Benefits of CFD in Modeling Solids Suspension in Stirred Vessels

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Session 174: Computational Fluid Mixing
2000 AIChE Annual Meeting
"Exchanging Ideas for Innovation"
Los Angeles, California, November 12-17

Overview

- Solids suspension processes
- Just-suspended speed
- Modeling solids suspension using CFD
  - Velocity distribution
  - Solids distribution
- Criteria for scale up

Suspending Solids

- Mechanical agitation is widely used in process industry operations involving solid-liquid flows
- The typical process requirement is for the solid phase to be suspended:
  - dissolution, reaction, feed uniformity
- The challenge is in understanding the fluid dynamics in the vessel and relating this knowledge to design
- CFD modeling can provide insight to both the multiphase transport and the design parameters

Suspending Solids (2)

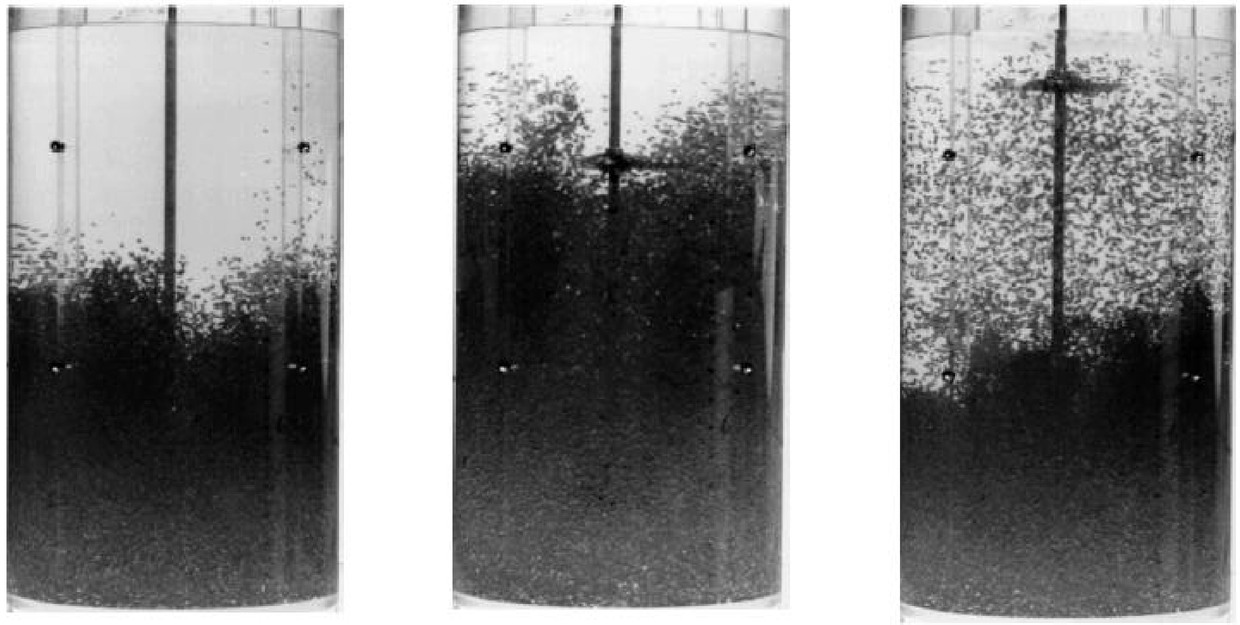
- The motivation of this study is to:
  - Elucidate the criteria of minimum suspension speed and it's prediction using CFD
  - Validate the CFD predictions of solids distribution with experimental data
  - Evaluate scale-up criteria for stirred tanks suspending solids

Just-Suspended Speed

- N_{JS} is the estimated speed when particle reside on the tank bottom for no longer than 1-2 seconds
  - Criteria of N_{JS} is subjective
  - Experiments typically performed in transparent bottom vessels
  - Acoustic methods have been used to measure the amount of solids on tank bottom
- What does mean N_{JS} fundamentally?
  - Is the *just-suspended* condition adequate?
  - This does not determine complete dispersion and particles may be segregated in the bottom of a tall tank
- Is N_{JS} related to the distribution of the solids?

Example of Just-Suspended Speed

- All three systems are operating at N_{JS} (Bakker et al, 1996)



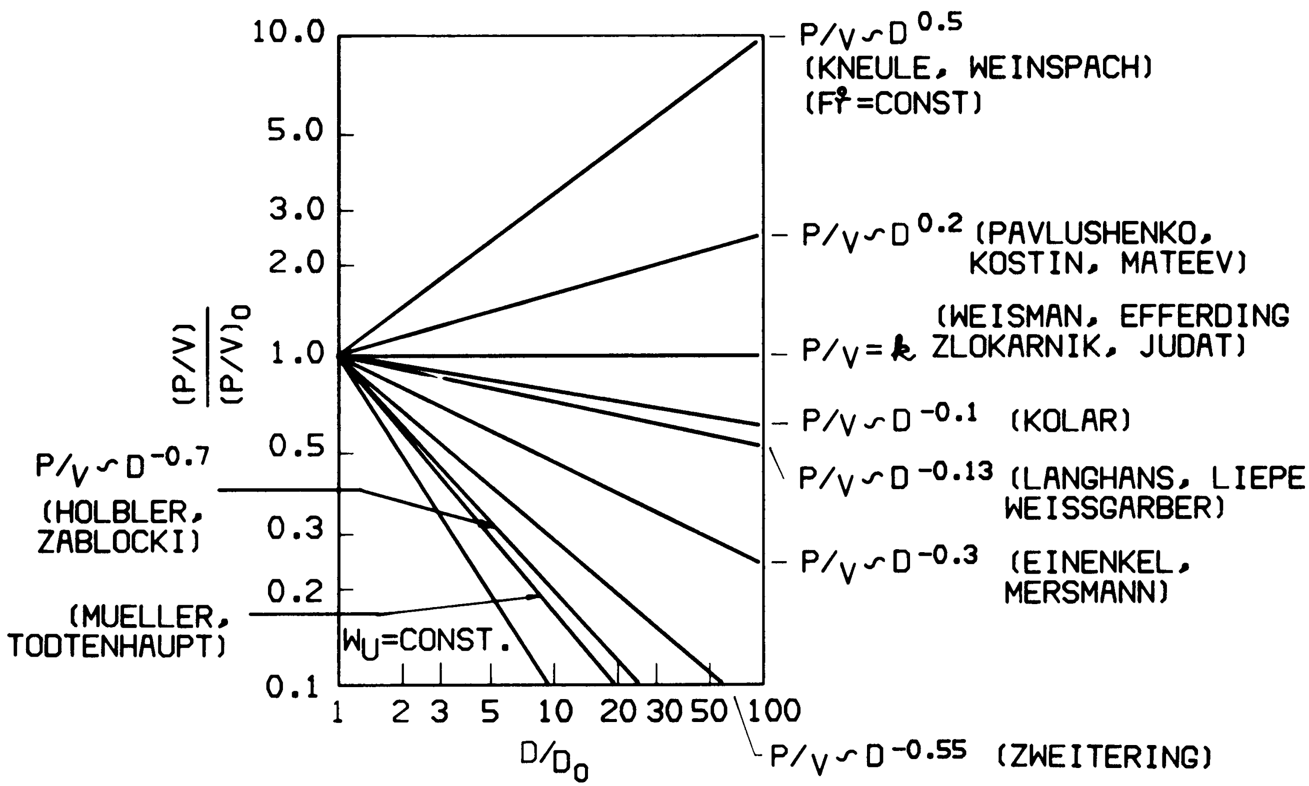
- Designing based on only N_{JS} or on power draw does not necessarily lead to an optimum design
- The impeller system has to be designed to provide the optimum flow pattern for the suspension duty

Estimating Just-Suspended Speed

- Numerous correlation's exist for N_{js}: Zwietering (1958), Chemineer (Myers et al, 1994), BHR/FMP
- Many recent N_{js} correlation's have extended the Zwietering correlation to include D/T and C/T
  - Armenante et al (1998), Penney et al (1999)
- Most correlation's are developed for low viscosity liquids, free-settling solids, low solids loading (<40%), and non-adhesive or non-coagulating solids
- Some of correlation's were developed with a narrow range of impeller blade styles, sizes and position in the lab scale tank
- The large variability in predicting N_{js} may or may not be acceptable

Power per Unit Volume

- Scale up criteria based on power per unit volume has divergent results depending on the correlation used



Needs from Modeling

- Prediction of N_{JS}
- Solids distribution
  - Cloud height
  - Amount of solids unsuspended
- Scaleup
- Other transport phenomena

Modeling Granular Flows

- Lagrangian models
- Drift Flux models
- Algebraic Slip Mixture models
- **Granular Eulerian models**
  - Granular Viscosity model (Syamlal & O'Brien, 1986)
  - Exchange coefficient (Di Felice et al, 199)
  - Restitution Coefficients (Inelastic collisions)
  - Dispersed Turbulence modeling
- 2D axisymmetric with swirl correction, 3D
- Impeller modeling (Implicit and Explicit)

Modeling N_{JS}

- Should CFD be used to predict N_{JS} ?
  - Requires optimization of design and operating conditions
    - Vary D/T, C/T, N
  - What mathematical criteria can describe analysis of "particles remaining on the tank bottom for 1-2 seconds"
  - Can be expensive (3D, sliding mesh, Granular Eulerian Multiphase models)

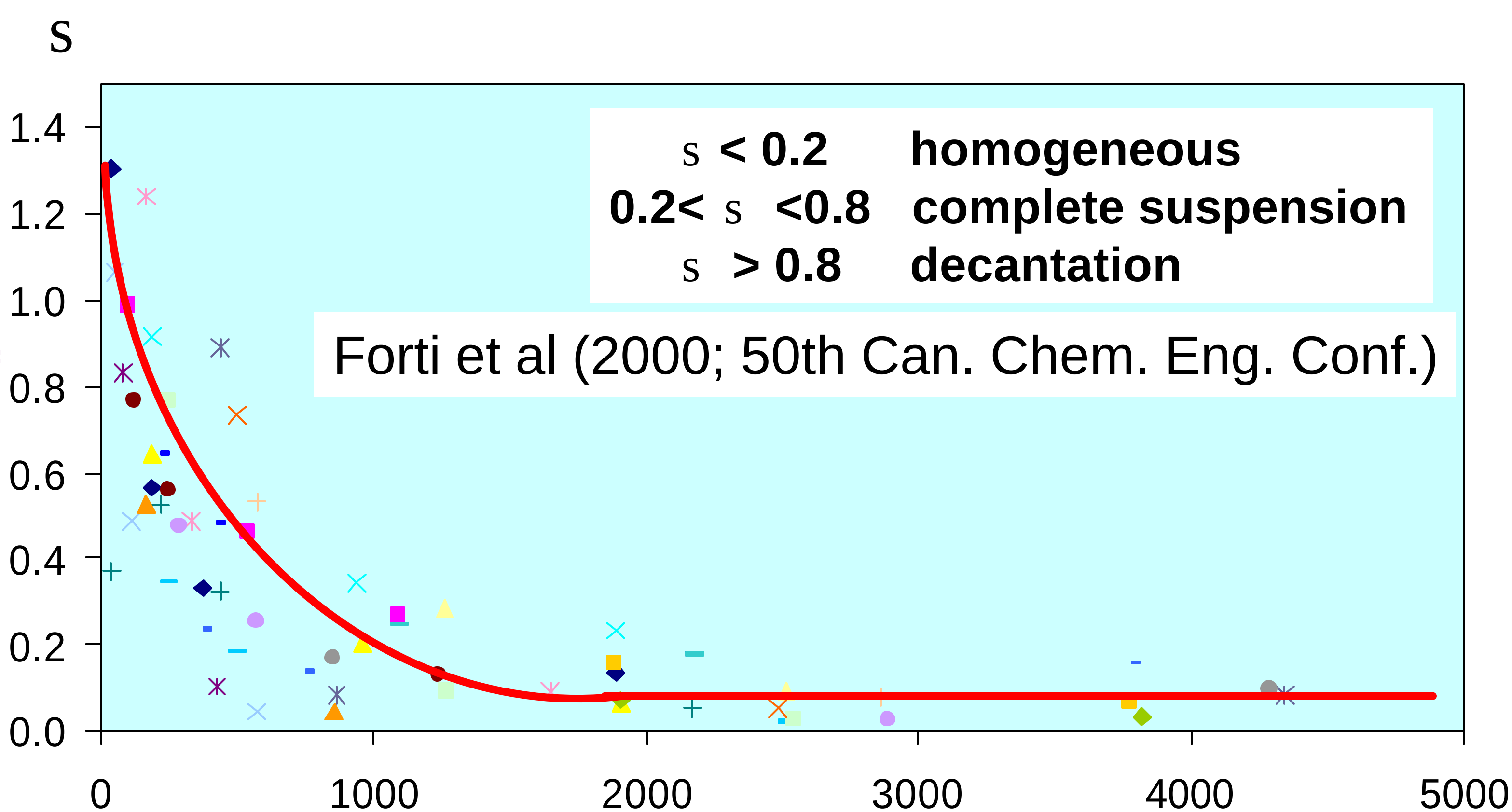
Modeling Suspension Distribution

- CFD has most immediate benefit from the prediction of the solids distribution
  - just-suspension distribution
  - fully-suspended distribution
- Concept of “Quality of Suspension”
  - Forti et al (2000; 50th Can. Chem. Eng. Conf.)
  - Degree of suspension σ related to the Froude number and impeller clearance

$$\sigma = \sqrt{\frac{1}{n}\sum_{1}^{n}\left(\frac{C}{C_{AV}} - 1\right)^{2}} = f\left(\frac{N^{2}D^{2}\rho}{d_{p}\Delta\rho g}\left(C/T\right)\right)$$

- Uniform suspension: $\sigma < 0.2$
- Just-suspended condition: $0.2 < \sigma < 0.8$
- Incomplete suspension: $\sigma > 0.8$

Modeling Suspension Distribution



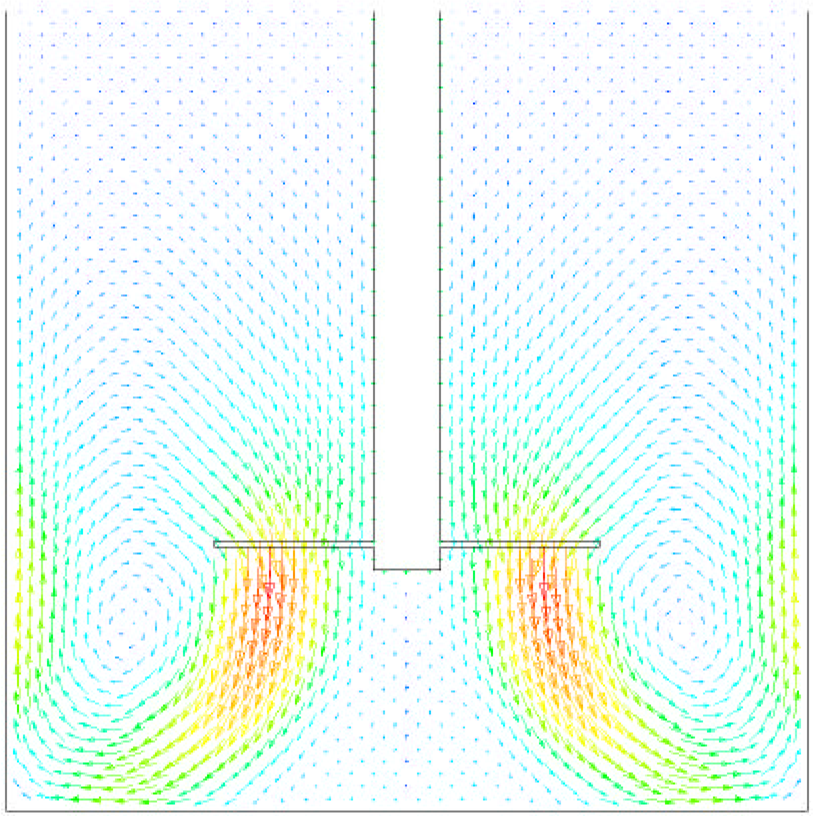
$$f\left\{Fr\left(C/T\right)\right\}$$

Two-Phase Velocity Distribution

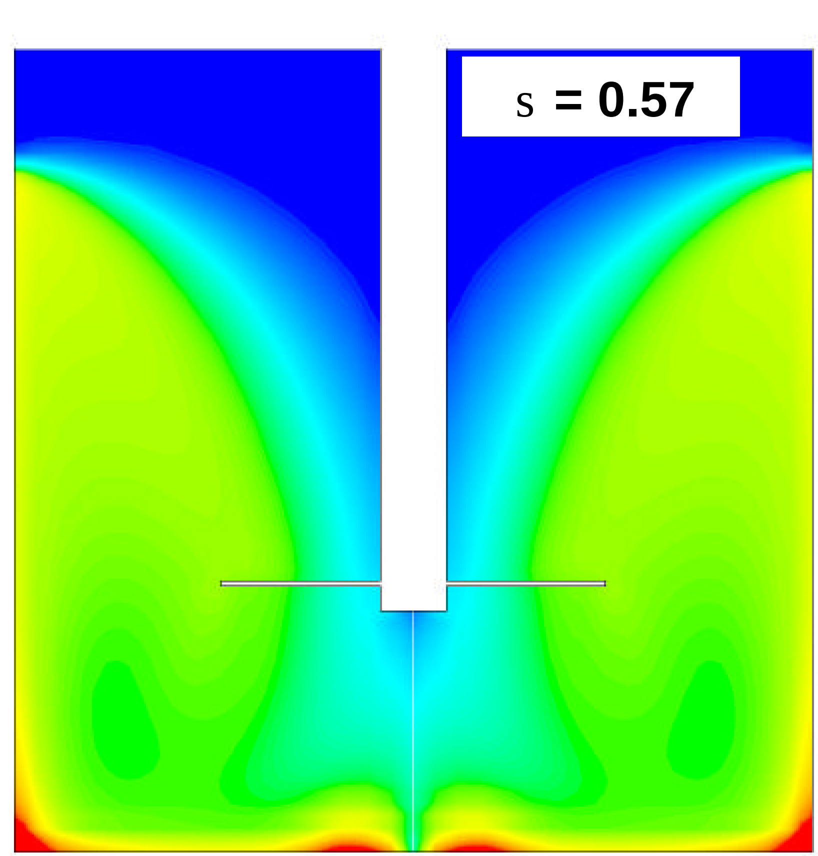
- Experimental study by Guiraud et al, “Local measurements of …”, *Chem. Eng. J.*,v.68, p.75 (1997)

- **Geometry**
  - 3 blade Mixel prop
  - D/T = 0.47
  - C = T/3
  - N = 5.1 rps
  - T = H = 0.3 m
  - $w = 5 \times 10^{-3}$ m
  - $d_{shaft} = 25 \times 10^{-3}$ m
- **Properties**
  - **Solids**
    - $\rho = 2230$ kg/m^3
    - $d_{50} = 253$ μm
    - $C_{av} = 0.5\%$
  - **Liquid**
    - $\rho = 1000$ kg/m^3
    - $\mu = 1$cp

Flow Field Distribution



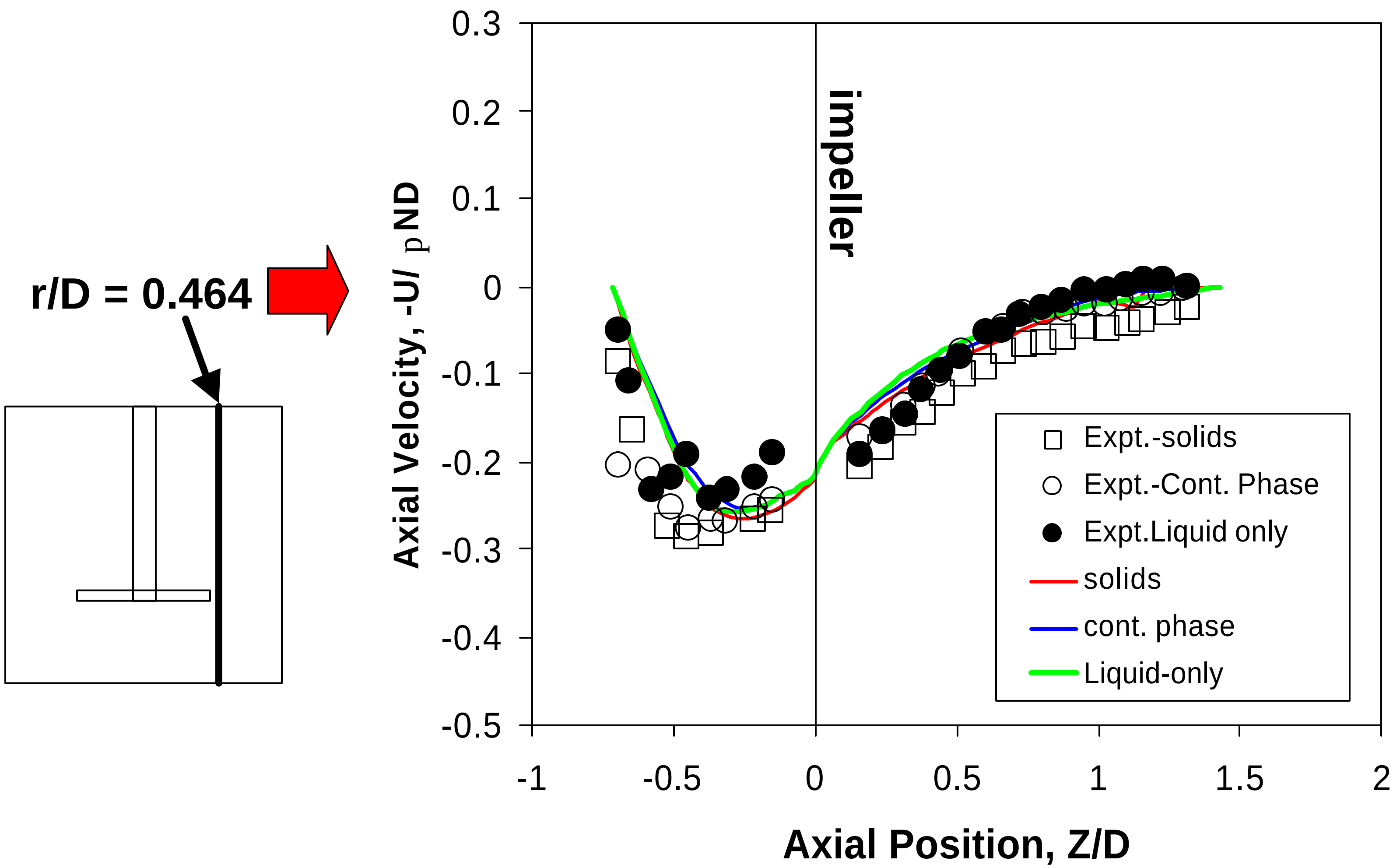
Velocity Magnitude (0 - 0.85 m/s)



Solids Volume Fraction (0 - 0.025)

$N = 306$ rpm $> N_{JS}^{z} = 160$ rpm

Single & Two-Phase Velocity Profiles



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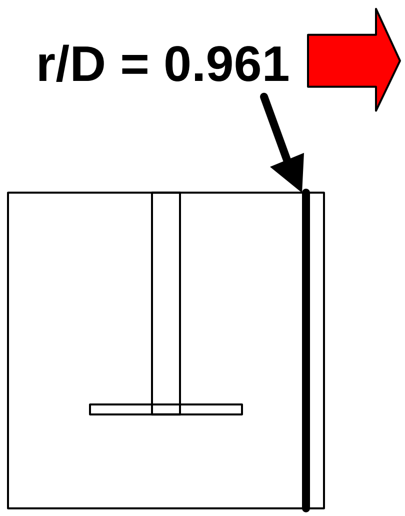
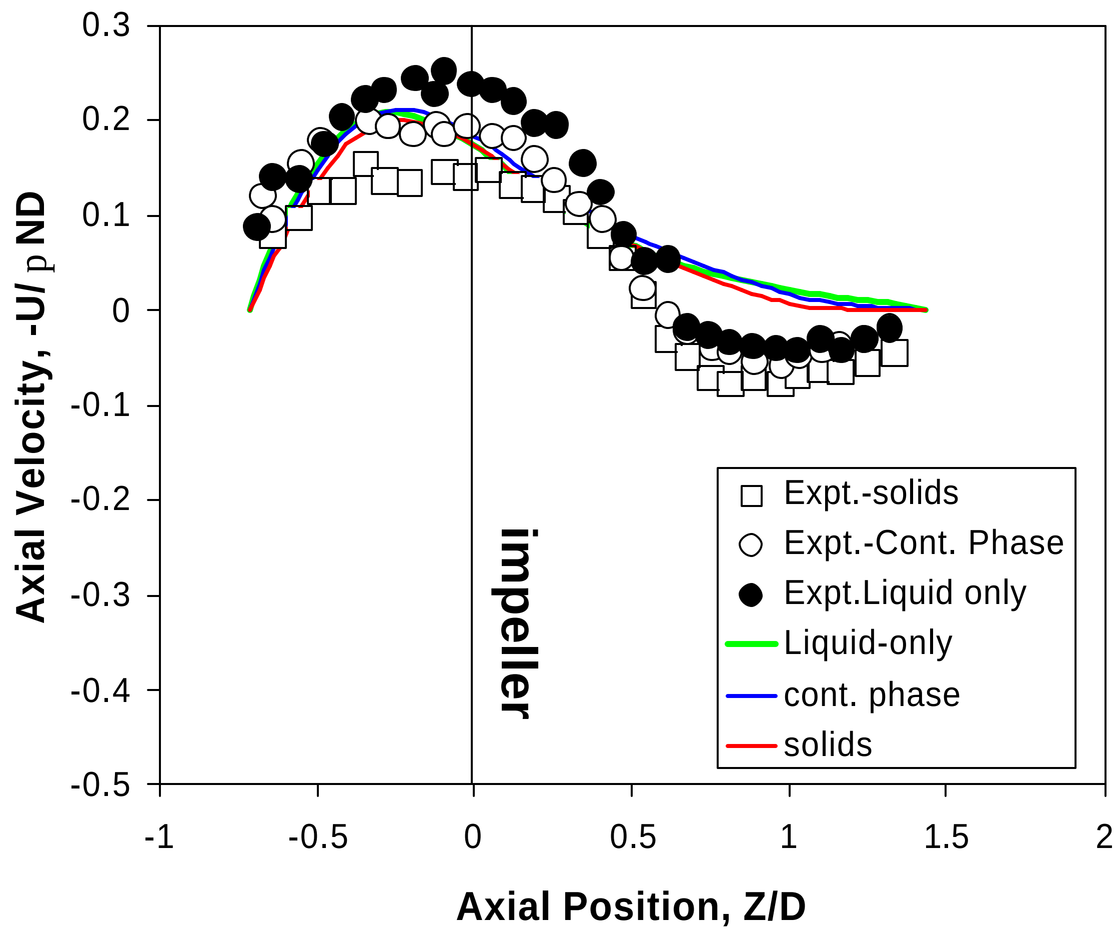
Single & Two-Phase Velocity Profiles





Axial Solids Concentration Profiles

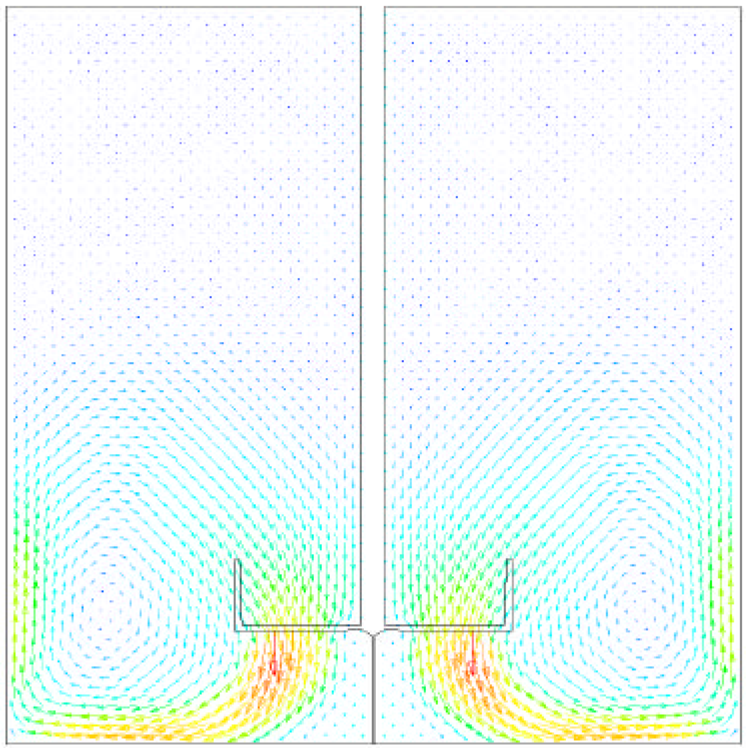
- Godfrey & Zhu, “Measurement of Particle-Liquid Profiles in Agitated Tanks”, AIChE Symp. Series, No. 299, Vol. 90

- **Geometry**
  - 4PBT45°
  - D = T/3
  - C = T/5
  - N = 1000, 1600 rpm
  - T = H = 0.154 m
  - w = T/10D

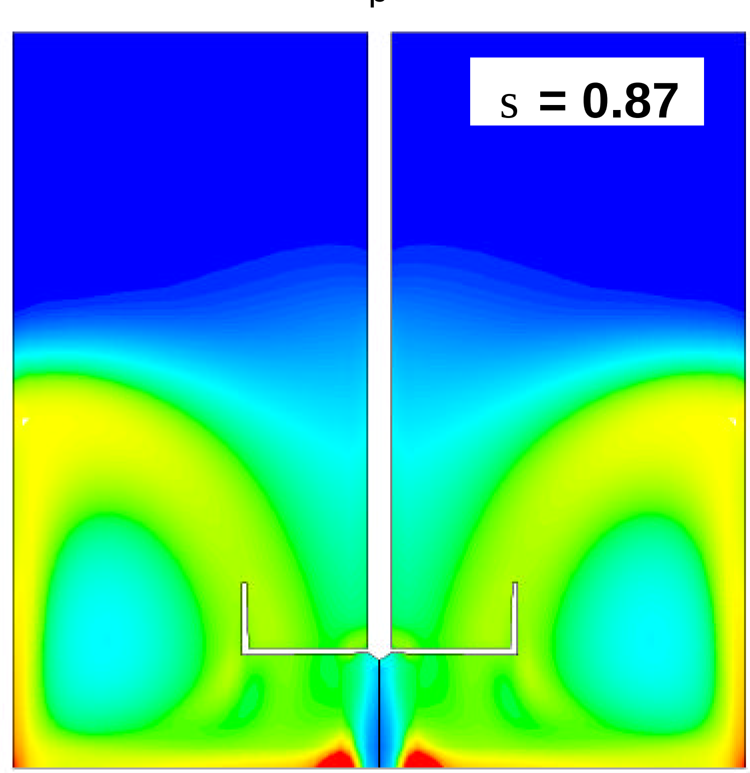
- **Properties**
  - **Solids**
    - $\rho = 2480\ kg/m^3$
    - $d_{50} = 390 \mu m$
  - **Liquid**
    - $\rho = 1096\ kg/m^3$
    - $\mu = 1.76$ cp

Axial Solids Concentration Profiles

- Flow field
  - N = 1000 rpm; Avg. vol. conc = 12%, d_p = 390 μm



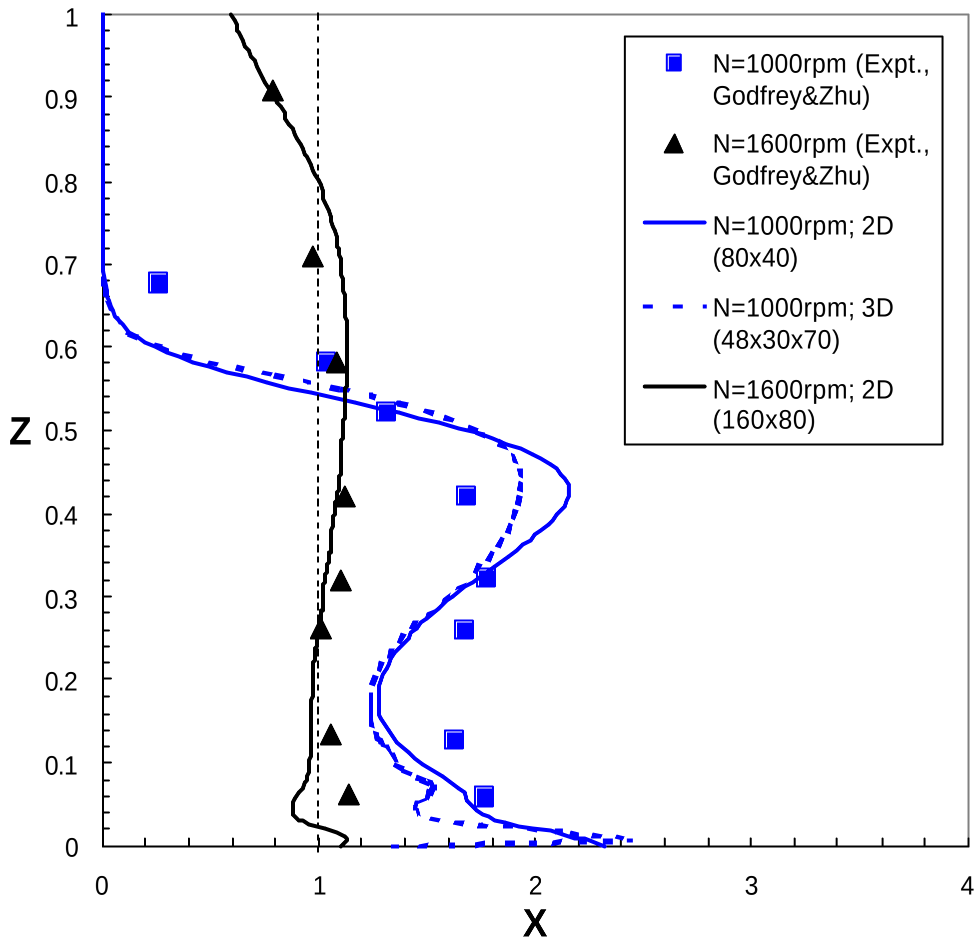
Velocity Magnitude (0 - 0.95 m/s)



Solids Volume Fraction (0 - 0.4)

$N_{JS}^{Chemineer}$ = 780 rpm < N = 1000 rpm < $N_{JS}^{Zwietering}$ = 1170 rpm

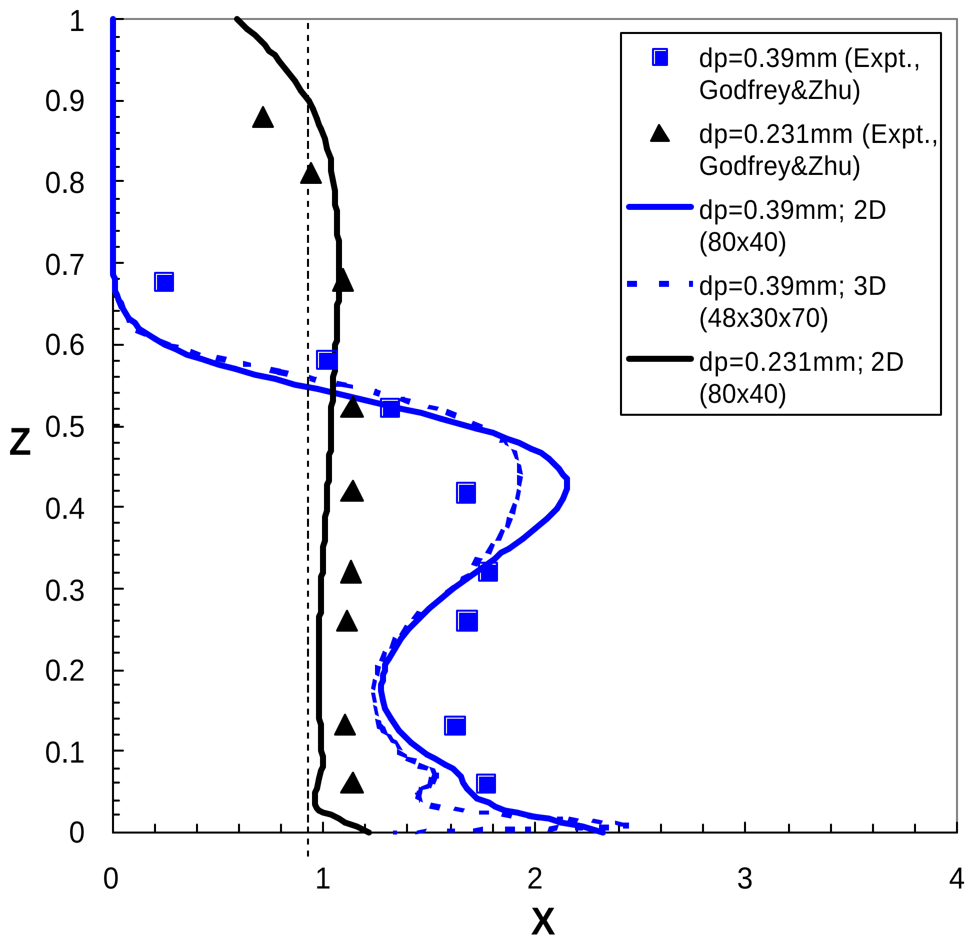
Effect of Agitation Speed



Average concentration = 12%

Particle Size = 390 μm

Effect of Particle Diameter

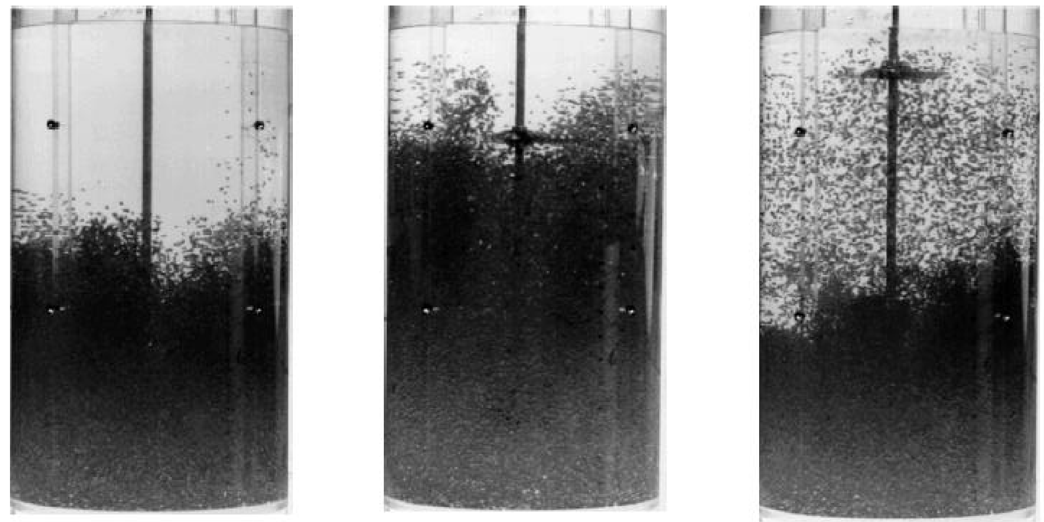


Average concentration = 12%

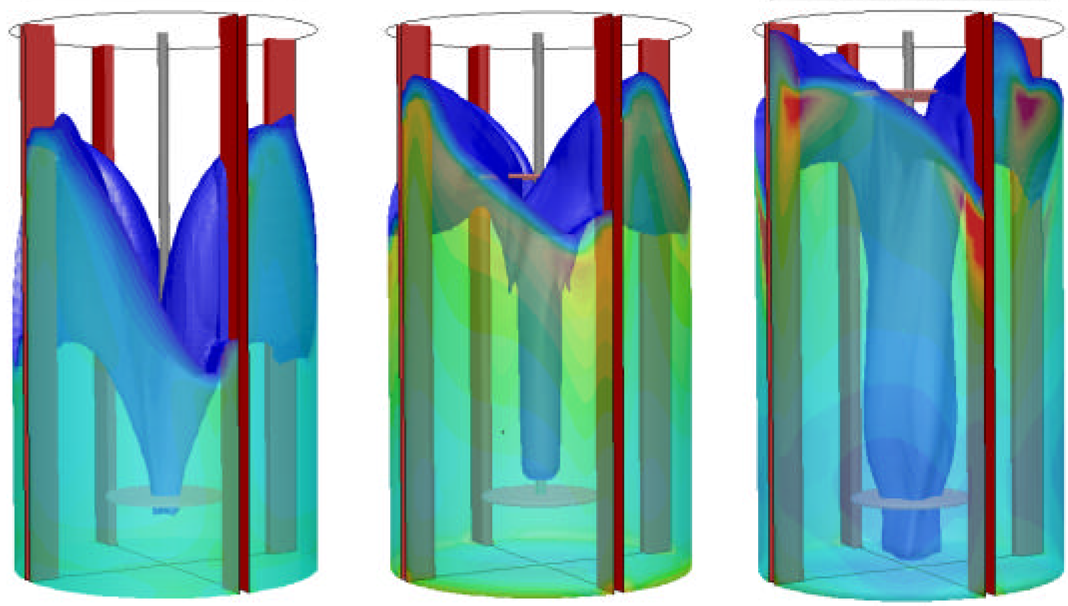
Impeller speed = 1000 rpm

Cloud Height Analysis

- Suspension experiments (Bakker et al, 1996)
  - Instantaneous

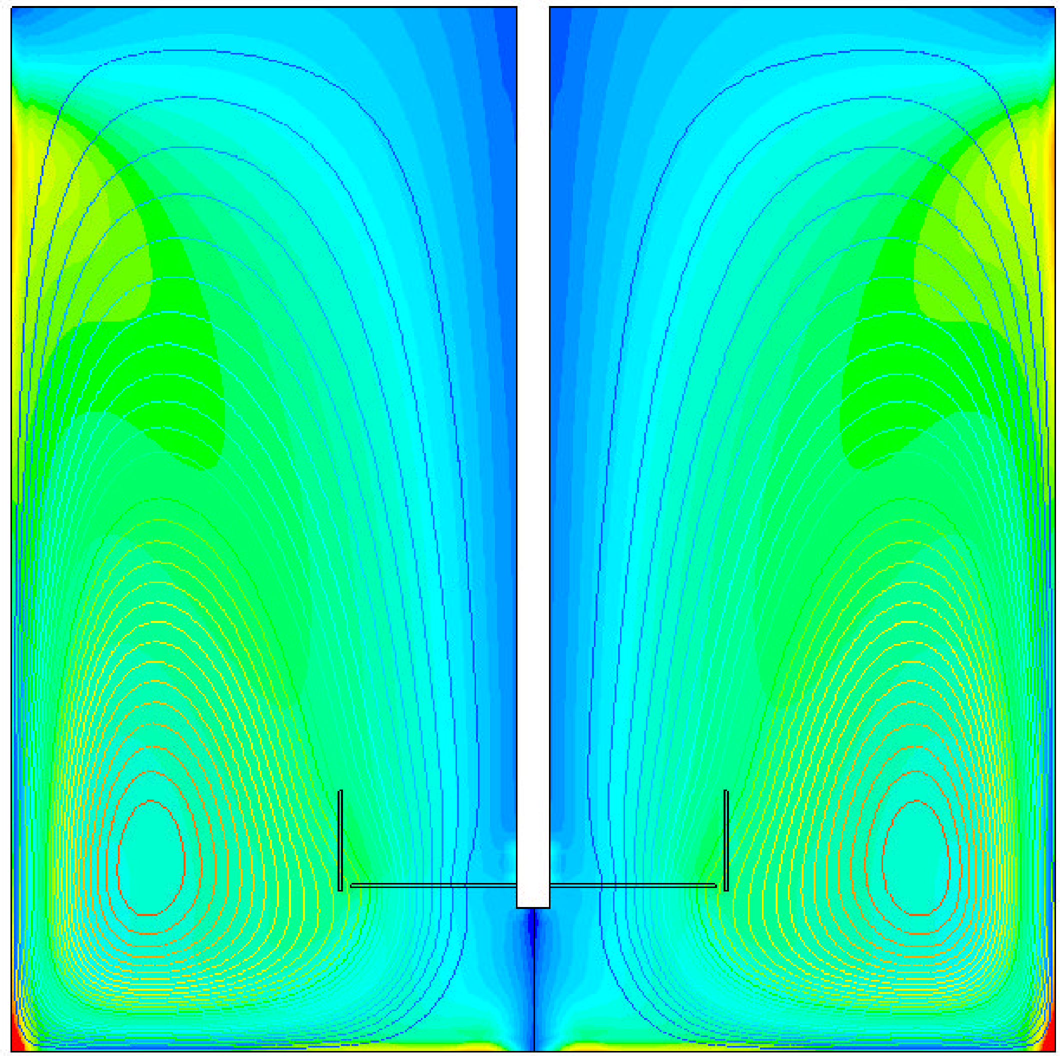


- CFD
  - Time-averaged
  - Cloud height (volume fraction of solids < 0.25%)



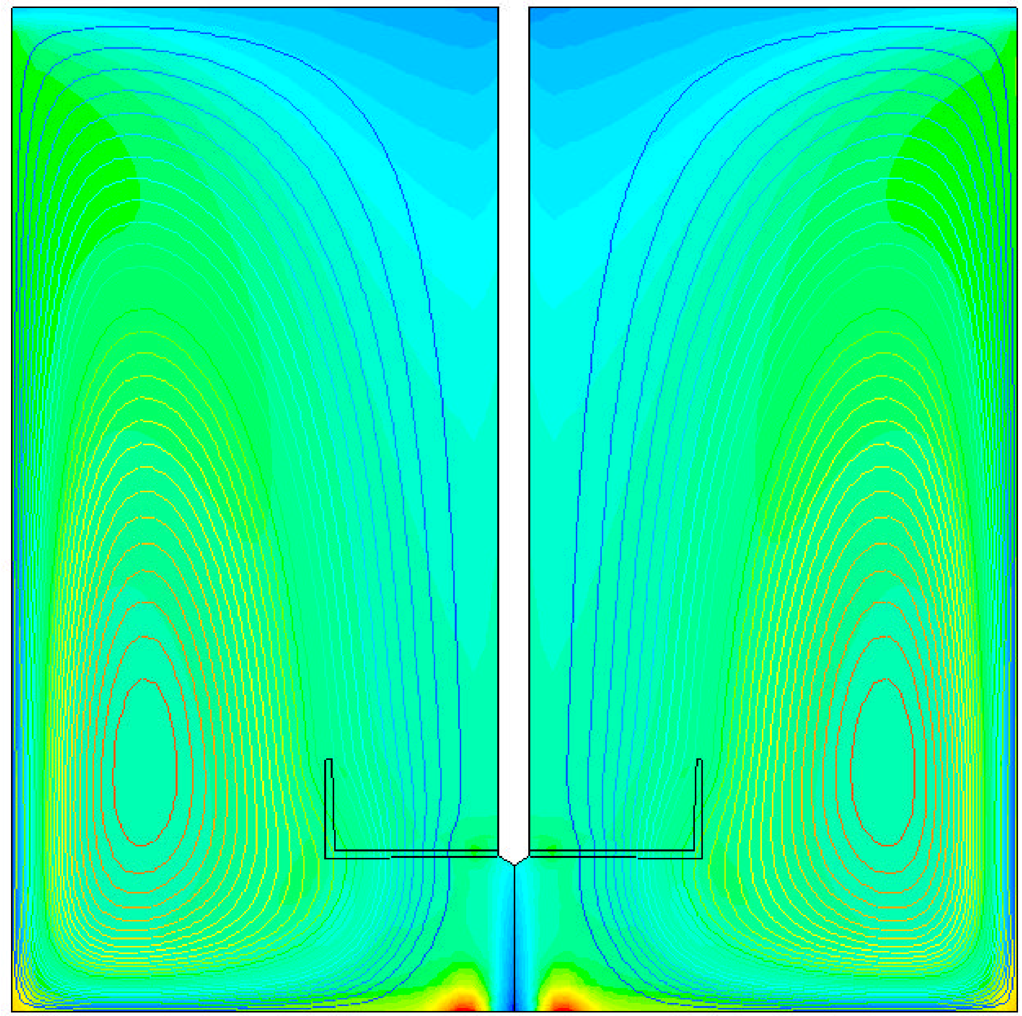
Correlation between Stream Lines/Tubes and Cloud Height (1/3)

- $N = 1600$ rpm
- $C_{AV} = 12\%$
- $d_p = 390\ \mu m$
- $N_{JS}^{z} = 1170$ rpm
- $\sigma = 0.28$



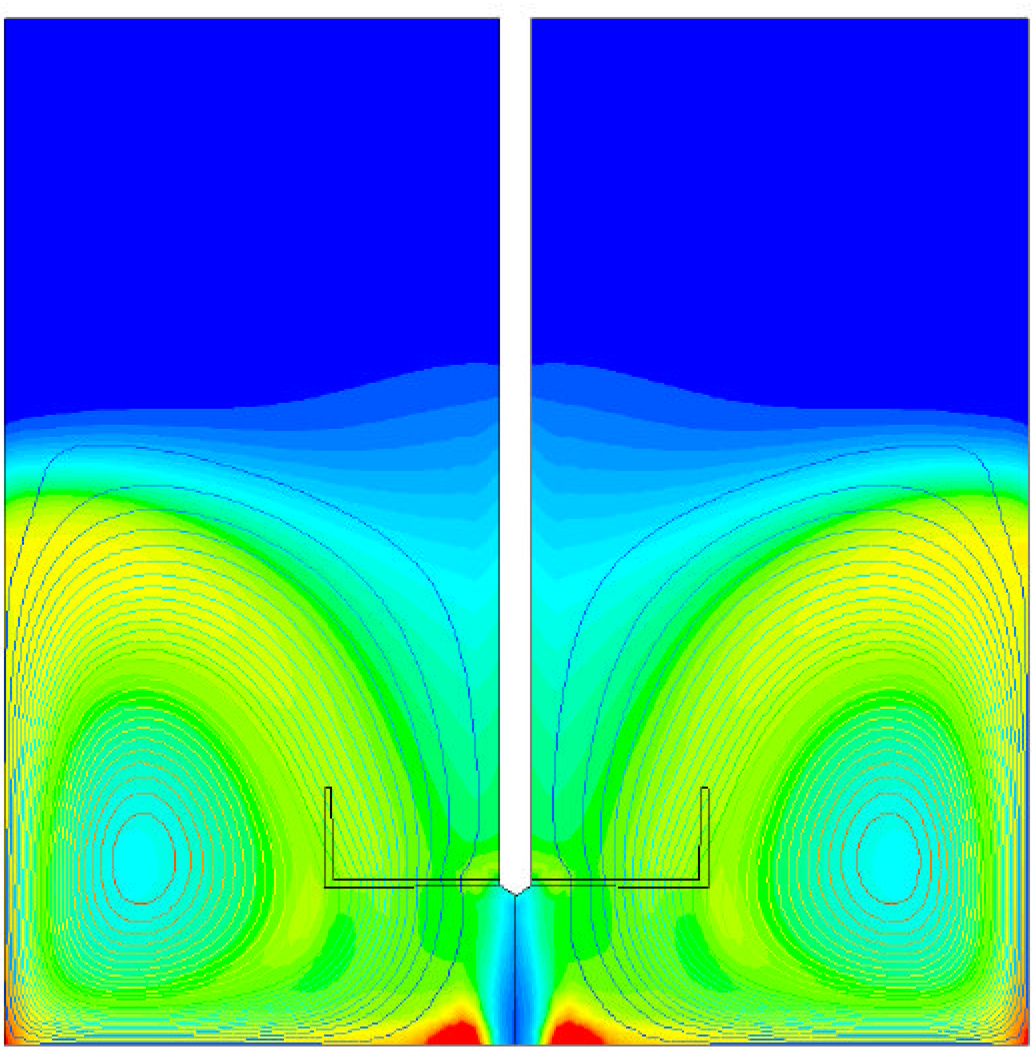
Correlation between Stream Lines/Tubes and Cloud Height (2/3)

- N = 1000 rpm
- C_{AV} = 12%
- d_p = 231 μm
- N_{JS}^{z} = 1050 rpm
- σ = 0.15



Correlation between Stream Lines/Tubes and Cloud Height (3/3)

- $N = 1000$ rpm
- $C_{AV} = 12\%$
- $d_p = 390\ \mu m$
- $N_{JS}^{z} = 1170$ rpm
- $\sigma = 0.87$



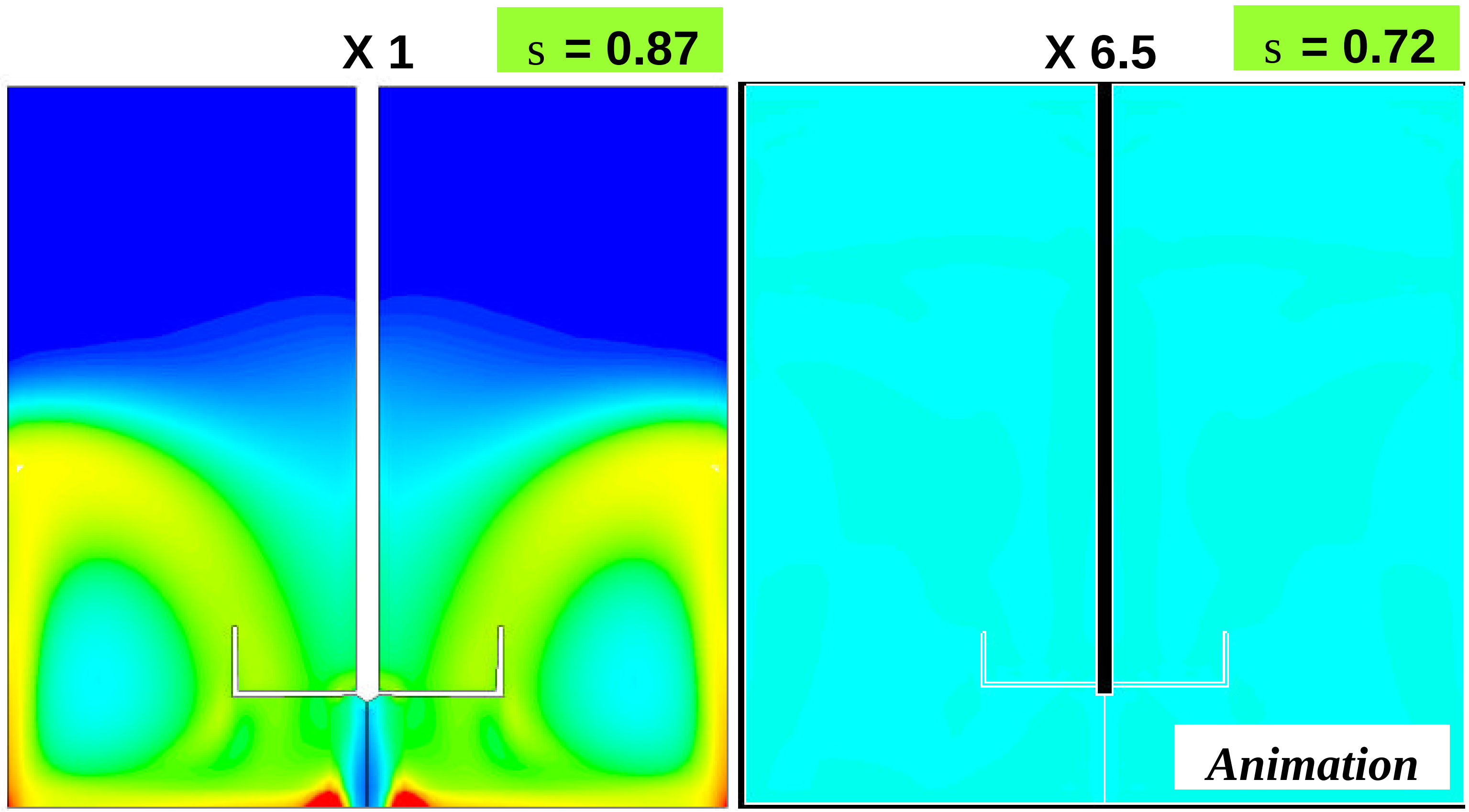
Scale-Up

- Use literature correlation's to predict N_{JS} for different scales to give ball-park number
- Possible scale up criteria
  - N_{JS}, Fr(C/T), ...
- P/V scale up criteria not consistent
- Run CFD calculation on design as confirmation

Scale-Up

- Scale-up Godfrey & Zhu case by factor of 6.5
  - Zwietering N_{JS}
    - Scale x 1 = 1170 rpm
    - Scale x 6.5 = 236 rpm
  - Quality of Suspension
    - Scale x 1, N = 1000 rpm (Godfrey & Zhu), σ = 0.86
    - Scale x 6.5, N = 236 rpm, σ = 0.72

Scale-Up (2)



Solids Volume Fraction (0 - 0.4)

Conclusions

- CFD can be used to model solids suspension in agitated vessels
- The velocity field and solids distribution compared very well with experimental data
- Standard deviation of solids volume fraction can be used to confirm the quality of suspension
- Process design and analysis can be rapidly performed:
  - Scale geometry
  - Modify tank geometry, baffling and draft tubes
  - Evaluate agitator performance rapidly

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