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STUDY OF PARTICLE ROTATION IN PSEUDO 2D FLUIDIZED BEDS

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ABSTRACT

The accurate modelling of gas-solid flows is of great importance to many industries. However, most CFD models for gas-solid flows are often limited to ideal spherical particles. Good prediction of particularly the translational particle velocity has gained a very large interest in the community as it dominates the time averaged movement of granular flow. Particle rotation has been given much less attention however, despite the fact this parameter will be particularly important when non-spherical particles are studied. In Discrete Particle Modelling (DPM) particle rotation is incorporated by calculating tangential force. More recently in Two Fluid Models (TFM) a balance for rotational granular temperature has been added.

Particle tracking techniques have been used to validate CFD models. However, most of these techniques cannot provide experimental data on the particle rotation. To overcome this issue, we use a novel Magnetic Particle Tracking (MPT) technique, which allows for measuring the position and orientation of the particles. Therefore it enables us to measure both the translational and rotational velocity of a solid magnetic tracer particle in a granular flow. The magnetic tracer generates a magnetic field that depends on the relative position and orientation of the marker with respect to sensors surrounding the fluidized bed. By back calculating the magnetic field at the sensor positions we are able to determine the most probable position and orientation of the magnetic tracer, and related to this the most probable translational and rotational velocities.

NOMENCLATURE

F Force, N
H magnetic field, A/m
I moment of inertia, kgm^2
N amount, -
P_r probability function, -
P pressure, Pa
S magnetic field strength, A/m
  momentum source term, N/m^3
T Torque, Nm
V volume, m^3

d diameter, m
e rotation unit vector, -
  coefficient of restitution, -
g gravitation constant, m/s^2
k spring stiffness, N/m
m mass, kg
n normal, -
r relative distance, m
t time, s
  tangent, -
u fluid velocity, m/s
v particle/solids velocity, m/s

Θ granular temperature, m^2/s^2

γ energy dissipation, kg/ms^3
β interphase momentum exchange, kg/m^{3}s
κ pseudo thermal conductivity, kg/ms
ε solid or fluid fraction, -
ρ density, kg/m^3
τ stress tensor, N/m^3
η damping factor, Ns/m
μ magnetic moment, Am^2
  dynamic viscosity, kg/(m·s)
  friction coefficient, -

INTRODUCTION

Study of granular flow has long been restricted to the translational behaviour. Mostly because this is of greater importance, but in large also because there is limited experimental data on rotation and orientation of granular media. This has limited the study to idealized spherical systems. In industry however non-spherical particles are often encountered in granulation, pelletisation and combustion of biomass. For these non-spherical, and sometimes strongly elongated particles, rotation and relative orientation to the flow direction becomes very important.

Many non-intrusive measurement techniques have been used to study granular flow (Chaouki, et al., 1997): Particle Image Velocimetry (PIV) (Jong, et al., 2012), Magnetic Resonance Imaging (MRI) (Köhl, et al., 2014), Positron Emission Particle Tracking (PEPT) (Parker, et al., 2002), Radioactive Particle Tracking (CARPT) (Degaleesan, et al., 2002), X-Ray (Saayman, et al., 2013). Some of these techniques have been used to study rotation as well. In particular in PEPT a multi-PEPT technique was used, placing 3 markers within one particle of 12 mm (Yang, et al., 2007). These techniques are either limited to optically accessible systems, are very expensive or require stringent safety measures.

In this work a Magnetic Particle Tracking (MPT) technique is presented that is by its nature capable of measuring the orientation and thus rotational velocity of a magnetic tracer particle. MPT is both less expensive than

PEPT and MRI and readily applicable to full 3D systems. It has limitations in the size of the particles that typically need to be 2 mm or larger, and accuracy, especially for smaller particles. The interested reader is referred to Buist, et al. (2014) for more details.

In Discrete Particle Modelling (DPM) rotation is often incorporated with a second force equation using either a linear spring (Cundall & Strack, 1979) or a non-linear spring (Hertzian model). The use of a friction parameter limits the maximum force to the normal component, thus allowing sliding instead of rolling of the particles.

In Two Fluid Modelling (TFM) rotation so far has received relatively little attention, however Yang et al. (2015) have incorporated a separate balance equation for the rotational granular temperature and derivations for the needed closures. The DPM and TFM and the respective implementations of the rotation are here tested against the results of the MPT to check their validity.

TECHNIQUES

Magnetic Particle Tracking

Magnetic Particle Tracking (MPT) differs from magnetic resonance technique in the sense that it is a passive technique. A magnetic tracer is added to the granular system and a set of Anisotropic Magneto Resistive (AMR) sensors is placed around the setup. These sensor pick up a magnetic field strength that depends on the relative position and orientation of the magnetic marker to the sensor, see Figure 1.

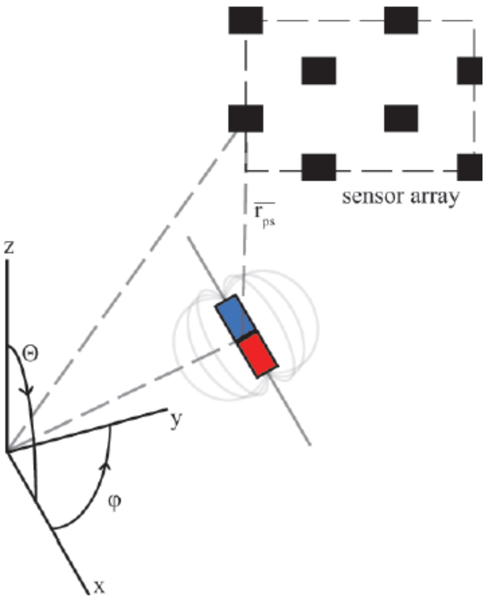

Figure 1: representation of the dependency of the magnetic field strength to the relative position and orientation of the magnet to the sensors.

The magnetic field is given as:

$$\overline{H} = \frac{1}{4\pi}\left(-\frac{\mu_m \bar{e}_p}{\left|\bar{r}_{ps}\right|^3} + \frac{3\mu_m\left(\bar{e}_p \cdot \bar{r}_{ps}\right)\bar{r}_{ps}}{\left|\bar{r}_{ps}\right|^5}\right) \quad (1)$$

The magnetic field strength is a projection of the field on the orientation:

$$S = \overline{H} \cdot \bar{e}_s \quad (2)$$

Determination of the position and orientation of the marker follows from minimizing the difference between the actual signal strength and a first estimate following equations 1 and 2. A probability function P is used to allow for weighting the signal to noise ratio. The use of the error function limits the solution to a very narrow range between 0 and 1, thus allowing better evaluation of the solution of this non-linear optimization problem:

$$P_r = \frac{\sum_{i=1}^{N} erf\left(\frac{S_{m,i} - S_{t,i}}{\sigma_{S_{m,i}}}\right)}{N} \quad (3)$$

A non-linear optimization technique from Matlab's optimization toolbox is used to perform the analysis: Sequential quadratic programming (SQP) allows for several other restriction to the solution of r_{ps} and e_p to only allow physical solutions within the bounds of the geometry.

Models

Both the Discrete Particle Model (DPM) and the Two Fluid Model (TFM) have been used extensively to model dense gas-fluidized beds. Both models use the Navier-Stokes equations for describing the gas phase:

$$\begin{aligned} &\frac{\partial \varepsilon_f \rho_f}{\partial t} + \nabla \cdot \varepsilon_f \rho_f \bar{u} = 0 \\ &\frac{\partial \varepsilon_f \rho_f \bar{u}}{\partial t} + \nabla \cdot \varepsilon_f \rho_f \bar{u}\bar{u} = \\ &-\varepsilon_f \nabla P - \nabla \cdot \varepsilon_f \bar{\bar{\tau}} + S_p + \varepsilon_f \rho g \end{aligned} \quad (4)$$

S_p is a source term that accounts for the particle-fluid momentum exchange; drag. The difference between the two models lies in the handling of the solid phase.

Discrete Particle Modelling

The DPM uses Newton's second law to update the particle position and orientation:

$$\begin{aligned} &m\frac{d^2\bar{r}}{dt^2} = -V\nabla P + \overline{F}_d + mg + \sum \overline{F}_{ab} \\ &I\frac{d^2\bar{\theta}}{dt^2} = \overline{T} \end{aligned} \quad (5)$$

With $\overline{F}_{ab}$ a force due to collision:

$$\begin{aligned} &\overline{F}_{ab,n} = -k_n\delta_n\bar{n}_{ab} - \eta_n\bar{v}_{ab,n} \\ &\overline{F}_{ab,t} = \min\left\{\begin{array}{l} -k_t\delta_t\bar{t}_{ab} - \eta_t\bar{v}_{ab,t} \\ -\mu_{fr}\left|\overline{F}_{ab,n}\right|\bar{t}_{ab} \end{array}\right\} \end{aligned} \quad (6)$$

For further reference the interested reader is referred to Deen, et al. (2007).

Two Fluid Modelling

The TFM differs quite a bit from the DPM in the fact that it regards the solid as a second fluid, fully interpenetrating the gas phase. It has separate balance equations for the solid phase mass and momentum conservation, the latter is given by:

$$\frac{\partial(\varepsilon_s \rho_s \bar{v})}{\partial t} + \nabla \cdot (\varepsilon_s \rho_s \bar{v}\bar{v}) = \\ -\nabla \cdot (P_s \bar{I} + \varepsilon_s \bar{\bar{\tau}}_s) + \varepsilon_s \rho_s g - S_p - \varepsilon_s \nabla P_f \tag{7}$$

To close the solids pressure and stress terms an extra equation for the granular temperature of the solid phase is solved, which follows from the Kinetic Theory of Granular Flow:

$$\frac{3}{2}\left[\frac{\partial(\varepsilon_s \rho_s \Theta_t)}{\partial t} + \nabla \cdot (\varepsilon_s \rho_s \bar{v} \Theta_t)\right] = \\ -\nabla \bar{v} : (P_s \bar{I} + \varepsilon_s \bar{\bar{\tau}}_s) - \varepsilon_s \nabla \cdot (-\kappa_t \nabla \Theta_t) \\ -\gamma_t - 3\beta_A \Theta_t \tag{8}$$

Here we do not show all the equations for the additional closures for stress, viscosity, thermal conductivity and energy dissipation rate. Instead the interested reader is revered to the work of Yang, et al. (2015).

Recently Yang, et al. (2015) have added a balance for the rotational granular temperature and respective closure equations:

$$\frac{3}{2}\left[\frac{\partial(\varepsilon_s \rho_s \Theta_r)}{\partial t} + \nabla \cdot (\varepsilon_s \rho_s \bar{v}_s \Theta_r)\right] = \\ -\varepsilon_s \nabla \cdot (-\kappa_{r1} \nabla \Theta_r - \kappa_{r2} \nabla \Theta_t) - \gamma_r \tag{9}$$

It should be noted that a theoretical derivation for the boundary conditions for the solid momenta and rotational granular temperature are still under development. For this paper highly simplified assumptions have been used in this work, namely partial slip boundary conditions with a specularity coefficient of 0.5, and a zero flux of rotational granular temperature at the walls. As we will show, these oversimplifications lead to discrepancies in the predictions by the TFM model.

SETUP

A pseudo-2D fluidized bed is used to study the rotational behaviour of 3 mm glass beads. The size of the setup is 30 by 100 by 1.5 cm. The sensor array is courtesy of Matesy GmbH.

The sensor array consists of 6 rows of 4 tri-axis AMR-sensors, giving in total 72 signals. The sensor array is capable of measuring at 1 kHz, but is down-sampled to 50 Hz to reduce the amount of data and noise.

Figure 2 shows a picture of the sensor array in front of the pseudo 2D fluidized bed setup.

The gas flow was controlled with a mass flow controller with 1200 L/min capacity. An even gas distribution was ensured by using a micro-porous plate with an average pore size of 10 micron. The magnetic marker was 4.7 mm in size and consists of a Neodymium core magnet, with a magnetic moment of 0.012 Am^2 and a polystyrene shell. The average density of the marker is 2100 kg/m^3. Comparison of MPT with particle image velocimetry showed that the magnetic marker, though larger and heavier, had similar circulation patterns and average translational velocities as the bed material, the interested reader is referred to Buist, et al., 2014.

Figure 2: Image of the 2D sensor array in front of the pseudo 2D fluidized bed setup.

A Helmholtz coil was placed around the bed to minimize the effect of the Earth's magnetic field on the rotation of the tracer particle.

THE DPM IS CAPABLE OF HANDLING DIFFERENT SIZED PARTICLES AND CONTAINS 1% OF TRACER PARTICLES WITH SIMILAR PROPERTIES AS THE MAGNETIC MARKER. FURTHER SIMULATION DATA IS GIVEN IN RESULTS

Table 1.

RESULTS

Table 1: Simulation parameters

Width	*0.3 m*	*d_p*	*3 mm*
Depth	0.015 m	ρ_F	1.2 kg/m3
Height	1.0 m	μ	1.8e-5 kg/ms
Nx	30	ρ_P	2525 kg/m3
Ny	2	k_n	12000
Nz	100	k_t	2800
		e_n	0.97
		e_t	0.33
		μ_{fr}	0.10

First the average solids fraction and translational velocities of the bed material are compared. This is done to ensure the systems behave in a similar way, at least in a qualitative sense. Comparison of rotation would have made no sense otherwise.

Figure 3 shows the solids fraction distribution inside the pseudo 2D fluidized bed for the MPT and the two models. All three results show a diluted centre core where bubbles predominantly propagate. Dense zones occur near the walls. All profiles are very similar except that the dense zone is slightly protruded towards the centre for the DPM and slightly indented at the top. For the TFM the maximum solids fraction seems to be at 50% which is lower than for the DPM and MPT. The dense zone also is higher in the fluidized bed than in the DPM and MPT. Also there is less raining of solids at the walls at the top part of the bed.

A comparison of the normal velocity profiles shows the expected circulation patterns. These are not shown here, but instead three cross-sections of the translational velocities inside the pseudo 2D fluidized bed setup are shown. Figure 4 shows the comparison of the vertical component of the translational velocities. The agreement between the DPM and the MPT is quite good. Except for the velocities near the wall that deviate at especially 20 and 30 centimetres from the distributor plate. This deviation has also been found in earlier work of van Buijtenen, et al., 2011 in spout fluidized beds and seems to be especially important for larger particles.

It has been subject of discussion and one likely suspect has been the rotation of the particles. Jajevic, et al., 2013 suggested to leave out rotation all together because the results better overlapped near the walls. Goniva, et al., 2012 instead suggested to add rolling friction on top of the regular friction parameter and found that a value of 0.125 best suited the results. In this work the rolling friction was kept at zero and a friction coefficient of 0.1 was maintained.

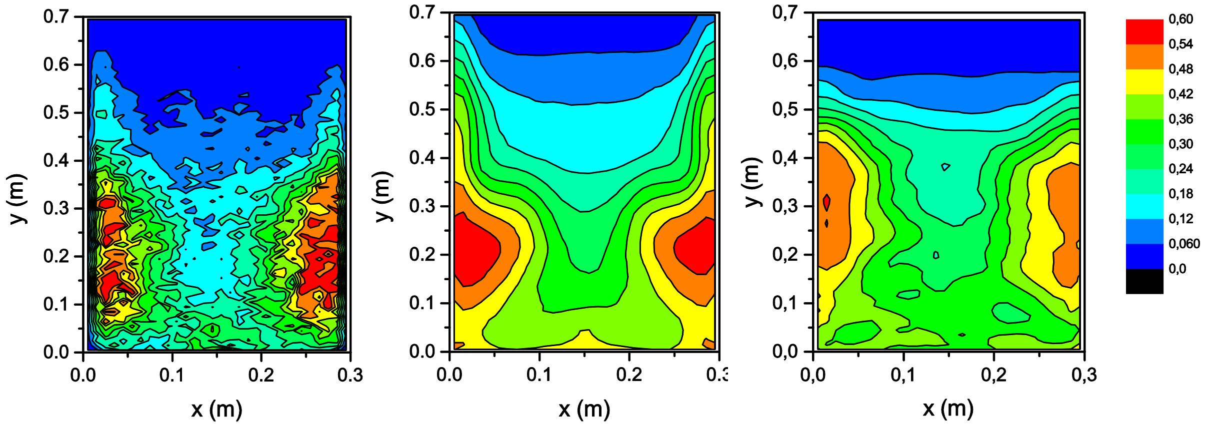

Figure 3: Solids fraction comparison, left; MPT and middle; DPM and right; TFM, at u_{bg}=3.5 m/s.

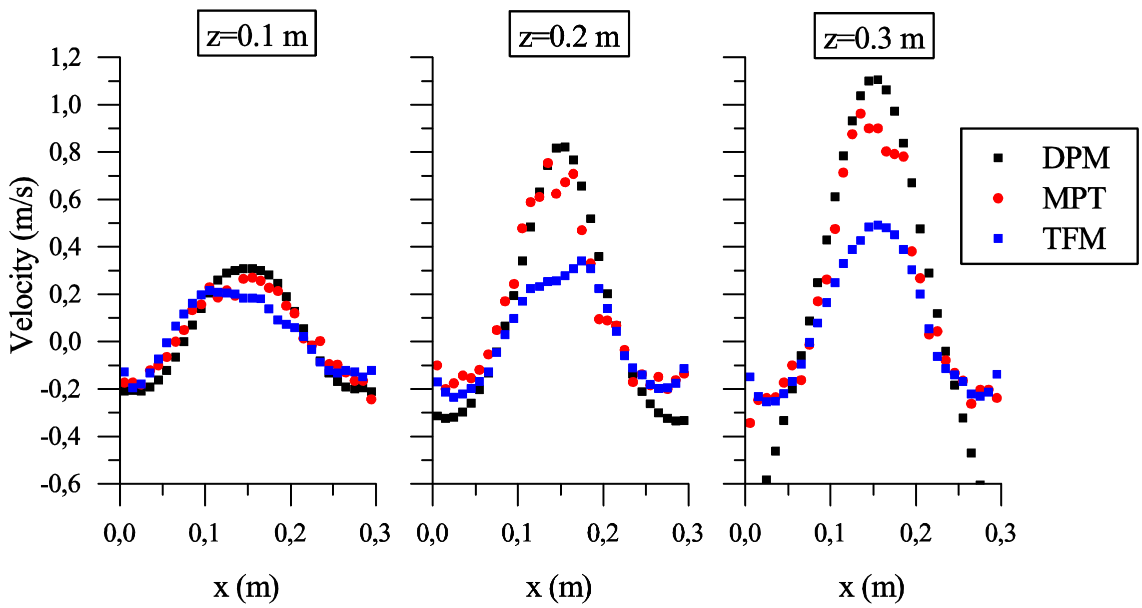

Figure 4: Translational velocity at several cross-sections above the distributor plate. u_{bg}=3.5 m/s.

The TFM however predicts much lower translational velocities. Especially at 0.2 and 0.3 meters from the distributor plate the magnitude of the translational velocities is about 40% lower. The reason for this discrepancy will be discussed later.

With the aid of MPT we are now for the first time able to properly study the rotation of the particles in dense granular flows.

Figure 5 shows the rotational velocity at several cross-sections above the distributor plate. The magnitude and overall profile of the rotational velocities agree reasonably well. There is a slight deviation of the rotational velocity near the wall at 0.3 m above the distributor plate. This deviation is closely related to the difference in translational velocity. Changing the friction parameter or adding rolling friction scales the rotational velocity linearly indicating that the friction parameter is key in a proper description of the rotational behaviour in granular flow. In the Pseudo 2D fluidized bed the rotational behaviour is thus dominated by friction. The results of the MPT and DPM have quite large error margins which is related to the limited amount of data points, 1 hour of measurements allow for 180.000 data points. This results in an average of about 200 data points per computational cell, and one can easily calculate the error related to the mean of a sample as:

$$\sigma_m = \frac{\sigma}{N}$$

This results in an estimated error of about 0.7 rotations per second. This is represented by the error bar in the bottom left of Figure 5.

The number of data points in the DPM has been matched with that in the MPT. Also the tracer-like nature does not allow for a significant increase of the amount of tracers in the DPM, otherwise the tracers would disturb the flow of the granular medium too much.

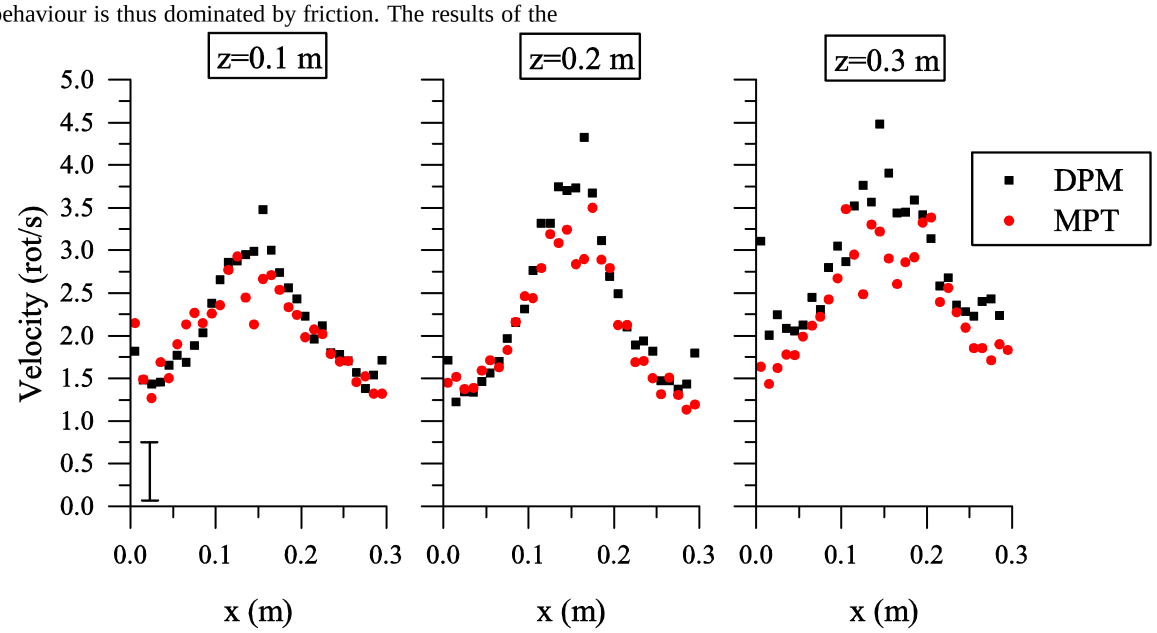

Figure 5: Rotational velocity of the tracers at several cross-sections above the distributor plate. u_{bg}=3.5 m/s. Error margin indicated at bottom left.

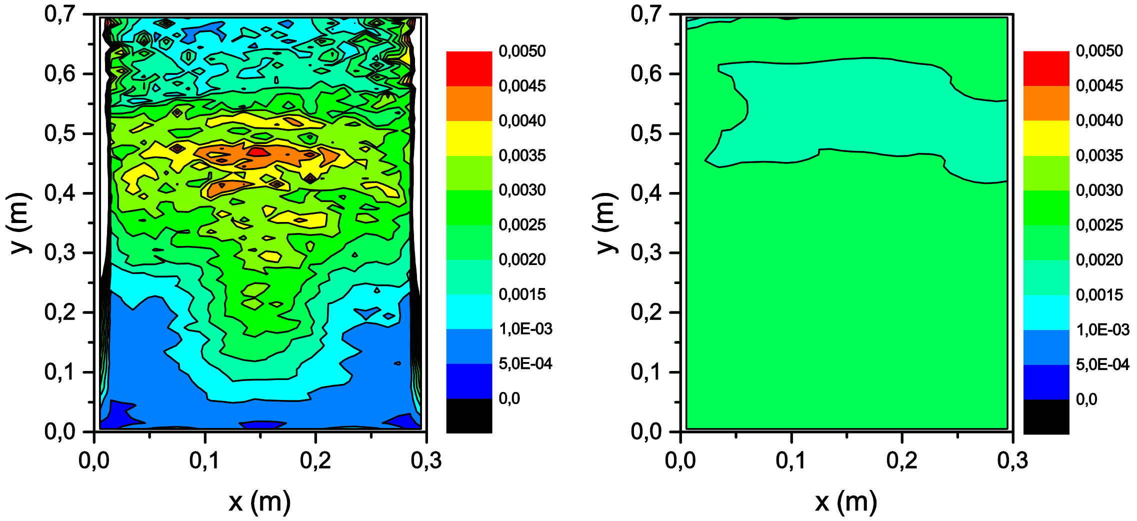

Figure 6: Granular temperature m²/s² for the DPM (left) and TFM (right). u_{bg}=3.5 m/s.

In the TFM the mean rotational velocity is assumed to be zero. Hence, we can only compare the fluctuations of the rotational velocity, which are characterized by the rotational granular temperature. Figure 6 shows a comparison of the rotational granular temperatures of the two models. First it is noted that the rotational granular temperature in the TFM is uniformly distributed in the bubbling bed whilst in the DPM there is a distinct mushroom like profile of the rotational granular temperature. The reasoning for this difference in profile must be found in the assumptions made for the TFM. First, the mean rotational velocity in TFM is assumed to be zero, which reduces the modelling of rotation to solving a rotational granular temperature balance only and not a balance for the rotational velocity too. Second, as a first approach to implementing a boundary condition the gradient of the rotational granular temperature at the wall is assumed to be zero, i.e. an adiabatic wall. These two limitations assume isotropic behaviour of the flow. It is therefore expected that the TFM with rotational granular temperature works well for bulk flow. Here we found that for a pseudo two system the granular flow near a wall is not captured well. So, both the assumptions of an adiabatic wall as well as a zero mean rotational flow need to be changed for sharp gradients in the translational velocities as well as for cases of granular flow near a wall.

Because the mean rotational velocity is assumed to be zero, the contribution of the rotation to the translation is also neglected. In this particular case a mismatch of a factor 2/7 is expected, accounting for the larger part of the differences in the translational velocity between the TFM and the DPM and MPT respectively.

CONCLUSION

Results of the rotational behaviour of granular media have been shown for a pseudo 2D fluidized bed with Discrete Particle Modelling, Two Fluid Model and Magnetic Particle Tracking. The use of a magnet has, for the first time, allowed the measurement of rotation of particles in dense granular flow. The measurement data enables us to validate the use of a spring-dashpot-slider model. The friction parameter suffices to describe rotation, inclusion of a rolling friction parameter seems of no use.

The addition of a rotation granular temperature has allowed for a study of rotation in the TFM. However the assumptions of zero mean rotational velocity and adiabatic walls do not hold for pseudo 2D fluidized beds. The correct boundary conditions for rotational TFM requires further study.

Future study of non-spherical particles is now possible, because the orientation of the particles can be checked. Furthermore the MPT technique can be used to study full 3D systems and stands as a more cost-effective alternative to other more expensive and non-invasive measurement techniques that are more difficult to use due to the required safety measures.

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