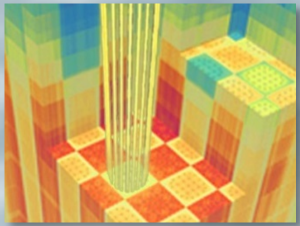
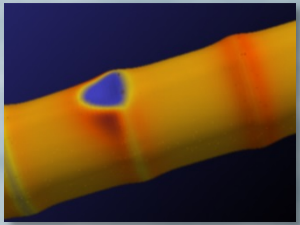
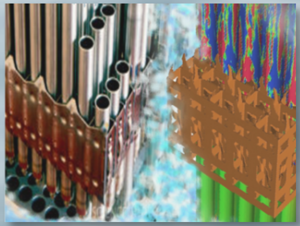
Assessment of Models for Near Wall Behavior and Swirling Flows in Nuclear Reactor Sub-systems SAND2015-7029 C







European Turbulence Conference 15
Delft Technical University
Delft, Netherlands
August 25-29, 2015

CCR
Center for Computing Research

Thomas M. Smith
Center for Computing Research
Sandia National Laboratories
Albuquerque, New Mexico USA
Mark A. Christon
Emilio Baglietto, Ben Magolan, MIT

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

CASL The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

Background

- Consortium for Advanced Simulation of Light Water Reactors (CASL)
  - U.S. DoE Energy Innovation Hub
  - 24 institutions involved
  - Beginning of the second five year research phase

- CASL Goals and Challenges
  - Develop/deploy software for advanced Simulation of PWR and BWR
    - Coupled high-fidelity Thermal Hydraulics, Neutronics, CHT
    - UQ, Parameter Sensitivities, Optimization
  - Objectives for Thermal Hydraulics (TH) Focus area
    - Full reactor core coupled physics simulations
    - Predict fuel rod performance on existing systems and new designs
    - Predict grid-to-rod-fretting, mechanical wear due to flow induced vibration
    - Predict CRUD (Chalk River Unidentified Deposit) deposition

- Hydra-TH
  - Hybrid finite-volume/finite-element incompressible/low-Mach number CFD code
  - Solves incompressible Navier-Stokes equations with heat conduction and transport on heterogeneous unstructured meshes

Assessment of Turbulence Models

- Large sub-system scale and full system scale simulations require the use of RANS

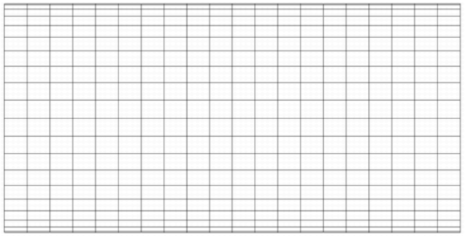
- Accurate prediction of QoI such as Cf and Nu require estimation of wall normal gradients

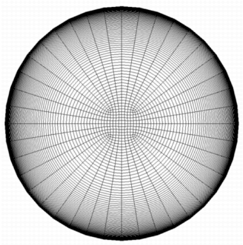
- Wall damping or wall functions or both?

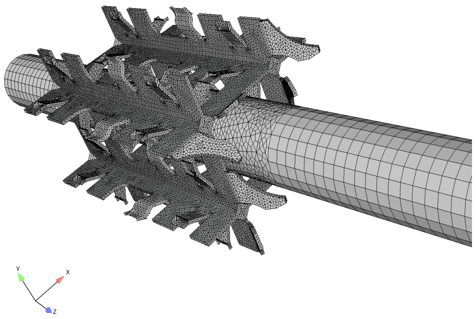
- RANS Eddy Viscosity Models
  - Spalart-Allmaras Eddy Viscosity Model with wall damping
    - Requires normal-distance to walls at every integration cell
    - Integrate to the wall y+<=5
    - Simple wall boundary condition nut=0
    - Surface gradients computed using finite-differences
  - k-ε Eddy Viscosity Models with y* insensitive wall function
    - Requires normal distance in wall adjacent cells
    - First cell in log layer, y+=20-40
    - Surface gradients and temperature are inferred based on the wall function
    - All of the k-ε model variations use the same wall function

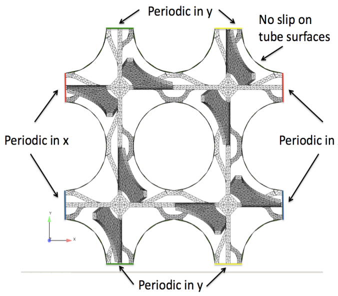
Assessment of Turbulence Models Cont.

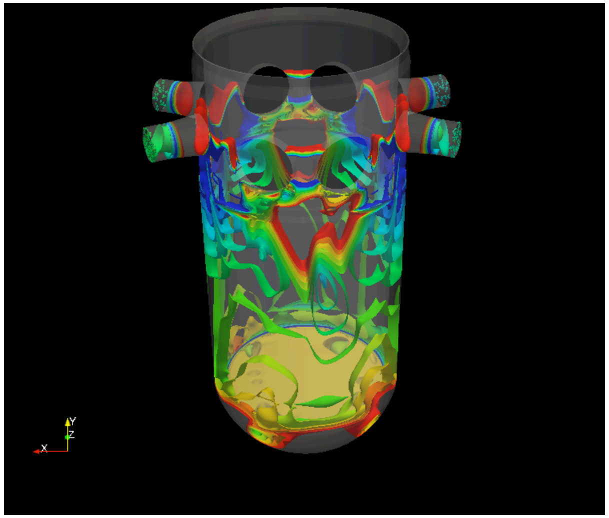
- Turbulence Sub-System Test Problems
  - Detailed examination of model accuracy and robustness
  - Known expected outcomes
  - Contain important flow features present in reactor cores
- From simple to complex
  - Flow structures
  - geometry
  - coupled physics

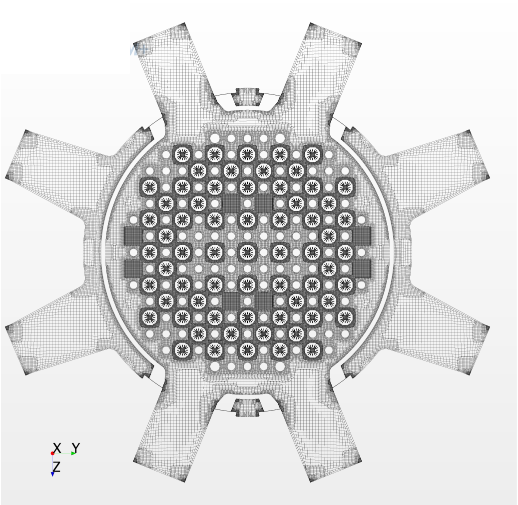


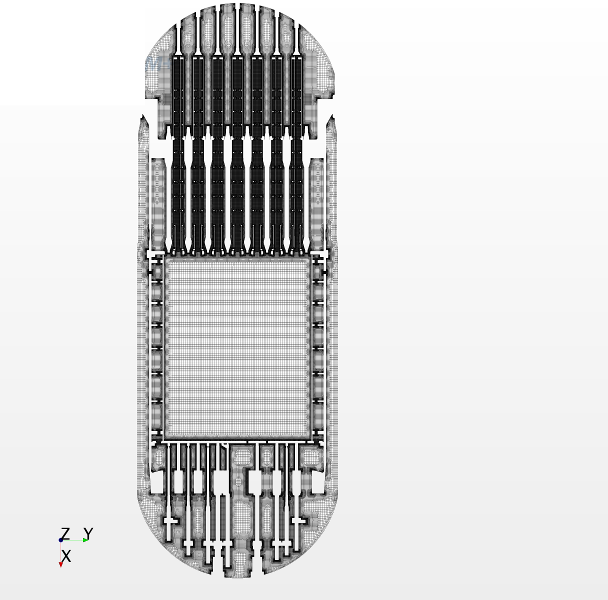












hydra.lanl.gov

Wall Functions y* insensitive 2 Level Model

(Launder&Spalding, 1974; Grotjans&Menter, 1989; Craft et al. 2002)

- Enforce Law-of-the-Wall behavior in the cells adjacent to walls
- Replace y+ and u+ with y* and u*
- The distance to the first cell value yp can be no less than the edge of the viscous sublayer yv

Theory

$$y_p^* = \frac{\rho C_\mu^{1/4} y_p k^{1/2}}{\mu}$$

$$y_v^* = \frac{\rho C_\mu^{1/4} y_v k^{1/2}}{\mu} = 11.225$$

$$Pk = \begin{cases} 0 & y_p^* < y_v^* \\ \dfrac{\tau_w^2}{\kappa C_\mu^{1/4} \rho k^{3/2} y_p} & y_p^* > y_v^* \end{cases}$$

$$\tau_w = \frac{C_\mu^{1/4} \rho u_p k^{1/2}}{\frac{1}{\kappa}\ln\left(E y_p^*\right)}$$

$$\varepsilon = \begin{cases} \dfrac{2\mu k}{y_v^2} & y_p^* < y_v^* \\ \dfrac{\rho C_\mu^{3/4} k^{3/2}}{\kappa y} & y_p^* > y_v^* \end{cases}$$

$$y_{p,\lim}^* = \max(y_p^*, y_v^*)$$

$$y_{p,\lim} = \frac{y_{p,\lim}^* \mu}{\rho C_\mu^{1/4} k^{1/2}}$$

Numerical Implementation

$$Pk_{ave} = \frac{1}{y_n}\int_0^{y_n} Pk\,dy = \frac{\tau_w^2}{\kappa C_\mu^{1/4} \rho k^{1/2} y_n}\ln\left(\frac{y_n}{y_v}\right)$$

$$Dk_{ave} = \frac{1}{y_n}\int_0^{y_n} Dk\,dy = \frac{2\mu k}{y_n y_v} + \frac{\rho C_\mu^{3/4} k^{3/2}}{\kappa y_n}\ln\left(\frac{y_n}{y_v}\right)$$

$$\varepsilon_p = \frac{C_\mu^{3/4} k^{3/2}}{\kappa y_p}$$

$$\mu_{eff} = \begin{cases} \mu & y_p^* < y_v^* \\ \dfrac{\rho C_\mu^{1/4} k^{1/2} y_p}{\frac{1}{\kappa}\ln\left(E y_p^*\right)} & y_p^* > y_v^* \end{cases}$$

$$\kappa_{eff} = \frac{\mu C_p y^*}{T^*}$$

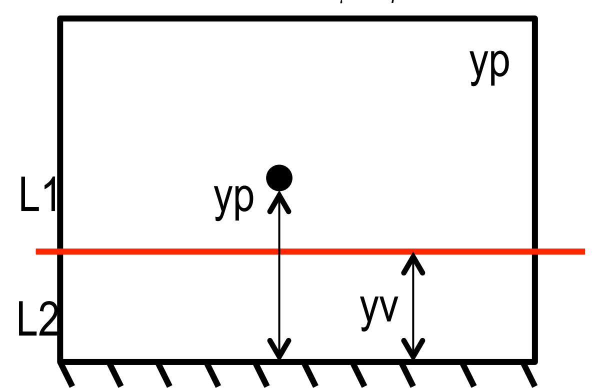
$$T^* = \begin{cases} \Pr y_p^* & y_p^* < y_v^* \\ \Pr t\left(\frac{1}{\kappa}\ln\left(E y_p^*\right) + P_J\right) & y_p^* > y_v^* \end{cases}$$

Output

$$\tau_w = \frac{C_\mu^{1/4} \rho u_p k^{1/2}}{\frac{1}{\kappa}\ln\left(E y_p^*\right)}$$

$$\dot{q}''_w = \frac{\left[T_w - T_p\right] \rho C_\mu^{1/4} C_p k^{1/2}}{\Pr t\left(\frac{1}{\kappa}\ln\left(E y_p^*\right) + P_J\right)}$$

$$T_w = T_p + \frac{\dot{q}''_w \Pr t\left(\frac{1}{\kappa}\ln\left(E y_p^*\right) + P_J\right)}{\rho C_\mu^{1/4} C_p k^{1/2}}$$



Fully Developed Pipe Flow

<u>Test Conditions</u>

$L/D = 20$

$\Delta P = 1.0, 4.0.14.0$

$T_{in} = 300$

$T_w = 350$

$q_w'' = 250$

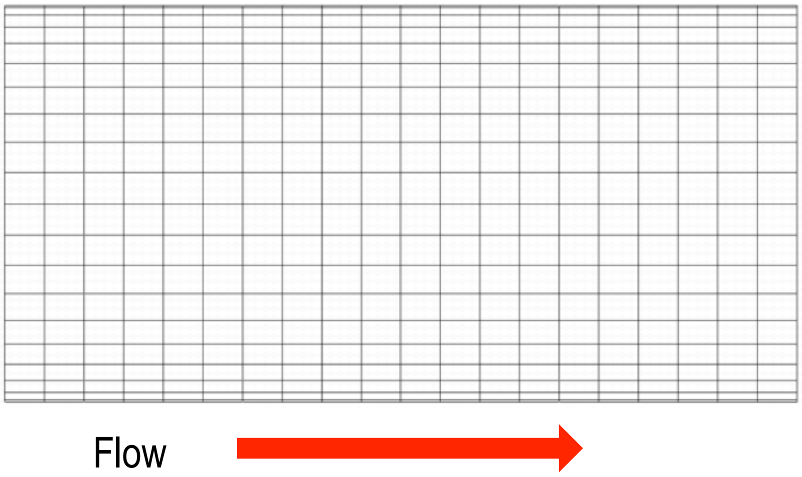
$\rho = 1$

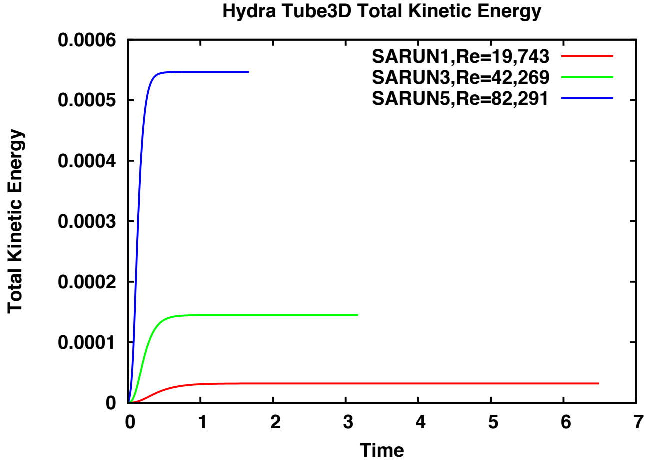
$\Pr = 1$

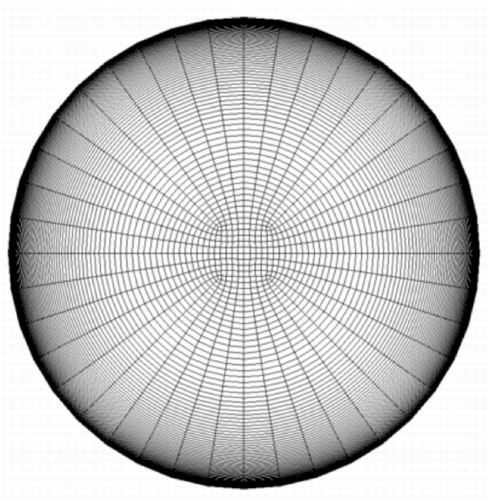
$\Pr_t = 1$

$\mu = 1.0E-6$

Cubit Mesh







Fully Developed Pipe Flow

- Domain: L/D=20
- Entry Length: L/D=20
- ReD: 19,743; 42,269; 82,291
- y+: 0.9, 1.7, 3.0
- Key:
  - calc – finite difference for grad T
  - ref – use BC value for qw

Nusselt Number

$$Nu = \frac{hD}{\kappa} = \frac{\dot{q}_w'' D}{\kappa (T_w - T_m)}$$

Newton's Law of Cooling

$$\dot{q}_w'' = h(T_w - T_m)$$

Mixing Vm and Tm

$$V_m = \frac{1}{\rho A} \int_A \rho \mathbf{u} \bullet \mathbf{n} dA$$

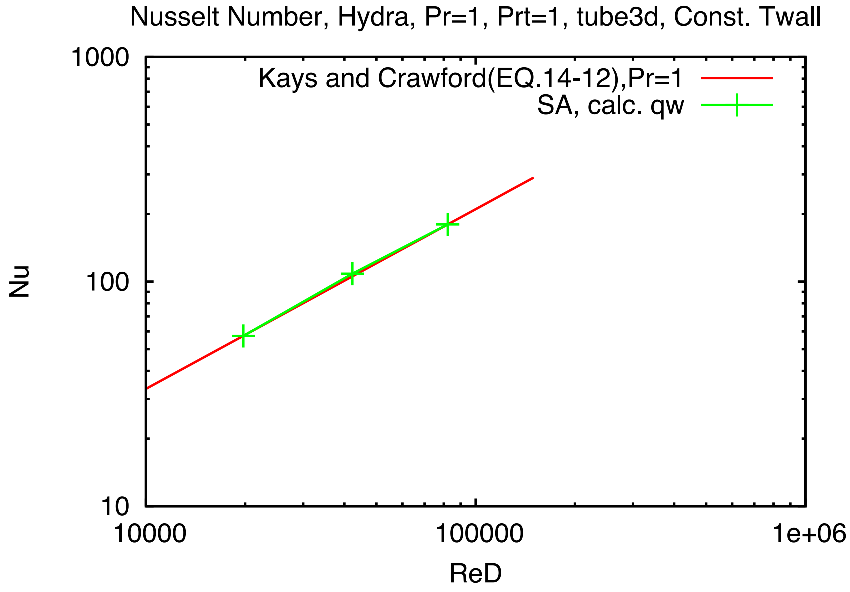
$$T_m = \frac{1}{\rho V_m A} \int_A \rho \mathbf{u} \bullet \mathbf{n} T dA$$

Wall heat flux and Temperature

$$\dot{q}_w'' = \frac{1}{L} \oint_L \kappa \frac{\partial T}{\partial n} dl$$

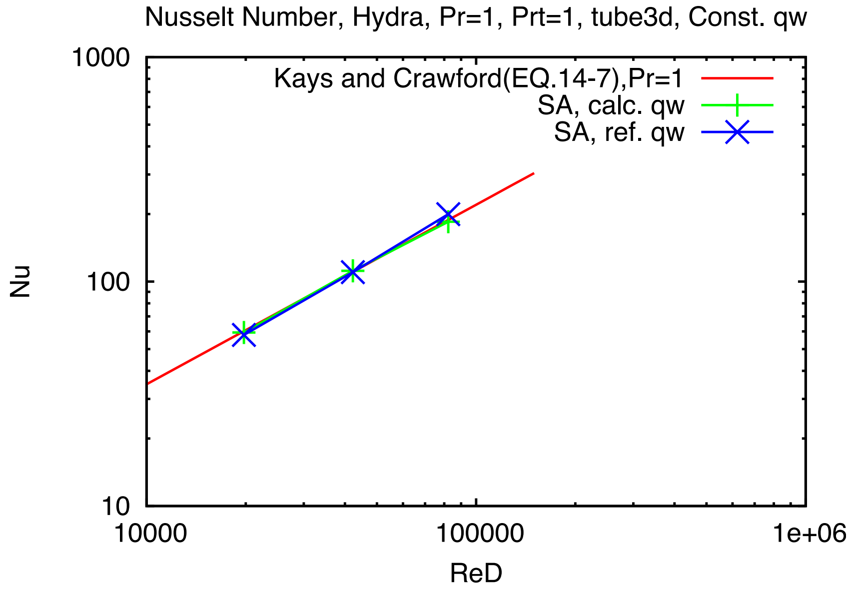
$$T_w = \frac{1}{L} \oint_L T dl$$

Constant wall temperature



$$Nu = 0.021 \mathrm{Pr}^{0.5} \mathrm{Re}_D^{0.8}$$ (EQ. 14-12, Kays&Crawford, 1993)

Constant wall heat flux



$$Nu = 0.022 \mathrm{Pr}^{0.5} \mathrm{Re}_D^{0.8}$$ (EQ. 14-7 Kays&Crawford, 1993)

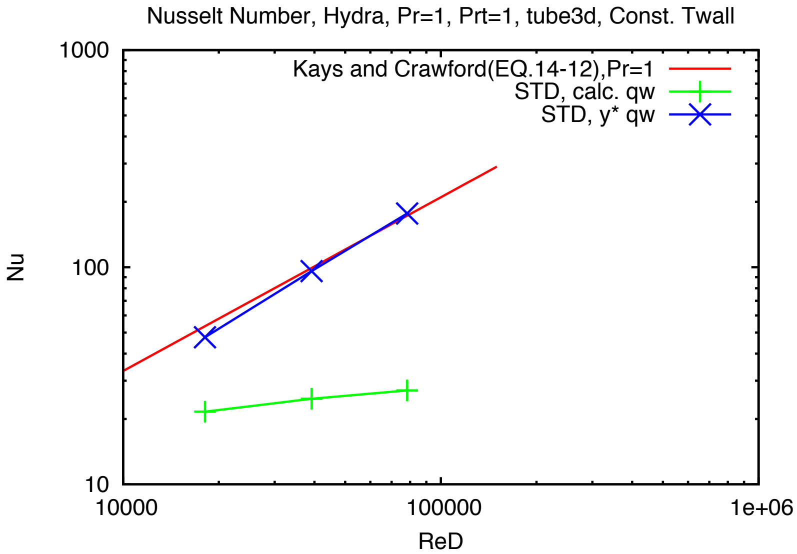
Fully Developed Pipe Flow

- Domain: L/D=20
- ReD: 18,100: 39,200; 78,300
- y*: 13, 29, 53

Key

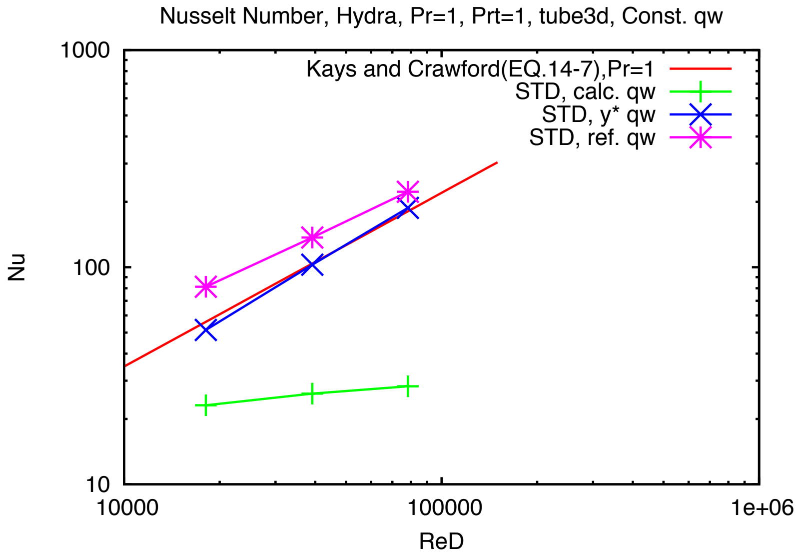
calc – finite difference for grad T
ref – use BC value for qw
y* - wall function

Constant wall temperature



$$Nu = 0.021 Pr^{0.5} Re_D^{0.8} \quad \text{(EQ. 14-12, Kays\&Crawford, 1993)}$$

Constant wall heat flux



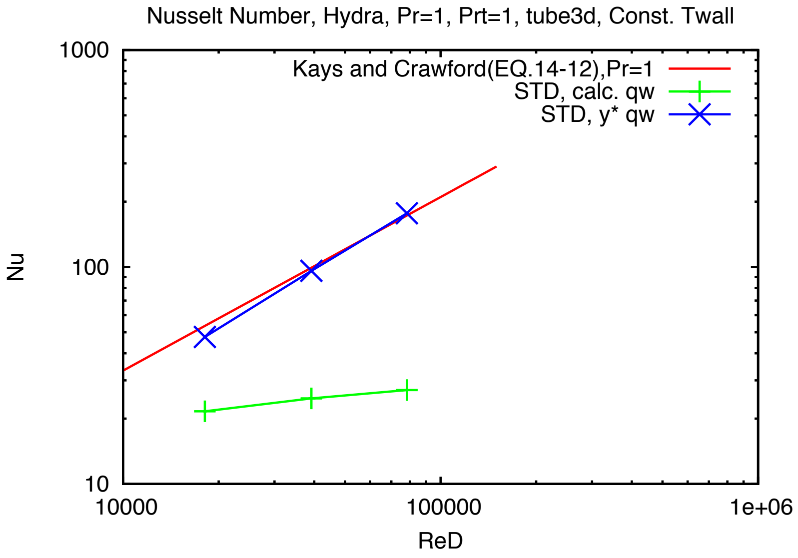
$$Nu = 0.022 Pr^{0.5} Re_D^{0.8} \quad \text{(EQ. 14-7 Kays\&Crawford, 1993)}$$

Fully Developed Pipe Flow

- Domain: L/D=20
- ReD: 18,100: 39,200; 78,300
- y*: 13, 29, 53

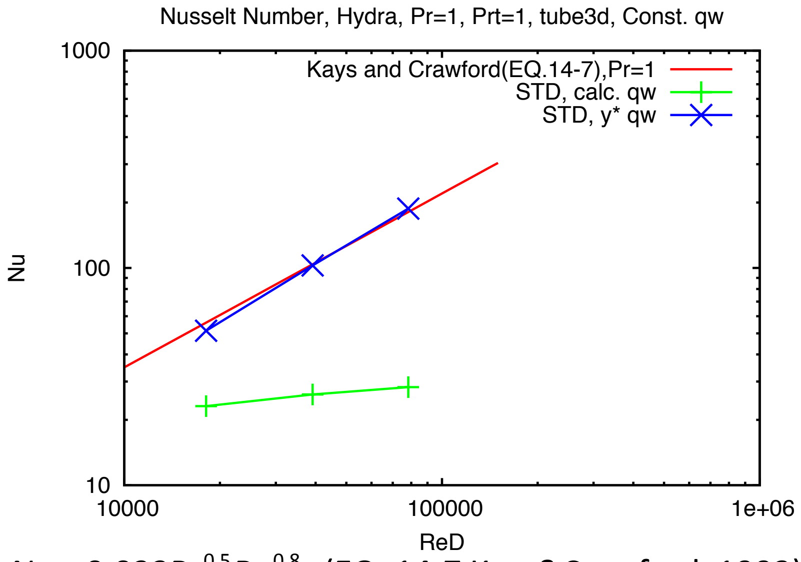
Key
calc – finite difference for grad T
ref – use BC value for qw
y* - wall function

Constant wall temperature



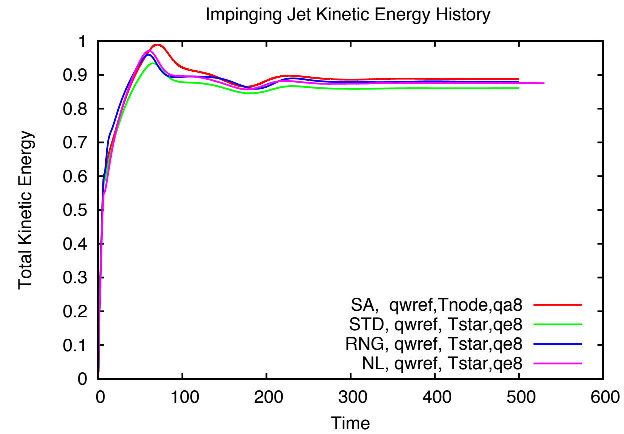
$$Nu = 0.021 Pr^{0.5} Re_D^{0.8} \quad \text{(EQ. 14-12, Kays\&Crawford, 1993)}$$

Constant wall heat flux



$$Nu = 0.022 Pr^{0.5} Re_D^{0.8} \quad \text{(EQ. 14-7 Kays\&Crawford, 1993)}$$

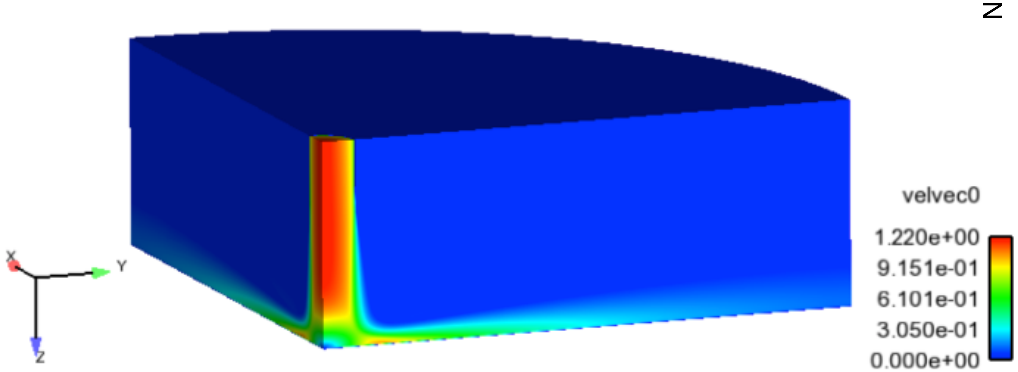
Impinging Jet Post Processing using Law of the Wall
(with E. Baglietto and B. Magolan, MIT)

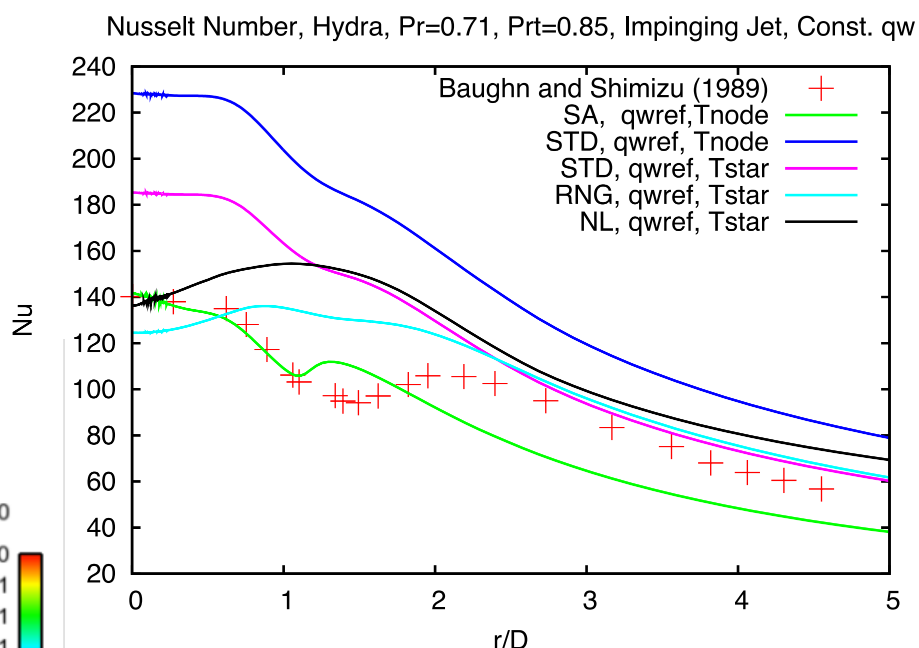


Test Conditions

$Re_D = 23{,}000,\ Pr = 0.71,\ Prt = 0.85,\ H/D = 2,\ r/D = 8,\ V_{intrain} 0.01U_z,\ p_{out} = 0$

Model	Scale	Range	Average
SA	y+	1.5-9.8	7.6
STD-KE	y*	3.6-21.1	16.7
RNG-KE	y*	3.8-13.2	11.1
NL-KE	y*	5.0-17.0	13.5





3x3 Rod/Spacer Grid Sub-Assembly-Energy Balance

- Two estimates of heat flux from hot rods
  - Post process using finite-difference to compute grad T
  - Wall Function
- Quantity of Interest is the steady-state heat balance

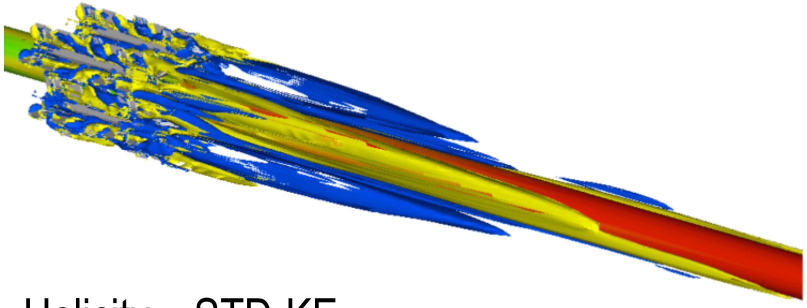
$$Q = \dot{q}''_w A$$

$$H = \rho C_p T u A$$

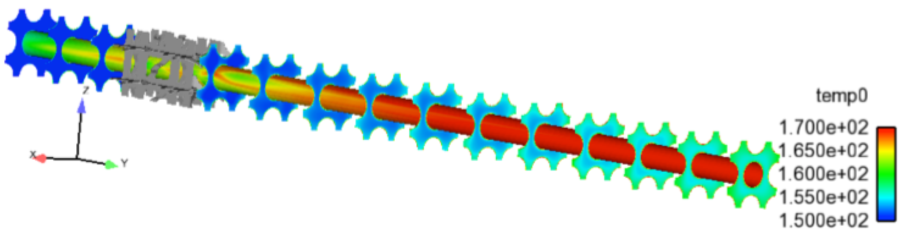
$$H_{out} = H_{in} + Q$$

Test Conditions
Mesh: ~3E6 heterogeneous elem
ReD=218,025
Pr=1
Prt=0.9
Tin=150.0
uin=5
qwin=1.0e6
Tw=300

	y*/y+	BC	Wall Func.	qw_in (fd) rods	H_in	total	H_out	%diff
KE	18 – 2206 / 252	const. qw	---	1,655 mod. T	1,019,647	1,021,302	1,038,597	1.7
SA	1 – 66 / 44	const. qw	---	23,769 mod. T	1,056,631	1,080,400	1,084,112	0.3
KE	18 – 2206 / 252	const. Tw	---	13,715	1,042,958	1,056,674	1,395,642	24
KE	18 - 2206 / 252	const. Tw	317,194	---	1,042,958	1,360,152	1,395,642	2.5
SA	1 – 66 / 44	const. Tw	---	18919	1,042,958	1,061,877	1,051051	1



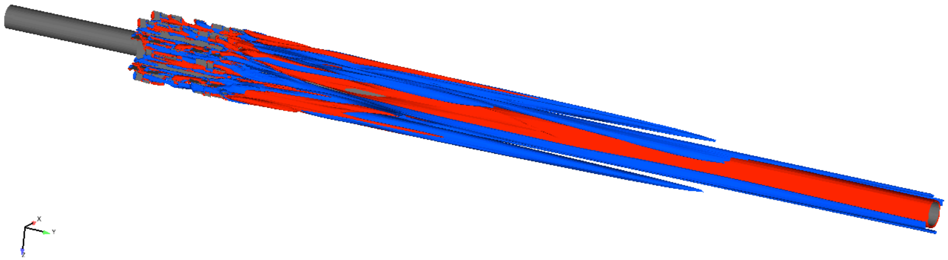
Helicity – STD-KE



Temperature – STD-KE

Summary

- Demonstrated the heat transfer capabilities for different eddy viscosity models that use damping or wall functions
- Based on this assessment of the CFD code near wall turbulence behavior has been identified as an area of concern
- Care must be exercised in interpreting surface QoIs when using wall functions
- Low Re K-epsilon models should be considered to try and improve predictions of surface QoIs and make fair comparison with wall function using the same base model
- Development plan and execution of the plan can be found in CASL documents
  - "Multi-Year Plan for Enhancing Turbulence Modeling in Hydra-TH," (**L3.THM.CFD.P10.02**), 2014
  - Findings from this first year will be reported later this year - "Enhanced Turbulence Model Capabilities in Hydra-TH," (**L3.THM.CFD.P11.04**), 2014



Helicity - SA with CC

CASL

A DOE Energy Innovation Hub

www.casl.gov