Modeling of turbulence in stirred vessels using large eddy simulation

André Bakker (presenter), Kumar Dhanasekharan, Ahmad Haidari, and Sung-Eun Kim

Fluent Inc.

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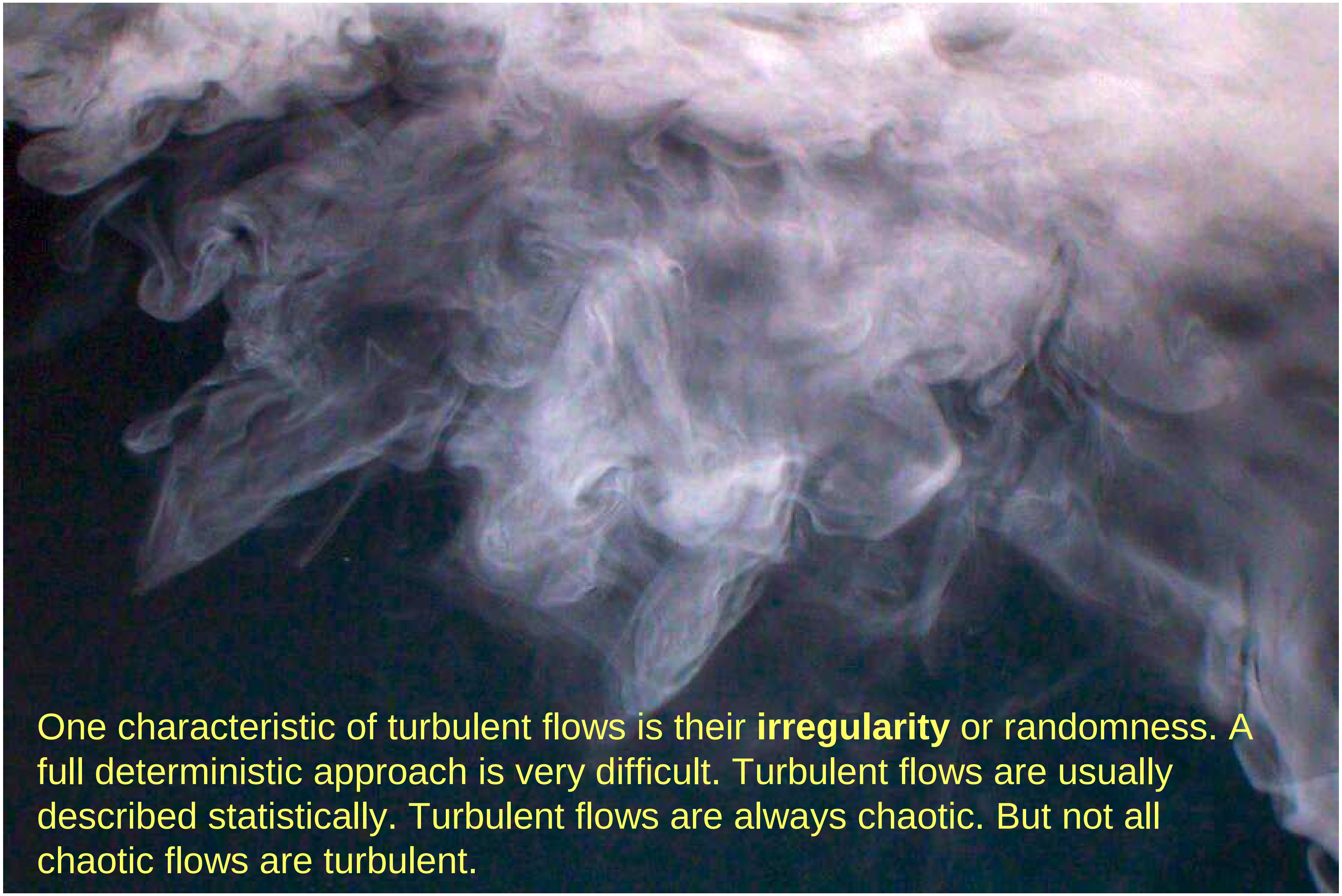
Introduction

- Nature of turbulence:
  - High Reynolds numbers, chaotic flow, dissipative, diffusive, vortex stretching, energy spectrum.
- Objective of turbulence modeling.
- Prediction methods and large eddy simulation models.
- Multiple hydrofoil impeller system example.
- Glass lined vessel example.
- When to use LES.

Turbulence: high Reynolds numbers

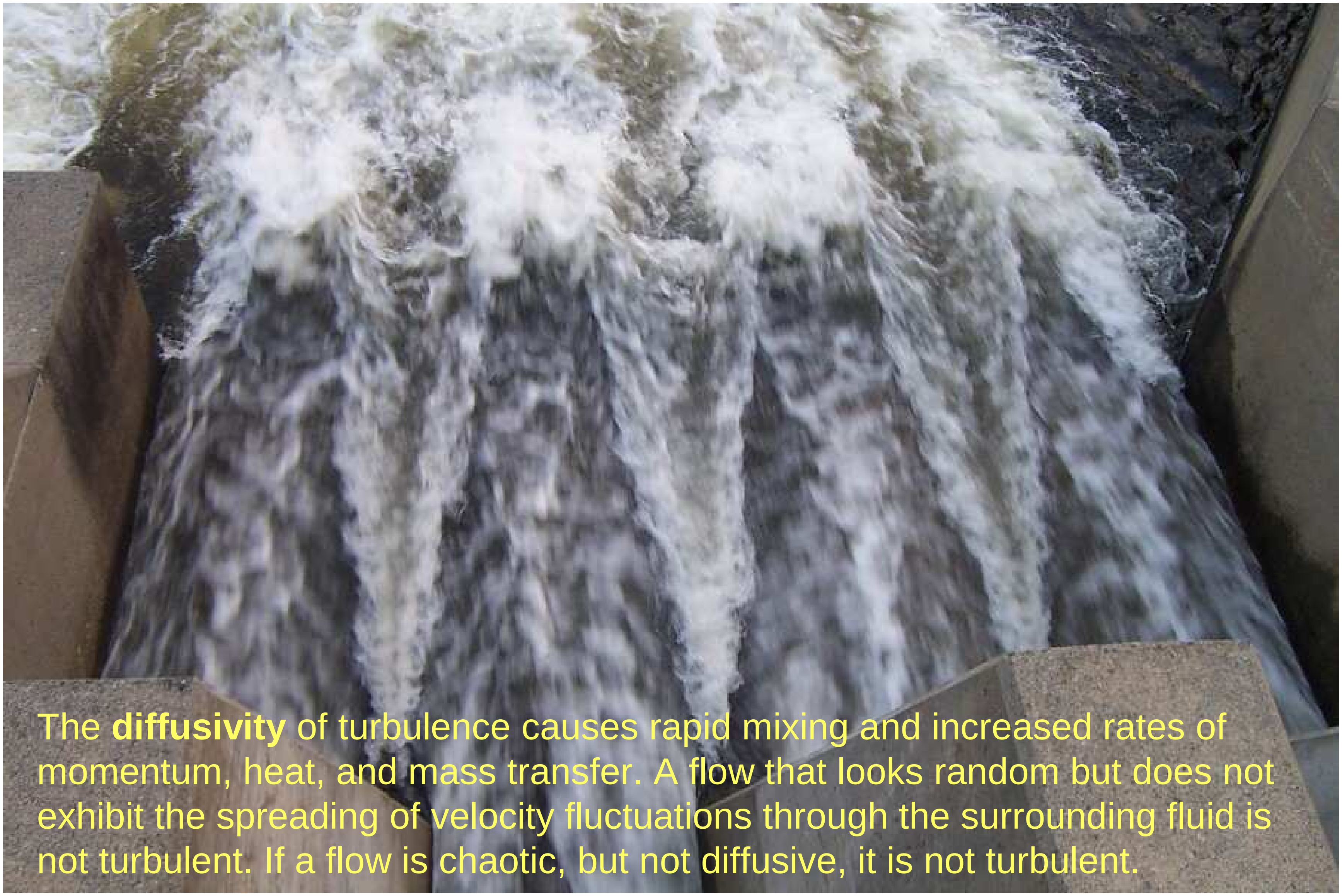
Turbulent flows always occur at **high Reynolds numbers**. They are caused by the complex interaction between the viscous terms and the inertia terms in the momentum equations.

Turbulent flows are chaotic



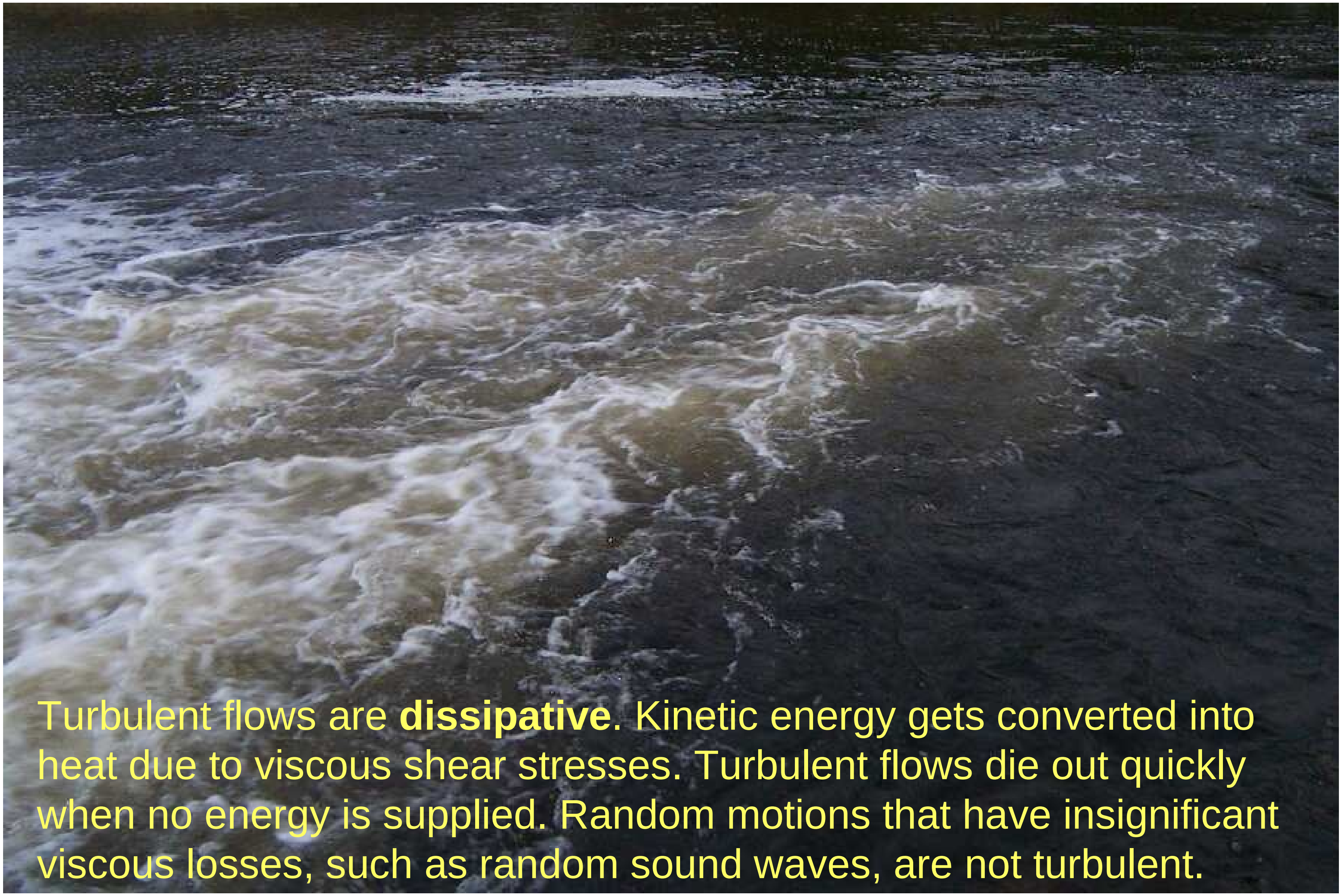
One characteristic of turbulent flows is their **irregularity** or randomness. A full deterministic approach is very difficult. Turbulent flows are usually described statistically. Turbulent flows are always chaotic. But not all chaotic flows are turbulent.

Turbulence: diffusivity



The **diffusivity** of turbulence causes rapid mixing and increased rates of momentum, heat, and mass transfer. A flow that looks random but does not exhibit the spreading of velocity fluctuations through the surrounding fluid is not turbulent. If a flow is chaotic, but not diffusive, it is not turbulent.

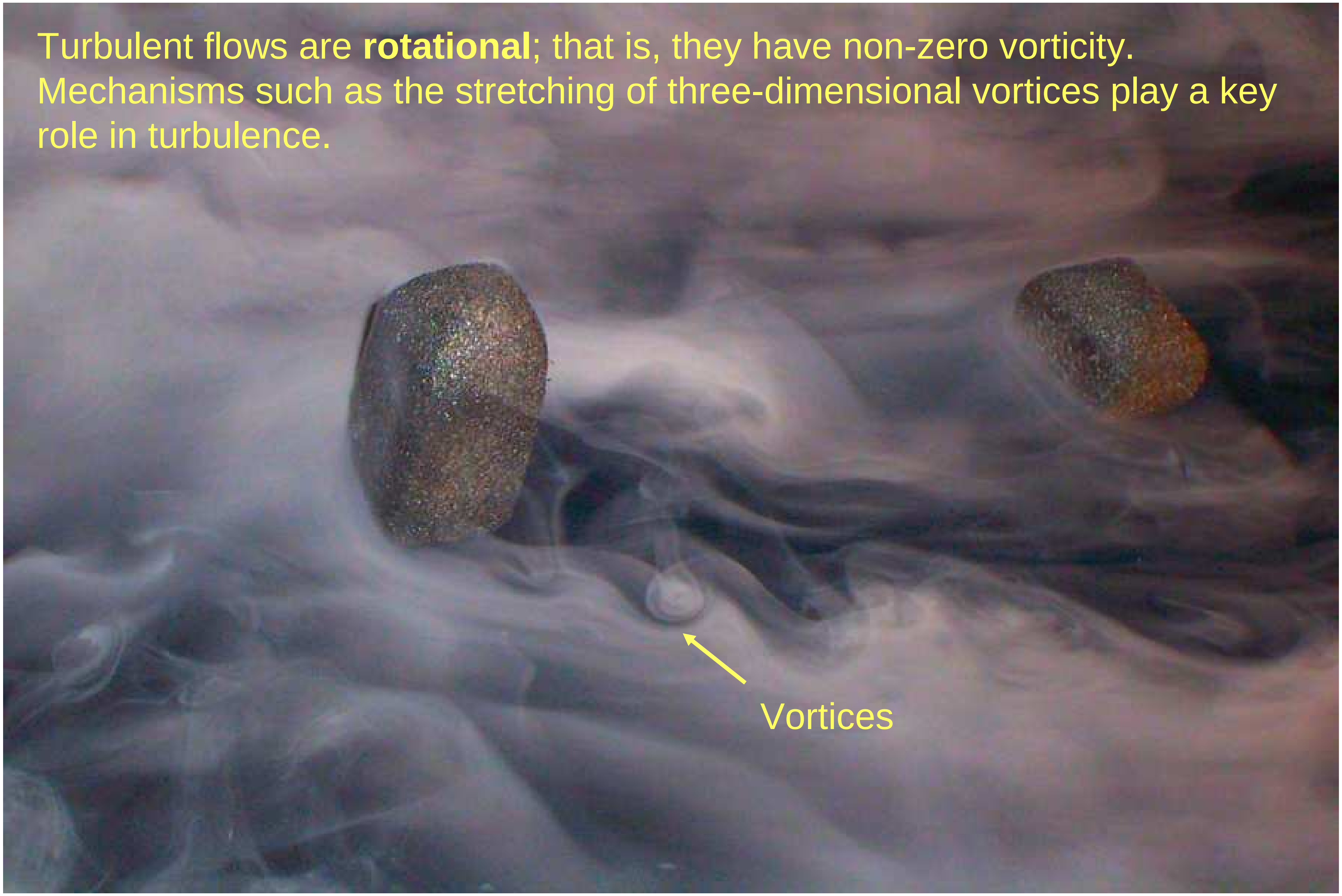
Turbulence: dissipation



Turbulent flows are **dissipative**. Kinetic energy gets converted into heat due to viscous shear stresses. Turbulent flows die out quickly when no energy is supplied. Random motions that have insignificant viscous losses, such as random sound waves, are not turbulent.

Turbulence: rotation and vorticity

Turbulent flows are **rotational**; that is, they have non-zero vorticity. Mechanisms such as the stretching of three-dimensional vortices play a key role in turbulence.



Turbulence: eddies and vortex stretching

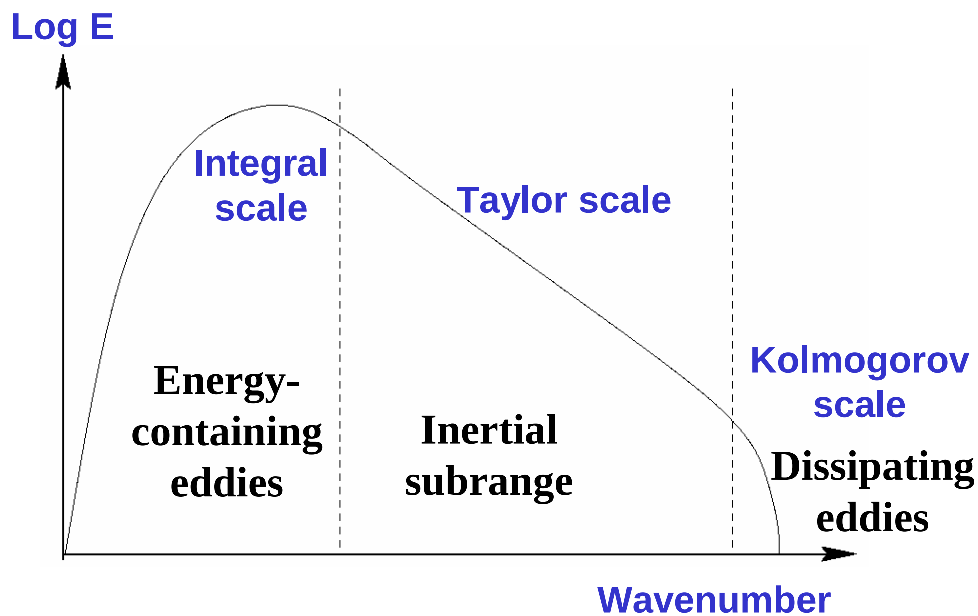
- Turbulence can be considered to consist of eddies of different sizes.
- An 'eddy' preludes precise definition, but it is conceived to be a turbulent motion, localized over a region of size l, that is at least moderately coherent over this region.
- The region occupied by a larger eddy can also contain smaller eddies.
- Existence of eddies implies rotation or vorticity.
- Vorticity concentrated along contorted vortex lines or bundles.
- As end points of a vortex line move randomly further apart the vortex line increases in length but decreases in diameter.
  - Vorticity increases because angular momentum is nearly conserved.
  - Kinetic energy increases at rate equivalent to the work done by large-scale motion that stretches the bundle.

Turbulence: energy cascade

- Viscous dissipation in the smallest eddies converts kinetic energy into thermal energy.
- Vortex-stretching cascade process maintains the turbulence and dissipation is approximately equal to the rate of production of turbulent kinetic energy.
- Typically energy gets transferred from the large eddies to the smaller eddies. However, sometimes smaller eddies can interact with each other and transfer energy to the (i.e. form) larger eddies, a process known as backscatter.

Kolmogorov energy spectrum

- Energy cascade, from large scale to small scale.
- E is energy contained in eddies of wavelength λ.
- Length scales:
  - Largest eddies. Integral length scale ($k^{3/2}/\varepsilon$).
  - Length scales at which turbulence is isotropic. Taylor microscale $(15\nu u'^2/\varepsilon)^{1/2}$.
  - Smallest eddies. Kolmogorov length scale $(\nu^3/\varepsilon)^{1/4}$. These eddies have a velocity scale $(\nu.\varepsilon)^{1/4}$ and a time scale $(\nu/\varepsilon)^{1/2}$.



ε is the energy dissipation rate (m^2/s^3)

k is the turbulent kinetic energy (m^2/s^2)

ν is the kinematic viscosity (m^2/s)

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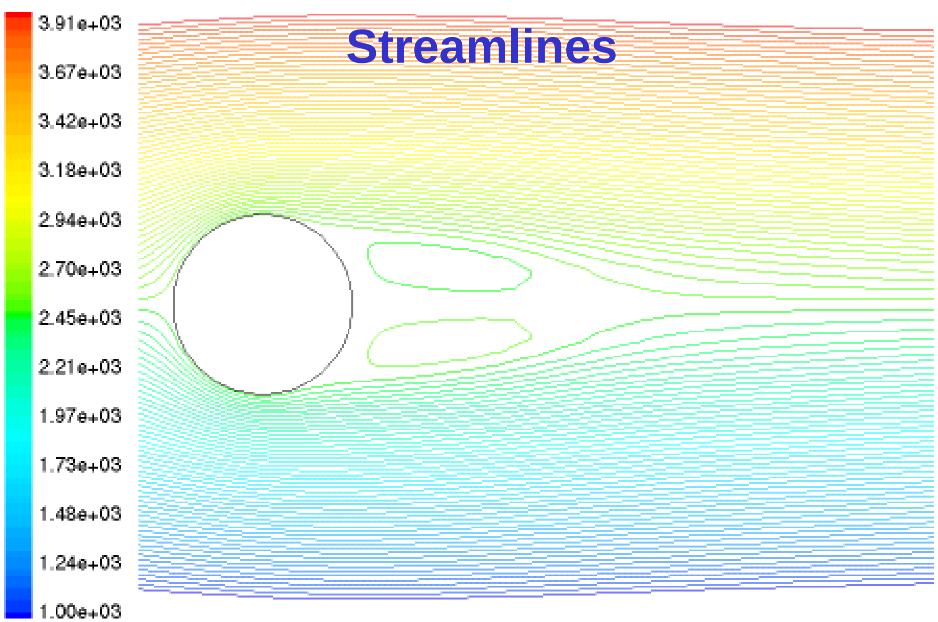
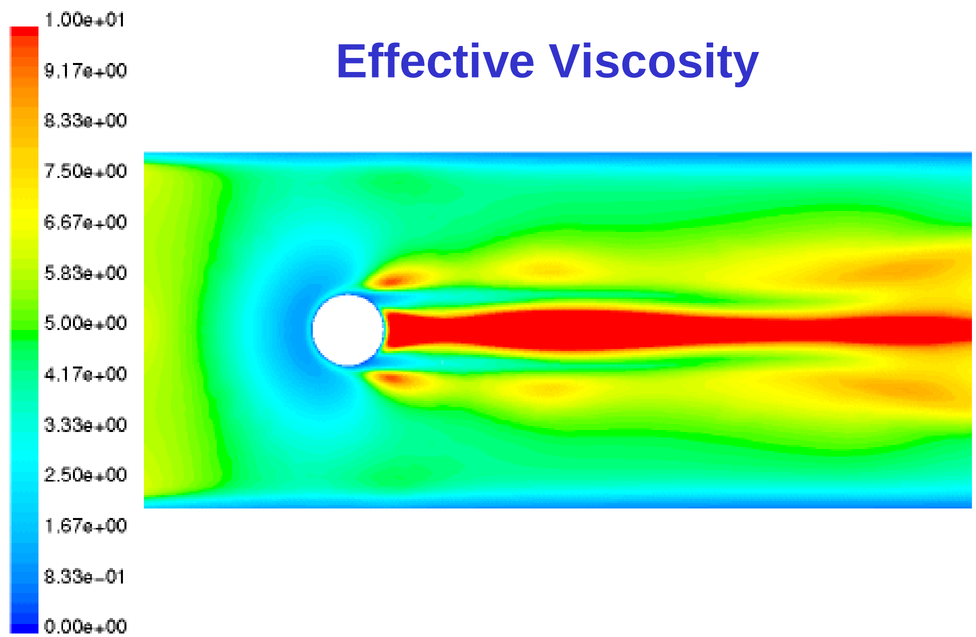
Turbulence modeling objective

- The objective of turbulence modeling is to develop equations that will predict the time averaged velocity, pressure, and temperature fields without calculating the complete turbulent flow pattern as a function of time.
  - This saves us a lot of work!
  - Most of the time it is all we need to know.
  - We may also calculate other statistical properties, such as RMS values.
- Important to understand: the time averaged flow pattern is a statistical property of the flow.
  - It is not an existing flow pattern!
  - The flow never actually looks that way!!

Example: flow around a cylinder at Re=1E4

- The figures show:
  - An experimental snapshot.
  - Streamlines for time averaged flow field. Note the difference between the time averaged and the instantaneous flow field.
  - Effective viscosity used to predict time averaged flow field.

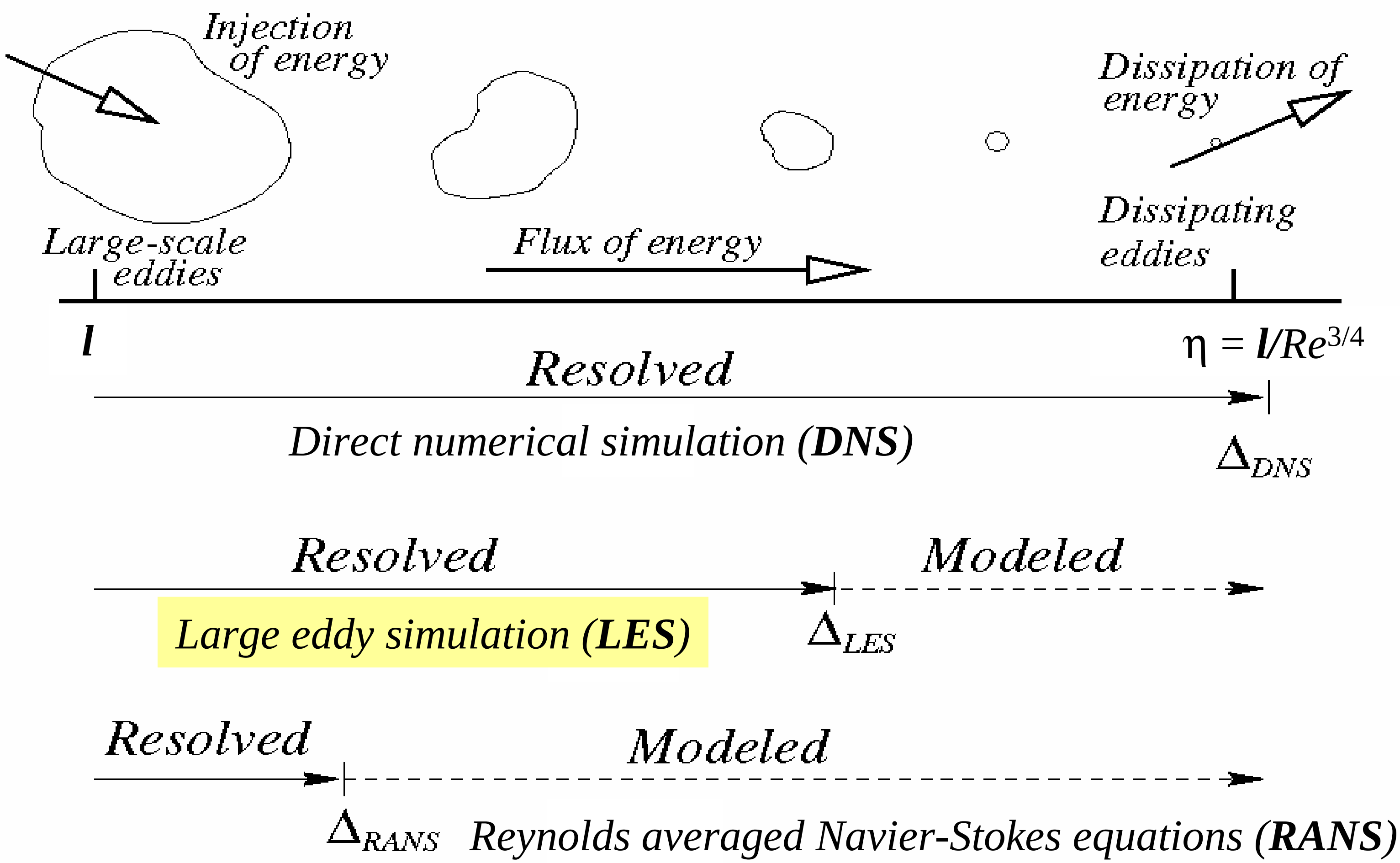




Predicting the turbulent viscosity

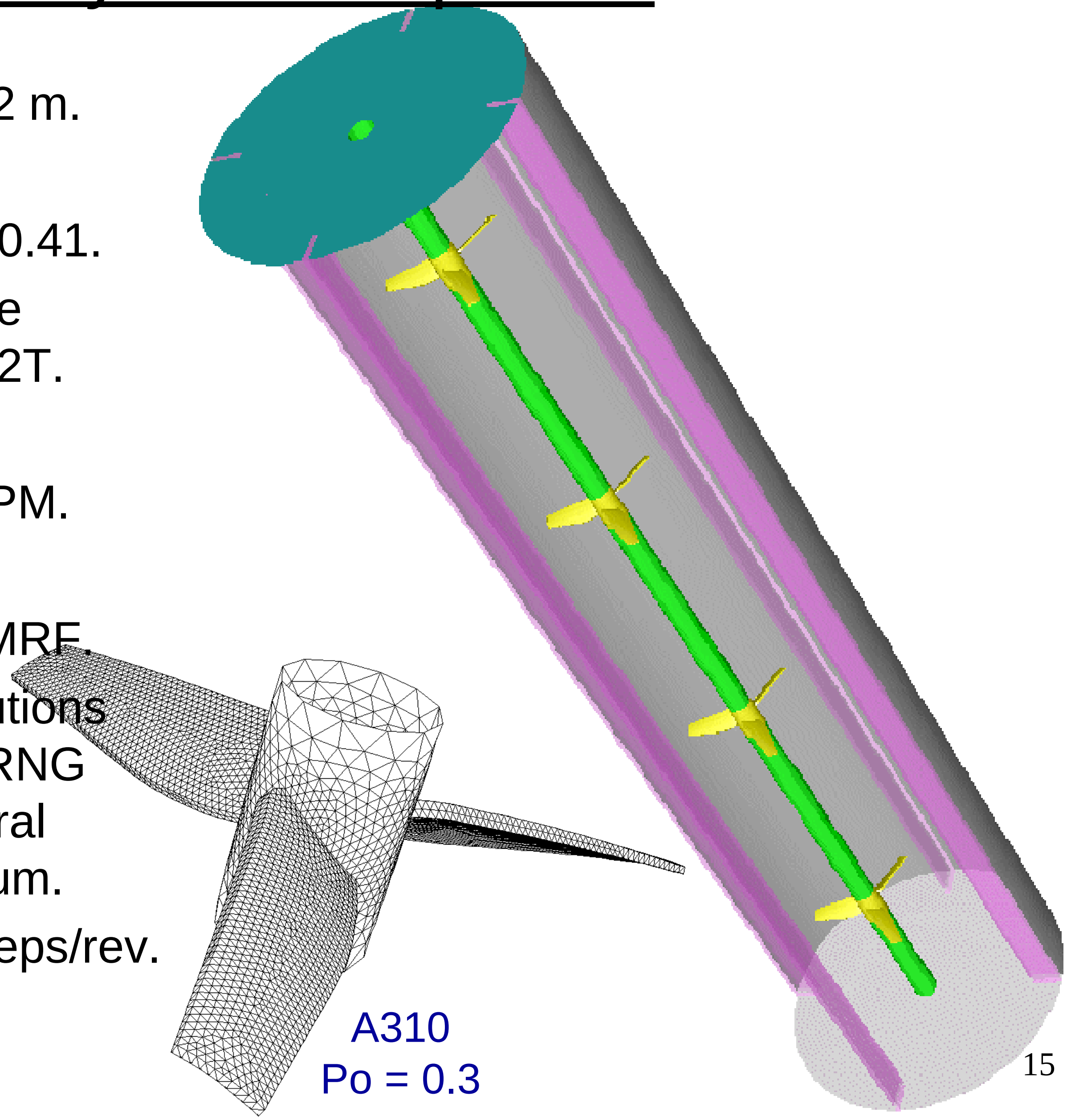
- The following models can be used to predict the turbulent viscosity:
  - Mixing length model.
  - Spalart-Allmaras model.
  - Standard k-ε model.
  - k-ε RNG model.
  - Realizable k-ε model.
  - k-ω model.
- Reynolds stress models do not use the turbulent viscosity concept.
- Large eddy simulation (LES) models do use the turbulent viscosity concept (then called the subgrid viscosity), but predict different and much lower values, so that only small eddies get suppressed.

Prediction methods



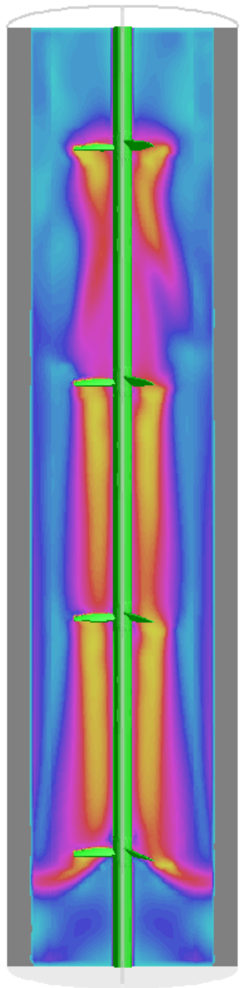
Example: multiple hydrofoil impellers

- Vessel diameter T=0.232 m.
- Vessel height H/T = 4.1.
- Impeller diameter D/T = 0.41.
- Center-to-center distance between impellers is 1.02T.
- Liquid is water.
- Impeller speed is 300 RPM.
- Impeller Re = 4.7E4.
- Solution initialized with MRF.
- Continued for 118 revolutions with sliding mesh, LES-RNG subgrid model, and central differencing for momentum.
- Time step of 5 ms; 40 steps/rev.

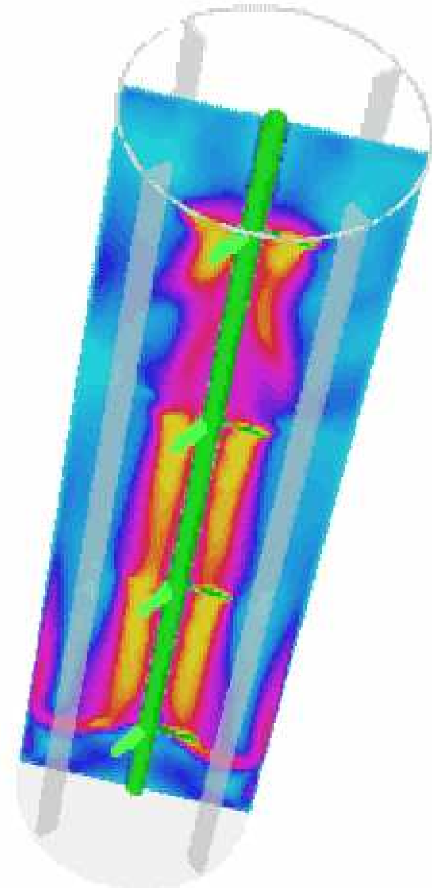


A310
Po = 0.3

Multiple A310 system

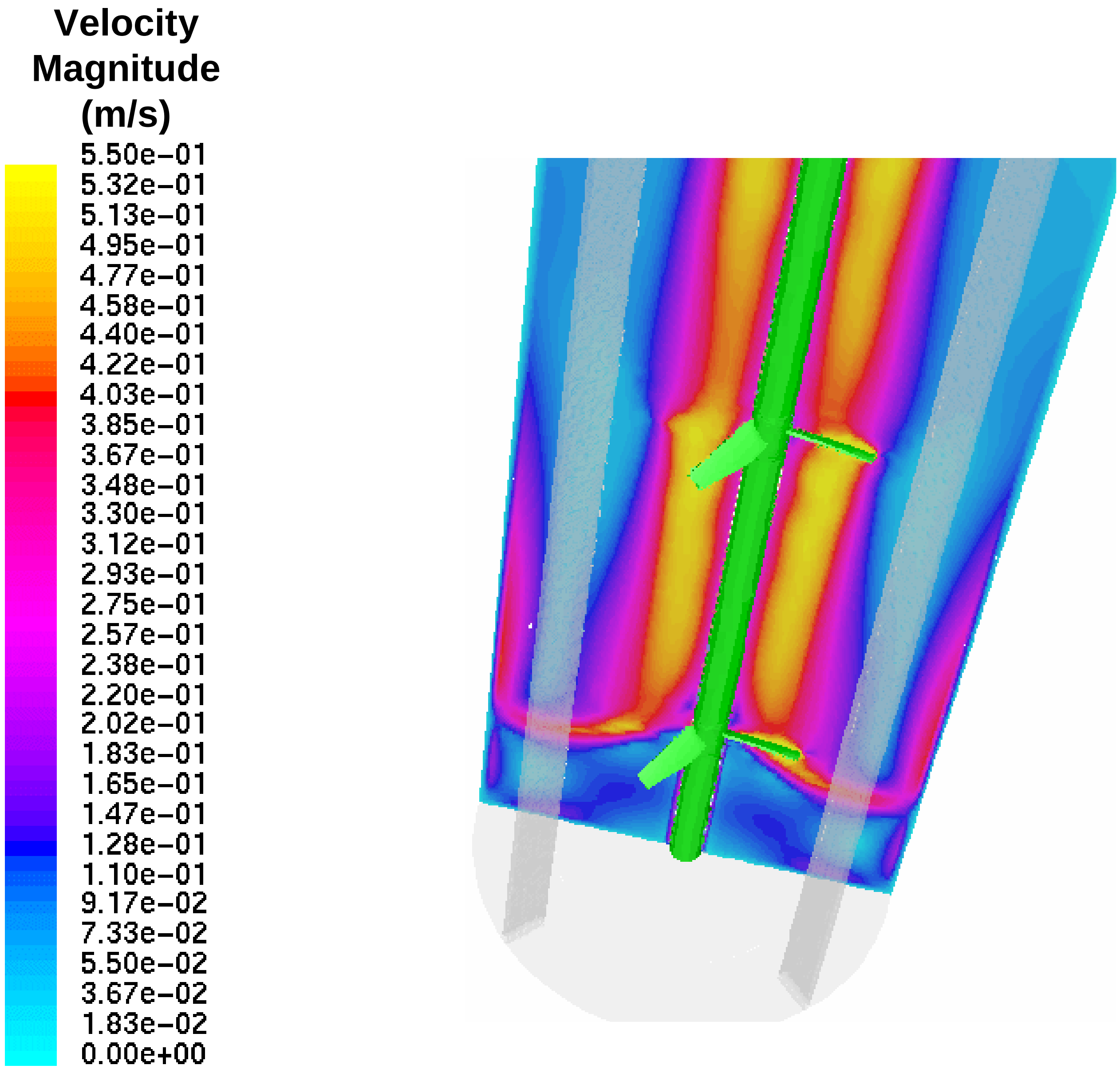


MRF with k-ε
Turbulent viscosity
ratio ~ 157

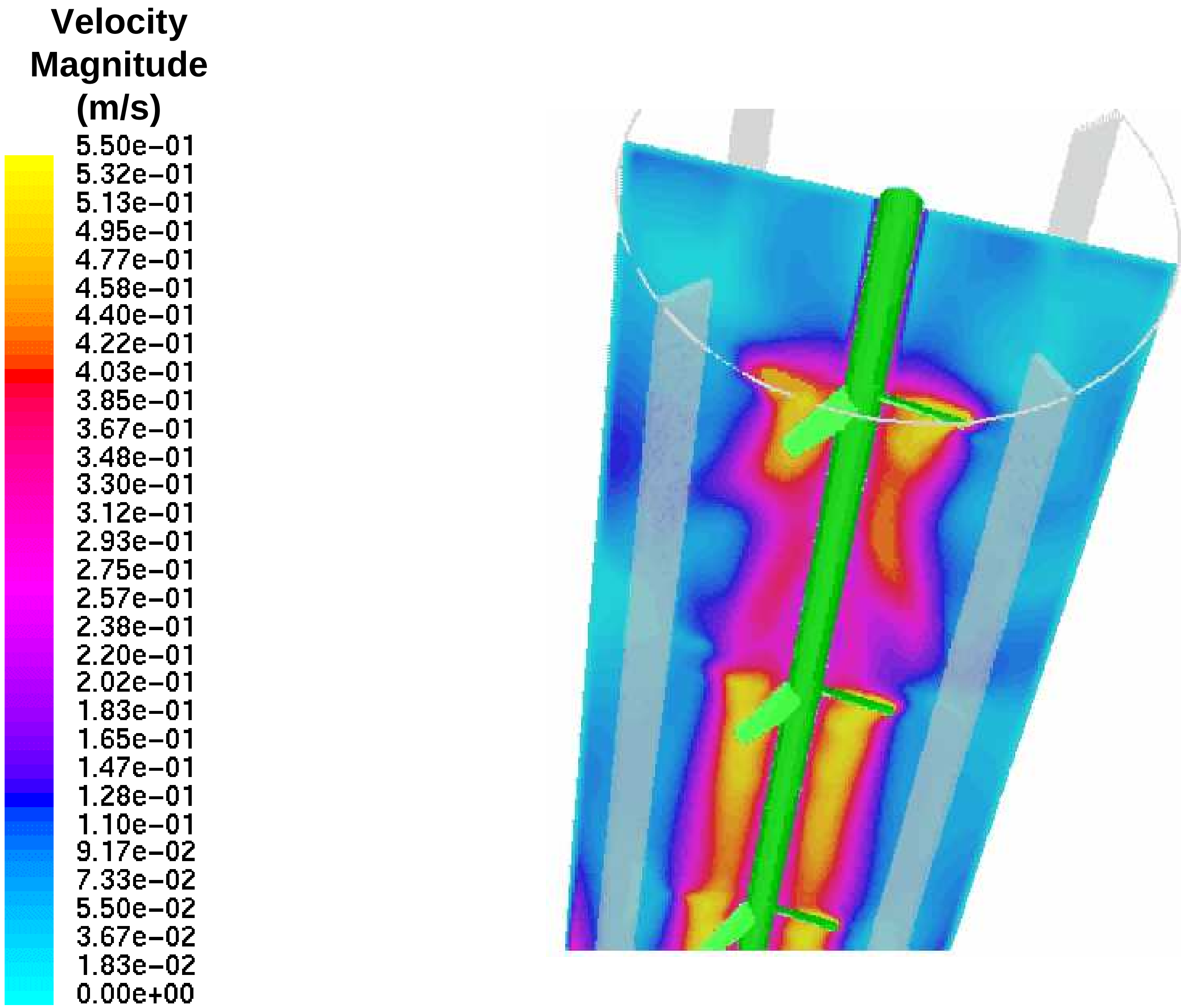


LES. Smagorinsky-RNG
Subgrid viscosity ratio ~ 10

Multiple A310 system



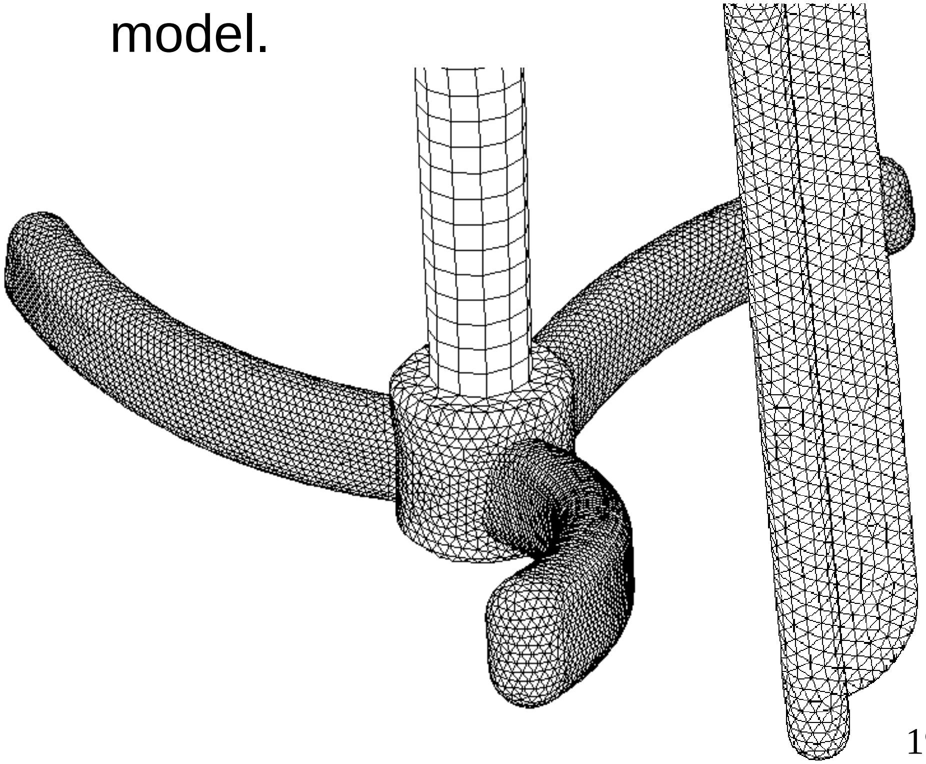
Multiple A310 system

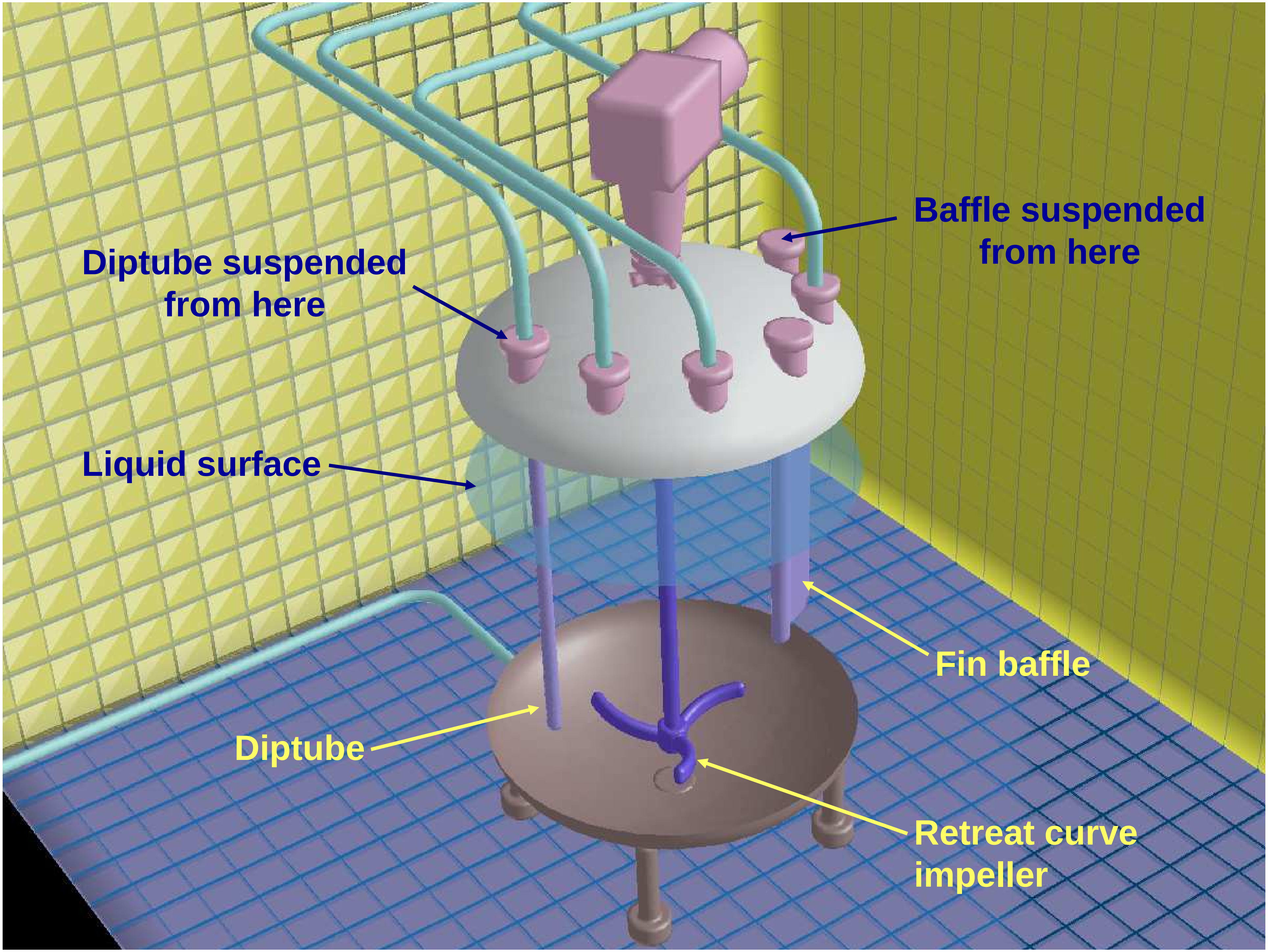


Glass lined equipment

- Glass lined equipment is characterized by the fact that all angles have to be rounded to prevent cracking of the glass coat.
- Vessels are typically equipped with either a classic retreat curve impeller or a combination of a radial flow impeller on the bottom and an axial flow impeller on the top.
- Glass lined vessels usually have one baffle and a diptube, which can have instrumentation.

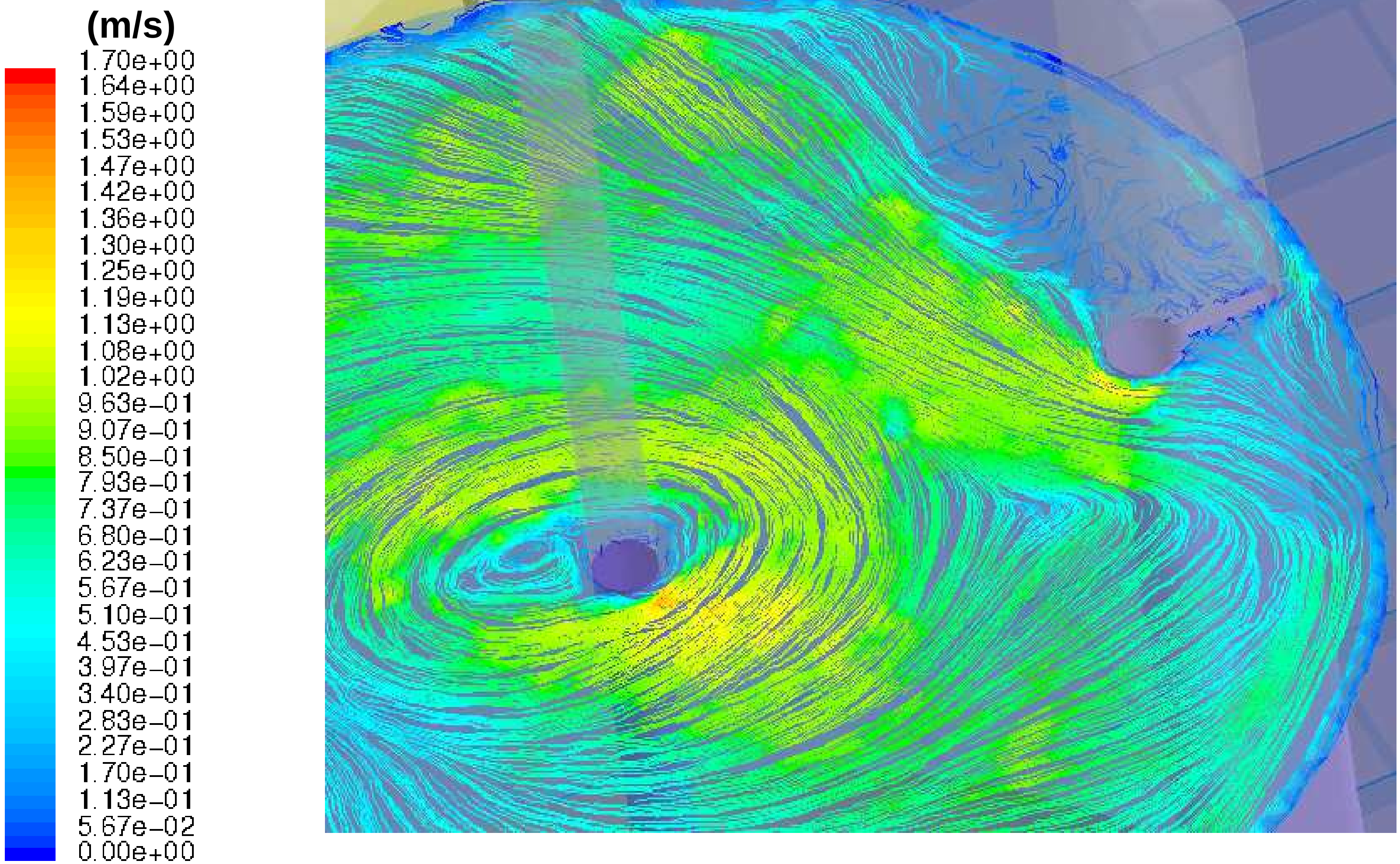
- 8 m^3 vessel at 5.8 m^3 fill level.
- 180 RPM with water. Re=3E6.
- RCI at D/T=0.49.
- Fin baffle and diptube.
- LES. Smagorinsky-RNG subgrid model.





Diptube suspended
from here
Baffle suspended
from here
Liquid surface
Fin baffle
Diptube
Retreat curve
impeller

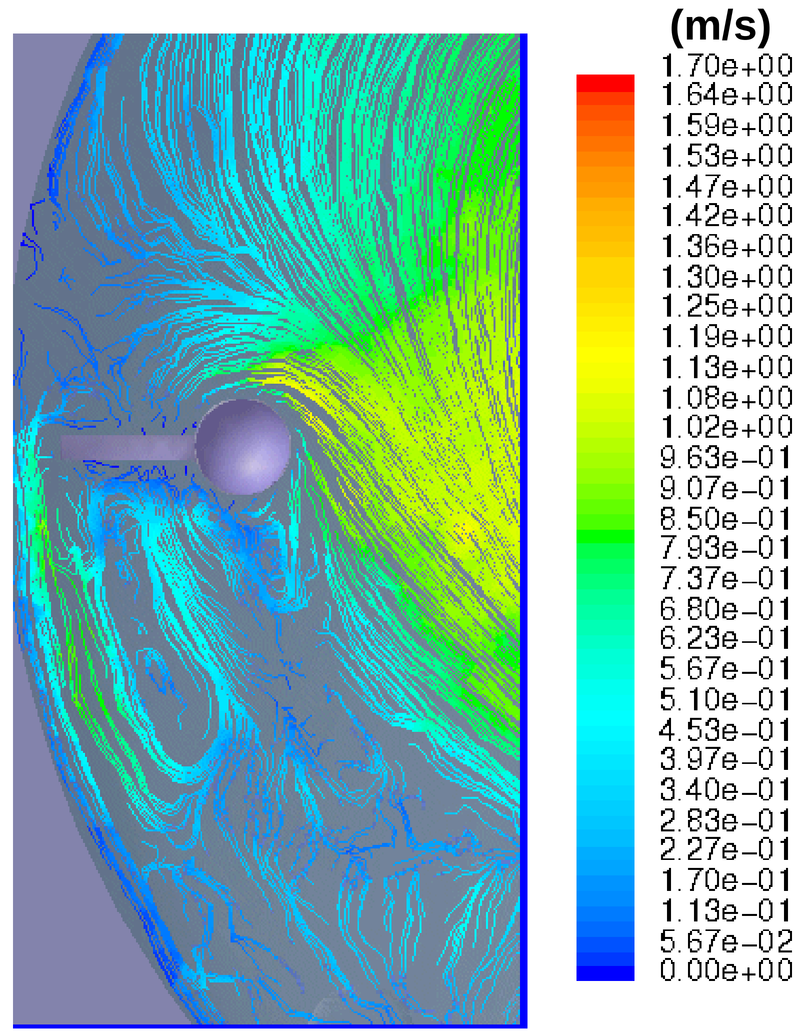
Flow field at liquid surface



Vortex precesses around shaft approximately once per 40 revolutions.

Flow field behind baffle

- Flow field visualized by means of “oilflow” lines.
- Oilflow lines are trajectories of flow following particles that are constrained to the surface of which they are released, in this case the liquid surface.
- The animation covers 8.4s real time, which corresponds to ~25 impeller revolutions.



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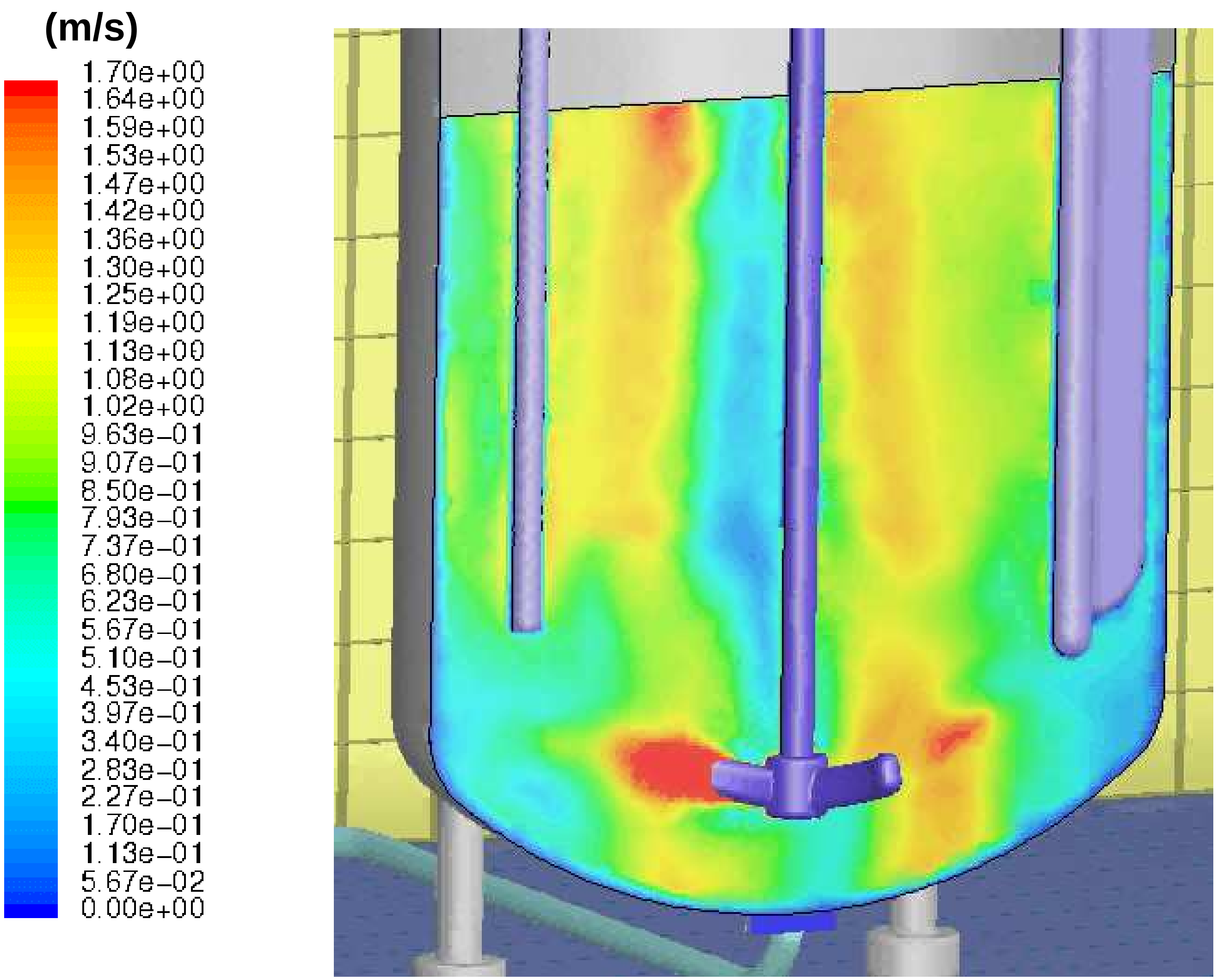
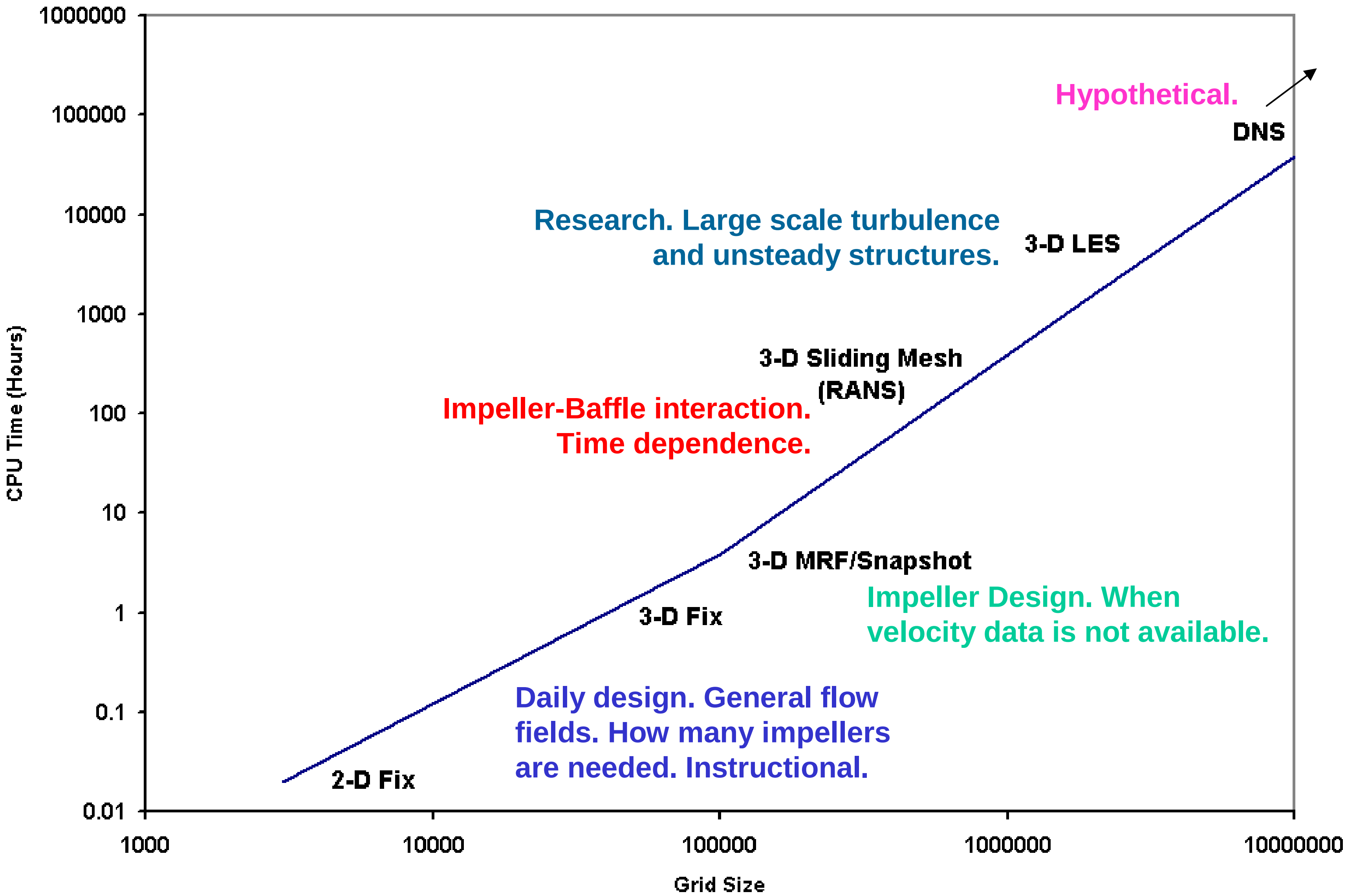
Velocity magnitude at plane through baffle



Animation covers ~ 25 revs.

Stirred tank modeling options



Summary

- LES is a transient turbulence model that falls midway between RANS and DNS models.
- The differences between predicted mixing patterns with RANS and LES are clear.
- LES has potential benefit for engineering applications, and is within reach computationally.
- However, 2-D fix, 3-D fix, and MRF models are much faster computationally, and still have their place.
- The results of these studies open the way to a renewed interpretation of many previously unexplained hydrodynamic phenomena that are observed in stirred vessels.