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Phantom Impeller Technique: A Novel Method to Accelerate Transient Simulations of Large Mixing Equipment

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FLOW FLUID DYNAMICS LOCAL TRANSPORT WATER TECHNOLOGIES

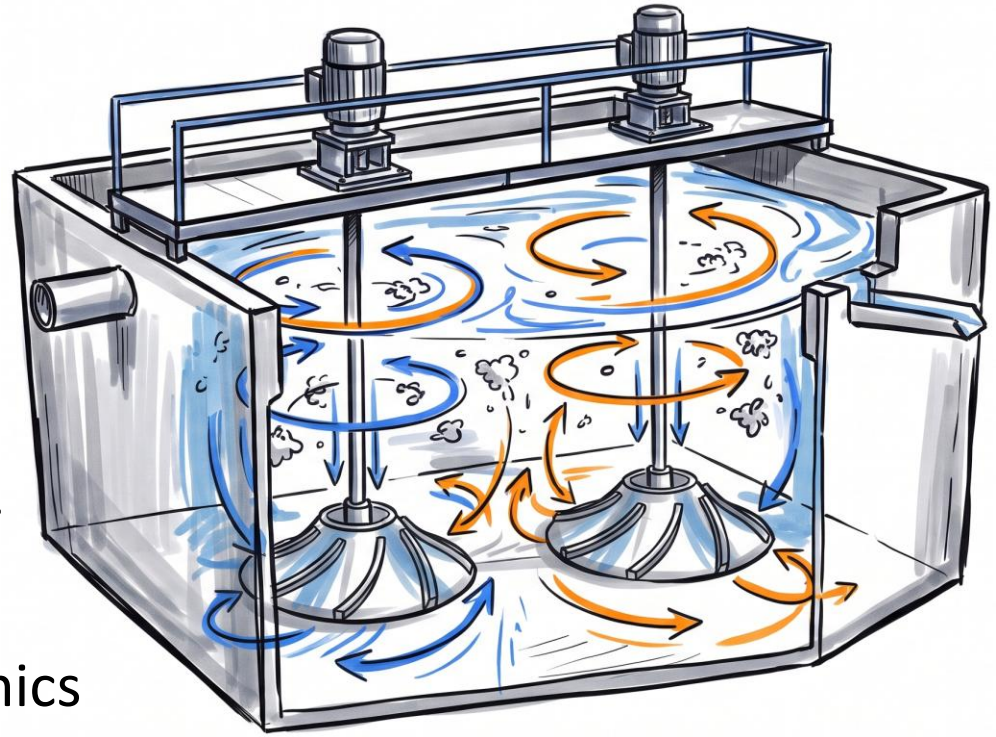
Institute of Hydrology of the CAS

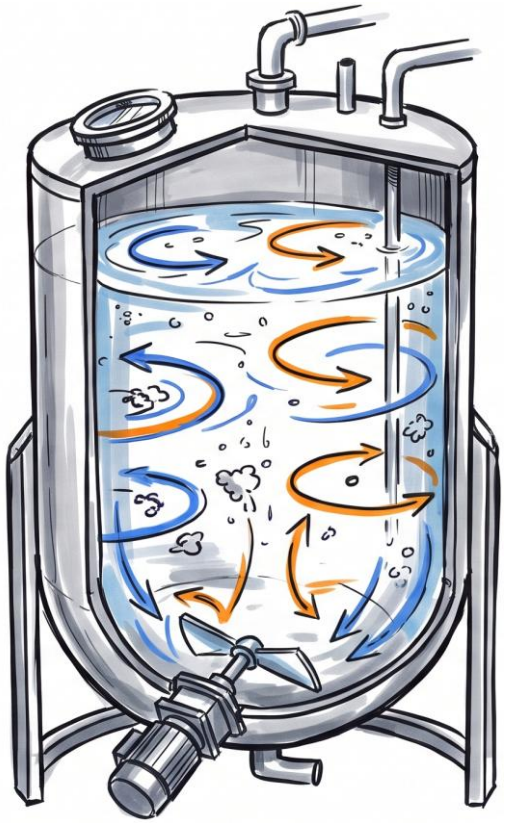
Large mixing equipment

- Waste/drinking water treatment
- Food industry
- Petrochemical industry

Characteristics

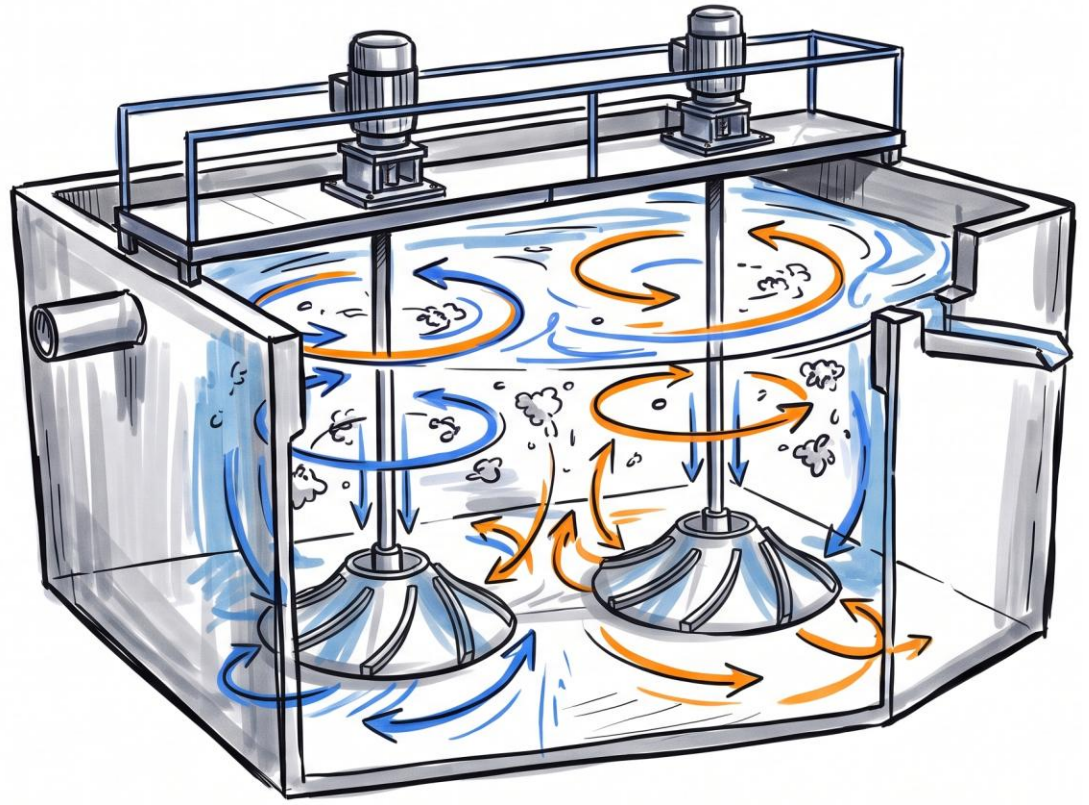
- Long mixing periods
- Volumes up to thousands of cubic meters
- Heterogeneous hydrodynamics conditions





Representative case – flocculation tank

- Waste/drinking water treatment
- Aggregation of impurities in the form of flocs
- Affects the separability of the resulting flocs
- Often rectangular tanks
- Single or multiple impellers of varying types



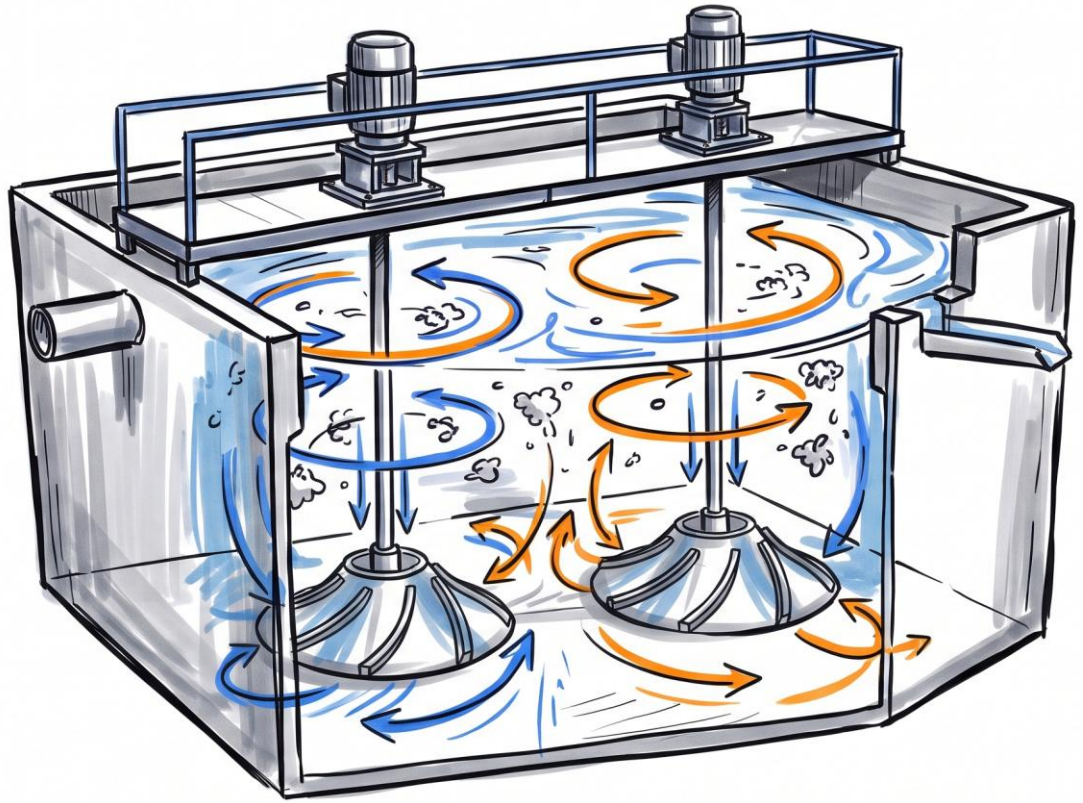
Representative case – flocculation tank design

State-of-the-art

- Empirical correlations
- Integral metrics (P/V, N_P, N_Q)
- Simplified, computationally low-demand models

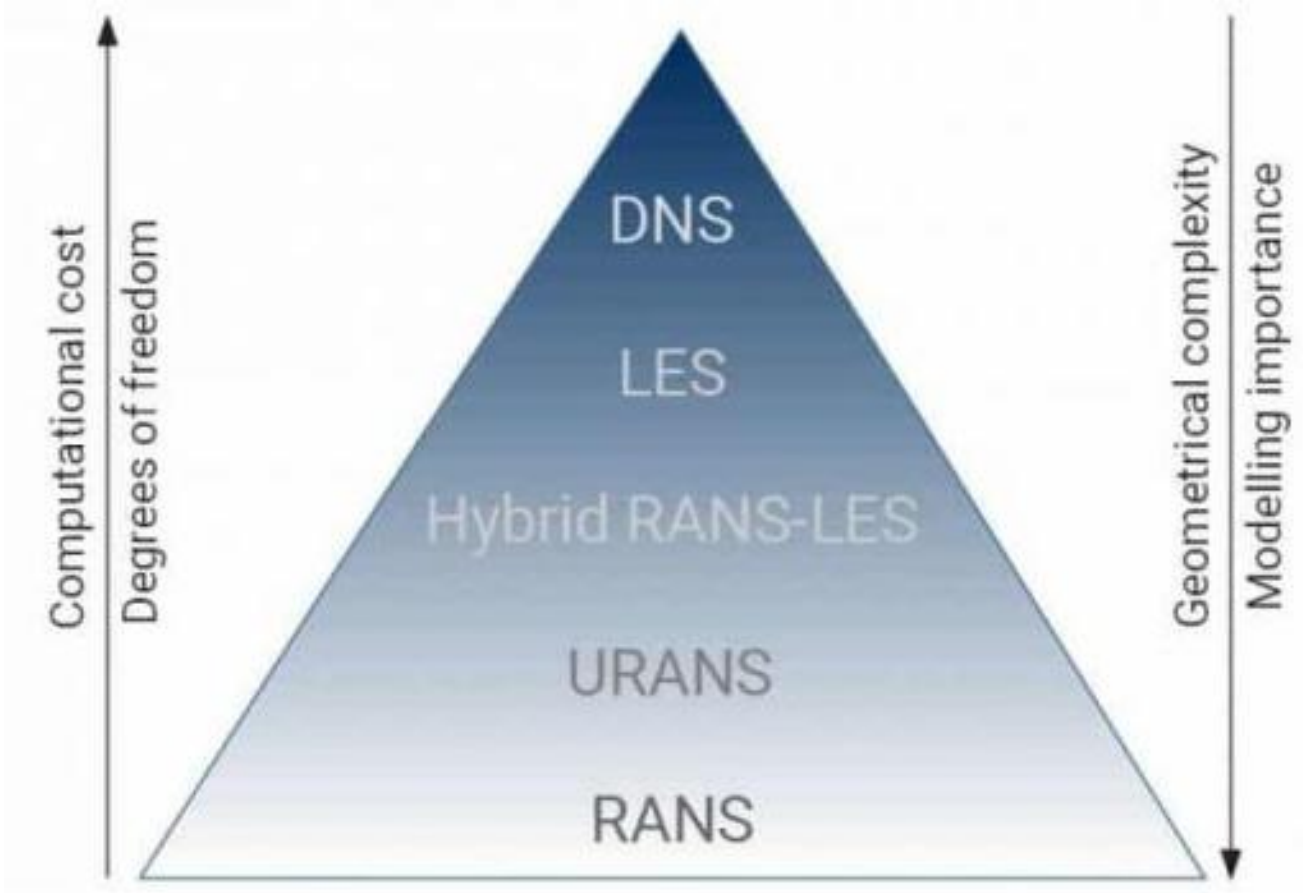
Weaknesses

- Potentially inaccurate
- Ignores local hydrodynamics
- Unreliable
- Compensated by chemical overdosing



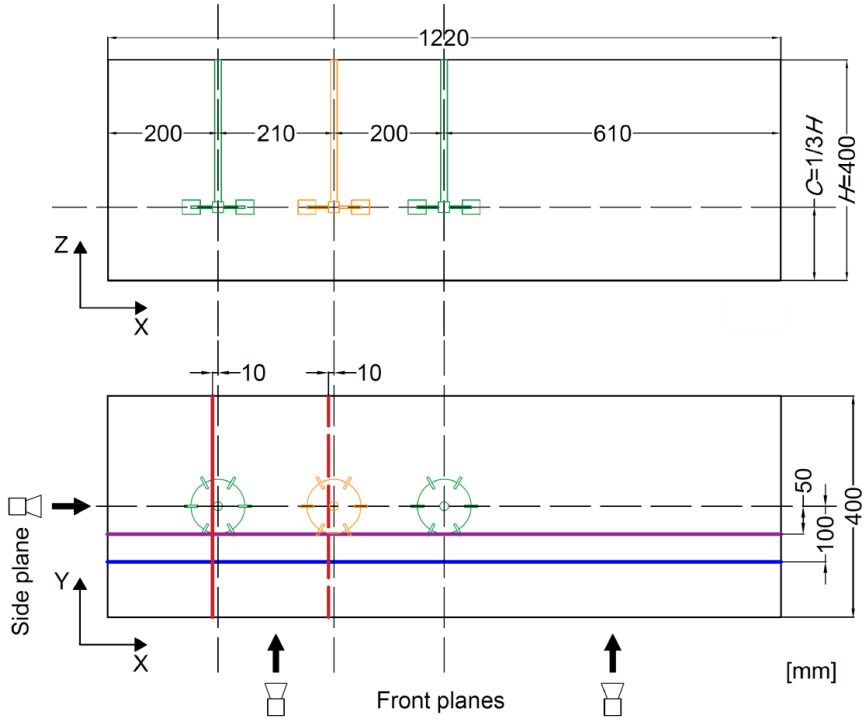
Obstacles of the local-scale approaches

- Experimental data
  - Price and feasibility of experiments
  - Missing full-scale experimental data
- CFD
  - Accuracy/cost trade-off
  - Lack of validated simulation protocols



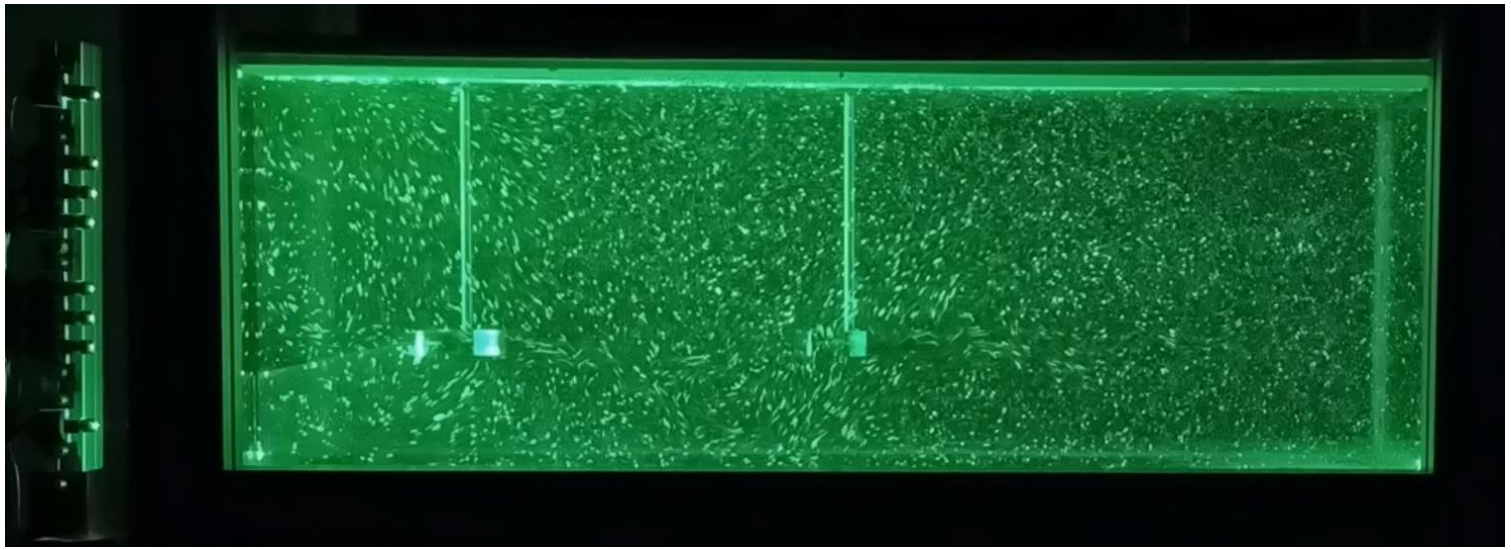
Initial targets of our research

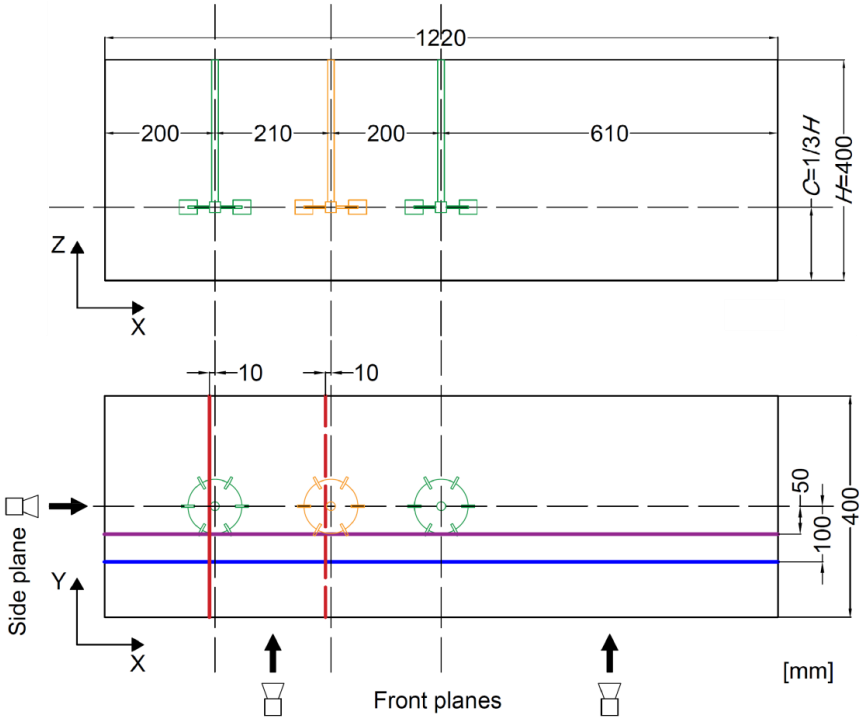
- Simulation protocol for mixing vessel:
  - Low computational demands
  - Versatility
  - Reliability
  - Validation against our in-house measured experimental data by large-scale 2D Particle Tracking Velocimetry technique [Gebousky et al., 2026]



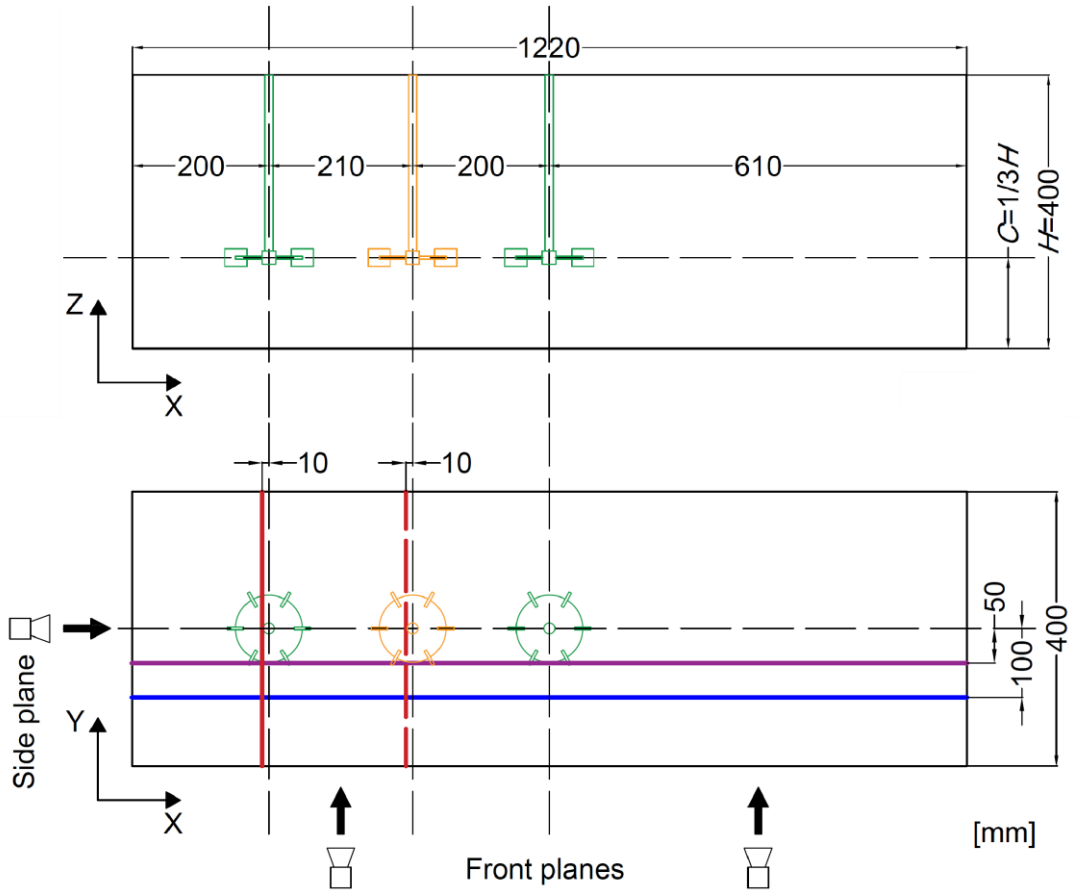
[Gebousky et al., 2026] Gebousky, O., Bilek, V., and Haidl, J. (2026). Methodology for velocity field measurement in pilot-scale stirred vessels using 2-d particle tracking velocimetry. In Topical Problems of Fluid Mechanics, pages 68 – 75, Prague, Czech Republic.

Large-scale 2D Particle Tracking Velocimetry



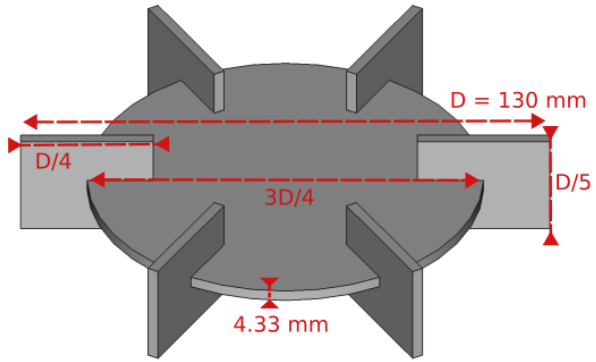


Mimicking a configuration of flocculation tank

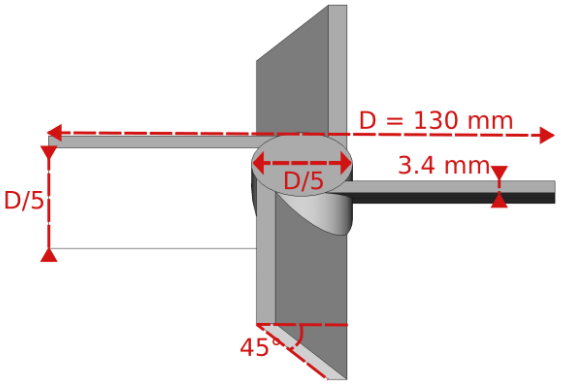


Two impeller types:

Rushton turbine (RT)



Pitched blade turbine (PBT)



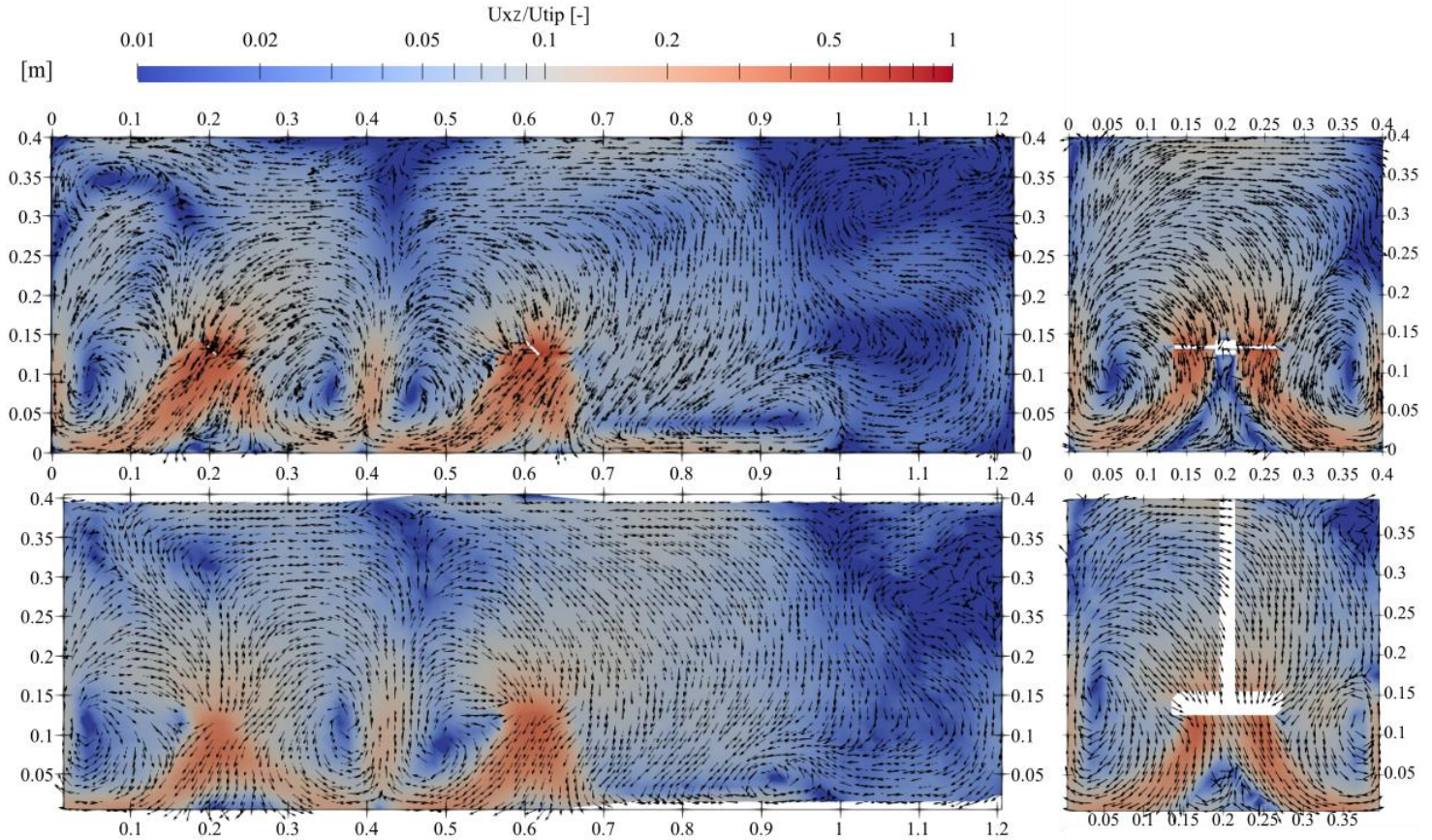
- Single impeller configuration
- Impeller pair configuration
- Sampled planes

Camera

First attempts to build up simulation protocol

- Steady RANS simulations
- Standard *k*-*ε* model
- Multiple Reference Frame

OpenFOAM®

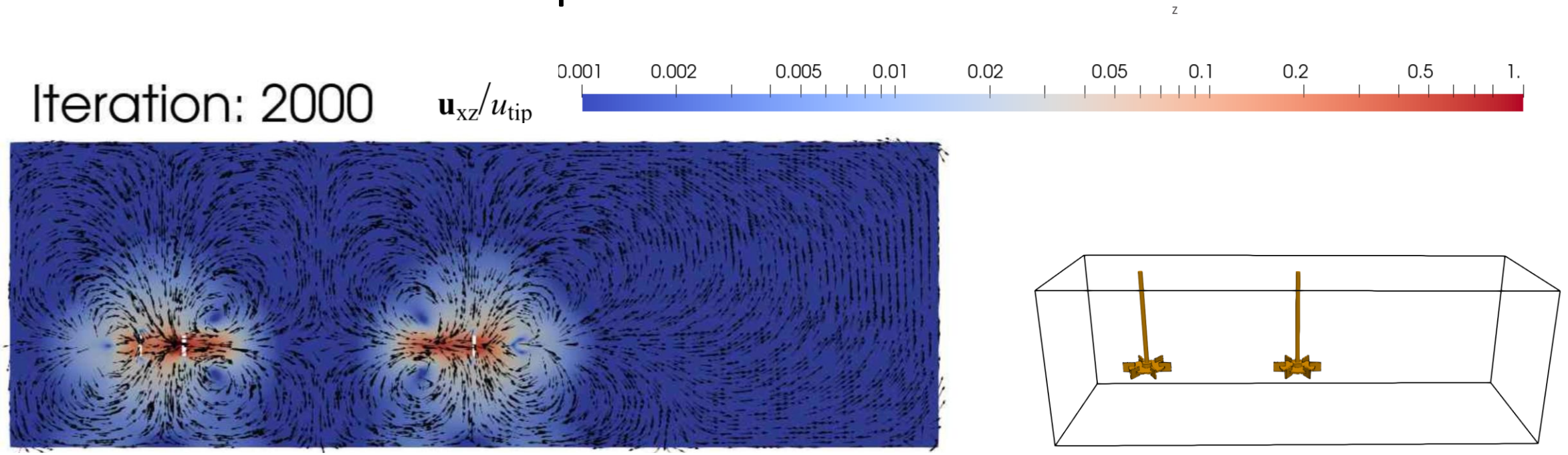


RANS

PTV

Successful for simpler cases BUT…

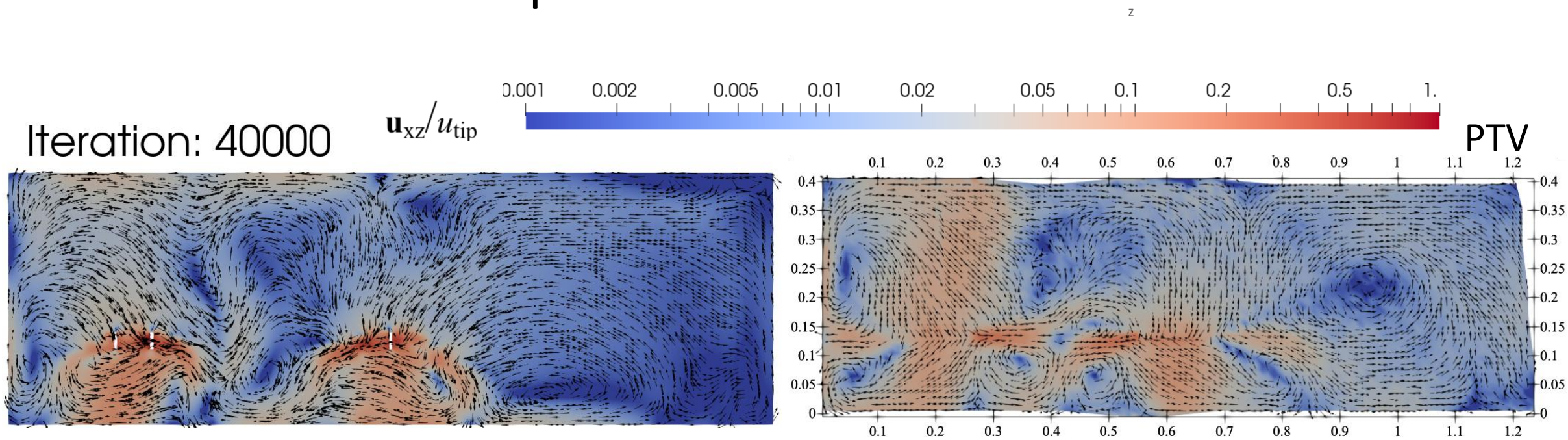
Problem of complex flows



- 2-RT configuration, 2 rps
- RANS

- Multiple Reference Frame
- Standard k-ε turbulence model

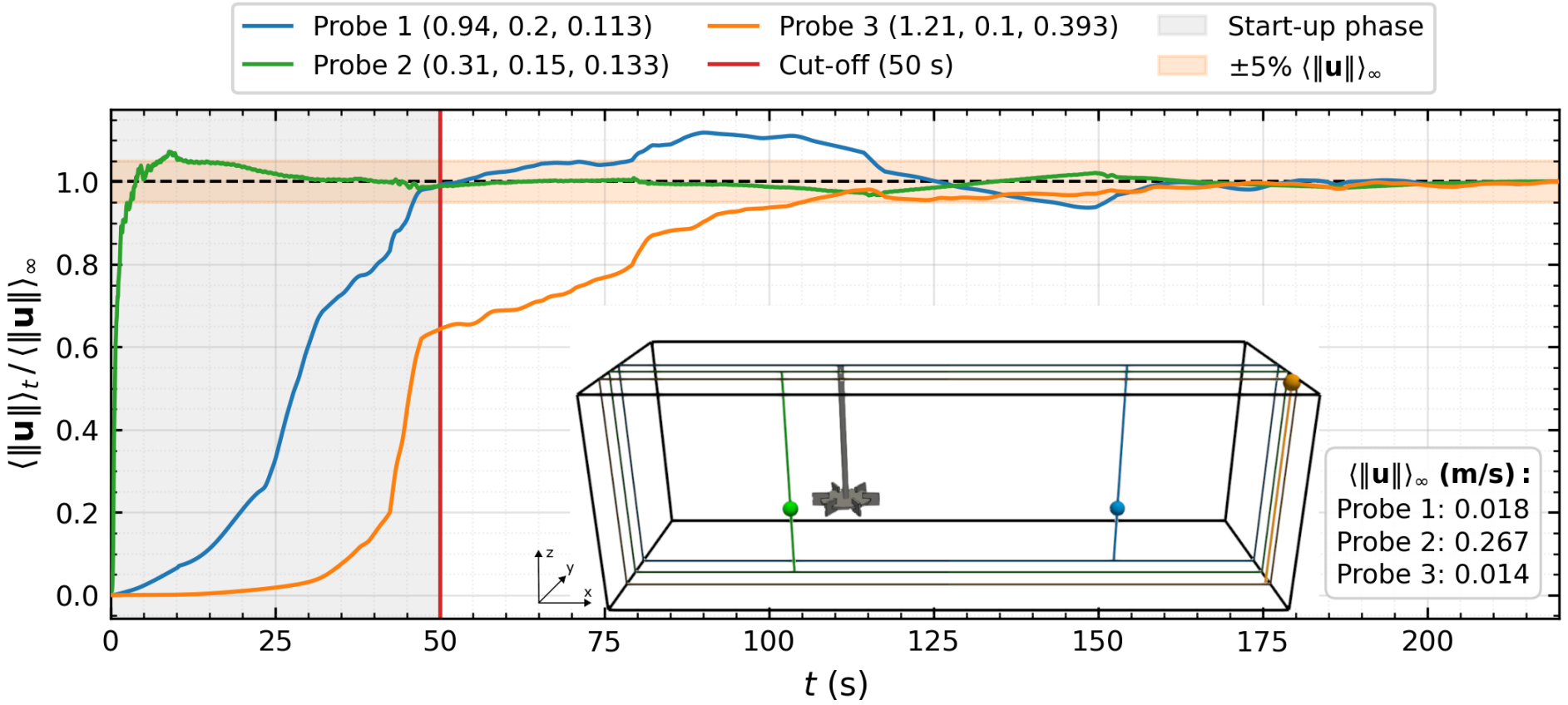
Problem of complex flows



- 2-RT configuration, 2 rps
- RANS

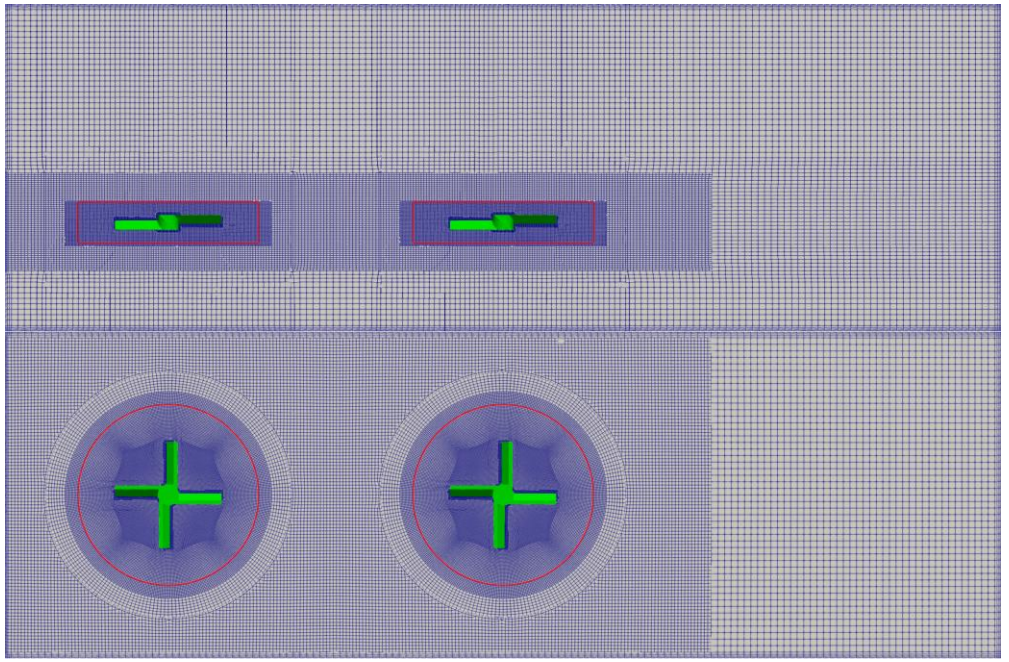
- Multiple Reference Frame
- Standard *k*-*ε* turbulence model

Velocity magnitude development and averaging



Idea of Phantom Impeller Technique

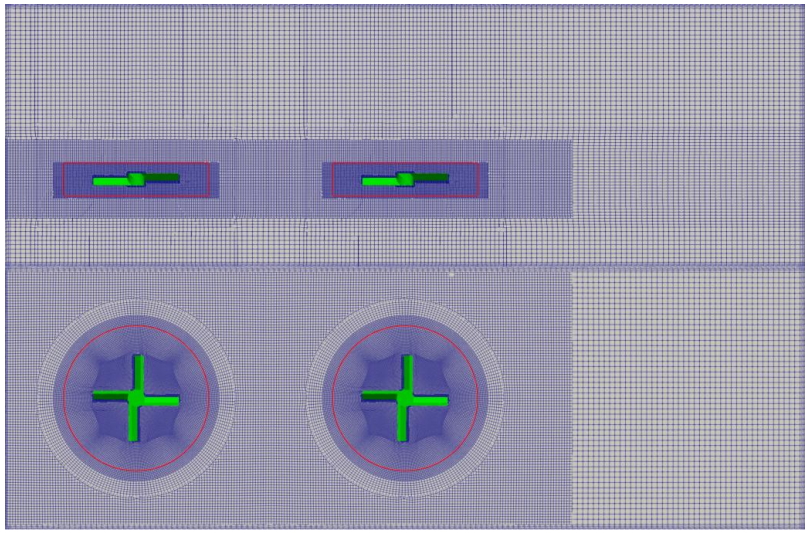
- Inspired by Mueller et al., 2018
- Difference in time scale
  - In the impeller vicinity – short periods
  - In the bulk of the tank – long periods
- Difference in computational load
  - In rotating zones – ≈50 % of all computational cells
  - Restricts time step length



[Mueller et al., 2018] Mueller, J., Schmidt, D., and Velten, K. (2018). Transient boundary condition approach for simulating mechanical mixing in large wine tanks. Computers and Electronics in Agriculture, 150:143–151.

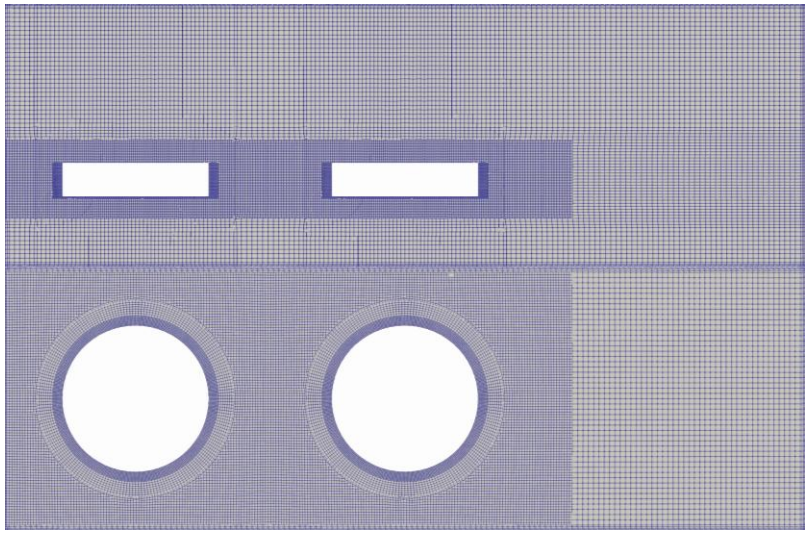
Phantom impeller interface

- Two simulation units
  - U1 – full-scale DDES simulation: data sampled at the rotating zone boundary
  - U2 – DDES simulation implementing time-varying boundary condition



$\sim 2\ s$

U1 ⟳ U2



$\sim 20\ s$

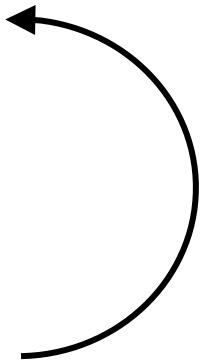
Phantom Impeller Technique setting

Simulation initialization

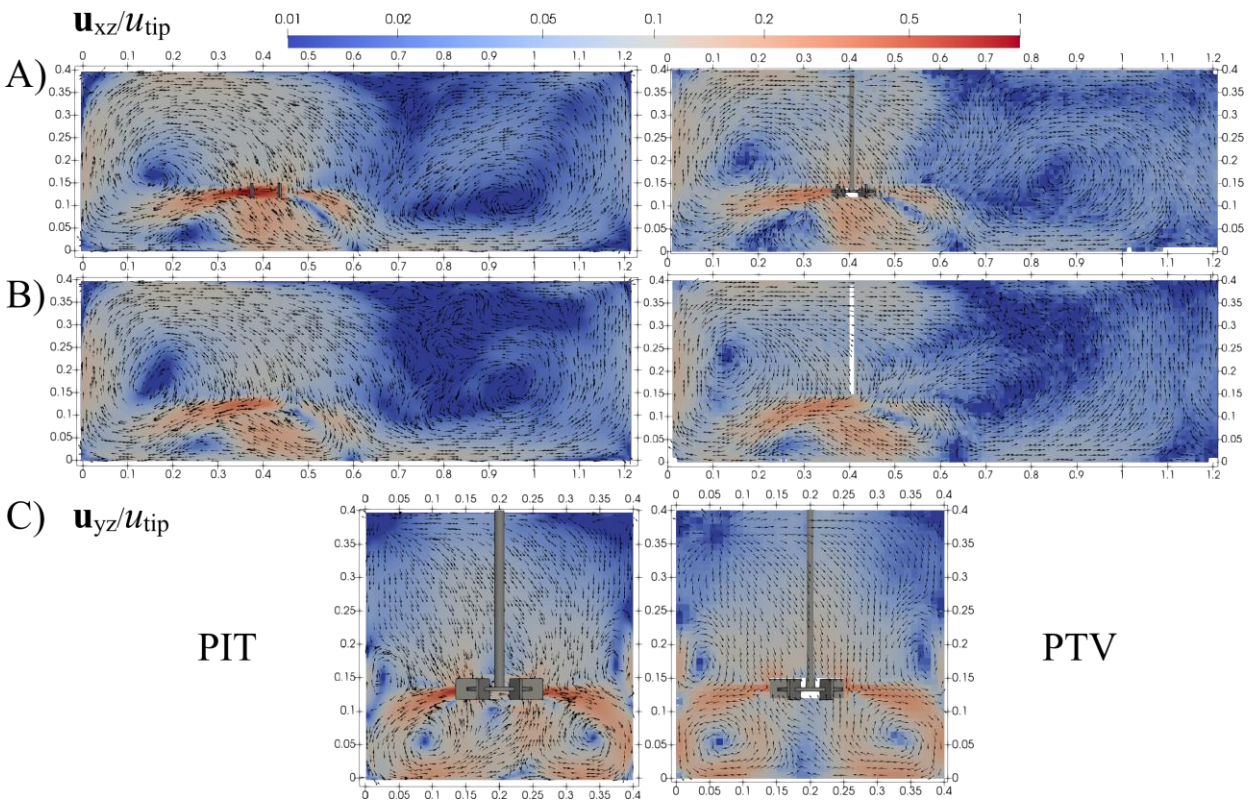
- Quiescent fluid
- U1 – until the velocity develops at the rotating zone boundary

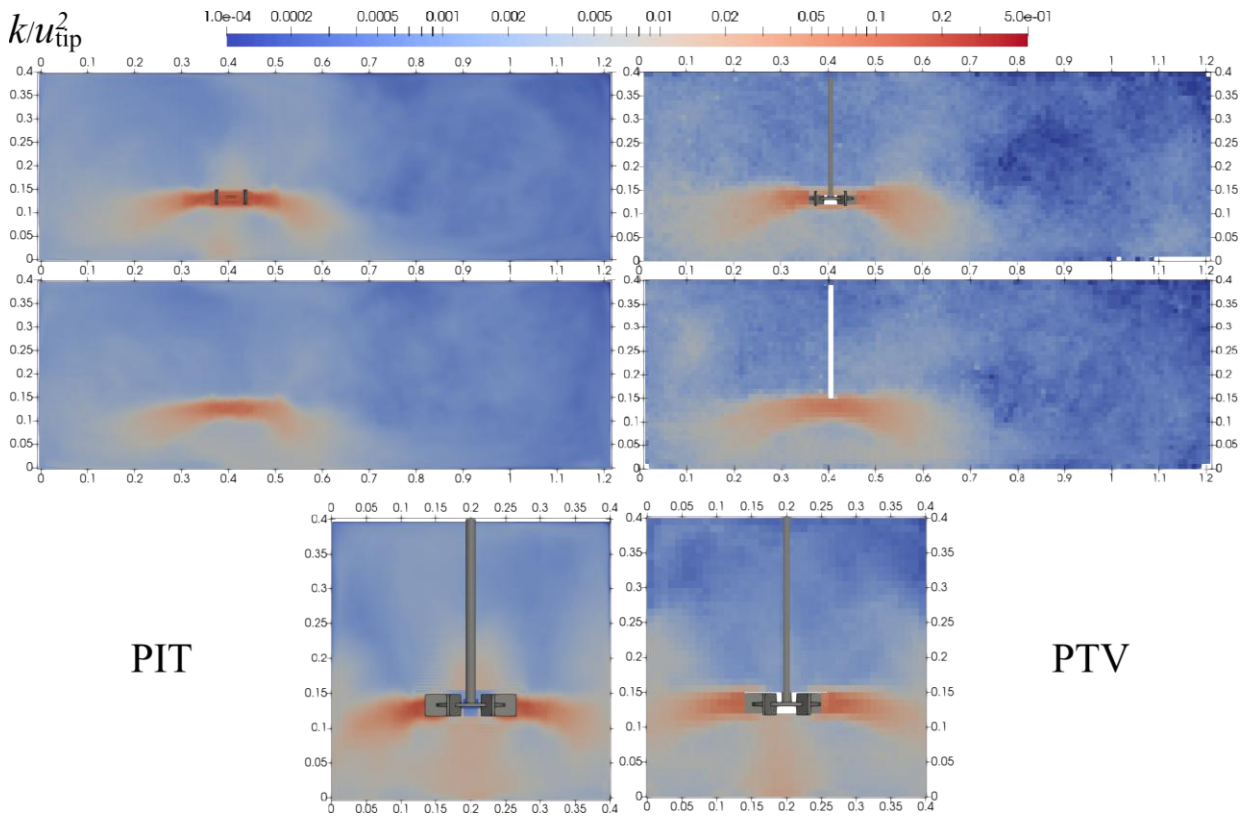
Phantom Impeller Technique loops

- Transfer from U1 to U2
- U2 for ~ 40 revolutions
- Transfer from U2 to U1
- U1 for ~ 4 revolutions of the impeller



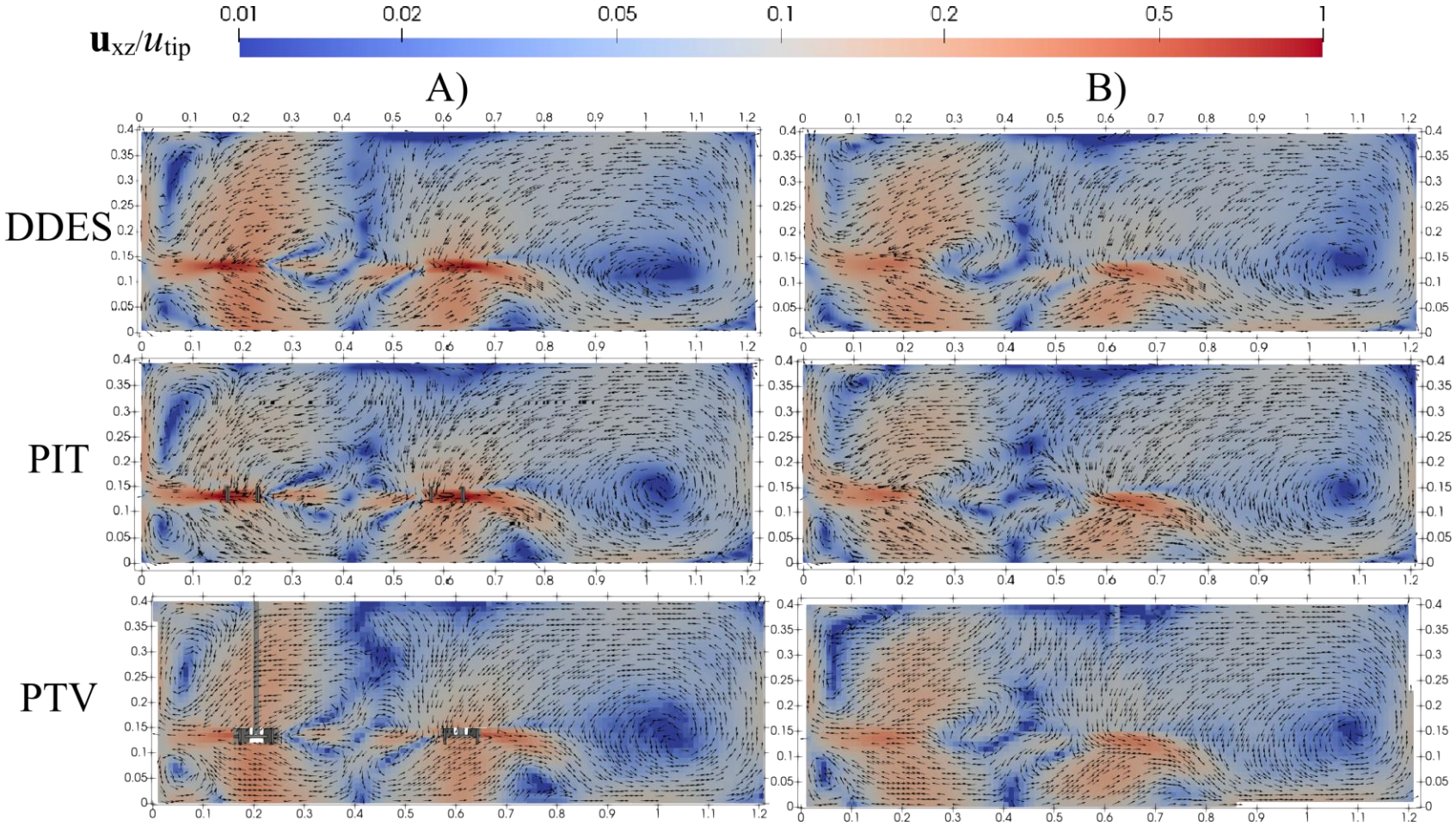
Validation of Phantom impeller technique - 1RT, 1.25 rps





Front planes 5 cm (A) and 10 cm (B) in front of the shaft center and side plane 1 cm (C) in front of the shaft center

Validation of Phantom impeller technique – 2-RT, 2.0 rps

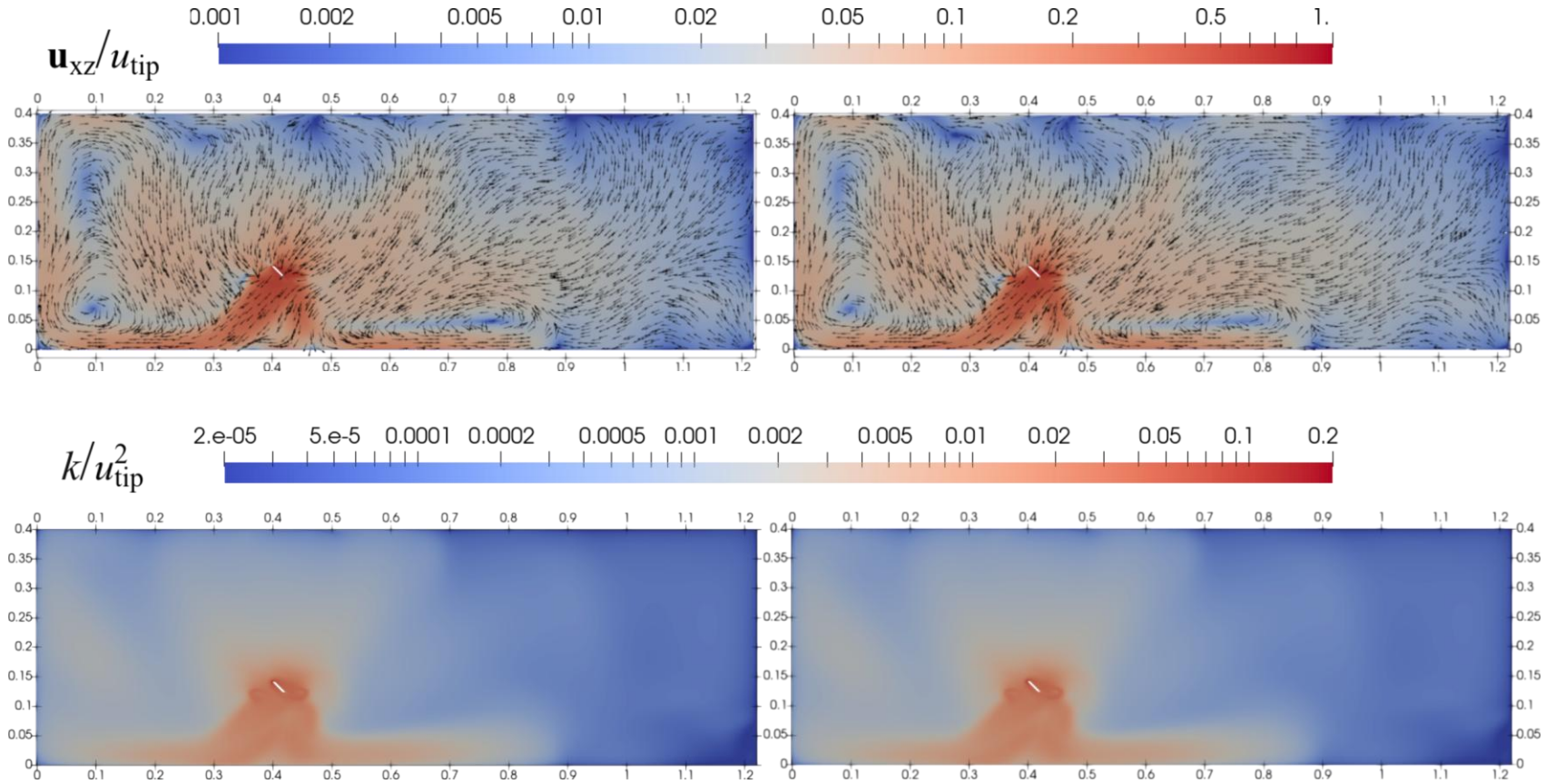


Front planes 5 cm (A) and 10 cm (B) in front of the shaft center

Conclusions

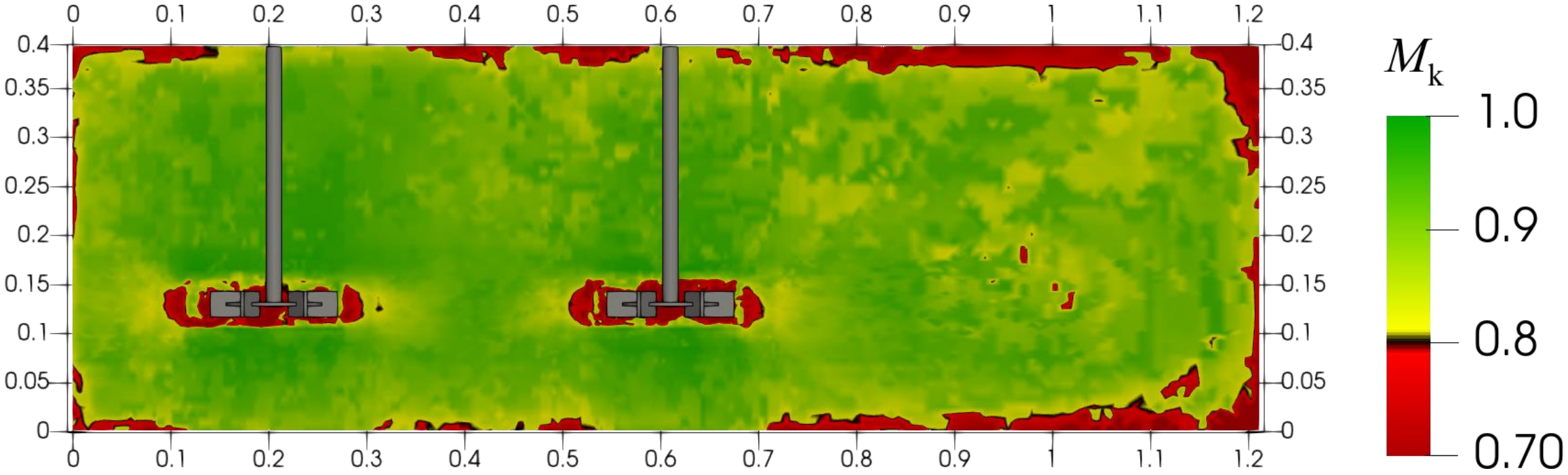
- New technique to accelerate transient simulations of mixing
- Velocity and turbulence kinetic energy fields validated against experimental data and standard transient simulations
- ≥ 10-fold acceleration against standard simulation protocol (DDES)
- Makes transient simulation of large vessels and long-time mixing affordable

Mesh Resolution RANS

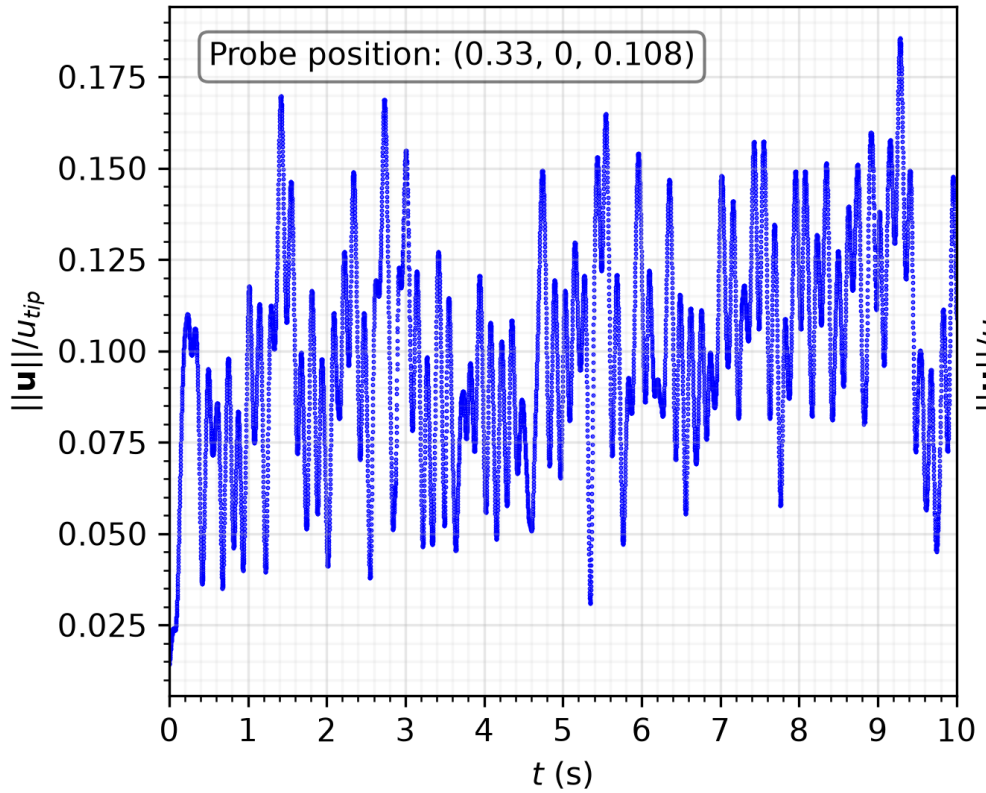


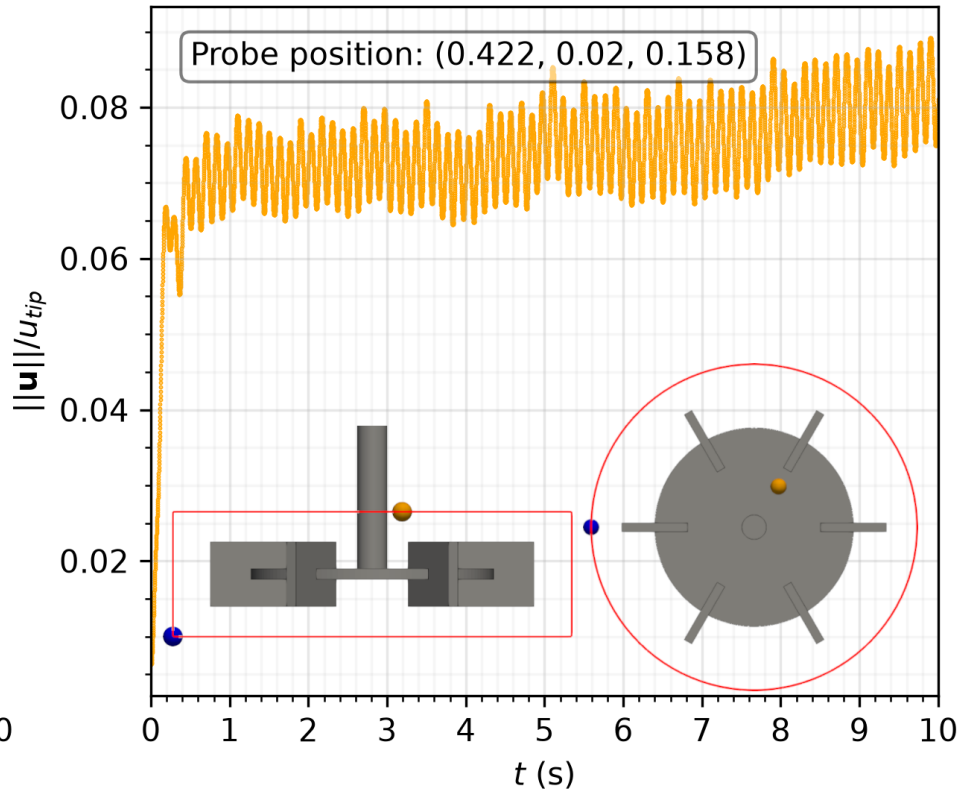
Pope's criterion DDES

$$M_{\mathrm{k}} = \frac{k_{res}}{k_{res} + k_{mod}}$$



1st U1


Probe position: (0.33, 0, 0.108)
0.175
0.150
0.125
0.100
0.075
0.050
0.025
||u||/u_tip
0 1 2 3 4 5 6 7 8 9 10
t (s)


Probe position: (0.422, 0.02, 0.158)
0.08
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0.04
0.02
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0 1 2 3 4 5 6 7 8 9 10
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