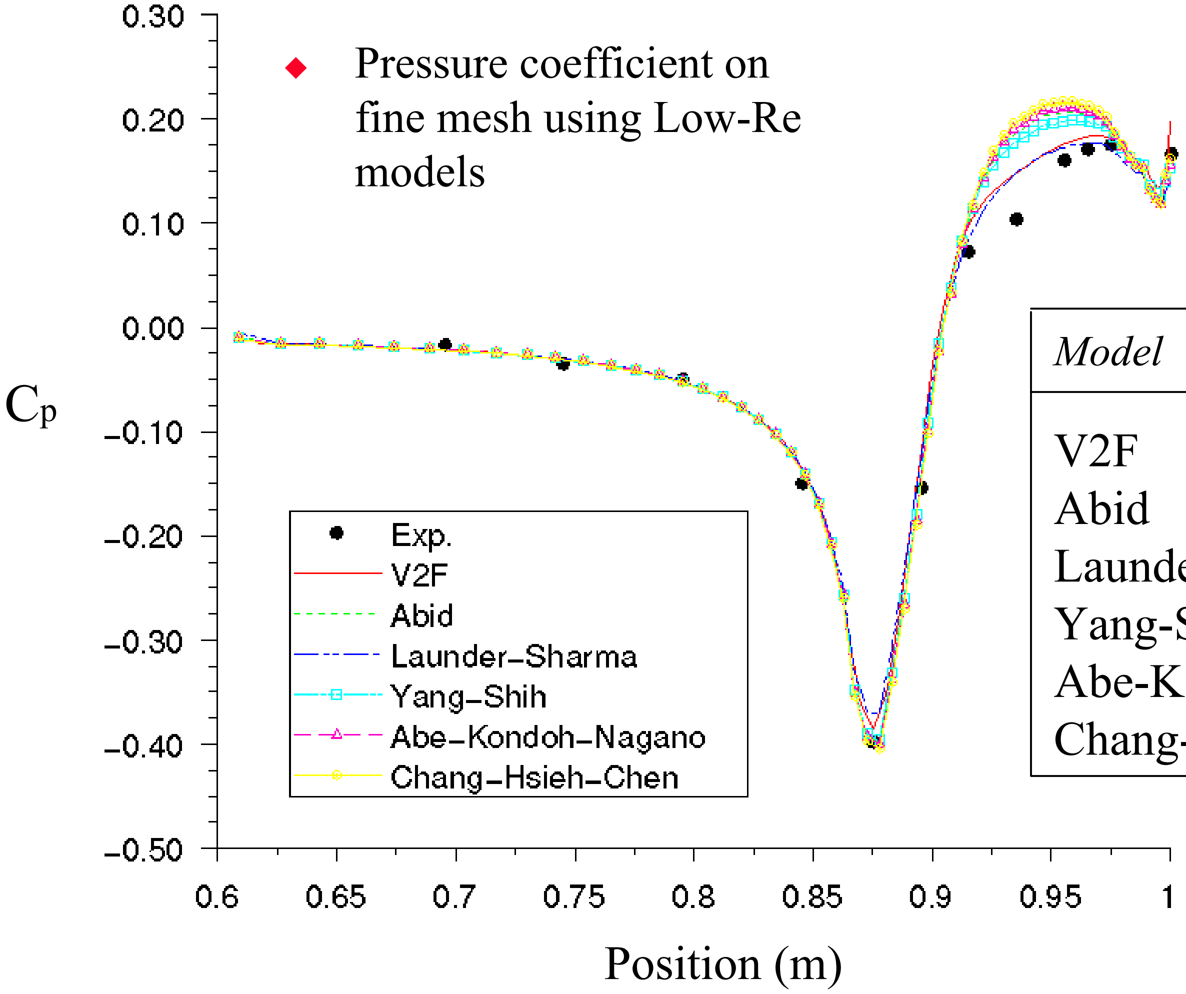
- The experiment shows the flow separates at x/L = 0.92 and reattaches at x/L = 0.97
- *k-ω* models gives too large a separation

Axisymmetric Afterbody

- Spalart-Allmaras gives consistent results on both meshes
- Separation not predicted by Standard k-ε on either mesh
- RSM separates on both meshes
  - C_p on body somewhat overpredicted on coarse mesh
  - "Wall reflection" term, or quadratic pressure-strain term, necessary to obtain coarse mesh separation
- Subtle separation illustrates effect of near-wall treatment
  - Realizable k-ε has smaller separation bubble on fine mesh
- Difficult to get grid-independent solutions using wall functions. Would a low-Re formulation work?

Axisymmetric Afterbody

◆ Pressure coefficient on fine mesh using Low-Re models

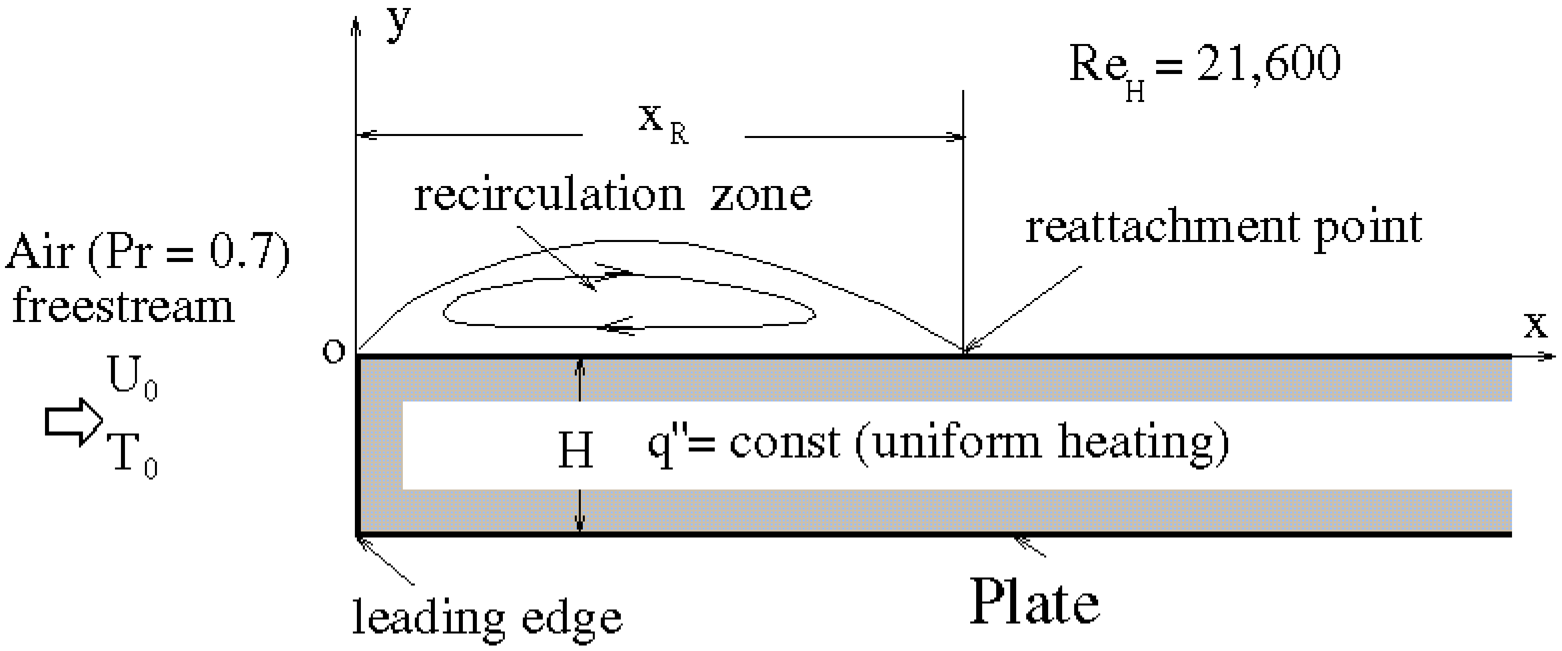


Model	*Separates?*
V2F	y
Abid	n
Launder-Sharma	n
Yang-Shih	n
Abe-Kondo-Nagano	n
Chang-Hsieh-Chen	n

Axisymmetric Afterbody

- Low-Re models using damping functions do not predict the separation
- Durbin’s V2F (4-equation) model predicts separation

Turbulent Heat Transfer Over a Blunt Plate

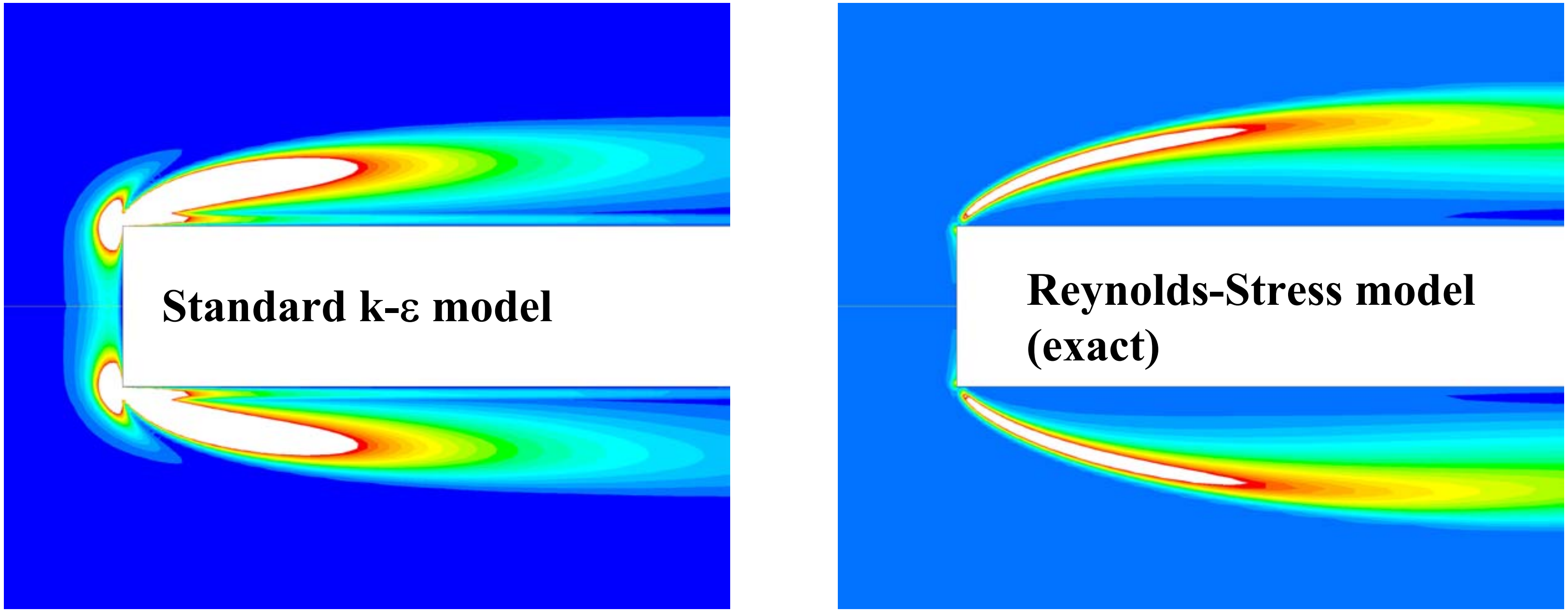


Ota & Kan

151x75 quad mesh

Blunt Plate

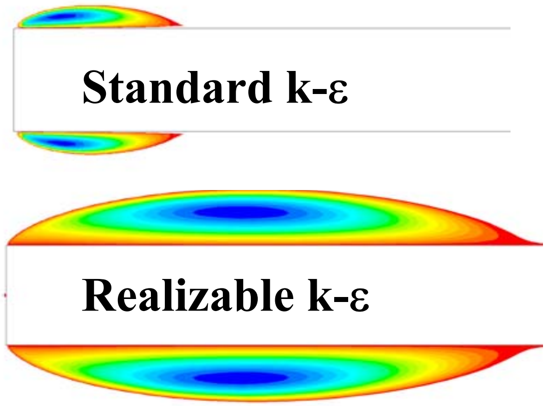
- The standard *k*-ε model gives spuriously large turbulent kinetic energy on the front face, underpredicting the size of the recirculation

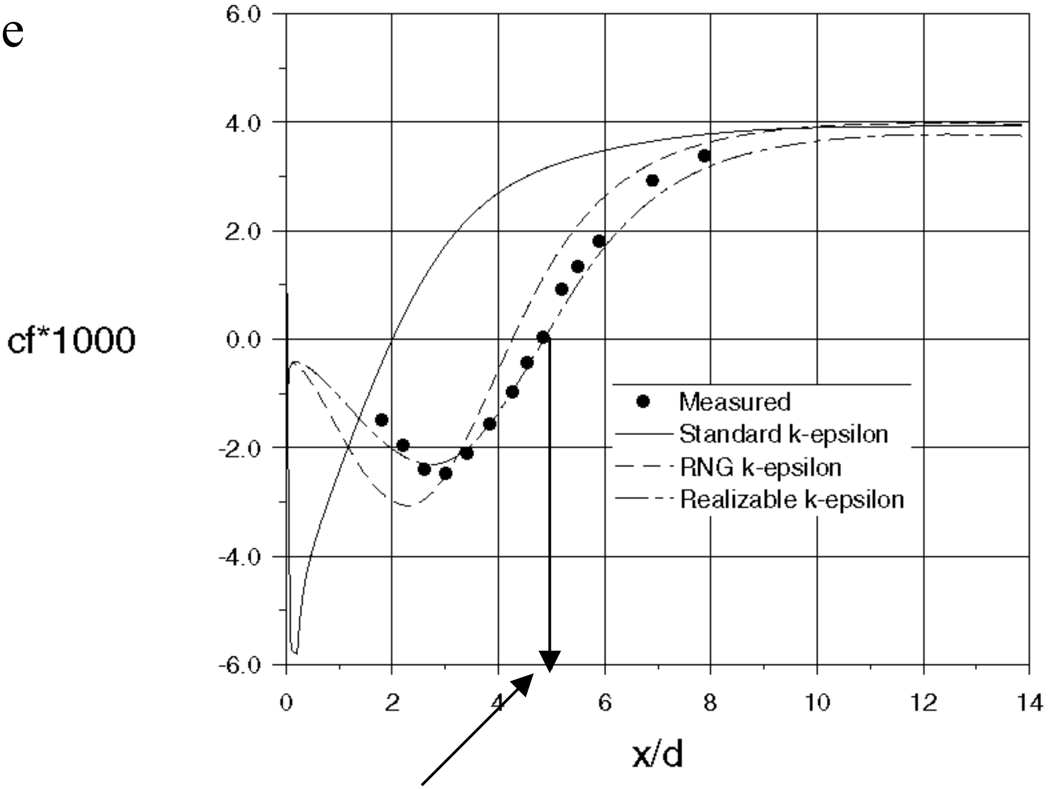


Contours of TKE production

Blunt Plate

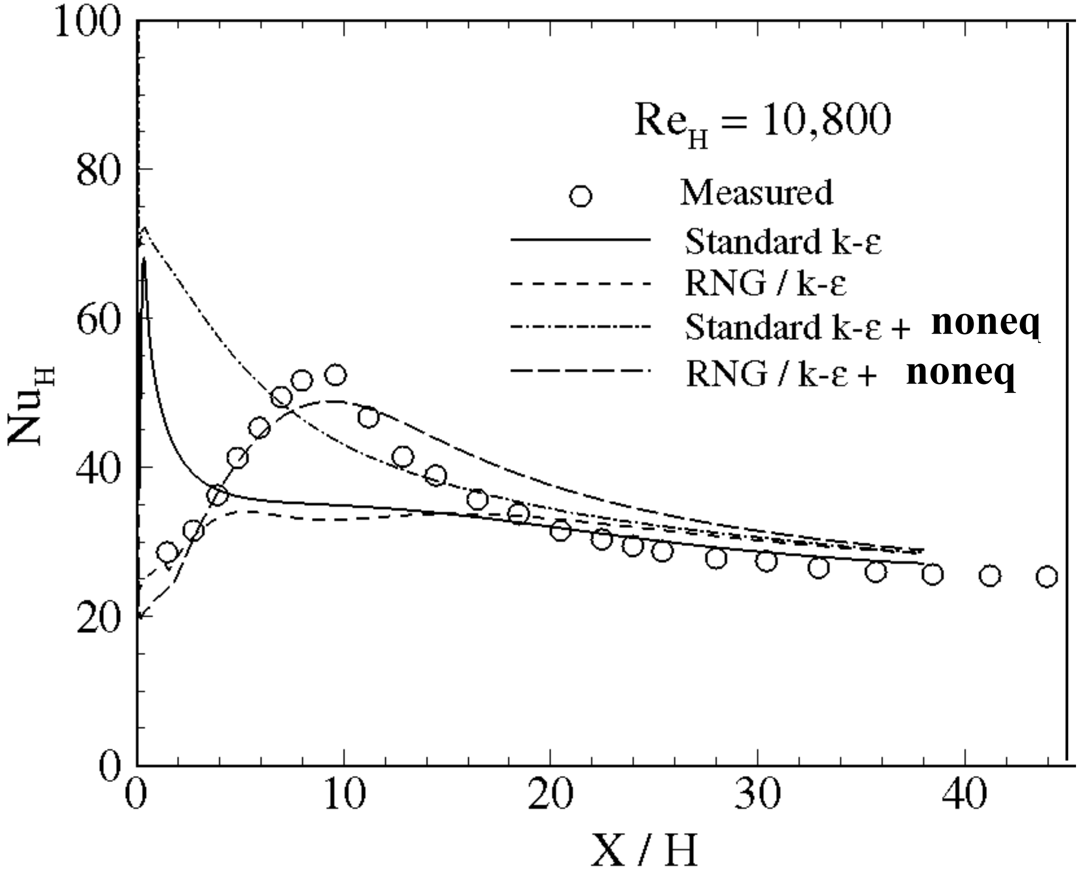
Predicted separation bubble





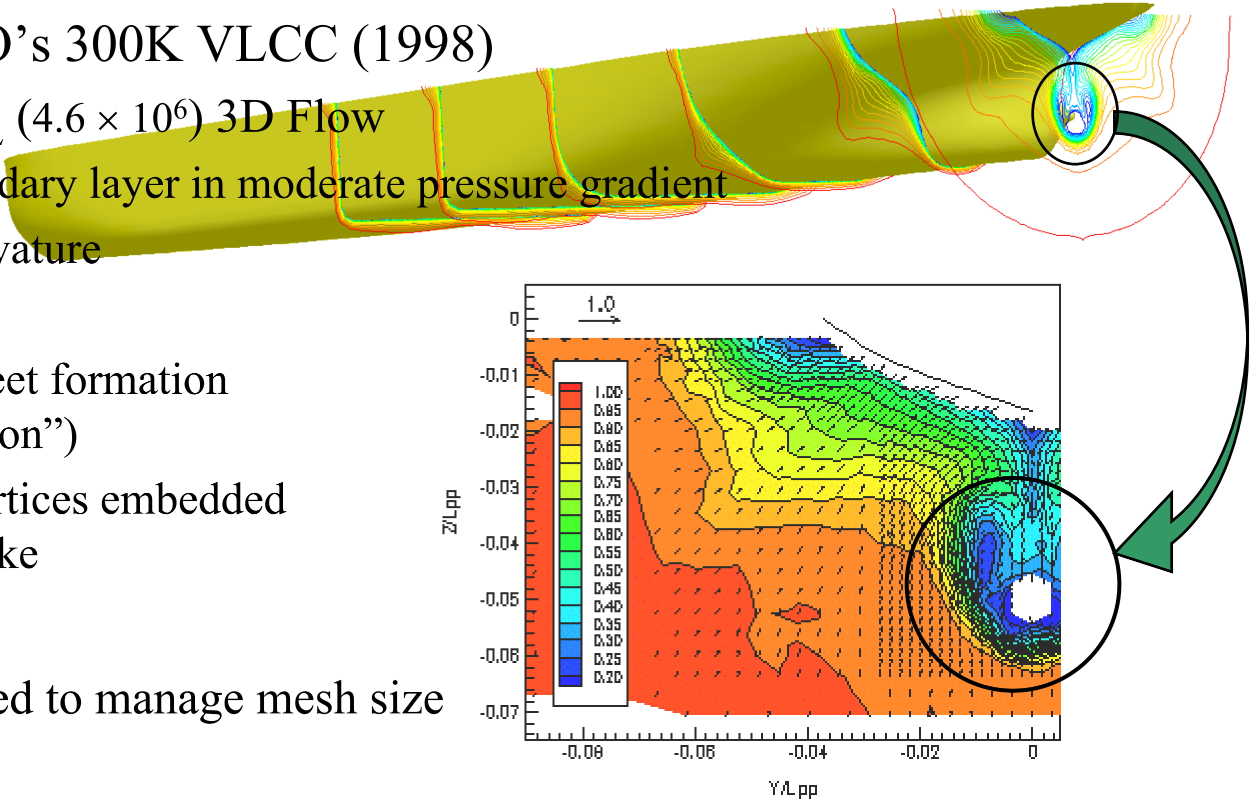
Experimentally observed reattachment point is at x/d = 4.7

Heat Transfer Over a Blunt Plate

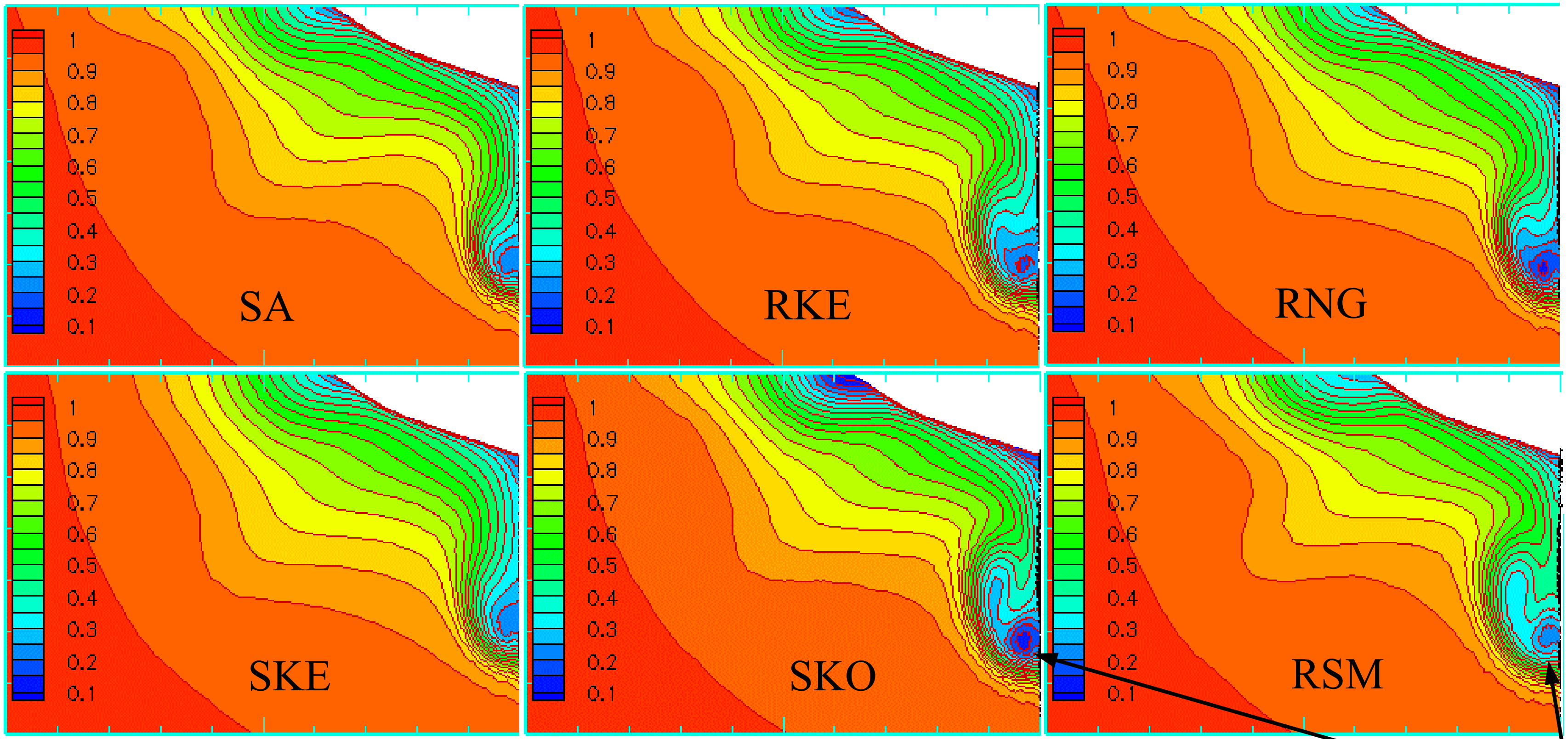


Example: Ship Hull Flow

- Experiments: KRISO’s 300K VLCC (1998)
  - Complex, high Re_L (4.6×10^6) 3D Flow
    - Thick 3D boundary layer in moderate pressure gradient
    - Streamline curvature
    - Crossflow
    - Free vortex-sheet formation (“open separation”)
    - Streamwise vortices embedded in TBL and wake
- Simulation
  - Wall Functions used to manage mesh size
    - $y^+ \approx 30 - 80$
    - Hex mesh ⇒ ~200,000 cells
- Contours of axial velocity compared with simulations



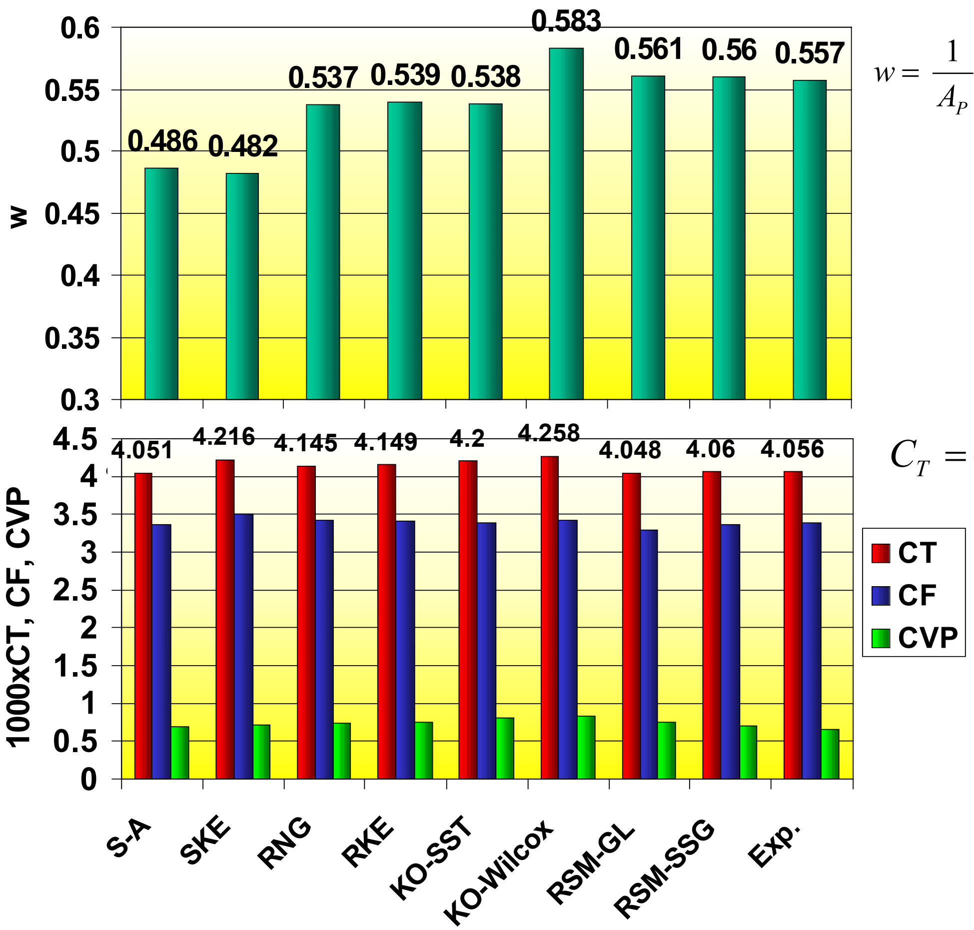
Comparing Contour Plots of Axial Velocity



- SKO and RSM models capture characteristic shape at propeller plane

Comparing Wake Fraction and Drag

- Though SKO (and SST) were able to resolve salient features in propeller plane, not all aspects of flow could be accurately captured
    - Eddy viscosity model
- RSM models accurately capture all aspects of the flow
- Complex industrial flows provide new challenges to turbulence models



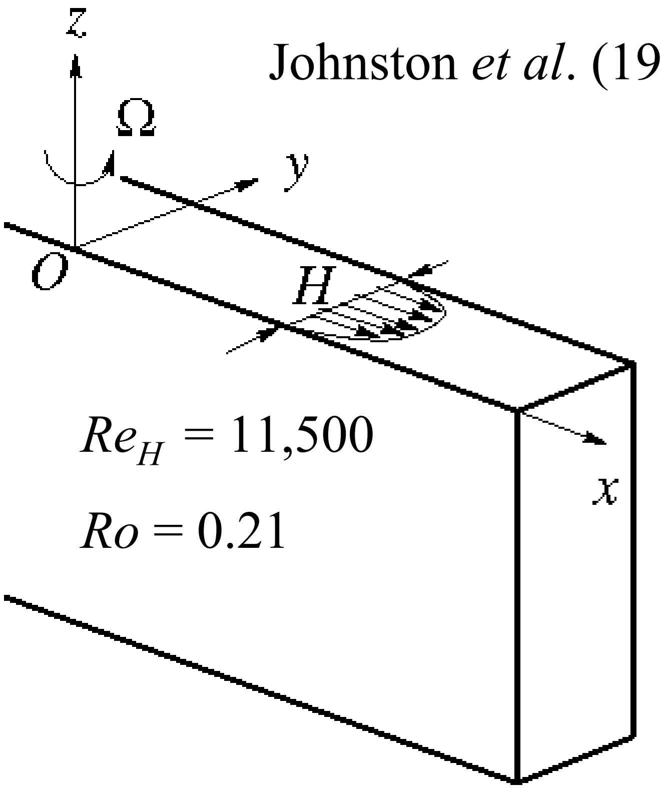
$$w = \frac{1}{A_P} \int_{A_P} \left(1 - \frac{u}{U_0} \right) dA$$

$$C_T = C_F + C_{VP}$$

Flow in a Rotating Channel

- Represents flows through rotating internal passages (e.g. turbomachinery applications)
- Rotation affects mean axial momentum equation through turbulent stresses
- Rotation makes mean axial velocity asymmetrical
- Computations are carried out using SKE, RNG, RKE and RSM models are with the standard wall functions

Flow configuration:



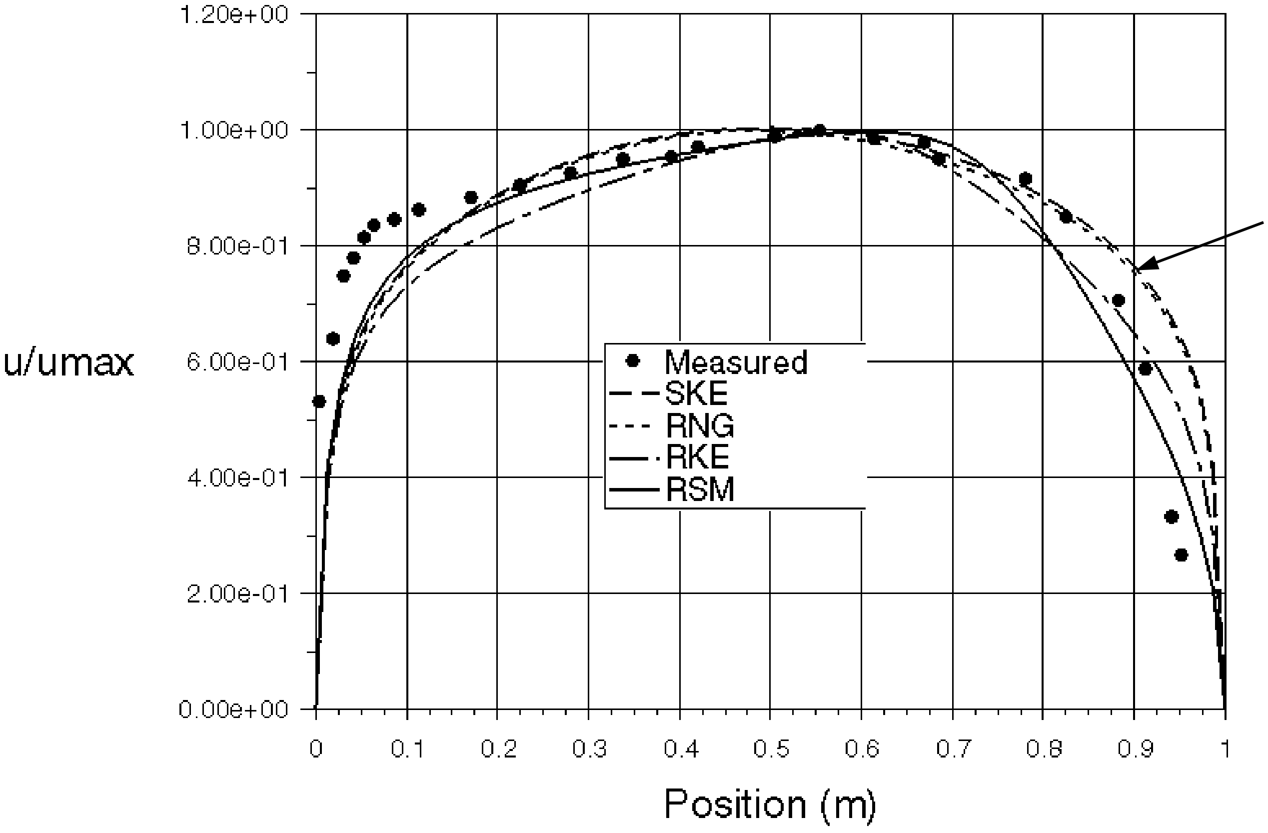
Johnston *et al*. (1972)

$Re_H = 11{,}500$

$Ro = 0.21$

Flow in a Rotating Channel

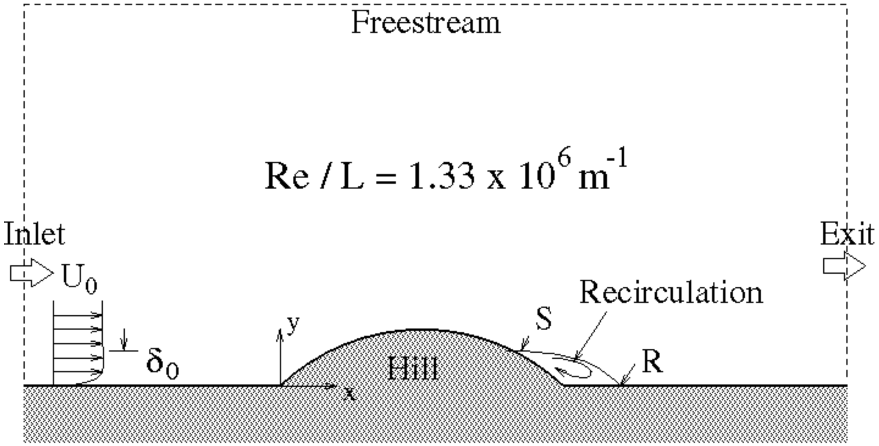
Predicted axial velocity profiles (Re_H = 11.500, Ro = 0.21)



Symmetric profiles

2-D Hill

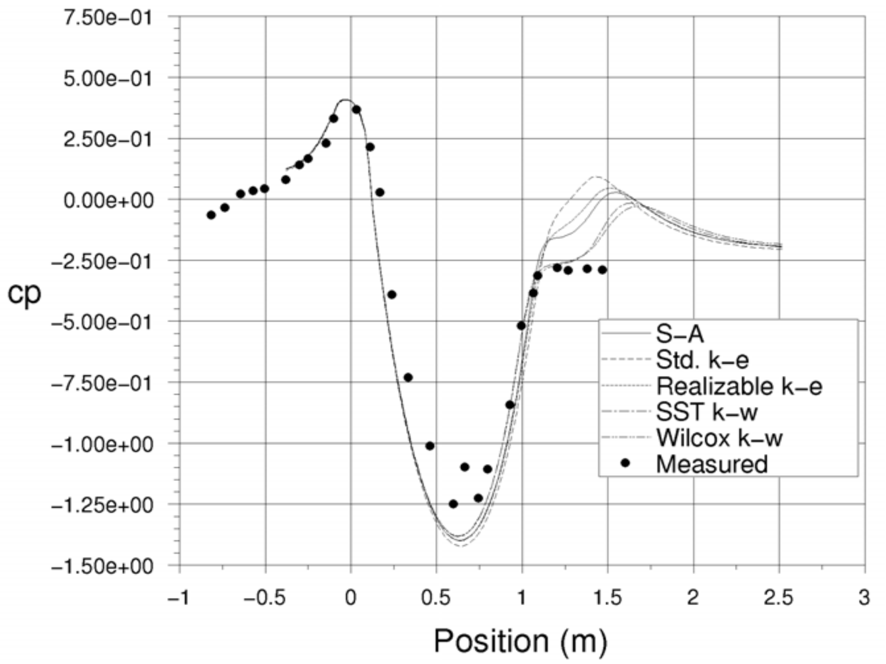
- Measured by Baskaran *et al.* (JFM, Vol. 182, 1987)
- High-Re (Re_L = 1.33 x 10^6/m) incompressible BL subjected to pressure gradient, streamline curvature
- The main interests are the skin-friction, static pressure, and extent of the BL separation (x=1.1 m)
- Computed using SA, SKE, RKE, and k-ω models



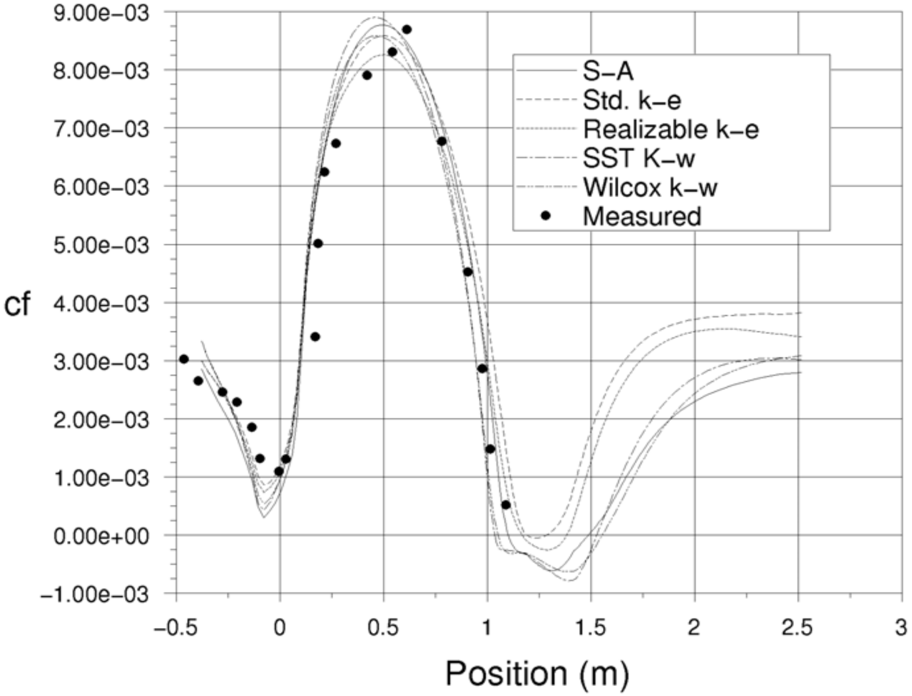
Two-Dimensional Hill of Baskaran et al. (1987)

Pressure and Skin Friction Distribution

Pressure distribution



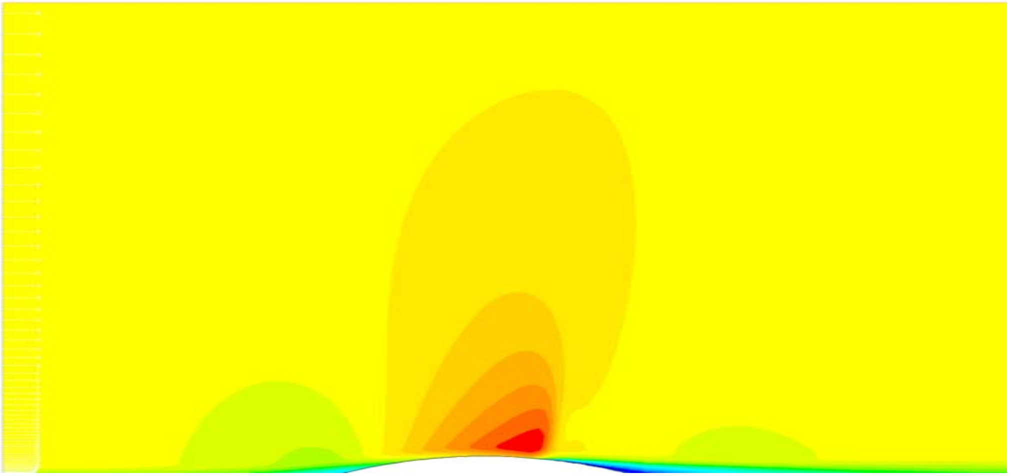
Skin-friction distribution



- The k-ω models predict the C_p plateau very closely
- The k-ω models give an earlier and larger separation than other models

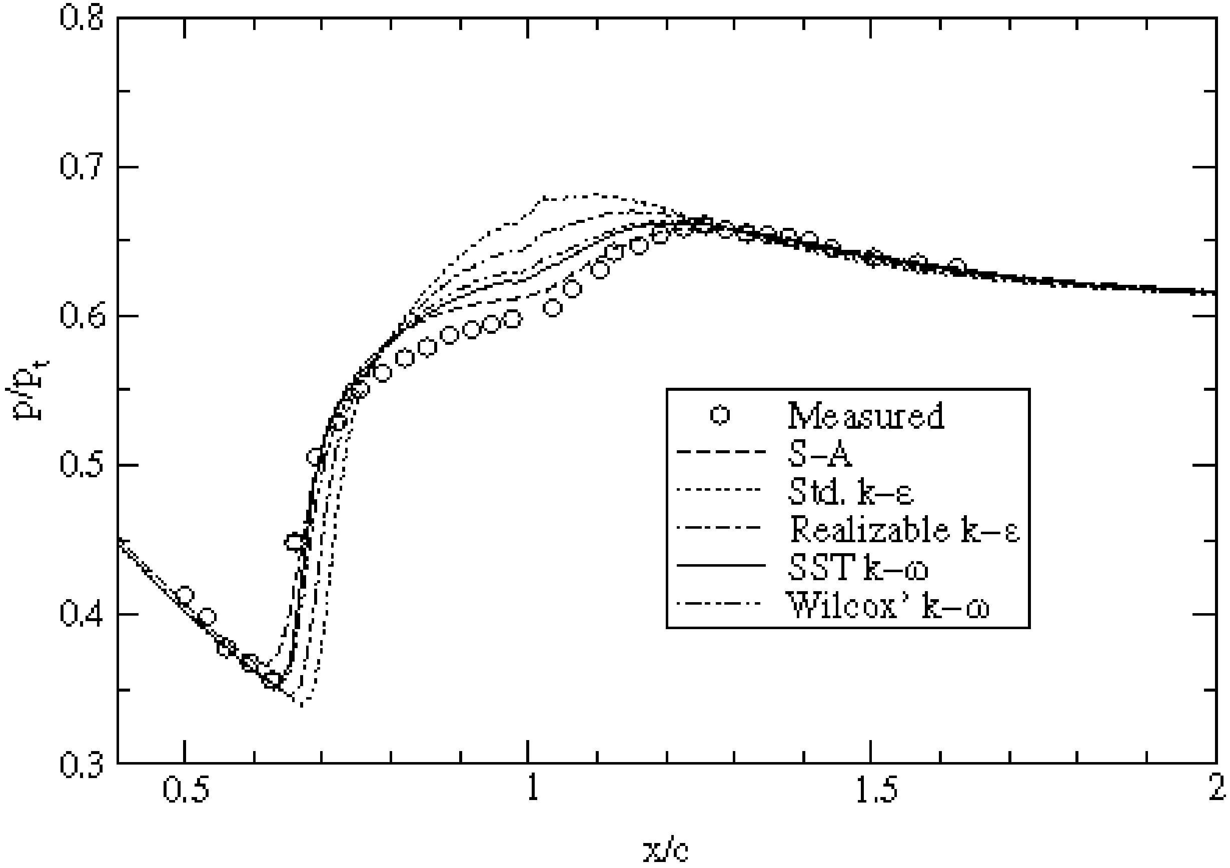
Axisymmetric Bump

- Measured by Bachalo and Johnson (1986)
- Transonic BL flow with a standing shock and a pocket of BL separation behind the shock
- Ma = 0.875, $Re_c = 13.6 \times 10^6$ at freestream
- Computed using S-A, SKE, RKE, KO, SST models



Axisymmetric Bump (2)

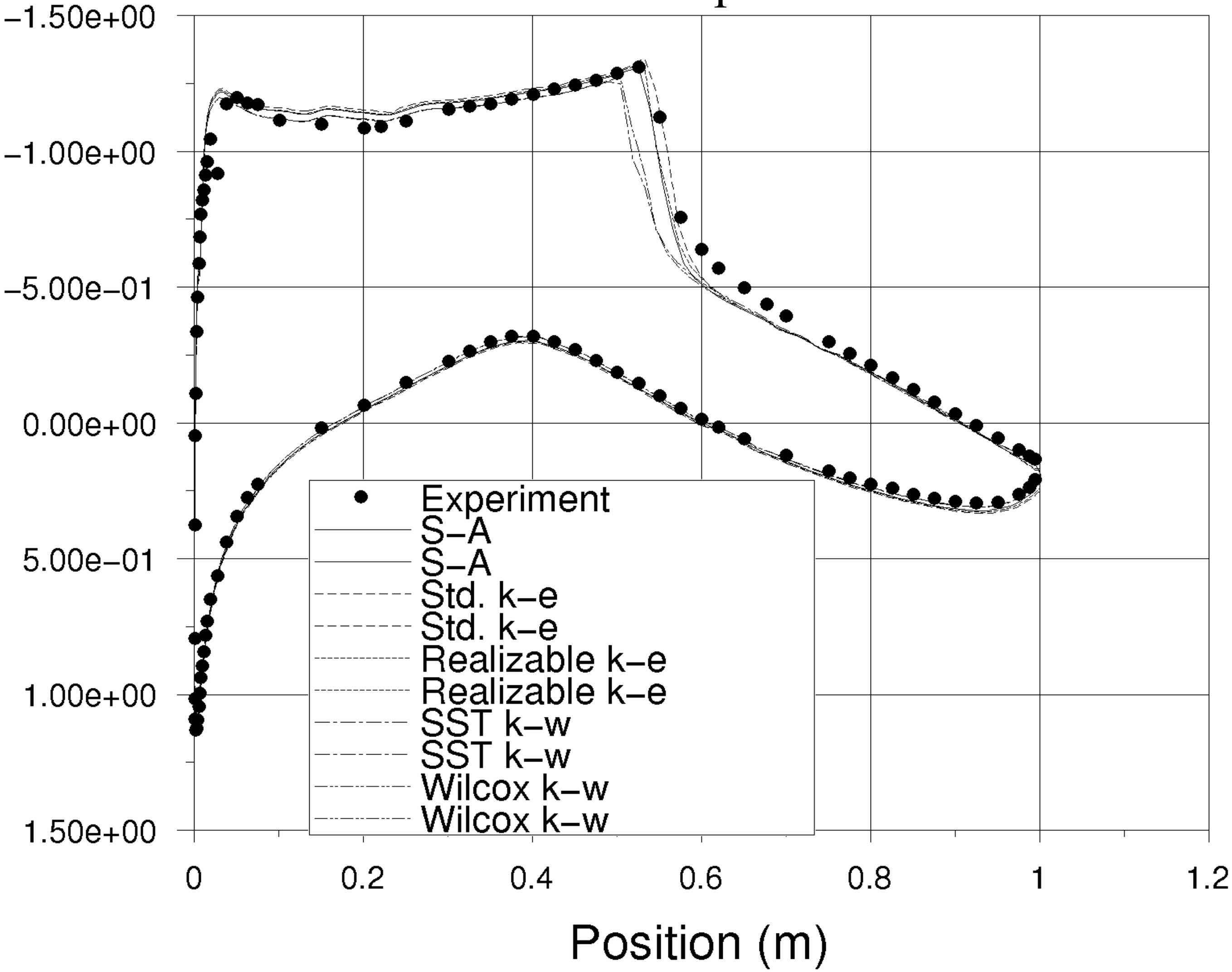
Wall pressure predictions



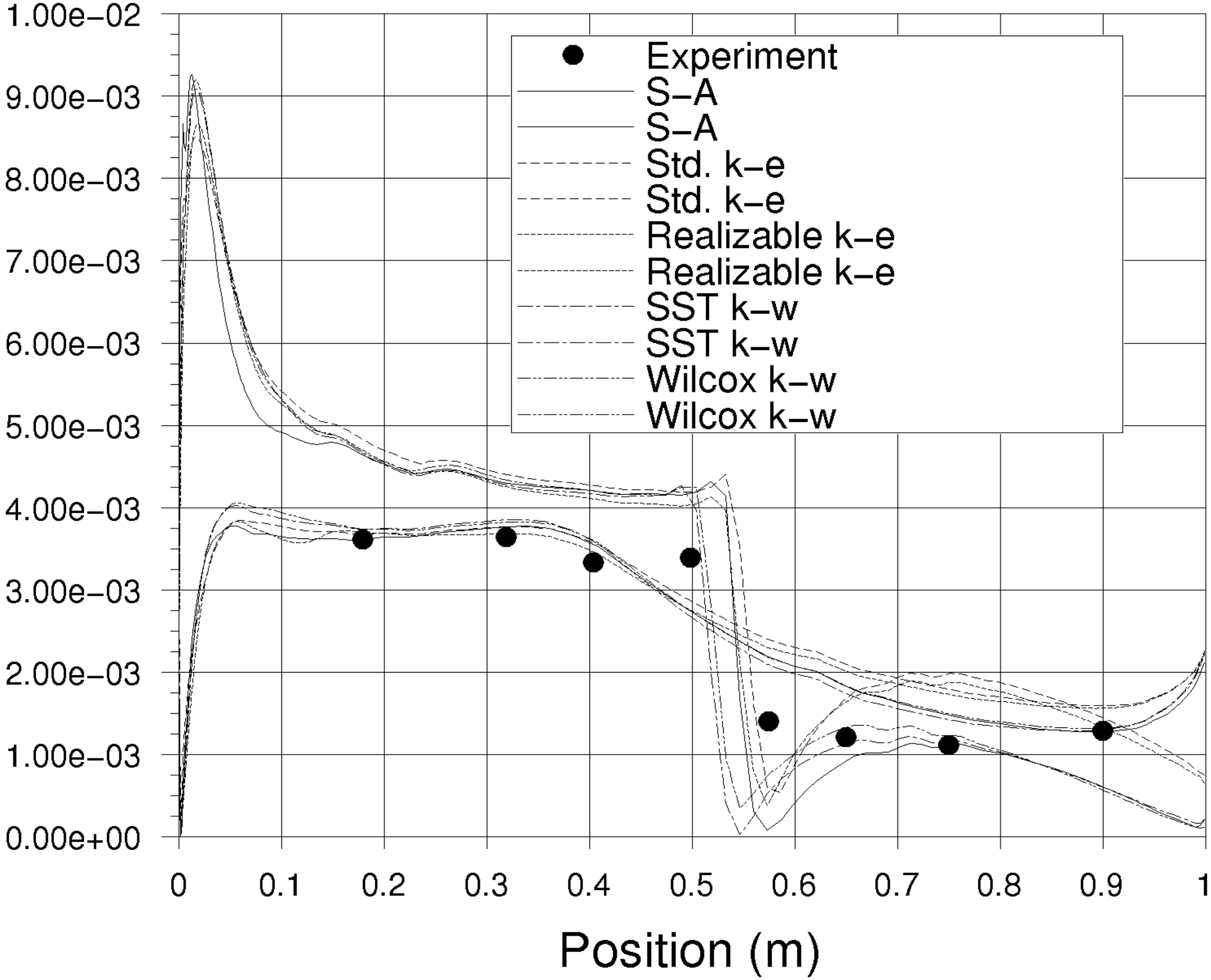
RAE 2822 Airfoil

- RAE2822 Transonic airfoil
- Measured by Cox (1981) (Case 9 in Stanford database)
- The corrected $\alpha = 2.79$ deg., Ma = 0.73, Re = 6.5×10^6
- Computed using SA, SKE, RKE, and k-ω models on a wall function (coarse) mesh

RAE 2822 Airfoil C_p Predictions



RAE 2822 C_f Predictions



RAE 2822 Airfoil Summary

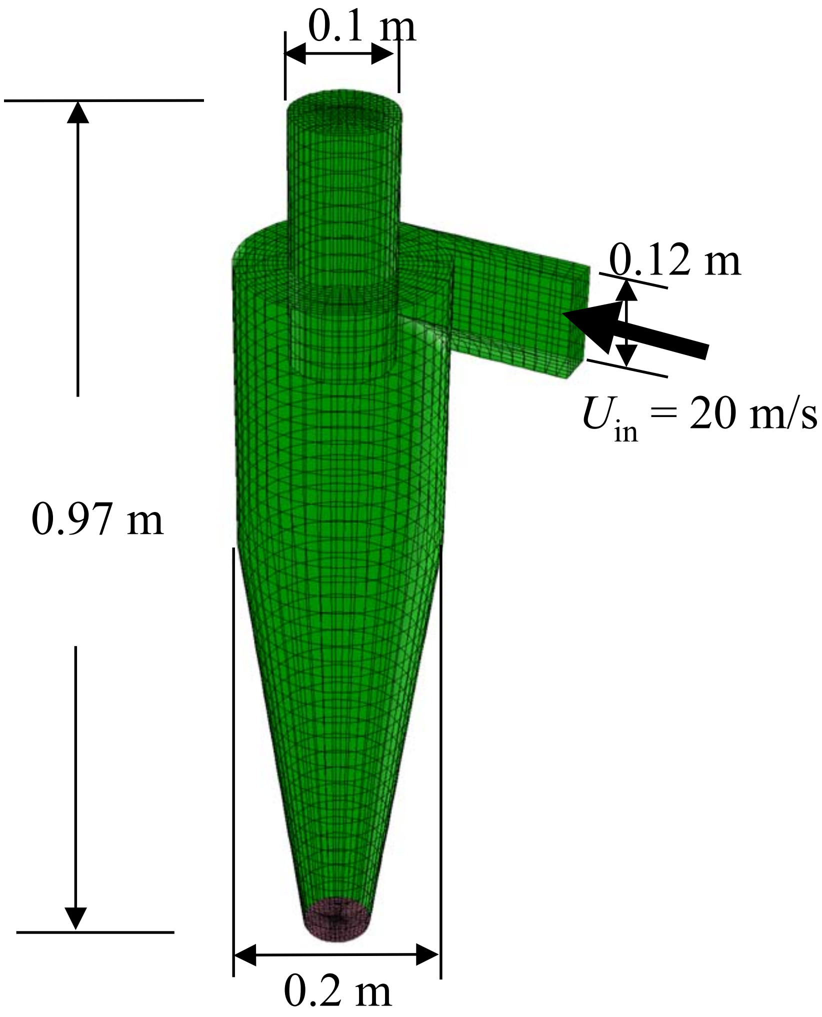
Forces and moment predictions

($\alpha = 2.79$, $Re = 6.5 \times 10^6$, $Ma = 0.73$)

Flow	S-A	SKE	RKE	SST k-ω	Wilcox k-ω	Exp.
CL	0.811	0.835	0.820	0.772	0.774	0.803
CD	0.0180	0.0198	0.0189	0.0172	0.0172	0.0168
CM	-0.1093	-0.1063	-0.1092	-0.1068	-0.1072	-0.099

- The shock location predicted k-ω models is slightly upstream of the measured one and the prediction by other models
- The two k-ω models gives a slightly lower lift coefficient, but their results are almost identical

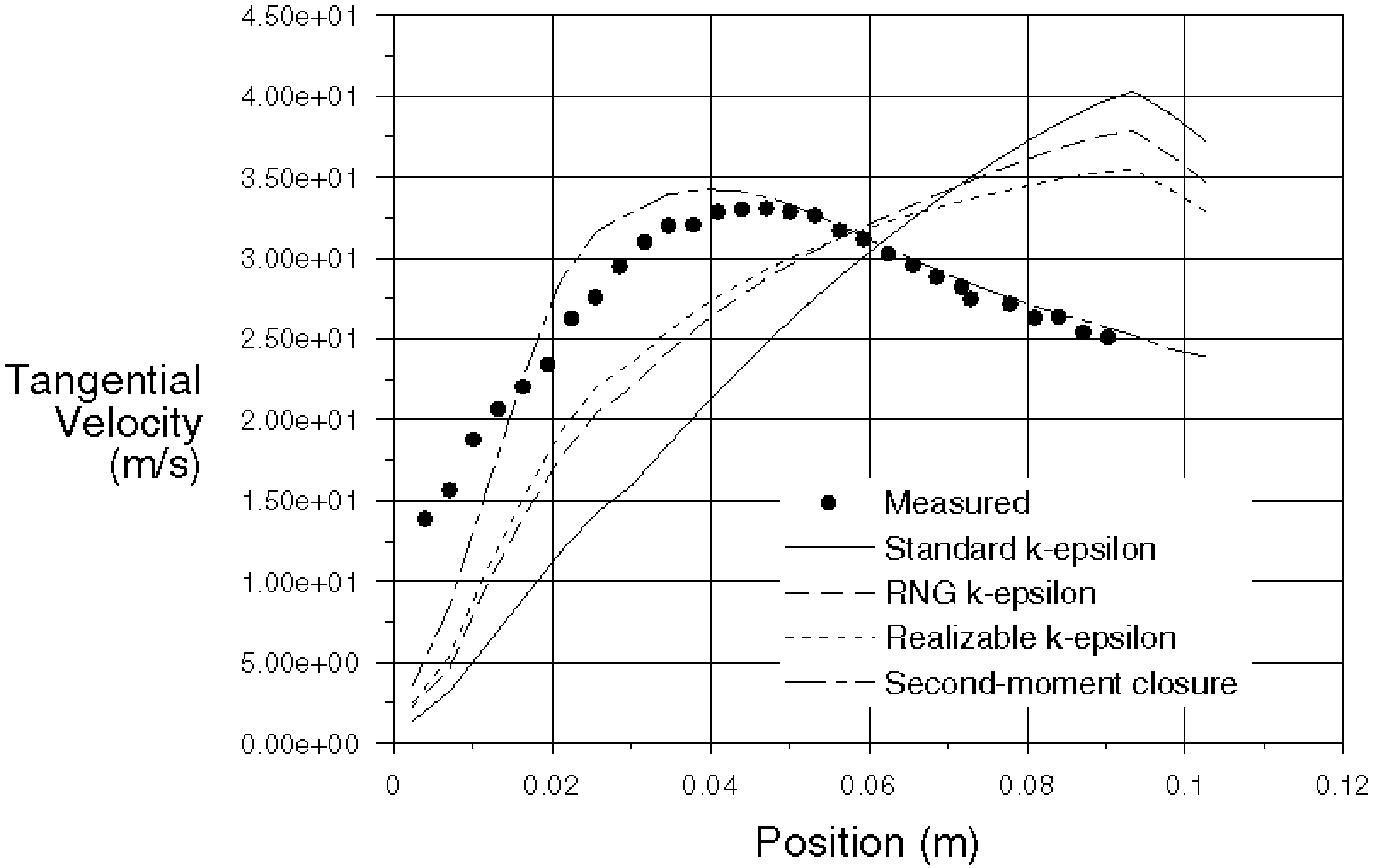
Flow in a Cyclone



- 40,000 cell hexahedral mesh
- High-order upwind scheme was used
- Computed using SKE, RNG, RKE and RSM models with the standard wall functions
- Represents highly swirling flows ($W_{max} = 1.8\ U_{in}$)

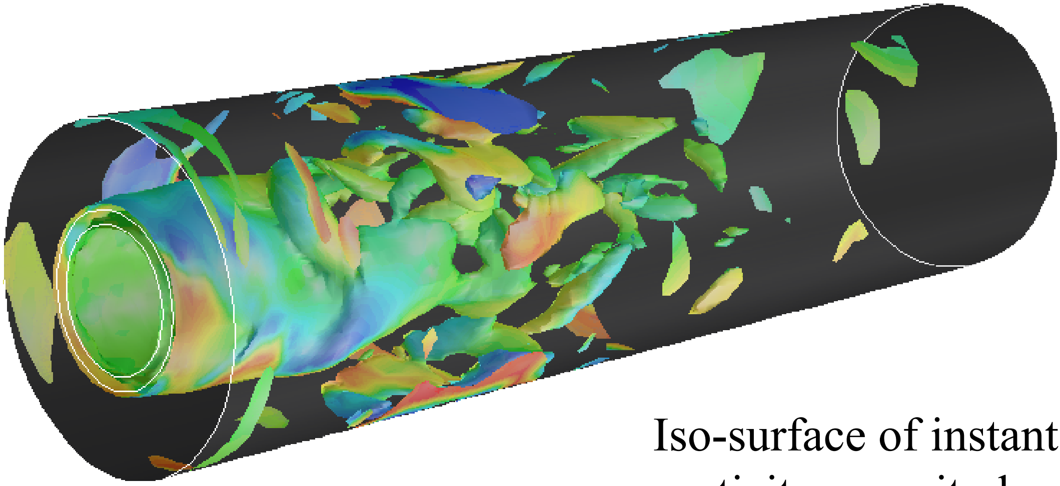
Flow in a Cyclone

- Tangential velocity profile at 0.41 m below the vortex finder



LES Example - Dump Combustor

- A 3-D model of a lean premixed combustor studied by Gould (1987) at Purdue University
- Non-reacting (cold) flow was simulated with a 170K cell hexahedral mesh using second-order temporal and spatial discretization schemes



Iso-surface of instantaneous vorticity magnitude colored by velocity angle

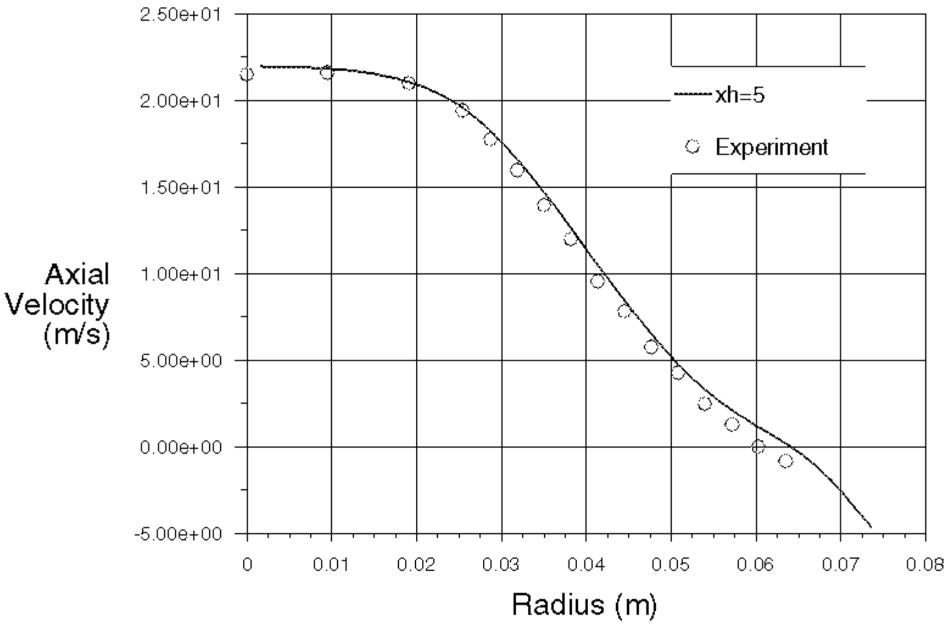
LES Examples - Dump Combustor

- Simulation done for:

$$\mathrm{Re}_d = 10^5 \left(\mathrm{Re}_\lambda \approx 150\right)$$

- Computed using RNG-based subgrid-scale model

- Mean axial velocity prediction at x/h = 5;



Mean axial velocity at x/h = 5

LES Examples - Dump Combustor

- RMS velocities predictions at x/h = 10