Proceedings Paper:

Wolde, B., Mortimer, L.F. and Fairweather, M. (2023) Prediction of critical deposition velocities in particleladen horizontal turbulent pipe flows. In: 10th International Symposium on Turbulence, Heat and Mass Transfer, THMT-23, Rome, Italy, 11-15 September 2023. The Tenth International Symposium on Turbulence, Heat and Mass Transfer, 11-15 Sep 2023, Rome, Italy. Begell House Inc. ISBN 978-1-56700-534-9

Prediction of critical deposition velocities in particle-laden horizontal turbulent pipe flows

B. Wolde[1], L. F. Mortimer[1] and M. Fairweather[1]

[1]*School of Chemical and Process Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom, pmbw@leeds.ac.uk, l.f.mortimer@leeds.ac.uk, m.fairweather@leeds.ac.uk*

Abstract – Particle-laden turbulent pipe flows are studied using direct numerical simulation of the continuous phase in combination with Lagrangian particle tracking (LPT) to determine critical deposition velocities at four particle Stokes numbers. The work was carried out using the computational fluid dynamic solver, Nek5000, enhanced with a four-way coupled LPT to enable high-fidelity modelling of particle-laden pipe flows. The results indicate that at high Stokes numbers, the particle dispersion function and mean vertical displacement values fall quickly, with the formation of particle beds. However, at lower Stokes number thinner dune-like structures are formed. It is determined that using a volume-coverage percentage in the near-wall region of the lower half of the pipe to identify the onset of deposition provides good agreement with experimental data and an empirical correlation for the critical deposition velocity. Insight into the migratory behaviour of the solid phase is determined through additional analysis of the particle dynamics.

1. Introduction

In many industrial and research applications, accurate simulation of particle-laden flows is of importance. The generation of understanding through precise modelling of complex multiphase flows is useful in various industries, including chemical engineering and nuclear waste processing, with the present work of relevance to technical challenges that are encountered within nuclear waste transportation. Developing and facilitating approaches for safer, cost-efficient waste management and decommissioning is a primary focus of this research. Understanding and modelling pond and silo sludge behaviour is essential to the management of radioactive wastes. In legacy ponds and silos, characterising how sludges and slurries containing dense particulates will deposit during transportation is vital for nuclear waste retrieval.

In the past, DNS of particle-laden flows has relied mostly on one-way coupling between the particles and continuous phase, with a notable absence of four-way coupled solutions, particularly in pipe flows. Four-way coupling refers to the interaction of particles with other particles as well as particle-fluid force feedback. Furthermore, no previous modelling studies have examined the critical deposition velocity in such flows, with most deposition studies being experimental. Rice (2013) used acoustic Doppler velocimetry to establish the critical deposition velocity of particles through experiments that investigated their resuspension from a particle bed. Pakzonka et al. (1981) reviewed the effects of solid concentration and particle size on depositing flows. The authors observed that the presence of fine particles ($< 75\ \mu m$) has a substantial impact on deposit velocity reduction for larger concentrations. With the help of advances in computational technology, it is now possible to simulate such flows. In this work, the deposition of particles over the course of a simulation in which the flow rate is slowly reduced from an initial shear Reynolds number of $Re_{\tau} = 720$ is studied, with a focus on determining a method for critical deposition velocity identification, as well as analysis of deposition out of the flow to form solid beds.

2. Methodology

The DNS solver, Nek5000, is utilised to predict the continuous phase flow. This solver is based on the spectral element method and is favourable due to its high accuracy, low numerical dispersion and dissipation, and is easily and efficiently parallelisable. To examine the bulk behaviour of high concentration dispersions, a Lagrangian particle tracker has been developed to model large quantities of dispersed solids which runs concurrently with Nek5000. A fourth order Runge-Kutta method is implemented to solve the Newtonian equation of motion for each particle within every time-step. The Navier-Stokes equations also include an extra forcing term that accounts for the two-way feedback force from particles to the fluid flow.

Rice (2013) studied the settling and deposition behaviour of dense particle suspensions in closed cylindrical pipes using ultrasonic techniques, focusing on the onset of particle deposition and resuspension from beds. Two methods were proposed for determining the critical deposition velocity, i.e., the bulk flow velocity at which particles first begin to deposit in a turbulent flow. These were either examining particles depositing as the flow rate is reduced or examining particles resuspending from the pipe floor as the flow rate is increased. It was argued that both were equivalent and represented different ways of obtaining the critical deposition velocity. A correlation model, Eq. (1), was developed for predicting the critical velocity in slurry transport flows by Oroskar and Turian (1980) which showed agreement with Rice's (2013) dataset:

$$\frac{V_c}{\sqrt{gd(s-1)}} = 1.85\left(\frac{d}{D}\right)^{-0.378} \phi^{0.1536}(1-\phi)^{0.3564}\left(\frac{D\rho_f\sqrt{gd(s-1)}}{\mu}\right)^{0.09}. \quad (1)$$

Here, μ is the dynamic viscosity, g the acceleration due to gravity, V_c the critical velocity, d the particle diameter, D the pipe diameter, ρ_f the density of fluid phase, ϕ the particle phase volume fraction and s the density ratio, $s = \rho_s/\rho_f$. In the present work, depositing pipe flows are simulated using the DNS and LPT codes over a range of values corresponding to the RHS of Eq. (1), spanning the Stokes numbers used by Rice (2013) to assess whether the overall model will predict the onset of deposition in line with the above correlation. A fully developed particle-laden turbulent pipe flow at $Re_\tau = 720$ was performed, with the flow rate decreased regularly until particle deposition occurred. To achieve this, the pressure gradient along the pipe was lowered over time by 2% every 2000 time-steps ($t^* = 2.$) In all cases, the gravitational force was applied in the vertical direction (Wolde et al. 2022). The dispersion function and mean displacement of the particles were also monitored to determine the extent of particle vertical migration, with the dispersion function (Fairweather and Yao 2009), $D^*_{y(t)}$, defined as:

$$D^*_{y(t)} = \left(\sum_{i=1}^{N_p}\frac{(y^*_{i(t)} - y^*_{m(t)})^2}{N_p}\right)^{1/2}, \quad (2)$$

with $y^*_{i(t)}$ the particle displacement in the vertical direction, $y^*_{m(t)}$ the mean vertical particle position, sampled across the entire domain, and N_p the total number of particles.

3. Results and Discussion

Single-phase and multiphase simulations were performed in order to validate the DNS and LPT solver being used. In all simulations, statistical data were gathered for analysis. The present

DNS results have been compared with various simulation and experimental datasets available in the literature at, or approximately equal to, the Reynolds numbers of the simulations performed. For each simulation the mean velocity profiles, and the root mean square of velocity fluctuations and shear stress, were compared. All the simulations showed good agreement with the DNS and experimental datasets of others. The validation results can be found in Wolde et al. (2022).

Figure 1 depicts the particle dispersion function $D^*_{y(t)}$ and the mean displacement of the particle position, $y^*_{m(t)}$. Both particle dispersion and mean vertical position drop significantly faster with time for the high Stokes number particles. This is due to the higher gravitational force that causes the particles to accelerate faster in the negative vertical direction.

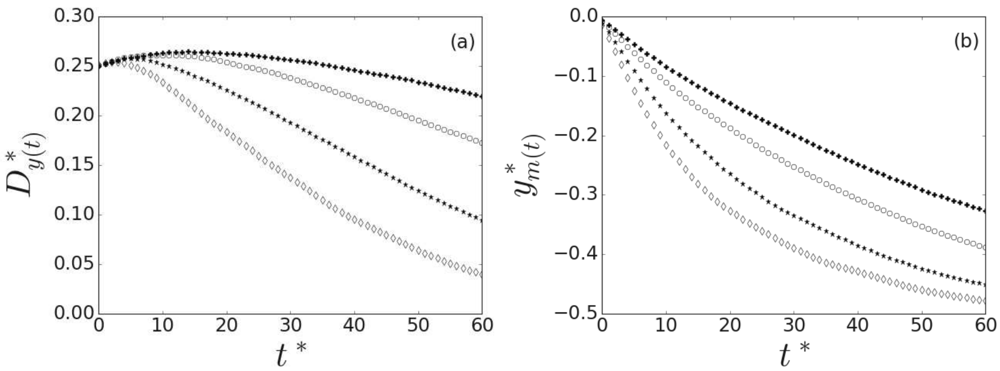

Figure 1: (a) Dispersion function in vertical direction and (b) mean vertical position of particles. ♦: St^+=5.55; ○: St^+= 7.2; ⋆: St^+=11.1; ◊: St^+=16.78.

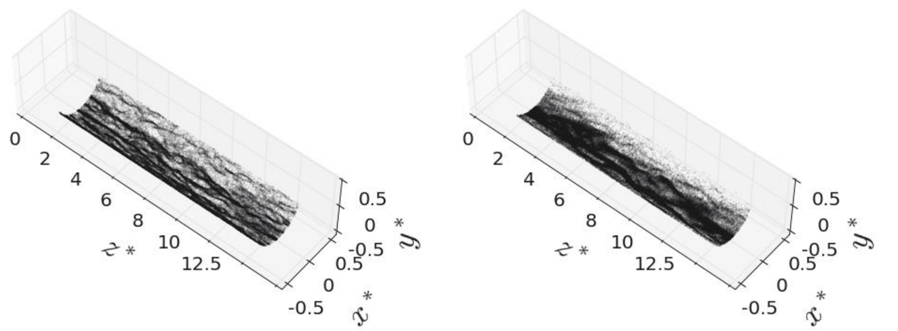

Figure 2: Instantaneous plots at $t^* = 50$ of particle positions within the near-wall region ($0.49 \leq r^* \leq 0.5$) of the lower half of the pipe, for $St^+ = 5.55$ (left) and $St^+ = 16.78$ (right).

Figure 2 shows the instantaneous positions of particles close to the wall ($0.49 \leq r^* \leq 0.5$) in the lower half of the pipe. At the start of the simulation, the particles are equally dispersed within the computational domain, however, with time, particle migration to the lower sections of the pipe occurs, and a particle bed forms for the large Stokes number case by t^*= 40. In contrast, at low St^+ preferential concentration in dune-like structures in low-speed regions occurs. Figure 3 (left) shows the ratio of the volume occupied by particles to the volume of the near-wall region, V_p/V_R, with time. The average volume coverage computed at which 20% (Avg. =1%), 50% (Avg. = 2.42%) and 80% (Avg. =3.87%) of the particles have migrated towards the bottom of the pipe is indicated. Figure 3 (right) shows the Rice (2013) resuspension datasets collapsed against the correlation of Eq. (1) and the present critical deposition predictions plotted against the same empirical correlation. It is noted that the present predictions at around Avg. = 2.42% are in line with Oroskar and Turian (1980) correlation and Rice's (2013) results indicating that this volume coverage performs well when used to identify the onset of deposition and hence the critical deposition velocity.

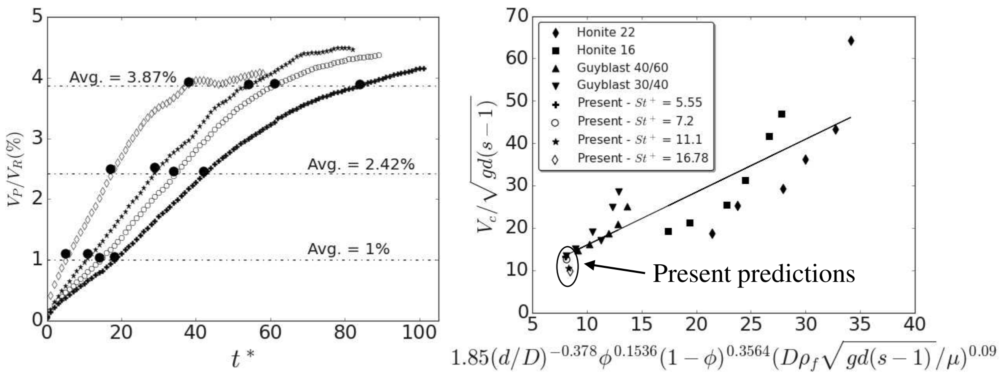

Figure 3: Deposition predictions at $0.49 \leq r* \leq 0.5$ (left) and Rice (2013) resuspension datasets collapsed using Eq. (1) and predicted results (right). ♦: St^+=5.55; ○: St^+= 7.2; ⋆: St^+=11.1; ◊: St^+=16.78.

4. Conclusions

The prediction of critical deposition velocity in particle-laden turbulent pipe flows using a DNS-LPT approach was considered. A fully-resolved $Re_\tau = 720$ pipe flow was used as an initial flow, with four-way coupling, with the flow rate reduced with time to determine a method for predicting the critical deposition velocity at four different Stokes numbers. Overall, the present predictions using a deposition region volume occupancy fraction of ~2.4% are in-line with an empirical correlation and critical velocities established through resuspension experiments. The particle critical deposition velocity was shown to be sensitive to Stokes number, such that high Stokes number particles begin to deposit at higher flow rates. This can be seen more clearly in particle dispersion function and particle mean displacement analysis.

Acknowledgements

The authors are grateful for funding from the UK Engineering and Physical Sciences Research Council and the University of Leeds through the TRANSCEND (Transformative Science and Engineering for Nuclear Decommissioning) project (EP/S01019X/1).

References

M. Fairweather and J. Yao. Mechanisms of particle dispersion in a turbulent, square duct flow. *AlChE. J.*, 55: 1667-1679, 2009.

A.R. Oroskar and R.M. Turian. The critical velocity in pipeline flows of slurries. *AlChE. J.*, 26: 550-558, 1980.

W. Pakzonka, J. M. Kenchington and M. E. Charles. Hydrotransport of solids in horizontal pipes: Effects of solids concentration and particle size on the deposit velocity. *Can. J. Chem. Eng.*, 59: 291-296, 1981.

H.P. Rice, Transport and deposition behaviour of model slurries in closed pipe flow. PhD Thesis, University of Leeds, 2013.

B. Wolde, L.F. Mortimer and M. Fairweather. Effects of Stokes number on particle deposition in particle-laden turbulent pipe flows. In *Proceedings of the Conference on Modelling Fluid Flow – CMFF'22 (Edited by J. Vad)*, pp. 149-156, 2022.