R&D NOTE

Numerical Study of Particle Turbulence Interaction in Liquid-Particle Flows

K. Mohanarangam and J. Y. Tu
School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Victoria 3083, Australia

DOI 10.1002/aic.11729
Published online April 7, 2009 in Wiley InterScience (www.interscience.wiley.com).

Keywords: multiphase flow, particle technology, computational fluid dynamics

Introduction

A comprehensive numerical model that was previously developed to study the turbulent behavior of dilute gas-particle flows and also the effect of the particles in modulating the gas turbulence behind sudden expansion geometry[1,2] was used to study the turbulent behavior of dilute liquid particle flow behind a sudden expansion geometry. The major endeavor of the study is to ascertain the response of the particles within the carrier liquid phase. The main aim prompting the current study is the density difference between the carrier and the dispersed phases which is less in terms of the liquid-particle flows in comparison to its counterpart gas-particle flow. The numerical simulations carried out in this study were validated against the experimental data of Founti and Klipfel[3] and qualitative results have been obtained. Furthermore, their response to the carrier phase has been investigated both at the mean and at the turbulence level for a range of particle Stokes number. While the particulate velocity seems to increase with the corresponding increase in Stokes number amidst the carrier phase the particulate turbulence shows entirely a different pattern.

Flows with particles amid liquid are an important class of two-phase flows classified under slurry flows. These flow systems are representative of many mineral processing operations and also provide useful operation correlations for such processes. They form an important class of flows encompassing pneumatic conveying system, turbines, and machineries operating in particulate-laden environments. Liquid particle flows provide a useful tool in the simulation of sprays in industrial and natural processes, since they have comparable phase-density ratios. Comparable densities are of particular interest, because all the effects of interphase momentum transfer are important.[4] They also serve as a good test of methods to predict particle motion in turbulent environments[4] as they exhibit high relative turbulence intensities for particle motion, which influence particle drag properties.[5]

In this article, we report the particle responsitivity at the mean and at the turbulence level in the presence of a liquid phase, the diesel oil. This is done to clarify the notion whether Stokes number (*St*) can be used as a universal parameter to define the particle motion both at the mean and at the turbulence level. The numerical model and the procedure used are similar to the studies outlined in Refs. 1 and 2. The note starts with the testing of the numerical model to replicate the experimental results of Founti and Klipfel[3] for both the phases. Followed by this the particle Stokes number is further varied to study its response at both the mean and the turbulence level.

Results and Discussion

Numerical code validation

In this section, the code is validated for mean streamwise velocities and fluctuations for both the carrier and dispersed phases against the benchmark experimental data of Founti and Klipfel.[3] This task is undertaken to verify the fact that particulate flow with liquid carrier phase can be handled by the code. The experimental set up consisted of a pipe flow with a sudden expansion ratio of 1:2, with a step height of 25.5 mm, as depicted in Figure 1, working at a Reynolds number of 28,000. The dispersed phase particles consisted of 450 μm glass particles with a mass loading of 15%.

An important, dimensionless scaling parameter in defining how the fluid-particle behave with the flow field is the Stokes number (*St*), which is given by the ratio of the particle relaxation time to a time characteristic of the fluid motion, i.e., $St = t_p/t_s$. This determines the kinetic equilibrium of the particles with the surrounding liquid. In choosing the appropriate fluid time scale t_s, the reattachment length has not been considered as it varies because of the addition of particles and is not constant in this study, rather a constant length scale of five step heights, which is in accordance

Correspondence concerning this article should be addressed to J. Y. Tu at jiyuan.tu@rmit.edu.au

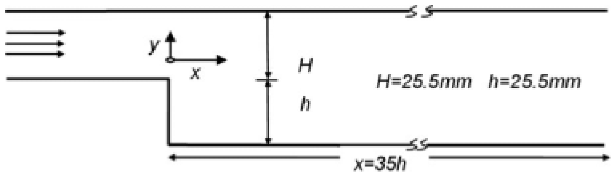

Figure 1. Backward facing step geometry.

with the reattachment length is used. The resulting time scale is given by $t_s = 5h/U_o$. A small stokes number ($St \ll 1$) signifies that the particles are in near velocity equilibrium with the carrier fluid. For larger stokes number ($St \gg 1$) particles are no longer in equilibrium with the surrounding fluid phase, which will be exemplified in the later sections. Based on the above definition, the Stokes number for the flow considered in our study works out to be 0.59.

The ability of the numerical code to aptly replicate the experimental results can be seen from Figure 2. Figure 2a shows the numerical findings of single phase (Diesel oil) mean velocities against the experimental data, although the overall behavior is replicated numerically there have been some under prediction for a height of $y/h > 1$ for midsection of the geometry, while a minor over prediction is felt along the entire height at section $x/h = 15.7$. Figure 2b shows the fluctuating liquid velocities along the step compared against the experimental findings, there have been some over prediction for a height of $y/h < 1$ at some sections, overall the majority of the results show a good comparison with the experimental data. Figures 2c,d depict the experimental and numerical comparison of particle mean and fluctuating velocities, and it can be seen that overall numerical results have a good agreement with the experimental data.

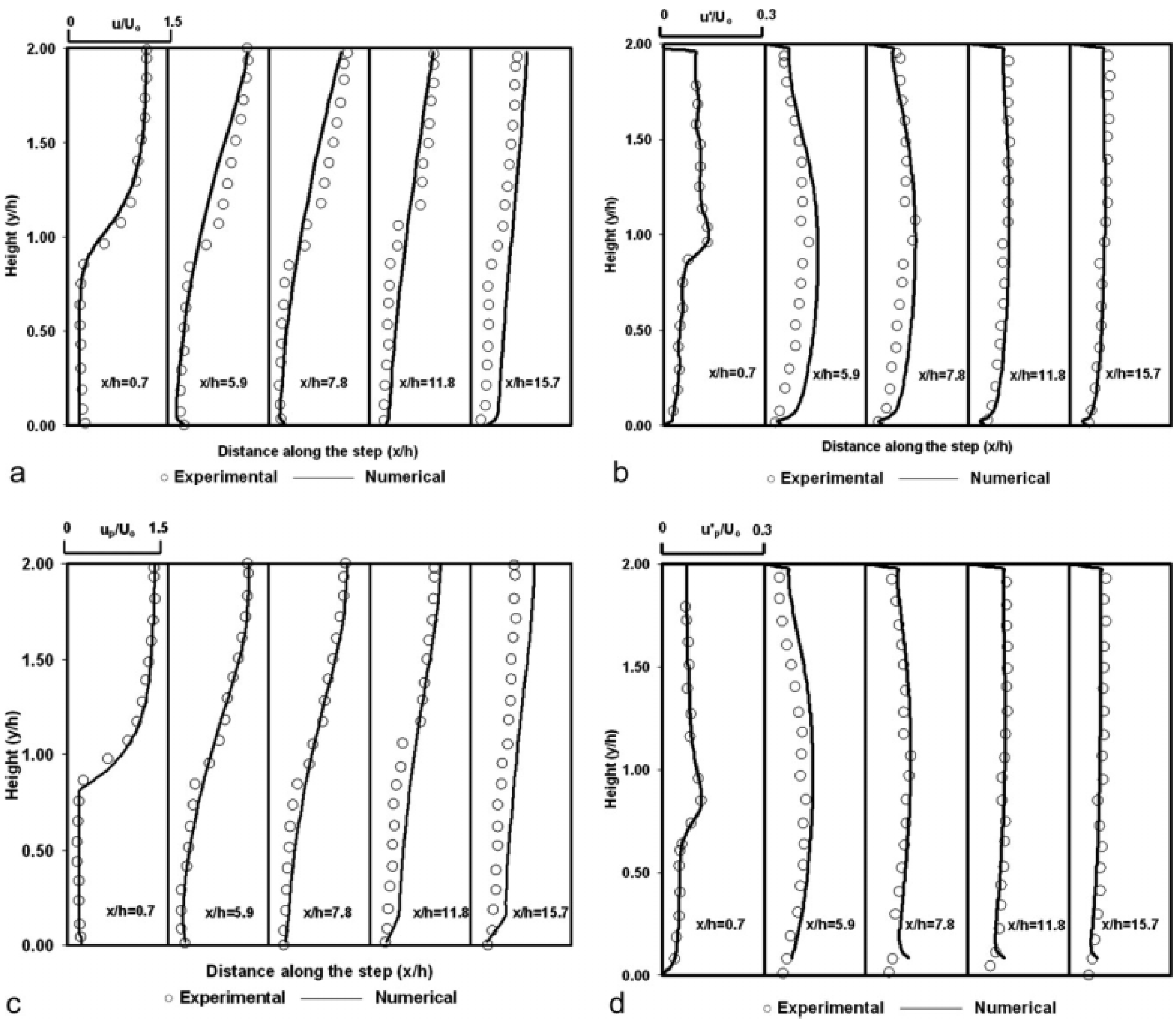

Figure 2. a: Axial liquid velocities along the step; b: fluctuating axial liquid velocities along the step articles; c: axial particle velocities along the step; d: fluctuating axial particle velocities along the step.

Investigation of particle response

With the numerical code able to replicate the experimental findings of the liquid particle flow, the study of the response of particles to the surrounding carrier phase is carried out. To proceed with this endeavor, four different Stokes numbers, by invariably changing the particle response times have been chosen. The four different Stokes numbers chosen correspond to 0.05, 0.5, 2.0, and 6.0. Particles with Stokes number 0.05 acts as tracers to the carrier phase and are widely used by experimentalists for LDA/PDA studies. The Stokes number of 0.5 corresponds to unveil realistically the response of particles for $St \leq 1$. Stokes number of 2.0 was chosen such as to fall within the range of overshoot phenomena,[6–8] wherein the particle is said to disperse more readily than the fluid, while higher Stokes number of 6.0 is to study the independent responsitivity of the particles in relation to the denser carrier phase namely the diesel oil. To represent the results more qualitatively, nine interrogation points made up of a matrix of three sections (x/h = 2, 7, and 14) along the length of the step and four sections along the height of the step (y/h = 0.5, 1.0, 1.5) have been considered.

Particle response-mean velocity level

In this part of the results and discussion section, the response of the particles to the mean flow are investigated in relation to varying Stokes number. Three sections along the step and three along the height of the step have been considered, but only their intersection points have been plotted here for brevity. Figure 3 shows the plots of the normalized mean particle velocities along with the single phase liquid velocities across varying Stokes numbers considered in our study. Figure 3a shows the particulate velocities within the recirculation region (x/h = 2.0) at a height of y/h = 0.5, while Figure 3b shows the same near the reattachment point at a height of y/h = 1.0 and Figure 3c near the exit at x/h = 14 and y/h = 1.5, where the flow tries to recover way aft of the recirculation zone. Throughout the length of the step it can be seen that there is an increase in velocities with a corresponding increase in Stokes number and for all the sections considered here the magnitude of the particulate velocities are always higher than that of the single phase liquid velocities.

From these plots it can also be seen that at section x/h = 2 the overall velocities are far lower than at the other sections. However, the particulate velocity at this section exceeds that of the carrier phase, and this is mainly attributed to the fact that particles do not respond readily unlike the carrier phase to adverse pressure gradients found aft of the step due to recirculation. As one moves further away from this section, both the carrier and the particulate velocities increase in magnitude, with the particulate velocities for higher Stokes number always higher than the carrier liquid phase. This phenomenon is attributed toward the fact that larger particles exhibit higher inertial and that the particles tend to maintain their inertial longer aft of the step in lieu of the liquid carrier phase.

Particle response-turbulence level

In this part of the results and discussion section, particles turbulent behavior is investigated. Figure 4 shows the plots of turbulent kinetic energies of particles along with the single phase liquid, normalized against its freestream velocity for varying Stokes number and sections. For all the sections presented here the turbulent kinetic energy of the particles are lower than its corresponding liquid velocities. This feature is mainly attributed to the reduction of shear between the layers of the particles (due to higher density of the liquid phase) that gives rise to the kinetic stress terms and is

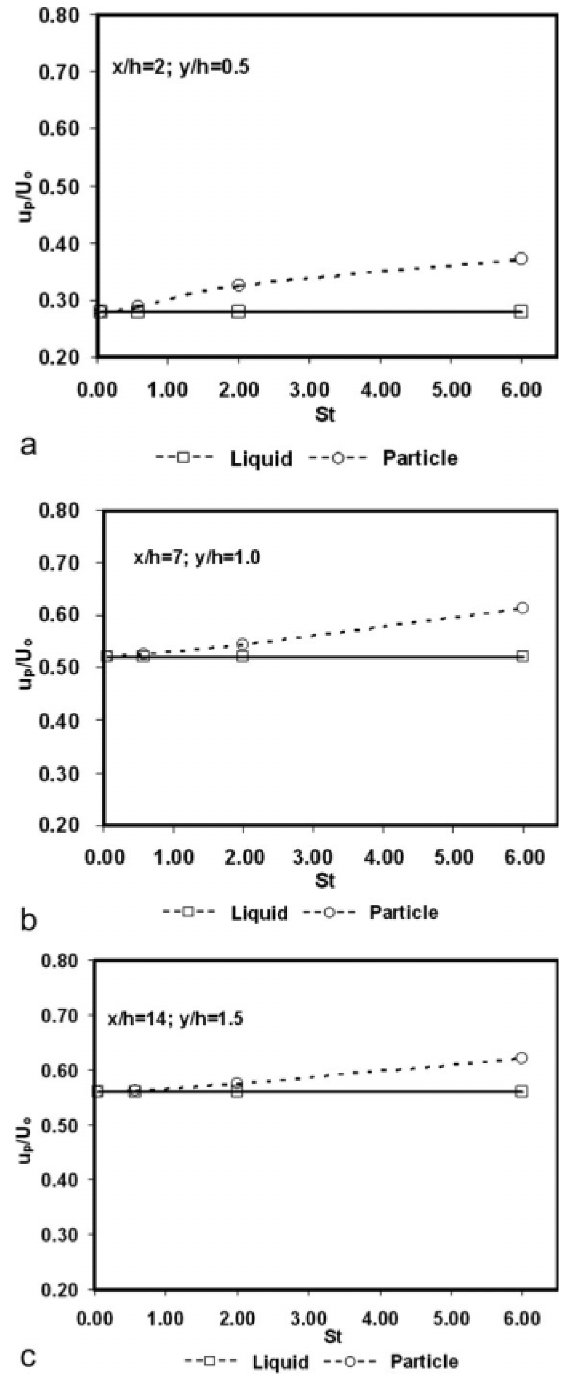

Figure 3. a: Mean streamwise velocities at x/h = 2 and y/h = 0.5; b: mean streamwise velocities at x/h = 7 and y/h = 1.0; c: mean streamwise velocities at x/h = 14 and y/h = 1.5.

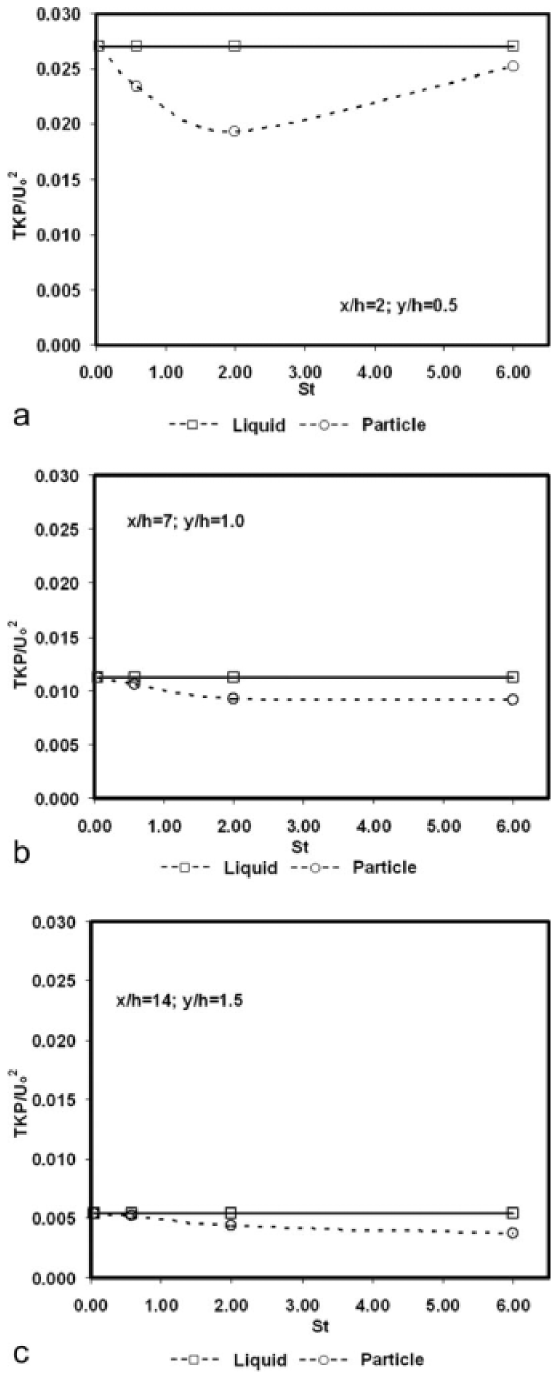

Figure 4. a: Fluctuating velocities at *x/h* = 2 and *y/h* = 0.5; b: fluctuating velocities at *x/h* = 7 and *y/h* = 1.0; c: fluctuating velocities at *x/h* = 14 and *y/h* = 1.5.

reflected in the turbulent kinetic energy of the particles. Here again three sections along the length of the step and three along its height have been considered. Figure 4a shows the turbulent kinetic energy of the particles and liquid at section $x/h = 2$, there has been a decrease in the particle kinetic energy with subsequent increase in Stokes number, except for the highest Stokes number considered in the study. Figure 4b shows the particulate turbulent kinetic energy for the section $x/h = 7$ of the step. Here again, there seem to be a steady decrease in the kinetic energy with a rise in the Stokes number. It can also be seen that the magnitude of the kinetic energy is a fold less than at the section $x/h = 2$ with a decrease being felt with a corresponding increase in the height of the step for the varying Stokes number. Figure 4c shows a similar pattern for the section $x/h = 14$ at the farther end near the exit of the geometry. The magnitude of the particulate turbulent kinetic energy here is lesser than the previous sections of $x/h = 2$ and 7.

The decrease in the kinetic energies may be explained by the flow behavior taking place behind the step. For instance, at section $x/h = 2$ which corresponds to a height of $y/h = 0.5$, turbulence is higher due to the presence of the recirculation found behind the step. As one moves further away from the step, the turbulence dies down for both the phases, as the flow recovers and assumes a channel flow.

Summary of particulate responsitivity

The above two sections which outlines the particle response at the mean velocity level and at the turbulence level show that the mean velocity of the particles increase with a subsequent increase in the Stokes number. The mean particulate velocity not only increase with the Stokes number but is also higher than its corresponding carrier phase velocities for the three Stokes number viz $St = 0.5$, 2.0, and 6.0 considered in our study. This is quite in lines with the recent experimental data of Ishima et al.[9] and the phenomenon is explained with the help of the particle terminal velocity which gives a rough approximation as a percentage of how much the particle velocity exceeds the carrier phase velocity. The other reason for the particle velocity to lead the carrier phase is the attribute of the particulate phase to respond slowly to the adverse pressure gradient dominant in shear flow geometries like backward facing step, in lieu of the carrier phase.

On the other hand, the particle turbulent kinetic energy plots depict the response of the particles at the turbulence level. Across these plots, it can be summarized that for liquid-particle flows, the magnitude of the particulate turbulence decreases across the increasing Stokes number, quite opposite to mean velocities outlined in the previous paragraph. The majority of the trend shows a decrease in particulate turbulent kinetic energies, after which they more or less remain a constant. Previous studies of liquid-particle flows in vertical channel[9,10] shows that with the increase in the Stokes number there is usually a corresponding increase in the particulate turbulence, however the flow considered in this study is a shear flow geometry, which basically depicts a totally different flow feature unlike the simple channel geometry. In these lines even the turbulence modification (TM) of the shear flow geometry for the well established gas-particle flow[11] does not seem to well correspond with the models been employed and formulated for the vertical channel flows.[2] Thereby, given the complexity of the problem much deeper understanding and experimental data may be required to ascertain the same.

With respect to the set of results described earlier, the particles response to the turbulence may be explained in terms of the carrier phase used to study the particle response.

Firstly, the density and the viscosity used to study these flows were higher, which basically prohibits the fluctuating motion of the particle. Another rationale being, in regions of strong mean velocity gradient, the streamwise particle fluctuating velocities are determined more by the mean gradient that by the actual response of the particles to turbulent fluctuations. In the absence of the same the particle velocity fluctuations tend to be lower than the fluid velocity fluctuations as noted from the experiments of Fessler and Eaton.[11] From these conclusions the eventual decrease in the particle fluctuation is more or less attributed to the decrease in the velocity gradient with a corresponding increase in Stokes number. The cross-stream mixing, which attributes toward higher particle fluctuating velocities in gas-particle flow may be prohibitive in liquid-particle flow considering the elevated density and viscosity of liquid particle flows.

Conclusion

Particles response to turbulent liquid-particle flow, behind a turbulent backward-facing step geometry was successfully analyzed and simulated numerically using an Eulerian two-fluid model. Numerically the code was validated against the benchmark experimental data of Founti and Klipfel.[3] The numerical results revealed good agreement with the experimental data. From there the code was further used to investigate the Stokes number effect on the carrier phase both at the mean velocity and at the turbulence level. At the mean velocity level the particles seem to move faster than the carrier phase. However, at the particle fluctuation level, there is a decrease with the increase in the Stokes number, wherein the particle fluctuation seems to decrease and almost flatten out with the increase in its Stokes number. The main reason for this behavior is the physical characteristics of the carrier phase namely the liquid, which is far denser prohibiting the motion of the particles at the turbulence level, which eventually changes the cross-stream and the mean gradient behavior.

Acknowledgments

The first author was supported by both Australian Government and RMIT University through International Post Graduate Research Scholarship (IPRS).

Literature Cited

1. Tu JY. Computational of turbulent two-phase flow on overlapped grids. *Numer Heat Transfer Part B Fundam*. 1997;32:175–195.
2. Mohanarangam K, Tu JY. Two-fluid model for particle-turbulence interaction in a backward-facing step. *AIChE J*. 2007;53:2254–2264.
3. Founti M, Klipfel A. Experimental and computational investigations of nearly dense two-phase sudden expansion flows. *Exp Therm Fluid Sci*. 1998;17:27–36.
4. Parthasarathy RN, Faeth GM. Structure of particle-laden turbulent water jets in still water. *Int J Multiphase Flow*. 1987;13:699–716.
5. Clift R, Grace JR, Weber ME. *Bubbles, Drops and Particles*. New York: Academic Press, 1978.
6. Chein R, Chung JN. Effects of vortex pairing on particle dispersion in turbulent shear flows. *Int J Multiphase Flow*. 1987;13:785–802.
7. Hishida K, Ando A, Maeda M. Experiments on particle dispersion in a turbulent mixing layer. *Int J Multiphase Flow*. 1992;18:181–194.
8. Ishima T, Hishida K, Maeda M. Effect of particle residence time on particle dispersion in a plane mixing layer. *J Fluids Eng*. 1993;115:751–759.
9. Ishima T, Hisanobu K, Naoki S, Tomio O. Turbulence characteristics in two-phase pipe flow lading with various particles. In: *Proceedings of 6th International Conference on Multiphase Flow, ICMF-2007*, Leipzig, Germany, July 9–13, 2007, Paper No. S3_Thu_B_50.
10. Borowsky J, Wei T. Kinematic and dynamic parameters of a liquid-solid pipe flow using DPIV/accelerometry. *J Fluids Eng*. 2007;129:1415–1421.
11. Fessler JR, Eaton JK. Turbulence modification by particles in a backward-facing step flow. *J Fluid Mech*. 1999;394:97–117.

Manuscript received Nov. 23, 2007, and revision received Sept. 1, 2008.