Numerical Simulations Studying Size Segregation in a Rotating Drum

Mohit P. Tandon, Aditya Karnik, Simon Lo

Cd-adapco

Motivation

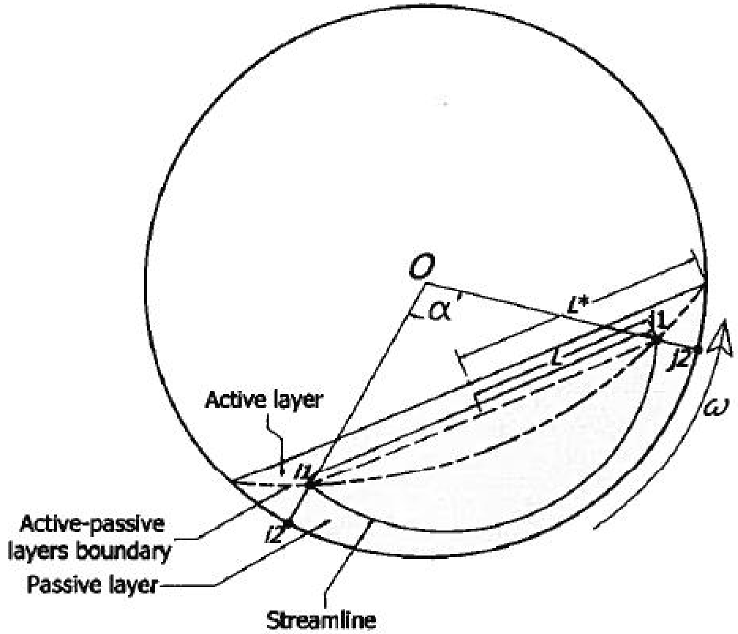
Investigate the effect on granular flow of a distribution of particle sizes inside the bed thereby, investigate how well theories and correlations developed for mono-dispersed perform for more complex poly-disperse systems

Granular Flows

- Particulate materials exist in many industries including metallurgical, chemical, food, pharmaceuticals, ceramic
- It is sometimes preferable to separate components from mixture whereas, sometimes mixing produces the final product
- Rotary drum is often used as granular mixer, gas/solid reactor, dryer

Experiments: Rotary Drum

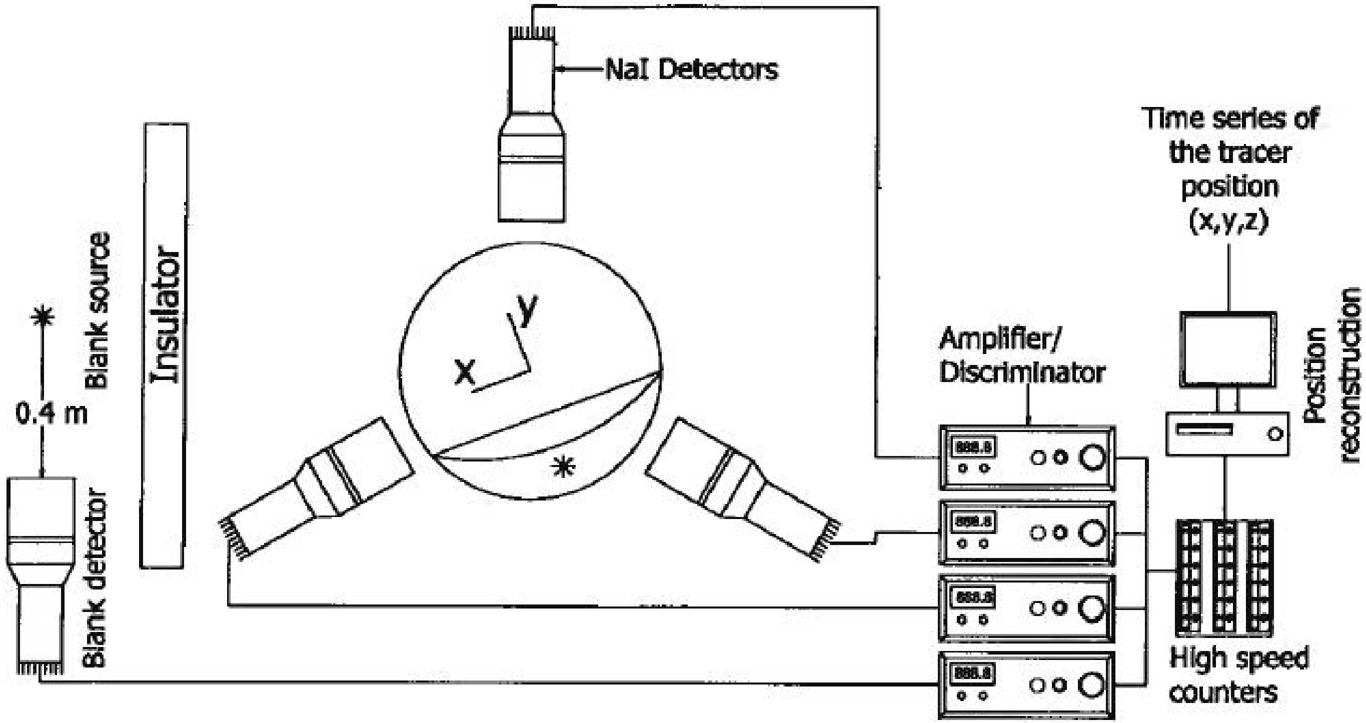
- Focus on rolling regime which is common for mixing purposes
- Granular bed in rolling mode can divided into two distinct regions:
  - Thin active layer
  - Larger passive layer



Source: Alizadeh et al., AIChE J., 59(6), 2013

Experiments: Rotary Drum

Radioactive tracing was used to collect data in plexi-glass drum



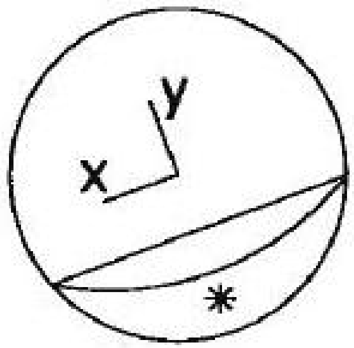
Experiments: Rotary Drum

Case	Type	Rotational Speed (RPM)
MD1	Monodisperse (3mm)	5.4
MD2	Monodisperse (3mm)	11.6
PD1	Polydisperse 3mm – 15%, 4mm – 35%; 5mm – 35%; 6mm – 15%	5.4
PD2	Polydisperse 3mm – 15%, 4mm – 35%; 5mm – 35%; 6mm – 15%	11.6

Composition of poly-disperse systems was chosen to ensure rapid segregation

Experiments: Rotary Drum

- Particle density, $\rho_s = 2500 kg/m^3$
- Gas density, $\rho_g = 1.18 kg/m^3$
- Gas viscosity, $\mu_g = 1.8 \times 10^{-5} Pa.s$
- Drum diameter, $D = 24 cm$
- Drum Length, $L = 36 cm$
- Bed height, $35\%\ of\ volume$



Model setup in STAR-CCM+

- Algebraic model for granular temperature
- Fluid particle drag modelled using Gidaspow drag
- Inter-particle drag modelled using Gera-Syamlal drag
- Particle kinetic viscosity modelled using Gidaspow model
- Frictional regime modelled using Schaeffer model
- Coefficient of restitution, $e = 0.9$
- Maximum particle volume fraction set at 0.624

Governing Equations

- Continuity

$$\frac{\partial}{\partial t}\alpha_k\rho_k + \nabla \bullet \alpha_k\rho_k u_k = 0$$

- Fluid Momentum

$$\frac{\partial}{\partial t}\alpha_k\rho_k u_k + \nabla \bullet \alpha_k\rho_k u_k u_k = -\alpha_k\nabla p + \alpha_k\rho_k g + \nabla \bullet \alpha_k\tau_k + F_I$$

- Solid Momentum

$$\frac{\partial}{\partial t}\alpha_s\rho_s u_s + \nabla \bullet \alpha_s\rho_s u_s u_s = -\alpha_s\nabla p - \nabla p_s + \alpha_s\rho_s g + \nabla \bullet \alpha_s\tau_s + F_I$$

Granular Temperature formulation

- Granular temperature is calculated by an algebraic relation derived by assuming local equilibrium between production and dissipation of fluctuating energy.

$$\sqrt{\theta} = \left\{ \frac{-K_1 \varepsilon_s D_{ii} + \sqrt{K_1^2 D_{ii}^2 \varepsilon_s^2 + 4K_4 \varepsilon_s \left[K_2 D_{ii}^2 + 2K_3 D_{ij} D_{ij} \right]}}{2\varepsilon_s K_4} \right\}$$

$$K_1 = 2\rho_s g_0 (1+e)$$

$$K_2 = \frac{4 d_s \rho_s \varepsilon_s g_0 (1+e)}{3\sqrt{\pi}} - \frac{2}{3} K_3$$

$$K_3 = \frac{\rho_s d_s}{2} \left\{ \frac{\sqrt{\pi}}{3(3-e)} \left[0.5(3e+1) + 0.4(1+e)(3e-1)\varepsilon_s g_0 \right] + \frac{8\varepsilon_s g_0 (1+e)}{5\sqrt{\pi}} \right\}$$

$$K_4 = \frac{12(1-e^2)\rho_s g_0}{d_s \sqrt{\pi}}$$

Particle diameter d_s

Particle density ρ_s

Strain rate tensor D_{ij}

Kinetic theory stress tensor

$$S_s = \left[-P_s + \left(\xi_s - \frac{2}{3}\mu_s \right) \nabla \cdot u_s \right] I$$

Solid pressure, $$P_s = \rho_s \varepsilon_s \theta + P_s^C$$

Collisional solid pressure, $$P_S^C = 2\rho_s \varepsilon_s^2 \theta g_0 (1+e)$$ (Lun et al.)

Particle shear viscosity, $$\mu_s = \frac{4}{5}\varepsilon_s^2 \rho_s d_s g_0 (1+e)\sqrt{\frac{\theta}{\pi}} + \mu_s^K$$

Particle kinetic viscosity, $$\mu_s^K = \frac{10\rho_s d_s \sqrt{\pi\theta}}{96(1+e)g_0}\left[1 + \frac{4}{5}(1+e)g_0\varepsilon_s\right]^2$$ (Gidaspow et al.)

Particle bulk viscosity, $$\mu_s = \frac{4}{3}\varepsilon_s^2 \rho_s d_s g_0 (1+e)\sqrt{\frac{\theta}{\pi}}$$ (Lun et al.)

Frictional stress tensor – Schaeffer

$$S_s^f = \left[-P_s^f + \left(\xi_s^f - \frac{2}{3}\mu_s^f \right) \nabla \cdot u_s \right] I$$

Frictional Solid pressure,

$$P_s^f = 10^{25}\left(\varepsilon_s - \varepsilon_s^{\max}\right)^{10} \qquad \varepsilon_s > \varepsilon_s^{\max}$$

$$= 0 \qquad \varepsilon_s \le \varepsilon_s^{\max}$$

Frictional viscosity,

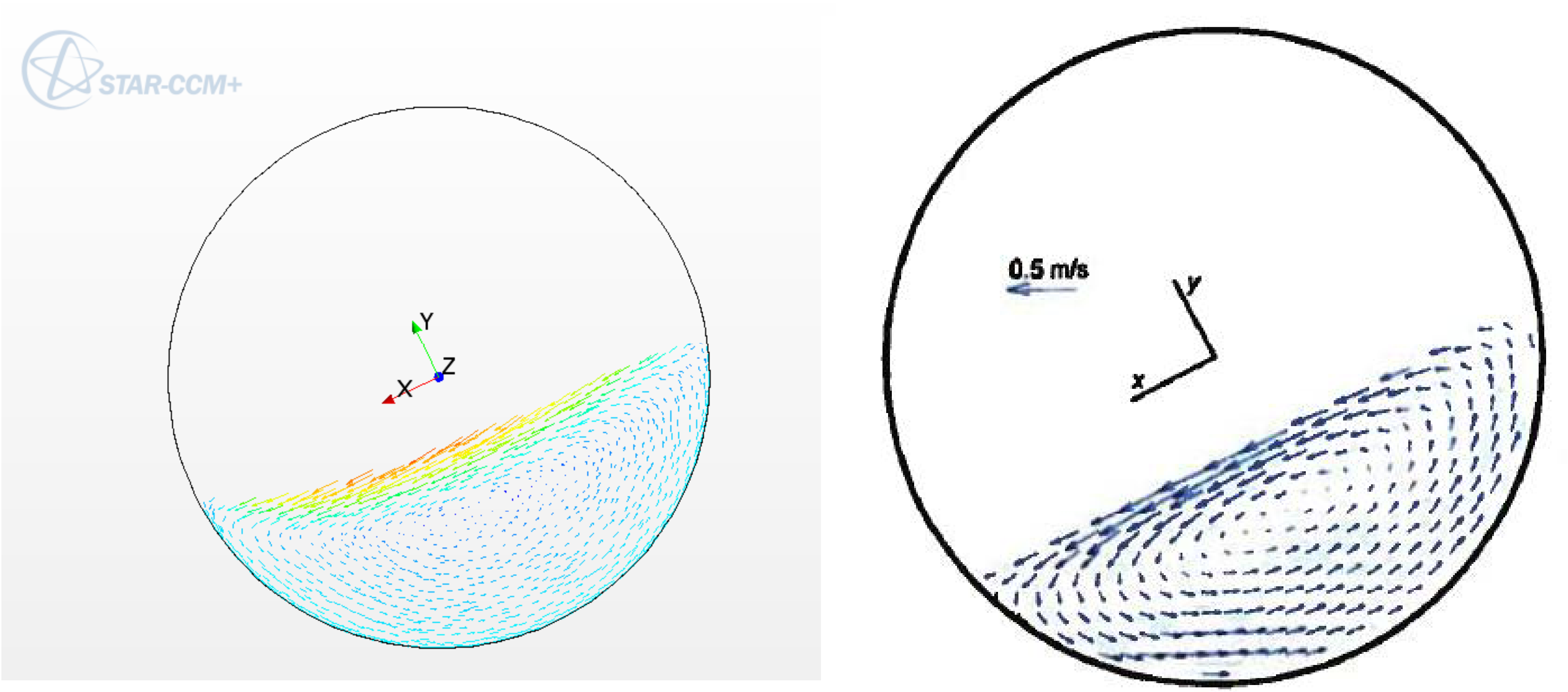
$$\mu_s^f = \min\left(\frac{P_s^f \sin\phi}{\sqrt{4 I_{2D}}}, \mu_{s,\max}^f \right) \qquad \varepsilon_s > \varepsilon_s^{\max}$$

$$= 0 \qquad \varepsilon_s \le \varepsilon_s^{\max}$$

$$I_{2D} = \frac{1}{6}\left[\left(D_{s,11} - D_{s,22}\right)^2 + \left(D_{s,22} - D_{s,33}\right)^2 + \left(D_{s,33} - D_{s,11}\right)^2 \right] + D_{s,12}^2 + D_{s,23}^2 + D_{s,31}^2$$

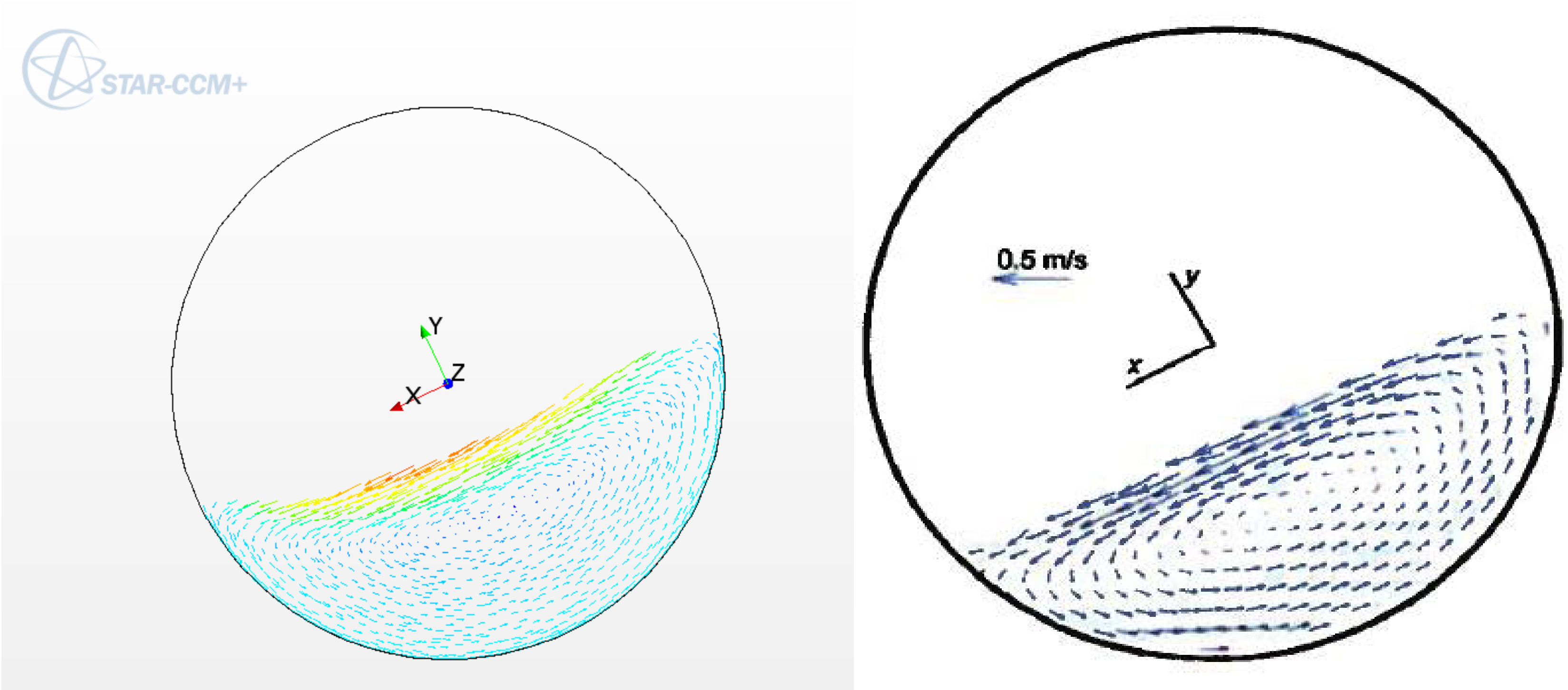
Particle bulk viscosity, $\xi_s^f = 0$

Results



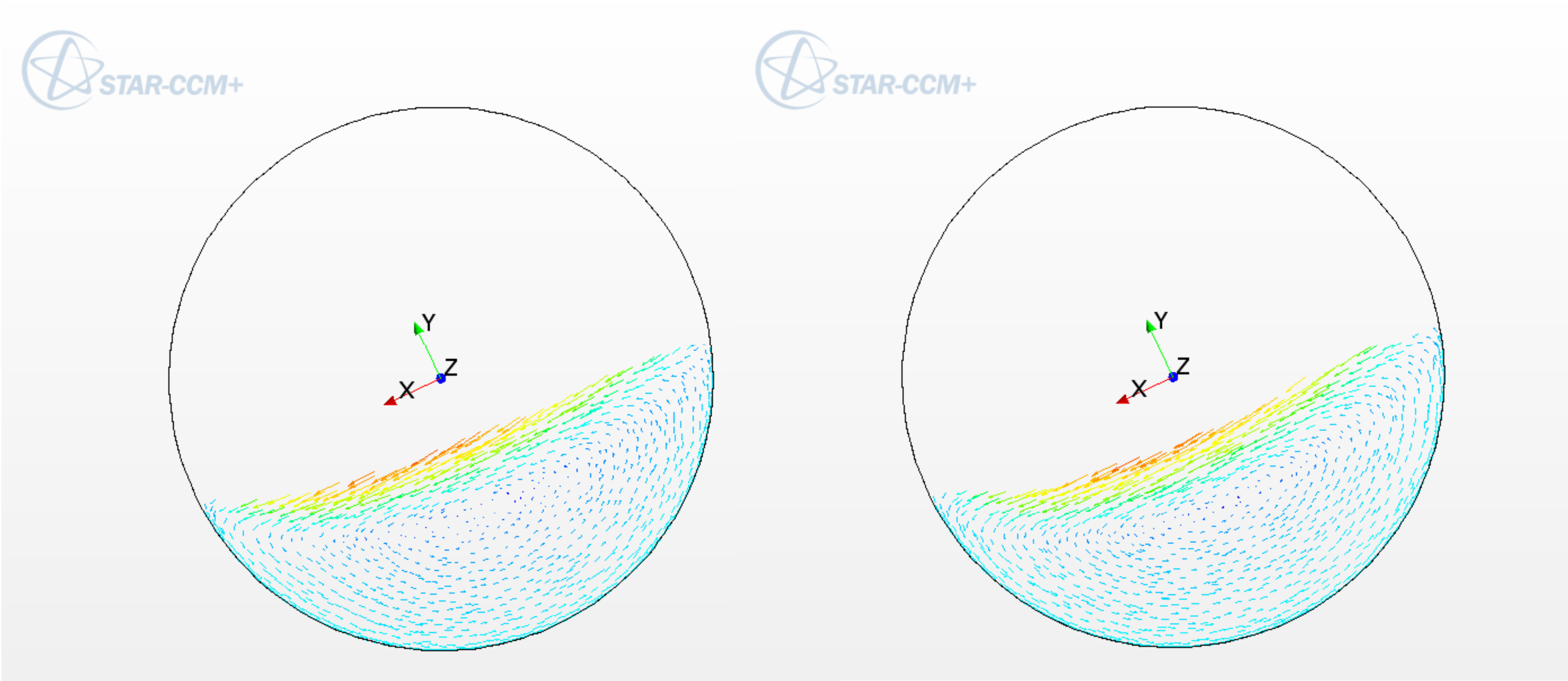
Velocity vectors in transverse plane of drum for MD2

Results



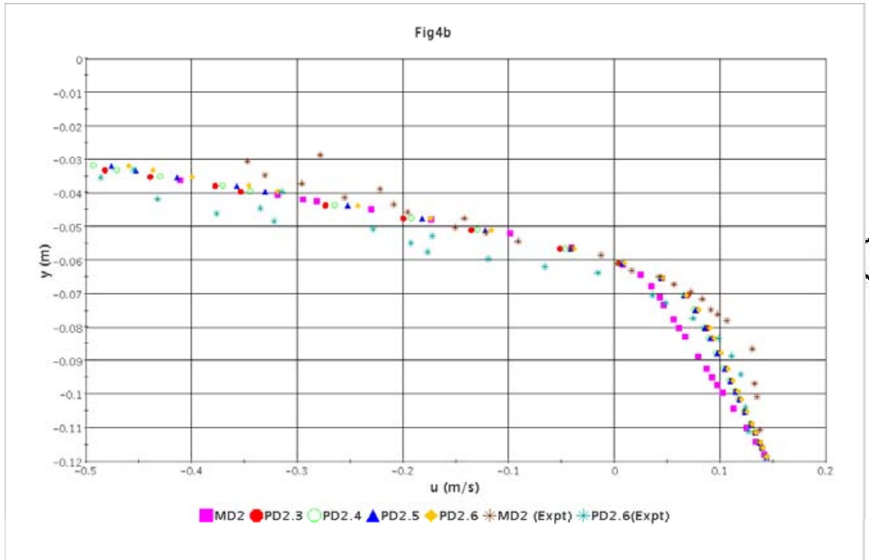
Velocity vectors in transverse plane of drum for PD2

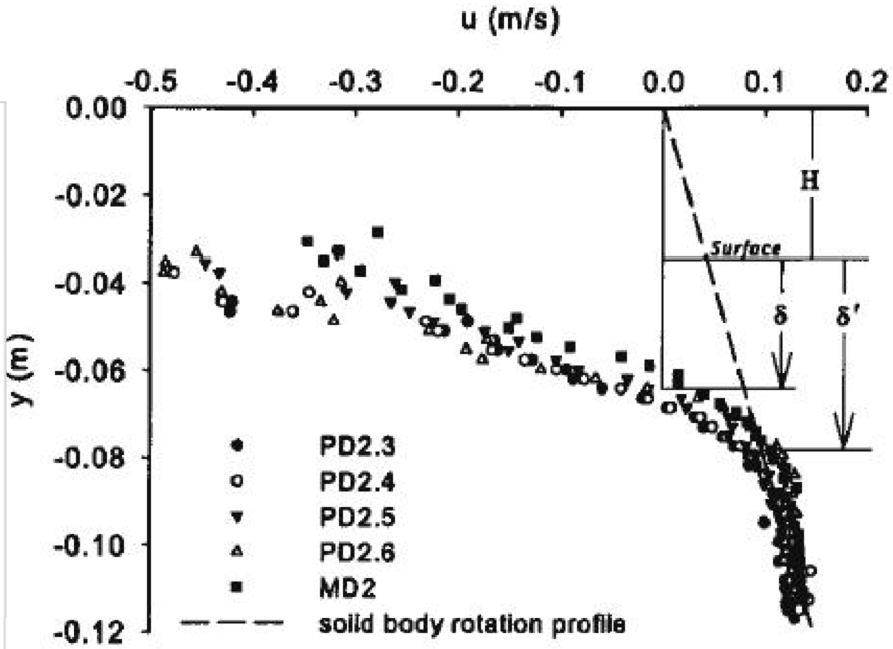
Results



Velocity vectors in transverse plane of drum for MD2

Results





Stream wise velocity profile in transverse plane of drum along x = 0

Results

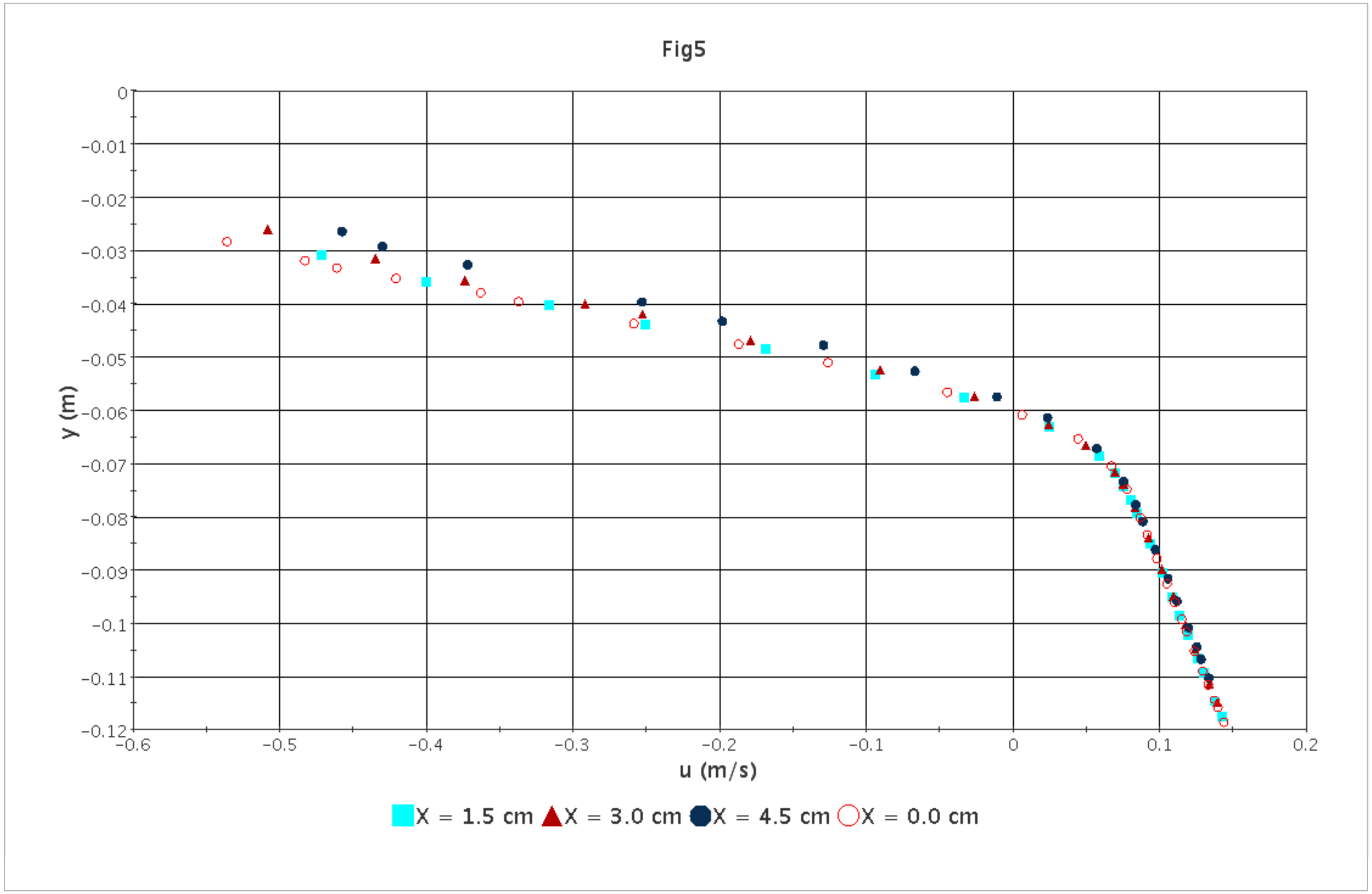
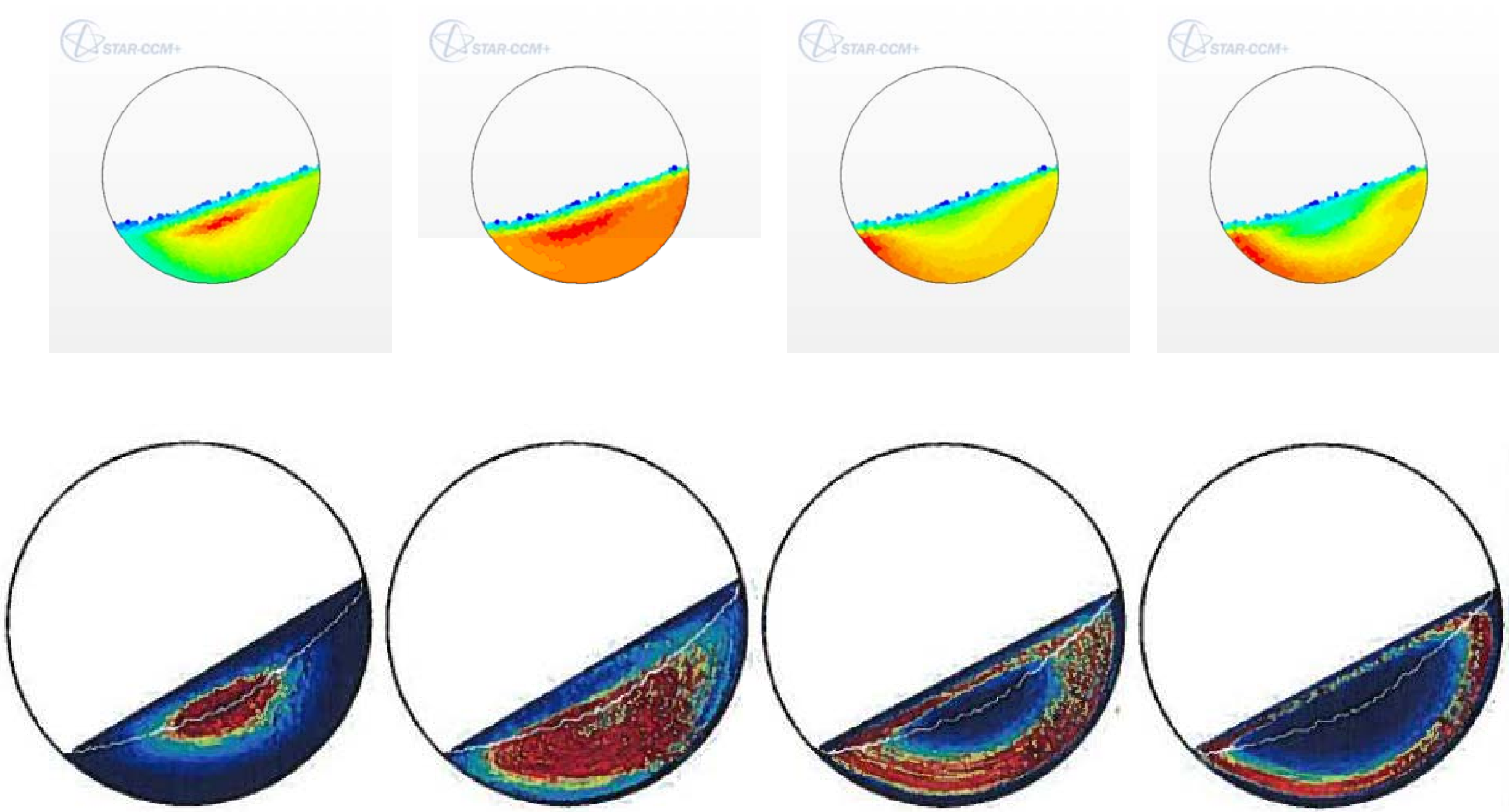


Fig5
y (m)
0
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
−0.08
−0.09
−0.1
−0.11
−0.12
−0.6
−0.5
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
u (m/s)
X = 1.5 cm
X = 3.0 cm
X = 4.5 cm
X = 0.0 cm

Results – Active layer thickness

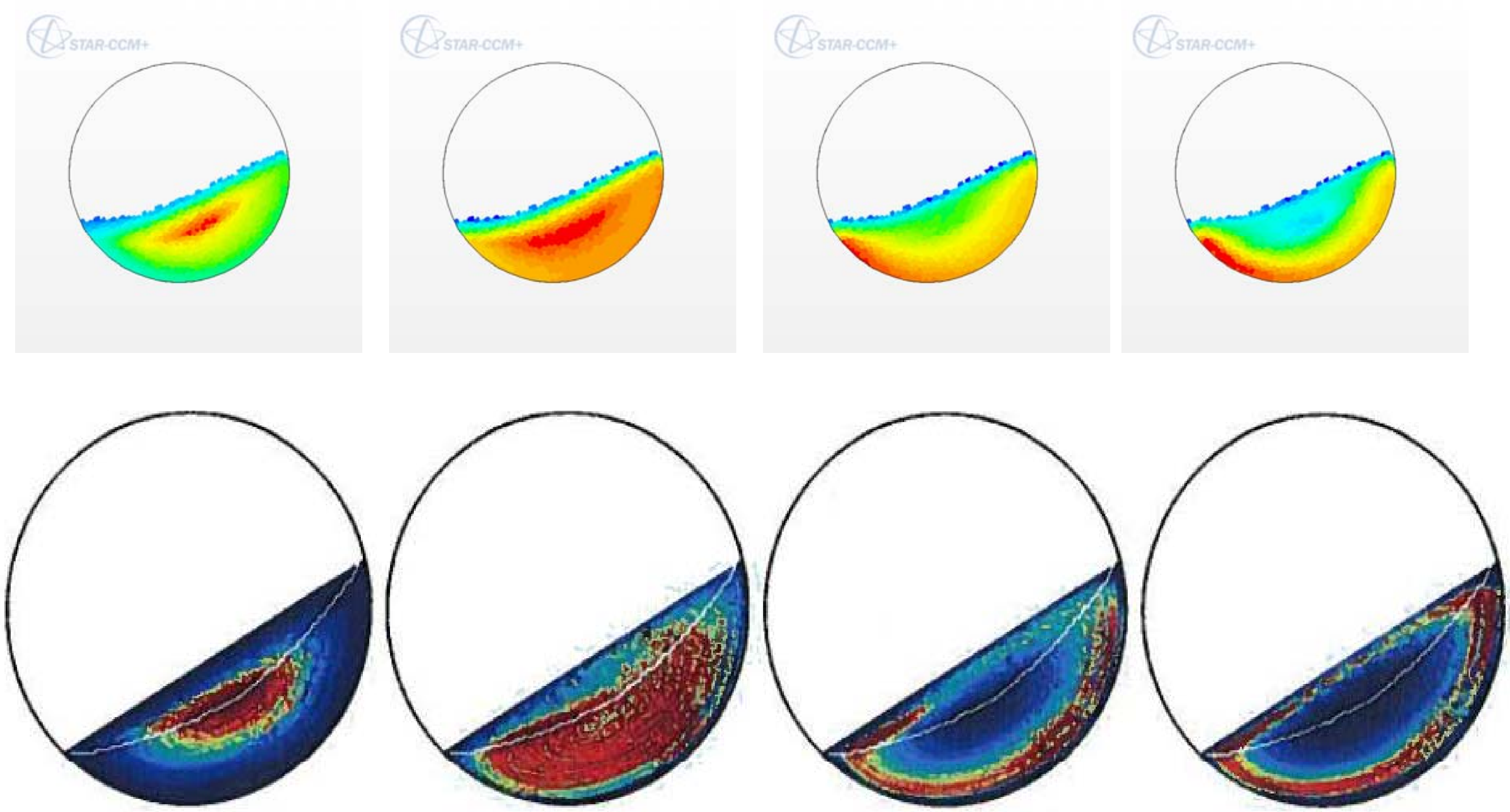
Case	Experiments	Simulations
MD1	2.4	2.9
PD1	2.6	2.7
MD2	3.3	2.9
PD2	3.5	3.2

Results – PD1



3 mm 4 mm 5 mm 6 mm

Results – PD2



3 mm 4 mm 5 mm 6 mm

Conclusions

- Qualitative trends in velocity profiles and void fraction distribution are captured
- Active layer thickness predicted reasonably well except for MD1
- Small difference between velocity profiles of poly-dispersed and mono-dispersed cases
- Small particles exist in core (3 mm), larger particles (5 and 6 mm) surround them while ones with 4 mm are spread across whole volume