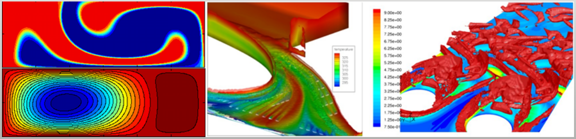
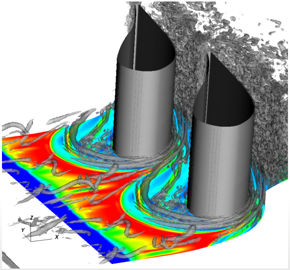
Using computers to go where fluid dynamics experiments cannot

Fluids, Turbulence and Fundamental Transport Lab
Mechanical Engineering, Texas A&M

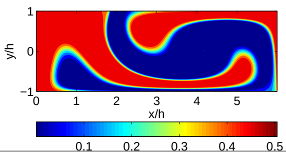
May 6, 2010



- Heat transfer analysis in internal turbine cooling



- Passive scalar separation using chaotic advection



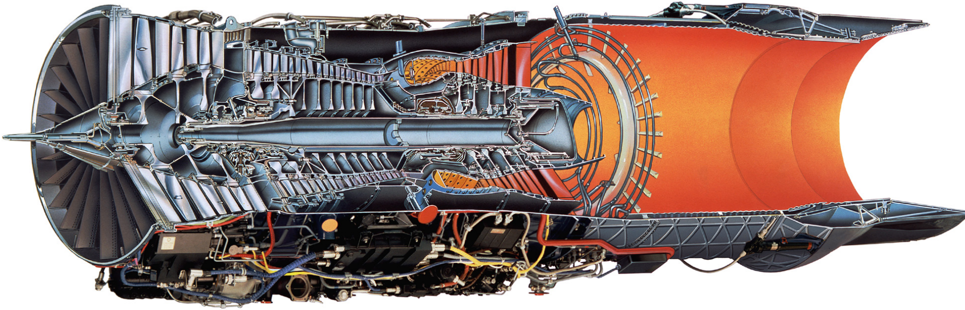
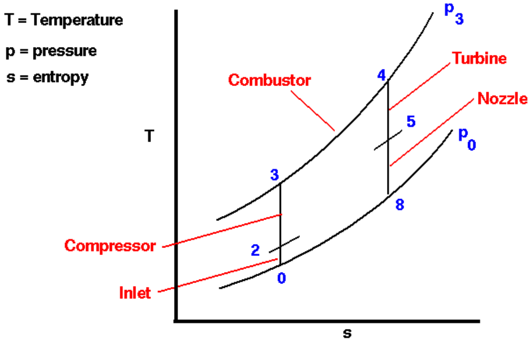


Figure: http://www.milnet.com/jeteng.htm



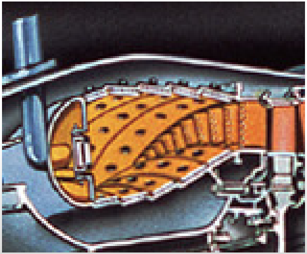


Figure: Brayton cycle http://grc.nasa.gov

Efficiency as a function of temperature ratio: $\eta_{cycle} = 1 - \frac{T_5}{T_4}$
Increase T_4, Limits: Metal melting temperature and part life

Transient hot spots can cause part failure

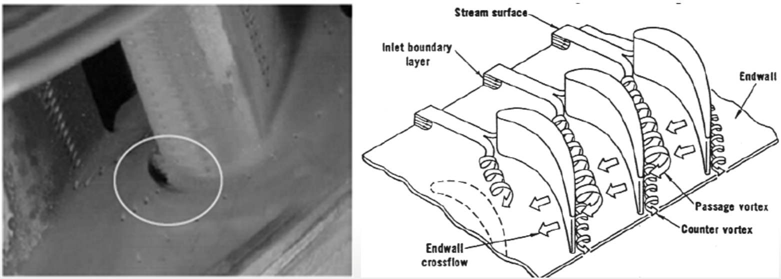


Figure: Turbine blade leading edge region, Right: from Langston (1980)

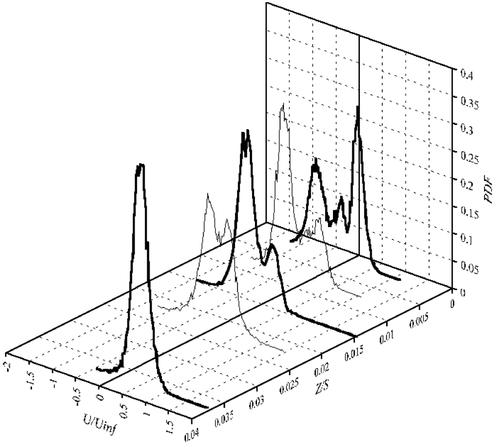


Figure: PDF measurements from Radomsky et al. (2000)

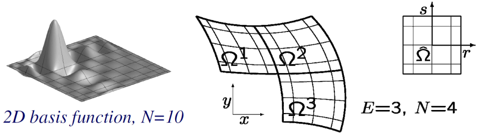
A highly resolved LES simulation is proposed

The large scales are solved on the grid while subgrid scales are modelled.

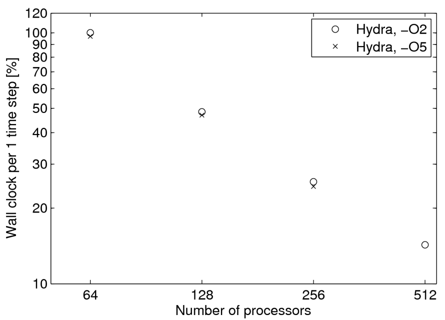
$$
\begin{aligned}
\nabla \cdot \mathbf{U} &= 0, & (1)\\
\partial_t \mathbf{U} + \mathbf{U} \cdot \nabla \mathbf{U} &= -\rho^{-1} \nabla P + \nabla \cdot \left(\left[\nu + \nu_t \right] \nabla \mathbf{U} \right), & (2)\\
\partial_t T + \mathbf{U} \cdot \nabla T &= \nabla \cdot \left(\left[\alpha + \alpha_t \right] \nabla T \right), & (3)
\end{aligned}
$$

- Initial estimates based on a steady RANS computation (Knost et al. 2009) at $Re_{Chord} \approx 150,000$:
  - 10^8 cells (for $x^+ \approx y^+ \approx z^+ \approx 50$)
  - 10^6 time steps per flow through (based on CFL)

- Highly scalable, open-source Spectral Element code

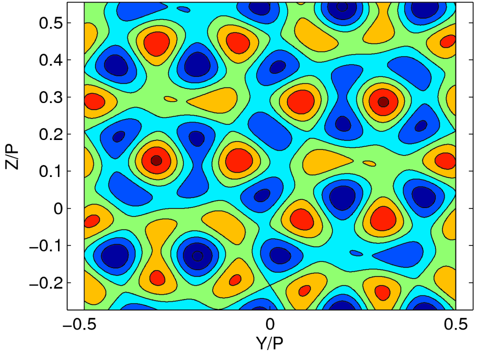


Fischer et al. 2007



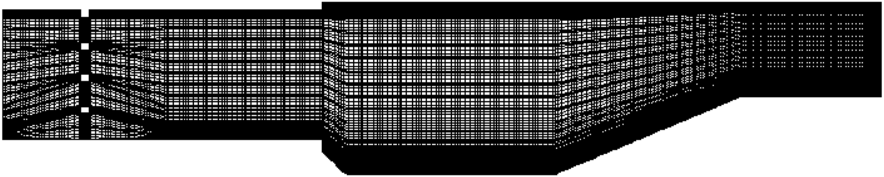
- Strong scaling for 7.8 mio grid points

Inflow boundary

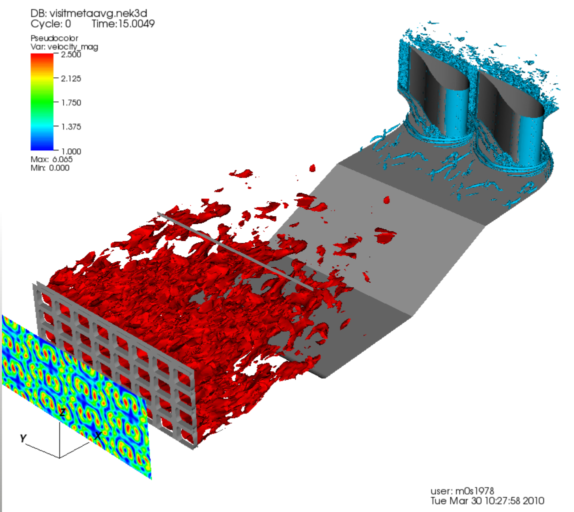


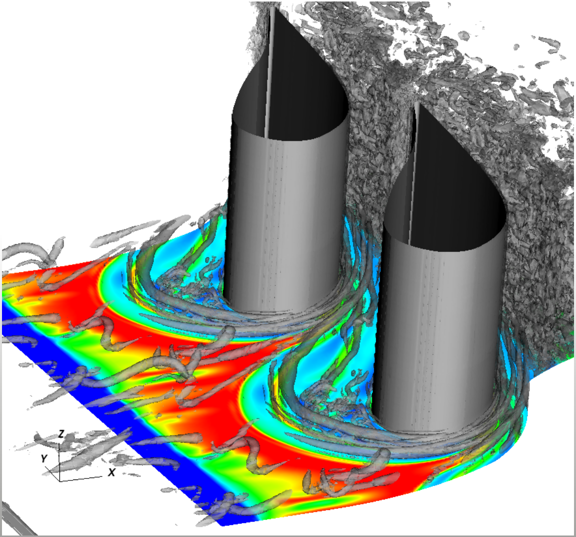
- 2D-periodic, divergence free solution of Navier-Stokes (Taylor vortices)

Side domain view

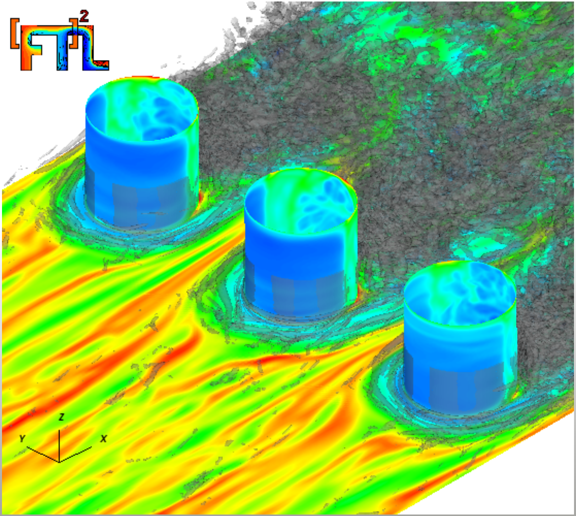


- Increased grid density near wall
- Length scale by grid spacing
- Freestream intensity by inflow vortex strength
- Boundary layer by slope and length of converging section

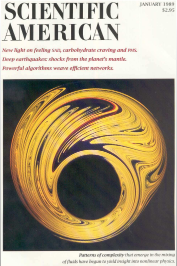

DB: visitmetaavg.nek3d
Cycle: 0 Time:15.0049
Pseudocolor
Var: velocity_mag
2.500
2.125
1.750
1.375
1.000
Max: 6.065
Min: 0.000
user: m0s1978
Tue Mar 30 10:27:58 2010


Z
Y
X

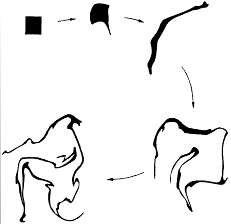
Preliminary results



- Exponential stretching of interface across which diffusion occurs
- Can be generated from simple flow fields.

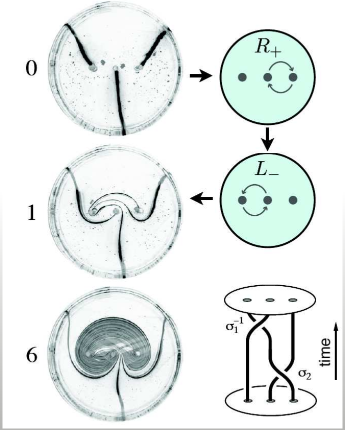


Source: Scientific American, January 1989



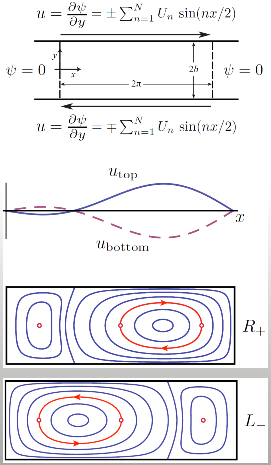
Source: P. Welander,"Studies of the general development of motion in a twodimensional, ideal fluid," Tellus 7, 141 1955.

Stirring in a braiding motion with physical rods



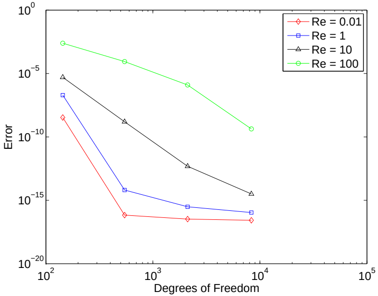
P. L. Boyland, H. Aref, and M. A. Stremler, "Topological fluid mechanics of stirring," J. Fluid Mech., 2000

Physical rods replaced by periodic orbits

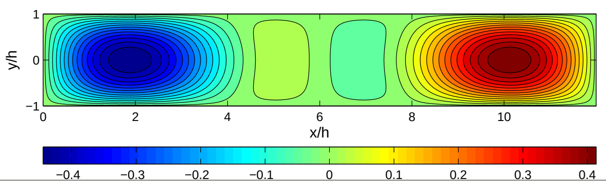


"Stirring with ghost rods in a lid-driven cavity," by Pankaj Kumar, Jie Chen, and Mark Stremler.

source: Roger Peyret, Spectral Methods for Incompressible Viscous Flow, 2002

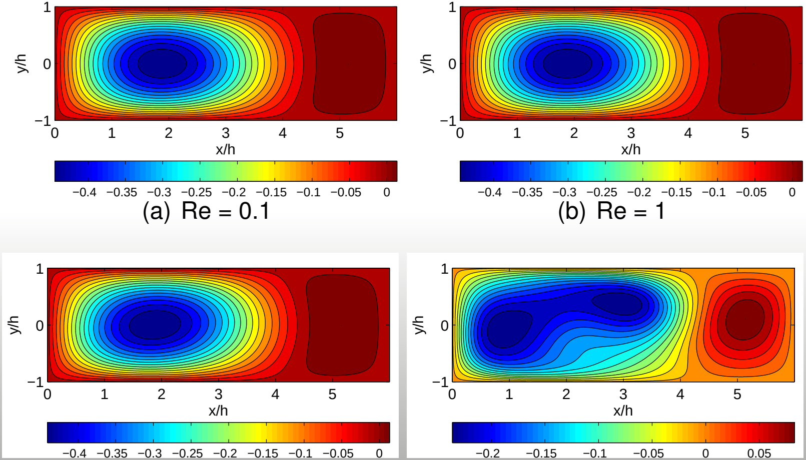


Convergence Plot for Stream Function, Re = $\frac{U_{max}h}{\nu}$



Contours of Stream Function

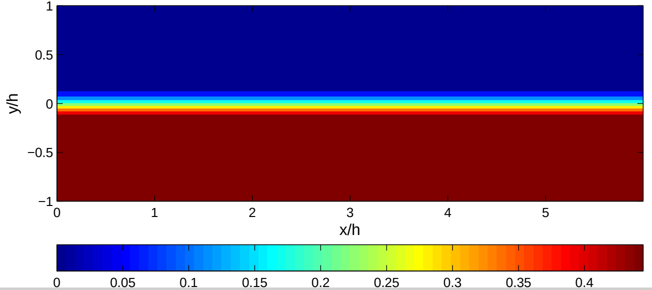
Contour Plots of Stream Function

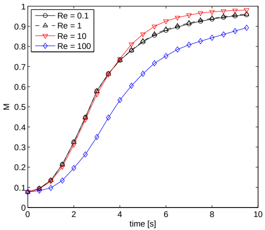


(a) Re = 0.1 (b) Re = 1

(c) Re = 10 (d) Re = 100

Mixing Index for Passive Scalar Transport

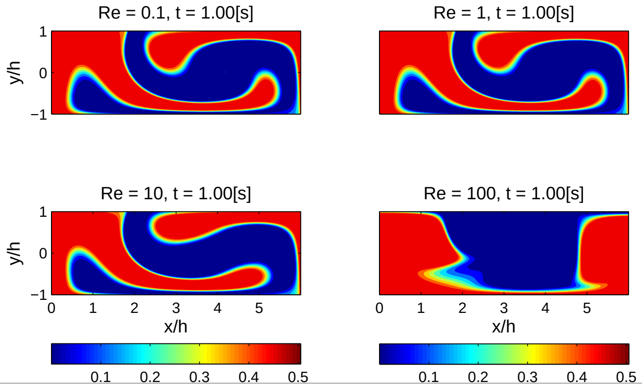




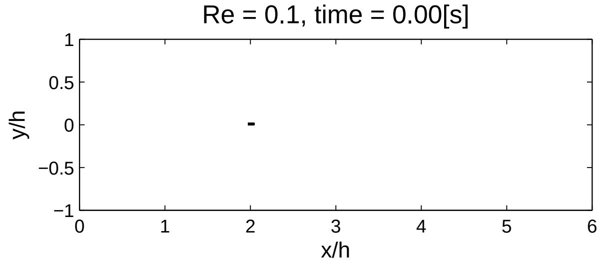
ReSc = 10,000

Mixing Index:

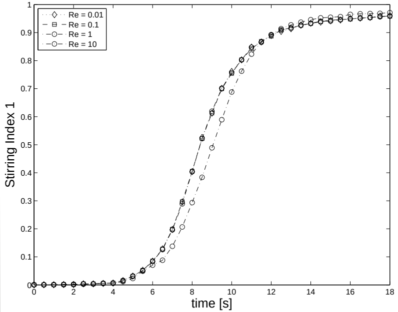
$$M = \frac{1}{N}\sum_{i=1}^{N}\frac{\theta_0 - |\theta_i - \theta_0|}{\theta_0}$$



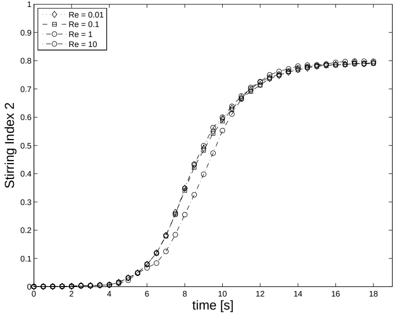
Dispersion of Particles



Stirring Index for Different Re Based on the Box Counting Method



(a) Stirring Index 1

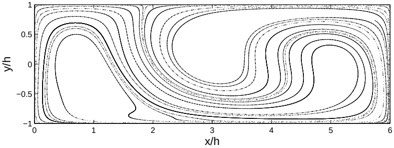


(b) Stirring Index 2

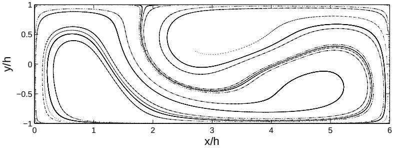
Stirring Index: $\epsilon = \frac{1}{K}\sum_{i=1}^{K}\omega_i$

$$\omega_i = \begin{cases} \frac{n_i}{n_{max}} & , \quad n_i < n_{max} \\ 1 & , \quad n_i \geq n_{max} \end{cases}$$

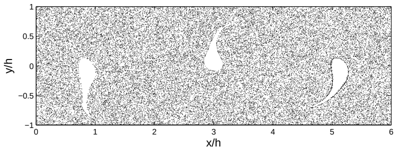
Comparison of Dispersion of Particles between Re = 0.1 and Re = 10



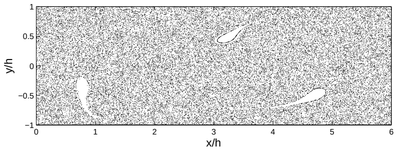
(a) Re = 0.1, 8 Advection Cycles



(b) Re = 10, 8 Advection Cycles

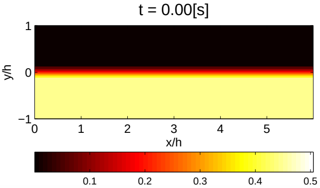


(c) Re = 0.1, 18 Advection Cycles

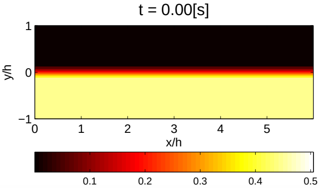


(d) Re = 10, 18 Advection Cycles

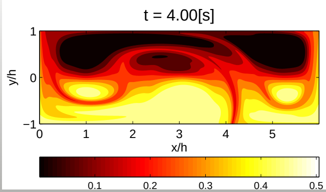
Separation of Substances with Close Diffusivities (Re=0.01, Sc=$\frac{\nu}{\overline{D}} = 10^6$, $\chi = \frac{D_1 - D_2}{\overline{D}} = 0.05$)



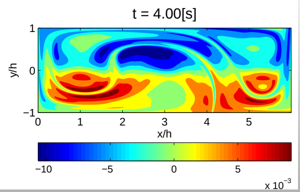
(a) Contours of θ_1



(b) Contours of θ_2

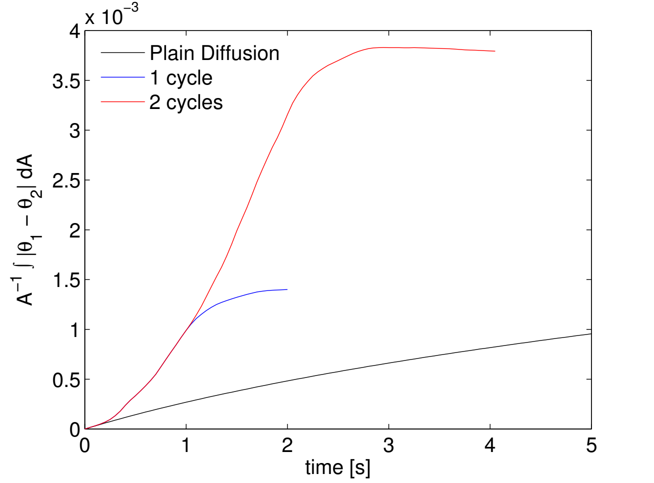


(c) Contours of θ_1 after unbraiding

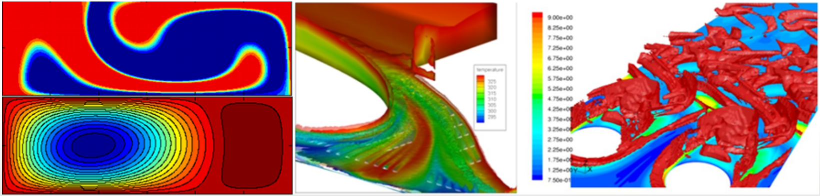


(d) Contours of $\theta_1 - \theta_2$

Chaotic Separation vs. diffusion



Using computers to go where fluid dynamics experiments cannot



Texas A&M Supercomputing Center has played an important role in this work.