Advances in SHARP thermal hydraulics modeling, verification, and validation.

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Outline

- Overview of TH Simulation Hierarchy
- FY09 – large-scale computations
- FY10 –
  - Verification – establish correctness
    - Verification document, automated build and test suite, active user group
  - Validation
    - Documenting validation cases
      - DNS, LES, RANS
      - Canonical flows, T-junction, pin + wire wrap, …
  - Application analysis
    - 217 pin bundle studies
    - VHTR
    - LWR
- FY11 plans

Overview of TH Modeling Approach

Multiscale simulation hierarchy involving:

Increased Costs ↑

1. Experiments
2. DNS (direct numerical simulation of turbulence)
3. LES (large eddy simulation)
4. RANS (Reynolds-averaged Navier-Stokes)
5. Subchannel or lumped-parameter models

↓ *Increased Modeling*

Leverage full range of DOE's computing resources

- ANL code Nek5000 is being used to span 2→4
- Star CD is covering 4
- SAS and variants are addressing 5

Multiscale approach provides an important validation path:

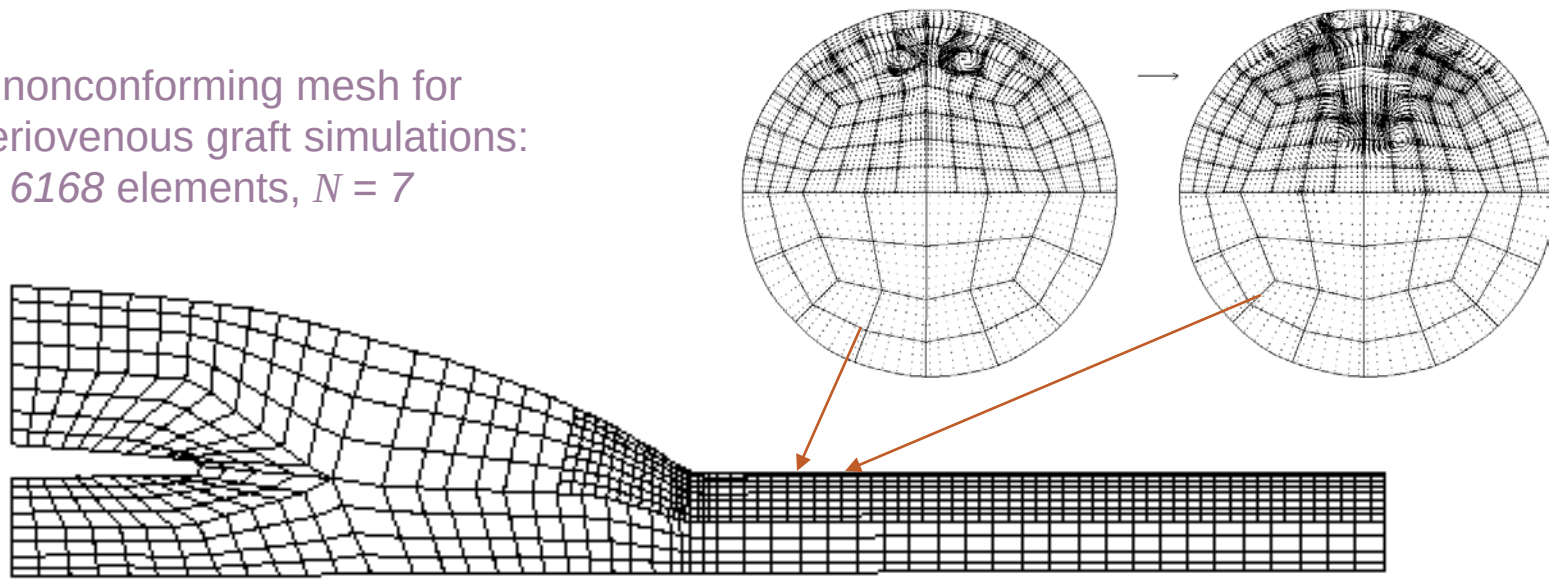
– In the past, only Options 1 and 5 were available.

Nek5000 Spatial Discretization: *Spectral Element Method*

(Patera 84, Maday & Patera 89)

- High-order variational method, similar to FEM
- Domain partitioned into E high-order quadrilateral (or hexahedral) elements (decomposition may be nonconforming - *localized refinement*)
- Functions represented as N th-order tensor-product polynomials within each element. (N ~ 4 -- 15, typ.)
- $n = EN^3$ gridpoints in 3D
- Converges *exponentially fast* with N for smooth solutions.

3D nonconforming mesh for arteriovenous graft simulations: $E = 6168$ elements, $N = 7$



Time Discretization

- Navier-Stokes time advancement:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u}$$
$$\nabla \cdot \mathbf{u} = 0$$

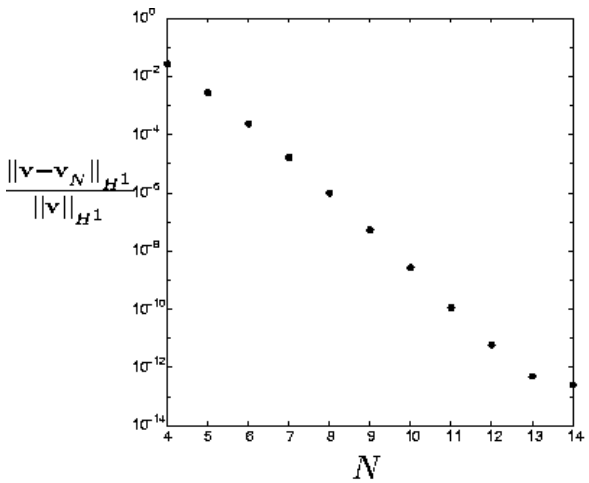
- Nonlinear term: *explicit*
  - k th-order backward difference formula / extrapolation (k =2 or 3)
  - k th-order characteristics (CFL > 1) (Pironneau '82, MPR '90)
- Linear Stokes problem: pressure/viscous decoupling:
  - 3 Helmholtz solves for velocity *("easy" w/ Jacobi-precond. CG)*
  - (consistent) Poisson equation for pressure *(computationally dominant)*
- LES subgrid-scale models
  - grid-scale filter – in spirit of HPF model (Schlatter 04)
  - Dynamic Smagorinsky (Germano 91, Lilly 92)
  -

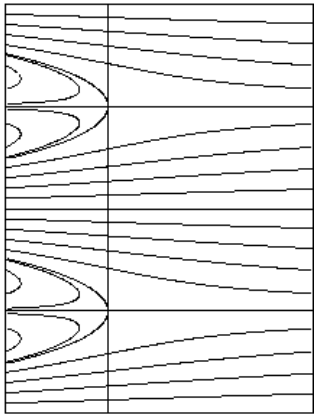
Spectral Element Convergence

- High-order spatial discretization minimizes numerical dispersion/dissipation when simulating evolution of small-scale structures over long times

- *Exponential convergence:*
  - *e.g., doubling the number of points in each direction leads to 10^4 reduction in error, vs. 4x for 2nd-order schemes.*

    Allows detection of subtle errors (e.g., $O(h^2)$) that might not manifest till err ~ 10^{-5}, say.



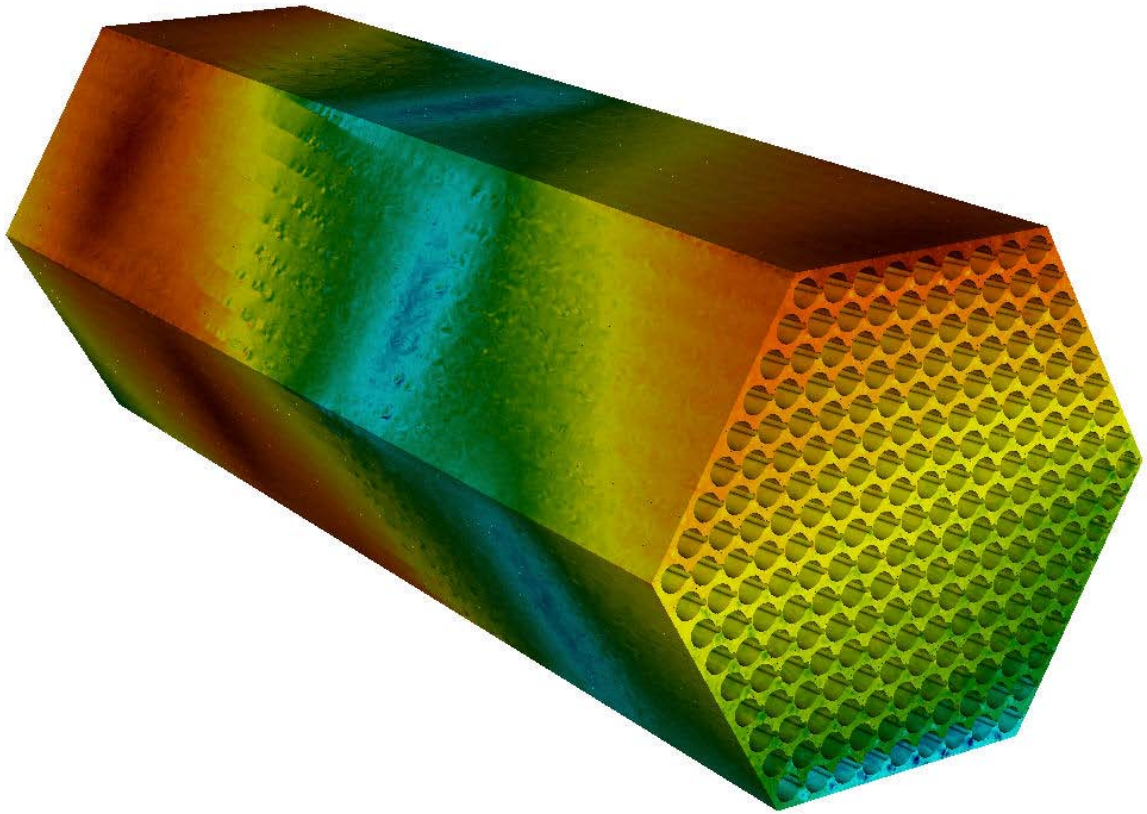


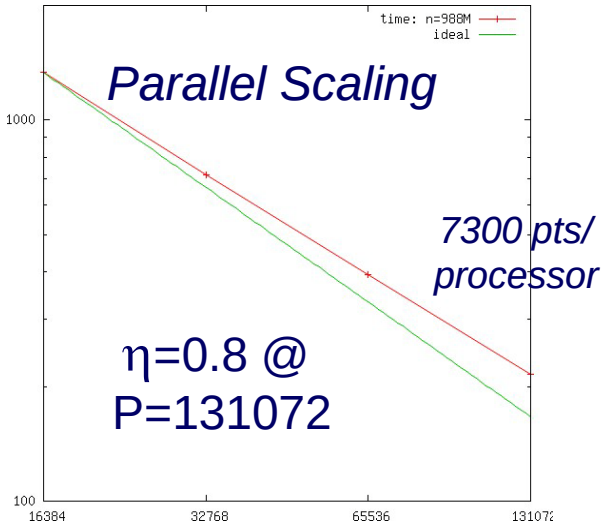
$$
\begin{aligned}
v_x &= 1 - e^{\lambda x}\cos 2\pi y \\
v_y &= \frac{\lambda}{2\pi} e^{\lambda x}\sin 2\pi y \\
\lambda &:= \frac{Re}{2} - \sqrt{\frac{Re^2}{4} + 4\pi^2}
\end{aligned}
$$

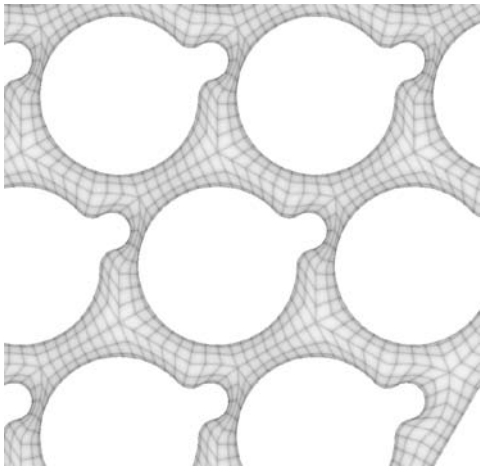
Exact Navier-Stokes solution, Kovazsnay(1948)

FY09: Subassembly with 217 Wire-Wrapped Pins

- 3 million 7th-order spectral elements (n=1.01 billion)
- 16384–131072 processors of IBM BG/P
- Data analysis later in this talk





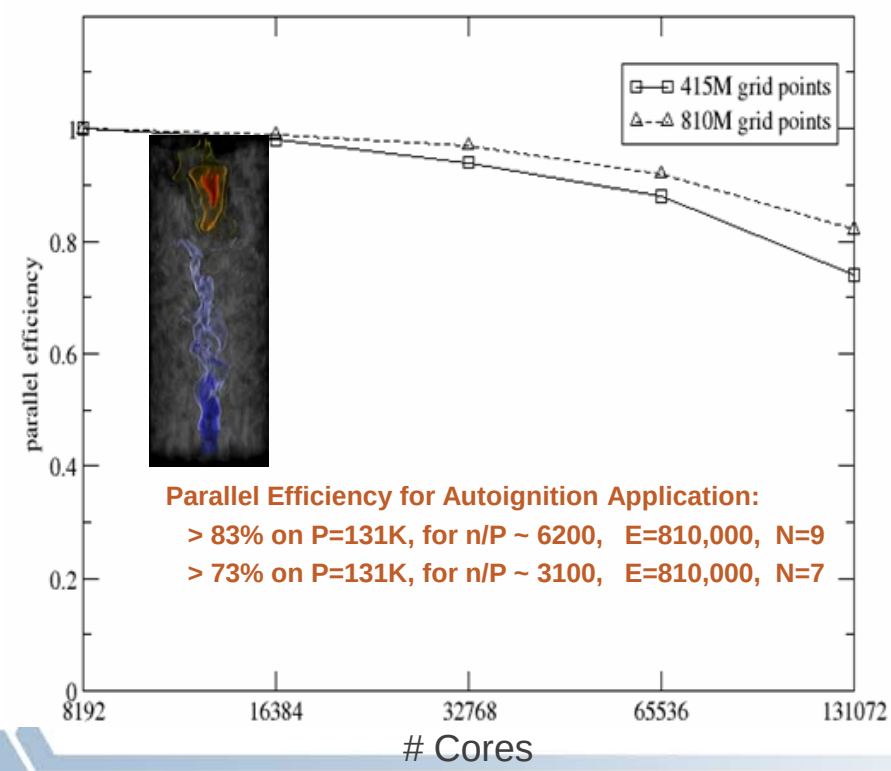


www.mcs.anl.gov/~fischer/sem1b

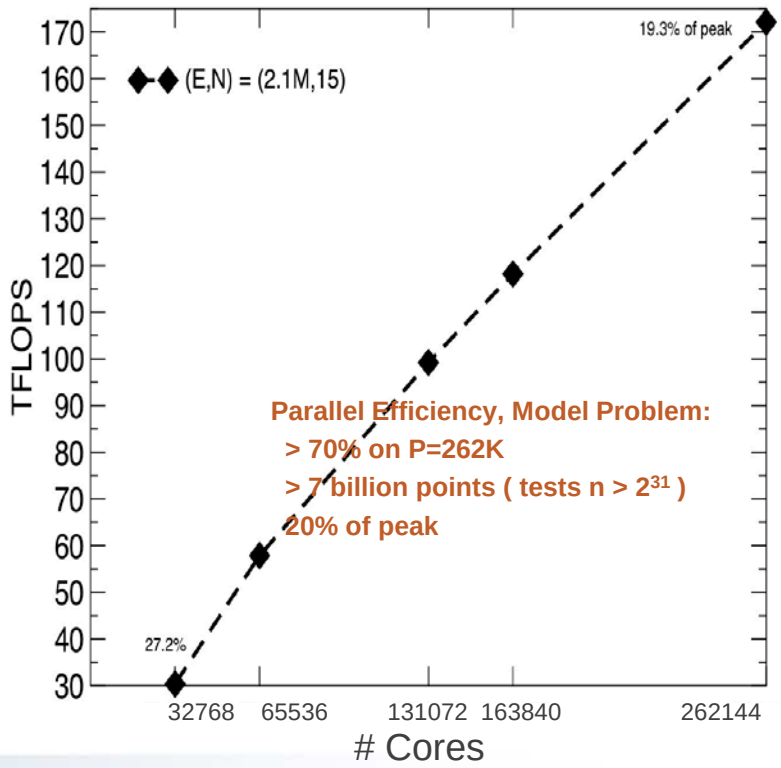
FY10: Scaling to P=262144 Cores

- Production combustion and reactor simulations on ALCF BG/P demonstrate scaling to P=131072 with n/P ~ 5000-10,000 and η ~ .7
- Test problem with 7 billion points scales to P=262144 on Juelich BG/P with η ~ .7

BG/P Strong Scaling: P=8192 – 131072



P=32768 – 262144



FY10 SHARP TH Verification and Validation Efforts

- Verification – establish correctness
  - Verification document
  - Automated build and test suite
  - Active user group
- Validation
  - Documenting validation cases
    - DNS, LES, RANS
    - Canonical flows, T-junction, pin + wire wrap, …

Past Verification Effort

- Nekton/Nek5000 has been going through verification for the past 25 years.
- Nek5000 open source for past 18 months (freely available for 20 years)
- Verification based on
  - *analytic solutions*
  - *challenging test problems*
- Verification done “by hand”
  - did not guarantee that the ***current code*** would solve problems tested last year…
  - NEAMS VU group urged automated verification

Current Verification Effort

- FY10: started automated code regression/testing using ***buildbot***

- Presently, after each svn repo update, run
  - w/ 4 different compilers (serial) + 1 (parallel)
  - 60 tests (400 runs in total) checking solution & runtimes

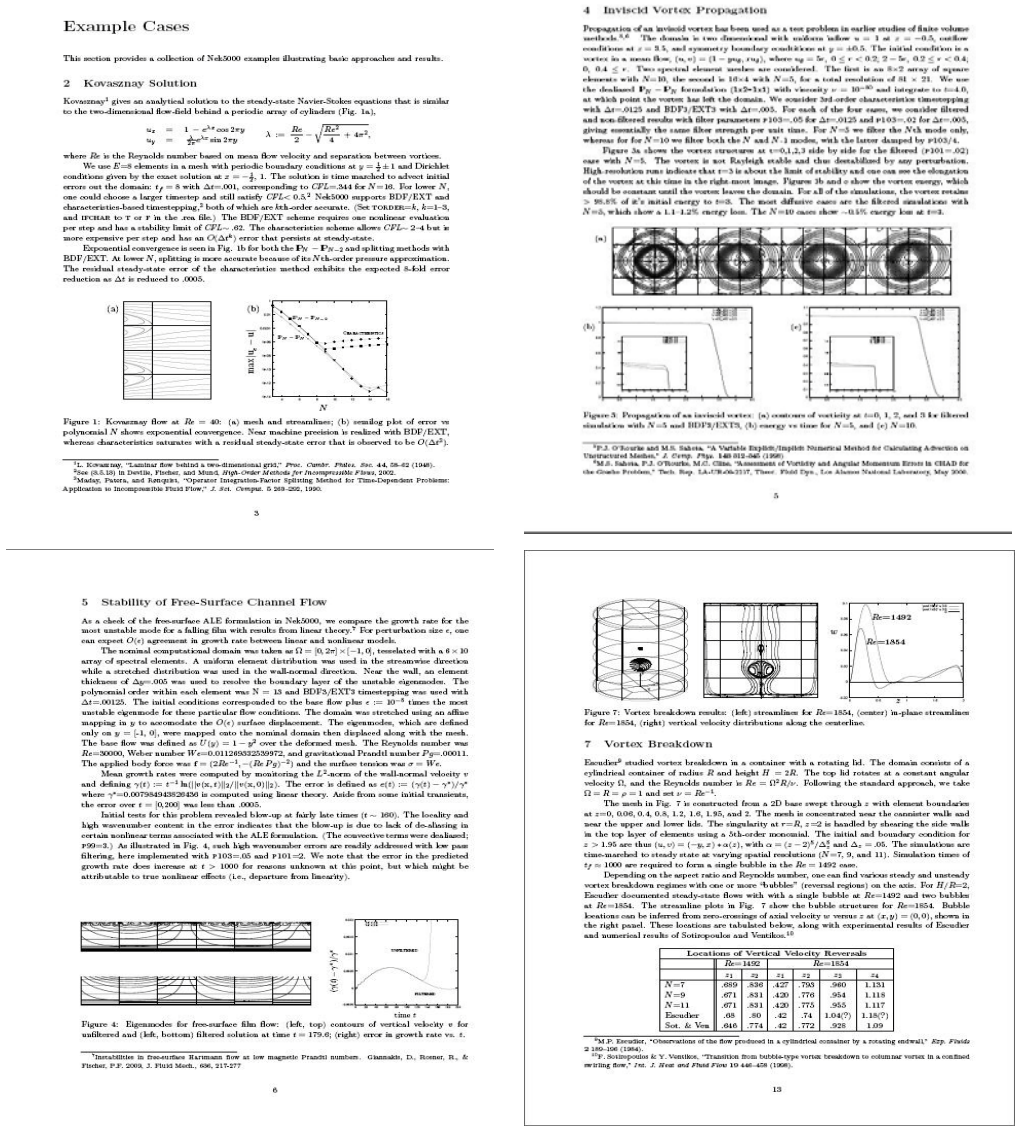
- Test suite extended to
  - include all example problems
  - include all verification problems to date (at least one pt./case)

- Being extended to
  - include bugs reported by users
  - have full ***feature coverage*** (more work needed here…)
  - automated monitoring (runtime error estimators)

- Active (and noisy) user forum
  - 60 registered users
  - generating 5-10 emails/day
  - helps to identify bugs/features and keep code on track

Verification Cases

- Several cases documented in (www.mcs.anl.gov/~fischer/users.pdf)
- Mostly analytical solutions or detailed experiments
- For each case:
  - 1 page description
  - convergence data
  - references
- Adding all cases to svn/examples directory and to automated regression tests.
  - *Currently, buidbot tests only a few parameter points from the full verification problem*
  - *Considering adding full convergence studies (expensive)*



Example Cases

2 Kovasznay Solution

4 Inviscid Vortex Propagation

5 Stability of Free-Surface Channel Flow

7 Vortex Breakdown

Eddy Solution Example

Evolution of exact Navier-Stokes eigenfunctions:

- 2 spatial discretizations x 2 temporal discretizations
- Several resolutions

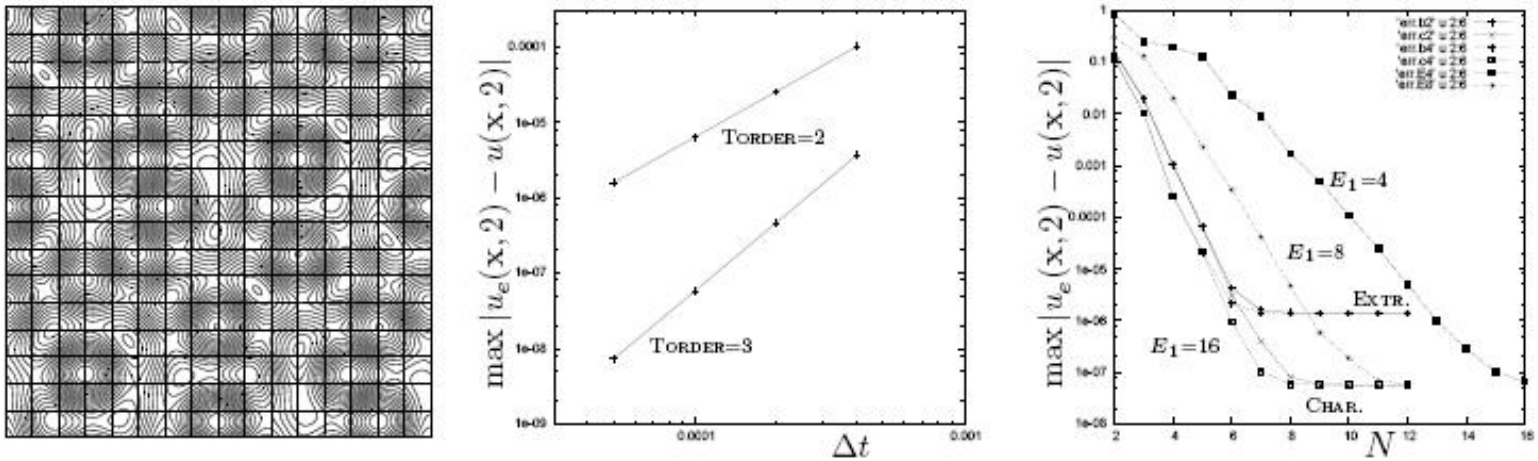


Figure 2: Eddy solution results: (left) vorticity at t=2 for N=15, (center) error vs Δt for $\mathbb{P}_N - \mathbb{P}_{N-2}$ with N=15 and IFCHAR=T, and (right) error vs polynomial order N for $\mathbb{P}_N - \mathbb{P}_{N-2}$ and $\mathbb{P}_N - \mathbb{P}_N$ with Δt=.0001 and IFCHAR=F/T (i.e., extrapolation or characteristics).

[4] O. Walsh, "Eddy solutions of the Navier-Stokes equations," *The NSE II-Theory and Numerical Methods*, J.G. Heywood, K. Masuda, R. Rautmann, and V.A. Solonikkov, eds., Springer, pp. 306–309 (1992)

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3D Vortex Breakdown Example

- Canister w/ rotating lid.
- Location and number of flow reversals a function of Re and aspect ratio.
- Comparison with experiment and alternate code for two values of Re and different polynomial orders

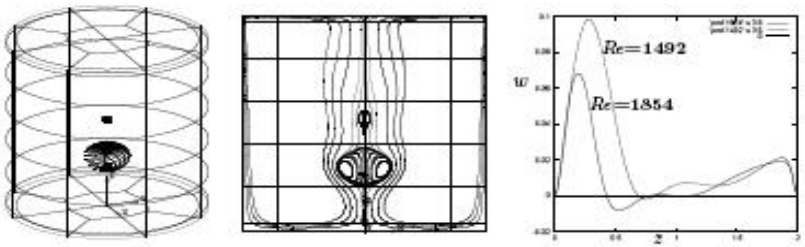


Figure 7: Vortex breakdown results: (left) streamlines for Re=1854, (center) in-plane streamlines for Re=1854, (right) vertical velocity distributions along the centerline.

7 Vortex Breakdown

Escudier[9] studied vortex breakdown in a container with a rotating lid. The domain consists of a cylindrical container of radius R and height $H = 2R$. The top lid rotates at a constant angular velocity Ω, and the Reynolds number is $Re = \Omega^2 R/\nu$. Following the standard approach, we take $\Omega = R = \rho = 1$ and set $\nu = Re^{-1}$.

The mesh in Fig. 7 is constructed from a 2D base swept through z with element boundaries at z=0, 0.06, 0.4, 0.8, 1.2, 1.6, 1.95, and 2. The mesh is concentrated near the cannister walls and near the upper and lower lids. The singularity at r=R, z=2 is handled by shearing the side walls in the top layer of elements using a 5th-order monomial. The initial and boundary condition for $z > 1.95$ are thus $(u, v) = (-y, x) + \alpha(z)$, with $\alpha = (z-2)^5/\Delta_z^5$ and $\Delta_z = .05$. The simulations are time-marched to steady state at varying spatial resolutions (N=7, 9, and 11). Simulation times of $t_f \approx 1000$ are required to form a single bubble in the $Re = 1492$ case.

Depending on the aspect ratio and Reynolds number, one can find various steady and unsteady vortex breakdown regimes with one or more "bubbles" (reversal regions) on the axis. For H/R=2, Escudier documented steady-state flows with with a single bubble at Re=1492 and two bubbles at Re=1854. The streamline plots in Fig. 7 show the bubble structures for Re=1854. Bubble locations can be inferred from zero-crossings of axial velocity w versus z at $(x, y) = (0, 0)$, shown in the right panel. These locations are tabulated below, along with experimental results of Escudier and numerical results of Sotiropoulos and Ventikos.[10]

Locations of Vertical Velocity Reversals						
	Re=1492		Re=1854			
	z_1	z_2	z_1	z_2	z_3	z_4
N=7	.689	.836	.427	.793	.960	1.131
N=9	.671	.831	.420	.776	.954	1.118
N=11	.671	.831	.420	.775	.955	1.117
Escudier	.68	.80	.42	.74	1.04(?)	1.18(?)
Sot. & Ven	.646	.774	.42	.772	.928	1.09

[9] M.P. Escudier, "Observations of the flow produced in a cylindrical container by a rotating endwall," *Exp. Fluids* 2 189–196 (1984).

[10] F. Sotiropoulos & Y. Ventikos, "Transition from bubble-type vortex breakdown to columnar vortex in a confined swirling flow," *Int. J. Heat and Fluid Flow* 19 446–458 (1998).

Problem Validation

- Validation must be done on a case-by-case basis.
- Typically, this is done by the user, who is a domain expert and knows the limits of the chosen model, the appropriate boundary conditions, etc.
- Turbulence benchmarks are validated against
  - experiments
  - direct numerical simulation (DNS)
- Validation cases include
  - Fluid dynamics / heat transfer problems unrelated to reactors
  - New problems that are specific to reactor applications.

Channel Flow at Re_b=13,000 (Re_τ =590)

- Nek5000 simulations by J. Ohlsson, KTH, Stockholm 288 x 288 x 192
- Compared to DNS of Moser, Mansour, Kim: 384 x 384 x 257

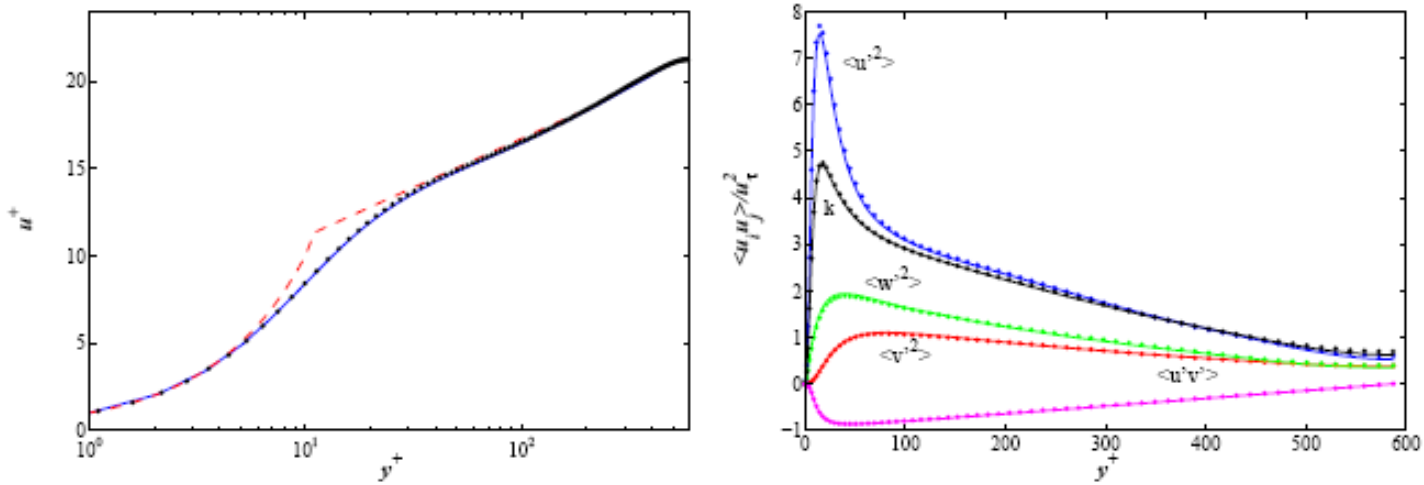
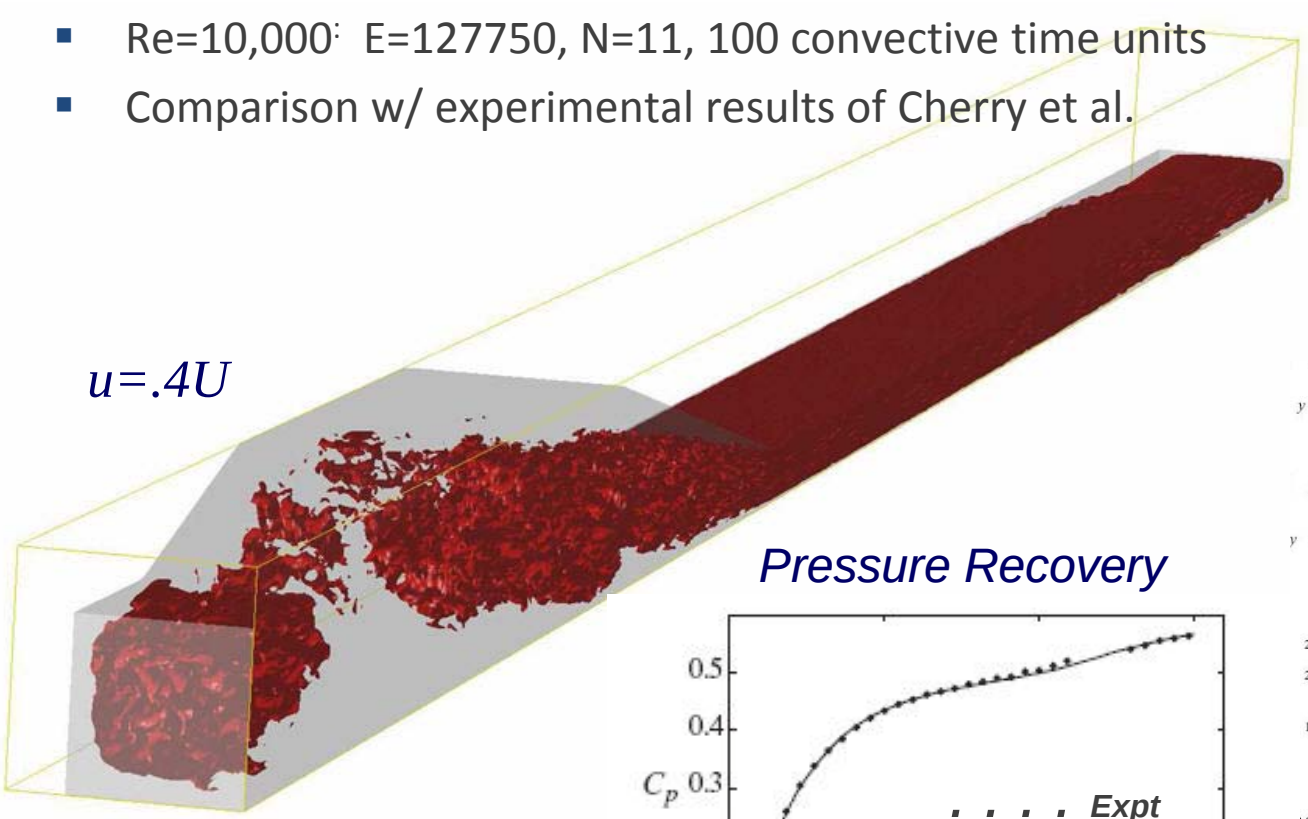


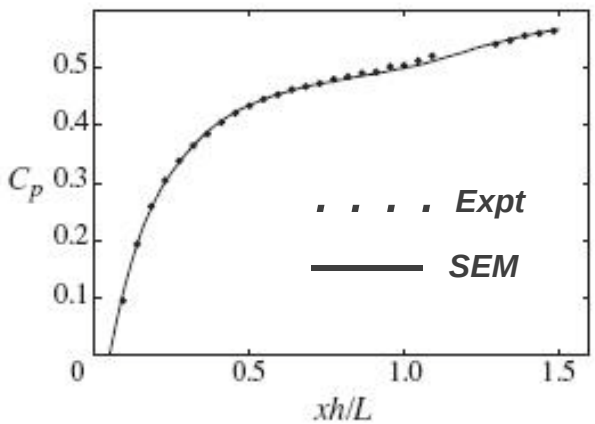
Figure 15: Turbulent channel flow simulations at Re_τ = 590 with polynomial order 15 (a resolution of 288 in the homogenous directions and 192 in the wall-normal direction) showing a) mean velocity profile and b) Reynolds stresses together with the turbulent kinetic energy as defined above. In this case only overintegration was used [Case iii)]. Same time step as for the filtered case. Comparison to DNS results (a resolution of 384 in the homogenous directions and 257 in the wall-normal direction) from Moser et al. [19]. ····· DNS data, ----Log Law, ——Nek5000.

DNS of Separation in an Asymmetric Diffuser

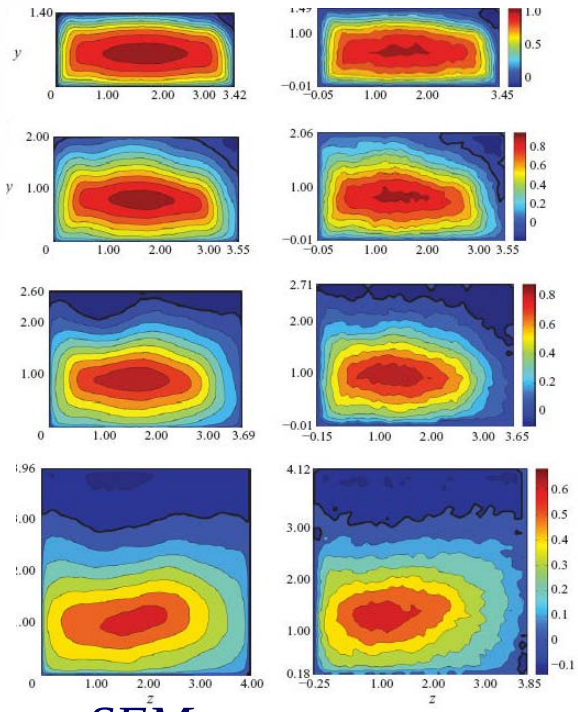
- Challenging high-Re case with flow separation and recovery
- Re=10,000: E=127750, N=11, 100 convective time units
- Comparison w/ experimental results of Cherry et al.



Pressure Recovery



Axial Velocity



SEM expt.

Ohlsson, Schlatter, Fischer, and Henningson. *J. Fluid Mech.*, **650** (2010)

Validation Cases for Reactor Problems

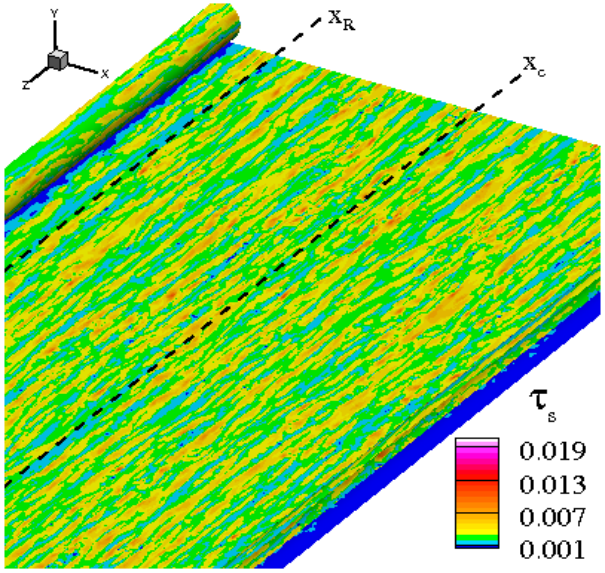
- Validation for reactor problems is a major thrust for NEAMS

- Benchmarks are based on:
  - Experiments — e.g., Japan T-junction
    Vattenfall T-Junction;
    ANL MAX Outflow plenum
  - DNS data — e.g., channel + wire (Ranjan et al., JFM 2010)
  - Code-vs.-code — e.g., 7- and 217-pin bundles w/ wire-wrap

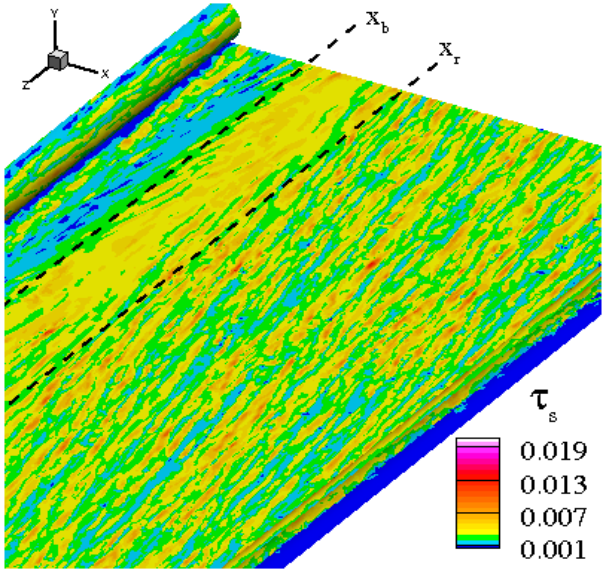
Validation: DNS Benchmark

- Plane channel + wire in turbulent cross flow
  - *Single wire in a channel with cross flow simulated at Re_b=6000*
  - *Spectral code, 100 million gridpoints, 3 million node hours through INCITE award*
  - *Hydrodynamic results published in 2010.*
  - *Heat transfer results submitted, 2010.*

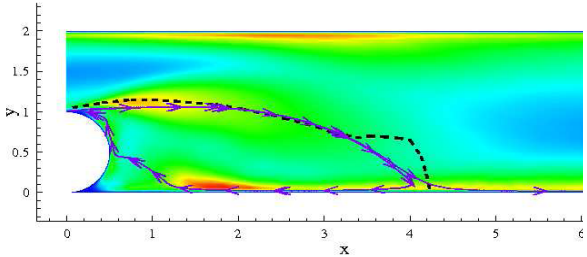
Wall Shear: No Cross-Flow



16% Cross-Flow



TKE, 16% CF



Separation in wire wake leads to increased variance in wall shear. Anticipate similar effects for heat transfer.

Ranjan, Pantano, Fischer *J. Fluid Mech. (2010)*

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Single-Wire LES-DNS Comparison

E. Merzari

- LES – 15 million points (64 core cluster), DNS – 100 million points (2048 core BGP)
- LES - Full conjugate heat transfer
  - hot spot / gap analysis published in FY10
- Working on coarser LES runs

Velocity Comparisons

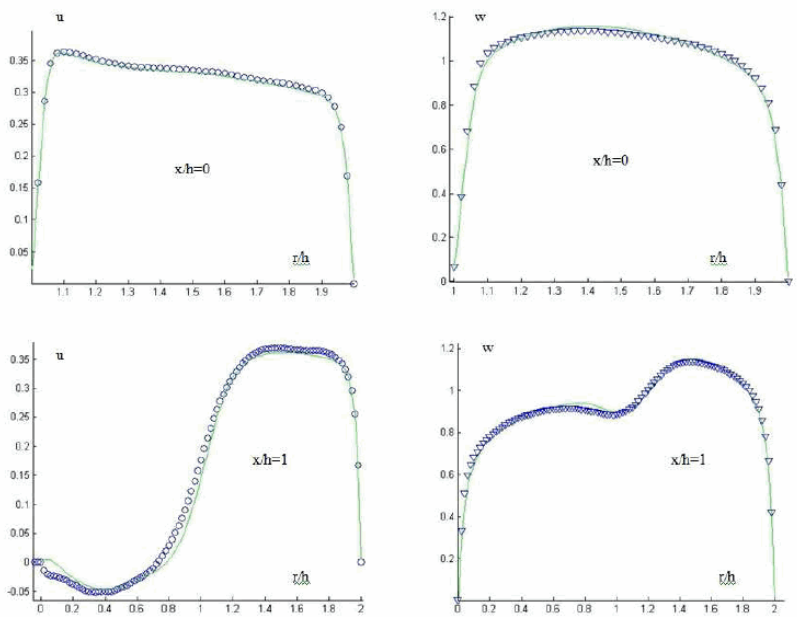
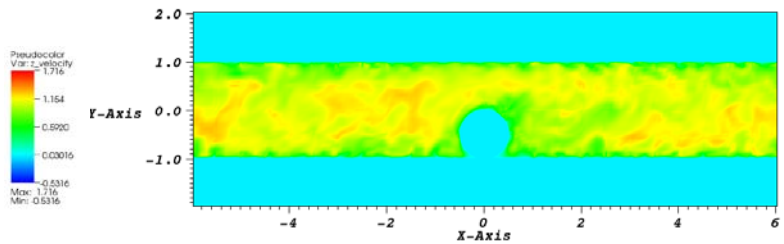
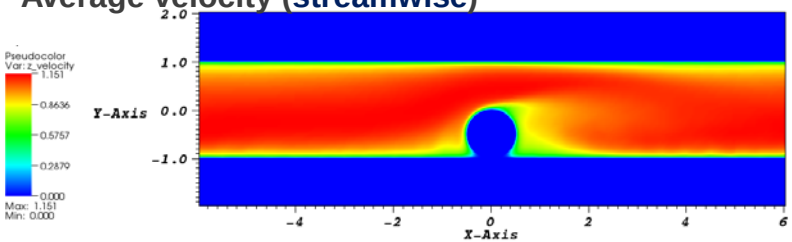


Figure 11: Comparisons of the streamwise velocity and the cross velocity at x/h=0 (wire centerline) and x/h=1. The solid line represents the DNS data [1]. All values are normalized by W_{bulk}. r represents the distance from the bottom wall.

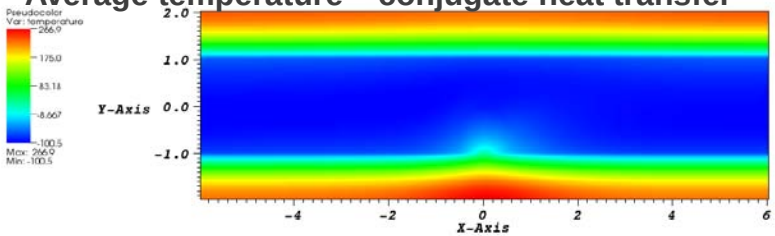
Instantaneous velocity (streamwise)



Average velocity (streamwise)



Average temperature – conjugate heat transfer



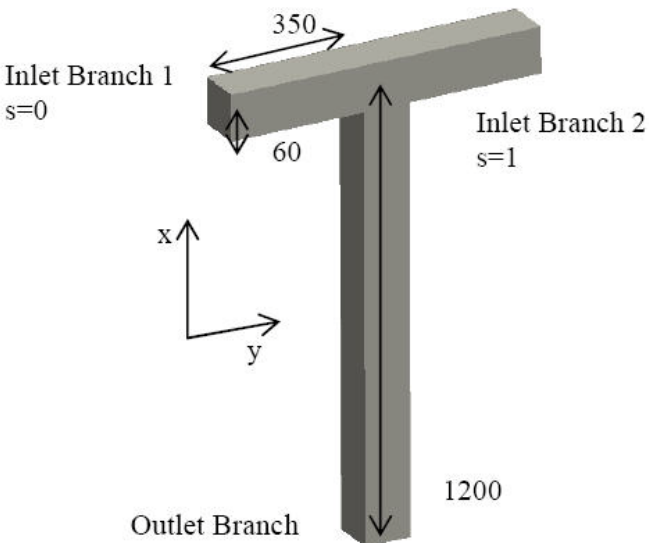
Merzari, Pointer, Smith, and Fischer. *CFD4NRS-3, September, 2010.*

Nek5000 LES Validation: T-Junction Studies

E. Merzari

Square T-junction simulation used as test problem for proper orthogonal decomposition (POD) development[1] and comparison with exptl data[2]

- *SEM: 20 M points, first point at $y^+ < 1$, $Re_{out} = 7000$*



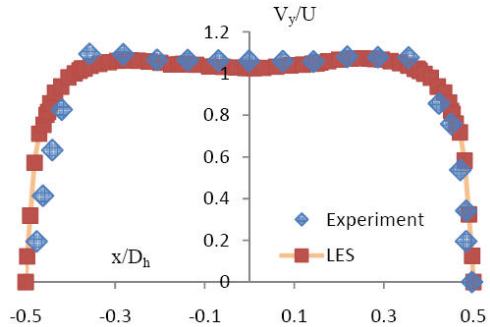


Fig. 6 Reynolds Averaged y-velocity at z=0, y=-30, values normalized by the Mixing Bulk Velocity

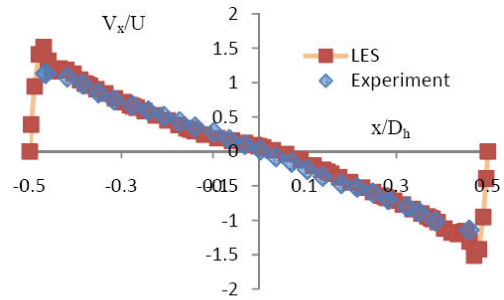


Fig. 8 Reynolds Averaged x-velocity at z=0, y=-30, values normalized by the Mixing Bulk Velocity

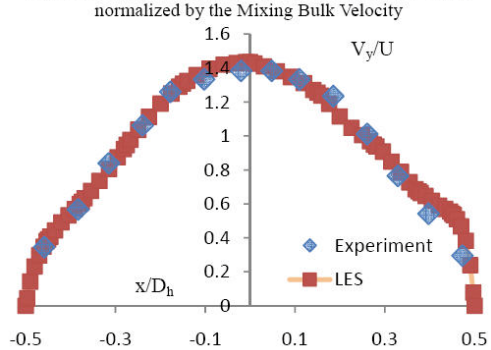


Fig. 7 Reynolds Averaged y-velocity at z=0, y=-90, values normalized by the Mixing Bulk Velocity

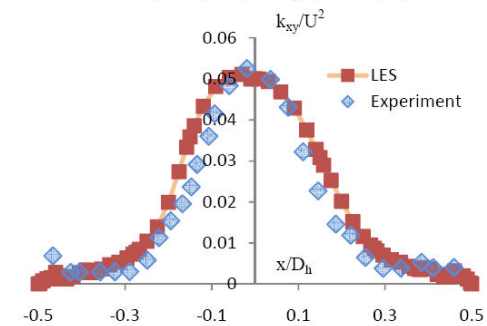


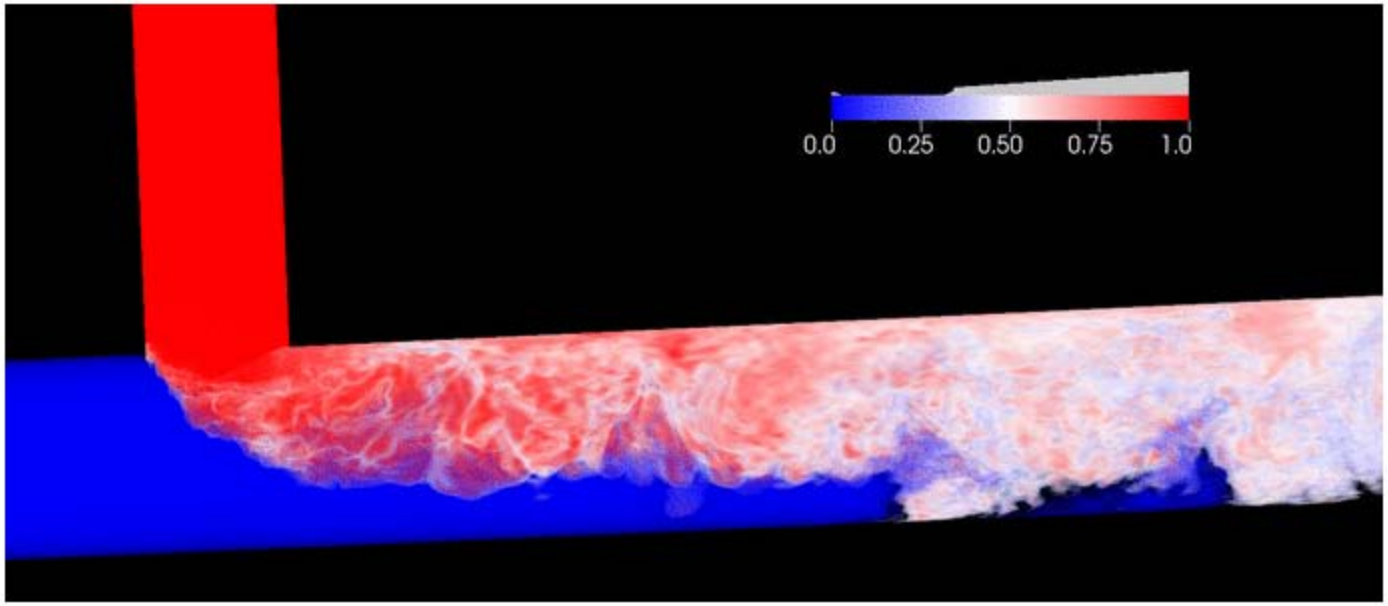
Fig. 11 Reynolds Averaged Turbulent kinetic energy at z=0, y=-90, values normalized by the square of the Mixing Bulk Velocity

[1] *Merzari et al., Proper Orthogonal Decomposition of the flow in a T-junction, Proc. ICAPP (2010)*

[2] *Hirota et al., Exptl Study on Turbulent Flow and Mixing in Counter-Type T-junction, J. Therm. Sci. & Tech. 3, 157 – 58 (2008)*

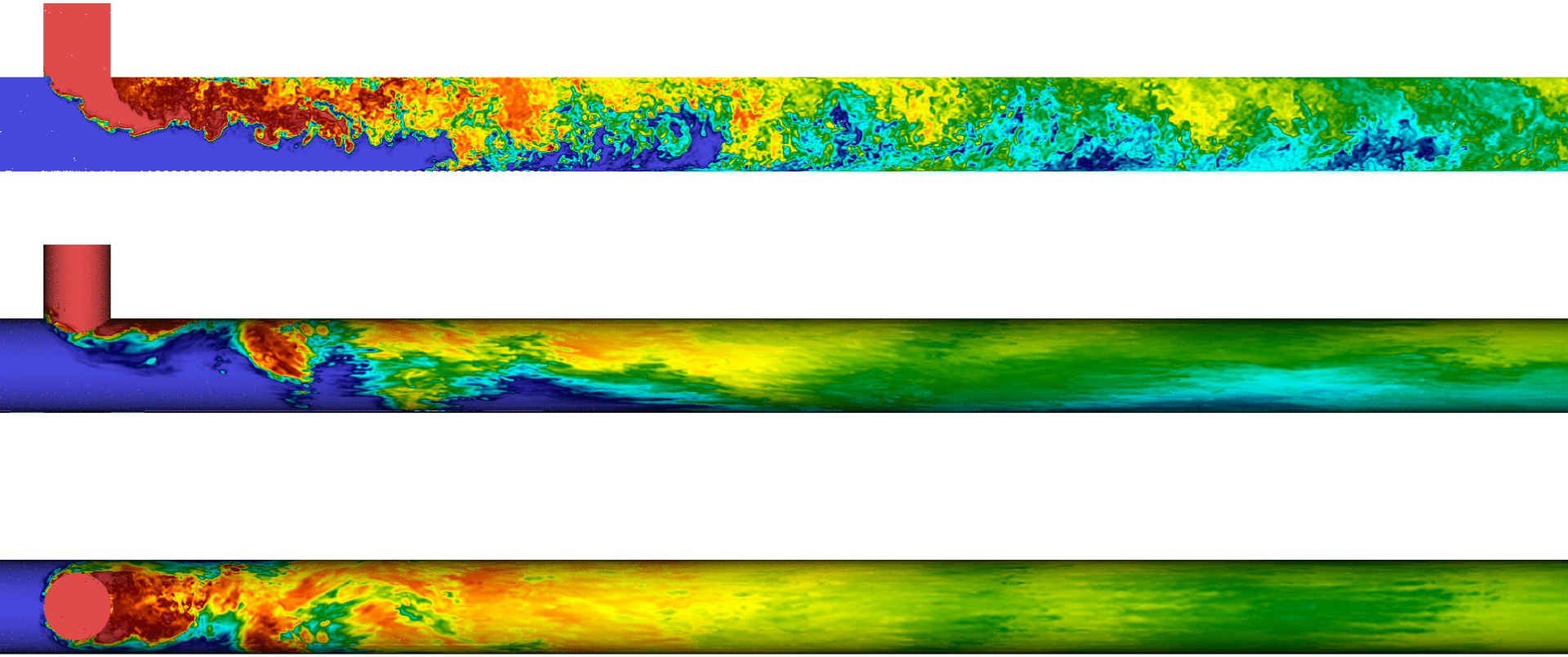
Vattenfall NEA/OECD T-Junction Blind Benchmark

- Experimental with hot/cold inlets at Re ~ 10^5
- Velocity and temperature inlet data provided by Vattenfall.
- Downstream LES & RANS results submitted 4/30/10.
- Comparison of results announced 9/15/10 at CFD4NRS meeting in DC



Instantaneous Temperature Distributions:

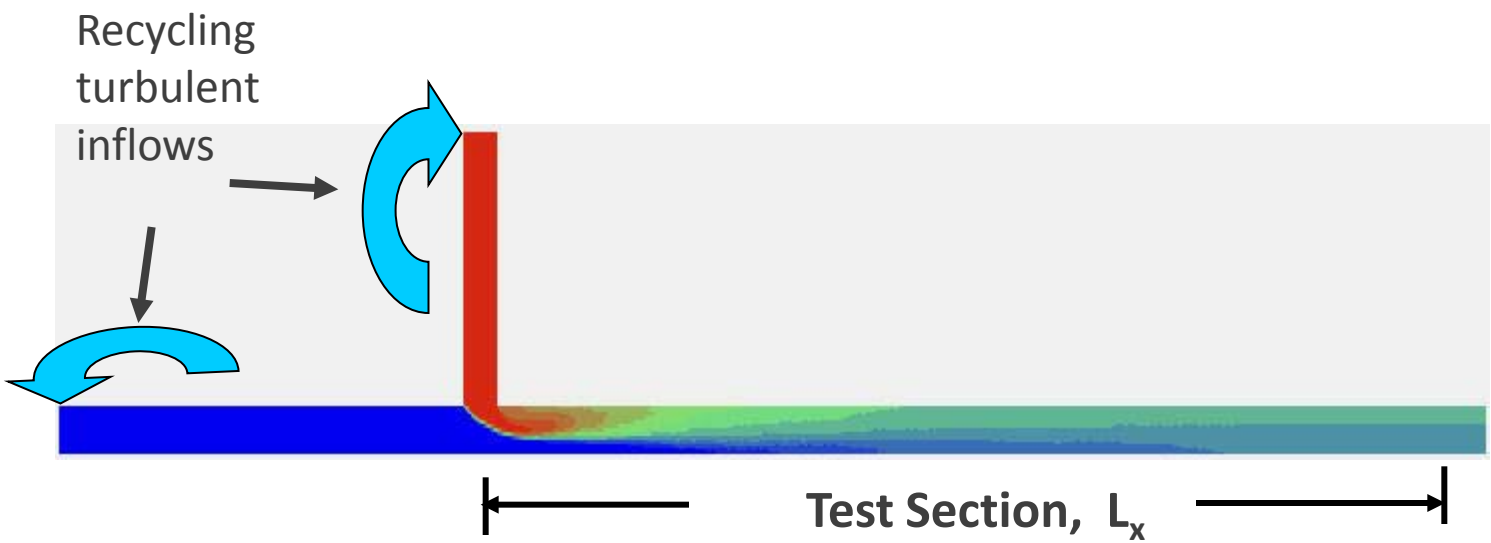
Thermal striping leads to thermal fatigue in structural components



Nek5000 Submission to T-Junction Benchmark

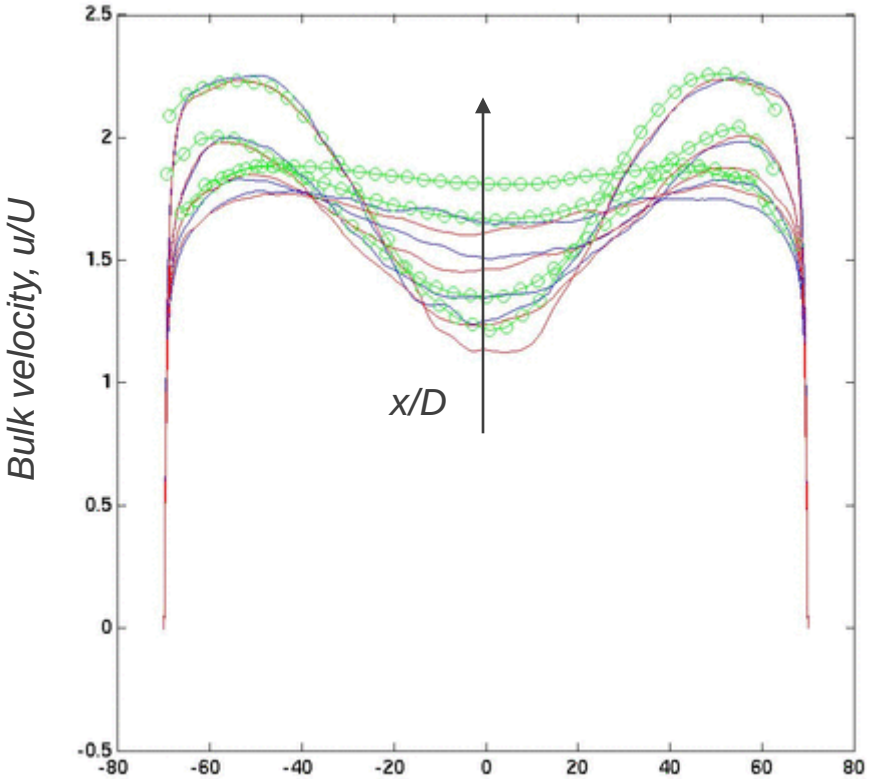
F., Obabko, Tautges, Caceres

- E=62000 spectral elements of order N=7 (n=21 million)
  - Mesh generated by SHARP framework group using CUBIT
  - Loaded into Nek5000 through parallel MOAB interface
  - A ***group*** effort at integrated process, under a time constraint…
- Re_D = 40,000 for inlet pipes
- Subgrid dissipation modeled with low-pass spectral filter
- L_x ~ 25 D (cost is quadratic in L_x)
- 24 hours on 16384 processors of BG/P (850 MHz) *~ 33x slower than uRANS*

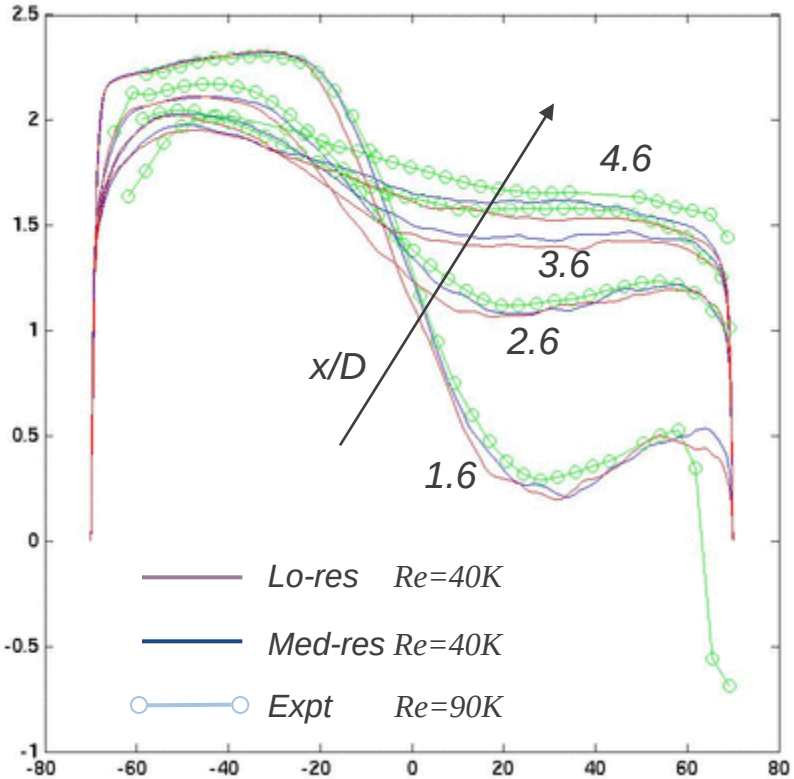


Velocity Comparison Downstream of T-junction

- Medium resolution results are in excellent agreement at x=1.6 & 2.6
- Experiment (Re=90K) exhibits more rapid recovery of profile than simulation (Re=40K)



— Horizontal position, y –



–Vertical position, z –

Results Presented by NEA/OECD Benchmark Organizers, CFD4NRS 9/15/10

- 29 entries, resolution n = 1 M to 70 M gridpoints
- Nek5000 ranked 1st in thermocouple prediction, 6th in velocity prediction, 17th in Fourier spectrum

Table 9. Submissions Ranked by Comparison to Thermocouple Data

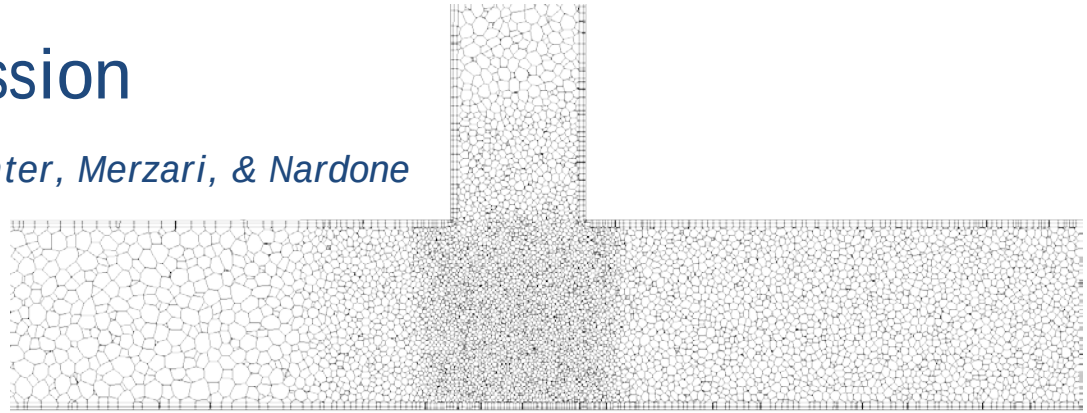
Submission	TC Score	Code	Turbulence	Volumes
S21	36	Nek5000	LES, spectral damping	21M
S16	45	Fluent 12	LES-WALE	7.7M
S8	48	STAR-CCM+/3.06.006	LES-Wale SGS	13.2 M
S4	57	Fluent 6.3.26	LES, Dyn. Smagorinsky	5.8M
S22	72	Star-CCM+	LES	4.4 M
S23	78	CFX	LES-WALE	1.9 M
S5	81	Saturne	LES, Dyn. Smagorinsky	6.2M
S2	82	FLUENT 12.1	LES, Dyn. Smagorinsky	34M
S20	82	FLUENT	LES, Dyn. Smagorinsky	70.5M
S19	83	FLUENT 12.1	SST-kω	11M
S14	88	CABARET	ILES	1.8M
S25	88	TransAT	LES-WALE	2.5 M
S18	93	CFX	DES-SST	2.4M
S10	105	Fluent 12	LES-Smagorinsky-Lilly	0.92M
S26	105	FLUENT v12.1	LES - Dynamic KE SGSl	7.2 M
S6	110	STAR-CCM+/3.06.006	LES-Wale	9.3 M
S17	121	OpenFOAM 1.6	LES, 1eqn. Dyn. eddy	0.28M
S7	124	CFX	SAS-SST	5.0 M
S11	138	CFX	LES-Wale	3.4M
S1	139	Fluent	LES	4.5M
S24	151	OpenFOAM 1.6	LES, Dyn. Smagorinsky	8 M
S9	164	Advance/FrontFlow/red v4	LES-Smagorinsky	4.1 M
S15	164	CFX	SAS-SST	2.3M
S13	186	CFX 12.0	SAS-SST	1.1M
S27	186	Star-CCM+	V^2F	0.62 M
S29	197	CFX	SAS-SST	1.0M
S3	201	CFX5 v12	LES, WALE	0.97M
S12	224	MODTURC_CLAS-IST	k-epsilon/RNG	0.89M
S28	232	STAR-CCM+	Dynamic Vreman	3.7M

Table 8. Submissions Ranked by Comparisons to PIV Data

Submission	Velocity Score	Code	Turbulence	Volumes
S20	75	FLUENT	LES, Dyn. Smagorinsky	70.5M
S2	166	Fluent 12	LES, Dyn. Smagorinsky	34M
S8	178	STAR-CCM+/3.06.006	LES-Wale SGS	13.2 M
S4	184	Fluent 6.3.26	LES, Dyn. Smagorinsky	5.8M
S24	212	OpenFOAM 1.6	LES, Dyn. Smagorinsky	8 M
S21	247	Nek5000	LES, spectral damping	21M
S16	270	Fluent 12	LES-WALE	7.7M
S3	311	CFX5 v12	LES, WALE	0.97M
S11	312	CFX	LES-Wale	3.4M
S19	322	FLUENT 12.1	SST-kω	11M
S18	349	CFX	DES-SST	2.4M
S14	358	CABARET	ILES	1.8M
S17	374	OpenFOAM 1.6	LES, 1eqn. Dyn. eddy	0.28M
S9	375	Advance/FrontFlow/red v4	LES-Smagorinsky	4.1 M
S22	404	STAR-CCM+	LES	4.4 M
S6	408	STAR-CCM+/3.06.006	LES-Wale	9.3 M
S26	432	FLUENT v12.1	LES - Dynamic KE SGS	7.2 M
S27	446	STAR-CCM+	V^2F	0.62 M
S23	458	CFX	LES-WALE	1.9 M
S10	477	Fluent 12	LES-Smagorinsky-Lilly	0.92M
S5	531	Saturne	LES, Dyn. Smagorinsky	6.2M
S25	585	TransAT	LES-WALE	2.5 M
S1	589	Fluent	LES	4.5M
S7	603	CFX	SAS-SST	5.0 M
S15	605	CFX	SAS-SST	2.3M
S13	706	CFX 12.0	SAS-SST	1.1M
S12	712	MODTURC_CLAS	k-epsilon/RNG	0.89M
S29	719	CFX	SAS-SST	1.0M

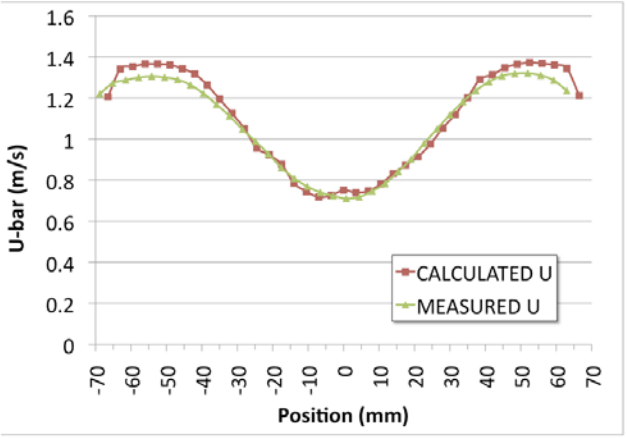
RANS T-Junction Submission

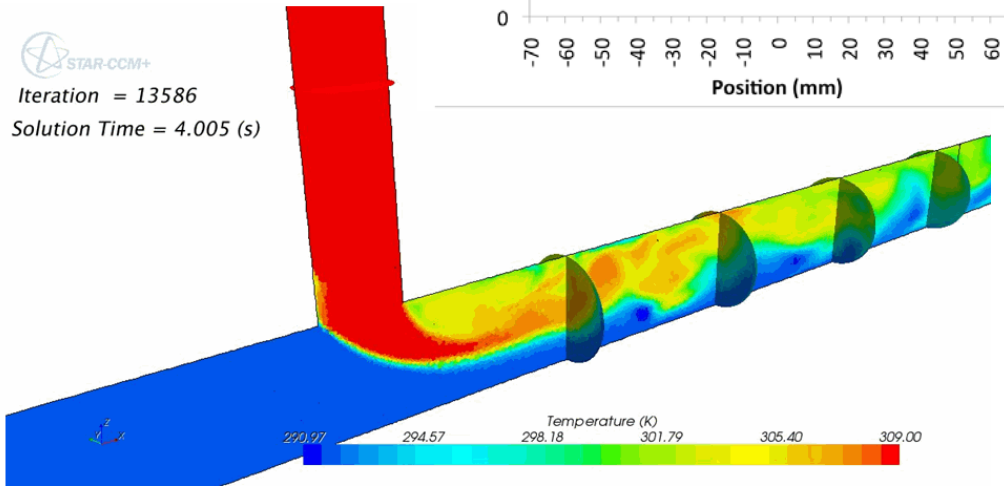
Pointer, Merzari, & Nardone



URANS using STAR-CCM+

- Stanford V^2F turbulence model with a two-layer all y+ wall treatment
- ~620000 polyhedral cells with prismatic extrusion wall layer
- ~4000 CPU hours for 5 seconds of simulation time
  - 10^{-3} s / timestep
  - second order in space and time
- Ranked
  - 25/29 for temperature
  - 18/29 for velocity comparison
  - 10/29 for fourier spectrum





Outlet Plenum Mixing Studies

- Mixing in the outlet plenum influences thermal striping effects on structures subjected to core outlet flows
- To reduce thermal striping, assembly-to-assembly temperature variations are constrained in the design process.
- A better understanding of the relevant mixing phenomena would lead to more flexibility in design.

Experimental Validation Study

- Argonne is constructing a highly instrumented experiment (MAX) to provide detailed velocity and temperature data for code validation.
  - 1 x 1 x 1.68 m^3 mock-up of mixing in outlet plenum (SFR or VHTR)
  - Two to four inlet jets w/ variable temperature/flow rates
  - PIV for velocity measurements
  - Fast thermal video imaging for temperature measurements

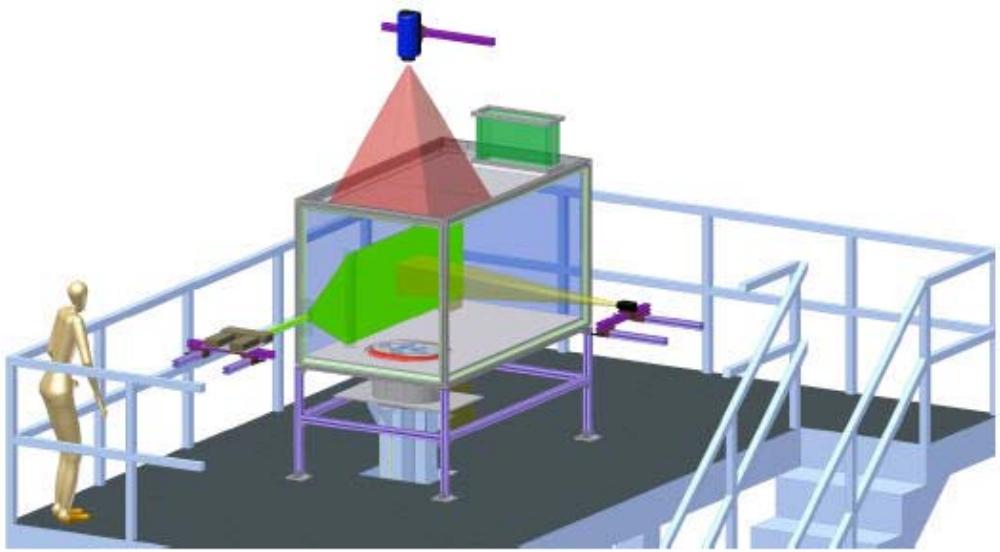
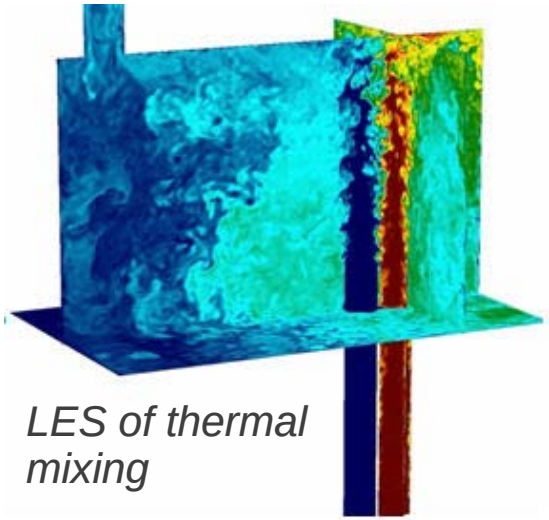


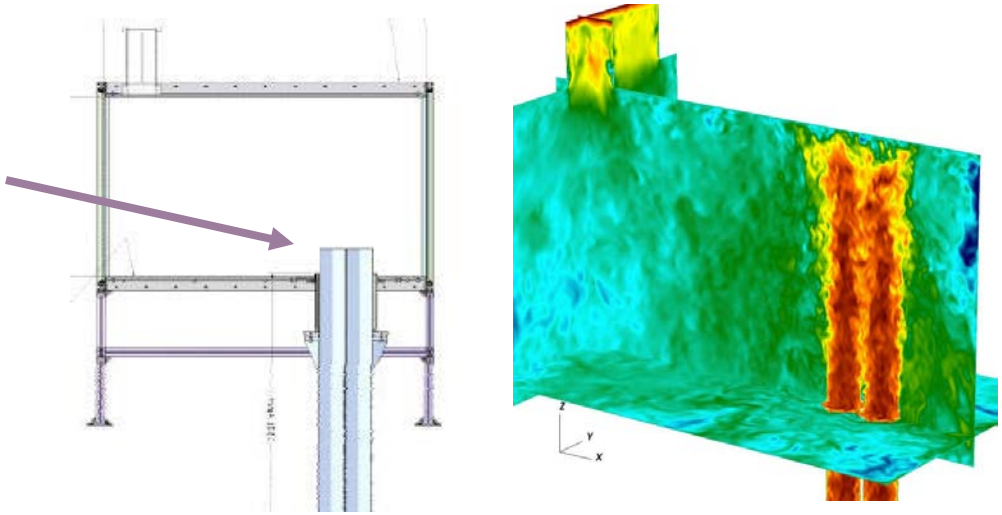
Figure 1. Apparatus for gas mixing experiments: Nd:YLF laser (left), infrared camera (top), PIV camera (right), and hexagonal flow channels (below).



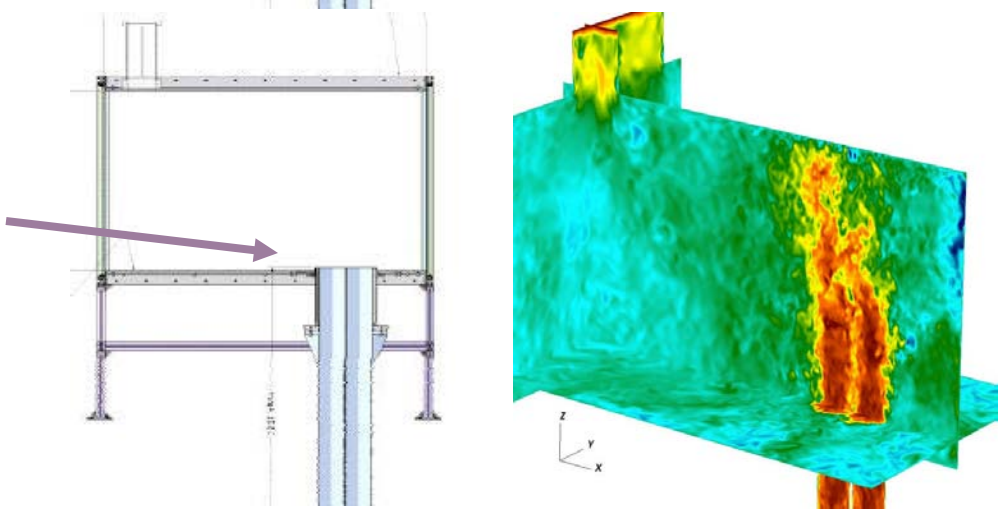
LES of thermal mixing

Major Difference in Jet Behavior for Minor Design Change

MAX1



MAX2



Simulation Results:

- *Small perturbation yields O(1) change in jet behavior*
- *Unstable jet, with low-frequency (20 – 30 s) oscillations*
- *Visualization shows change due to jet / cross-flow interaction*
- *MAX2 results* ***NOT*** *predicted by steady RANS (URANS ok)*

LES & RANS Comparison, MAX 1 and 2

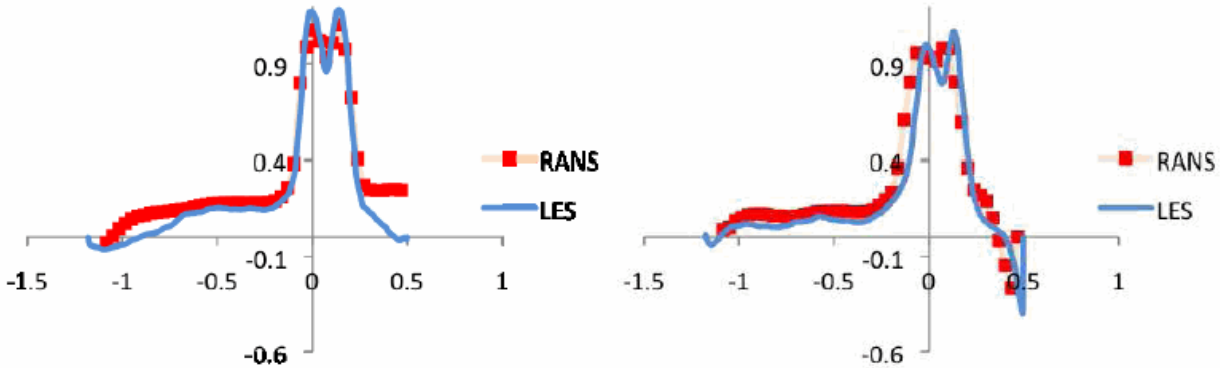


Figure 28: Comparison between the axial velocity profile V_z for LES and RANS calculations in configuration #1 (with protrusion) at two different altitudes z : $z = 0.5$ (left) $z = 0.75$ (right)

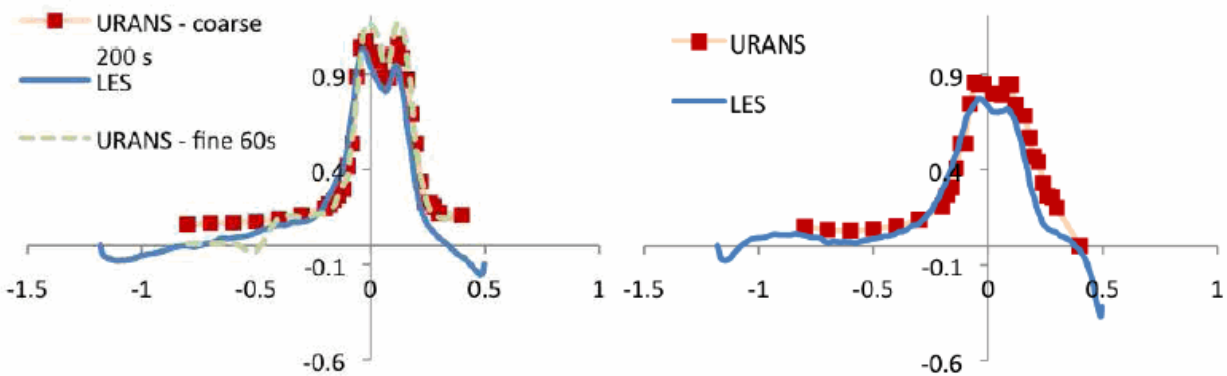
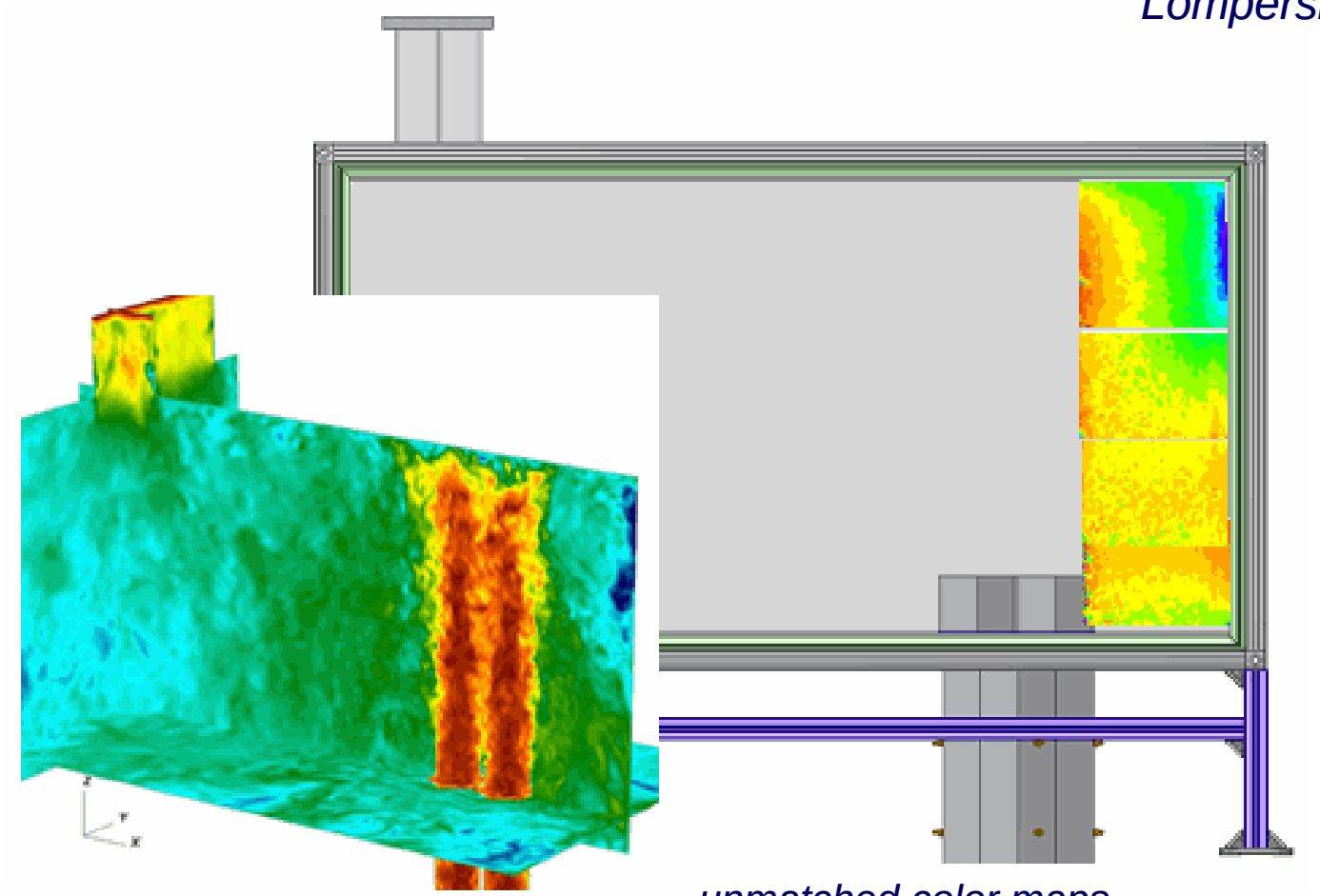


Figure 29: Comparison between the axial velocity profile V_z for LES and RANS calculations in configuration #2 (flush with the bottom) at two different altitudes z : $z = 0.5$ (left) $z = 0.75$ (right)

MAX Preliminary Time-Averaged PIV Data

Lomperski & Pointer, ANL



unmatched color maps

S. Lomperski, E. Merzari, D. Pointer, P. Fischer, and A. Obabko. Max Startup Tests. *Tech. Rep. ANL-NE-10/28*, 2010.

Where We Stand

- Building confidence in our simulation hierarchy
  - 25 years of verification, > 100 scientific articles based on Nek5000
  - Automated regression testing, open source, and active user mailing list is helping to ensure that the code remains verified
  - Validation studies are pointing to new directions for code development:
    - Improved SGS models for Re = 50-100K
    - Reduced order models (POD), uRANS capabilities

- Can start to apply these codes to design questions, e.g.,
  - Alternate wire-wrap designs
  - Wire-wrap vs. spacer-grids
  - VHTR bypass flows
  - LWR

- Continuing VU efforts to build additional confidence as problem scope broadens

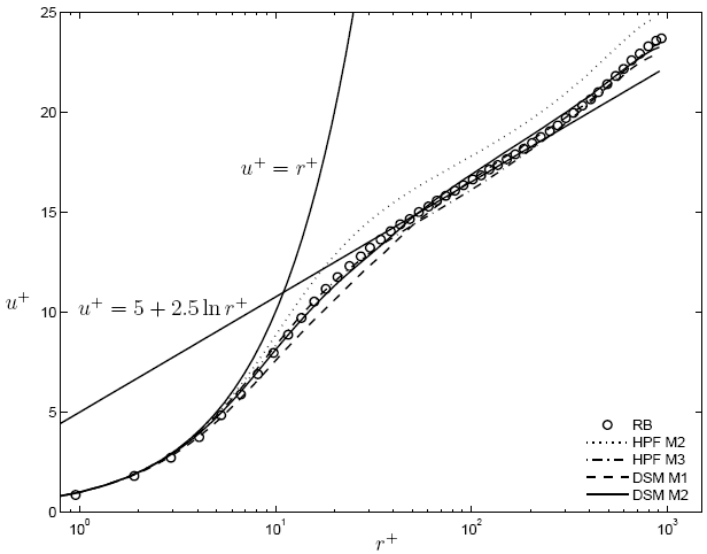


Figure 4: Comparison of mean velocity profiles with the Log Law and LES results of Rudman and Blackburn [24] for Re_D=36,700.

Some Recent Analysis Results

- 6 slides + summary slide

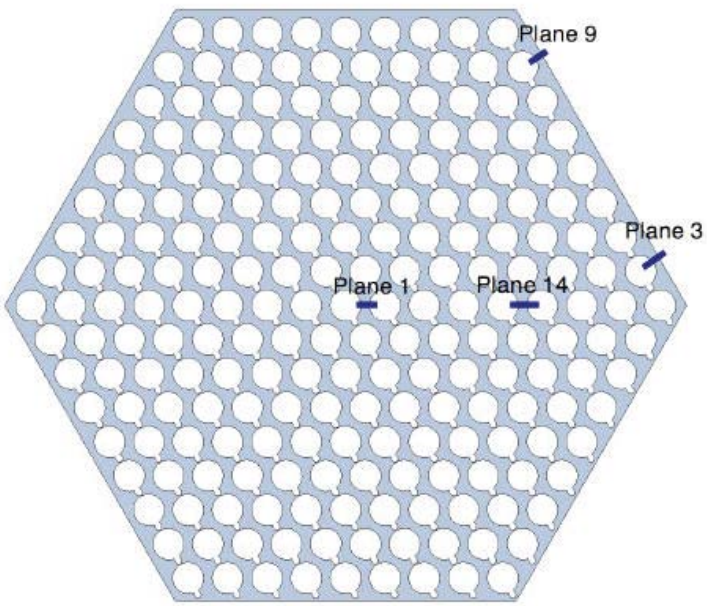
Nek5000/Star 217 Pin Cross-Channel Velocity Comparison

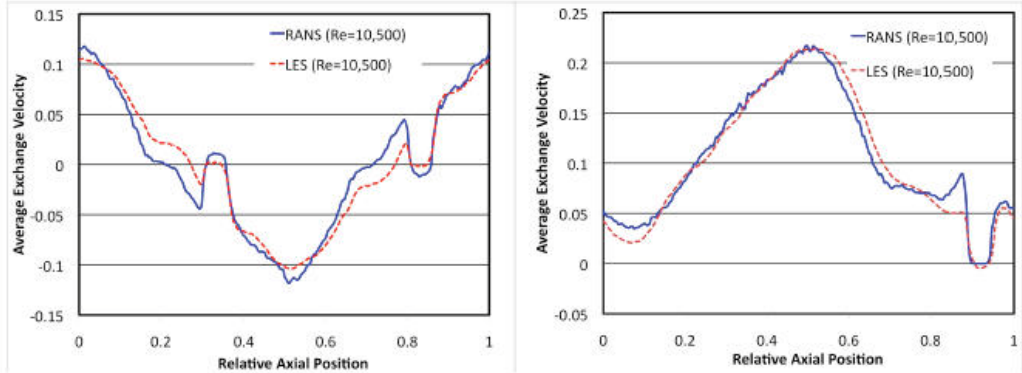
Pointer, Smith, Obabko, F.

Re_h = 10,500

LES – 1 billion points

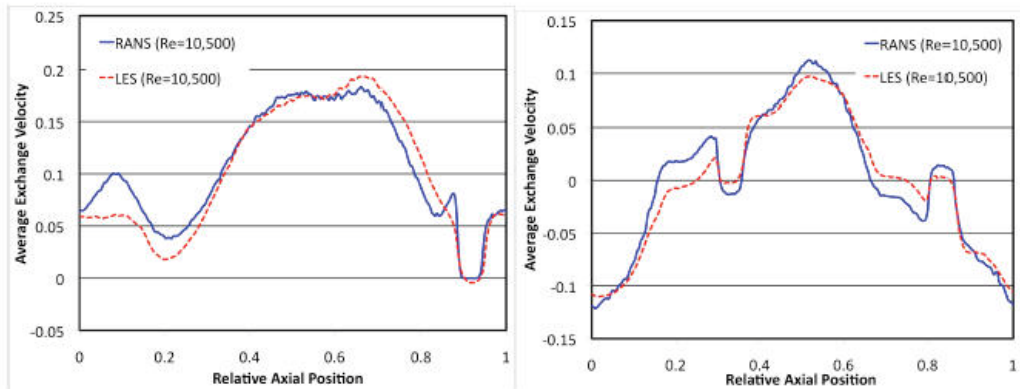
RANS – 14 million cells





(a) *(b)*

Figure 7. Comparison of predicted normal velocity profile for (a) plane group 1 and (b) plane group 3. RANS data is shown in blue and LES data is shown in red.



(a) *(b)*

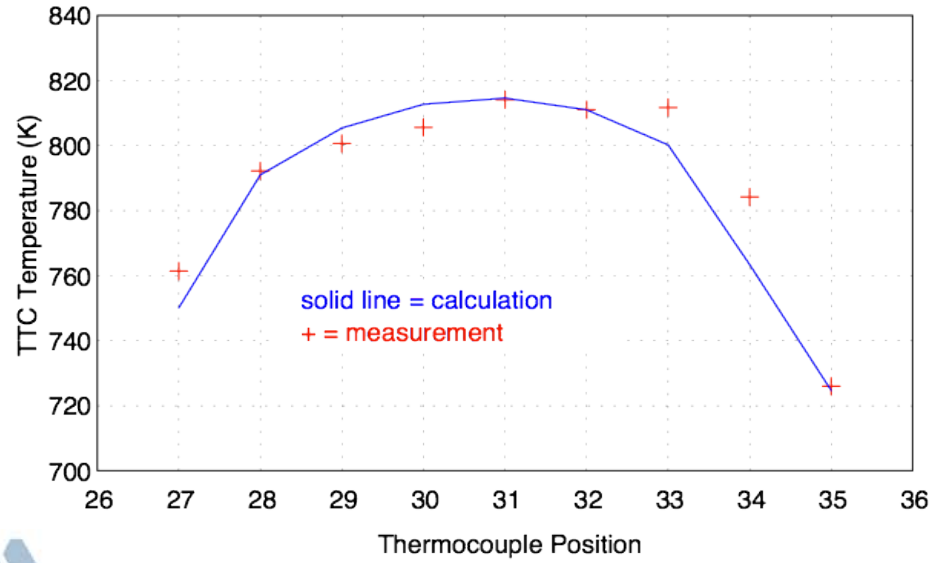
Figure 8. Comparison of predicted normal velocity profile for (a) plane group 9 and (b) plane group 14. RANS data is shown in blue and LES data is shown in red.

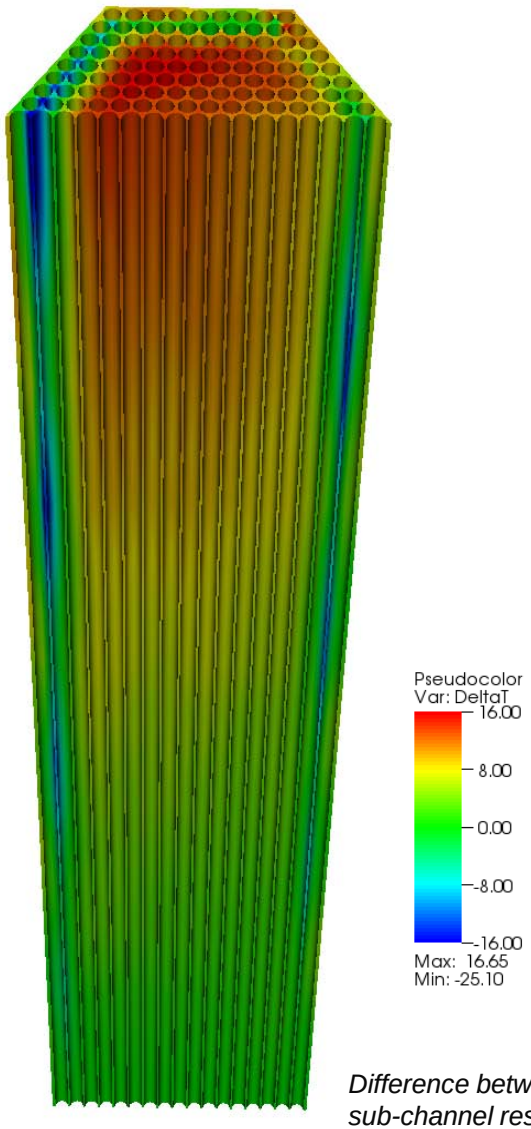
W.D. Pointer et al., *Simulations of Turbulent Diffusion in Wire-Wrapped Sodium Fast Reactor Fuel Assemblies, Best Paper Award*, FR09, Kyoto.

Key Findings: 1-D vs. 3-D pin bundle simulations

T. Fanning, D. Pointer, J. Smith - Argonne

- Comparison between sub-channel models and RANS simulations from Star-CD reveal multi-dimensionality of SFR fuel assembly flow
- 30 year old mystery explained?
  - Asymmetry observed in temperature distribution in EBR-II reactor experiments



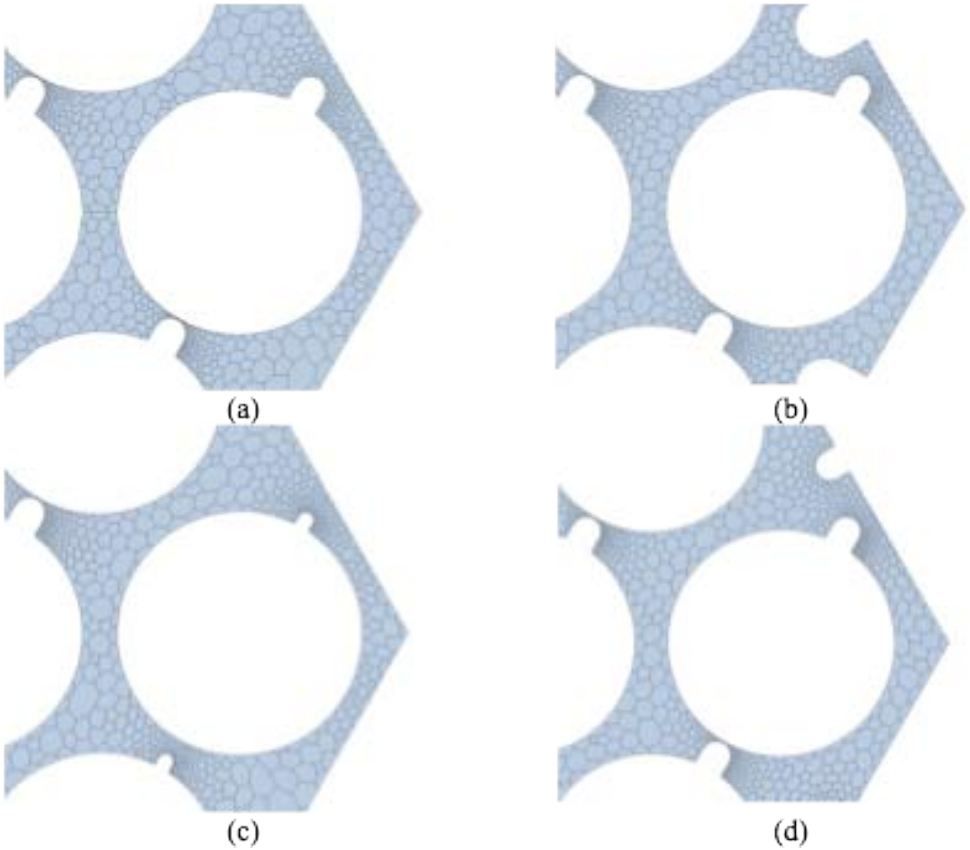


Difference between RANS, sub-channel results

Hydrodynamic Analysis of Can Wall Modifications

Jeff Smith and Dave Pointer, Argonne

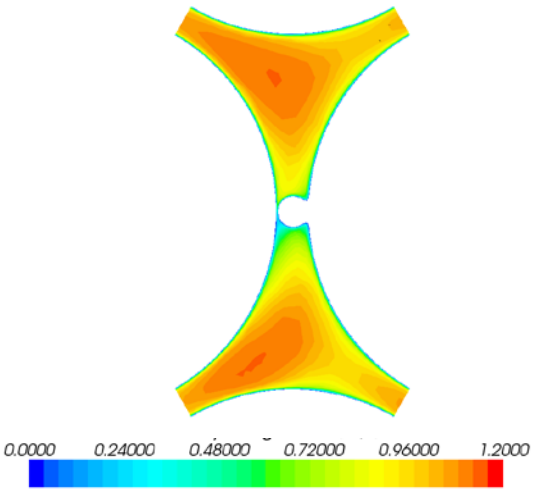
- Consider three modifications to the design of the can wall
  - reduce bypass flow in edge channels
  - reduce swirling flow in assembly
- (a) = nominal smooth can design
- (b) = large wire welded to can wall so that it provides a point of contact for the wire wrap
- (c) = reduced wire wrap diameter on edge row pins + reduced can cross section
- (d) = wire of the same diameter in edge channel

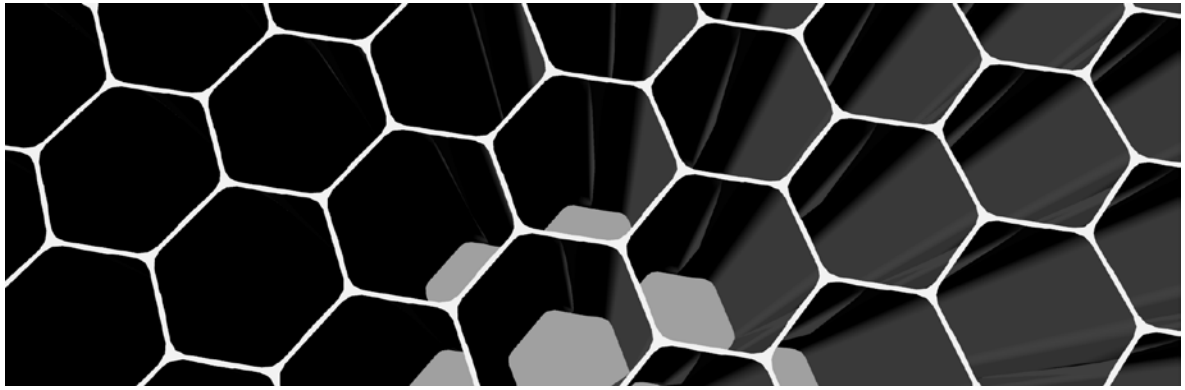


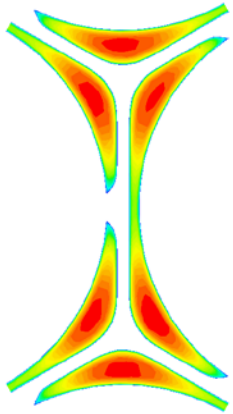
Hydrodynamic Analysis of Different Spacing Strategies for a Tight-Lattice SFR bundle

> Comparison between spacer grids and wire wrappers for P/D =1.08

> Spacers lead to considerably higher pressure losses (1.5 times the value of the wire-wrap case)







Identical mass flow rate.

E. Merzari, J. G. Smith and W.D. Pointer, “Hydrodynamic Analysis of Different Spacing Strategies for a Tight-Lattice SFR bundle,” 2010 ANS Winter Meeting, Las Vegas, NV.

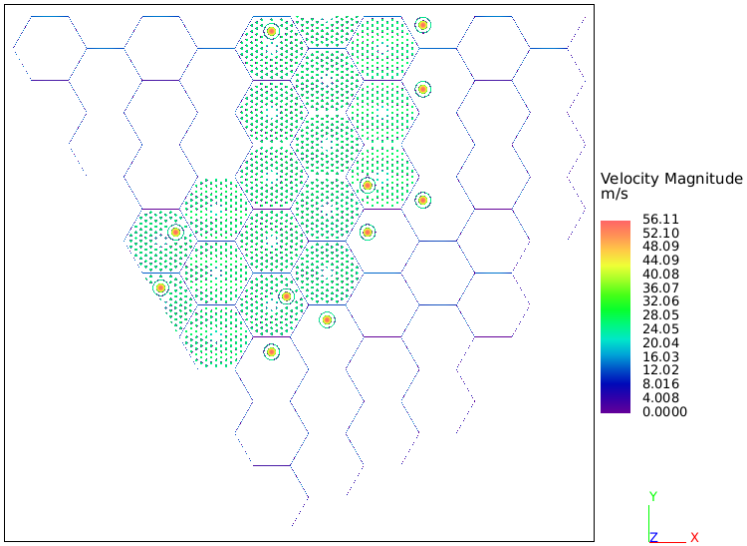
RANS Simulations of VHTR Prismatic Block Core

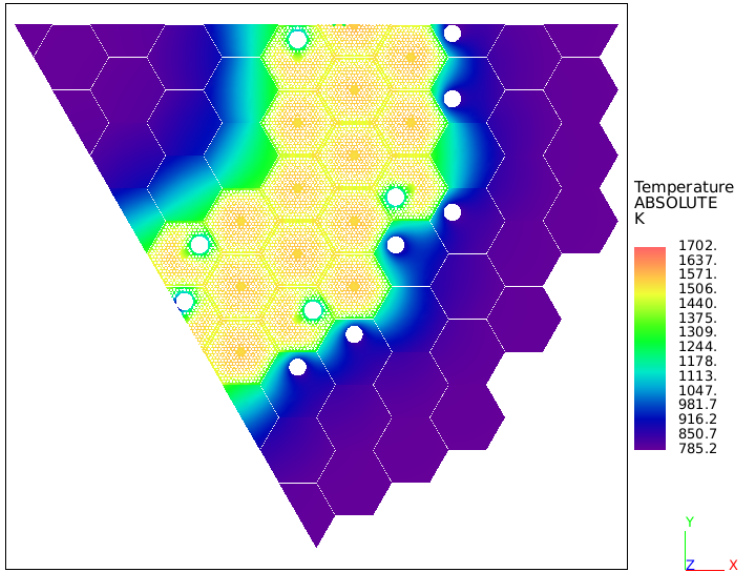
D. Pointer and J. Thomas

Predicted flow splits:

- 75% through coolant channels
- 25% through bypass: 10% between blocks, 15% in control rod holes

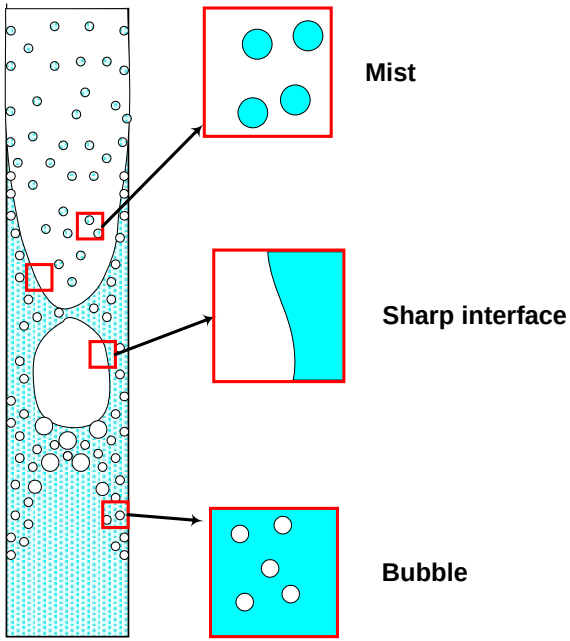
Bypass coolant flow paths impact predicted graphite temperatures





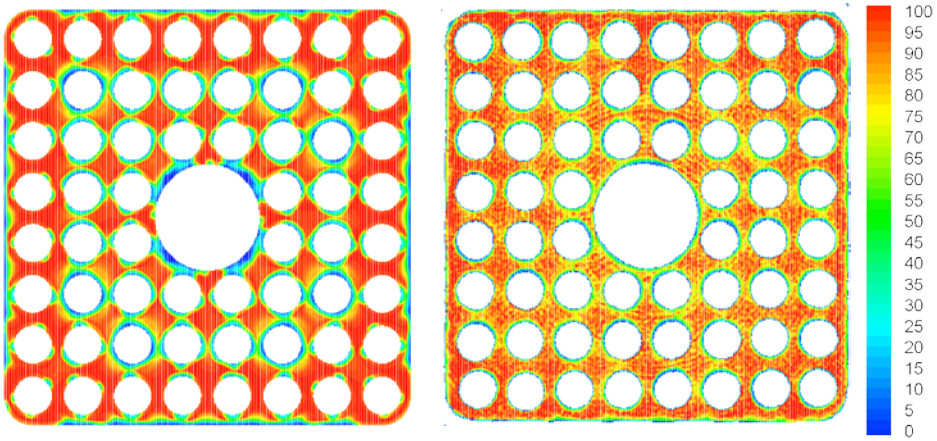
LWR Simulation Development

- Developing Eulerian-Eulerian 2-phase extended boiling framework (E2P) with CD-adapco
  - Initiated in STAR-CD v. 3.27
  - Now transitioning to STAR-CCM+
  - Provides three flow topologies which can be used to reconstruct flow regime map on a CFD cell by cell basis



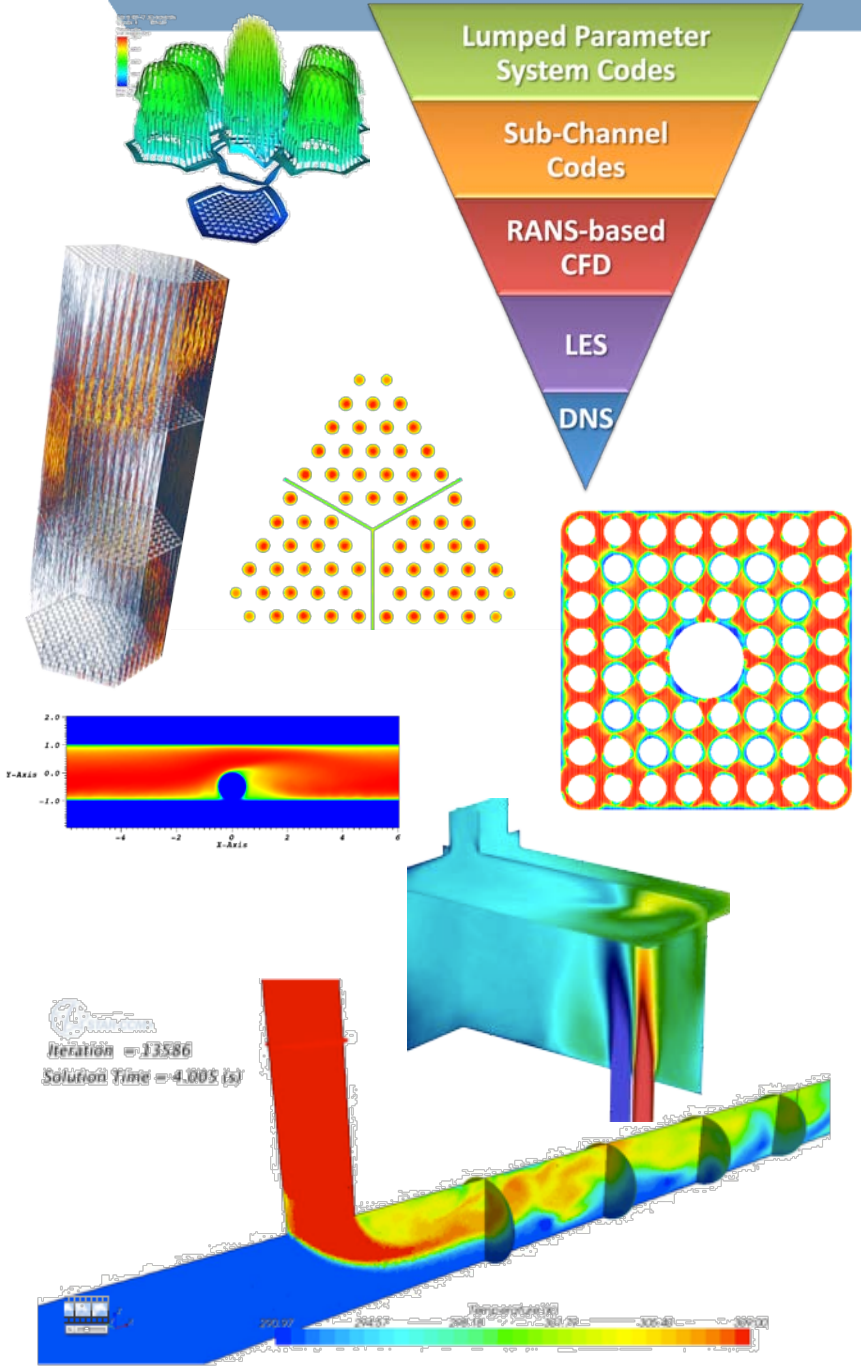
- Completed OECD/NRC full-size BWR assembly benchmark (BFBT)
  - Best agreement among CFD codes.
  - Used by participants to improve corrections applied to experimental data set for comparison to sub-channel codes

- Initiated participation in OECD/NRC PWR Sub-channel and Bundle Benchmark (PSBT)



predicted measured

Prediction of Exit Void Fraction Distribution in an Electrically Heated Full Size BWR Fuel Assembly Using Extended Boiling Framework Developed as an Extension of STAR-CD (OECD/NRC BFBT Benchmark)

NEAMS Reactor IPSC Proposed FY11 Effort

- Continue extension of capabilities of high fidelity DNS/LES code Nek5000
  - Implement reduced-order methods for acceleration of Nek5000 TH simulations
    - Unsteady RANS
    - Proper Orthogonal Decomposition
- Continue extension of SHARP framework to high-fidelity simulation of light water reactor (LWR) reactors
  - Demonstrate RANS-based 2-phase boiling CFD through participation in OECD/NRC PSBT benchmark
  - Continue implementation of level set and VOF methods for DNS/LES
- Continue VU and benchmarking efforts for SFR, VHTR and LWR
- Apply SHARP TH multi-resolution tool suite to fluid flow and conjugate heat transfer in a selected region of EBR-II core in support of a global simulation