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Computational Characterisation of Intermittent Hydrodynamic Behaviours in a Riser with Geldart A Particles

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Abstract

In the riser of a gas-solid circulating fluidised bed (CFB) with Geldart A particles, the multiscale interactions and diverse coherent structures give rise to an important hydrodynamic phenomenon called flow intermittency. In this work, the two-fluid model incorporating the energy minimisation multi-scale (EMMS) drag model is employed to simulate the gas-solid flow in the riser. The predicted fluctuating signals are processed to acquire the intermittency indices, wavelet flatness factors, power spectra of solids volume fraction fluctuation, probability density function (PDF) of wavelet coefficients for solids fluctuating velocity, and PDF of solids volume fraction, based on which the flow intermittency and effects of coherent structures are characterised. The results presented in this paper reveal that the EMMS-based computational fluid dynamics (CFD) simulation in combination with the fluctuating signal analysis provide an in-depth understanding of the intermittent flow behaviours in the riser with Geldart A particles. Particle clusters and particle vortices are identified as typical coherent structures in the riser, and the flow intermittency, caused by the flow field heterogeneity and the presence of coherent structures, is found to be significantly dependent on the radial locations and operation conditions.

Keywords

Flow intermittency, coherent structures, CFD simulation, energy minimisation multi-

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scale approach, fluctuating signal analysis

1. Introduction

In view of the excellent performance in interphase mixing, heat and mass transfer, and handling capability of particles, CFBs are extensively employed in industrial processes, such as fluid catalytic cracking (FCC), pyrolysis of coal, Fischer-Tropsch synthesis to name but a few. Geldart A particles (e.g. pulverised coal, FCC particles) are commonly used as the bed materials of CFBs. Owing to the small sizes, lower apparent densities and high specific surface areas, Geldart A particles are highly prone to form heterogeneous flow structures, typically the particle clusters, under the complex gas-solid interactions during fluidisation. These flow structures along with the intermittent nature of local solids flow yield an important consequence called flow intermittency, referring to the intermittent occurrence of large-magnitude fluctuations reflected in the flow signals [1, 2]. As the flow intermittency is closely related to the heterogeneous distribution of hydrodynamic parameters and the non-equilibrium flow state, which can further result in fluidisation faults such as stagnant zones, hot spots, particle adhesion to the wall, slugs, and even defludisation, it is necessary to understand the hydrodynamic characteristics of the intermittent flow behaviours in a CFB with Geldart A particles. Despite extensive studies conducted on the experimentation and simulation of CFBs with Geldart A particles [3-9], the knowledge about flow intermittency is still limited. Brereton and Grace [10] derived an intermittency index from the measured suspension density fluctuating signals to quantify the non-uniformity of the flow field in a riser. This parameter was then used to indicate the occurrence of flow structures (e.g. particle agglomerates, particle clusters) at a given location, namely, the higher the index value, the stronger the influence of these structures [2, 11, 12]. However, the intermittency index only offers a rough quantification and is far from describing the complex intermittent flow behaviours in a CFB. If referring to single-phase turbulence, the flow intermittency due to the presence of coherent flow structures was characterised through the analysis of fluctuating velocity signals, using the processing approaches such as energy spectra, wavelet transform and auto-correlation [13-18]. Such a methodology has been applied to a bubbling fluidised bed with Geldart B particles in our previous studies [19, 20]. However, the flow field in a CFB is more complex than that in the bubbling bed, such as the fiercer gas-solids flow, full-loop solids circulation, coexistence of different flow regimes, and dependence of operation conditions on both the gas velocity and solids flux. Therefore, the flow intermittency and coherent structure behaviours in a CFB are different from those in a bubbling bed and require special characterisation. In addition, as Geldart A particles exhibit significantly different fluidisation characteristics from the previously studied Geldart B particles [19, 20], the effects of operating conditions on the intermittent behaviours of Geldart A particles are expected to be different from those of Geldart B particles. It is thus necessary to study this issue in the present work.

CFD simulation is now extensively accepted as a desirable tool for characterising the flow behaviours in gas-solid systems. The two-fluid model employing coarse grids is widely used for the simulation of commercial equipment, owing to its less computational expense than that of the discrete element method and direct numerical simulation. As the sizes of flow structures (e.g. particle clusters) in the CFBs with Geldart A particles range from several particle diameters to the riser diameter, adequate sub-grid models are required to take the effects of the unresolved mesoscale structures on the constitutive laws into account [21, 22]. One approach is the adoption of the so-called filtered models developed to describe the sub-grid closures of drag force [23-25]. The other is to use the EMMS drag model, with which the heterogeneity and mesoscale-structure effects on the interphase interactions within a computational grid are accounted for [4, 26-29]. Therefore, the EMMS-based two-fluid model, in combination with the aforementioned fluctuating signal processing approaches originating from single-phase turbulence, is naturally suitable for characterising the roles of flow structures on the flow intermittency in a CFB. However, very little relevant work has been reported to date. In this work, the two-fluid model incorporating the EMMS model, with closures from the kinetic theory of granular flow, is used to simulate the riser section of a CFB with Geldart A particles based on the experimental set-up by Li and Kwauk [26]. The predicted fluctuating signals are further processed to obtain the intermittency indices, wavelet flatness factors, power spectra of solids volume fraction fluctuation, PDF of wavelet coefficients for solids fluctuating velocity, and PDF of solids volume fraction, from which the understanding of flow intermittency and flow structure characteristics in the riser is advanced.

2. CFD model

The CFD model employed in this work consists of conservation equations (mass and momentum) and constitutive equations, most of which is the same as that used in our previous work [19, 20], except for the solids kinetic viscosity and drag models. Readers can refer to the work [19, 20] for more detailed information. The solids kinetic viscosity, $\mu_{s,kin}$, is computed from the Gidaspow model [30],

$$\mu_{s,kin}=\frac{10\rho_s d_s\sqrt{\theta_s\pi}}{96\varepsilon_s\left(1+e_{ss}\right)g_{0,ss}}\left[1+\frac{4}{5}g_{0,ss}\varepsilon_s\left(1+e_{ss}\right)\right]^2 \tag{1}$$

where ρ_s is the particle density, d_s the particle diameter, ε_s the solids volume fraction, θ_s the granular temperature, e_{ss} the restitution coefficient, $g_{0,ss}$ the radial distribution function.

The interphase momentum exchange is described by the EMMS drag model [28],

$$\beta=\frac{3}{4}\frac{\left(1-\varepsilon_g\right)\varepsilon_g\rho_g\left|u_g-u_s\right|}{d_s}C_D\varepsilon_g^{-2.65}\omega\left(\varepsilon_g\right),\qquad \varepsilon_g>\varepsilon_g^* \tag{2}$$

$$\beta=150\frac{\left(1-\varepsilon_g\right)^2\mu_g}{\varepsilon_g d_s^2}+\frac{7}{4}\frac{\left(1-\varepsilon_g\right)\rho_g\left|u_g-u_s\right|}{d_s},\qquad \varepsilon_g\le\varepsilon_g^* \tag{3}$$

$$C_D=\begin{cases}\dfrac{24}{Re_s}\left[1+0.15Re_s^{0.687}\right], & Re_s\le 1000\\ 0.44, & Re_s>1000\end{cases} \tag{4}$$

$$Re_s=\frac{\varepsilon_g\rho_g\left|u_g-u_s\right|d_s}{\mu_g} \tag{5}$$

where β is the interphase momentum transfer coefficient, ε_g the voidage, ρ_g the gas density, u_g and u_s the velocity of gas and solids phases, respectively, C_D the drag force coefficient, $\omega\left(\varepsilon_g\right)$ the heterogeneous index depending on both the locally transient and globally averaged information of the two-phase flow, ε_g^* the critical gas volume fraction (critical voidage), μ_g the gas viscosity, Re_s the Reynolds number. In this work, the computation scheme proposed by Yang et al. [28] is used to derive the expressions of $\omega\left(\varepsilon_g\right)$ for different operation conditions. A brief introduction is presented here for the sake of clarity, and the reader is referred to Yang et al. [28, 31] for the details.

The basic concept of the EMMS model is that the heterogeneous structures are resolved into a particle-rich dense cluster phase and a gas-rich dilute phase. The gas-solid interactions are correspondingly resolved into the interaction between the gas and particles within each phase and that between the dense and dilute phases. In addition, the energy consumption for suspending and transporting particles, N_{st}, should be minimum to achieve the system stability condition [26, 32]. Three gas-solid interactions, derived from the momentum balance for particles and the pressure drop balance for gas, are computed from,

$$M_c F_{dense} = \frac{f\left(1-\varepsilon_c\right)}{\pi d_s^3/6} C_{Dc} \frac{\pi d_s^2}{4} \frac{\rho_g}{2} U_{slip,c}^2 = f\left(\rho_s-\rho_g\right)\left(g+a\right)\left(1-\varepsilon_g\right) \tag{6}$$

$$M_i F_{cluster} = \frac{f}{\pi d_{cl}^3/6} C_{Di} \frac{\pi d_{cl}^2}{4} \frac{\rho_g}{2} U_{slip,i}^2 = f\left(\rho_s-\rho_g\right)\left(g+a\right)\left(\varepsilon_g-\varepsilon_c\right) \tag{7}$$

$$M_f F_{dilute} = \frac{\left(1-f\right)\left(1-\varepsilon_f\right)}{\pi d_s^3/6} C_{Df} \frac{\pi d_s^2}{4} \frac{\rho_g}{2} U_{slip,f}^2 = \left(1-f\right)\left(\rho_s-\rho_g\right)\left(g+a\right)\left(1-\varepsilon_f\right) \tag{8}$$

where M_c and M_f are the number of particles per unit volume in the dense and dilute phases, respectively, M_i the number of clusters per unit volume, F_{dense} and F_{dilute} the drag force on a single particle in the dense and dilute phases, respectively, $F_{cluster}$ the drag force on a single cluster, f the volume fraction of the dense phase, ε_c and ε_f the voidage of the dense and dilute phases, respectively, d_{cl} the hydrodynamic equivalent cluster diameter, C_{Dc} and C_{Df} the effective drag coefficients for a particle in the dense and dilute phases, respectively, C_{Di} the effective drag coefficient for a cluster, $U_{slip,c}$, $U_{slip,f}$ and $U_{slip,i}$ the superficial slip velocities in the dense phase, dilute phase and interphase, respectively, g the gravitational acceleration, a the average acceleration of particles in a control volume.

The system stability condition is expressed as,

$$\frac{N_{st}}{N_T} = 1 - \frac{\varepsilon_f - \varepsilon_g}{1-\varepsilon_g} f\left(1-f\right)\frac{U_{gf}}{U_g} = \min \tag{9}$$

where N_{st} is the mass-specific energy consumption for suspending and transporting particles, N_T the mass-specific total energy consumption for particles, U_{gf} the superficial gas velocity in the dilute phase, U_g the superficial gas velocity.

By solving the relevant nonlinear equations with specified U_g, G_s and ε_g, the heterogeneous index $\omega\left(\varepsilon_g\right)$ is obtained. The derived expressions of $\omega\left(\varepsilon_g\right)$ for different operation conditions are,

For U_g=1.52 m/s, G_s=14.3 kg/(m^2·s) [28],

ε_g^*=0.74

$$\omega\left(\varepsilon_g\right)=\begin{cases} -0.5760+\dfrac{0.0214}{4\left(\varepsilon_g-0.7463\right)^2+0.0044}, & \varepsilon_g^* < \varepsilon_g \le 0.82 \\ -0.0101+\dfrac{0.0038}{4\left(\varepsilon_g-0.7789\right)^2+0.0040}, & 0.82 < \varepsilon_g \le 0.97 \\ -31.8295+32.8295\varepsilon_g, & \varepsilon_g > 0.97 \end{cases} \tag{10}$$

For U_g=1.52 m/s, G_s=26.9 kg/(m^2·s),

ε_g^*=0.732

$$\omega\left(\varepsilon_g\right)=\begin{cases} -0.0988+\dfrac{0.0025}{4\left(\varepsilon_g-0.7308\right)^2+0.0005}, & \varepsilon_g^*<\varepsilon_g\leq 0.815 \\ 0.0014+\dfrac{0.0014}{4\left(\varepsilon_g-0.7667\right)^2+0.0066}, & 0.815<\varepsilon_g\leq 0.936 \\ -14.4183+15.4183\varepsilon_g, & \varepsilon_g>0.936 \end{cases} \tag{11}$$

For U_g=2.1 m/s, G_s=24.1 kg/(m^2·s),

ε_g^*=0.74

$$\omega\left(\varepsilon_g\right)=\begin{cases} -0.1471+\dfrac{0.0057}{4\left(\varepsilon_g-0.7356\right)^2+0.0010}, & \varepsilon_g^*<\varepsilon_g\leq 0.818 \\ 0.0007+\dfrac{0.0026}{4\left(\varepsilon_g-0.7780\right)^2+0.0084}, & 0.818<\varepsilon_g\leq 0.952 \\ -19.5589+20.5589\varepsilon_g, & \varepsilon_g>0.952 \end{cases} \tag{12}$$

In addition, the two-phase turbulence is depicted by the standard *k*-*ε* dispersed model, which is applicable when the concentration of the secondary phase is low [33].

3. Simulation configuration

Two-dimensional simulations were carried out for the riser section of the CFB used in the experiments by Li and Kwauk [26], as illustrated in Figure 1. The inner diameter and height of the riser were 0.090 m and 10.5 m, respectively. The air introduced from the bottom was assumed to be in a uniform distribution with a specified superficial velocity. FCC particles were used as the bed materials with an average diameter of 54 μm and density of 930 kg/m^3. The solids were initially packed up to a certain height H_0 with the minimum fluidisation voidage for all the testing cases. During the fluidisation, the solids were carried upward by air to exit from the outlets, and in turn fed back into the solids inlets at the bottom by specifying that the solids flow rate at the two side inlets was equal to that at the top outlets [28].

The computation geometry and grids of the riser in this work were generated using the commercial software package GAMBIT 2.3.16. A uniform-grid scheme was adopted in both the axial and lateral directions, and three grid resolutions, 40×150

(coarse grids), 40 × 300 (medium grids), and 40 × 600 (fine grids) corresponding to a refinement factor of 2, were tested to quantify the spatial discretisation errors of the simulations. The grid analysis results will be presented in Section 4.1.

The commercial CFD software package ANSYS-FLUENT 15.0 was applied to solve the aforementioned conservation and constitutive equations, with the numerical parameters and boundary conditions under different operation conditions given in Table 1. The second order upwind scheme and QUICK scheme were used to discretise the momentum and volume fraction equations, respectively. The phase-coupled SIMPLE algorithm was used for pressure-velocity coupling. The under relaxation factors of 0.5, 0.3, 0.2, 0.4, 0.4, and 0.5 were adopted for the iteration of momentum, volume fraction, granular temperature, turbulent kinetic energy, turbulent dissipation rate, and turbulent viscosity, respectively. All the simulations were performed on an I620-G20 Sugon Server with Intel E5-2600V3 CPUs for 40 s in an unsteady mode with a time step of 0.0005 s, and the convergence criterion was reached when all the residues were less than 0.001. The flow quantities such as solids volume fraction and solids velocity were sampled at a frequency of 500 Hz. To eliminate the start-up effects of the simulations, the quantities obtained between 20 s and 40 s were used for further analysis.

Table 1 Numerical parameters and boundary conditions used in the simulations

Description	**Value**
Air density, ρ_g	1.225 kg/m^3
Air viscosity, μ_g	1.81×10^{-5} Pa·s
Particle diameter, d_s	54 μm
Particle density, ρ_s	930 kg/m^3
Initial condition	
Static bed height, H_0 [4, 28]	1.22 m, 2.80 m, 1.22 m
Minimum fluidisation voidage, ε_{mf}	0.5
Gas inlet boundary condition	
Superficial gas velocity, U_g [4, 28]	1.52 m/s, 1.52m/s, 2.10 m/s
Solids volume fraction, ε_s	0

Solids inlet boundary condition	
Solids flux, G_s [4, 28]	14.3 kg/(m^2·s), 26.9 kg/(m^2·s), 24.1 kg/(m^2·s)
Solids volume fraction, ε_s	0.5
Outlet boundary condition	
Outlet pressure, p_g	1.01325×10^5 Pa
Wall boundary condition	
Gas phase	No slip
Particle-particle restitution coefficient	0.95
Particle specularity coefficient	0.6

4. Results and discussion

4.1. Model verification

Although it has been demonstrated that the drag models employing sub-corrections such as the EMMS model are capable of capturing finer flow structures with relatively coarse grids [34], the effects of grid resolution on the simulation results are still to be quantified. Figure 2 shows the time-averaged axial voidage profiles at U_g=1.52 m/s and G_s=14.3 kg/(m^2·s) obtained from the coarse-, medium- and fine-grid simulations, respectively. Both the medium and fine grids result in good consistency with the experimental data from Li and Kwauk [26], while the coarse ones lead to more obvious deviation. Therefore, the medium grids were used in the following simulations as a compromise between the computational accuracy and expense.

4.2. Intermittency indices

The intermittent nature and heterogeneity of local solids flow in the riser can be quantified by the intermittency index. It was defined by Brereton and Grace [10] and derived from the instantaneous solids volume fraction fluctuating signals [11, 12, 34], expressed as,

$$\gamma=\frac{\sigma}{\sigma_s} \tag{13}$$

where σ is the standard deviation of solids volume fraction fluctuation at a given location, σ_s the standard deviation of solids volume fraction fluctuation for an ideal cluster flow, with a consistent time-averaged solids volume fraction at the same location, and computed from,

$$\sigma_s = \sqrt{\overline{\varepsilon_s}\left(\varepsilon_{s,mf} - \overline{\varepsilon_s}\right)} \tag{14}$$

where $\overline{\varepsilon_s}$ is the time-averaged solids volume fraction and $\varepsilon_{s,mf}$ the solids volume fraction under the minimum fluidisation condition. The index value of 0 represents a perfectly homogeneous local suspension and no variation of solids volume fraction with time occurs. The value of 1 indicates an ideal cluster flow with particles segregated into clusters or agglomerates, surrounded by the solids-free gas [11, 12]. It is thus concluded that the higher the value of γ, the stronger the flow intermittency is and the more flow structures exist. Figure 3 compares the axial profiles of intermittency index in the bed centre (R=0 mm) and near the wall (R=35 mm) under different conditions. At U_g=1.52 m/s, G_s=14.3 kg/(m^2·s) the intermittency index in the bed centre varies between 0.25 and 0.3, indicating a relatively uniform flow pattern along the axis, as shown in Figure 3(a). The intermittency indices near the wall are higher than those in the bed centre and exhibit more significant oscillation along the axis, representing stronger flow intermittency and particle cluster motion near the wall. With the increase of solids flux in Figure 3(b), a core-annulus flow pattern is formed, resulting in significantly higher intermittency indices compared to those in Figure 3(a), along with increased differences between the two profiles in the bed centre and near the wall in the lower positions. Under this dense suspension condition, the stronger flow heterogeneity near the wall is related to the wall restriction and the shear exerted on solids flow, and the formation of more particle clusters moving along the wall, especially in the lower dense region. Meanwhile, the less heterogeneous dilute suspension is conveyed upward in the central region. Such flow pattern is consistent with that deduced from the experimental intermittency index distribution in a riser with coal ash particles [11]. When the superficial gas velocity increases to 2.10 m/s while the solids flux basically remains unchanged, the phase mixing and radial solids exchange are again enhanced, making the cross-sectional solids flow more uniform and the two index profiles closer, as shown in Figure 3(c). Yet in the lower positions, the intermittency indices near the wall are still much higher than those in the bed centre. Moreover, the intermittency indices are lower than those in Figure 3(b), since the stronger upward gas flow and solids interactions at U_g=2.10 m/s inhibit the formation of particle clusters and other flow structures.

4.3. Wavelet flatness factors

Through statistical analysis of solids volume fraction fluctuating signals, the intermittency index provides an 'average' description of flow intermittency, which is related directly to the particle cluster motion in the CFB. However, the flow signals contain multi-scale hydrodynamic information owing to the multi-scale nature of the flow in the CFB, and the intermittency is also a multi-scale hydrodynamic property of a flow field [13, 19, 35]. Therefore, it is necessary to decompose the flow signals into multiple scales, based on which the intermittency at different scales is quantified, and the relationships between the intermittency and various flow behaviours are characterised. This is an approach different from the intermittency index for understanding the flow intermittency. More specifically, the multi-scale intermittency is characterised by analysing the fluctuating signals through wavelet transform incorporating flatness factors [19]. The flatness factor of wavelet coefficients (abbreviated as wavelet flatness factor hereinafter) at each scale is computed from,

$$FF\left(r\right)=\frac{\left\langle \left(w^{(r)}\left(t\right)\right)^{4}\right\rangle}{\left\langle \left(w^{(r)}\left(t\right)\right)^{2}\right\rangle^{2}} \tag{15}$$

$$\left\langle \left(w^{(r)}\left(t\right)\right)^{2}\right\rangle=\int_{-\infty}^{\infty}\left(w^{(r)}\left(t\right)\right)^{2}p\left(w^{(r)}\left(t\right)\right)d\left(w^{(r)}\left(t\right)\right) \tag{16}$$

$$\left\langle \left(w^{(r)}\left(t\right)\right)^{4}\right\rangle=\int_{-\infty}^{\infty}\left(w^{(r)}\left(t\right)\right)^{4}p\left(w^{(r)}\left(t\right)\right)d\left(w^{(r)}\left(t\right)\right) \tag{17}$$

where r represents the wavelet scale, $w^{(r)}\left(t\right)$ the wavelet coefficient at scale r and time t, $p\left(w^{(r)}(t)\right)$ the probability density of $w^{(r)}(t)$, and $\langle\ \rangle$ the average over the time. In addition,

$FF(r)=3$ representing no flow intermittency and the signal in Gaussian distribution,

$FF(r)<3$ representing strong randomness of the signal,

$FF(r)>3$ representing strong flow intermittency caused by coherent structures.

The coherent structures mentioned here refer to specific flow structures. According to the definition in single-phase turbulence, coherent structures are the connected, large-scale turbulent fluid mass with phase-correlated vorticities over their spatial extents, containing high flow energy [36]. They play a dominant role in determining the flow intermittency. Similarly in a riser with Geldart A particles, it is already known from Section 4.2 that the flow intermittency is strongly dependent on the presence of particle clusters, which should therefore be regarded as ‘coherent structures’. Moreover, as typical coherent structures in a bubbling fluidised bed [20], particle vortices also frequently appear in the riser. They are generated by the velocity gradients and wall shear, carrying flow energy and heterogeneity. It is thus logical to classify the particle vortices as coherent structures in the riser as well. Figure 4 shows the simulated contours of instantaneous solids volume fraction and solids velocity vector. The arrows in the figure represent the directions of solids motion, and the values on the colour bar stand for the solids volume fractions. Particle clusters and particle vortices are distinguished from the solids volume fraction and solids velocity distributions, respectively. Specifically, particle clusters are indicated by the protrusion from the wall and the strands in the bed with higher solids volume fraction than the dilute phase, and are continuously formed and broken due to the interactions with the gas stream. While an ideal particle vortex is a flow structure with the solids vector lines rotating around a centre. However, such particle vortices are difficult to exist continuously in the riser due to the chaotic nature of the flow field. Therefore, in the simulated contours of solids velocity vector, the regions with rotating vector lines or sharp changes of vector directions are identified as particle vortices. Based on these criteria, typical particle clusters and particle vortices are identified in the local enlarged map in Figure 4. It is found that the particle vortices tend to appear in the diluter regions close to the particle clusters. Therefore, the occurrences of particle clusters and particle vortices are likely to be associated in the riser with Geldart A particles. Moreover, it is shown that the existence of these coherent structures affects both the solids volume fraction and solids velocity distributions, from which the flow intermittency is reflected. As the coherent structures are mainly distributed near the wall, we focused on the flow intermittency analysis at R=35 mm in the following work.

In terms of the aforementioned wavelet transform for intermittency representation, it is required to determine the wavelet basis and decomposition scale firstly. Referring to turbulence flow, owing to the optimal combination between the wavelet length and vanishing moments and the good localization in space and scale domains, the Daubechies 3 and 4 wavelets are recommended for characterising the flow energy transport and effects of localised events (intermittency) on wavelet spectra [37, 38]. The Daubechies 3 wavelet is thus employed in this work for the wavelet transform of the simulated solids axial fluctuating velocity signals. On the other hand, as the discrete wavelet transform is commonly used for the wavelet flatness factor calculation [13, 16, 35], the velocity signals obtained in this work are decomposed into 12 scales through discrete wavelet transform. Figure 5 presents the effects of solids flux on the wavelet flatness factor variation with the frequency and height. For the sake of clarify, the variation profiles are divided into two groups, namely, the lower and higher parts of the riser, respectively. In addition, the results at higher than 125 Hz are excluded as the corresponding signal components are of fairly small amplitude and may contain numerical errors. It is shown in Figure 5 that the variation tendencies of wavelet flatness factor with the frequency are similar for all the heights under investigation. The wavelet flatness factors are around 3 at the frequencies lower than 3 Hz, indicating weak flow intermittency. According to the cascade theory of turbulence energy [1, 39], such frequency scope belongs to the energy-containing range and inertial range, where the temporal and spatial distributions of the low-frequency fluctuation are relatively uniform owing to their longer periods. At the frequencies higher than 3 Hz is the dissipation range, in which the wavelet flatness factor increases first slowly and then rapidly with the frequency. The flow intermittency in this range is significantly enhanced since the flow energy transport from low frequencies (large scales) to high frequencies (small scales) results in the formation of small-scale structures with heterogeneity. Moreover, the energy distribution at small scales is less uniform due to the impacts of the quasi-ordered motion of coherent structures [39]. In the riser, such motion refers to the intermittent formation, disintegration and falling of particle clusters, as well as the rotation of particle vortices. It is also shown that the wavelet flatness factors at higher than 50 Hz are much larger than the rest. Therefore, they are used as a main indication of the flow intermittency in the whole spectrum. Based on this concept, the flow intermittency is found to be strengthened with the solids flux at all the heights under investigation, as shown in Figure 5. This is because the overall solids holdup in the riser is increased with the solids flux, leading to the formation of a core-annulus flow pattern and more particle clusters flowing along the wall. A consistent conclusion was also derived from the variation of intermittency index in Figure 3. In the meanwhile, more particle vortices are induced near the wall owing to the increased flow heterogeneity and velocity gradients, and their influence on the flow intermittency is also reflected from the wavelet flatness factor variation. In addition, no direct relationship between the wavelet flatness factor and height is exhibited, probably due to the complex effects of various flow behaviours on the axial distribution of flow intermittency.

Figure 6 shows the effects of superficial gas velocity on the wavelet flatness factor variation with the frequency and height. The energy-containing range, inertial range and dissipation range are also clearly identified, with a similar frequency division as that in Figure 5. When the superficial gas velocity increases to 2.10 m/s, the overall solids holdup is correspondingly decreased. Particles are thus prone to be conveyed upward in a more dilute flow pattern, and the formation of particle clusters is weakened. Besides, the intensity of particle vortices is reduced due to the less heterogeneity of the flow field. Therefore, the flow intermittency, mainly indicated by the wavelet flatness factors at higher than 50 Hz, is significantly weakened with the superficial gas velocity, as shown in Figure 6. A consistent conclusion was also obtained from Figure 3.

4.4. Power spectra of solids volume fraction fluctuation

Spectral analysis yields valuable information in the frequency domain about the dynamic behaviours in a fluidised bed. The most commonly used spectral analysis is the power spectrum of pressure fluctuation. Johnson et al. [40] and Zarghami et al. [41] found that the low-frequency range (up to 4 Hz) in a pressure power spectrum was related to some macro-structures in the beds, while the ranges of 4-10 Hz and 20-200 Hz corresponded to the meso-structures and micro-structures, respectively. Aghabararnejad et al. [42] also identified the three ranges in a log-log pressure spectrum, with the two fall-off ranges at higher frequencies linearly fitted with different slopes. However, the pressure spectra are dominantly determined by bubble behaviours while contain limited information about solids motion in a fluidised bed. In this work, the power spectra of solids volume fraction fluctuation were derived to indicate some hydrodynamic properties related to the solids flow in the riser. Figure 7 shows typical power spectra in the bed centre under different conditions. To eliminate high-frequency numerical errors, the original simulated signals were resampled to 250 Hz in prior to further analysis. Figure 7 exhibits that despite the strong fluctuation of the frequency components, three segments are still identified in each spectrum curve, as separated by the two green lines. The low-frequency fluctuation (<1 Hz) with large magnitude is in the energy-containing range, followed by the inertial range between 1 Hz and 3 Hz, in which the flow energy is transported from low to high frequencies [1]. A more rapid decay of the spectrum curve with the frequency is exhibited at higher than 3 Hz, which can be regarded as the dissipation range. Such division of the frequency range is consistent with that based on the wavelet flatness factor distribution, as stated in Section 4.3. A similar conclusion was also drawn from the power spectra of solids fluctuating energy (abbreviated as solids energy spectra) in our previous work [19].

Although the power spectra under different conditions in Figure 7 have similar trends, the flow information embedded in them is different from each other. It was already revealed that the Levy-Kolmogorov law was obeyed in the inertial range of a solids energy spectrum, with the corresponding decay index (slope) representing the flow intermittency [19]. In this work, we applied this analysis method to the spectrum curves in Figure 7, with an aim to identify the flow intermittency from similar 'decay indices'. Table 2 lists the decay indices of the power spectra in the bed centre under different conditions. For all the heights under investigation, the decay index decreases with the solids flux and increases with the superficial gas velocity. According to the Levy-Kolmogorov law, the decay index for turbulence flow is an indication of flow intermittency and varies between -3 and -5/3 [14, 19]. As the Reynolds number decreases or the flow heterogeneity increases, the decay index decreases towards -3, representing stronger intermittency, and vice versa. While in this work, based on the variation of flow intermittency with the operation conditions stated above (Section 4.2 and 4.3), similar relationship between the decay indices in Table 2 and the flow intermittency is found, namely, the smaller the decay index, the stronger the flow intermittency. However, the range of decay indices presented in Table 2 is not strictly between -3 to -5/3, as the distributions of frequency components in the solids volume fraction spectra and solids energy spectra may be different. The unusual small decay index at h=9.0 m, U_g=1.52 m/s and G_s=14.3 kg/(m^2·s) may be attributed to the extremely complex influence of flow structure behaviours on the intermittency in the chaotic gas-solid flow field.

Table 2. Decay indices of the power spectra under different conditions (*R*=0 mm)

Height /m	U_g=1.52 m/s, G_s=14.3 kg/(m^2·s)	U_g=1.52 m/s, G_s=26.9 kg/(m^2·s)	U_g=2.10 m/s, G_s=24.1 kg/(m^2·s)
3.0	-0.46	-0.93	-0.59
6.0	-0.91	-1.77	-1.36
9.0	-2.25	-1.01	-0.86

Figure 8 further presents typical power spectra near the wall under different conditions, with the decay indices listed in Table 3. Similar variation tendencies are exhibited as those shown in Figure 7 and Table 2.

Table 3. Decay indices of the power spectra under different conditions (*R*=35 mm)

Height /m	U_g=1.52 m/s, G_s=14.3 kg/(m^2·s)	U_g=1.52 m/s, G_s=26.9 kg/(m^2·s)	U_g=2.10 m/s, G_s=24.1 kg/(m^2·s)
3.0	-0.98	-1.90	-1.08
6.0	-0.84	-0.98	-0.50
9.0	-1.18	-2.11	-1.15

4.5. PDF of wavelet coefficients

It is known that the singularities in fluctuating signals are reflected in the wide tails of the PDF of wavelet coefficients derived from these signals [15, 20]. Such wide tails with large negative and positive wavelet coefficients thus represent the events of large and small amplitudes, compared to the mean, which make an important contribution to the statistics and are usually related to flow intermittency [43]. In this Section, the Mexican hat wavelet is adopted as the wavelet basis owing to its suitability for fluctuating signal interpretation and coherent structure analysis [20, 44]. However, this wavelet is only applicable to continuous wavelet transform. It is noteworthy that the relationship between the decomposition scale of the continuous wavelet transform (r_{con}) and that of the discrete wavelet transform (r_{dis}) is $r_{con}=2^{r_{dis}}$. Due to the high computational cost of continuous wavelet transform with a high decomposition scale, r_{con}=256 is used for the decomposition of the simulated solids axial fluctuating velocity signals, based on which the PDF of wavelet coefficients at each scale is computed. Figure 9 shows the PDF of wavelet coefficients at the wavelet scales of 32, 64, 128, and 256, employing U_g=1.52 m/s and G_s=14.3 kg/(m^2·s). With the increase of scale, the PDF becomes ‘wider and shorter’, indicating that the occurrence probability of the small wavelet coefficients (e.g. 0~1.5) decreases while that of the large wavelet coefficients (e.g. 8.0~20.0) correspondingly increases. This is owing to the higher flow energy carried by the lower-frequency fluctuations. Besides, significant non-smooth and asymmetry wide tails are exhibited in Figure 9, especially at the scales 128 and 256, which are related to the complex effects of the quasi-ordered coherent structure behaviours on flow intermittency, as the Mexican hat wavelet acts as a 'probe' for the detection of coherent structures in the fluctuating signals. Compared Figure 9(a) to Figure 9(b), with the increase of radial distance, the wide tails are broadened and the largest negative and positive wavelet coefficients in the wide tails markedly increase. In addition, the probability of wide tails also increases. This indicates that the flow intermittency and coherent structure effects are stronger near the wall than those in the bed centre, agreeing well with the results from the intermittency index variation shown in Figure 3.

Apart from the intermittency index, it is possible to relate the PDF of wavelet coefficients with turbulent granular temperature, a hydrodynamic parameter derived from the simulated solids fluctuating velocity signals and strongly dependent on the motion of particle clusters/bubbles [45]. The turbulent granular temperature is computed from,

$$\theta_{turbulent} = \frac{1}{3}\overline{v_y^{'} v_y^{'}} + \frac{1}{3}\overline{v_x^{'} v_x^{'}} + \frac{1}{3}\overline{v_z^{'} v_z^{'}} \tag{18}$$

where $v_y^{'}$, $v_x^{'}$ and $v_z^{'}$ represent the solids fluctuating velocities in the axial direction and two radial directions, respectively. As the axial fluctuating velocity $v_y^{'}$ is much higher than the other two velocities, Eq.(18) is simplified as,

$$\theta_{turbulent} = \frac{1}{3}\overline{v_y^{'} v_y^{'}} + \frac{2}{3}\overline{v_x^{'} v_x^{'}} \tag{19}$$

Figure 10 shows the axial profiles of turbulent granular temperature at different radial positions, employing U_g=1.52 m/s and G_s=14.3 kg/(m^2·s). The turbulent granular temperature in the bed centre basically remains unchanged, while that near the wall is significantly higher and decreases with the height. This is attributed to the stronger motion of particle clusters near the wall and also related to the variation of the PDF of wavelet coefficients as shown in Figure 9.

Figure 11 shows the effects of solids flux on the PDF of wavelet coefficients near the wall at different heights. Since the coherent structure behaviours are mainly reflected at larger scales, the results at the scales of 64, 128, and 256 were adopted for analysis. Figure 11(a) shows that the wide tails at r=64 and r=128 with G_s=26.9 kg/(m^2·s) basically cover those with G_s=14.3 kg/(m^2·s), while the two wide tails at r=256 intersect each other. As the flow intermittency and coherent structure motion were already proven to be stronger at the higher solids flux, it is deduced that the influence of coherent structure behaviours on the flow intermittency is a compromised result from different scales (frequencies). In Figure 11(b) the wide tails at all the scales with G_s=26.9 kg/(m^2·s) basically cover those with G_s=14.3 kg/(m^2·s), showing increased probability with the solids flux.

Figure 12 presents the effects of superficial gas velocity on the PDF of wavelet coefficients near the wall. At h=3.0 m, the two wide tails with U_g=1.52 m/s and U_g=2.10 m/s intersect each other at all the scales, similar to those in Figure 11(a). While at h=9.0 m, the probability of the wide tails at all the scales basically decreases with the superficial gas velocity, indicating decreased flow intermittency due to the weakened formation and motion of coherent structures. This conclusion is also consistent with the analysed results obtained above.

4.6. PDF of solids volume fraction

In addition to the PDF of wavelet coefficients derived from the solids fluctuating velocity signals, the PDF of local solids volume fraction provides useful information about the flow pattern and flow structures in a riser [2]. Figure 13 shows the PDF of solids volume fraction at h=3.0 m, U_g=1.52 m/s and G_s=26.9 kg/(m^2·s). In the bed centre, two peaks are exhibited at the low solids volume fraction and the probability density decreases with the solids volume fraction, indicating the dominant influence of dilute flow in this region. While near the wall, the PDF curve becomes more diverse with a wider span. A narrow peak is identified at the low solids volume fraction, along with the wide tails with higher solids volume fraction and probability than those in the bed centre. This is primarily attributed to the coexistence of particle clusters and dispersed particle flow near the wall. Although the probability density representing particle clusters is relatively low, the role of particle clusters on the flow field properties is very important.

Figure 14 shows the PDF of solids volume fraction near the wall under different conditions. At h=3.0 m, the increase of solids flux to 26.9 kg/(m^2·s) results in a much wider span of the PDF curve, consistent with the experimental results from Zhang et al. [2]. Besides, the probability density at the low solids volume fraction decreases while that at the high solids volume fraction increases, with a small peak even appearing around the solids volume fraction of 0.52. This is caused by the increase of solids holdup in the bed with the solids flux, as well as the enhanced formation and motion of particle clusters. When the superficial gas velocity is increased to 2.10 m/s, the PDF curve is significantly narrowed with a sharp peak clearly identified at the low solids volume fraction, which implies a much narrower fluctuation range of solids volume fraction than that at U_g=1.52 m/s and G_s=26.9 kg/(m^2·s). This is due to the decrease of solids holdup and the weakened formation and motion of particle clusters. Compared Figure 14(a) to Figure 14(b), the PDF curves under the same operation condition exhibit similar trends, indicating consistent influence of the operation conditions on solids volume fraction at different heights. Moreover, the maximum solids volume fractions at U_g=1.52 m/s, G_s=26.9 kg/(m^2·s) and at U_g=2.10 m/s, G_s=24.1 kg/(m^2·s) both decrease with the height owing to the coexistence of a dense region at lower locations and a dilute region at higher locations. However, the maximum solids volume fraction at U_g=1.52 m/s, G_s=14.3 kg/(m^2·s) basically remains unchanged with the height, indicating a more uniform axial distribution of solids holdup under this condition.

5. Conclusions

The flow intermittency and coherent structure behaviours in a riser with Geldart A particles have been characterised through the EMMS-based CFD simulation and fluctuating signal analysis. The foremost important conclusion drawn from this work is that the flow intermittency, determined by the flow field heterogeneity and coherent structure motion, is significantly dependent on the radial locations in the riser and the operation conditions. In addition, the particle clusters and particle vortices are found to be coherent structures in the riser. Specifically, the intermittency index generally increases with the radial distance and solids flux, and decreases with the superficial gas velocity. According to the wavelet flatness factor distribution with frequency, the flow field in the riser is divided into the energy-containing range, inertial range and dissipation range. The wavelet flatness factors at higher than 50 Hz, representing the flow intermittency in the whole spectrum, increase with the solids flux and decrease with the superficial gas velocity. Three segments are also identified in each power spectrum of solids volume fraction fluctuation, which is consistent well with the division of frequency range based on the wavelet flatness factor distribution. The decay index obtained from the inertial range is found to be related to flow intermittency, namely, the smaller the decay index, the stronger the flow intermittency. The significant non-smooth and asymmetry wide tails of the PDF of wavelet coefficients, derived from the solids fluctuating velocity signals, indicate the complex effects of the quasi-ordered coherent structures on the flow intermittency. Broadened wide tails are observed near the wall owing to the stronger motion of coherent structures compared to that in the central region, which is also related to the distribution of turbulent granular temperature. The comparison of PDF of wavelet coefficients under different conditions has revealed that the influence of coherent structure behaviours on the flow intermittency is a compromised result from different scales. Moreover, the PDF of solids volume fraction, which indicates the flow pattern and flow structure behaviours in the riser, is significantly broadened with the solids flux and narrowed with the superficial gas velocity. The results presented in this paper have demonstrated that the EMMS-based CFD simulation in combination with fluctuating signal analysis provide an in-depth understanding of the flow intermittency and coherent structure characteristics in a riser with Geldart A particles. It is envisaged that such in-depth knowledge will lead to optimised design, scale up and operation of CFBs.

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FIGURE CAPTIONS

Figure 1. Schematic configuration of the simulated riser

Figure 2. Simulated and experimental axial voidage profiles (U_g=1.52 m/s, G_s=14.3 kg/(m^2·s))

Figure 3. Axial profiles of intermittency index in the bed centre (R=0 mm) and near the wall (R=35 mm) under different conditions (a) U_g=1.52 m/s, G_s=14.3 kg/(m^2·s), (b) U_g=1.52 m/s, G_s=26.9 kg/(m^2·s), (c) U_g=2.10 m/s, G_s=24.1 kg/(m^2·s)

Figure 4. Simulated contours of instantaneous solids volume fraction and solids velocity vector (U_g=1.52 m/s, G_s=14.3 kg/(m^2·s), t=30 s, not to scale)

Figure 5. Effects of solids flux on the wavelet flatness factors near the wall (R=35 mm) (a) In the lower part of the riser, (b) In the higher part of the riser

Figure 6. Effects of superficial gas velocity on the wavelet flatness factors near the wall (R=35 mm) (a) In the lower part of the riser, (b) In the higher part of the riser

Figure 7. Power spectra of solids volume fraction fluctuation in the bed centre under different conditions (R=0 mm, h=3.0 m)

Figure 8. Power spectra of solids volume fraction fluctuation near the wall under different conditions (R=35 mm, h=3.0 m)

Figure 9. PDF of wavelet coefficients at different wavelet scales and radial positions (h=3.0 m, U_g=1.52 m/s, G_s=14.3 kg/(m^2·s)) (a) In the bed centre, R=0 mm, (b) Near the wall, R=35 mm

Figure 10. Axial profiles of turbulent granular temperature at different radial positions (U_g=1.52 m/s, G_s=14.3 kg/(m^2·s))

Figure 11. Effects of solids flux on the PDF of wavelet coefficients near the wall (R=35 mm) (a) h=3.0 m, (b) h=9.0 m

Figure 12. Effects of superficial gas velocity on the PDF of wavelet coefficients near the wall (*R*=35 mm) (a) *h*=3.0 m, (b) *h*=9.0 m

Figure 13. PDF of solids volume fraction at different radial positions (*h*=3.0 m, U_g=1.52 m/s, G_s=26.9 kg/(m^2·s))

Figure 14. PDF of solids volume fraction near the wall under different conditions (*R*=35 m) (a) *h*=3.0 m, (b) *h*=9.0 m