

Blend Times in Stirred Tanks

Reacting Flows - Lecture 9

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Evaluation of mixing performance

- Methods to evaluate mixing performance:
 - Characterization of homogeneity.
 - Blending time.
- General methods to characterize homogeneity:
 - Visual uniformity.
 - Quantitative change in local concentration as a function of time.
 - Review instantaneous statistics about the spatial distribution of the species.
 - Average concentration
 - Minimum and maximum
 - Standard deviation in the concentration.
 - Coefficient of variation $CoV = \text{standard deviation}/\text{average}$.

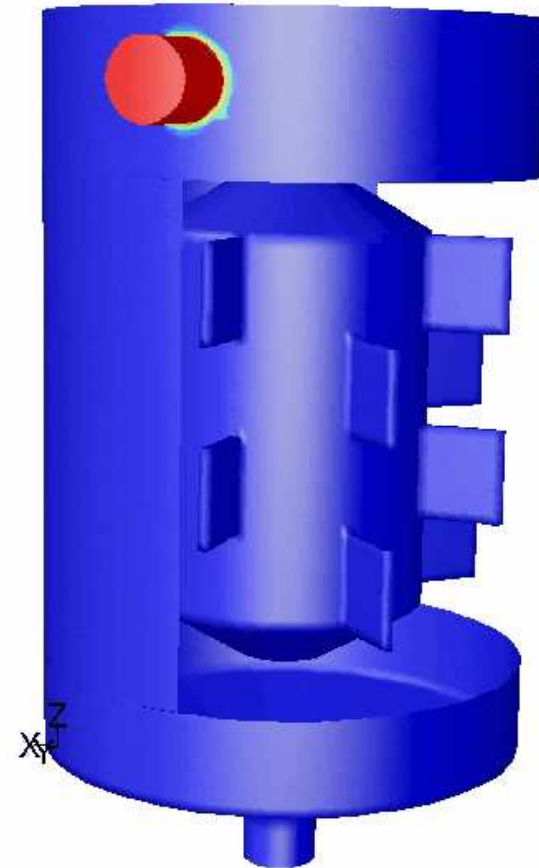
Visual uniformity

- Experimentally measure the time it takes to obtain visual uniformity.
- Can be done with acid-base additions and a pH indicator.
- Offers good comparisons between performance of different mixing systems.
- Not a suitable approach for CFD.



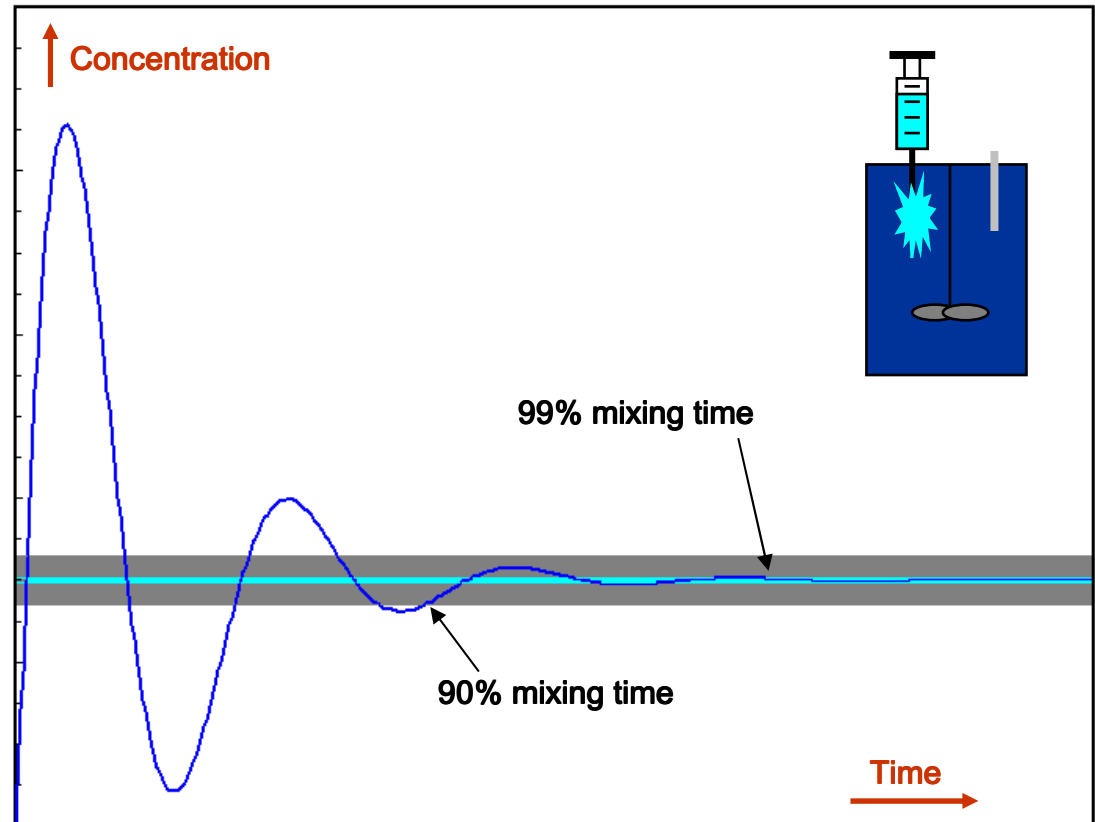
Visual uniformity example: glass mixing

- Glass exits the glass ovens with variations in temperature and material concentrations.
- As a result, when the glass hardens, there will be visual non-uniformities.
- So, glass needs to be mixed before it is used. Because of the high-viscosity and temperature, special mixers are used,
- Optical quality of glass is still often determined visually.



Quantitative variation in a point

- Measuring the tracer concentration as a function of time $c(t)$ in one or more points in the vessel, is a common experimental method.
- The mixing time is then the time it takes for the measured concentration $c(t)$ to stay within a certain range of the final concentration c_∞ .
- Advantage: easy to use in experiments.
- Disadvantage: uses only one or a few points in the vessel.
- Does not use all information present in a CFD simulation.



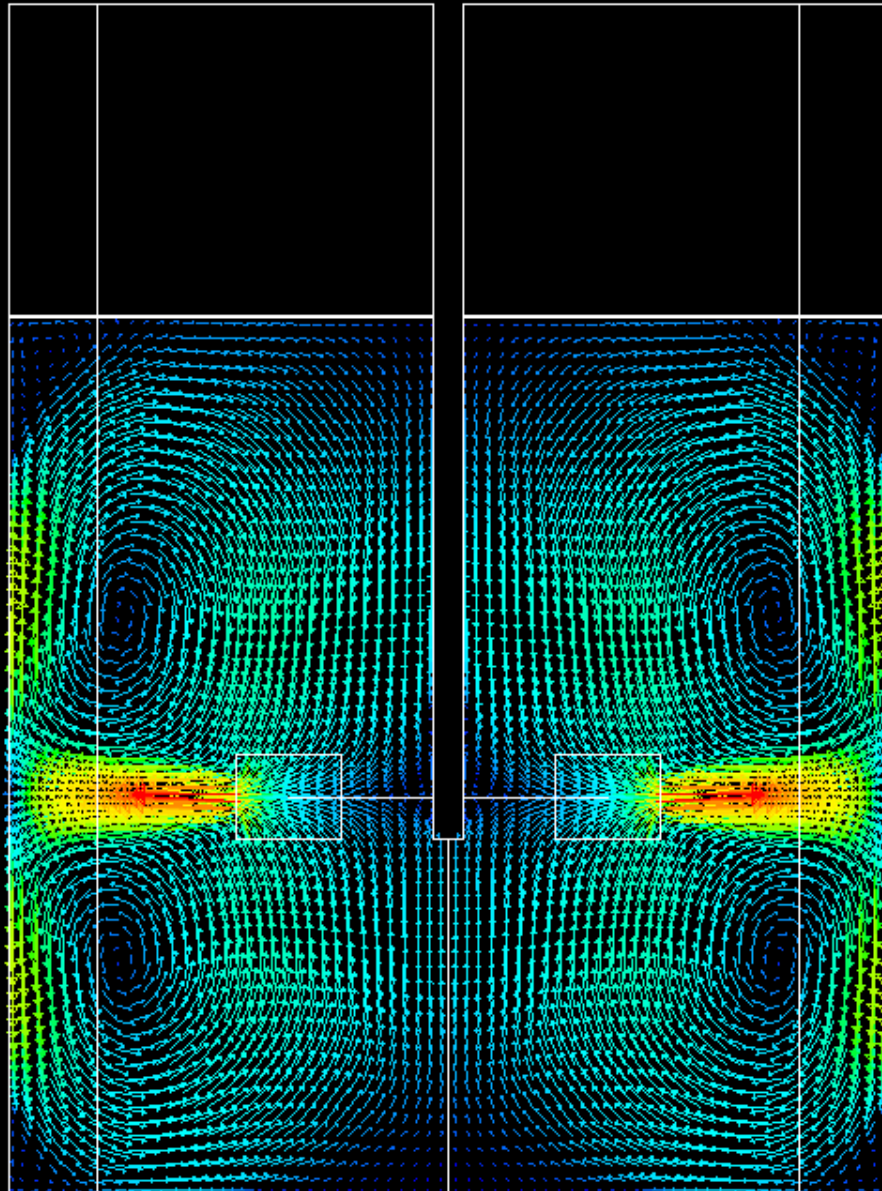
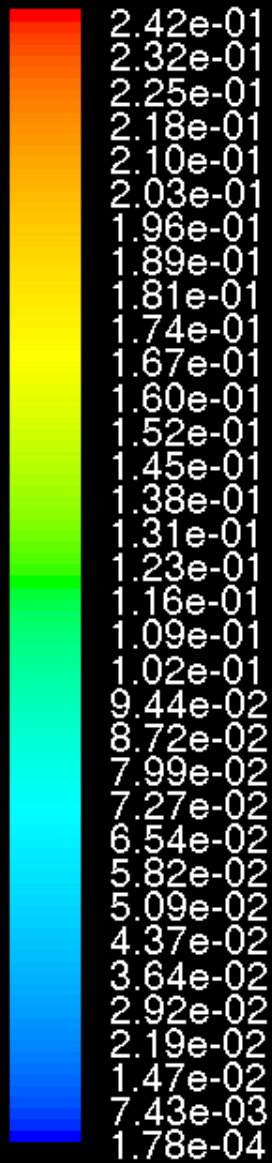
Blend time calculations with CFD

- Transport and mixing of a tracer:
 - Add tracer to the domain.
 - Mass fraction of tracer calculated and monitored as a function of time.
 - Determine blend time based on the mass-fraction field satisfying a pre-specified criterion.
- Flow field required can be steady, frozen unsteady or unsteady.
- Benefit of CFD:
 - The full concentration field is known.
 - Can use more data to determine blend time than what can be measured experimentally using probes.
- Main question: what should be the mixing criterion?

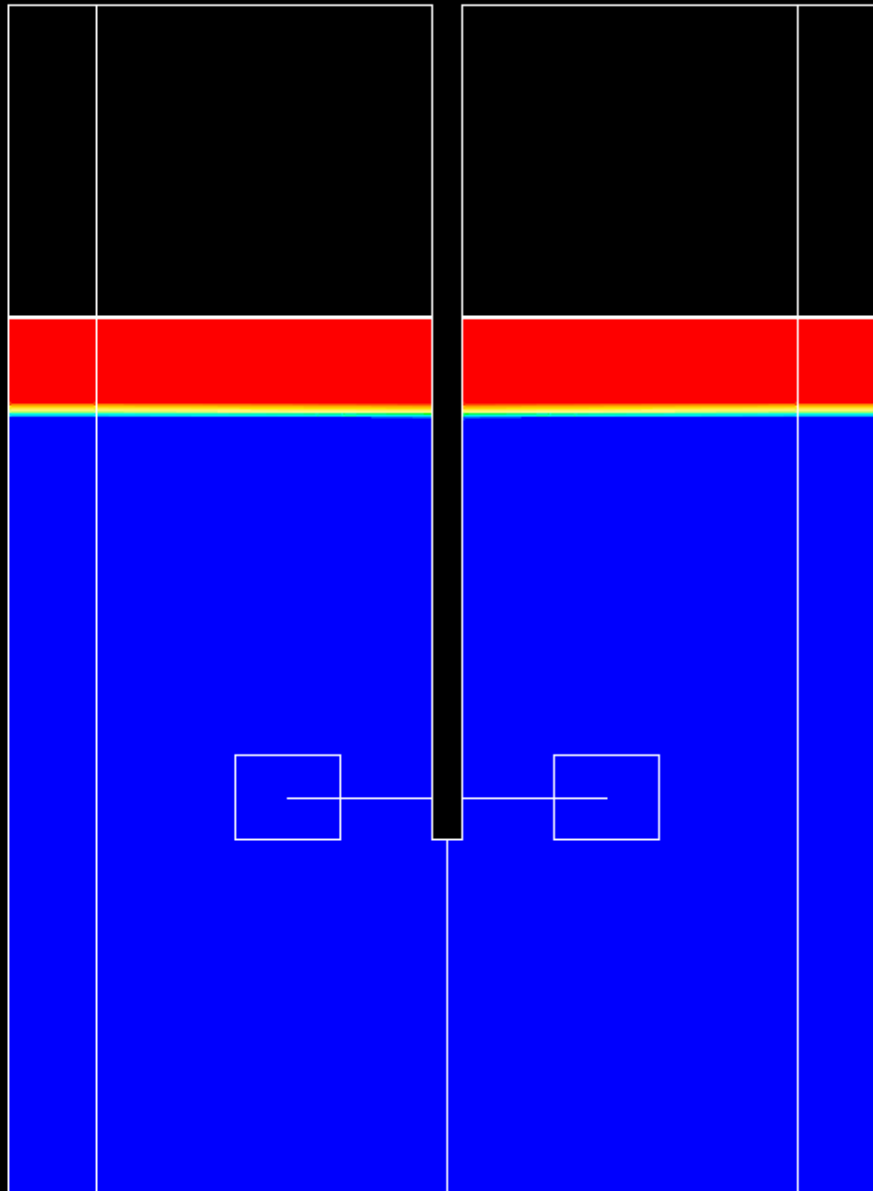
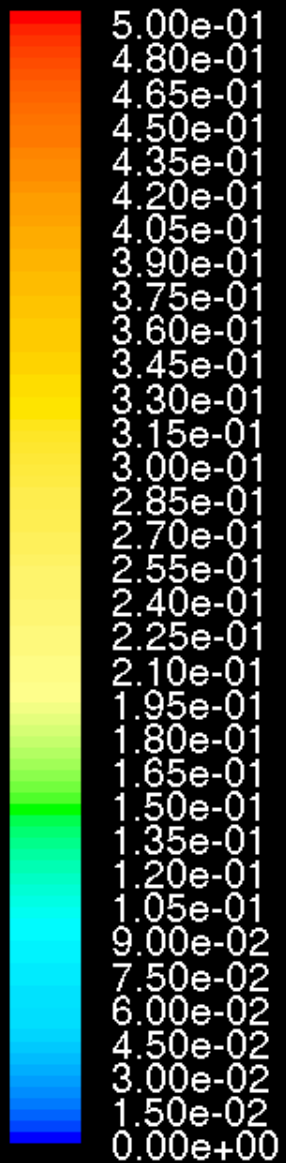
CFD analysis for blend time

		<i>Physical Lab</i>	<i>CFD Lab</i>
<i>Addition of Tracer</i>	Volume of Tracer	Controlled	Exact
	Delivery Time	finite	zero
	Location	variable	fixed
<i>Concentration Measurement of Tracer</i>	Conductivity	Yes	No
	Color	Yes	No
	Mass Fraction	inferred	Yes

- We will now:
 - Illustrate the blend time analysis using a 2-D Rushton turbine flow field example.
 - Tracer added and its transport and mixing calculated. Mass fractions are monitored as a function of time.
 - Blend time is calculated using different criteria.



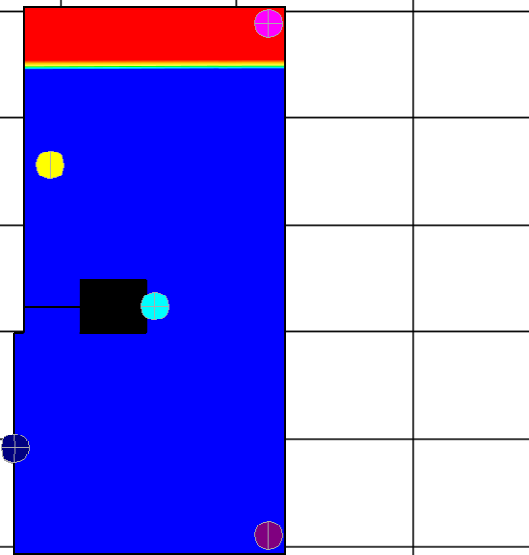
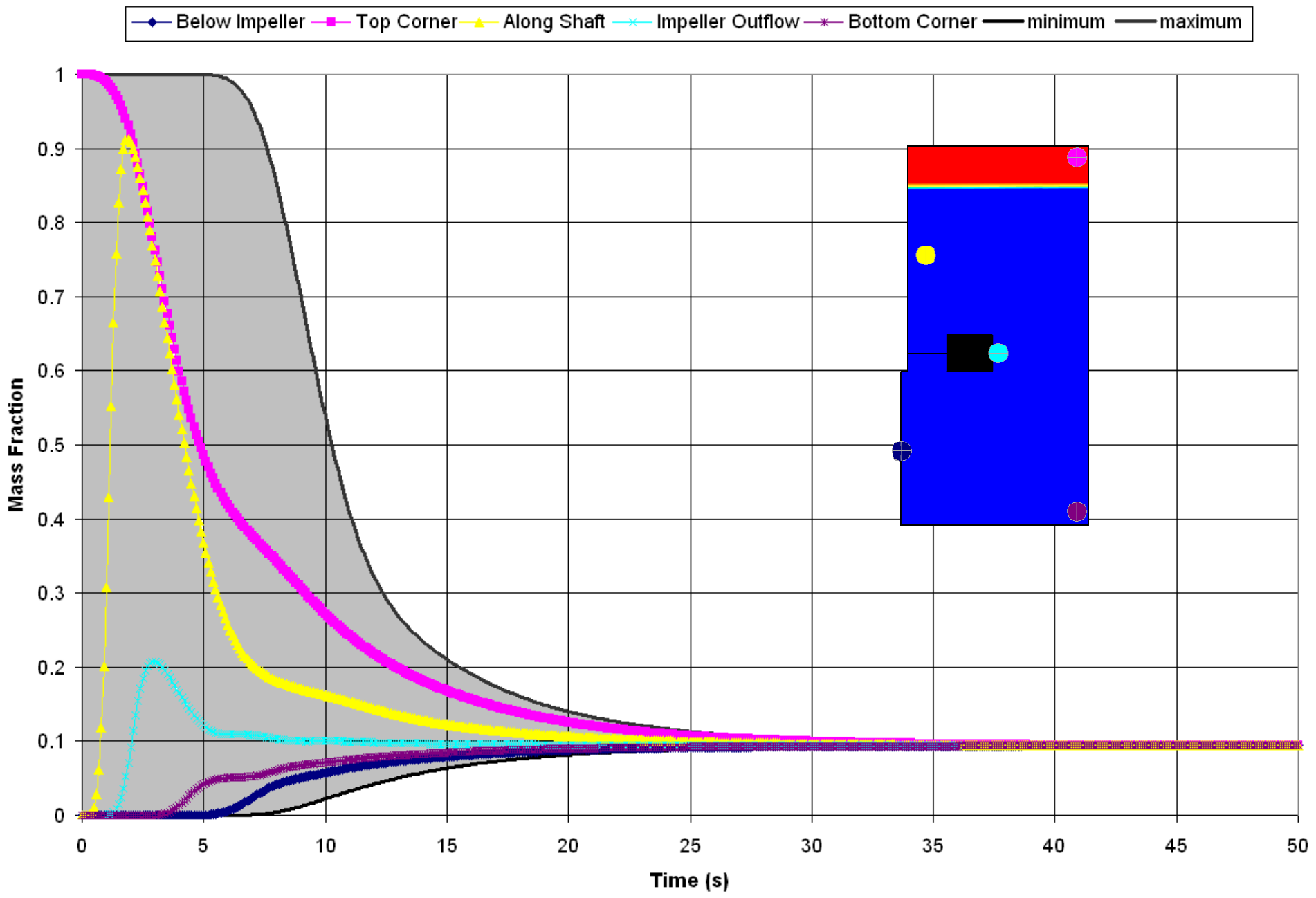
Rushton Impeller - 50 RPM - 31.6l Vessel
Velocity Vectors Colored By Velocity Magnitude (m/s)



Rushton Impeller - 50 RPM - 31.6l Vessel

Contours of Mass fraction of water-liquid-tracer (Time=0.0000e+00)

FLUENT 6.2 (axi, segregated, spe, rke, unsteady)



Measures of variation

- Variations in Y , the mass fraction of tracer, can be measured in several ways. For all measures, greater numbers indicate a greater variation with no upper bound.
- Coefficient of variation. Ratio between standard deviation σ_Y and the average $\langle Y \rangle$:

$$CoV = \frac{\sigma_Y}{\langle Y \rangle}$$

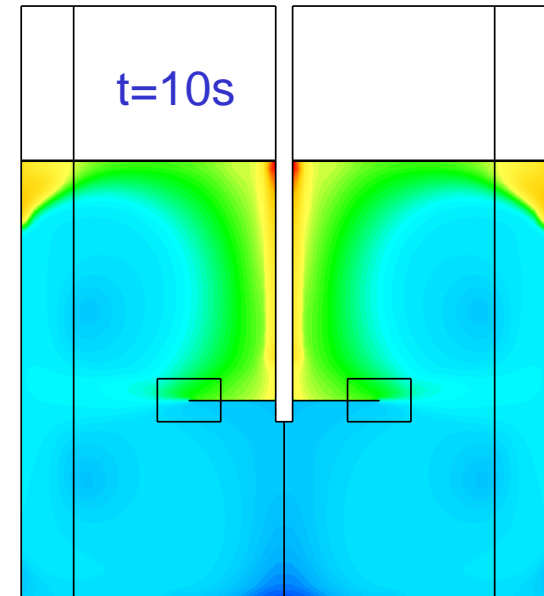
- Ratio between maximum and minimum mass fractions Y_{\max}/Y_{\min} .
- Largest deviation between extremes in the mass fraction and the average:

$$\Delta_{\max} = \max(Y_{\max} - \langle Y \rangle, \langle Y \rangle - Y_{\min})$$

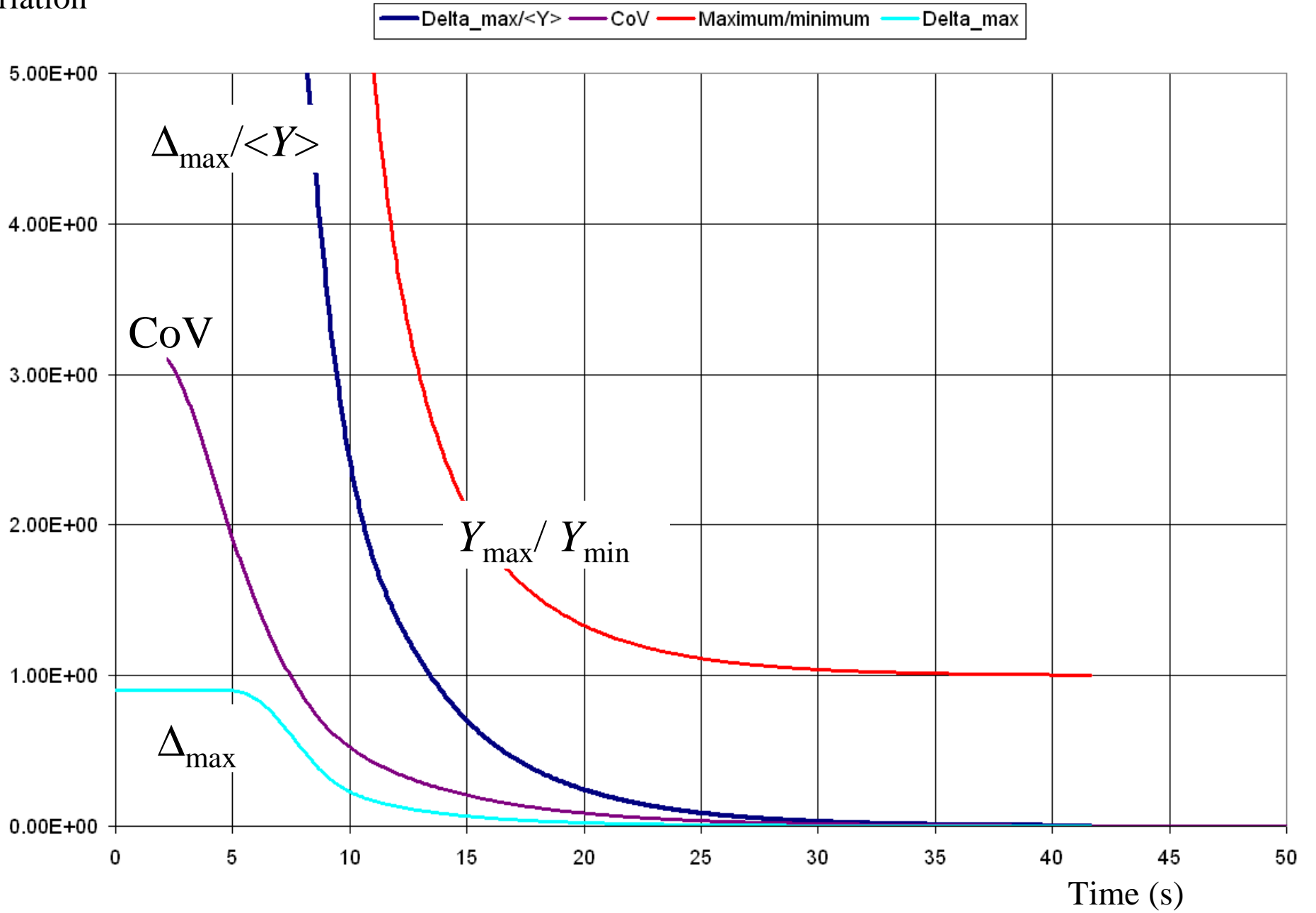
Can also be normalized over $\langle Y \rangle$.

Variation calculation example

- Mass fraction data:
 - Min-max anywhere: 0.0223-0.539
 - Min-max from probes: 0.0574-0.272
 - Average: 0.0943
 - Standard deviation: 0.0493
- Measures of variation:
 - $\text{Max/min} = 0.539/0.0223 = 24.2$ (anywhere)
 - $\text{Max/min} = 0.272/0.0574 = 4.7$ (from probes)
 - $\text{CoV} = 0.0493/0.0943 = 0.52$
 - $\Delta_{\text{max}} = \max(0.539-0.0943, 0.0943-0.0223) = 0.44$
 - $\Delta_{\text{max}}/\langle Y \rangle = 0.44/0.0943 = 4.7$



Variation



Measures of uniformity - absolute

- There is a need to have an absolute measure of uniformity U that is ≤ 1 with 1 (or 100%) indicating perfect uniformity.

- Ratio between the minimum and maximum mass fractions.

- Bounded between 0 and 1.

$$U_{\min/\max} = \frac{Y_{\min}}{Y_{\max}}$$

- Based on coefficient of variance CoV:

- Not bounded: can be less than 0.

$$U_{CoV} = 1 - CoV$$

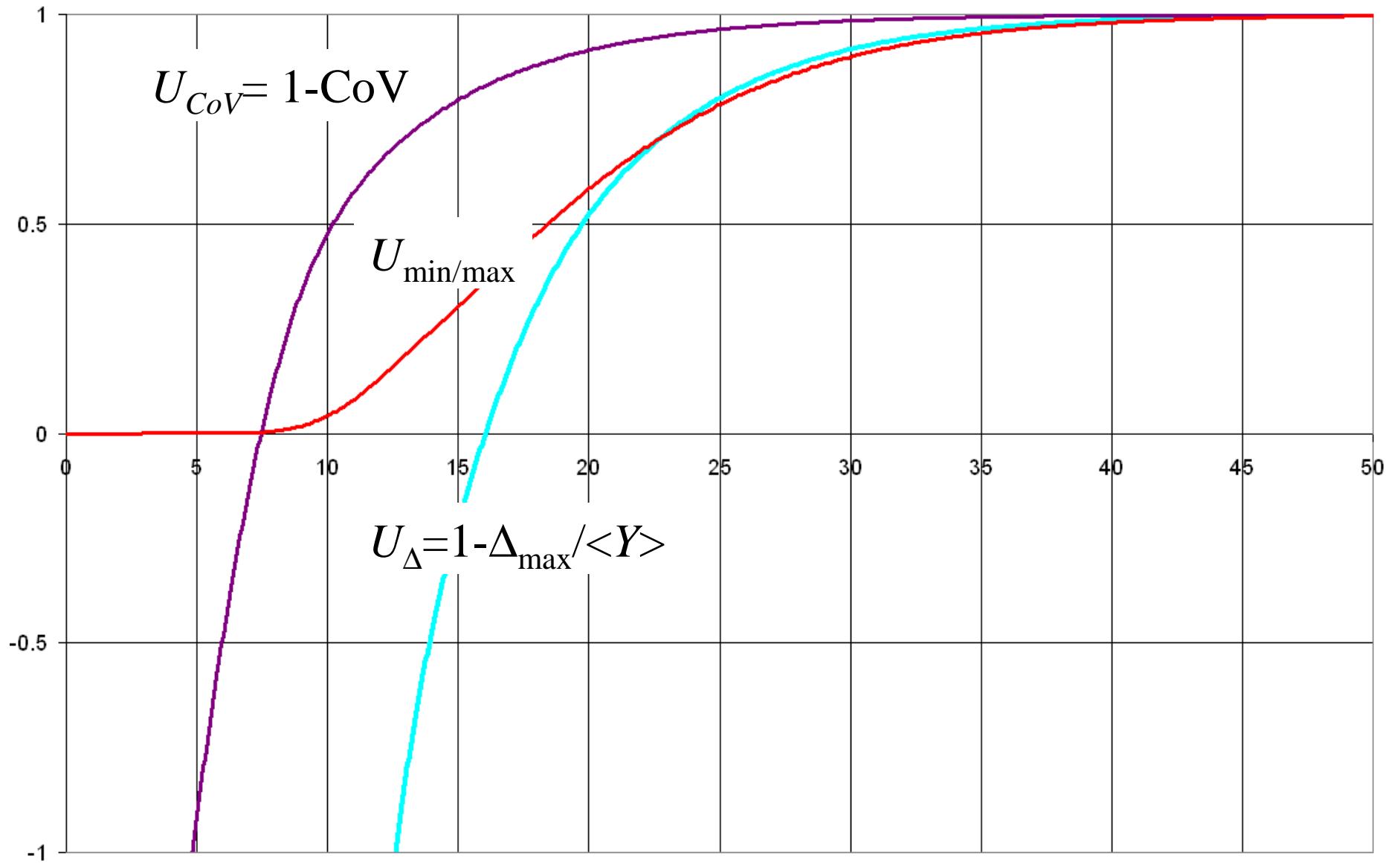
- Based on largest deviation from the average:

- Conceptually closer to common experimental techniques.

- Not bounded: can be less than 0.

$$U_{\Delta} = 1 - \frac{\Delta_{\max}}{\langle Y \rangle}$$

Uniformity



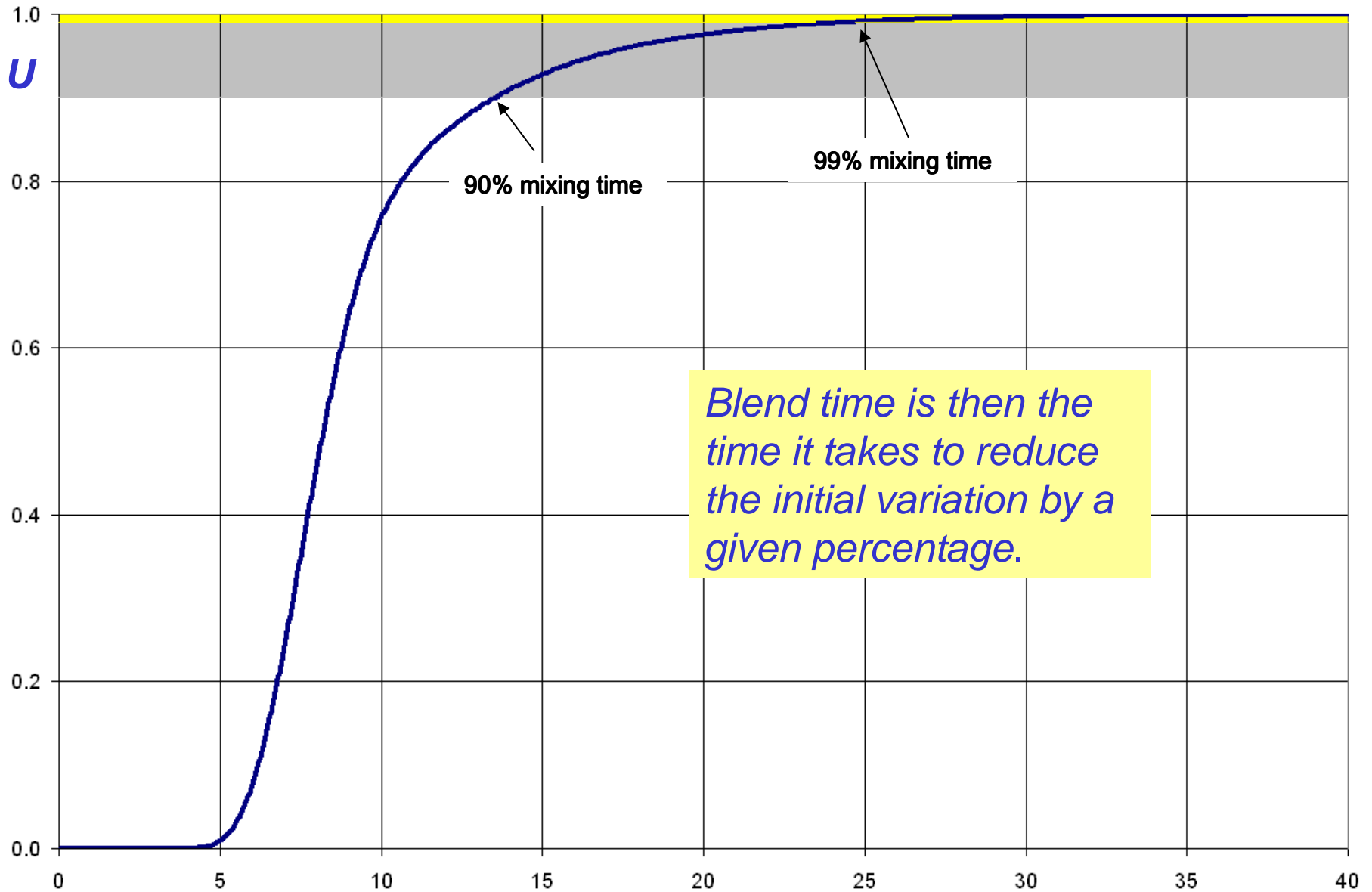
Time (s)

Uniformity

- These measures of uniformity:
 - All indicate perfect uniformity at values of 1.
 - Are not all bounded between 0 and 1.
 - Do not take initial conditions into account.
- Generally, it is most useful to be able to predict the time it takes to reduce concentration variations by a certain amount.
- This is then done by scaling the largest deviation in mass fraction at time t by the largest deviation at time $t=0$.

$$U(t) = 1 - \frac{\Delta_{\max}(t)}{\Delta_{\max}(t=0)}$$

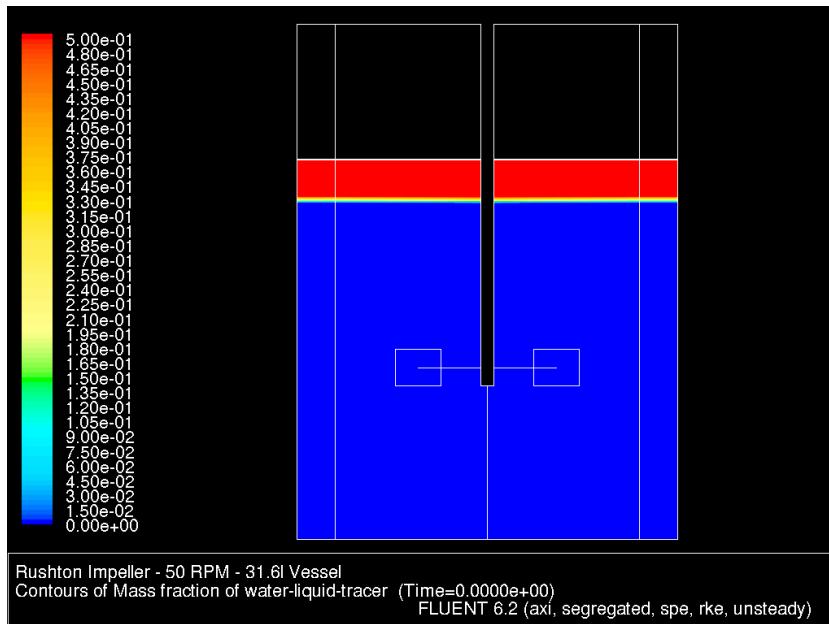
- E.g. for the example case:
 - At $t=0$ s, $Y_{\max}=1$ and $\langle Y \rangle=0.0943 \rightarrow \Delta_{\max}(t=0) = 0.906$.
 - At $t=10$ s, $\Delta_{\max}(10\text{s}) = 0.44 \rightarrow U(10\text{s}) = 0.51$.
- Data are often correlated in terms of number of impeller revolutions, at $t=10$ s and 50RPM, there were $10 \cdot \text{RPM}/60=8.33$ impeller revolutions.



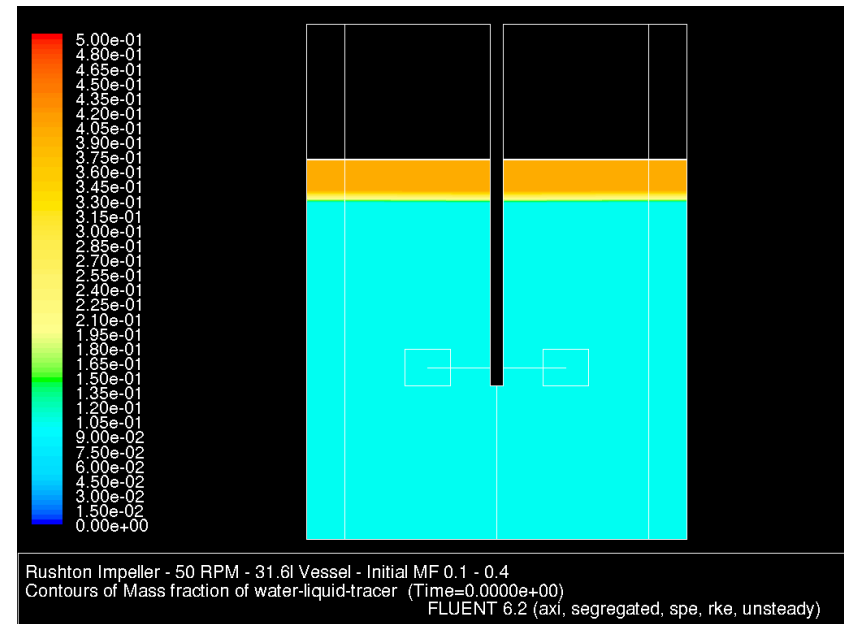
Impeller revolutions

Comparison between systems

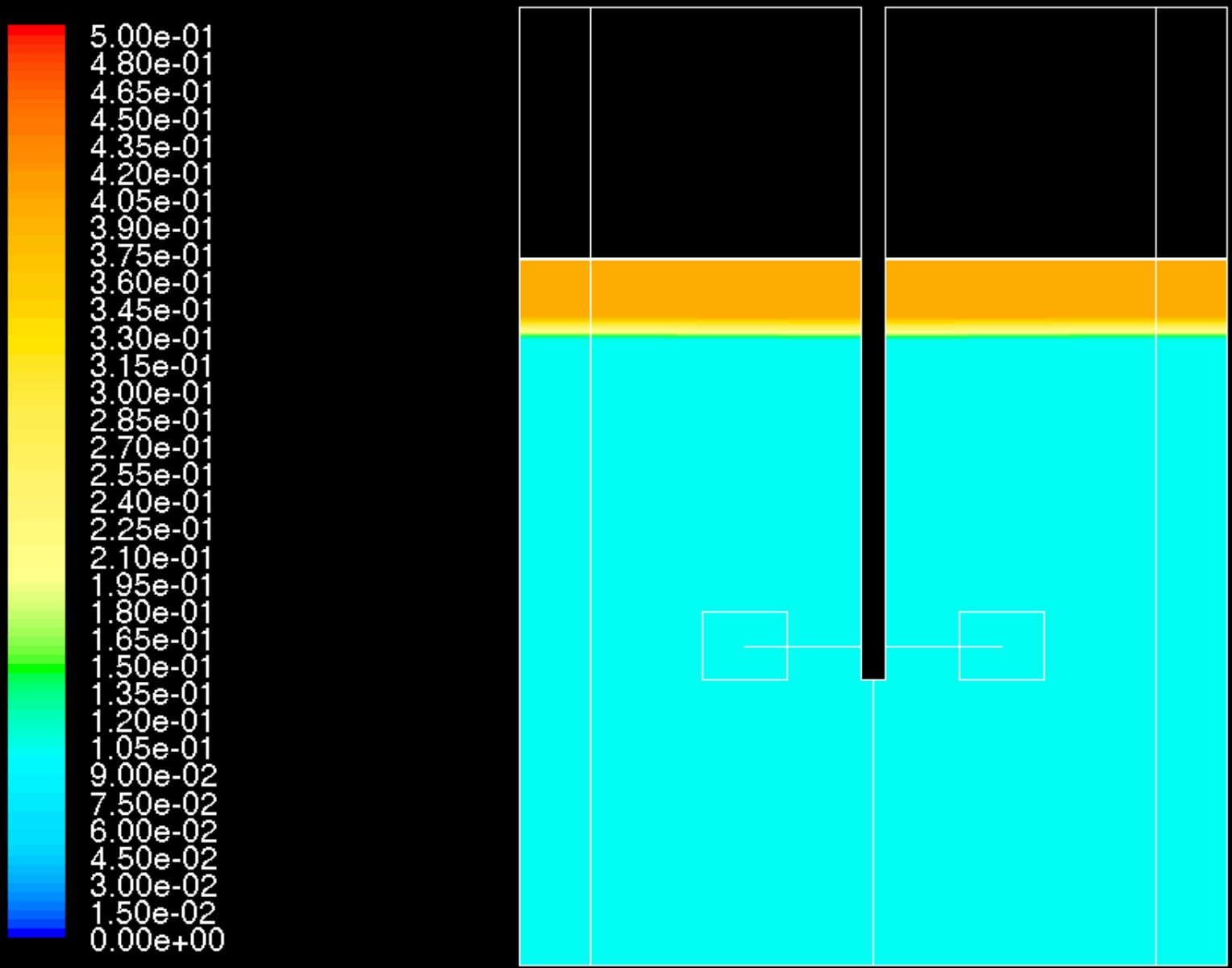
- Let's compare two systems with:
 - The same flow field.
 - The same spatial distribution of species.
 - But different initial mass fractions of species.



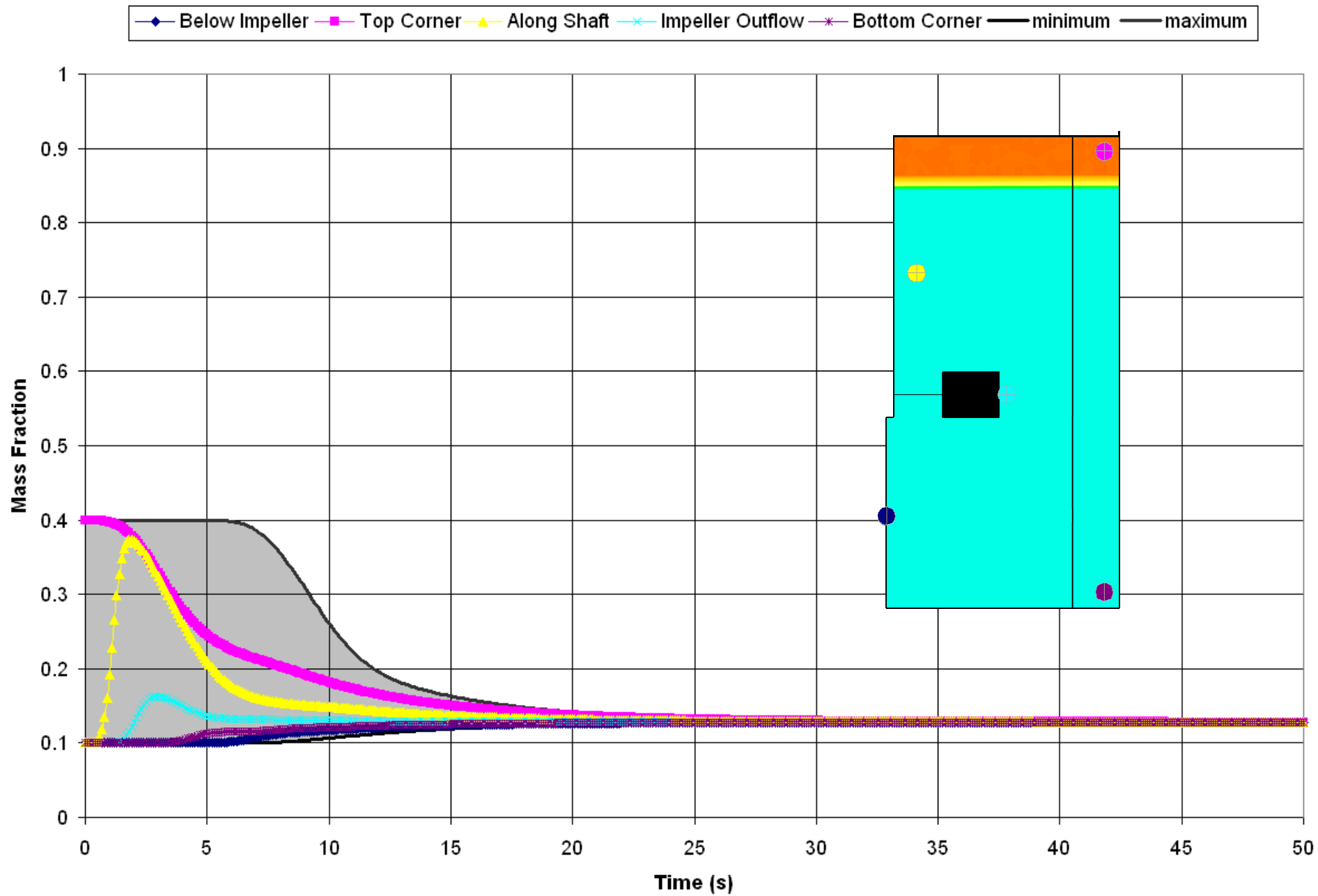
Layer with $Y_{tracer}=1$ on top of fluid
with $Y_{tracer}=0$. $\langle Y \rangle = 0.094$.

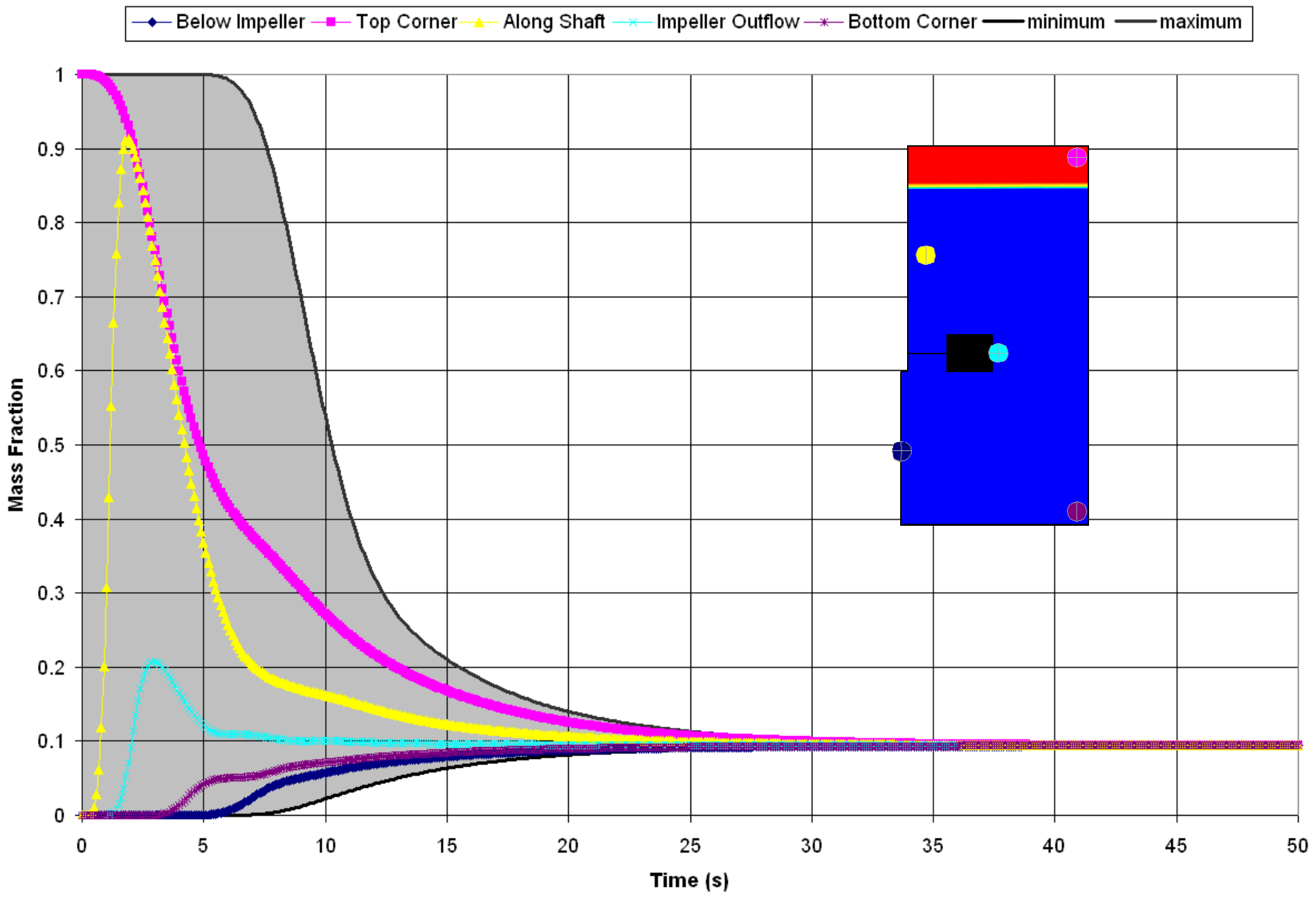


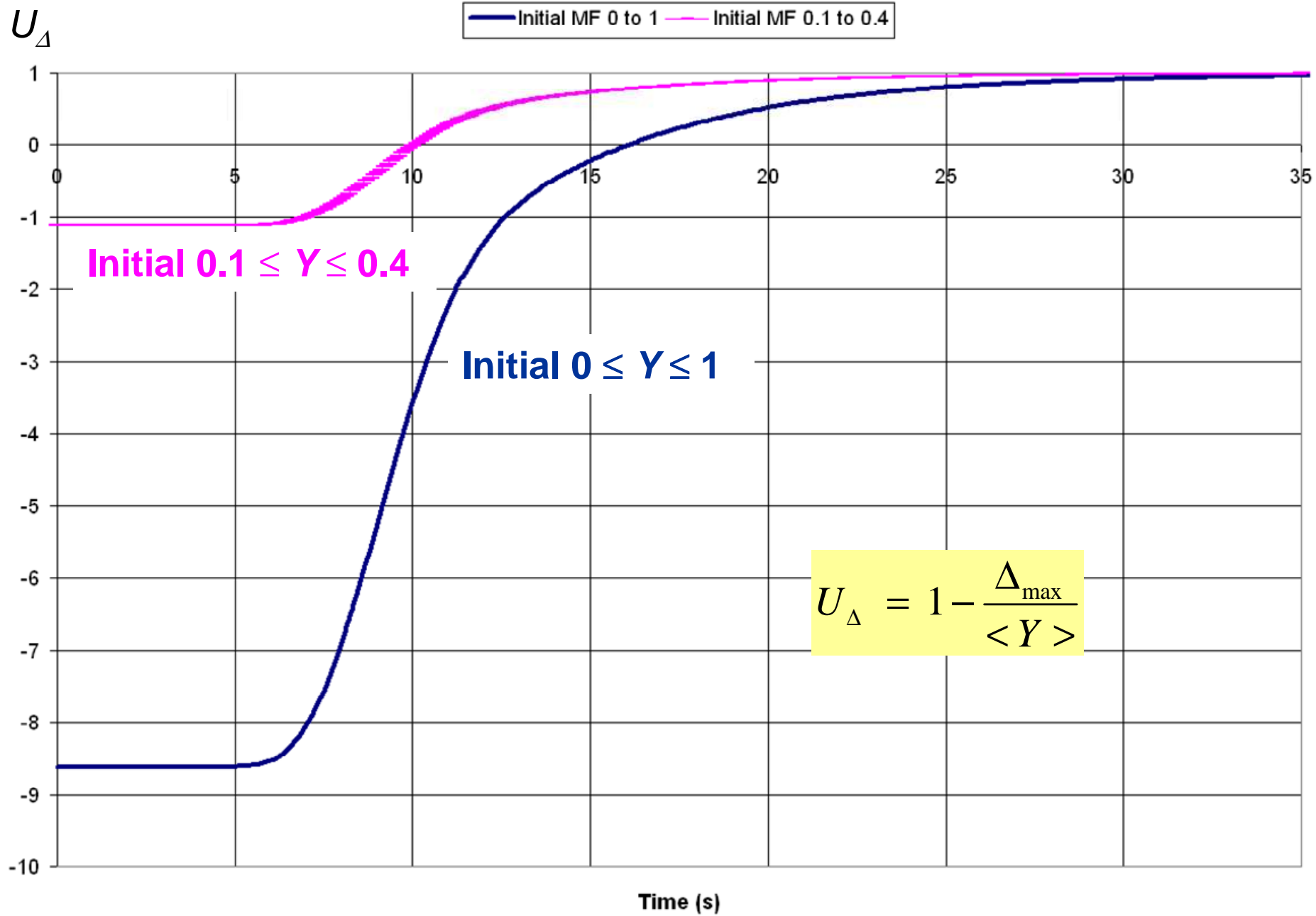
Layer with $Y_{tracer}=0.4$ on top of fluid
with $Y_{tracer}=0.1$. $\langle Y \rangle = 0.13$.

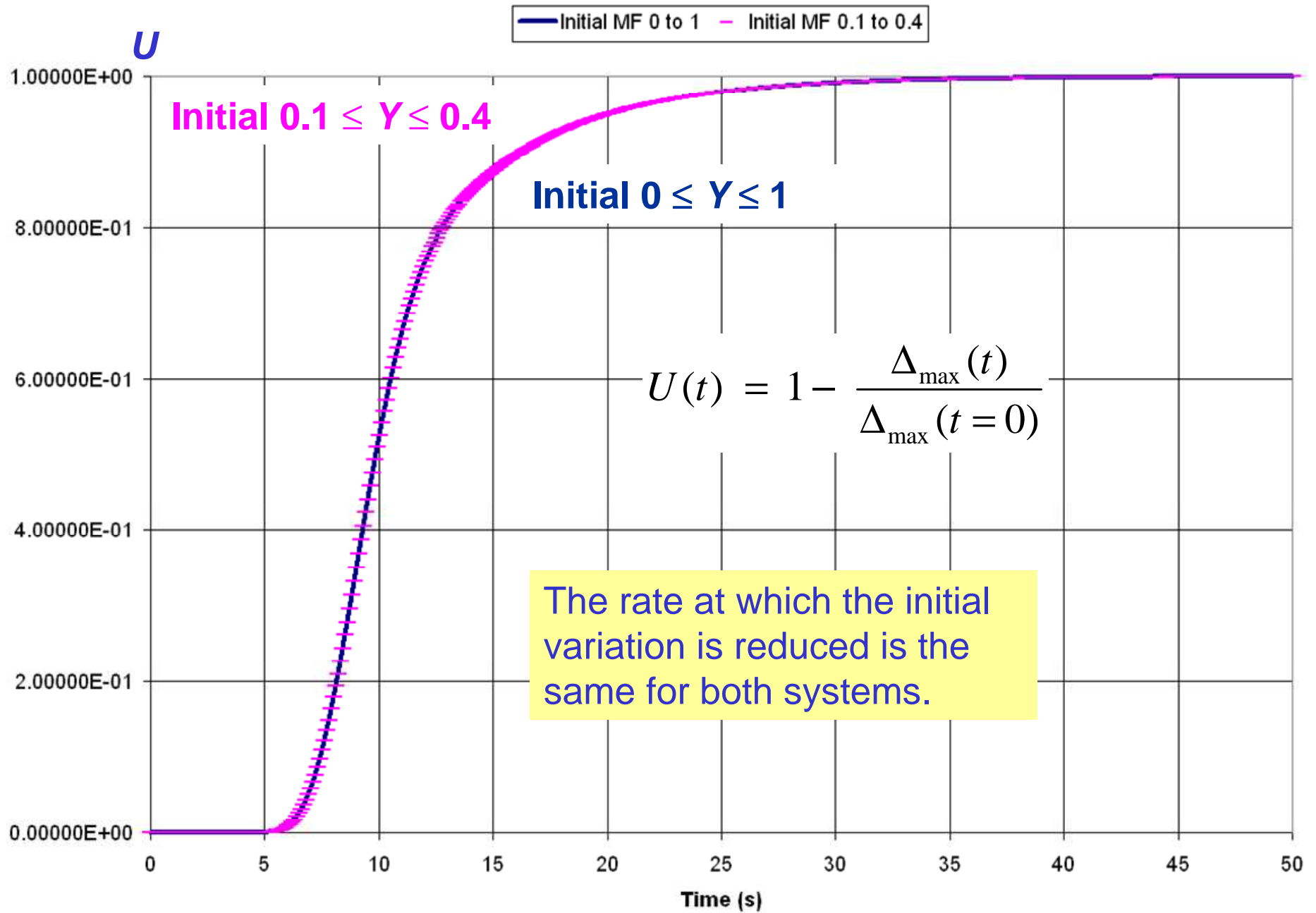


Rushton Impeller - 50 RPM - 31.6l Vessel - Initial MF 0.1 - 0.4
 Contours of Mass fraction of water-liquid-tracer (Time=0.0000e+00)
 FLUENT 6.2 (axi, segregated, spe, rke, unsteady)



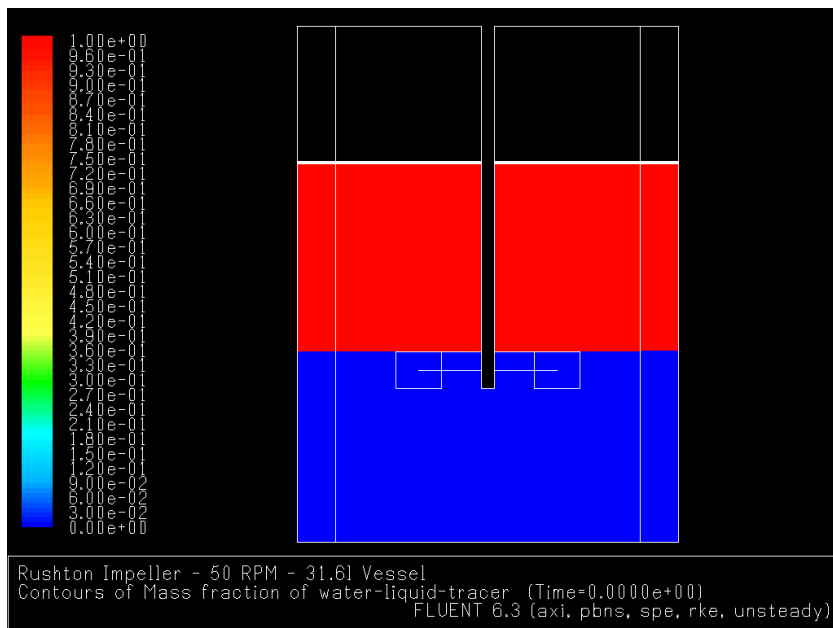




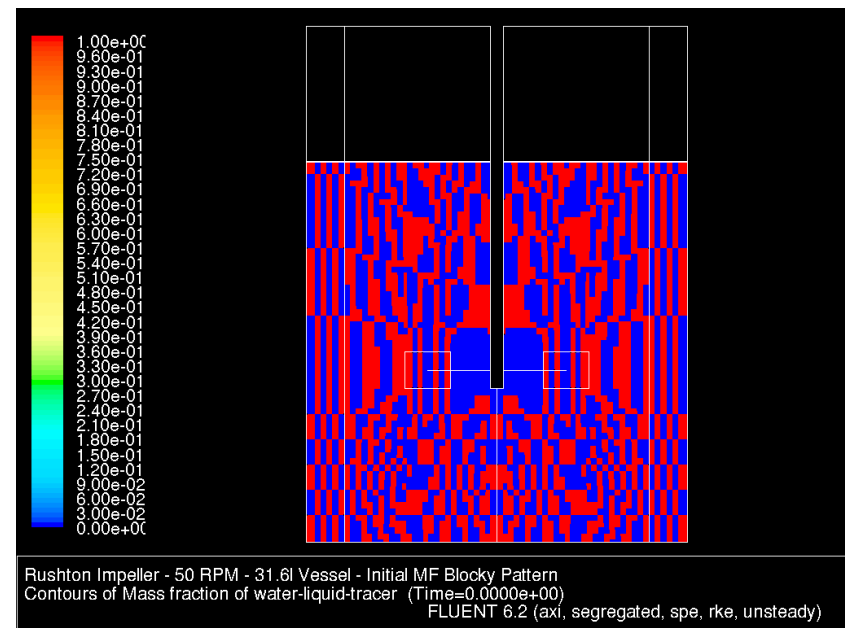


Compare two more systems

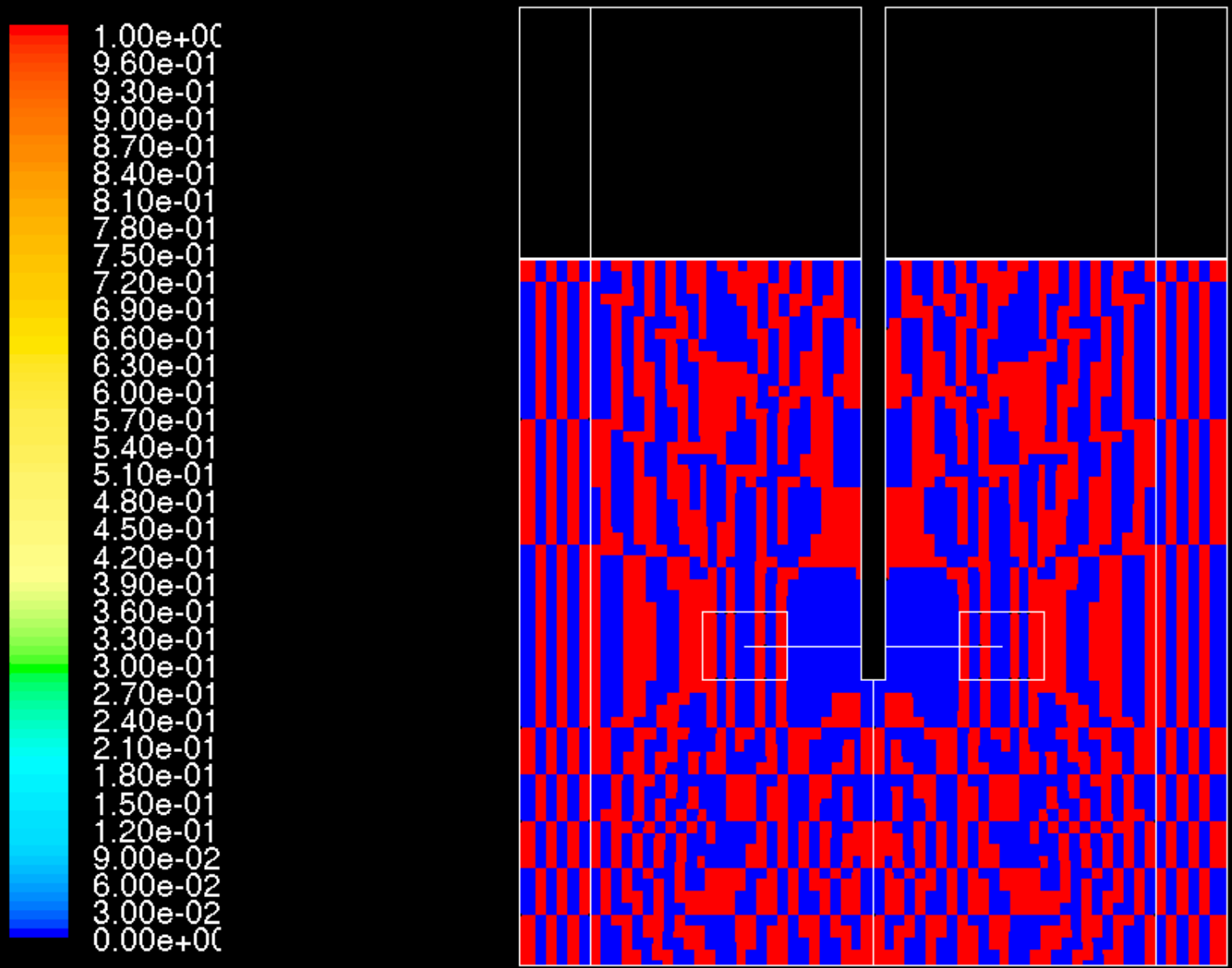
- Two systems with approximately the same average mass fraction of tracer $\langle Y \rangle \cong 0.5$.
- The initial distributions are very different: layered vs. blocky pattern.



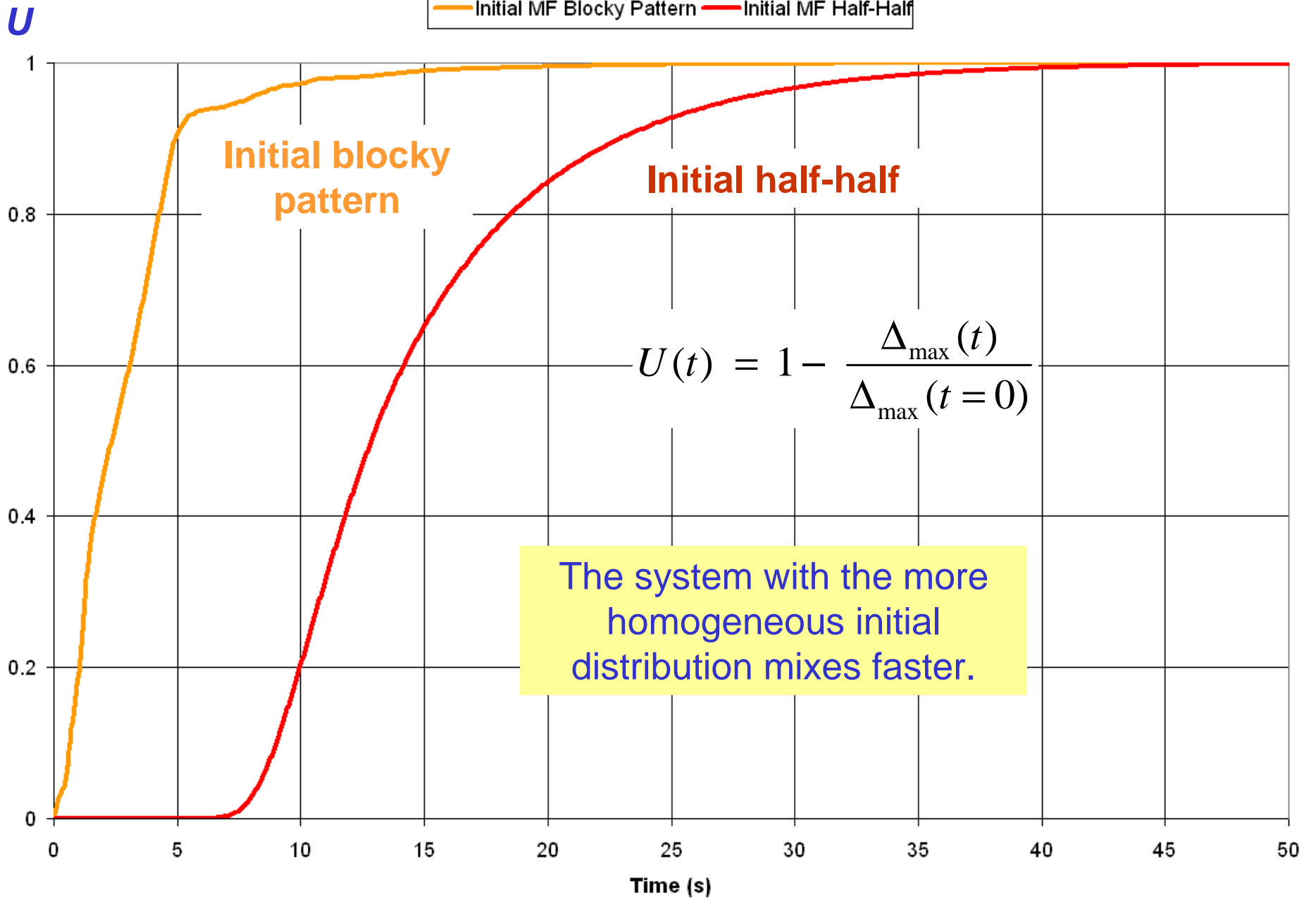
Layer with $Y_{tracer}=1$ on top of fluid
with $Y_{tracer}=0$. $\langle Y \rangle = 0.497$.



Blocky pattern of fluid with $Y_{tracer}=0$.
and fluid with $Y_{tracer}=1$. $\langle Y \rangle = 0.491$.



Rushton Impeller - 50 RPM - 31.6l Vessel - Initial MF Blocky Pattern
 Contours of Mass fraction of water-liquid-tracer (Time=0.0000e+00)
 FLUENT 6.2 (axi, segregated, spe, rke, unsteady)



Compare all four systems

Initial Y	U
Layer (0 to 1)	20.3
Layer (0.1 to 0.4)	20.3
Blocky Pattern	10.7
Half-Half	26.1

- Table shows number of impeller revolutions it takes to achieve 99% uniformity for all four systems using the two main criteria:
 - U based on reduction in initial variation.
 - U_{Δ} based on variation from the average.
- Conclusion: systems with good initial distributions mix faster.
- General recommendation: use U (reduction in initial variation) to correlate results or to compare with literature blend time correlations.

Continuous systems

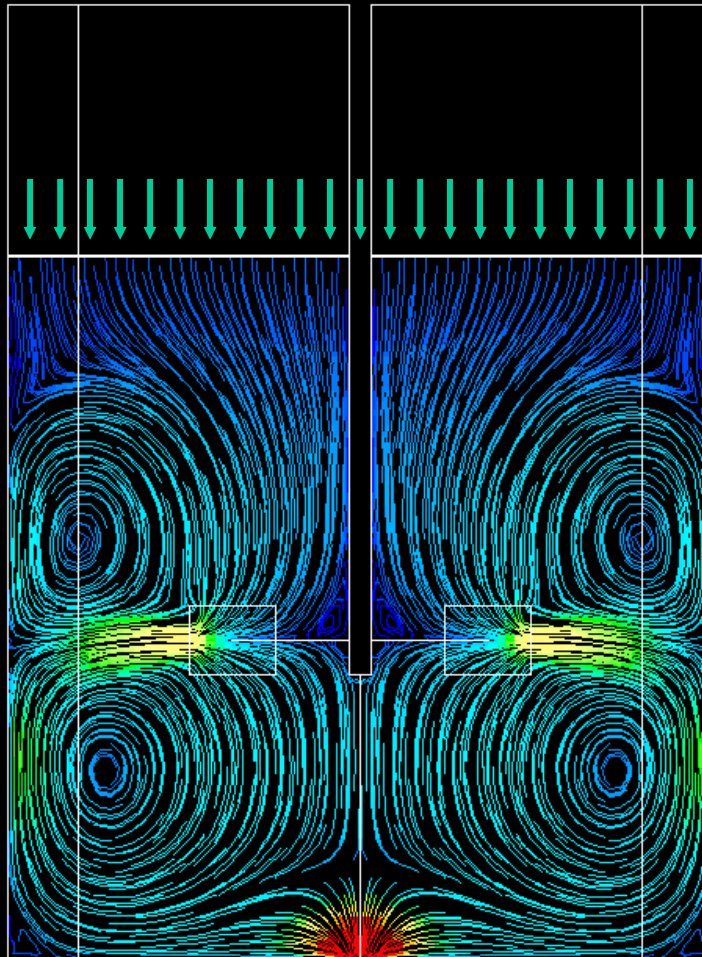
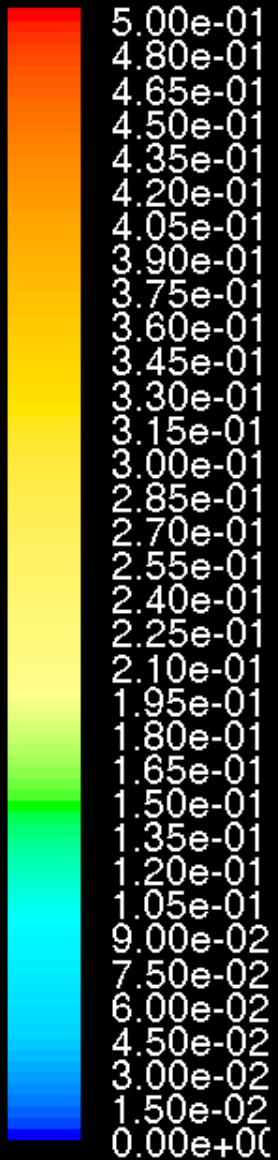
- Methods so far are for batch systems.
- Do these methods work for continuous systems?
 - Requires some modification.
 - Looking at mass fraction extremes does not work, because these may be fixed by the inlet mass fractions.
- Various approaches used:
 - Compare batch blend time with average residence time of the material ($RT = \text{liquid volume} / \text{volumetric flow rate}$). If batch blend time is much smaller than RT , assume there is no mixing problem.
 - Perform particle tracking simulation, similar to shown for static mixers in previous lectures. Analyze residence time distributions.
 - Perform tracer mixing calculation.

Tracer mixing calculation

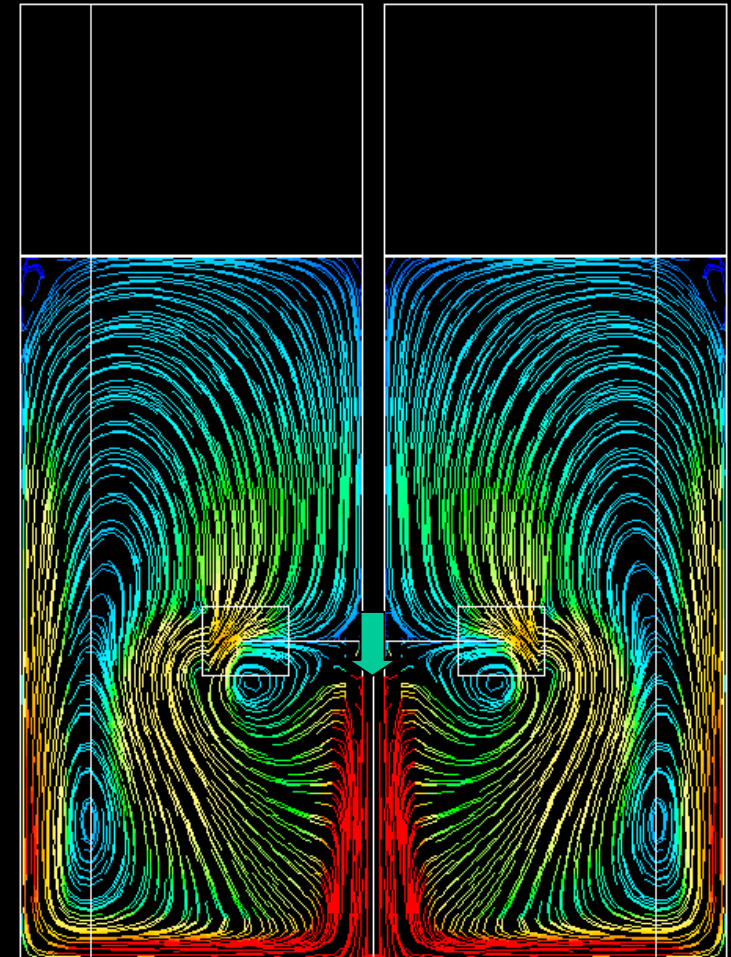
- Calculate continuous, steady state flow field.
- Initial mass fraction of tracer is zero everywhere.
- Perform transient calculation for tracer mixing, with non-zero mass fraction tracer at inlet.
- Monitor:
 - Average mass fraction in domain $\langle Y \rangle$.
 - Mass fraction at outlet Y_{out}
 - Optional: monitor CoV.
- Definition of perfectly mixed system: $Y_{out} = \langle Y \rangle$.
- Mixing time is then the time it takes for the ratio $Y_{out}/\langle Y \rangle$ to be within a specified tolerance of 1.
- Mixing time can be expressed in number of residence times: t/RT .

Compare two systems

- Rushton turbine flow field.
- Continuous system with two different injections:
 - Low velocity feed (0.01 m/s) distributed across liquid surface.
 - Affects flow in upper part of the vessel only.
 - High speed jet feed (9.6 m/s) entering through bottom shaft.
 - Because of the large momentum contained in the jet, it alters the flow field significantly.
- Outflow at center of bottom.
- Average residence time $RT=30s$, equivalent to 25 impeller revolutions. The RT is similar to the batch blend time.



**Surface inlet,
bottom outflow.**

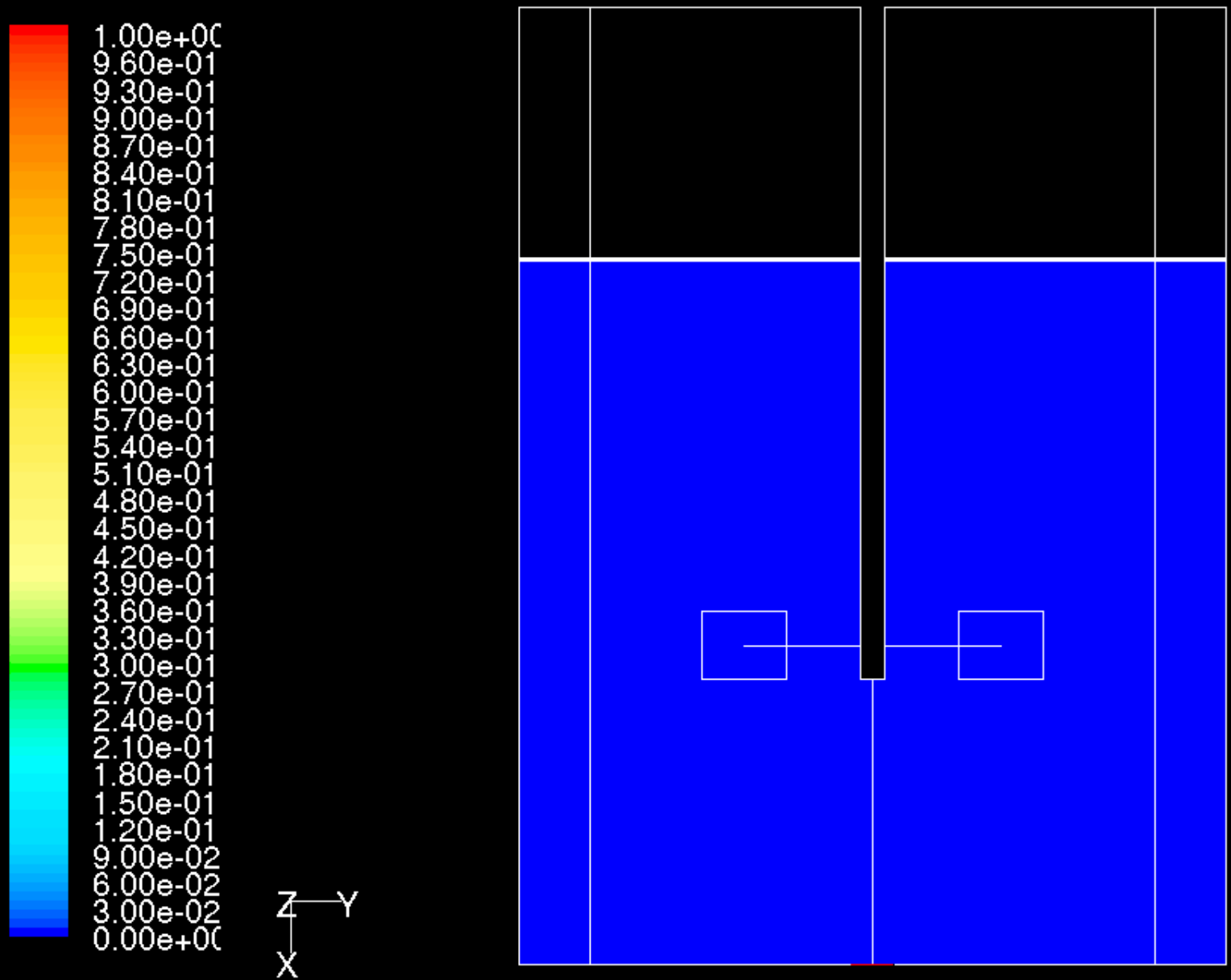


**Shaft inlet,
bottom outflow.**

Rushton Impeller - 50 RPM - 31.6l Vessel - Continuous flow
 Path Lines Colored by Velocity Magnitude (m/s)

Average residence time RT=30s.

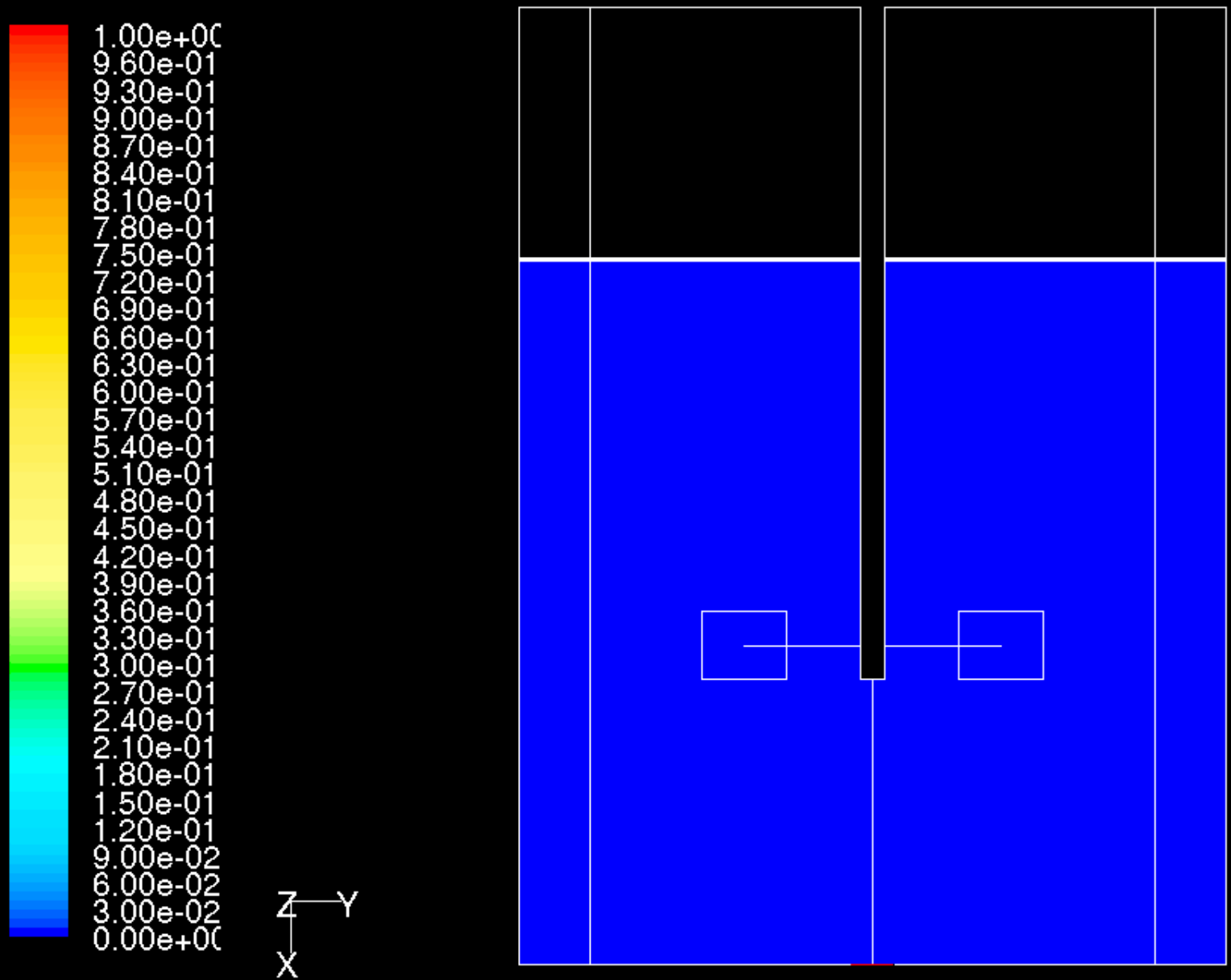
FLUENT 6.2 (axi, segregated, spe, rke)



Rushton Impeller - 50 RPM - 31.6l Vessel - Continuous flow - Surface Inlet

Contours of Mass fraction of water-liquid-tracer (Time=0.0000e+00)

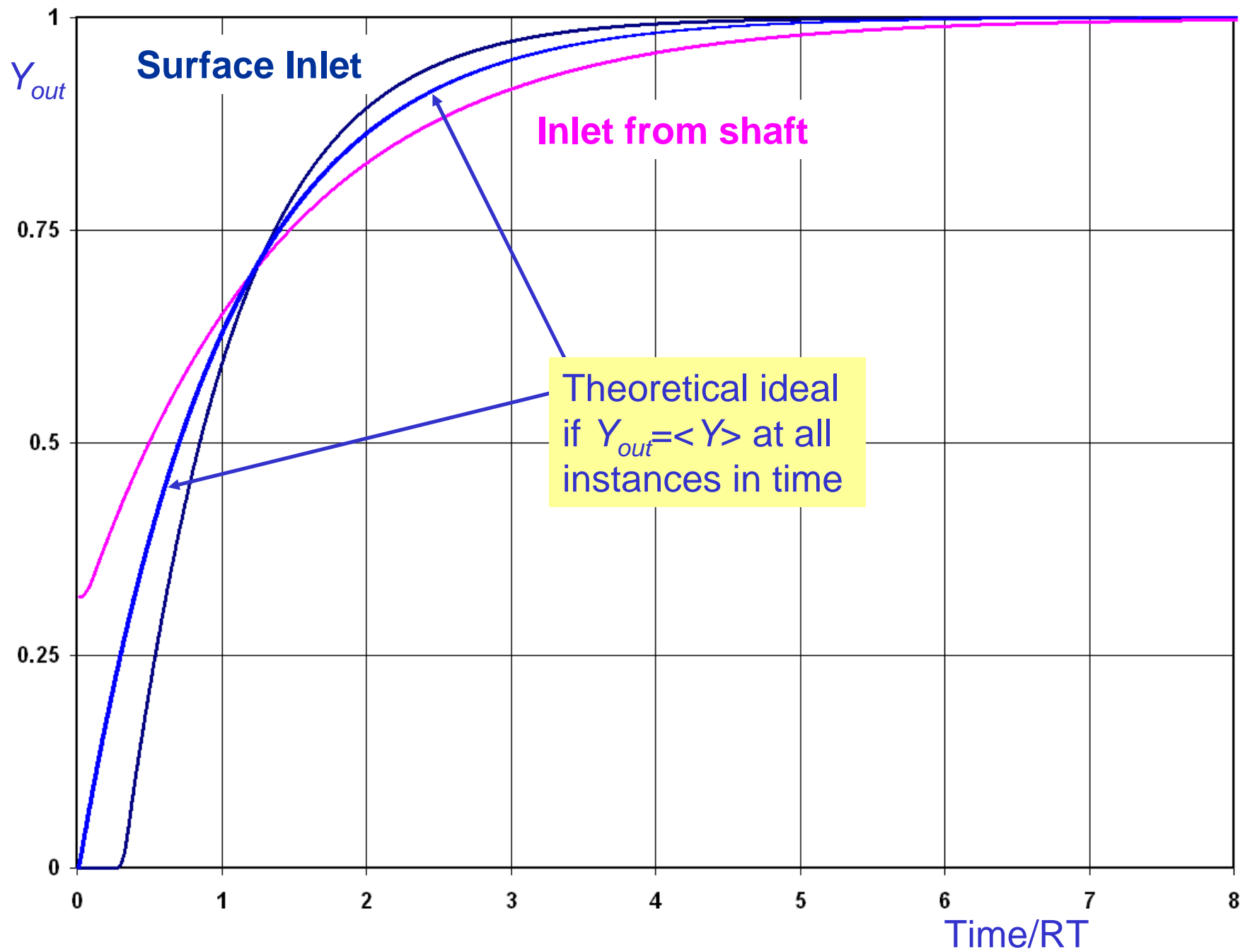
FLUENT 6.2 (axi, segregated, spe, rke, unsteady)



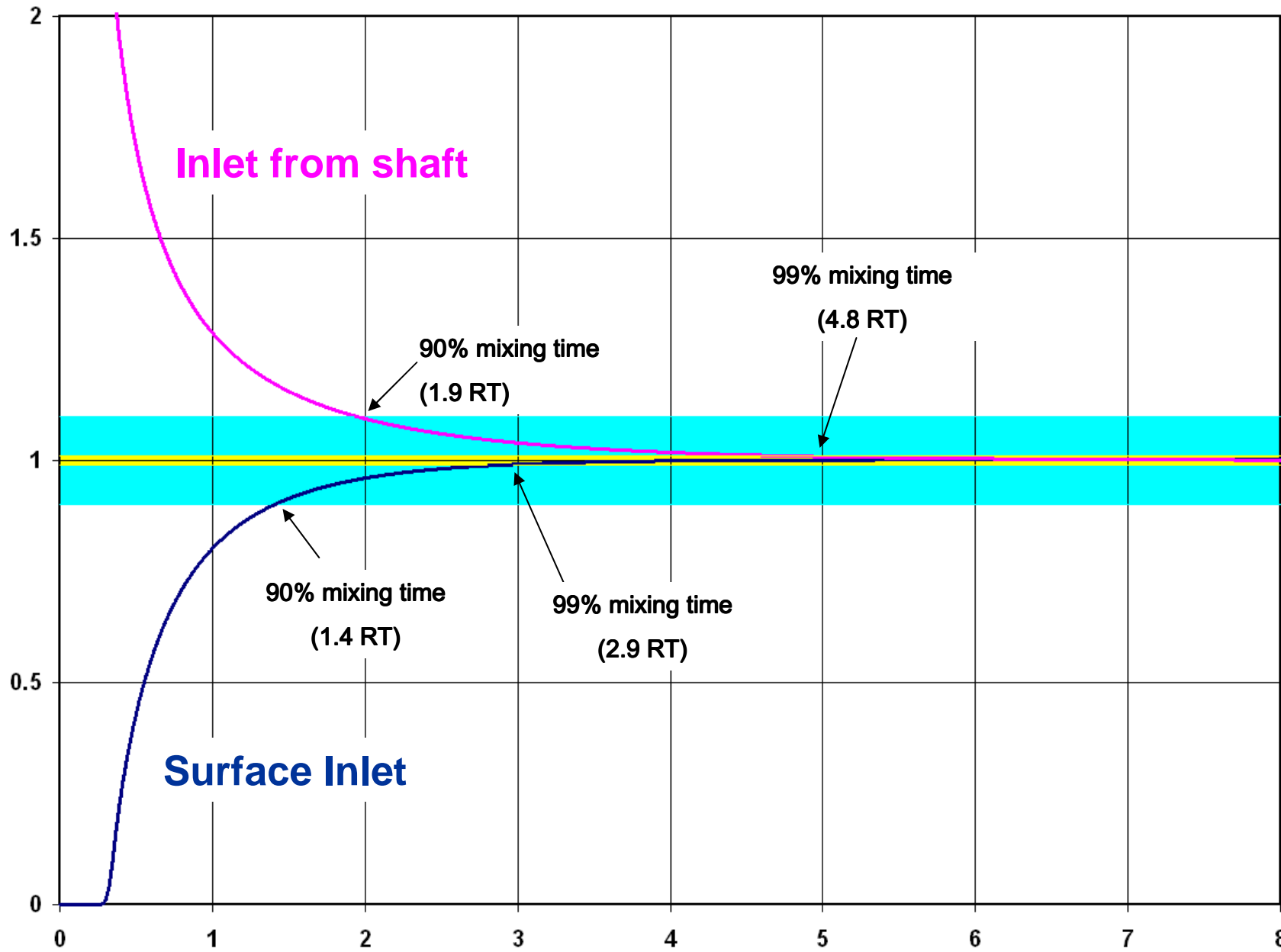
Rushton Impeller - 50 RPM - 31.6l Vessel - Continuous flow - Shaft Inlet

Contours of Mass fraction of water-liquid-tracer (Time=0.0000e+00)

FLUENT 6.2 (axi, segregated, spe, rke, unsteady)



$$Y_{out}/\langle Y \rangle$$



Time/RT

Comments

- The main assumption behind this approach is that the system will eventually reach a steady state where $Y_{out} = \langle Y \rangle$.
 - Not all industrial systems may have a steady state operating condition which, in general, is an undesirable situation that would need to be addressed.
- CoV can still be used to compare uniformity of different systems under steady state operating conditions with multiple species.