A comparison of the performance of mixing systems for viscous solid-liquid mixing using CFD-DEM

Bruno Blais*, Bastien Delacroix, Louis Fradette, François Bertrand

What is solid-liquid mixing?

Mixing of solid particles in a liquid

Flow regime at tank level

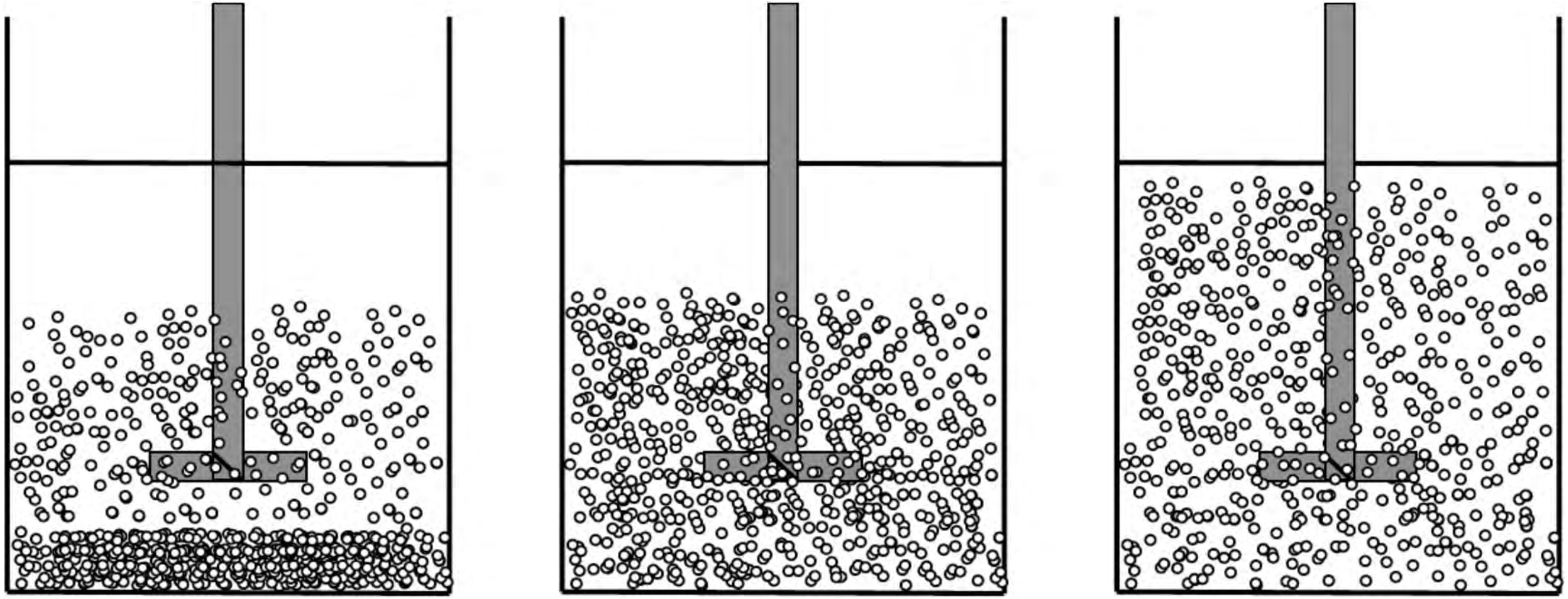
- Laminar
- Transitional
- Turbulent

$$\mathrm{Re} = \frac{\rho_f N D^2}{\mu}$$

Flow at the particle level

$$\mathrm{Re}_p = \frac{\rho_f \left\| \mathbf{u} - \mathbf{v} \right\| d_p}{\mu}$$

Industrial requirement



Partial | Complete Complete | Homogenous

Maximal contact area between the phases

N_{js} is the impeller velocity for complete suspension

Issues related to N_{js}

$$N_{js} = S\nu_f^{0.1}\left(\frac{(\rho_p - \rho_f)\,g}{\rho_f}\right)^{0.45} d_p^{0.2} X^{0.1} D^{0.15}$$

N_{js} is hard to estimate

- Work has only focused on the turbulent regime
- Unclear role of fluid and particle properties

Approach limited to correlations

- Empirical or semi-empirical
  - i.e Zwietering correlation

A new set of experiments for each geometry?

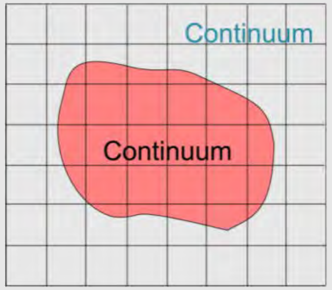
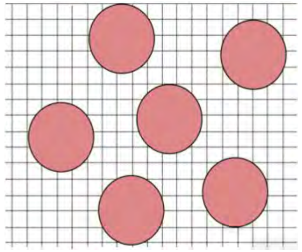
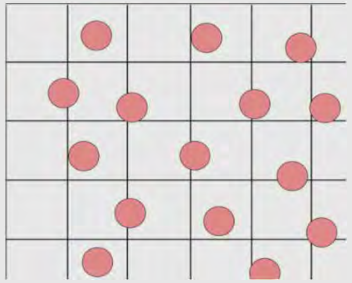
Today's talk

Unresolved CFD-DEM model for solid-liquid mixing

Model validation

Investigation of the influence of the agitator on suspension dynamics

- Fraction of suspended solid
- Concentration profiles
- Cloud height
- RSD

Models	+	-
Two-fluid model 	• Fast • Large number of particles	• Limited to dense flow regime • Hard to model maximal packing fraction
Resolved CFD-DEM 	• Direct numerical simulation	• Computationally intensive • Limited number of particles
Unresolved CFD-DEM 	• Accurate • Scales well to larger systems • Models maximal packing accurately	• Still quite computationally intensive • Not extensively used for solid-liquid flows

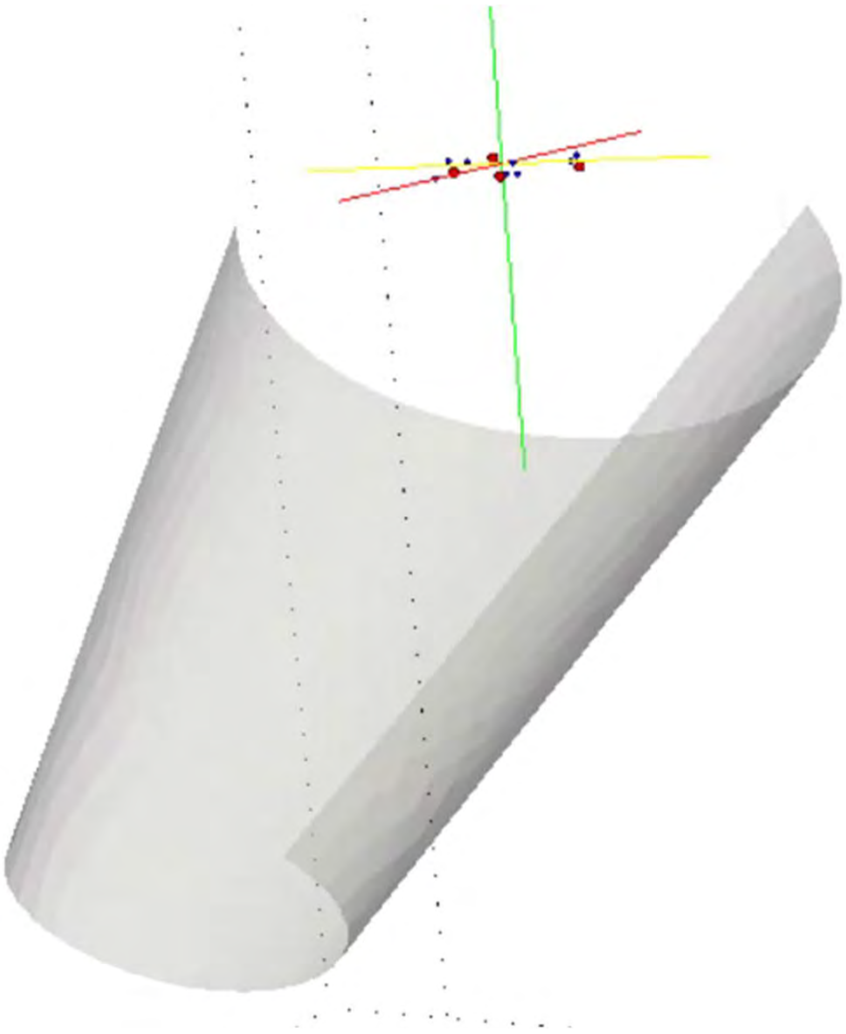
What is unresolved CFD-DEM?

Combine CFD for the liquid with DEM for the solid

Position and velocity of each particles are tracked

Particle-Particle and Particle-Geometry collisions are handled using simple contact laws

Two-way solid-fluid coupling calculated via expressions for the hydrodynamic forces



Unresolved CFD-DEM model

Fluid

Volume-Averaged Navier-Stokes (VANS)

$$\partial_t\left(\varepsilon_f\right)+\nabla\cdot\left(\varepsilon_f \boldsymbol{u}\right) = 0$$

$$\partial_t\left(\varepsilon_f \boldsymbol{u}\right)+\nabla\cdot\left(\varepsilon_f \boldsymbol{u}\otimes\boldsymbol{u}\right) = -\frac{\varepsilon_f}{\rho_f}\nabla p+\nabla\cdot\boldsymbol{\tau}-\boldsymbol{F}_{pf}$$

Solid particles

Newton's second law

$$m_i \frac{d^2\mathbf{x}_i}{dt^2} = \boldsymbol{f}_{\mathrm{pf},i} + \boldsymbol{f}_{contact,i}$$

Solid-liquid coupling

$$\boldsymbol{F}_{pf} = \frac{1}{\Delta V}\sum_i^{n_p} \boldsymbol{f}_{pf,i}$$

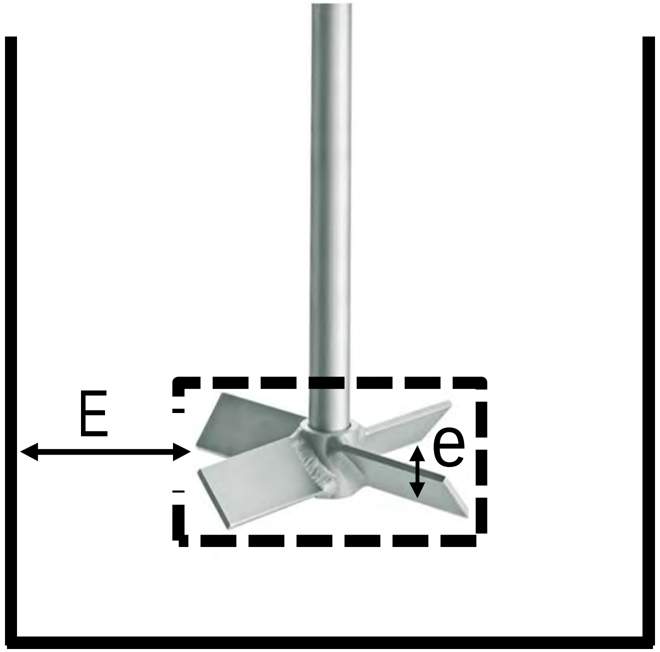
$$\boldsymbol{f}_{pf,i} = \boldsymbol{f}_{d,i} + \boldsymbol{f}_{\nabla p,i} + \boldsymbol{f}_{\nabla\cdot\tau,i} + \boldsymbol{f}_{\mathrm{Saff},i}$$

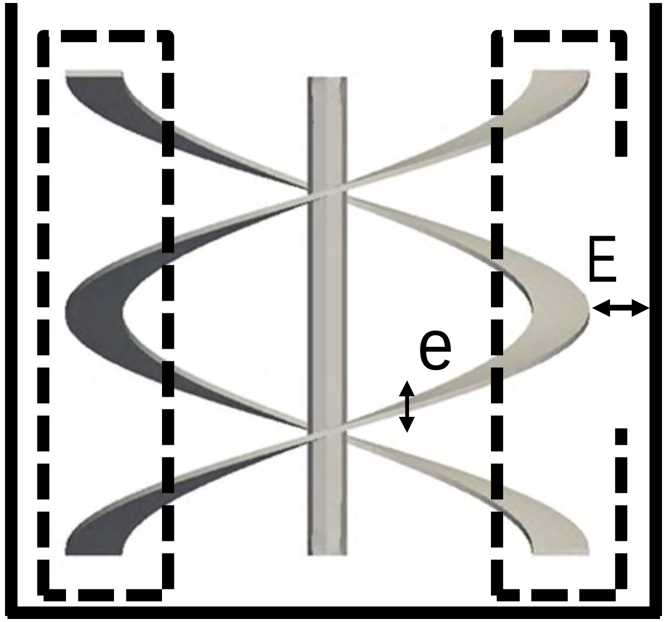
- Pressure gradient
- Viscous stress
- Drag

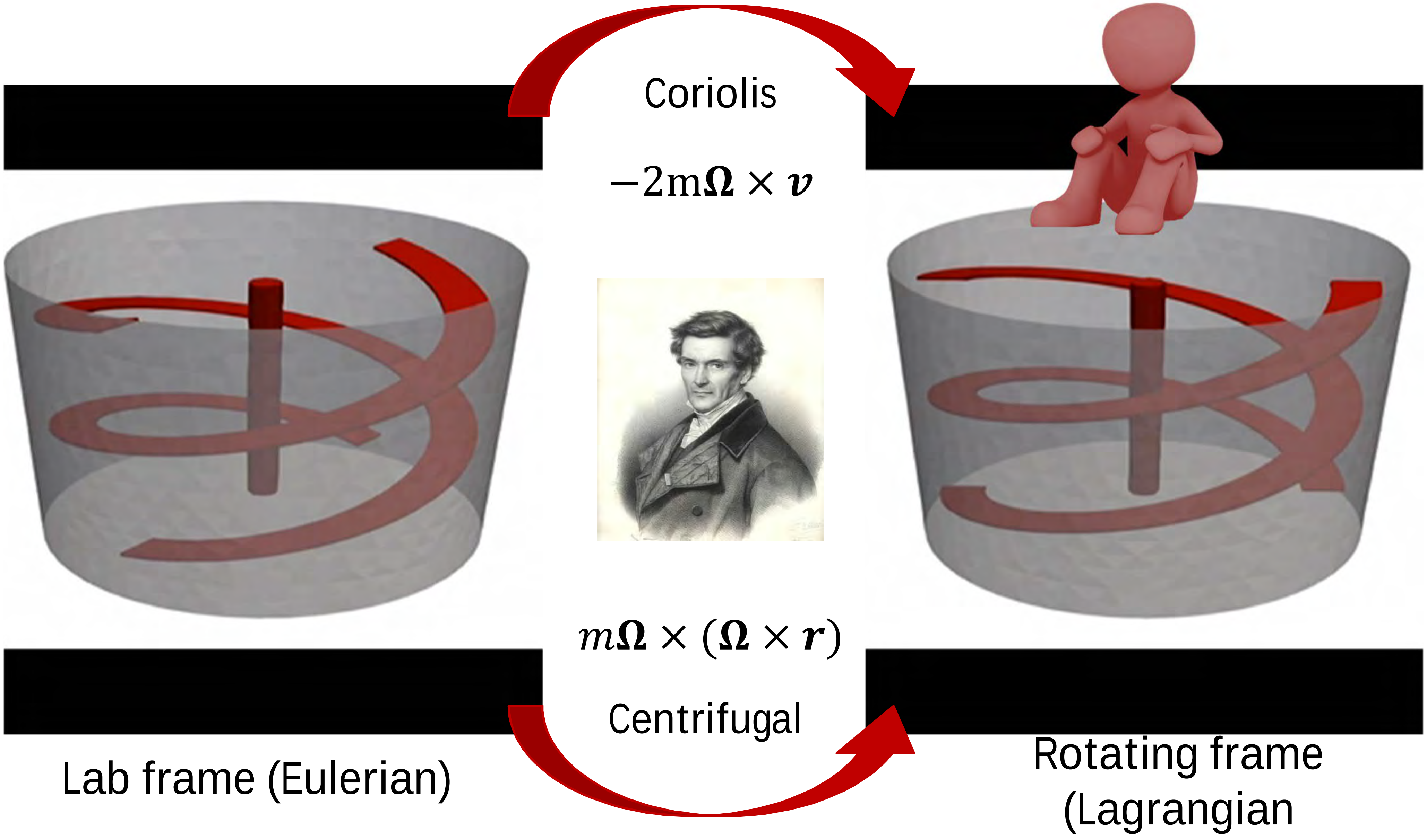
Rotating geometry

Immersed Boundary
- See Blais et al (2015,2016,2017a,2017b)

Rotating frame of reference
- Delacroix et al (2020a, 2020b)







Coriolis
$-2m\boldsymbol{\Omega} \times \boldsymbol{v}$
$m\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \boldsymbol{r})$
Centrifugal
Lab frame (Eulerian)
Rotating frame (Lagrangian

Model validation

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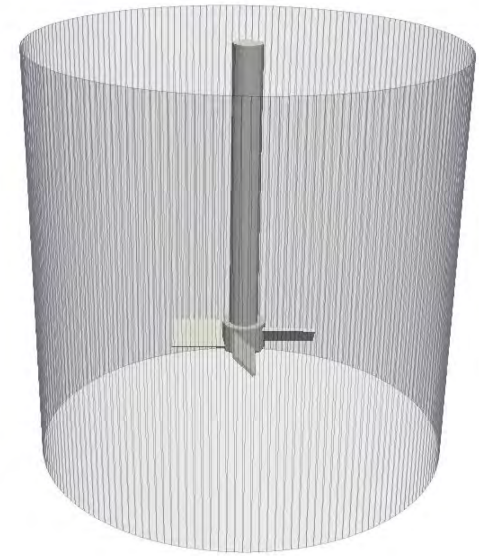
System studied

Pitched blade turbine

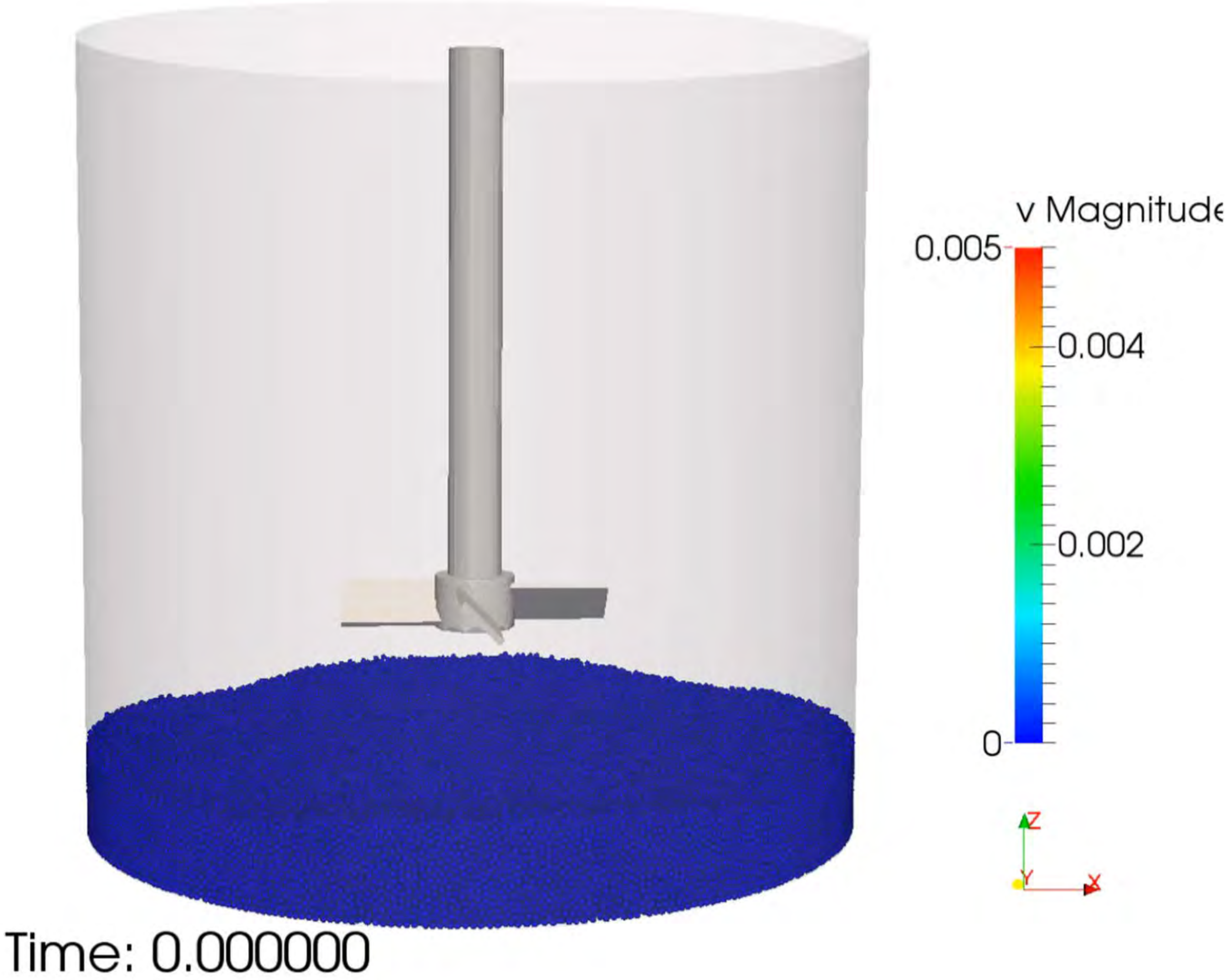
- Tank diameter (T) – 0.365m
- Impeller diameter (D) – 0.122m
- Viscosities – 1 and 0.05 Pa.s
- Density of the fluids – 1400 and 1200 kg/m^3
- Density of the particles – 2500 kg/m^3
- Sauter diameter of the particles – 3mm
- Mass fraction of solids – 10% (~150k particles)

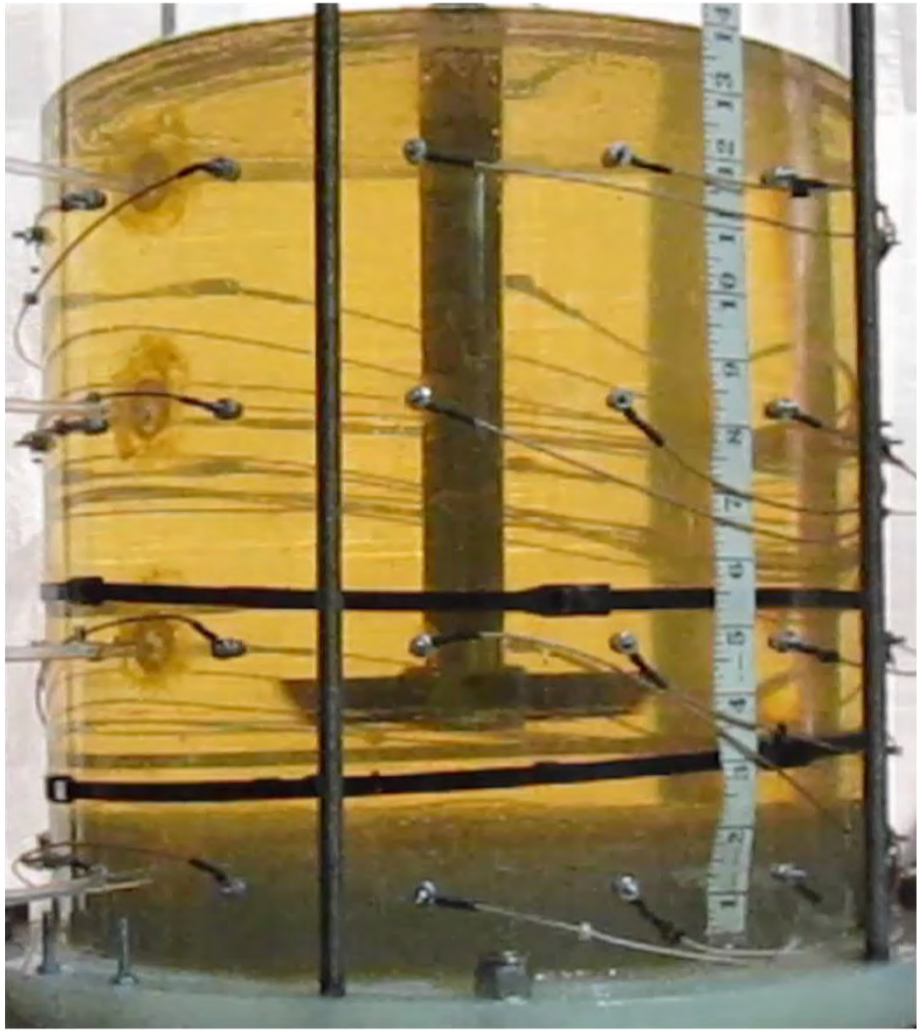


Visual observation

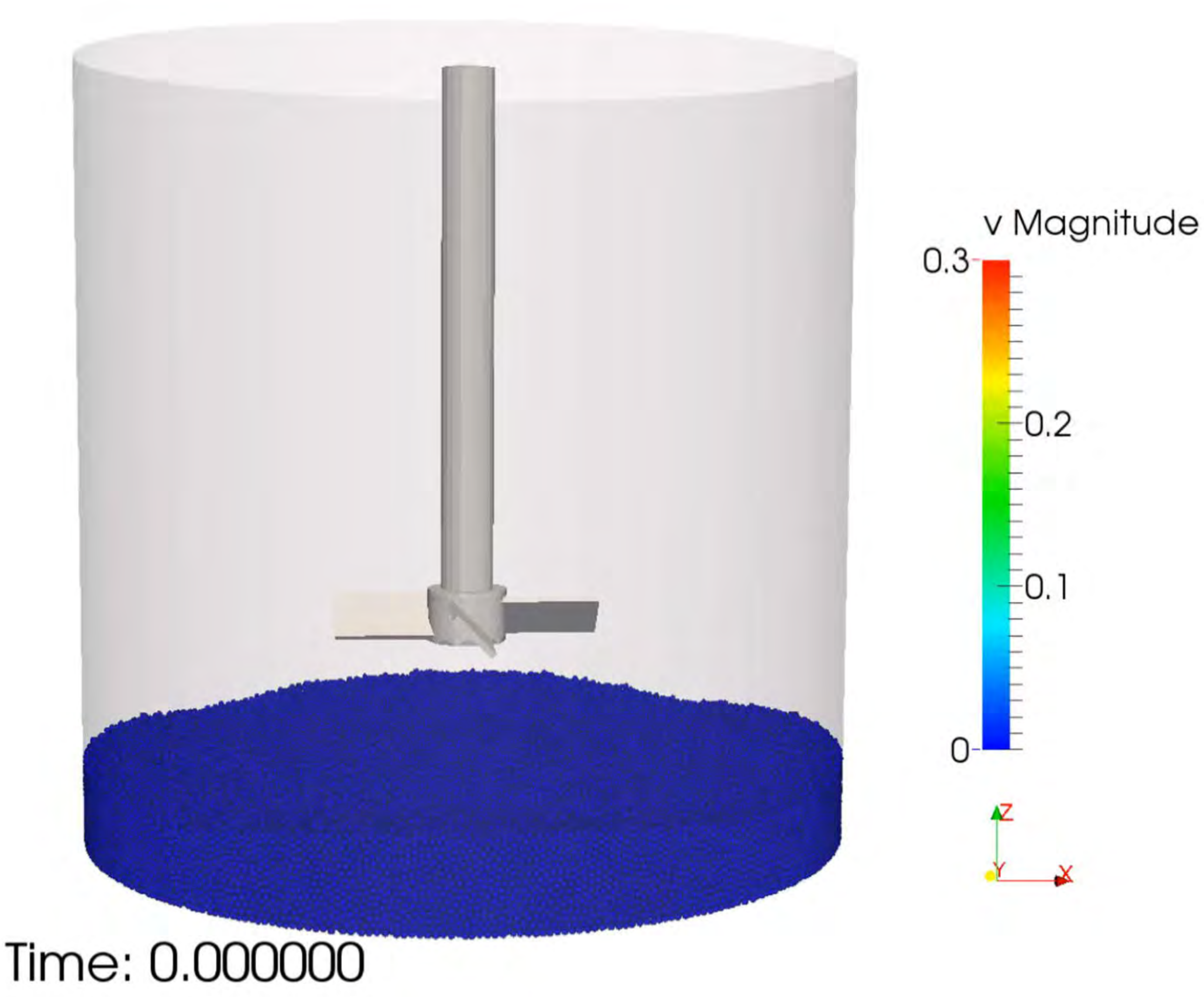
Pressure gauge technique

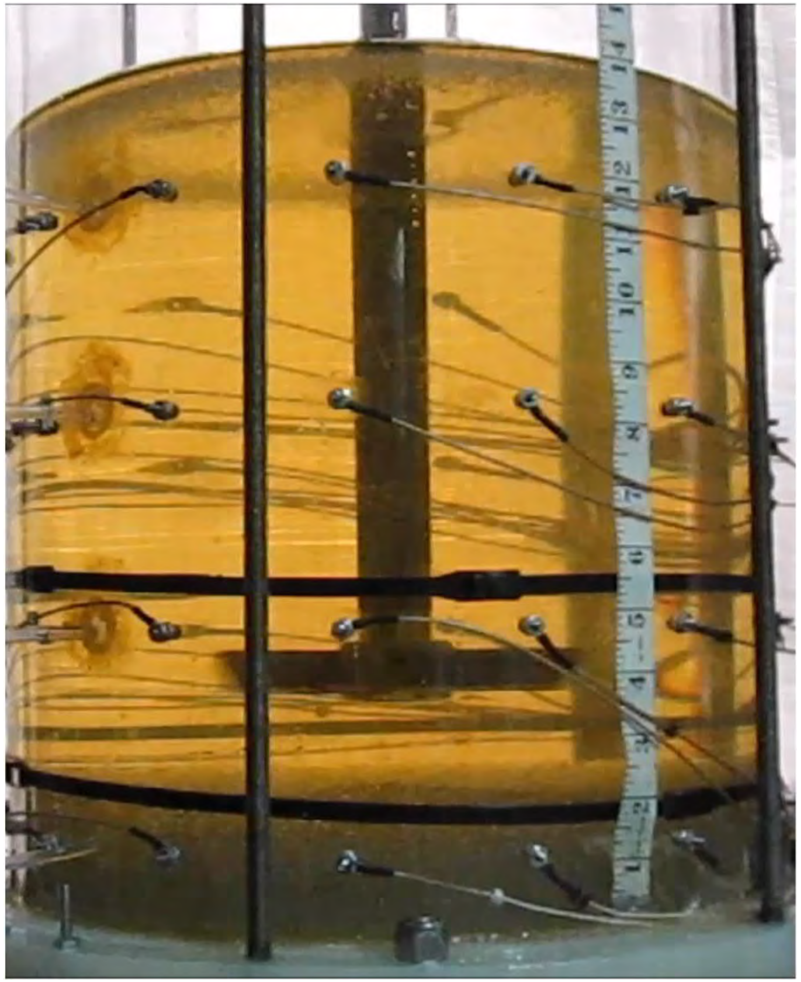
Gentle simmering at low speed



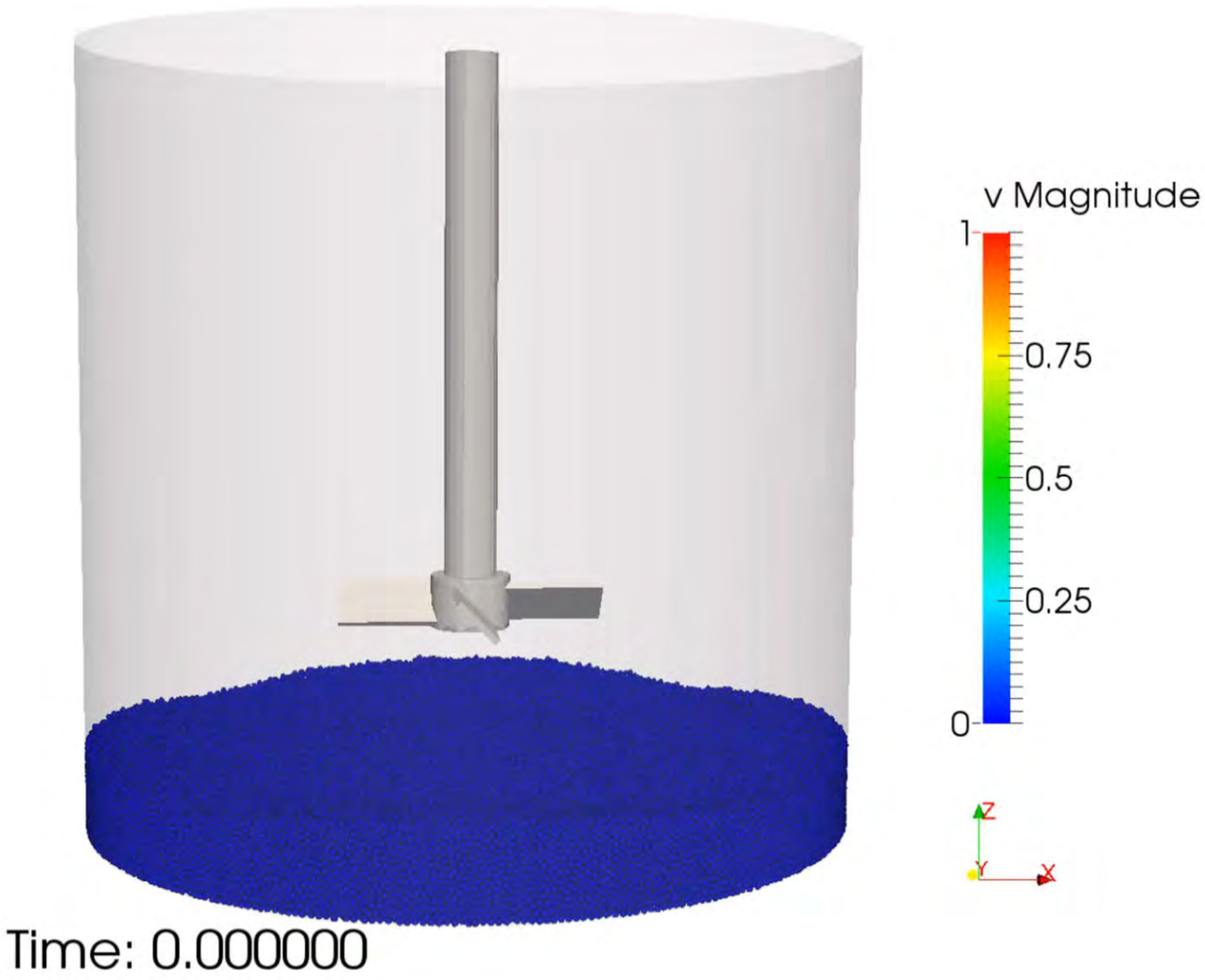


Umbrella – 250 RPM



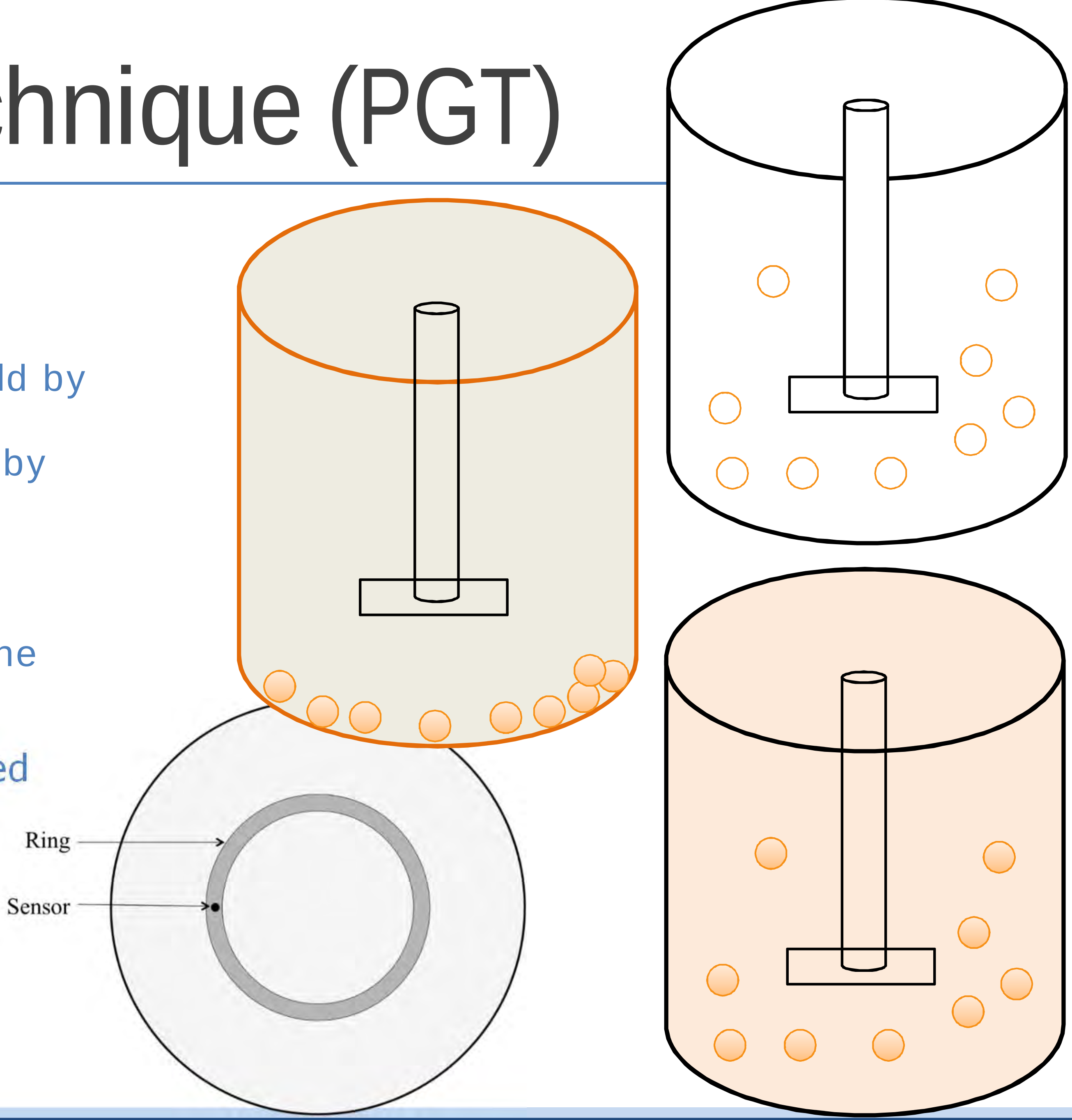


Suspension - 450 RPM



Pressure gauge technique (PGT)

- To obtain the fraction of suspended solids
  - Initially, weight of the particles is held by the tank walls
  - Once suspended, this weight is held by the liquid
  - Increases apparent density
  - Increases hydrostatic pressure
  - Total pressure can be measured at the bottom of the tank
  - Substracting dynamic pressure, hydrostatic pressure can be recovered
  - Fraction of suspended particles is obtained
- Can also be used in CFD-DEM simulations



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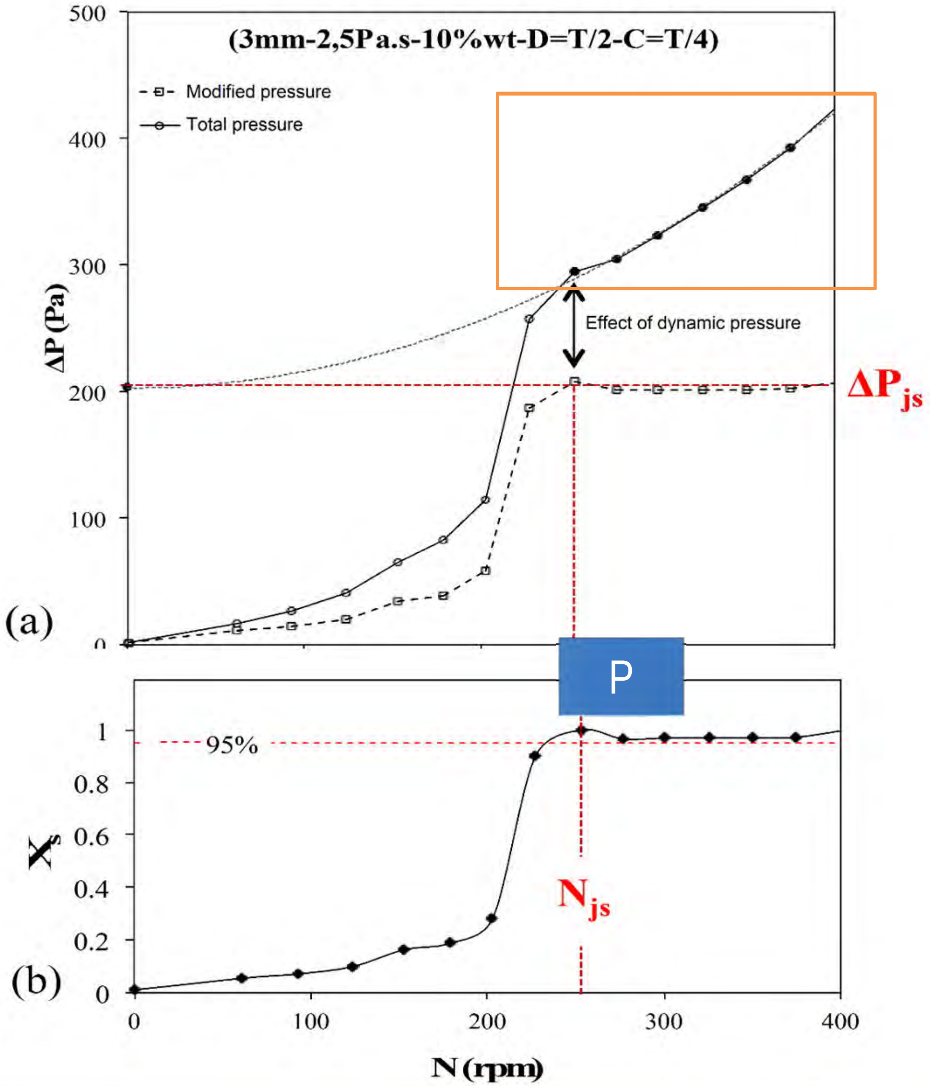
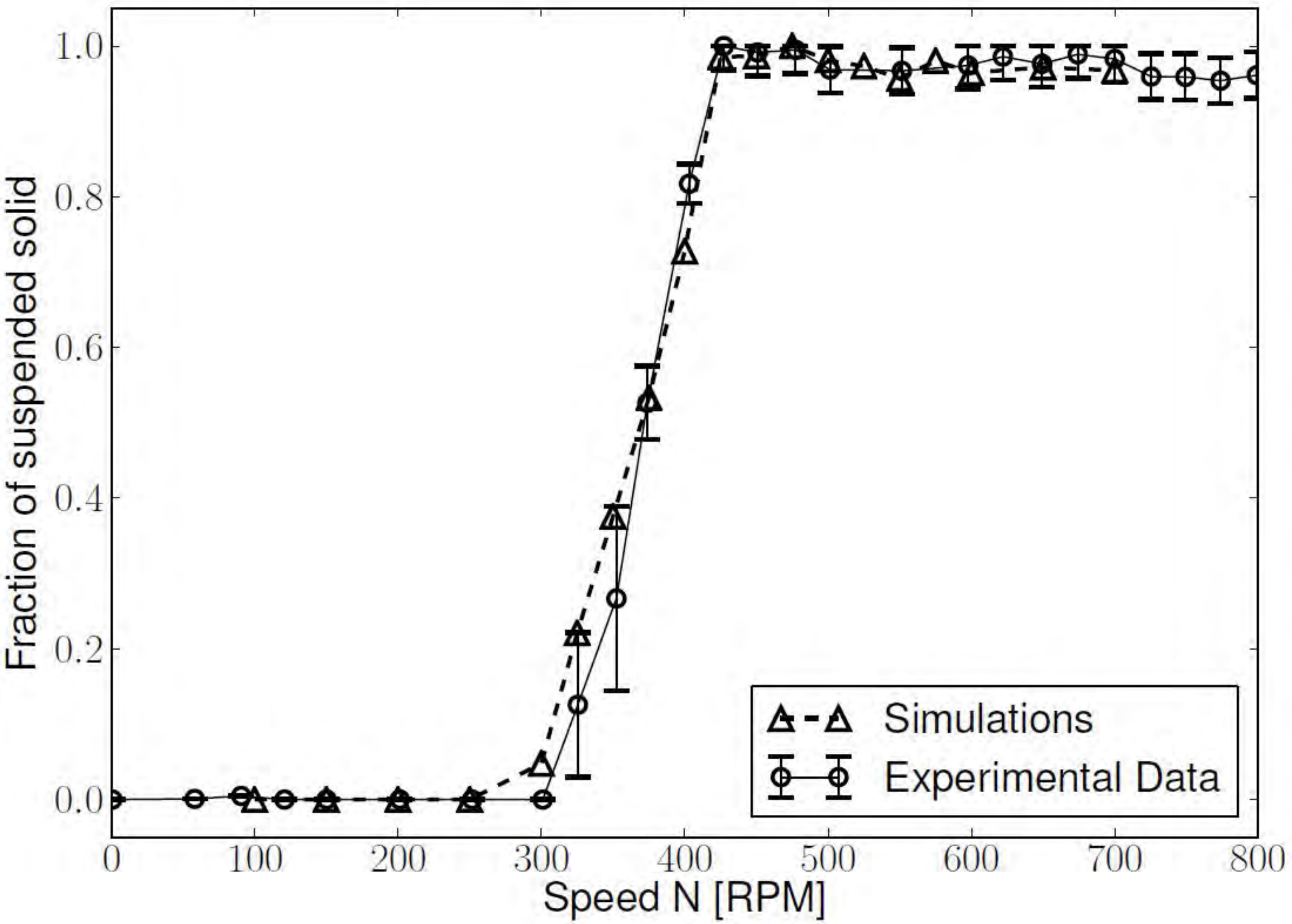


Fraction of suspended particles

Pitched blade turbine
- Tank diameter (T) – 0.365m
- Impeller diameter (D) – 0.122m
- Viscosities – 1 Pa.s
- Density of the fluids – 1400 kg/m^3
- Density of the particles – 2500 kg/m^3
- Sauter diameter of the particles – 3mm
- Mass fraction of solids – 10% (~150k particles)



References

- B. Blais et al. (2016), Journal of Computational Physics, 318, 201-221.
- Delacroix, B et al. (2020) Chemical Engineering Science, 230, 116-137.

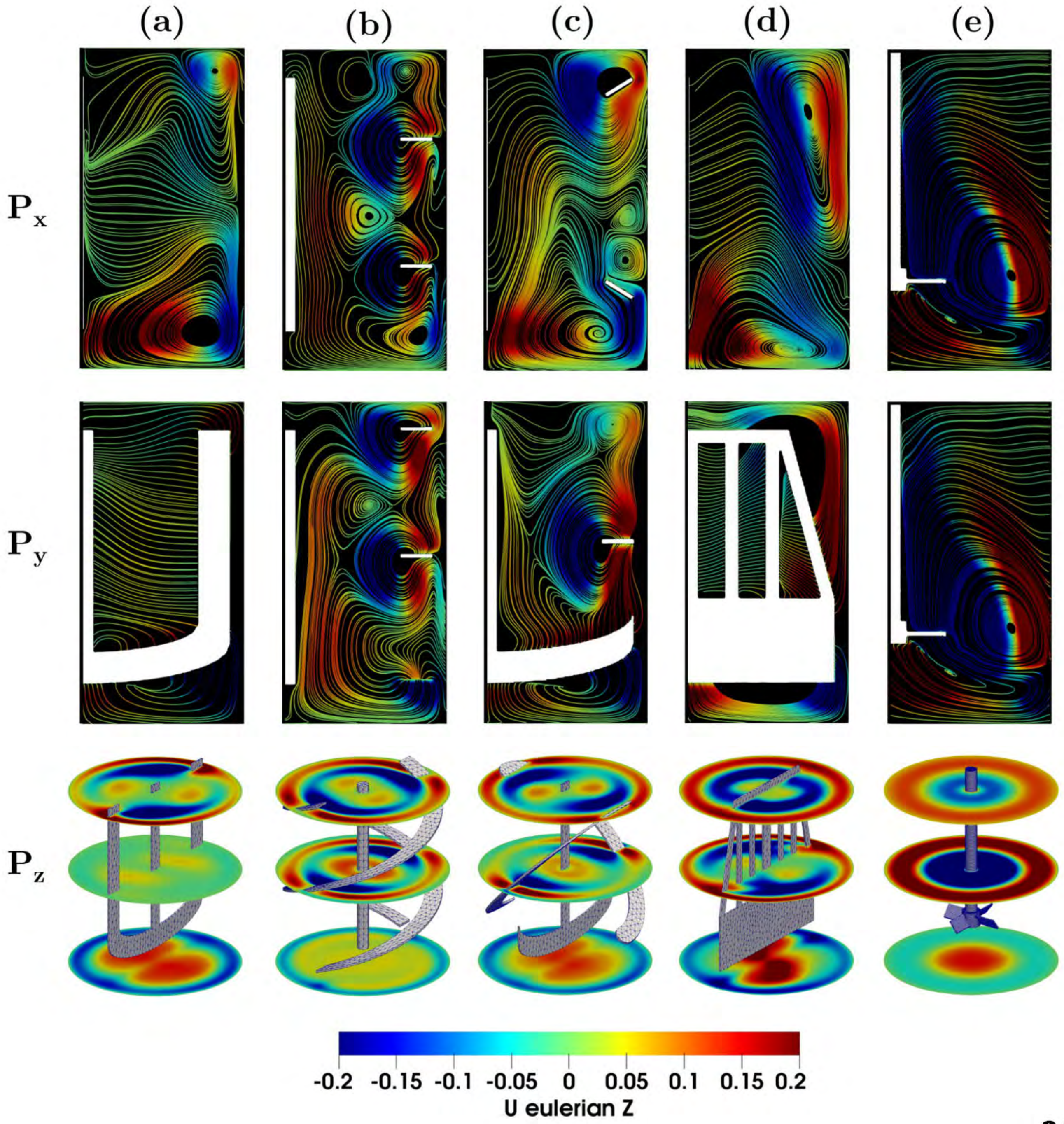
Comparing the performance of viscous mixers

Impellers

Wide range of geometries in the laminar regime
- Anchor (a)
- Helical ribbon (b)
- Paravisc (c)
- Maxblend (d)
- PBT (e)
  - Shall act as our reference comparison

Each configuration generate different flow patterns

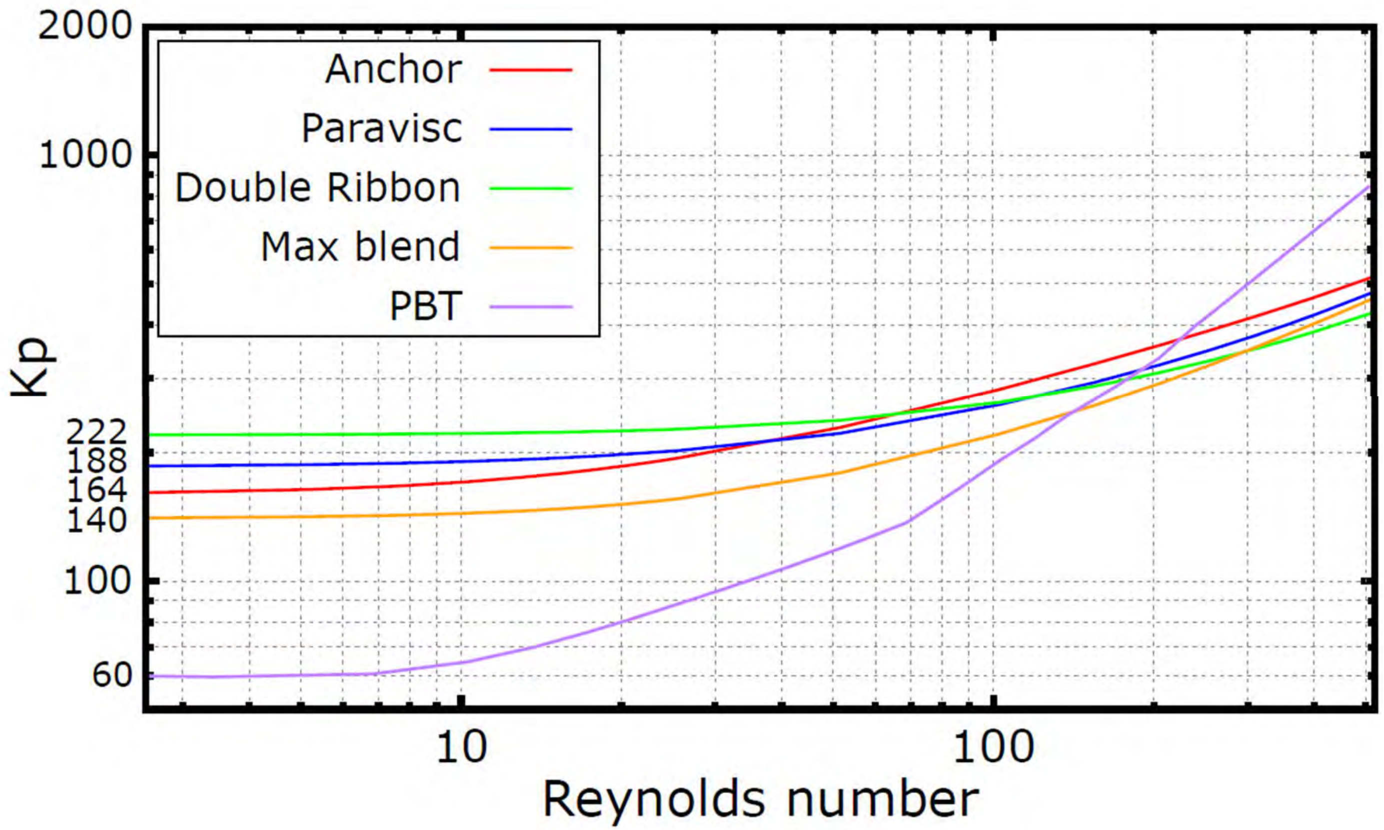
Which one is the most efficient for solid-liquid mixing?



Single phase power consumption

At low Reynolds number, the PBT has a lower Kp

The other agitators are similar

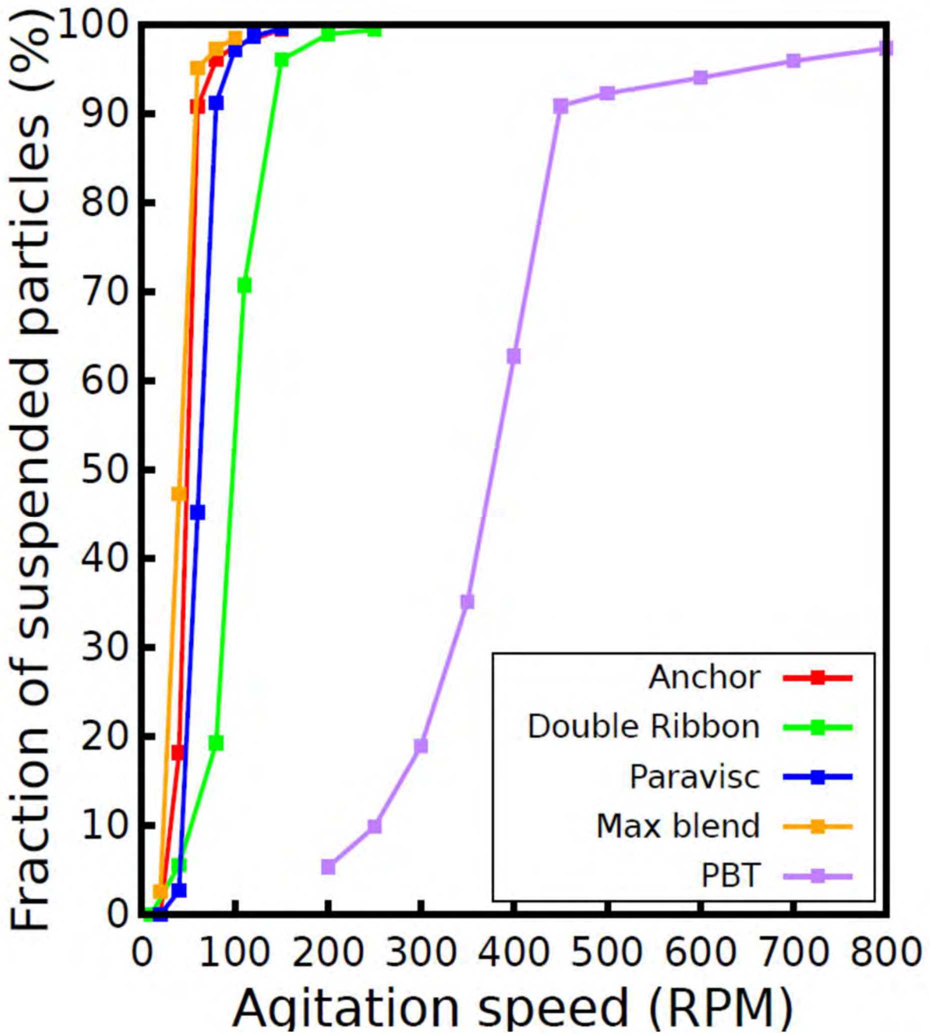


Fraction of suspended particles

The PBT requires significantly higher impeller velocity to suspend particles

This is an unfair comparison

- PBT has a much smaller diameter!



URPEI

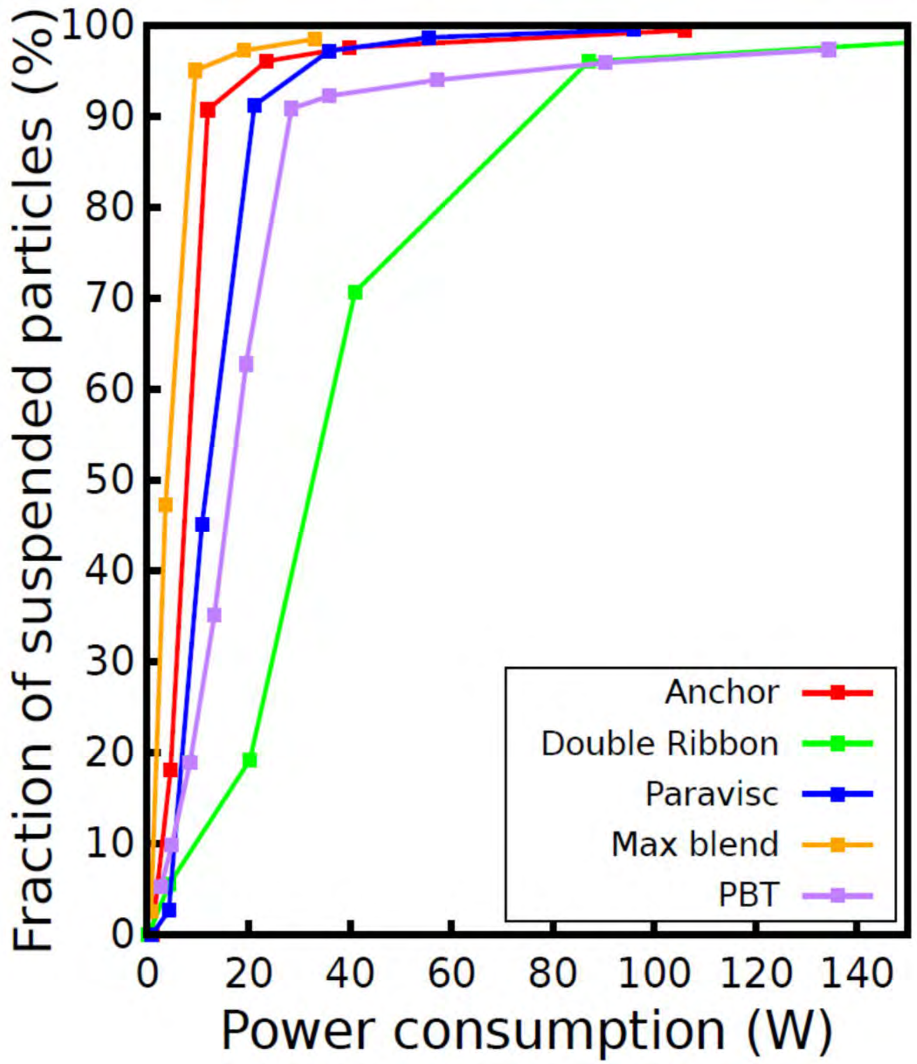
Power consumption

Most impeller perform similarly

- Maxblend and anchor seem to be slightly better

Helical ribbon is a clear outlier…

- It is by far the worst…

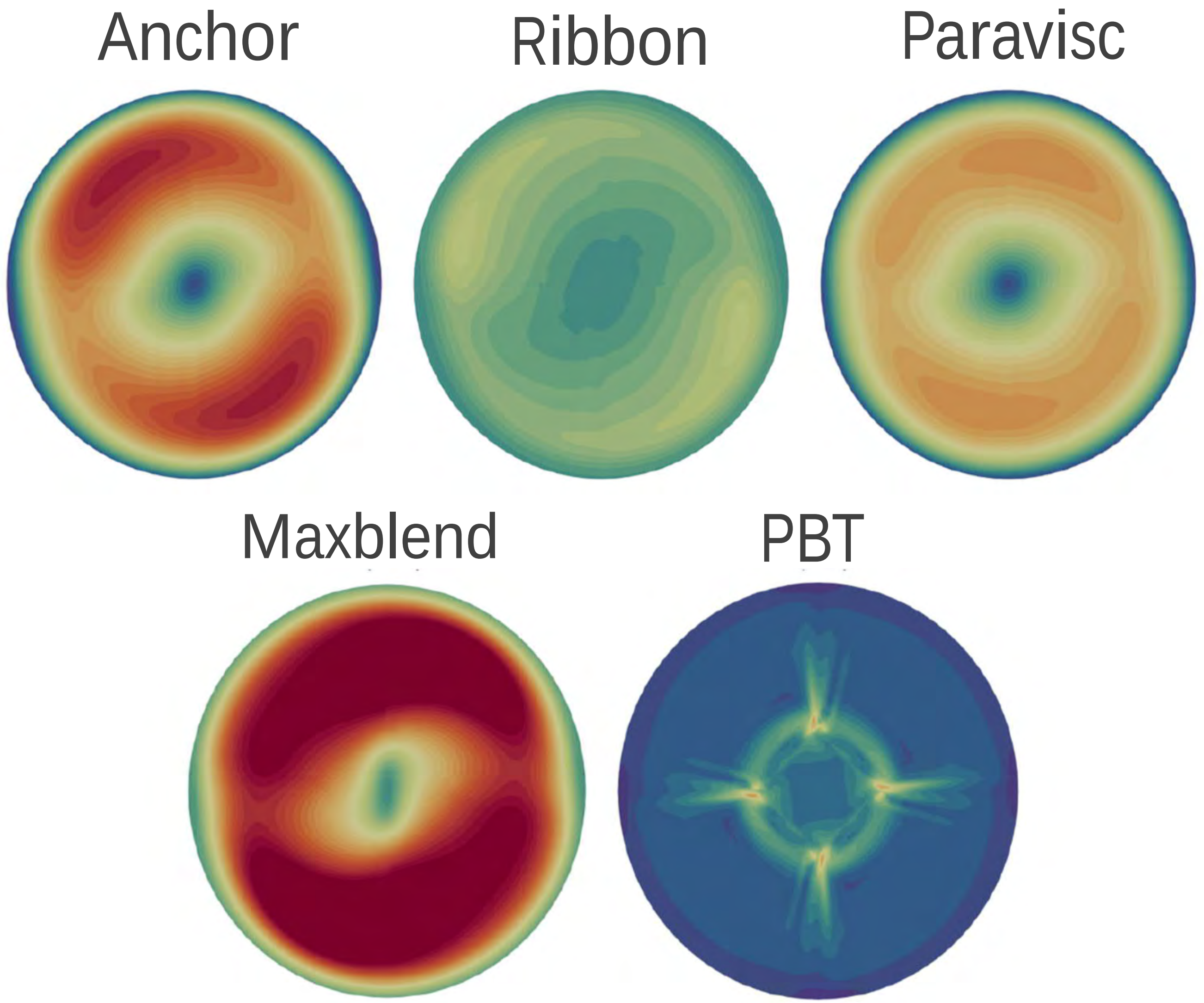


Mechanism

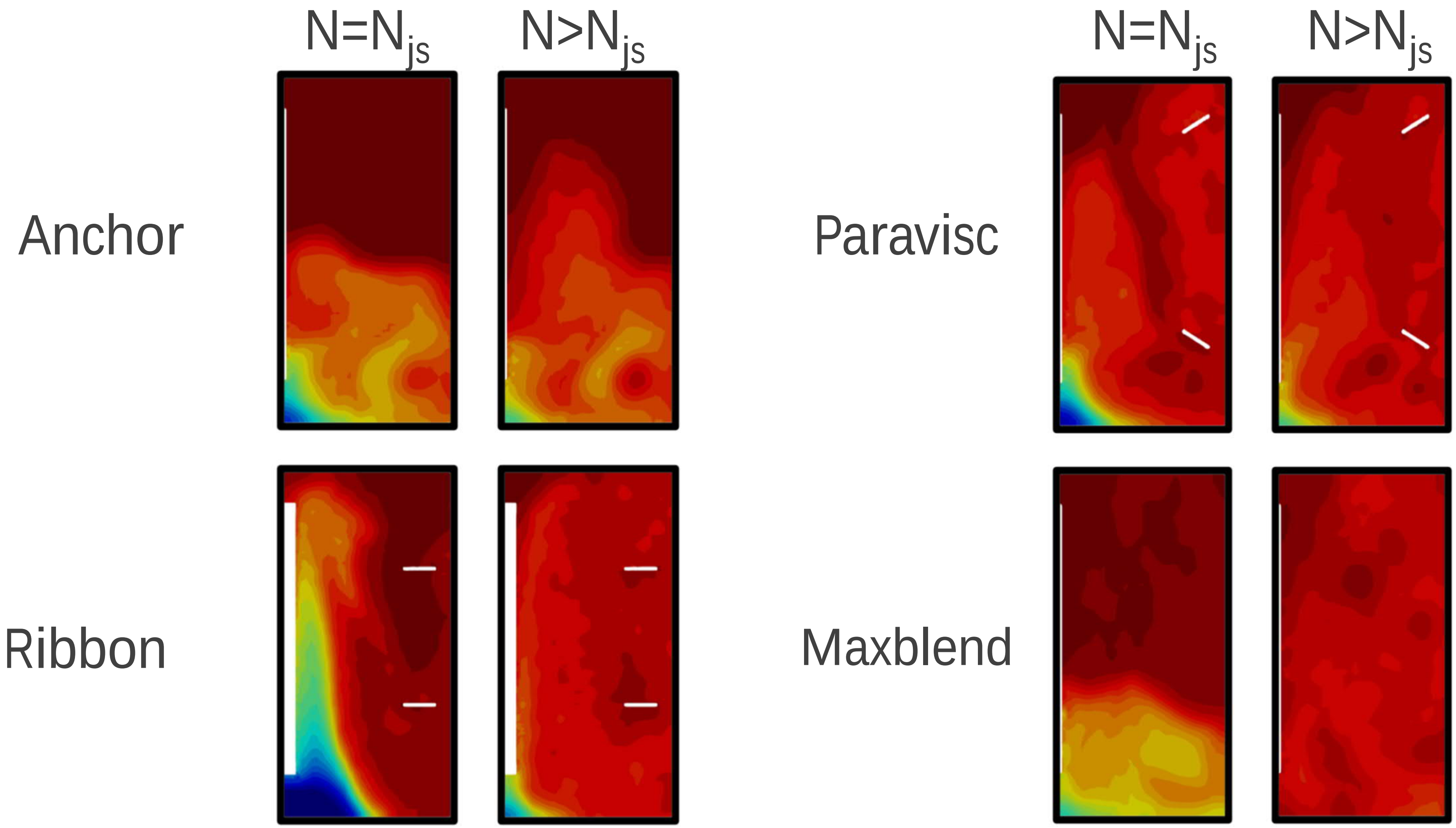
Shear stress generated at the bottom of the vessel strongly correlates with the capacity to suspend

Is the fraction of suspended particle all there is to it?

- Solid concentration
- Cloud height
- RSD



Void fraction



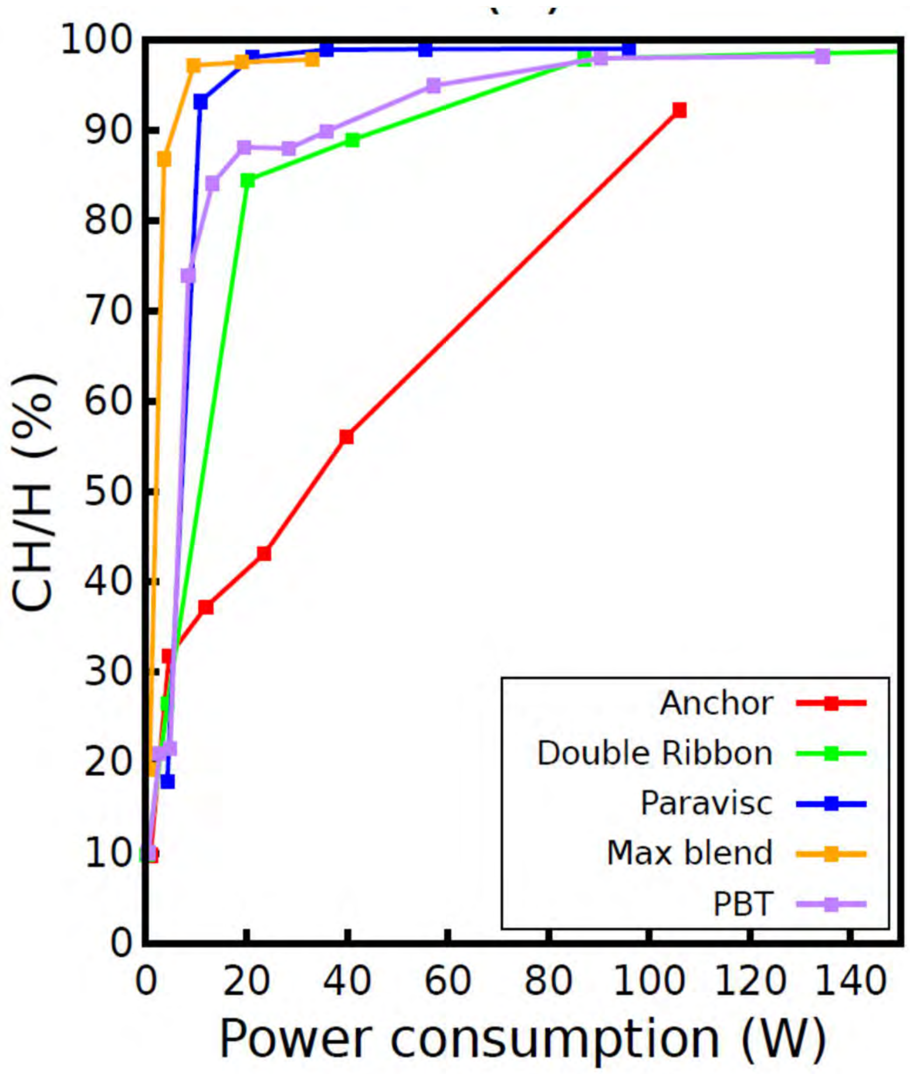
Cloud height

High-shear impeller do not behave as well

Axial flow and shear are required

- Paravisc
- Maxblend

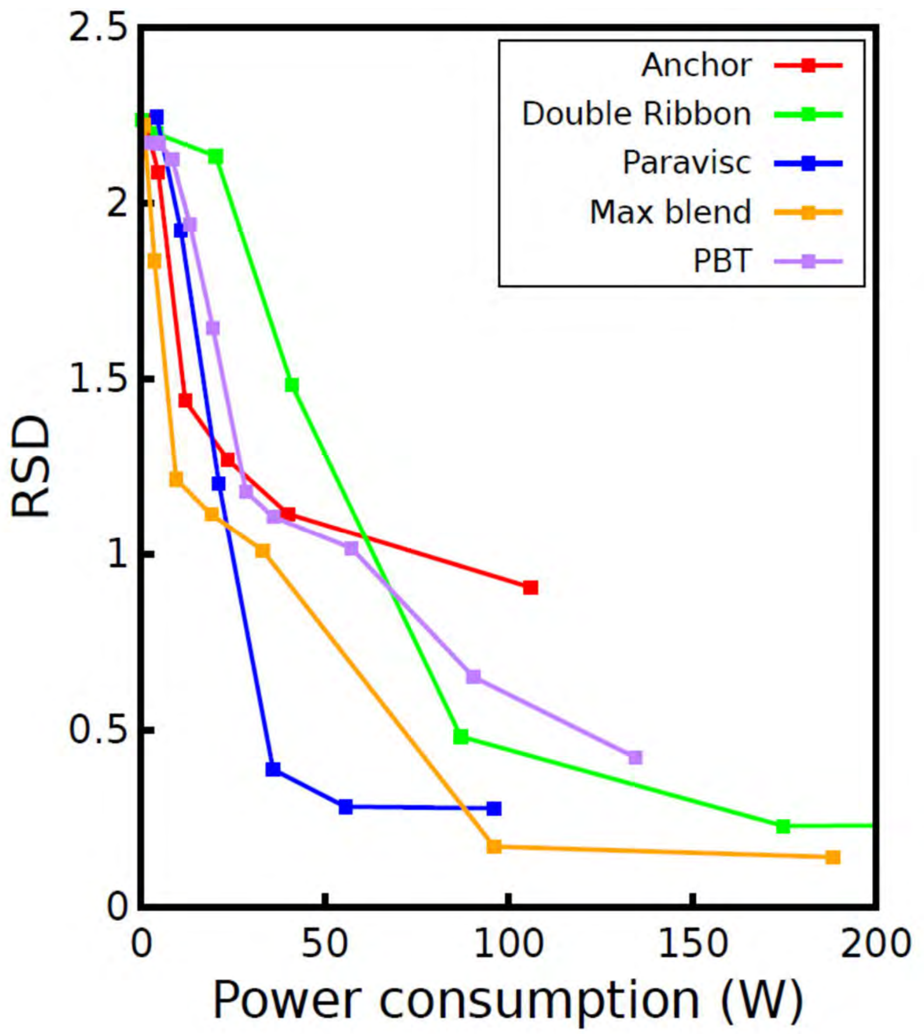
The PBT is still surprisingly good



RSD

Agitators that provide the most distributed flow throughout the vessel offer better RSD

- Paravisc
- Maxblend



Conclusions

Unresolved CFD-DEM can be used to predict solid-liquid mixing

- Fraction of suspended particles
- Solid distribution / cloud height
- RSD

Viscous solid-liquid mixing requires two elements

- Shear forces on the particle bed
- Strong axial circulation

Agitators that provide both of these perform extremely well

- Paravisc
- Maxblend (to a lesser extent)

The PBT is actually a pretty decent agitator for viscous fluids…

Thank you for your time!

Bruno Blais
Assistant Professor
Polytechnique Montreal
Bruno.Blais@polymtl.ca

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References to some of the work presented :

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