Particuology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

CFD–DEM simulation of turbulence modulation in horizontal pneumatic conveying

Mohammadreza Ebrahimi [a], Martin Crapper [b,*]

[a] Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, The King's Buildings, Edinburgh EH9 3JL, UK
[b] Department of Mechanical and Construction Engineering, Northumbria University, Ellison Place, Newcastle-upon-Tyne, NE1 8ST, UK

ARTICLE INFO

Article history:
Received 14 June 2015
Received in revised form 4 May 2016
Accepted 18 May 2016
Available online xxx

Keywords:
Turbulence modulation
Pneumatic conveying
Eulerian–Lagrangian approach
Laser Doppler anemometry

ABSTRACT

A study is presented to evaluate the capabilities of the standard k–ε turbulence model and the k–ε turbulence model with added source terms in predicting the experimentally measured turbulence modulation due to the presence of particles in horizontal pneumatic conveying, in the context of a CFD–DEM Eulerian–Lagrangian simulation. Experiments were performed using a 6.5-m long, 0.075-m diameter horizontal pipe in conjunction with a laser Doppler anemometry (LDA) system. Spherical glass beads with two sizes, 1.5 and 2 mm, were used. Simulations were performed using the commercial discrete element method software EDEM, coupled with the computational fluid dynamics package FLUENT. Hybrid source terms were added to the conventional k–ε turbulence model to take into account the influence of the dispersed phase on the carrier phase turbulence intensity. The simulation results showed that the turbulence modulation depends strongly on the model parameter $C_{\varepsilon 3}$. Both the standard k–ε turbulence model and the k–ε turbulence model with the hybrid source terms could predict the gas phase turbulence intensity trend only generally. A noticeable discrepancy in all cases between simulation and experimental results was observed, particularly for the regions close to the pipe wall. It was also observed that in some cases the addition of the source terms to the k–ε turbulence model did not improve the simulation results when compared with those of the standard k–ε turbulence model. Nonetheless, in the lower part of the pipe where particle loading was greater due to gravitational effects, the model with added source terms performed somewhat better.

Introduction and background

Turbulence modulation in fluid–particle flows

Carrier phase turbulence structure changes as a particulate phase is added to a clear fluid phase. This phenomenon is referred to as turbulence modulation in the literature (Elghobashi & Abou-Arab, 1983). It is important because any change in continuous phase turbulence has a direct influence on the fluid mean velocity, heat and mass transfer as well as particle mixing and dispersion (Fokeer, Kingman, Lowndes, & Reynolds, 2004; Kenning & Crowe, 1997; Lightstone & Hodgson, 2004). It has also been pointed out that in a dilute phase particle-laden flow, turbulence modulation impacts drastically on the conveying line pressure drop (Curtis & van Wachem, 2004). Laín, Bröder, Sommerfeld, and Göz (2002) also highlighted the influence of turbulence modulation on the prediction of the hydrodynamic behaviour of a bubble in a bubble column. Therefore understanding the interaction between a dispersed phase and fluid phase turbulence appears to be one of the crucial steps in understanding the complex characteristics of two-phase systems.

Both attenuation and augmentation of fluid phase turbulence have been reported in previous studies. Despite much research focused on this topic, there is no generally accepted explanation for the influence of the solid phase on the carrier phase (Crowe, 2000; Mandø, 2009). In general, it is recognizable from previous studies that small particles tend to suppress the carrier phase turbulence level whereas large particles increase it. Previous observations reveal that small particles (particle diameter $d_p < 200\ \mu m$) follow the fluid flow and as a result these particles may break turbulent eddies. These small particles may be accelerated by eddies, and so extract kinetic energy from them (dissipation of energy), leading to a reduction in the turbulence level of the fluid flow (Geiss et al., 2004; Lightstone & Hodgson, 2004). However, fluid flow tur-

* Corresponding author.
E-mail address: Martin.Crapper@Northumbria.ac.uk (M. Crapper).

http://dx.doi.org/10.1016/j.partic.2016.05.012

Nomenclature

C_D	Drag coefficient
e	Coefficient of restitution
G^*	Equivalent shear modulus (Pa)
I_i	Particle moment of inertia (kg m^2)
k	Turbulent kinetic energy (m^2/s^2)
m_i	Particle mass (kg)
m^*	Equivalent mass (kg)
R^*	Equivalent radius (m)
$T_{i,j}$	Torque (N m)
u_p	Particle velocity (m/s)
u'_{pi}	Particle fluctuating velocity (m/s)
$\bar{u}_p$	Mean particle velocity (m/s)
v'_i	Gas fluctuating velocity (m/s)
$\bar{v}$	Mean gas velocity (m/s)
V_t^{rel}	Relative tangential velocity (m/s)
V_n^{rel}	Relative normal velocity (m/s)
ω_p	Particle angular velocity (rad/s)
Y^*	Equivalent Young's modulus (Pa)

Greek letters

δ_n	Normal overlap (m)
δ_t	Tangential overlap (m)
ε	Dissipation (m^2/s^3)
μ	Dynamic viscosity (Pa s)
ρ	Fluid density (kg/m^3)
ρ_p	Particle density (kg/m^3)
τ_e	Eddy turnover time (s)
τ_p	Particle response time (s)
ϕ_p	Particle volume fraction

bulence augmentation by large particles can be explained as a result of the wake generated behind the particles. This wake creates an additional disturbance to the flow which may increase the level of turbulence. These phenomena are considered to be the core reasons of turbulence reduction and enhancement (Bolio & Sinclair, 1995).

In addition to these two predominant mechanisms, other factors such as fluid flow turbulence modification due to particle–particle interaction, changes in turbulence dissipation as a result of the introduction of new length scales, and changes in the continuous phase velocity gradient are believed to be other influential reasons for turbulence modification. However, these mechanisms may be negligible in a dilute particle suspension (Yuan & Michaelides, 1992). Lightstone and Hodgson (2004) also mentioned the influence of the crossing trajectory, i.e. the relative mean velocity between the particles and the turbulence eddies, as another source of gas phase turbulence generation.

Some researchers have tried to formulate turbulence modulation based on the observation of experimental results (Crowe, 2000; Mandø, 2009). However, these formulations are valid only for the specific range of solid loading ratios and system specifications observed in each case.

According to the explanation regarding the turbulence modulation, it seems that particle size, particle concentration (loading), fluid velocity and ratio of particle to fluid length scale are important parameters to evaluate the turbulence modulation. These four parameters may be expressed as (1) mass/volumetric solid loading, (2) the ratio of particle diameter to the fluid turbulence length scale, (3) particle Reynolds number ($Re_p = \rho \left(v - u_p \right) d_p / \mu$), and (4) Stokes number ($St = \tau_p/\tau_e$) (Fokeer et al., 2004; Gouesbet & Berlemont, 1999; Mandø, 2009; Yarin & Hetsroni, 1994), where ρ is the fluid density, v is the fluid velocity, u_p is the particle velocity, d_p is particle diameter, and μ is the dynamic viscosity; τ_p and τ_e are the particle response time and eddy turnover time, respectively.

Based on the Elghobashi (1994) study, for particle volume fraction less than 10^{-6}, the influence of particles on the fluid phase turbulence is weak. For particle volume fractions ϕ_p in the range $10^{-6} < \phi_p < 10^{-3}$, the particles can augment or attenuate the carrier phase turbulence depending on the ratio of τ_p/τ_e. For $\tau_p/\tau_e < 1$, the turbulence is reduced by the particle presence whereas for $\tau_p/\tau_e > 1$ the carrier phase turbulence is enhanced. Elghobashi (1994) also explained turbulence augmentation due to wake formation.

Gore and Crowe (1989) reviewed the wide range of experimental data for pipe and jet flows and suggested that the ratio of particle diameter (d_p) to the integral length scale (l_e) may be used as a criterion to examine the augmentation or attenuation of turbulence level. The length scale ratio 0.1 is a distinguishing point for turbulence modulation; for a length scale ratio $d_p/l_e < 0.1$, turbulence intensity decreases, whereas for $d_p/l_e > 0.1$, particles tend to increase the turbulence intensity.

Hetsroni (1989) investigated various experimental data for horizontal and vertical two-phase pipe flows and concluded that particles with Re_p higher than 400 tend to increase the turbulence intensity due to vortex shedding from particles, while particles with Re_p less than 400 tend to suppress the turbulence intensity. Yuan and Michaelides (1992) also noted that for $Re_p > 20$ a wake is formed behind a particle, and for $Re_p > 400$ vortices are shed behind the solid particles. Lun (2000) also reported that turbulence modulation depends significantly on Re_p; however, he found vortex shedding occurs when Re_p is around 300. He observed that particles tend to attenuate the carrier phase turbulence when $Re_p < 300$, whereas if the Re_p is more than a critical Re_p, turbulence enhances.

Previous experimental work on turbulence modulation

As laser Doppler anemometry (LDA) is a non-contact optical measurement which can handle velocity components with high temporal and spatial resolution, it has been used extensively for measuring gas and particle velocities in gas–solid flows (Fan, Zhang, Cheng, & Cen, 1997; Lu, Glass, Easson, & Crapper, 2008; Lu, Glass, & Easson, 2009; Mathisen, Halvorsen, & Melaaen, 2008; Tsuji & Morikawa, 1982). Tsuji and Morikawa (1982) observed that air flow turbulence level depended heavily on particle size, that 3.4 mm particles increased the turbulence whereas 0.2 mm particles reduced it. The influence of the particle size on the carrier phase turbulence level was also reported by (Henthorn, Park, & Curtis, 2005; Tsuji, Morikawa, & Shimoni, 1984). Fan et al. (1997) applied LDA to measure both velocity and turbulence intensity in dilute vertical pneumatic conveying and compared experimental measurements with simulation. They concluded that the turbulence intensity of the gas phase was attenuated and the mean gas velocity profile was flattened by adding particles. Turbulence intensity reduction by adding fine particles (50–90 μm) was also mentioned by Kulick, Fessler, and Eaton (1994), observing that the degree of attenuation increased by increasing the particle mass loading ratio and distance from the wall.

Numerical modelling of turbulence modulation

Generally, to model the turbulence modulation phenomenon, source terms are added to the single-phase flow equations for turbulent kinetic energy and dissipation to take into account the presence of the solid phase. Some research has been conducted to formulate these source terms (Geiss et al., 2004; Gouesbet & Berlemont, 1999; Rao, Curtis, Hancock, & Wassgren, 2012). These formulations mainly depend on the turbulence model used to close the fluid momentum equation (Laín & Sommerfeld, 2003).

Please cite this article in press as: Ebrahimi, M., & Crapper, M. CFD–DEM simulation of turbulence modulation in horizontal pneumatic conveying. *Particuology* (2016), http://dx.doi.org/10.1016/j.partic.2016.05.012