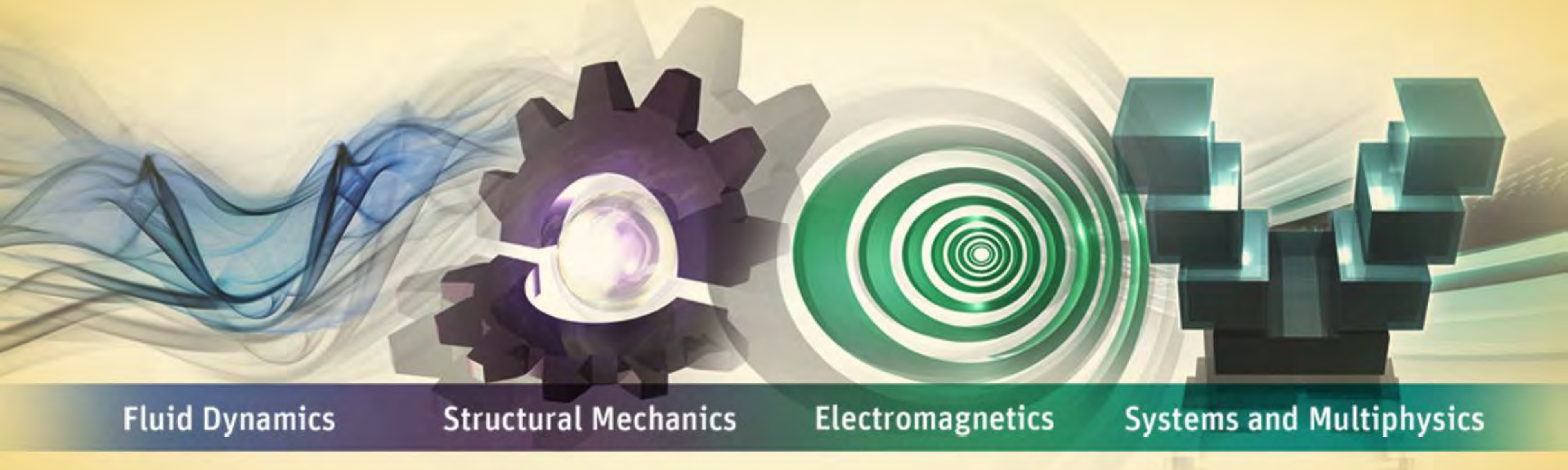
Realize Your Product Promise™

The Most Accurate and Advanced Turbulence Capabilities



Brian Bell

Presented at Confidence by Design Workshop, Minneapolis, MN

May 8, 2012

ANSYS

Agenda

- **Introduction to Turbulent Flow**
- **Steady State Turbulence Modeling**

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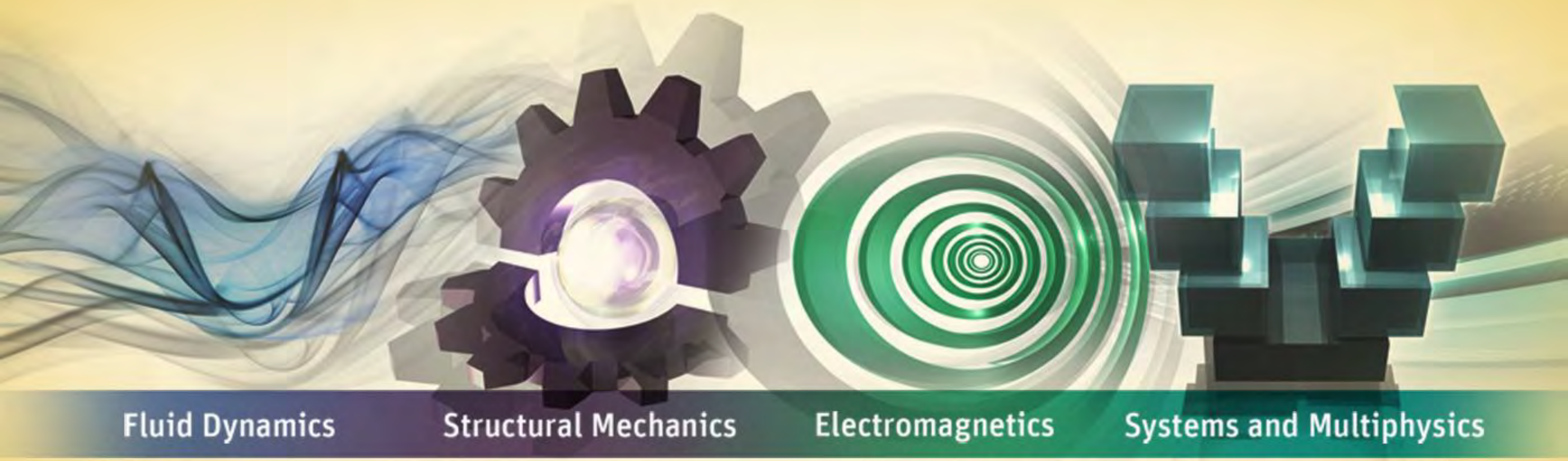
Introduction to Turbulent Flow



Characteristics of Turbulent Flows

- **Unsteady, irregular (aperiodic) motion in which transported quantities (mass, momentum, scalar species) fluctuate in time and space**
  - **The fluctuations are responsible for enhanced mixing of transported quantities**
- **Instantaneous fluctuations are random (unpredictable, irregular) both in space and time**
  - **Statistical averaging of fluctuations results in accountable, turbulence related transport mechanisms**
- **Contains a wide range of eddy sizes (scales)**
  - **Typical identifiable swirling patterns**
  - **Large eddies 'carry' small eddies**
  - **The behavior of large eddies is different in each flow**
    - Sensitive to upstream history
  - **The behavior of small eddies is more universal in nature**

Reynolds Number

- **The Reynolds number is defined as**

$$\mathrm{Re}_L = \frac{\rho U L}{\mu}$$

where U and L are representative velocity and length scales for a given flow. $L = x, d, d_h$, *etc*.

- **Turbulent flows occur at large Reynolds numbers**

External Flows

$\mathrm{Re}_x \geq 500{,}000$ along a surface

$\mathrm{Re}_d \geq 20{,}000$ around an obstacle

Internal Flows

$\mathrm{Re}_{d_h} \geq 2{,}300$

Other factors such as free-stream turbulence, surface conditions, blowing, suction, and other disturbances *etc.* may cause transition to turbulence at lower Reynolds numbers

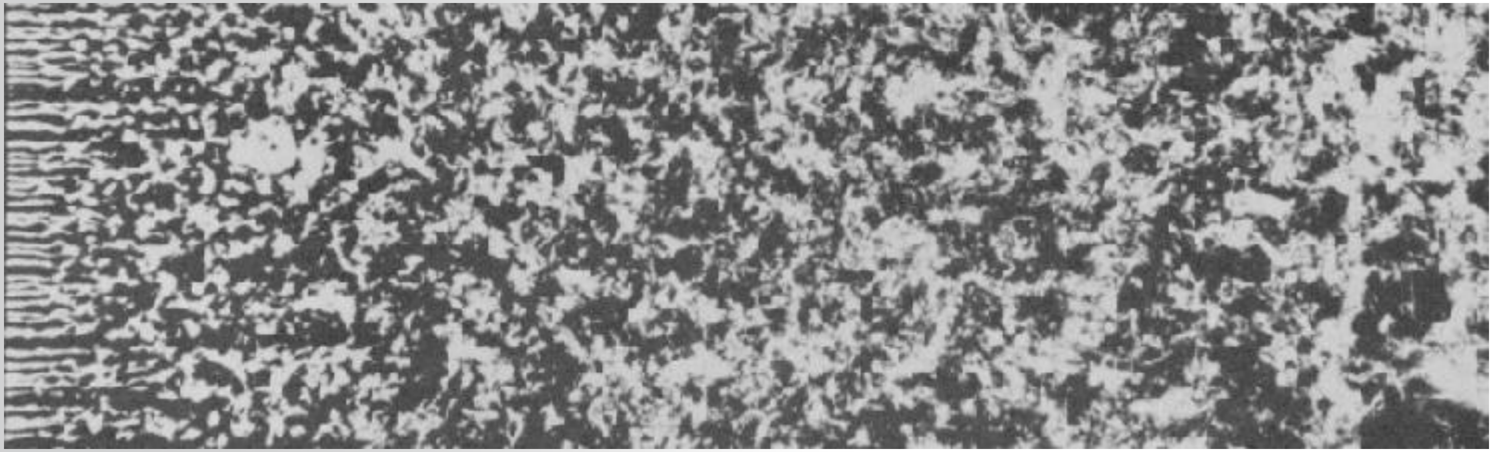
Natural Convection

$$\mathrm{Ra} = \frac{\beta g L^3 \Delta T}{\nu \alpha} = \frac{\rho^2 c_p \beta g L^3 \Delta T}{\mu k}$$ (Rayleigh number)

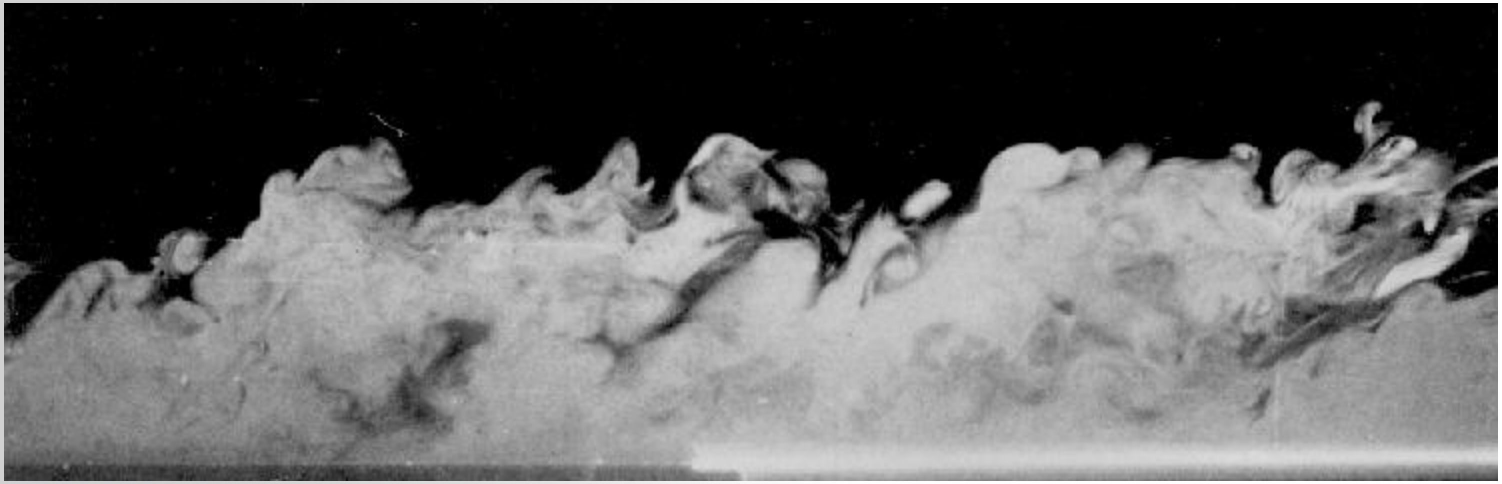
$$\frac{\mathrm{Ra}}{\mathrm{Pr}} \geq 10^9$$ where $$\mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\mu c_p}{k}$$ (Prandtl number)

Two Examples of Turbulence

Homogeneous, decaying, grid-generated turbulence



Turbulent boundary layer on a flat plate



Energy Cascade

- Larger, higher-energy eddies, transfer energy to smaller eddies via vortex stretching
  - Larger eddies derive energy from mean flow
  - Large eddy size and velocity on order of mean flow
- Smallest eddies convert kinetic energy into thermal energy via viscous dissipation
  - Rate at which energy is dissipated is set by rate at which they receive energy from the larger eddies at start of cascade

Smallest Scales of Turbulence

- **Smallest eddy --- the Kolmogorov scales:**
  - **large eddy energy supply rate is balanced by the small eddy energy dissipation rate $\rightarrow \varepsilon = -dk/dt$**
    - $k \equiv \frac{1}{2}(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})$ **is (specific) turbulent kinetic energy [L² / T²]**
    - ε **is dissipation rate of k [L² / T³]**
  - **Motion at smallest scales dependent upon dissipation rate, ε, and kinematic viscosity, ν [L² / T]**
  - **From dimensional analysis, the Kolmogorov scales can be estimated as follows:**

length scale	time scale	velocity scale
$\eta = (\nu^3 / \varepsilon)^{1/4}$;	$\tau = (\nu / \varepsilon)^{1/2}$;	$V = (\nu\varepsilon)^{1/4}$

Small scales *vs* Large scales

- **Largest eddy scales:**
  - Assume $\boldsymbol{l}$ is a characteristic size of a larger eddy.
  - Dimensional analysis is sufficient to estimate the order of large eddy supply rate for $\boldsymbol{k}$ as: $\boldsymbol{k} / \tau_{turnover}$.
  - The order of $\tau_{turnover}$ can be estimated as $\boldsymbol{l} / \boldsymbol{k}^{1/2}$ (i.e., $\tau_{turnover}$ is a time scale associated with the larger eddies).
  - Since $\boldsymbol{\varepsilon} \sim \boldsymbol{k} / \tau_{turnover}$, $\boldsymbol{\varepsilon} \sim \boldsymbol{k}^{3/2} / \boldsymbol{l}$ or $\boldsymbol{l} \sim \boldsymbol{k}^{3/2} / \boldsymbol{\varepsilon}$.
- **Comparing $\boldsymbol{l}$ with $\boldsymbol{\eta}$:**

$$\frac{\boldsymbol{l}}{\boldsymbol{\eta}} = \frac{\boldsymbol{l}}{(\boldsymbol{\nu}^3 / \boldsymbol{\varepsilon})^{1/4}} \approx \frac{\boldsymbol{l}(\boldsymbol{k}^{3/2} / \boldsymbol{l})^{1/4}}{\boldsymbol{\nu}^{3/4}} \approx \mathrm{Re}_T{}^{3/4} \Rightarrow \frac{\boldsymbol{l}}{\boldsymbol{\eta}} >> 1$$

  - where $\mathrm{Re}_T = \boldsymbol{k}^{1/2} \boldsymbol{l} / \boldsymbol{\nu}$ (turbulence Reynolds number)

Implication of Scales

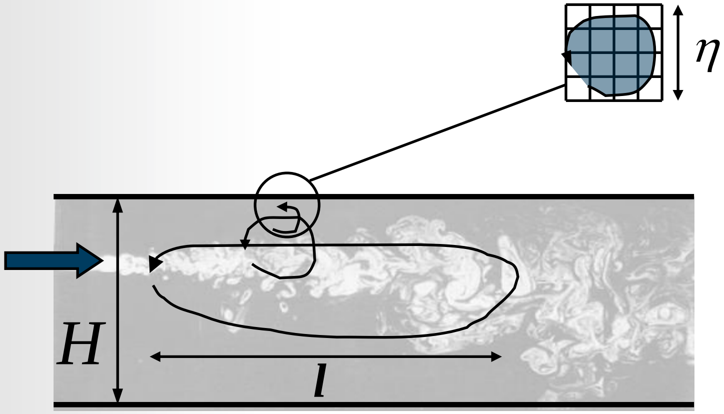
- Consider a mesh fine enough to resolve smallest eddies and large enough to capture mean flow features
- Example: 2D channel flow
- $N_{cells} \sim (4\,l/\eta)^3$

  or

  $N_{cells} \sim (3\mathrm{Re}_\tau)^{9/4}$

  where

  $\mathrm{Re}_\tau = u_\tau H / 2\nu$
- $\mathrm{Re}_H = 30{,}800 \rightarrow \mathrm{Re}_\tau = 800 \rightarrow N_{cells} = 4\mathrm{x}10^7$!



$$\frac{l}{\eta} \approx \frac{l}{(\nu^3/\varepsilon)^{1/4}}$$

Direct Numerical Simulation

- **"DNS" is the solution of the time-dependent Navier-Stokes equations without recourse to modeling**

$$\rho\left(\frac{\partial U_i}{\partial t}+U_k\frac{\partial U_i}{\partial x_k}\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_k}\left(\mu\frac{\partial U_i}{\partial x_j}\right)$$

- Numerical time step size required, $\Delta t \sim \tau$
  - For 2D channel example
    - Re_H = 30,800
    - Number of time steps ~ 48,000

$$\Delta t_{2D\,Channel} \approx \frac{0.003H}{\sqrt{\mathrm{Re}_\tau}\,u_\tau}$$

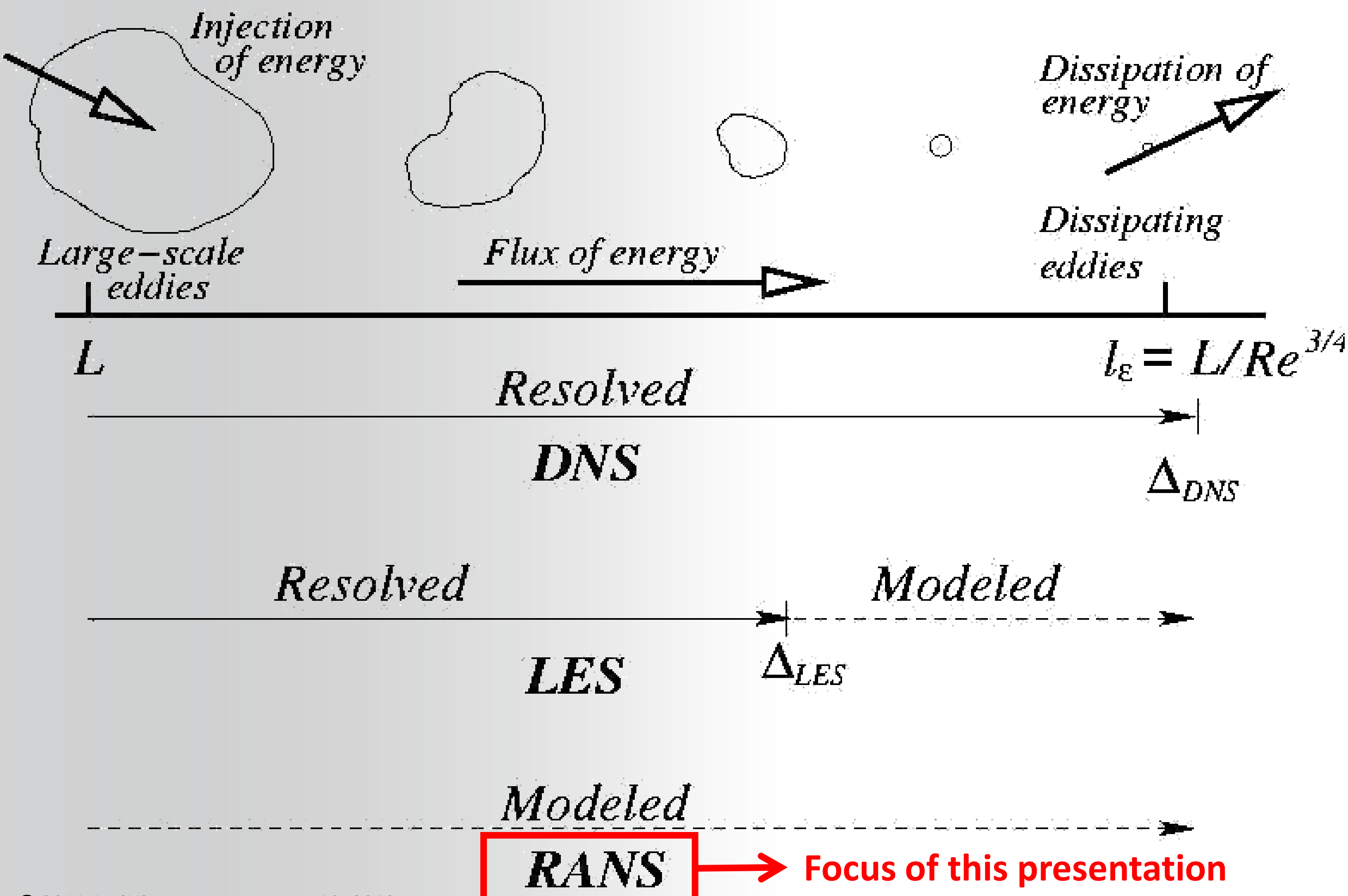
- DNS is not suitable for practical industrial CFD
  - DNS is feasible only for simple geometries and low turbulent Reynolds numbers
  - DNS is a useful research tool

Removing the Small Scales

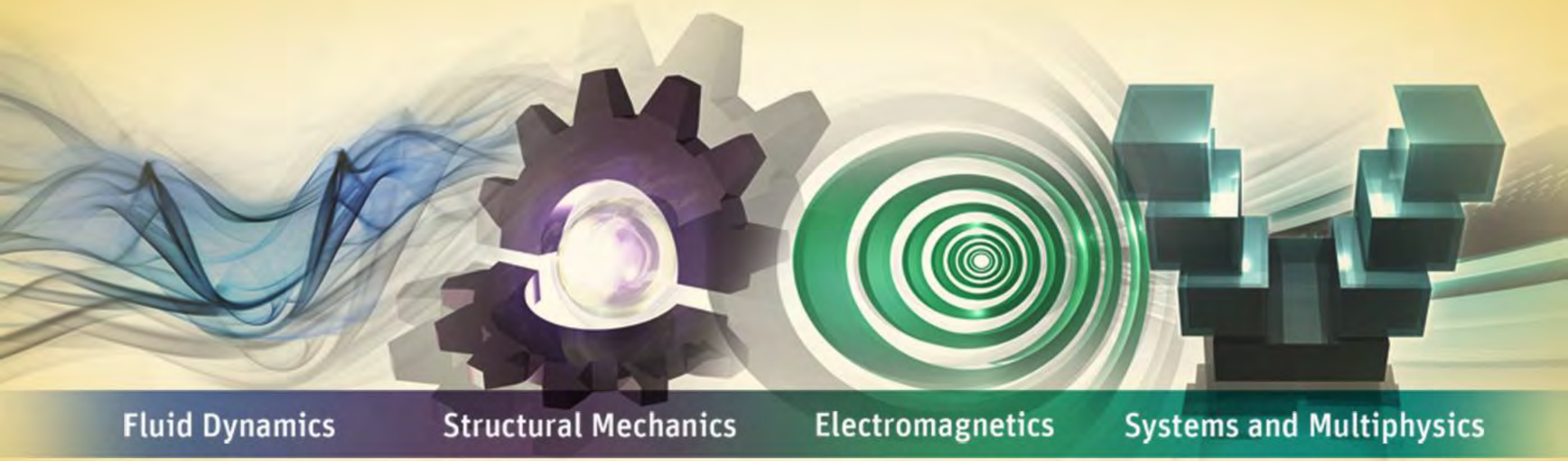
- **Two methods can be used to eliminate need to resolve small scales:**
  - Reynolds Averaging
    - Transport equations for mean flow quantities are solved
    - All scales of turbulence are modeled
    - Transient solution Δt is set by global unsteadiness
  - Filtering (LES)
    - Transport equations for 'resolvable scales'
    - Resolves larger eddies; models smaller ones
    - Inherently unsteady, Δt dictated by smallest resolved eddies

- **Both methods introduce additional terms that must be modeled for closure**

Prediction Methods



Steady State Turbulence Modeling



Overview

- **The Role of Steady State (RANS) Turbulence Modeling**
- **Overview of Reynolds-Averaged Navier Stokes (RANS) Modeling Capabilities in ANSYS CFD**
  - Model overview
  - Wall treatment
  - Model extensions and other interesting new features

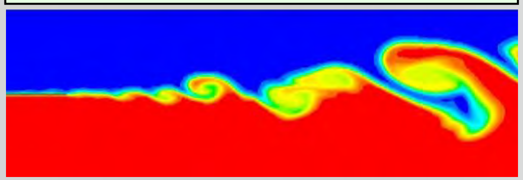
Motivation for Steady State Turbulence Modeling

- **The majority of all flows of engineering interest are turbulent**
- **The motion of eddies in a turbulent flow is inherently unsteady and three-dimensional**
  - Even if the flow is steady in a mean flow sense
- **Steady state simulations are preferred for many engineering applications because they are easier**
  - Shorter simulation time
  - Simplified post-processing
  - In many cases, only time-averaged values are of interest
- **Turbulence models that allow steady state simulations to be performed for turbulent flows are therefore desirable and important**

Turbulent Flow Simulation Methods

DNS

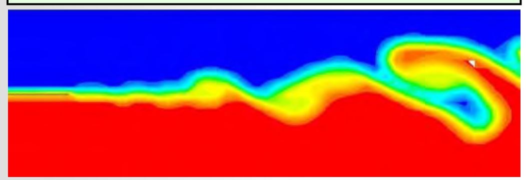
(Direct Numerical Simulation)



- Numerically solving the full unsteady Navier-Stokes equations
- No modeling is required
- A research tool only– far too much information for industrial applications

SRS

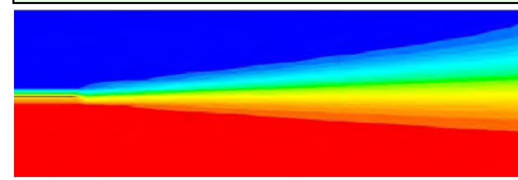
(Scale Resolving Simulations)



- Includes Large Eddy Simulation (LES)
- The motion of the largest eddies is directly resolved in the calculation, in at least a portion of the domain, but eddies smaller than the mesh are modeled
- Inherently unsteady method

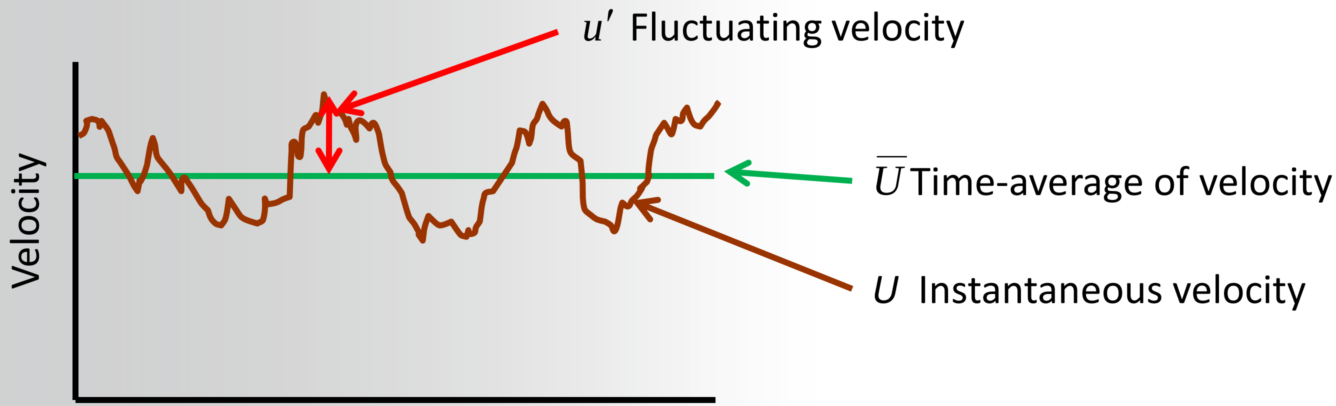
RANS

(Reynolds Averaged Navier-Stokes Simulations)



- Solve Reynolds-averaged Navier-Stokes equations (time-average)
- Steady state solutions are possible
- All turbulence is modeled. Larger eddies are not resolved
- RANS turbulence models are the only modeling approach for steady state simulation of turbulent flows
- This is the most widely used approach for industrial flows

RANS Models – Definition



- **In other words,** $\mathrm{U}(\vec{\mathrm{x}},\mathrm{t}) = \overline{\mathrm{U}}(\vec{\mathrm{x}}) + \mathrm{u}'(\vec{\mathrm{x}})$
- **We can apply the same time averaging procedure to the governing equations, which gives us the Reynolds-Averaged Navier-Stokes (RANS) equations**

Reynolds stress tensor, R_{ij}

$$\frac{\partial\left(\rho\overline{u}_i\right)}{\partial t} + \frac{\partial\left(\rho\overline{u}_i\overline{u}_j\right)}{\partial x_j} = -\frac{\partial\overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial\overline{u}_i}{\partial x_j} + \frac{\partial\overline{u}_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial\overline{u}_m}{\partial x_m}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i'u_j'}\right)$$

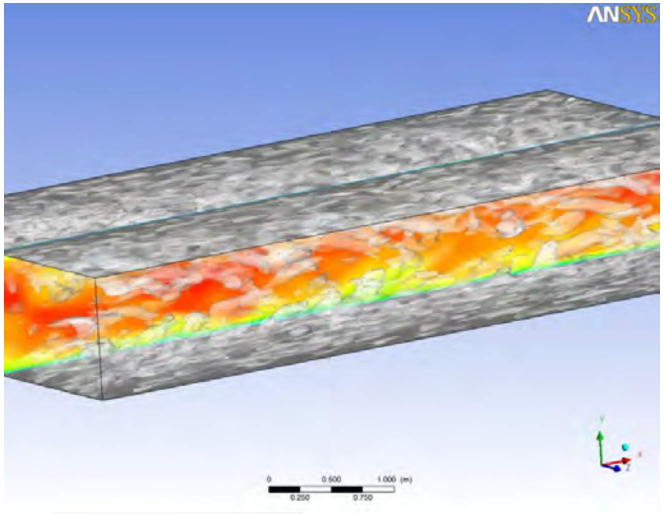
- **RANS turbulence models provide closure for the Reynolds stress tensor, which represents the effect of turbulent fluctuations on the mean flow.** ***This allows us to perform steady state simulations of turbulent flow.***

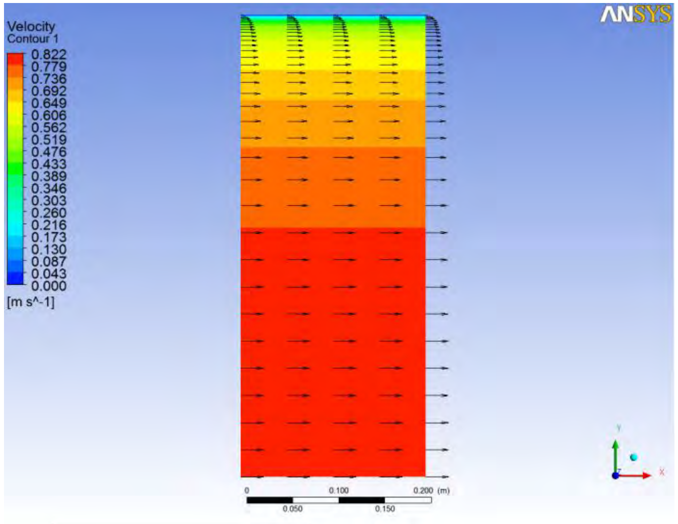
Comparison of SRS and RANS

- **RANS**
  - Advantages: For many applications, steady state solutions are preferable, and for many applications a good RANS model with a good quality grid will provide all the required accuracy
  - Disadvantages: For some flows, challenges associated with RANS modeling can limit the level of accuracy that it is possible to attain
- **SRS**
  - Advantages: Potential for improved accuracy when the resolution of the largest eddies is important or when unsteady data is needed
  - Disadvantages: computationally expensive
    - Higher grid resolution required
    - Unsteady simulation with small time steps generates long run times and large volumes of data

Computational Expense: SRS vs. RANS in Wall-Bounded Flow

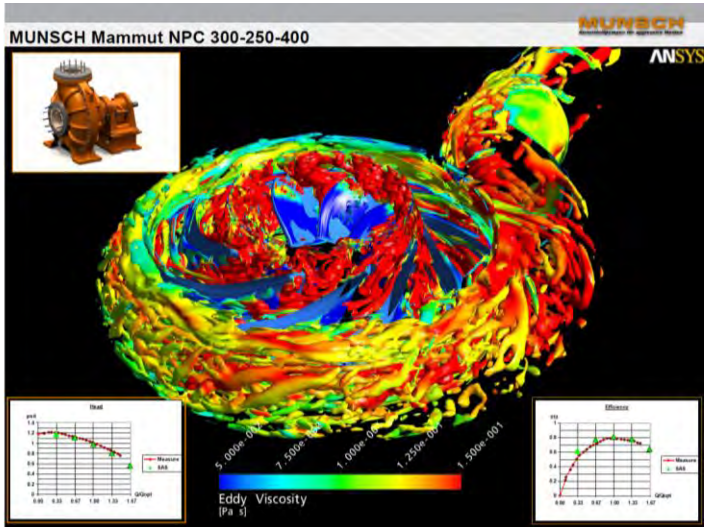
- **Example: Channel flow at Re = 114,000**
  - Boundary layer thickness, δ, equal to channel half-width
- **Top: WMLES**
  - 1.2 million cells, transient calculation, run time is order of days
- **Below: RANS**
  - 140 cells, steady calculation, run time is order of minutes
- **Important**
  - For wall-bounded flows, in a more typical 3D industrial geometry, RANS would still be 2 orders of magnitude fewer cells and run times of hours versus days.



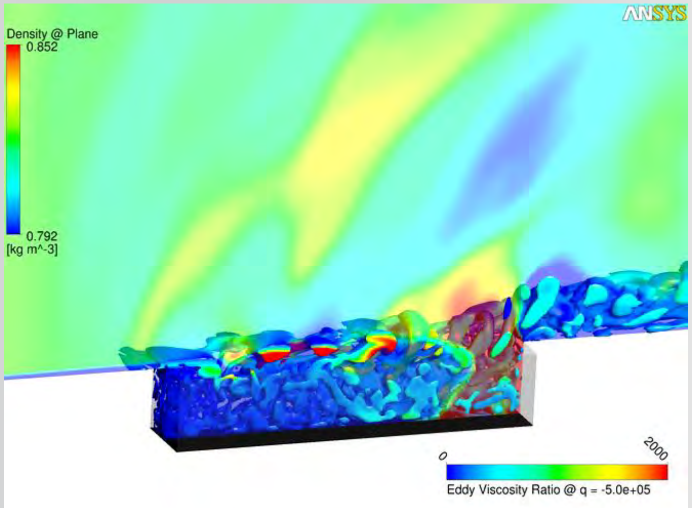


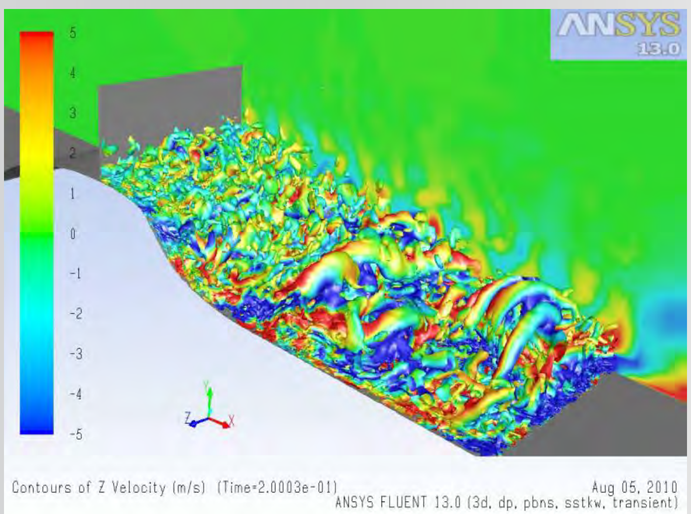
Motivation for Scale-Resolving Simulations (SRS)

- Accuracy Improvements over RANS
  - Flows with large separation zones (stalled airfoils/wings, flow past buildings, flows with swirl instabilities, etc.)
- Additional information required
  - Acoustics - Information on acoustic spectrum not reliable from RANS
  - Vortex cavitation – low pressure inside vortex causes cavitation – resolution of vortex required
  - Fluid-Structure Interaction (FSI) – unsteady forces determine frequency response of solid.



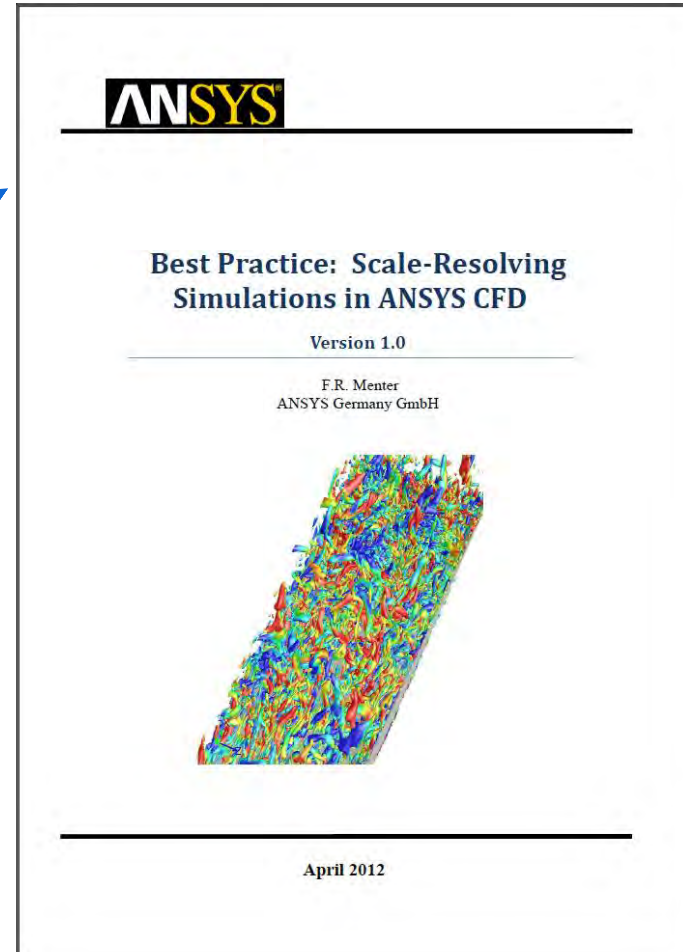
SRS Models in ANYS CFD





- **Scale-Adaptive Simulation (SAS) models**
  - SAS-SST model (Fluent, CFX)
- **Detached Eddy Simulation (DES) models**
  - DES-SST (Fluent, CFX), DES-Spalart-Allmaras and DES-Realizable k-ε (Fluent)
- **Large Eddy Simulation (LES)**
  - Smagorinsky-Lilly (+ dynamic) (Fluent, CFX)
  - WALE model (Fluent, CFX)
  - Algebraic Wall Modeled LES (WMLES) (Fluent,CFX)
  - Dynamic kinetic energy subgrid model (Fluent)
- **Embedded LES (ELES) model**
  - Combination of all RANS modes with all non-dynamic LES models (Fluent)
  - Zonal forcing model (CFX)
- **Synthetic turbulence generator**
  - Harmonic Turbulence Generator (HTG) (CFX)
  - Vortex method (Fluent)

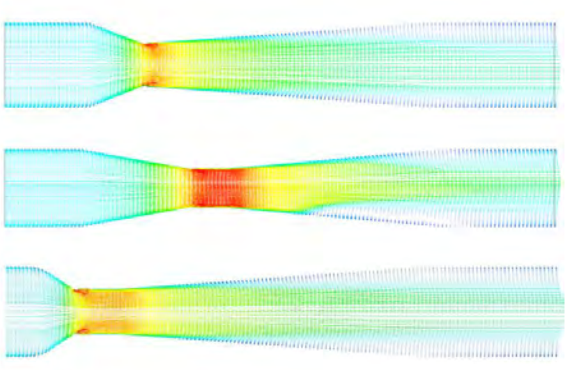
Best Practices for SRS

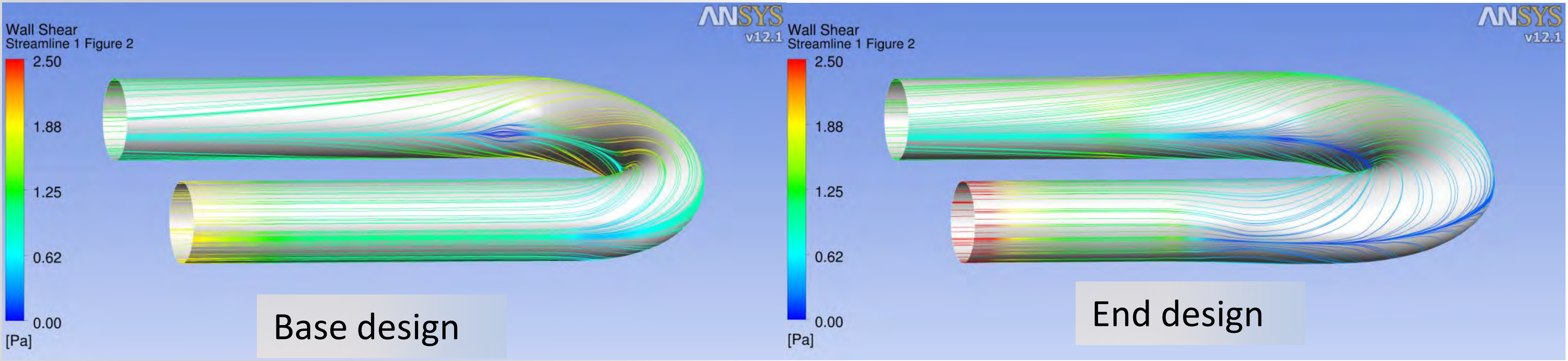


- **Best practices document written by Florian Menter**
  - Everything you want to know about SRS in ANSYS

Steady RANS

- **Steady state RANS calculations will remain an important modeling practice for years to come**
  - Model the entire system versus modeling the component
  - Increase the number of simulated design points in optimization/parametric studies
- **Providing state-of-the-art RANS modeling capabilities remains an important focus of ANSYS development**



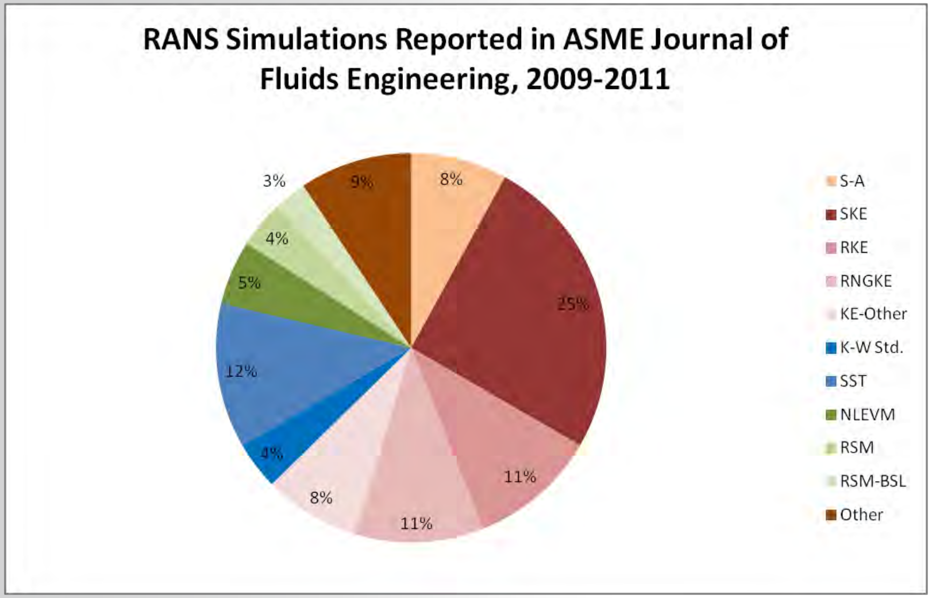


Example: Optimization study achieves 1/3 reduction in pressure drop in u-bend over 30 different design iterations

RANS Capabilities in ANSYS CFD

- **Models and Boundary treatments**
- **Model Extensions**

What RANS Models are People Using?



- **Informal survey of single phase RANS model usage based on papers published in the Journal of Fluids Engineering during 2009 – 2011**
- **The CFD user community requires a broad range of models to choose from in order to meet its needs**
  - Over 2/3 of all simulations reported using some variation of 1 or 2 equation model (S-A, k-ε family, k-ω family)
  - In some applications, one model may be more dominant than others (example: aerodynamics & SST, cyclones & RSM), but for a broad range of applications, a variety of models is needed to match the appropriate model to the appropriate application

Steady RANS Turbulence Models in ANSYS

- **A wide array of models is available for steady state calculations**
  - Includes all commonly used models in the (CFD world)
  - Includes useful extensions to the models such as curvature correction and EARSM
  - Important to be able to ensure whatever the application, you can choose the most suitable model

One-Equation Models

Spalart-Allmaras

$(k\text{-}\varepsilon)_{1E}$

Two-Equation Models

k–ε (Standard, Realizable, RNG)

k–ω (Standard, SST)

Curvature Correction (all 1 & 2 eqn. models)

V2F (4 eqn.)*

Explicit Algebraic Reynolds Stress Model (EARSM)

Reynolds Stress Models

Launder-Reece-Rodi, Speziale-Sarkar-Gatski

Stress-ω

k–kl–ω Transition Model

SST Transition Model

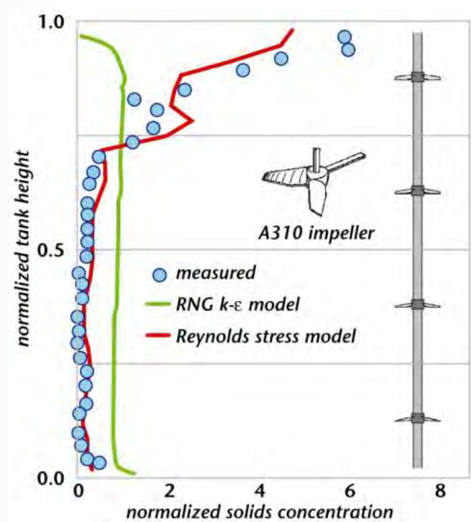
* additional license required

ANSYS

ANSYS Models

- **It is not enough just to provide many choices**
- **More importantly, for the models that are available, emphasis is placed on**
  - Correct implementation
    - Models should be well understood and tested
  - Accurate and validated for some class(es) of applications
  - Robust performance on all mesh topologies
  - Interoperability with other physical models, e.g. multiphase, dynamic mesh, ….
  - Wall treatment

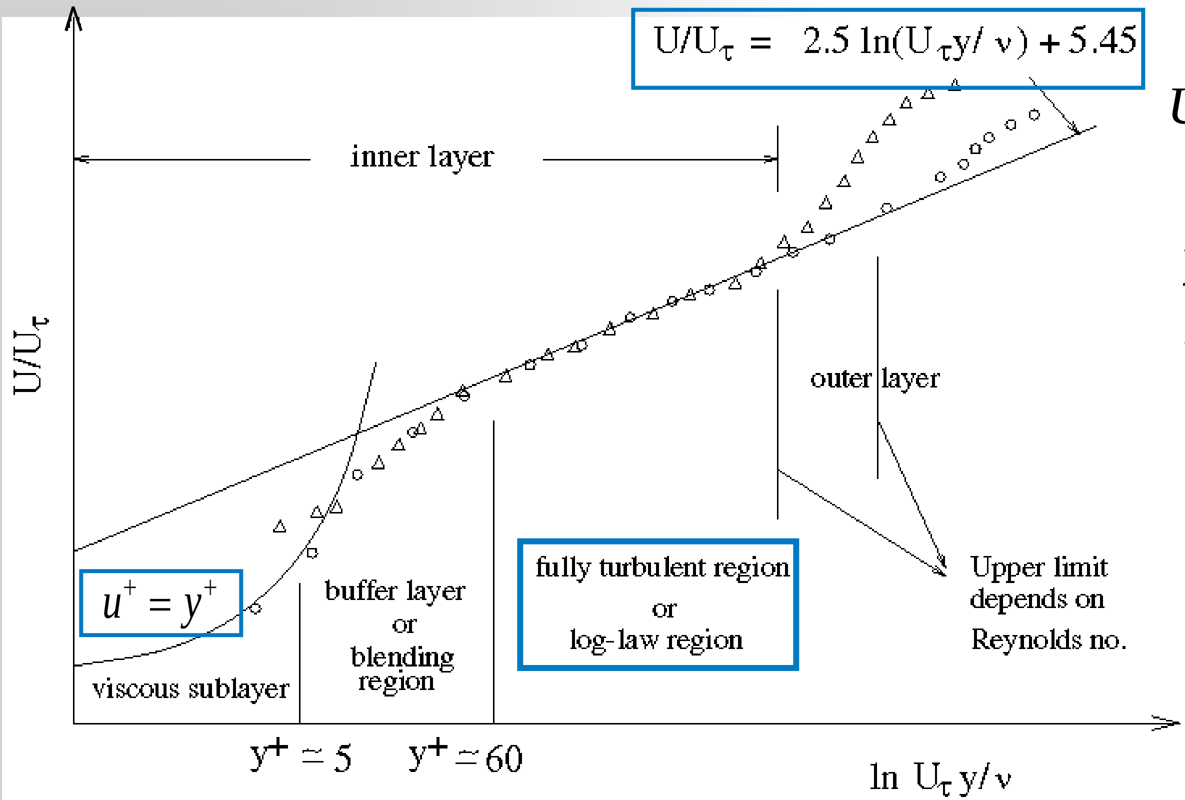
Example: Solids suspension in a tall, unbaffled tank. Reynolds stress model together with Eulerian granular multiphase model



Courtesy of the University of Bologna

Near Wall Turbulence and the Law of the Wall

- The law of the wall describes the relationship between the velocity profile and wall shear in turbulent boundary layers
- Close to the wall, in the inner part of the boundary layer, with the appropriate normalization, there is a universal velocity profile
- This universal behavior forms the basis for near wall modeling in RANS



$$U_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

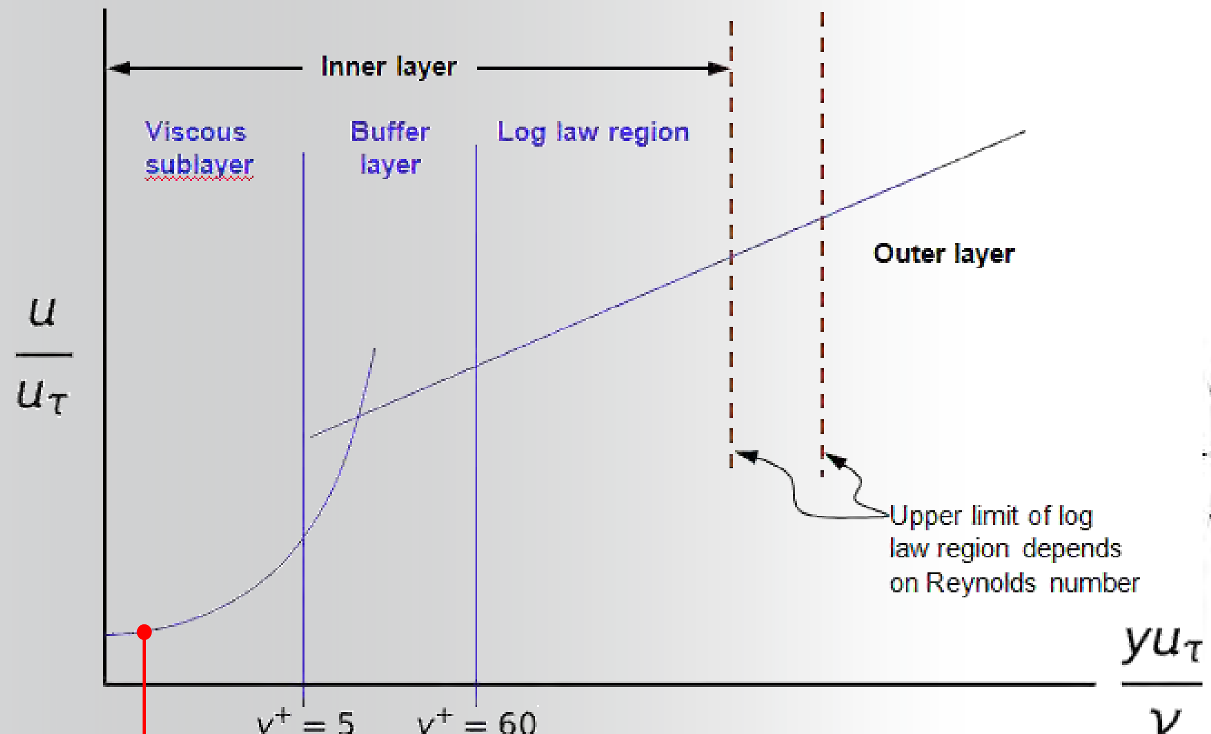
Wall shear stress

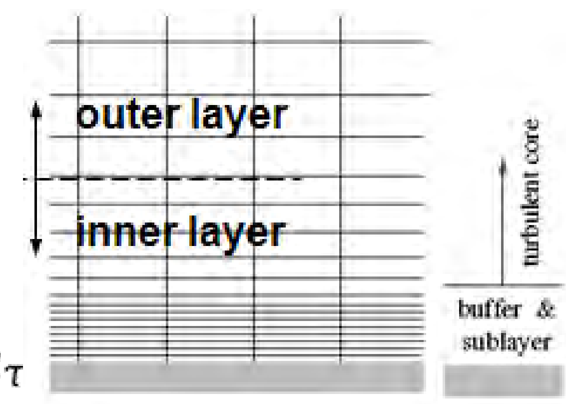
$$y^+ = \frac{yU_\tau}{\nu} \qquad u^+ = \frac{u}{U_\tau}$$

where *y* is the normal distance from the wall

Viscous Sublayer Modeling Approach

- **Used in cases where meshes that resolve the viscous sublayer can be afforded or are absolutely necessary (flow separation, laminar-turbulent transition, heat transfer…)**

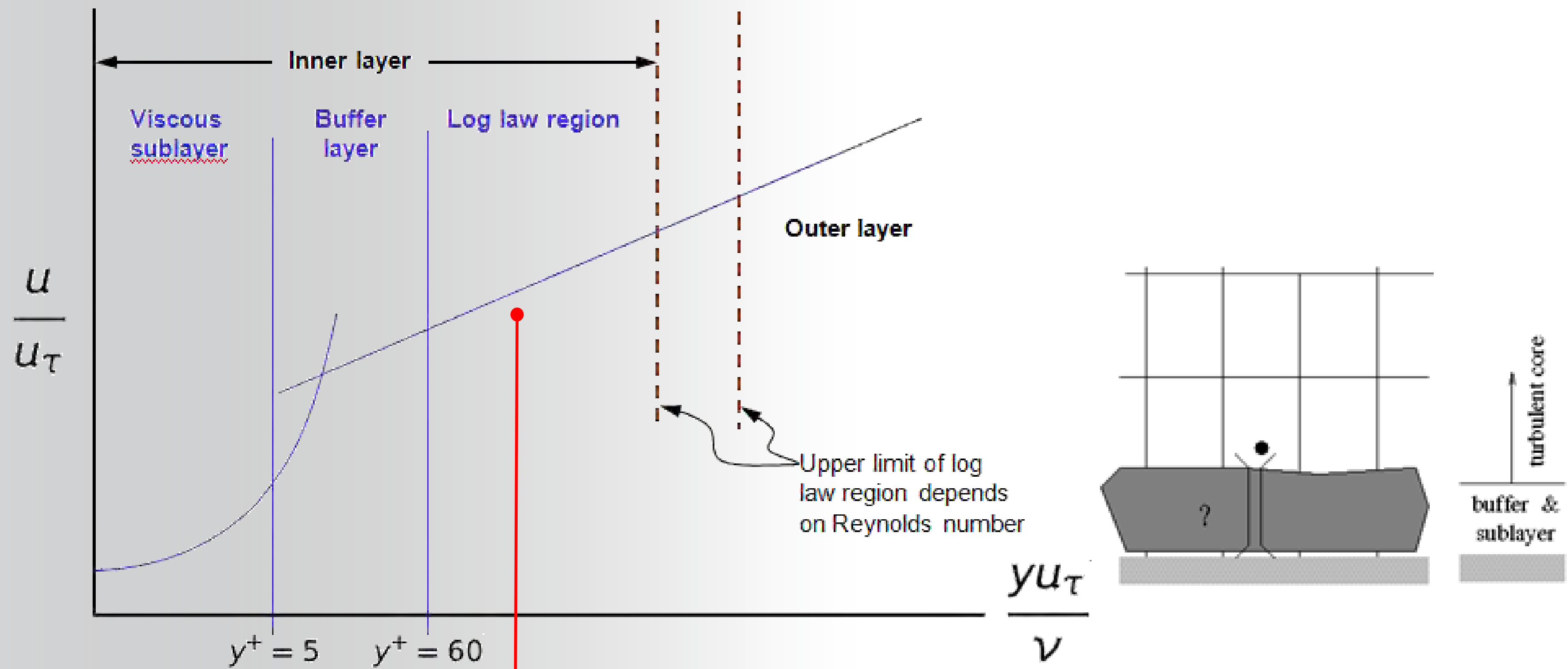




1st cell centroid at $y^+ \sim 1$

Wall Function Modeling Approach

- **Cases where high near-wall resolution is unaffordable. Wall functions bridge the gap between the wall and the log region where the first cell centroid is located**



1st cell centroid at 30 < y^+ < 300

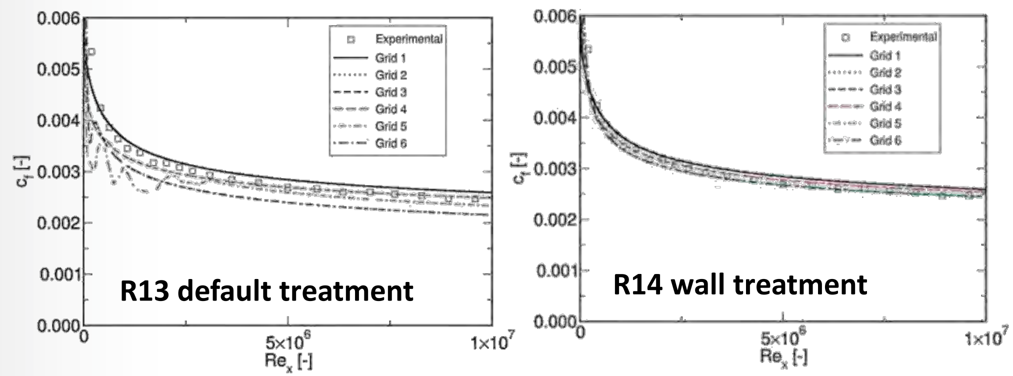
The Importance of Mesh Insensitive Wall Treatment

- In practice, maintaining a prescribed value of y+ in wall-adjacent cells throughout the domain for industrial cases is challenging
- Maintaining a value of y+ > 30 when using wall functions under cases of grid refinement can be especially problematic
- Grid refinement can be a critical component of achieving a grid-independent solution, which is a universally accepted CFD best practice. Therefore wall treatments that are insensitive to y^+ values as the mesh is refined are critical for RANS models in industrial CFD

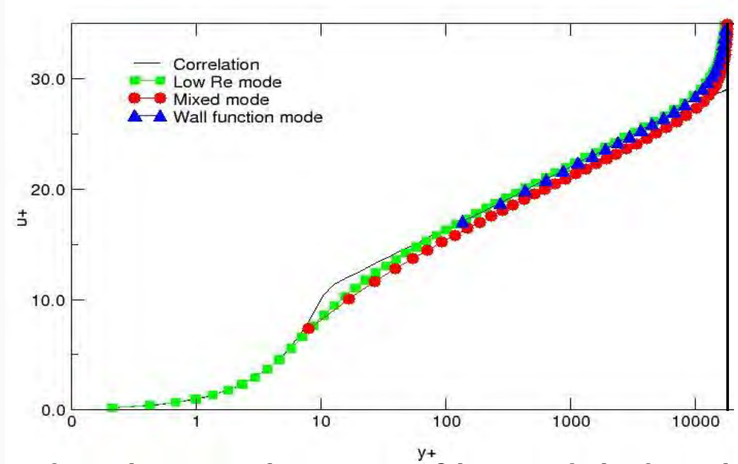
ANSYS

Y^+ Insensitive Treatments in ANSYS CFD

- **Y^+ insensitive wall modeling treatments are available for all RANS models in ANSYS CFD**
- **New enhanced wall treatment for Spalart-Allmaras model in R14**
- **Enhanced wall treatment and scalable wall functions for k-ε family of models**
- **Automatic wall treatment for SST and k-ω models**



Sensitivity of the skin friction coefficient to mesh density in an incompressible flat boundary layer modeled with Spalart-Allmaras



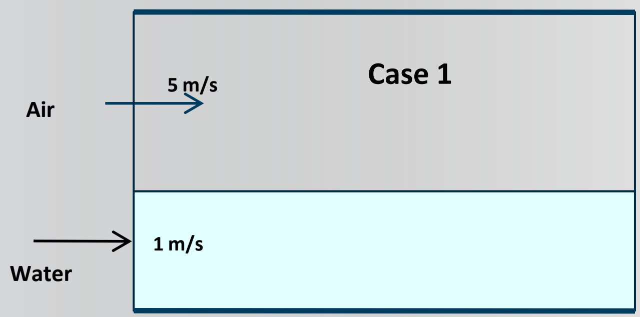
Boundary layer velocity profile modeled with standard k-ε for three different mesh densities using Enhanced Wall Treatment

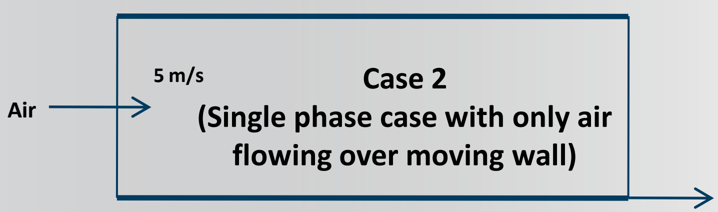
RANS Model Extensions

- Turbulence Damping at Free Surface
- Wall Functions at Boundary of Porous Medium
- Curvature Correction for all 1- and 2-Equation Models
- Explicit Algebraic Reynolds Stress Model (EARSM)

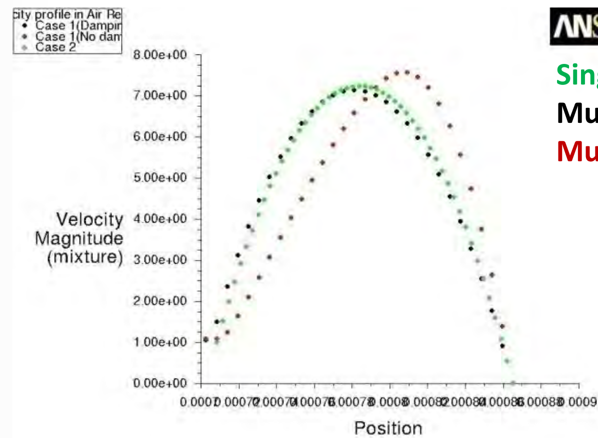
Turbulence Damping for Free Surface Flows

Special turbulence treatment available for SST and k-w models accurately represents the effect of the free surface on turbulence, allowing accurate calculation of the velocity profile



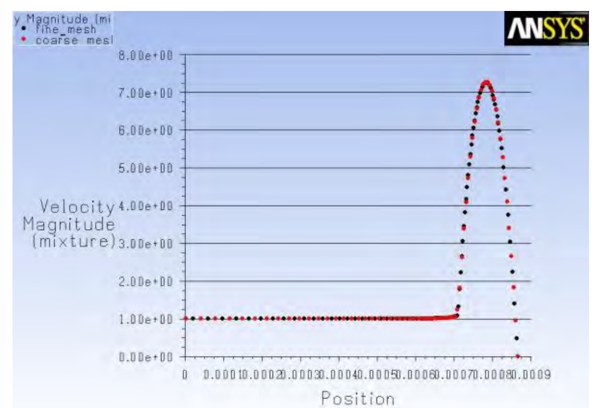


Wall Velocity = 1 m/s



Single phase
Multiphase + damping
Multiphase + No damping

Velocity profile in air region



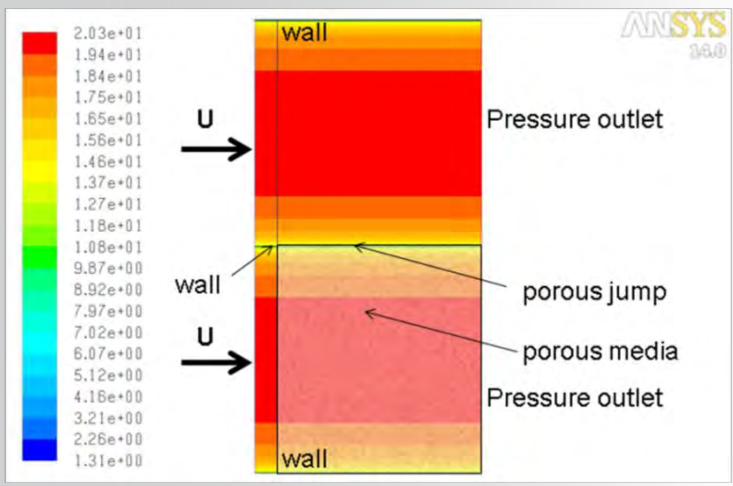
Fine mesh : 77520 cells

Coarse mesh: 19380 cells

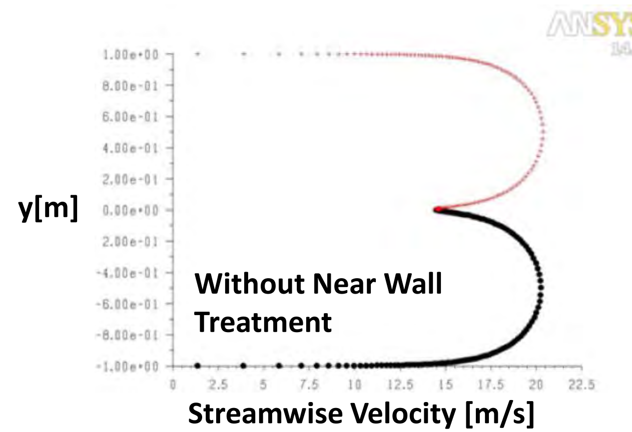
Fine mesh vs Coarse mesh with turbulence damping

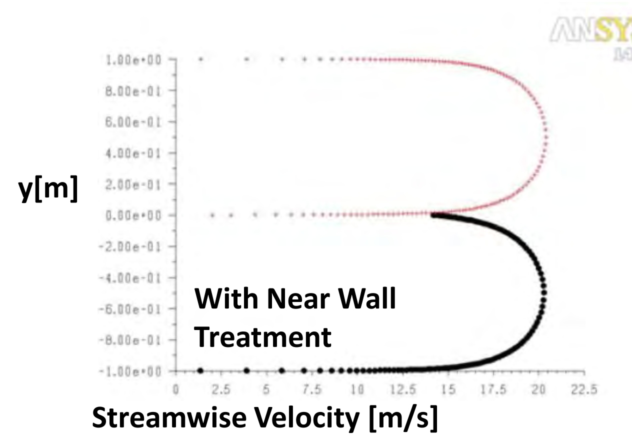
Turbulent Near Wall Treatment at Porous Medium Interface

- **Improved accuracy for turbulence near porous jump interfaces (FLUENT beta feature)**
  - Use wall functions to include the effects of solid porous material on the near-wall turbulent flow on the fluid side of porous jump interfaces



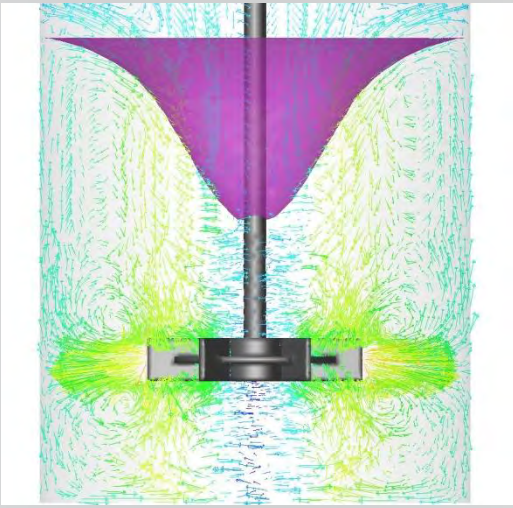
Contours of velocity showing the impact of a porous jump on velocity in bordering cells

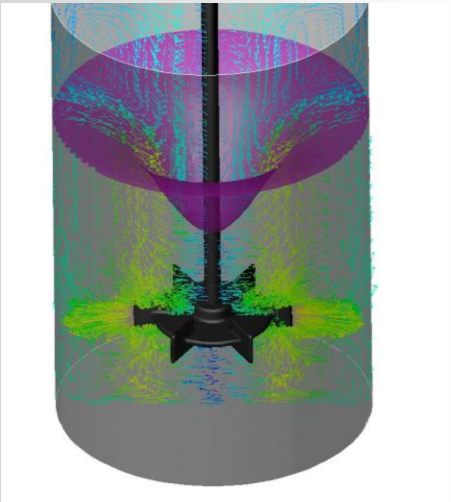


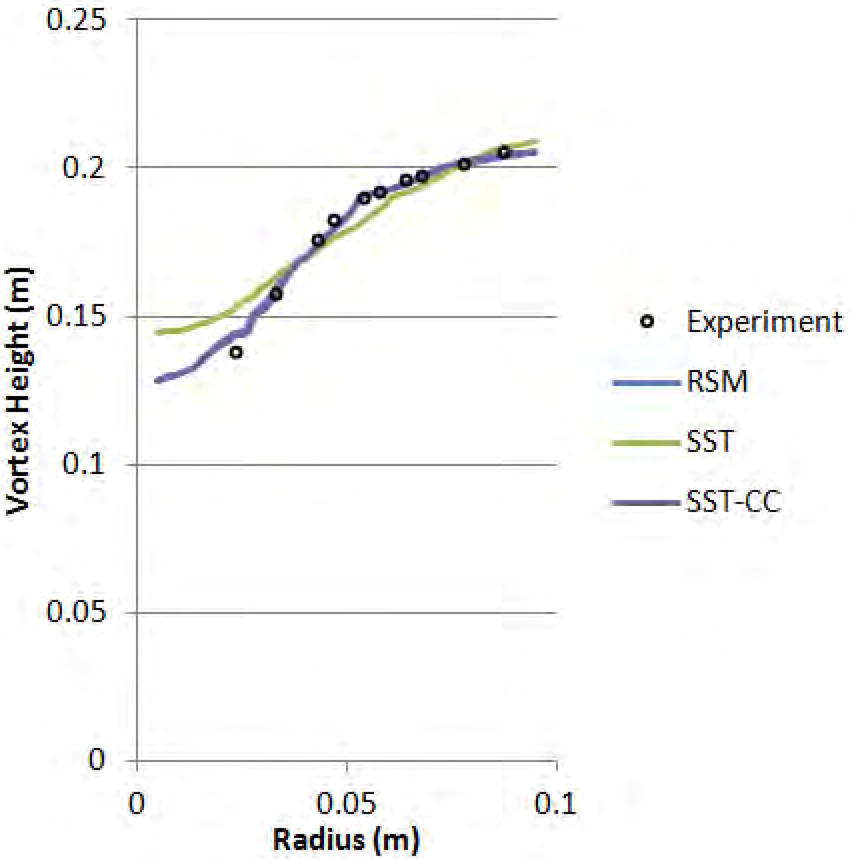


Curvature Correction for One and Two Equation Models

- Option to apply a correction term sensitive to rotatation and streamline curvature for one and two equation RANS models
- Can offer comparable accuracy to Reynolds Stress models with less computational effort for swirl dominated flows



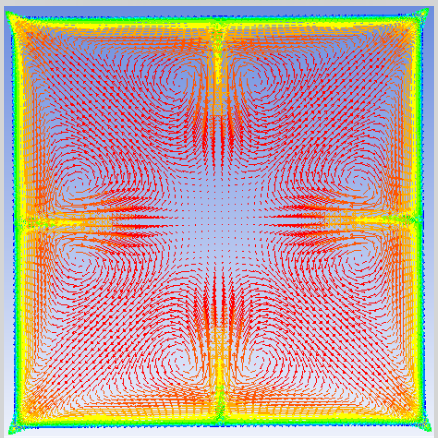


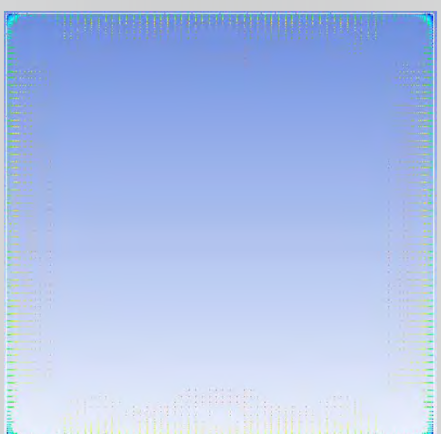


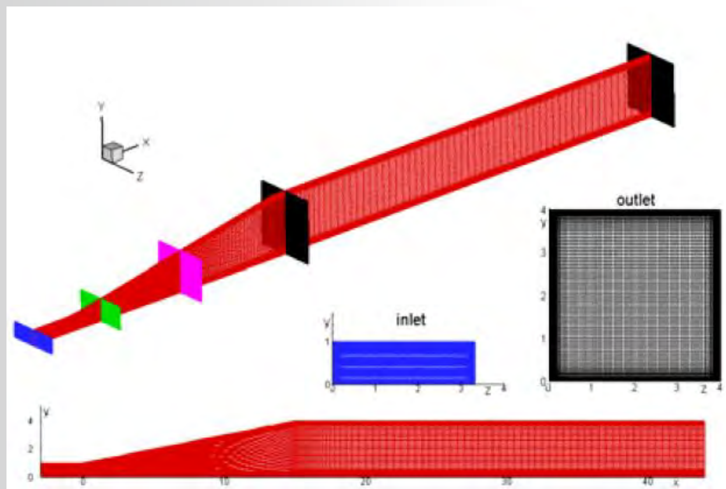
Example: Prediction of the vortex free surface in an unbaffled mixing tank

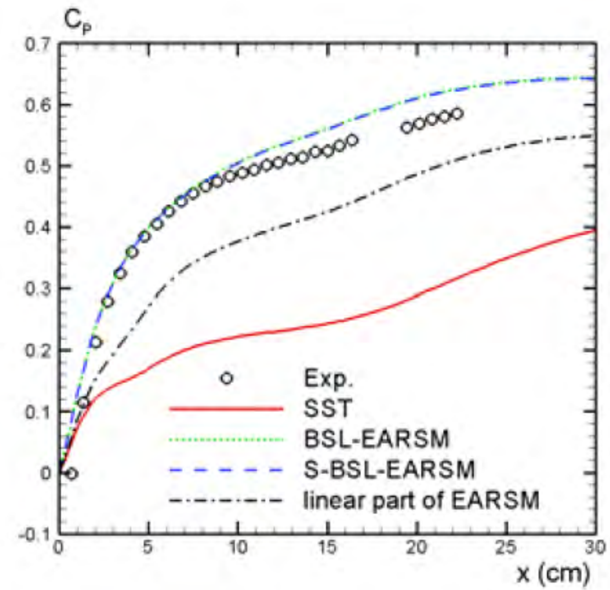
Explicit Algebraic Reynolds Stress Model (EARSM)

- **Non-linear algebraic expansion of Reynolds stress tensor allows two-equation model to capture anisotropic effects such as stress induced secondary flows in rectangular ducts**









Left: In-plane component of velocity vectors for Periodic flow in a square duct. EARSM (above) predicts secondary flow patterns with velocity ~2.4 percent of bulk velocity. SST (below) predicts no secondary flow
Above and Right: Flow in a rectangular, asymmetric diffuser. EARSM correctly predicts pressure coefficient on bottom surface

Summary and Conclusions

- **Steady state RANS simulations will remain the dominant simulation method for turbulent flows for many years**
  - While increasing use of LES and other scale resolving simulation methods for engineering applications is predicted, RANS will still maintain important advantages in some areas
- **ANSYS strives to provide RANS models for use which are**
  - Accurate
  - Robust
  - Y+ insensitive wall treatment
  - Interoperable with other physical models
- **Developments in recent ANSYS releases extend the range of capabilities of the core turbulence models**
  - Curvature correction, EARSM, free surface turbulence damping, porous media near wall treatment