Mixing Time: A CFD Approach

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Overview

- Description and background of mixing time
- Mixing tank modeling using CFD
- Estimating the mixing time
- Case studies: Experimental validation
- Mixing time results
  - Steady and unsteady flow fields
- Summary and Conclusions

Mixing Time

- Mixing time is the time taken to homogenize the liquid contents of the tank after a step change in composition
- The transport of a tracer helps to understand the degree of homogeneity in the agitated tank
  - Circulation time used to gauge the bulk motion induced by the impeller(s)
  - Mixing (or blend) time can be used to evaluate the mixing equipment design to obtain ideal mixing

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Mixing Time: Complications

- Typically, correlations of mixing time data are used
- Mixing time depends on a large number of variables:
  - Impeller type, diameter and Reynolds number
  - Scale
  - Feed location and the location of probes
  - Multiple impellers
  - Internals
  - Fluid properties, etc.
- Difficulties establishing a set of correlations for the wide range of variables, most importantly, scale
- Can lead to inaccuracies in mixing time prediction

Mixing Time: CFD Approach

- Utilize CFD for the prediction of mixing time by eliminating the guesswork in tank configuration, scale, and fluid properties
- Leverage the flexibility to change tank scale, flow regimes/impeller location and number of impellers
- Evaluate a method of predicting mixing time

CFD Modeling of Mixing Tanks

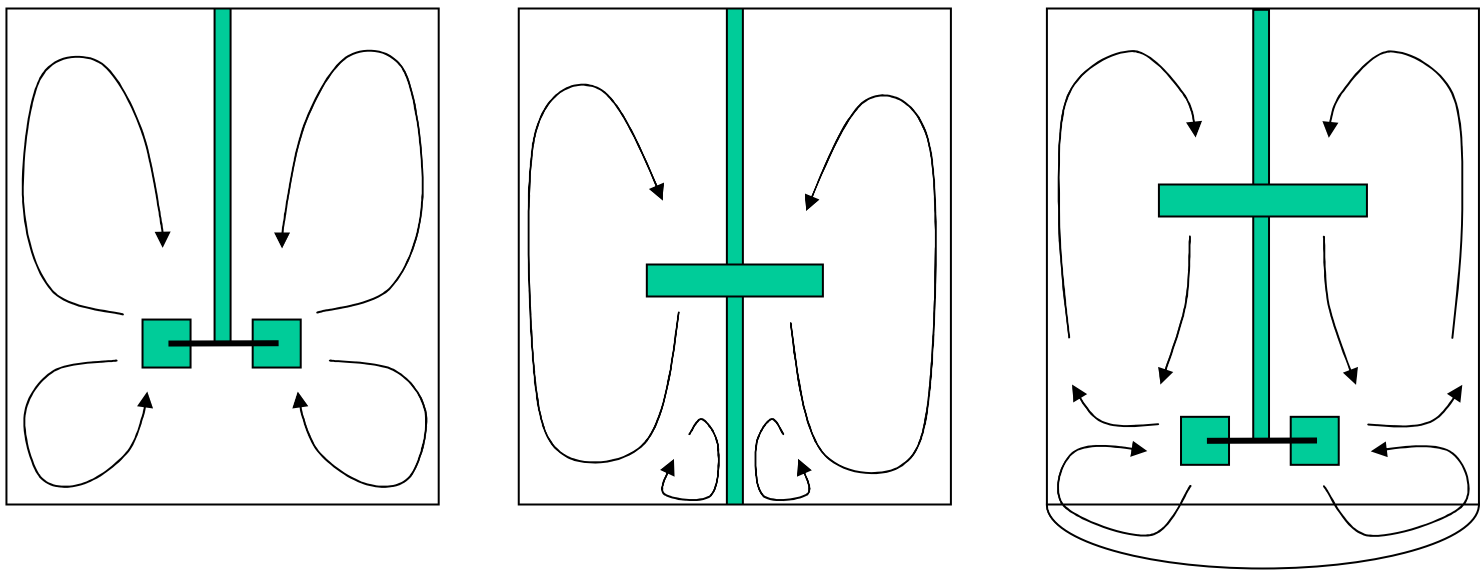
- Impeller Modeling was done using:
  - Impeller boundary conditions applied from LDA
  - Multiple Reference Frame (MRF) Model, *steady-state*
  - Sliding Mesh Model, *time-dependent*

- Turbulence Models used were:
  - Standard k-ε, RNG k-ε, Reynolds Stress Model, LES

    → Increasing computational expense →

- Mixing time was predicted using:
  - Unsteady Particle Tracking
  - Transient transport of a neutrally-buoyant tracer (Scalar)

Flow Regimes



Radial Disk turbine

- H=T= 0.202 m
- D_i= 0.074 m
- C/T=0.33
- N = 290 rpm
- Re_D = 26,000

Pitched Blade turbine

- H=T= 0.292 m
- D_i=0.102 m
- C/T=0.46
- N = 60 rpm
- Re_D = 10,000

Hydrofoil + Concave-Blade Turbine

- T = 2 m
- D_{CD-6}=0.8 m; C=0.6m
- D_{HE-3}=1.04 m; Z=1.04m
- N = 84 rpm
- Re_D ~ 1e6

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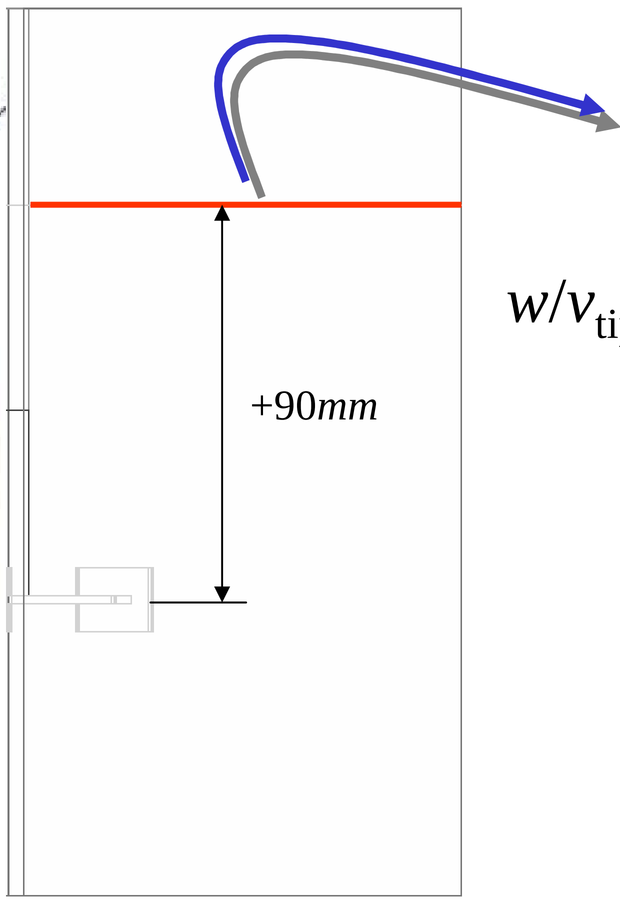
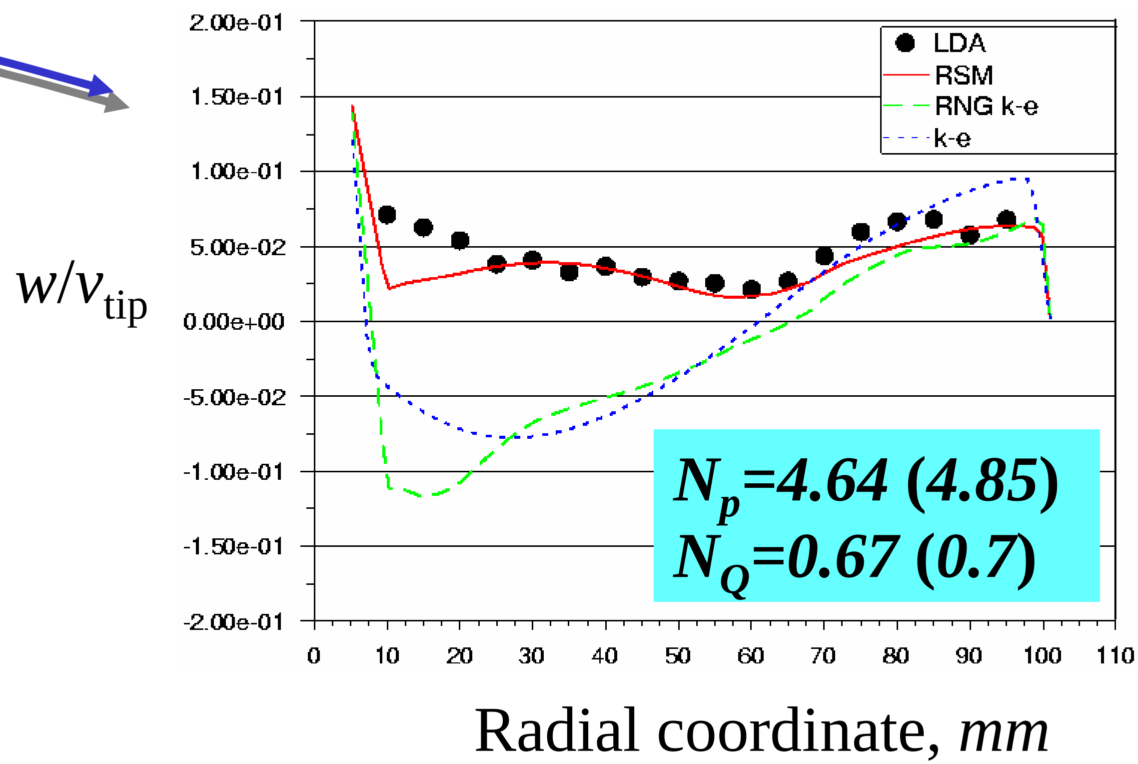
Validating the Radial Disk Turbine

Influence of Turbulence Models

Normalized tangential velocity profiles at the mid-baffle position





LDA data : Z. Jaworski, K. N. Dyster and A. W. Nienow
University of Birmingham, UK

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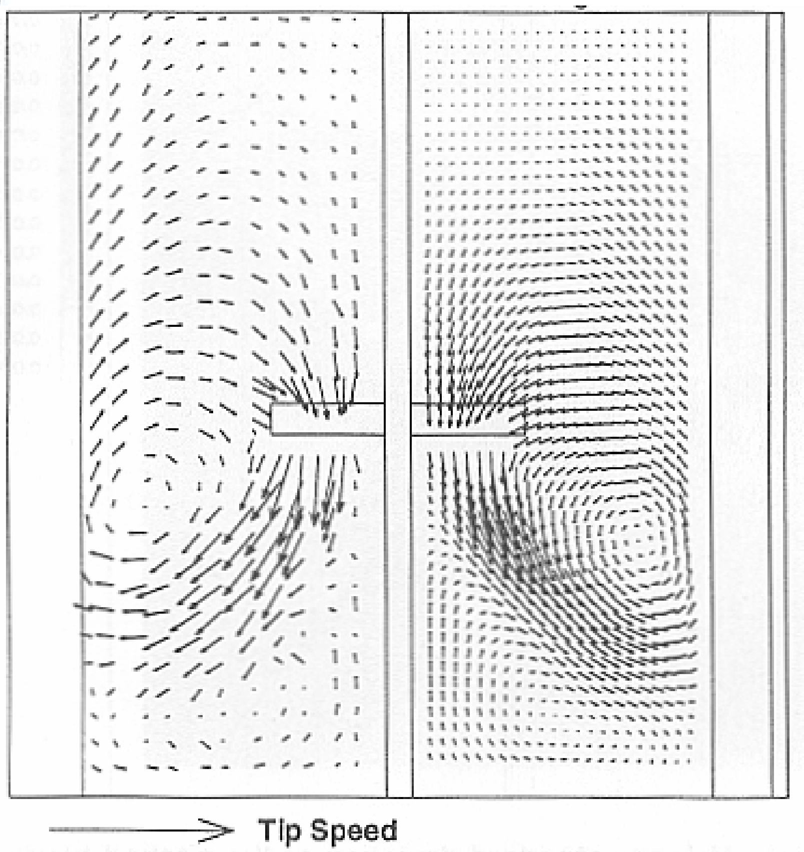
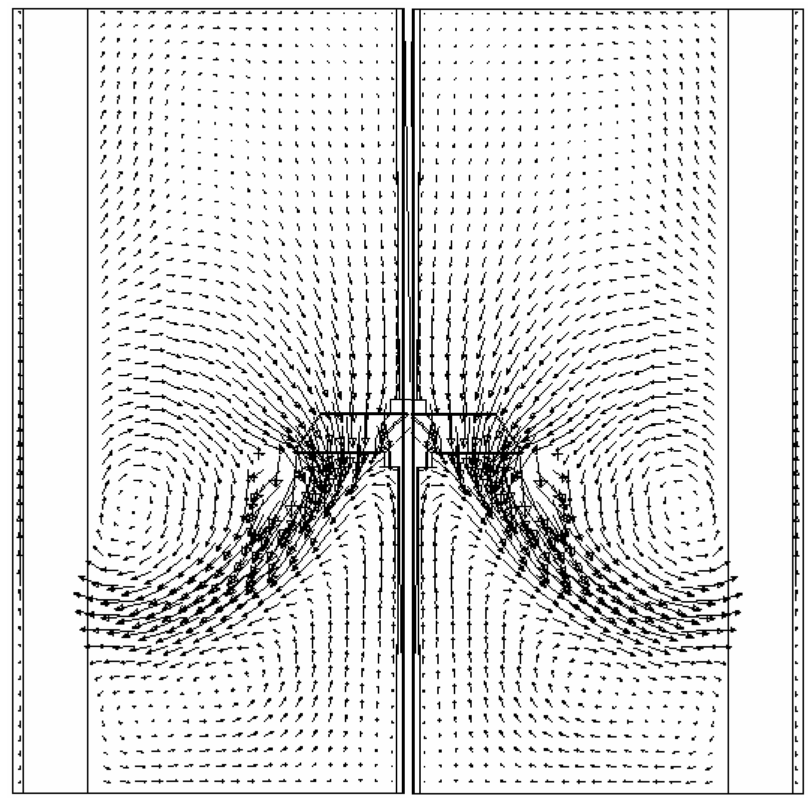
MIXING XVII

Validating the Pitched Blade Turbine

LDA **PIV**



CFD



Velocity vector field in mixing tank

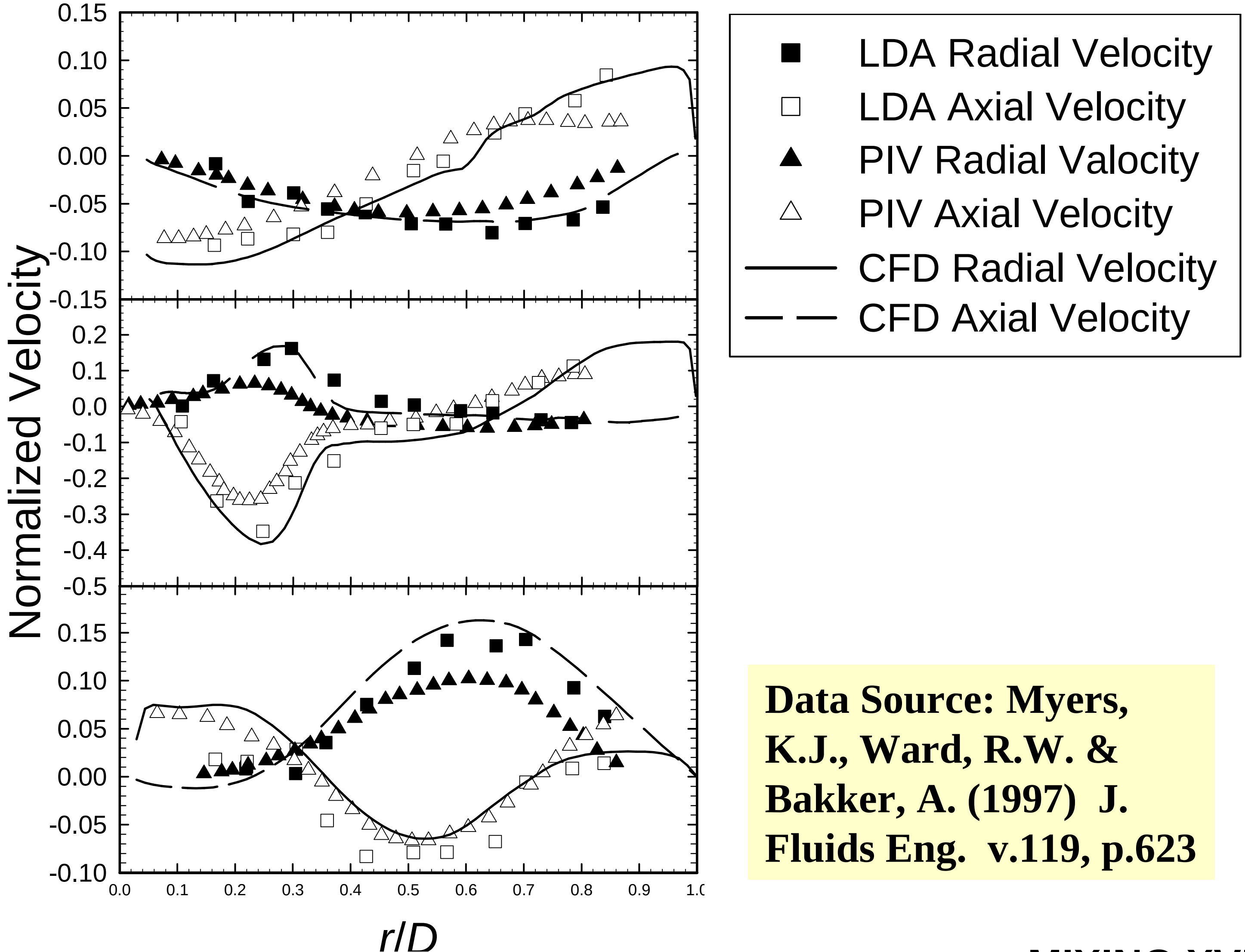
Data Source: Myers, K.J., Ward, R.W. & Bakker, A. (1997) *J. Fluids Eng*. v.119, p.623

Validating the PBT, contd.

y/*H*=0.6

y/*H*=0.4

y/*H*=0.2



Data Source: Myers, K.J., Ward, R.W. & Bakker, A. (1997) J. Fluids Eng. v.119, p.623

Mixing Time Calculations

- Unsteady particle tracking
  - Release of a number of neutrally-buoyant particles
  - Turbulent dispersion of particles accounted for
  - Particle concentration sampled at various times

- Transport of a tracer
  - Small amount of liquid tracer added near liquid surface
  - Concentration of tracer monitored as a function of time
  - Similar to experimental techniques

- Flow field required can be steady, frozen unsteady or unsteady

Time-varying Concentration

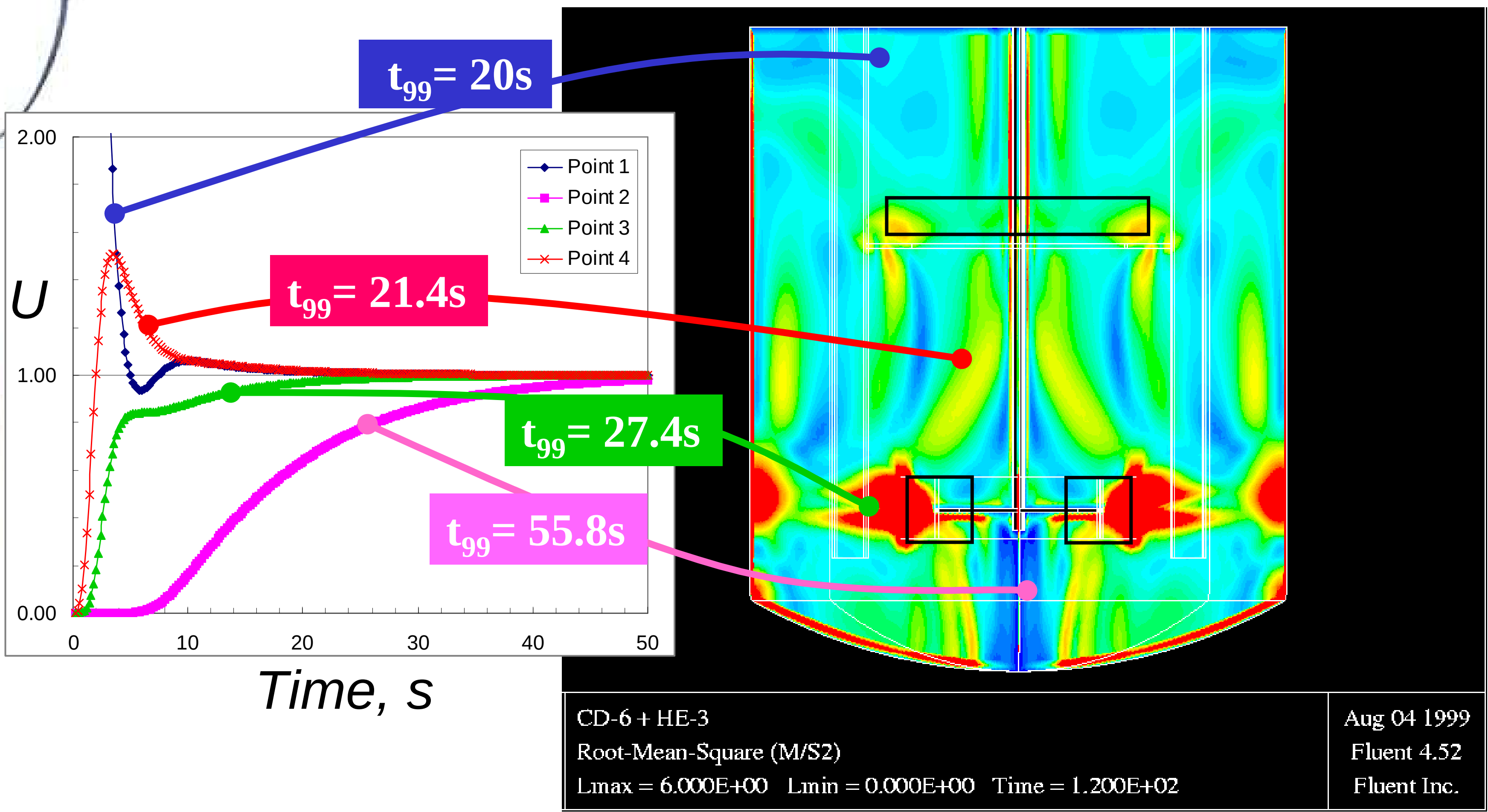
- Multiple locations can be sampled simultaneously to show concentration changes in many locations in the tank
- Mixing time, t_{99}, is the time taken for the uniformity, U, to reach 0.99, where

$$U = 1 - \frac{\left(C_\infty - C(t)\right)}{C_\infty}$$

- The t_{99} is determined at various locations in the tank and averaged to obtain the ***mixing time***

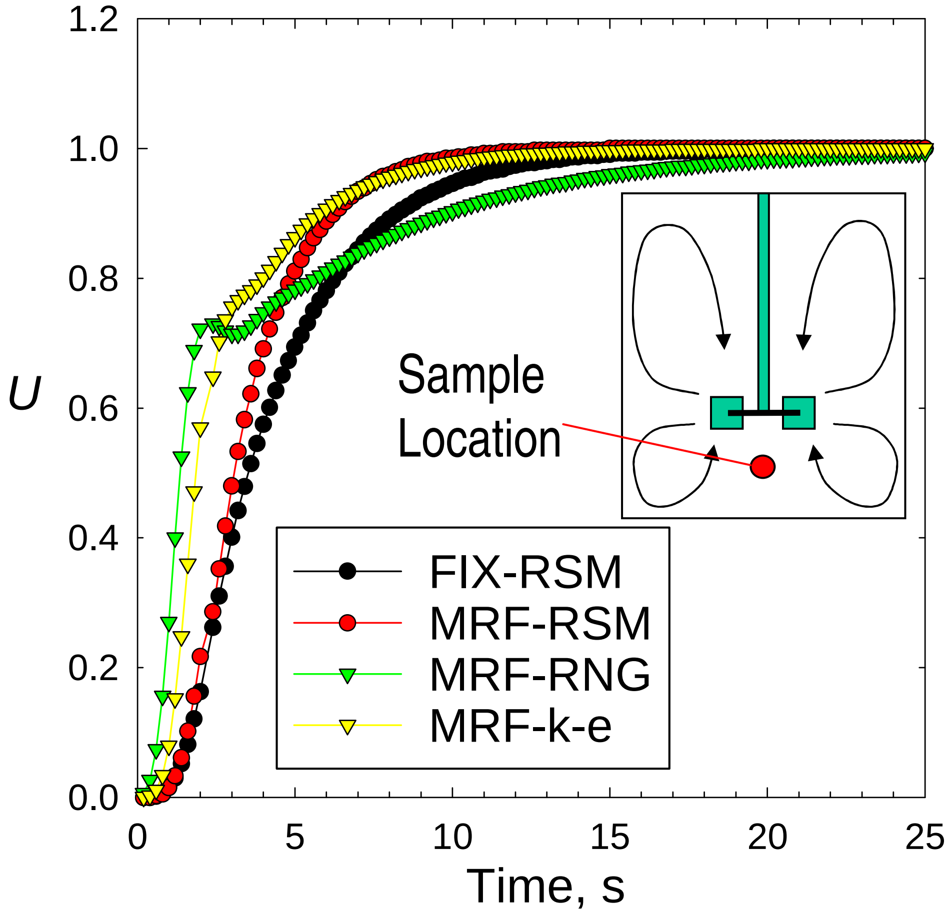
Influence of Measurement Location

Dual impeller HE-3 + CD-6



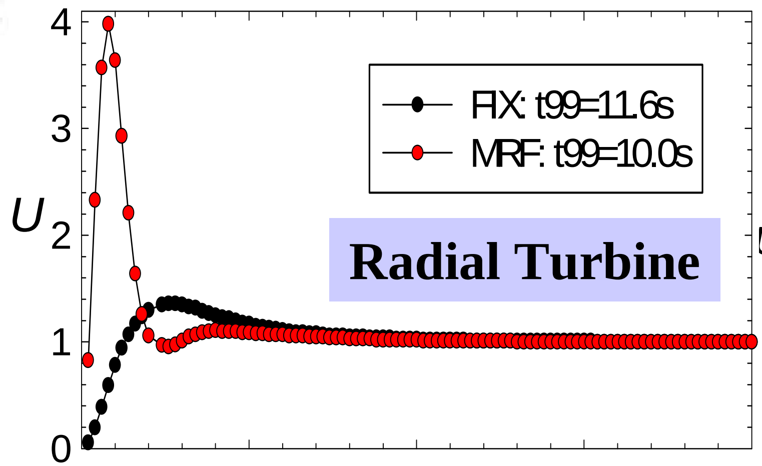
Influence of Turbulence Models

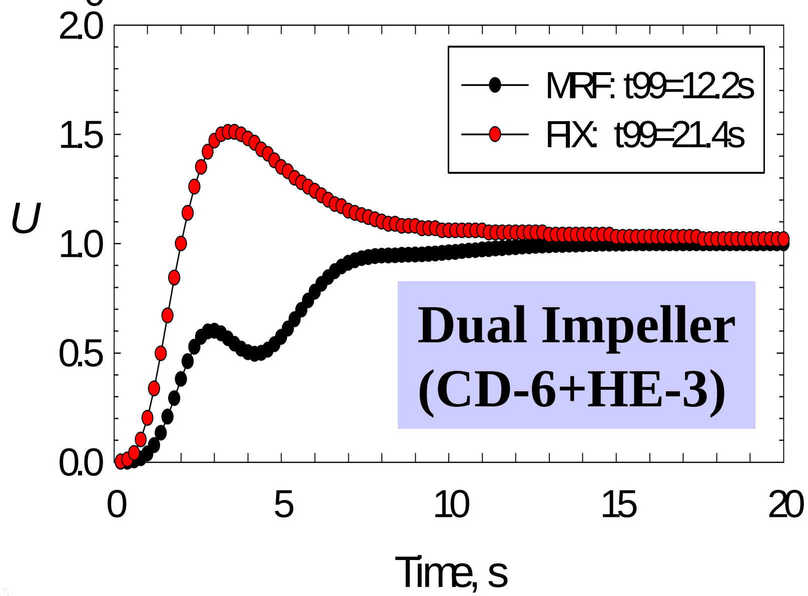
Uniformity; Radial Disk Turbine

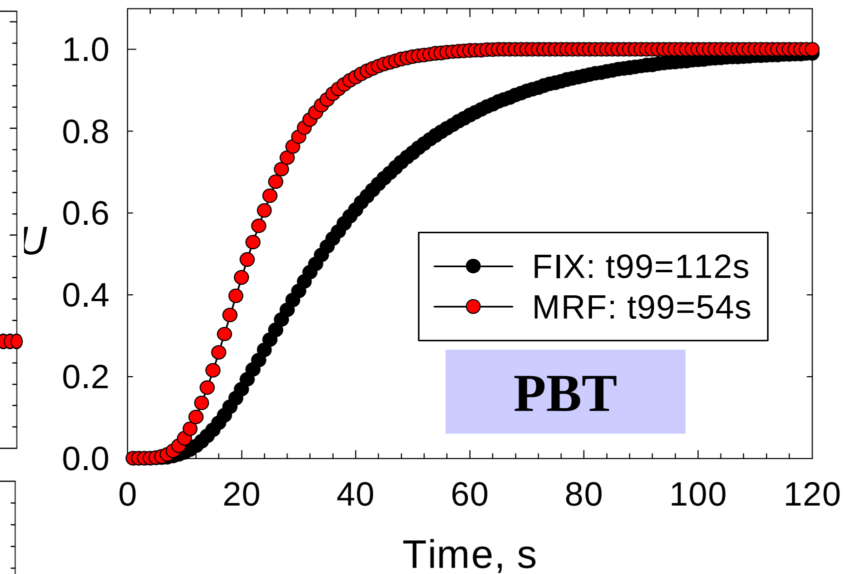


- Predicted mixing times, t_{99}, at the **sample** location
  - FIX, RSM = 13.6s
  - MRF, *k*-ε = 9.6s
  - MRF, RNG = 22.8s
  - MRF, RSM = 11.6s

Influence of Impeller Modeling







- Modeling impeller with velocity data predicts greater t_{99}

Mixing Time Correlations

- Fasano, J.B., Bakker, A. & Penney, W.R. (1994)

$$t_{99} = \frac{-\ln(1-U)}{aN\left[\frac{D}{T}\right]^{b}\left[\frac{T}{Z}\right]^{0.5}}$$

Impeller Style	*a*	*b*
Radial Disk 6 blades	1.06	2.17
Pitched 4 blades	0.641	2.19
High-efficiency 3 blades	0.272	1.67

- Prochazka and Landau (1961), Moo-Young et al (1972), Sano & Usui (1985), Raghav Rao and Joshi (1988)

Comparison to Correlations

	t_{99}(Corr.)	t_{99}(CFD)
RT	8 (±30%)	10.5±0.9
PBT	72 (±30%)	61.5±9.3
HE-3+CD-6	15 (±30%)	32±34.7 (17.6,13.6,12.8, 84)

Time in seconds

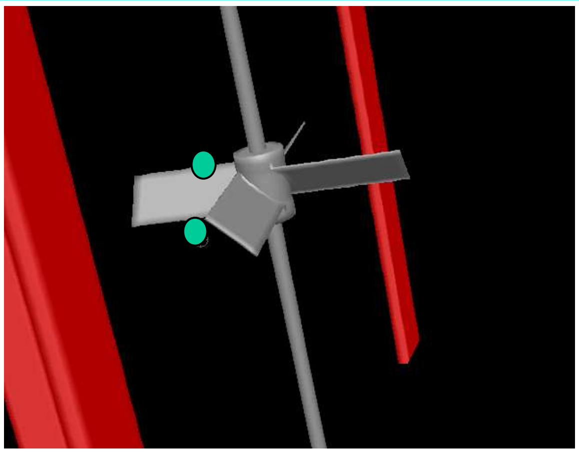
- The CFD mixing time results were the average of multiple locations in the tank
- The dual impeller systems shows the influence of locally poor mixing on the average mixing time in the tank

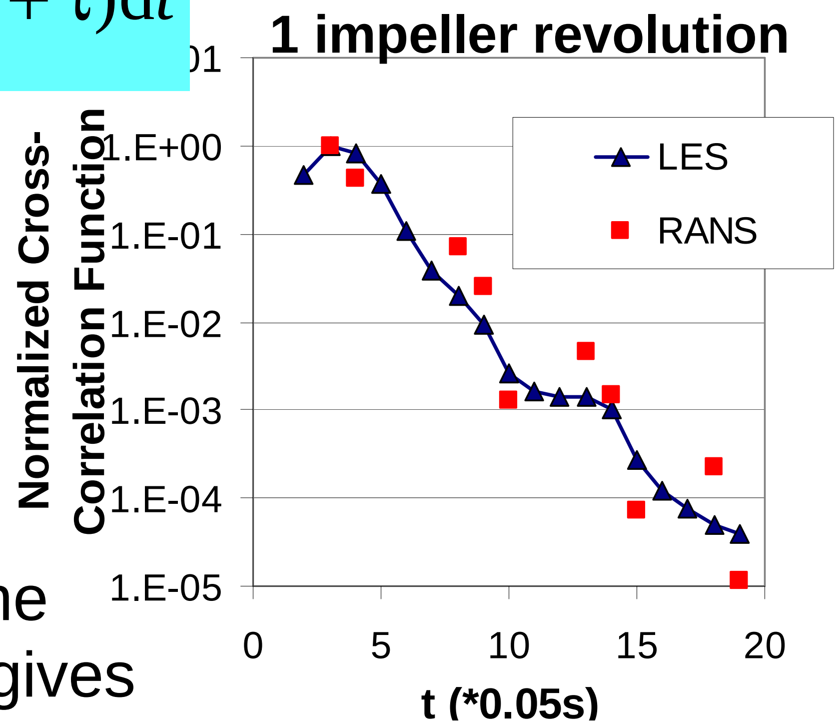
Mixing Time Calculations in an Unsteady Flow Field

- The sliding mesh model was used to set up the transient motions of the impeller in the tank.
- Two turbulence model approaches were evaluated:
  - Reynolds-Averaged Navier-Stokes turbulence model, i.e., Standard k-ε, RNG k-ε, Reynolds Stress Model
  - Large Eddy Simulation or LES

Cross-correlation results

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int C_1(t) C_2(t+\tau) \mathrm{d}t$$





- The time delay between the maximum values of $R_{xy}(t)$ gives the average convection velocity of the tracer “front”
- Can be related to mixing efficiency

Summary

- Mixing time can predicted using CFD in a variety of tank configurations
- Unsteady tracer CFD calculations on a steady-state flow field gave good comparisons with correlations of experimental data
- Modeling the presence of the impeller is important for improving mixing time predictions
- Both RANS-based and LES turbulence modeling can be used with an unsteady sliding mesh model to calculate the transport of the tracer