Characterisation of Flow Intermittency and Coherent Structures in a Gas-Solid Circulating Fluidised Bed through Electrostatic Sensing

Jingyuan Sun[*,†], Yong Yan[†]

[†]School of Engineering and Digital Arts, University of Kent, Canterbury, Kent CT2 7NT, U.K.

ABSTRACT

Flow intermittency and coherent structures are important hydrodynamic phenomena in a gas-solid circulating fluidised bed (CFB). In this work, an electrostatic measurement system based on arc-shaped sensing electrodes is designed and implemented on a CFB test rig. Cross correlation, statistical analysis, wavelet transform and probability density function (PDF) are applied to the electrostatic signal processing, providing a comprehensive description of the solids velocity, solids holdup, flow intermittency and coherent structure behaviours. A conditional sampling method is used to extract the coherent structure signals from the electrostatic signals. By comparing the extended self-similarity (ESS) scaling law curves before and after the extraction, the effects of coherent structures on the flow intermittency are further confirmed. Experimental results have demonstrated that the electrostatic signals contain important information about the intermittent hydrodynamic behaviours in a CFB, and the analysis of electrostatic signals through appropriate methods results in an in-depth understanding of the fluidisation process.

1. INTRODUCTION

Gas-solid circulating fluidised beds (CFBs) enable the particle handling and chemical reaction proceeding in various flow regimes, such as turbulent fluidisation, fast fluidisation and dilute transport. Owing to the versatility, high gas-solid contact efficiency and excellent heat and mass transfer capability, CFBs are extensively employed in industrial processes such as fluid catalytic cracking, coal gasification, Fischer-Tropsch synthesis, propylene polymerization and acrylonitrile production[1]. In spite of the widespread applications, we still have limited understanding of the hydrodynamic characteristics of CFBs, which limits the design and operation optimization of the industrial installations[2]. The main reason for this underdevelopment is that the chaotic solids motion, diverse flow structures and multiscale interactions in a CFB are difficult to be comprehensively described. Moreover, such complex flow behaviours yield an important hydrodynamic property named the flow intermittency, which refers to the intermittent occurrence of large-magnitude fluctuations reflected in the flow signals[3]. The flow intermittency is caused by the intermittent nature of local solids flow and the presence of coherent flow structures[4-7], and is closely related to the non-uniform distribution of hydrodynamic parameters and the non-equilibrium flow state. Therefore, it is of significant importance to achieve an in-depth understanding of the flow intermittency and coherent structures for the fluidisation quality improvement and operation optimization.

The intermittent phenomena in CFBs were originally characterised by the intermittency index. It was derived from the solids holdup fluctuation data and used to indicate the non-uniformity of the flow field[8]. The higher the index value, the more flow structures (e.g. particle agglomerates, particle clusters) existing at the given location[5, 6, 9]. However, this index only provides a rough quantification and is in fact insufficient to describe the complex intermittent flow behaviours in a CFB. If referring to single-phase turbulence, the flow intermittency was indicated by the deviation of the Kolmogorov -5/3 scaling law in the energy spectrum[10, 11]. Furthermore, the intermittency distribution and the behaviours of coherent flow structures were characterised through the wavelet transform and auto-correlation of fluctuating velocity signals[12-15]. Based on the similarities between the single-phase flow and gas-solid fluidisation, the flow intermittency and coherent structures in a bubbling fluidised bed were studied for the first time in our previous work[16, 17]. The computational fluid dynamics (CFD) simulation was used to obtain solids fluctuating velocity signals for analysis. It was found that the flow intermittency increased with the radial distance and height, and the coherent structures were mainly presented in the form of particle vortices. Although this work provides a potential way to characterise the intermittent flow behaviours in a CFB from a new perspective, there’re still two important issues that need to be addressed. Firstly, the flow field in a CFB is more complex than that in a bubbling bed, such as the fiercer gas-solids flow, full-loop solids circulation, coexistence of different flow regimes (e.g. dense-phase regime at the bottom of the riser, dilute pneumatic conveying regime in the upper part of the riser, moving-bed regime in the downer) 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 more difficult for accurate description and require special characterisation. Secondly, very limited experimentation has been conducted to characterise the intermittent hydrodynamic behaviours in a CFB, which limits the application of the characterisation methodology still in simulation results. A suitable measurement approach is thus required to obtain fluctuating signals related to the solids motion for intermittency analysis.

Electrostatic induction sensors are increasingly used to probe the flow hydrodynamics in gas-solid fluidised beds by sensing the fluctuations of electrostatic fields generated by particles collision and friction[18-21]. As these sensors are highly sensitive to moving particles and immune to net charge accumulation and particles accretion effects, rich information about the solids motion is encoded in the electrostatic fluctuating signals. Therefore, the electrostatic measurement is especially suitable for characterising the flow intermittency and coherent structure behaviours in a fluidised bed. However until now, most work employing the electrostatic induction sensors on fluidised beds still focused on the measurement of solids velocity and charge level[18-21]. Little work has been carried out for intermittency characterisation through the analysis of the electrostatic fluctuating signals. For instance, Zhang et al.[18] measured the solids velocity in a triple-bed combined CFB using ring- and arc-shaped electrostatic sensors in combination with electrical capacitance tomography. Similar measurement approach was then applied on a bubbling bed[19]. Dong et al.[20] employed electrostatic sensor arrays to monitor the charge level of the fluidised particles. Yang et al.[21] studied the influence of agglomerates on the electrostatic potential fluctuation measured by the electrostatic sensor arrays. In this study, in consideration of the aforementioned two important issues and the advantages of electrostatic induction sensors, an electrostatic measurement system is designed and applied on a CFB test rig to acquire the electrostatic signals. Wavelet transform, probability density function and ESS scaling law are applied for the first time to the electrostatic signal processing, in order to provide a comprehensive description of the flow intermittency and coherent structure behaviours in the CFB. The localized solids velocity and relative solids holdup are also obtained through cross correlation and statistical analysis.

2. EXPERIMENTAL SETUP

Experiments were carried out on a gas-solid CFB test rig as shown in Figure 1. It consists of a riser with an inner diameter of 0.1 m and a height of 2.1 m, a cyclone separator, a downer and a butterfly valve. The entire system is made of transparent Plexiglas except for two PVC-bend connections. A perforated-plate distributor with a pore diameter of 3.0 mm and an opening ratio of 10% is installed at the bottom the riser. Amino plastic particles (Martyn's Bargains Ltd, UK, Geldart B group) with an average diameter of 0.505 mm and density of 1500 kg/m^3 were used as bed materials in this research. Compressed air is introduced into the riser through a pressure regulator, a diaphragm valve and a flowmeter. The gas flow rate is measured by the flowmeter and adjusted through the diaphragm valve. The superficial gas velocity (U_g) varies between 3.9 m/s and 5.1 m/s. In the riser, particles are carried upward by air and exit at the top through a right-angled bend into the cyclone, where those particles are separated from air. Subsequently, the particles drop into the downer and are fed back to the bottom of the riser through the butterfly valve. The solids flux (G_s) is controlled by adjusting the butterfly valve opening and varies between 4.0 kg/(m^2·s) and 19.4 kg/(m^2·s). G_s is determined through measuring the bed height increase in the downer after closing the butterfly valve. Initially, particles were packed in the downer with a static bed height of 1.13 m and a solids volume fraction of 0.51. Experiments were conducted at 21 ℃ and atmospheric pressure. The air density and viscosity during the experiments were 1.225 kg/m^3 and 1.81×10^{-5} Pa·s, respectively.

Figure 1 also shows two electrostatic sensor arrays mounted flush to the inner pipe wall of the riser. Each of them consists of two identical non-intrusive arc-shaped electrodes. The axial width of each electrode is 5 mm, with a central angle of 70°. The centre-to-centre spacing between the two adjacent electrodes in each array is 20 mm. The very weak signal from the electrode is converted into a voltage signal and pre-amplified to a certain level before being further amplified through an adjustable amplifier. A low-pass filter with a cut-off frequency of 10 kHz is used to eliminate high-frequency noise. Before data acquisition, the particles were fluidised at a certain superficial gas velocity for 20 min to ensure that they were charged to a steady level. The electrostatic signals were sampled at a frequency of 25 kHz with a duration of 120 s. To further remove high-frequency noise from the signals, a digital low-pass filter with a cut-off frequency of 2 kHz was applied and a wavelet de-noising technique based on Daubechies5[22] was also adopted for signal decomposition and reconstruction.

3. MEASUREMENT PRINCIPLES OF ELECTROSTATIC SENSORS

The basic measurement principles of electrostatic sensors have been well published in the literature[23-27] and are only included here for the convenience of the reader. When particles pass through a pair of identical parallel electrodes in a sensor array, the upstream and downstream signals should be similar, although the gas-solid flow in the CFB is highly chaotic. Figure 2 shows typical voltage signals from the upper sensor array under U_g=4.5 m/s, G_s=19.4 kg/(m^2·s). Here the ‘upstream’ and ‘downstream’ electrodes refer to the lower and upper ones, respectively. High similarity exists between the two signals in Figure 2, indicating that within the short distance between the upstream and downstream electrodes, the solids velocity and concentration only change slightly. Cross correlation is thus applicable to the solids velocity measurement from the electrostatic signals.

The correlation velocity is calculated from,

$$v_c = \frac{L}{\tau} \tag{1}$$

where L is the centre-to-centre spacing between the upstream and downstream electrodes in a sensor array, τ the time delay between the two signals. The normalized cross-correlation function between the two signals x_i and y_i (i=1, 2, …, N) is expressed as,

$$R_{xy}(m)=\frac{\sum_{i=1}^{N}\left(x_i-\bar{x}\right)\left(y_{i+m}-\bar{y}\right)}{\sqrt{\sum_{i=1}^{N}\left(x_i-\bar{x}\right)^2}\sqrt{\sum_{i=1}^{N}\left(y_{i+m}-\bar{y}\right)^2}} \tag{2}$$

where N is the number of samples in the correlation computation, m (m=0, 1, 2, …, N) the number of delayed points, $\bar{x}$ and $\bar{y}$ the mean values of the two signals, respectively. The location of the dominant peak in the correlation function indicates the time delay τ, and the dominant peak is regarded as the correlation coefficient, as shown in Figure 3. The correlation coefficient mainly depends on the similarity of the two signals rather than the signal amplitude. In this work, the correlation computation for each pair of electrodes employed 8192 samples from both the upstream and downstream signals during each data processing cycle. A total of 254 solids velocity and correlation coefficient readings were taken for each operation condition.

Although an arc-shaped electrode is more sensitive to the solids motion in its vicinity, it is still applicable to characterising the relative solids holdup in the cross-sectional area occupied by moving particles in a vertical pipe[23-26]. The charges on moving particles rely on particle properties (e.g. particle species, size, shape, velocity and moisture content) and experimental conditions (e.g. geometry of the test rig, wall roughness and temperature). When these factors are kept relatively constant, the magnitude of an electrostatic signal is mainly determined by solids holdup. Therefore, the root-mean-square (RMS) charge level A_{rms} is used to indicate the relative solids holdup in the riser[25]:

$$A_{rms}=\sqrt{\frac{1}{M}\sum_{i=1}^{M}x_i^2} \tag{3}$$

where x_i (i=1, 2, …, M) is the electrostatic signal and M the total number of the samples collected. It is noteworthy that this method cannot offer the exact value of solids holdup.

4. RESULTS AND DISCUSSION

4.1. SOLIDS VELOCITY AND CONCENTRATION

Figure 4 shows the variations of the solids velocities near the wall with time under typical operation conditions. The solids velocity fluctuates significantly around the average, reflecting the chaotic nature of the CFB and the dynamic stable state of the gas-solid flow.

Table 1 lists the time-averaged solids velocities near the wall, showing that particles are accelerated upward with the height, due to the significant difference between the gas and solids velocities at the riser bottom. In addition, the average solids velocities at h=570 mm and h=1860 mm both decrease with the solids flux and increase with the superficial gas velocity. The negative velocities at U_g=4.5 m/s and G_s=19.4 kg/(m^2·s) indicate the existence of a core-annulus flow pattern, in which particles are conveyed upward in the core dilute region while flow downward in the wall dense region. Table 2 lists the time-averaged correlation coefficients, all of which are greater than 0.55 and represent strong correlation between the upstream and downstream electrostatic signals. Particularly, the passage of particle clusters through a pair of electrodes always gives rise to highly similar upstream and downstream electrostatic signals, as the velocity and shape of particle clusters are relatively unchanged within a short distance. Therefore, the correlation coefficients are the highest at U_g=4.5 m/s and G_s=19.4 kg/(m^2·s), under which particle clusters dominate the solids flow near the wall.

Table 1 Time-averaged solids velocities near the wall under typical operation conditions

Operation conditions	U_g=4.5 m/s, G_s=7.4 kg/(m^2·s)	U_g=4.5 m/s, G_s=19.4 kg/(m^2·s)	U_g=5.1 m/s, G_s=19.0 kg/(m^2·s)
h=570 mm	1.26 m/s	-0.94 m/s	1.07 m/s
h=1860 mm	1.32 m/s	-0.62 m/s	1.33 m/s

Table 2 Time-averaged correlation coefficients under typical operation conditions

Operation	U_g=4.5 m/s, G_s=7.4	U_g=4.5 m/s, G_s=19.4	U_g=5.1 m/s, G_s=19.0

conditions	kg/(m²·s)	kg/(m²·s)	kg/(m²·s)
h=570 mm	0.55	0.77	0.56
h=1860 mm	0.56	0.76	0.68

Figure 5 shows the axial profiles of the RMS charge level of the electrostatic signals (A_{rms}) under more operation conditions. The relative solids holdup basically decreases with the height, except for that at U_{g}=4.5 m/s, G_{s}=7.4 kg/(m^2·s) and U_{g}=5.1 m/s, G_{s}=7.4 kg/(m^2·s). This may be attributed to the strong solids mixing and relatively uniform distribution of the solids suspension in the axial direction under these conditions. Moreover, at both U_{g}=4.5 m/s and U_{g}=5.1 m/s, A_{rms} significantly increases with the solids flux, showing a consistent variation tendency with the solids holdup measured through an optical fibre probe[28]. However, when G_{s} is kept unchanged no monotonous tendency is exhibited in the variations of A_{rms} with the superficial gas velocity, due to the opposite effects of the simultaneously changed solids holdup and velocity on A_{rms}.

Apart from A_{rms}, the variation tendencies of solids holdup can be predicted through empirical correlations. Due to the non-uniform solids axial distribution in the riser, the solids holdup in the lower denser part, ε_{d}, is used as an indicator of the overall solids holdup in the riser. When G_{s} is lower than the critical solids flux, G_s^*, ε_{d} increases with G_{s} and decreases with U_{g}. While when G_{s} is higher than G_s^*, ε_{d} is independent on G_{s}[29]. G_s^* is calculated from[30],

$$\frac{G_s^* d}{\mu_g} = 0.125 Fr^{1.85} Ar^{0.63} \left(\frac{\rho_s - \rho_g}{\rho_g} \right)^{-0.44} \tag{4}$$

$$Fr = \frac{U_g}{\left(gd\right)^{0.5}} \tag{5}$$

$$Ar = \frac{d^3 \rho_g g \left(\rho_s - \rho_g\right)}{\mu_g^2} \tag{6}$$

where d is the particle diameter, μ_g the gas viscosity, Fr the Froude number,

Ar the Archimedes number, ρ_s the particle density, ρ_g the gas density, g the gravitational acceleration. Therefore, for U_g =3.9 m/s, 4.5 m/s and 5.1 m/s, G_s^* is 87.9 kg/(m^2·s), 114.5 kg/(m^2·s) and 144.4 kg/(m^2·s), respectively. All the G_s employed in the present work is lower than the corresponding G_s^*. Therefore, the overall solids holdup always increases with the solids flux and decreases with the superficial gas velocity.

4.2. WAVELET FLATNESS FACTORS AND FLOW INTERMITTENCY

A CFB is a typical complex system composed of multiscale flow structures and showing both irregular and non-random characteristics. As stated above, the flow intermittency, referring to the intermittent occurrence of large-magnitude fluctuations, is primarily determined by the presence of coherent structures[10]. In single-phase turbulence, coherent structures are defined as the connected, large-scale turbulent fluid mass with phase-correlated vorticities and containing high flow energy[31]. They were also found to exhibit symmetric, periodic and apparent flapping motion[15]. Similarly in a riser, it is known that the flow intermittency is strongly dependent on the presence of particle clusters[5, 6, 9], which should thus be regarded as coherent structures. In addition, particle vortices are classified as typical coherent structures in a bubbling fluidised bed, as they are generated by velocity gradients and wall shear, carrying flow energy and heterogeneity[17]. Owing to the frequent appearance of particle vortices in the chaotic flow field in a riser[32], it is logical to classify the particle vortices as coherent structures as well. The flow intermittency and effects of coherent structures can be characterised by analysing the fluctuating flow signals through wavelet transform in combination flatness factors[16]. Since electrostatic signals contain much information about the solids flow in a CFB, they are employed for the intermittency characterisation in this work. Moreover, owing to the differencing characteristics, the Daubechies 1 wavelet (Haar wavelet) is commonly used for identifying the ‘events’ that produce sudden variations of the flow field and the presence of intermittency[33-36]. Therefore, the electrostatic signals collected were firstly resampled to 200 Hz and then decomposed into 14 scales based on Daubechies1.

The flatness factor of wavelet coefficients (abbreviated as wavelet flatness factor hereinafter) at each scale was computed from,

$$FF(r)=\frac{\left\langle \left(w^{(r)}(t)\right)^{4}\right\rangle}{\left\langle \left(w^{(r)}(t)\right)^{2}\right\rangle^{2}} \tag{7}$$

$$\left\langle \left(w^{(r)}(t)\right)^{2}\right\rangle=\int_{-\infty}^{\infty}\left(w^{(r)}(t)\right)^{2} p\left(w^{(r)}(t)\right) d\left(w^{(r)}(t)\right) \tag{8}$$

$$\left\langle \left(w^{(r)}(t)\right)^{4}\right\rangle=\int_{-\infty}^{\infty}\left(w^{(r)}(t)\right)^{4} p\left(w^{(r)}(t)\right) d\left(w^{(r)}(t)\right) \tag{9}$$

where r represents the scale, $w^{(r)}(t)$ 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.

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

$FF(r)$<3 for strong periodicity of the signal,

$FF(r)$>3 for strong flow intermittency caused by coherent structures,

Figure 6 shows the variations of wavelet flatness factor with the frequency and height under U_g=4.5 m/s, G_s=19.4 kg/(m^2·s). Similar tendencies are exhibited at all the heights under investigation. The wavelet flatness factors are around 3 at the frequencies lower than 2 Hz, indicating weak flow intermittency. Based on the cascade theory of turbulent energy[3, 37], such frequency scope belongs to the energy-containing range and inertial range, in which the temporal and spatial distributions of low-frequency fluctuations are relatively uniform owing to their longer periods. From 2 Hz to 150 Hz is the dissipation range, where the wavelet flatness factor first slowly and then rapidly increases with the frequency, along with more significant differences among the profiles at different heights. It is known that when the flow energy is transported from low frequencies (large scales) to high frequencies (small scales), some small-scale flow structures with heterogeneity are generated. Moreover, the energy distribution at small scales becomes less uniform due to the impacts of the quasi-ordered motion of coherent structures[37]. Such motion in the riser mainly refers to the intermittent formation, disintegration and fluctuation of particle clusters, as well as the rotation of particle vortices. Based on these reasons, the flow intermittency is significantly enhanced in the dissipation range. In addition, the wavelet flatness factors in the dissipation range basically increase with the height, representing increased flow intermittency at the higher positions. This is because the higher suspension density at the riser bottom homogenizes particle clusters near the wall and restricts their fluctuation motion to some extent, while the diluter flow condition in the upper part of the riser leads to more significant fluctuation of particle clusters. The two profiles at h=560 mm and 580 mm, as well as those at h=1850 mm and 1870 mm, are close to each other, since the particle cluster motion are highly similar within such a short distance (stated in Section 4.1). Figure 6 also shows that the flow intermittency is mainly exhibited in the dissipation range. Therefore in the following discussion, the wavelet flatness factors in this range are adopted as an indication of flow intermittency in the whole spectrum.

Figure 7 shows the variations of wavelet flatness factor with the frequency and solids flux under U_g=4.5 m/s. The heights of 1850 mm and 1870 mm are focussed on owing to the more significant flow intermittency in the upper part of the riser, as stated above. The wavelet flatness factors under G_s=4.0 kg/(m^2·s) and G_s=7.4 kg/(m^2·s) are relatively low and close to each other, as particles in the riser are mainly conveyed upward at the low solids fluxes and less flow structures and heterogeneity exist in the flow field. However, the sudden increase in the wavelet flatness factors in 2~10 Hz under G_s=7.4 kg/(m^2·s) may still be caused by some intermittent solids behaviours in the upper part of the riser. With the solids flux increased to 19.4 kg/(m^2·s), the wavelet flatness factors in the dissipation range significantly increase. As stated in Section 4.1 the overall solids holdup in the riser increases with the solids flux, which leads to the formation of a core-annulus flow pattern and more particle clusters flowing along the wall. The flow intermittency is thus enhanced. The existence of particle clusters is also confirmed by the negative solids velocities as shown in Table 1. 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 variations. Moreover, the wavelet flatness factor distribution under U_g=4.5 m/s, G_s=19.4 kg/(m^2·s) is much steeper than the other two profiles, indicating more sensitive dependence of flow intermittency on the frequency due to the stronger influence of coherent structures on the flow field.

Figure 8 further shows the variations of wavelet flatness factor with the frequency and solids flux under U_g=5.1 m/s. Similar to Figure 7, the wavelet flatness factors gradually increase with the solids flux, especially in the dissipation range, owing to the enhanced formation and motion of coherent structures. In addition, the high wavelet flatness factors in 0.1~0.6 Hz under U_g=5.1 m/s, G_s=7.4 kg/(m^2·s) in Figure 8(a) is attributed to some low-frequency intermittent solids behaviours under this condition.

Figure 9 shows the variations of wavelet flatness factor with the frequency and superficial gas velocity under G_s=7.4 kg/(m^2·s). The wavelet flatness factors in the dissipation range significantly decrease with the superficial gas velocity, mainly due to the decrease of the overall solids holdup as stated in Section 4.1. As the flow patterns under U_g=4.5 m/s, G_s=7.4 kg/(m^2·s) and U_g=5.1 m/s, G_s=7.4 kg/(m^2·s) are close to the pneumatic conveying, particles are prone to be conveyed upward in the riser, leading to the reduction of the formation and motion of particle clusters. In addition, the intensity of particle vortices is reduced due to the less heterogeneity existing in the flow field.

4.3. PDF of WAVELET COEFFICIENTS

Flow intermittency yields an important consequence named the flow singularity, which is reflected in the wide tails of the PDF of wavelet coefficients derived from the fluctuating flow signals[12,17]. 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[38]. In this section, the electrostatic signals were firstly resampled to 2.5 kHz and then decomposed into 256 scales through continuous wavelet transform, based on which the PDF of wavelet coefficients at each scale was computed. The Mexican hat wavelet was chosen as the wavelet basis as it is suitable for the fluctuating signal interpretation and the coherent structure analysis[17, 39]. The relationship between the wavelet scale and frequency is expressed as[40],

$$f_r = \frac{F_c f_s}{r} \tag{10}$$

where f_r is the pseudo-frequency corresponding to the wavelet scale r, F_c the central frequency of the wavelet basis, and f_s the sampling frequency. Figure 10 shows the typical PDF of wavelet coefficients at scales 4, 16, 32, 64, 128 and 256. The frequency range represented by these wavelet scales is 2.4~156.2 Hz, basically consistent with the dissipation range as shown in Figure 6~Figure 9. With the increase of scale, the PDF curve shifts to a 'wider and shorter' shape, indicating that the probability of the small wavelet coefficients decreases while that of the large wavelet coefficients correspondingly increases. This is because most flow energy contained in the electrostatic signals is occupied by low-frequency solids fluctuations. In addition, Figure 10 shows significant non-smooth and asymmetrical wide tails at scales 64, 128 and 256, which are related to the complex effects of the quasi-ordered coherent structure behaviours at the lower frequencies on the flow intermittency at the higher frequencies, as the Mexican hat wavelet acts as a 'probe' for detecting coherent structures from the fluctuating signals. In the following work, we will focus on the scales 32, 64, 128 and 256, at which coherent structures play an important role.

Figure 11 shows the PDF of wavelet coefficients under U_g=4.5 m/s, G_s=7.4 kg/(m^2·s) and U_g=4.5 m/s, G_s=19.4 kg/(m^2·s). At all the heights investigated, the wide tail probability at a certain scale significantly increases with the solids flux, and the non-smoothness and asymmetry of the wide tails are also enhanced. As aforementioned, the formation and motion of coherent structures (particle clusters, particle vortices) are strengthened with the increase of solids flux, resulting in stronger influence on the flow intermittency at smaller scales (higher frequencies). Therefore, more singularities are exhibited in the fluctuating signals. Compared Figure 11(c) and (d) to Figure 11(a) and (b), the PDF curves under G_s=19.4 kg/(m^2·s) show more significant non-smoothness and asymmetry at the higher positions, indicating stronger influence of coherent structures on the flow field in the upper part of the riser. A consistent conclusion was also derived from the variations of wavelet flatness factor in Figure 6. In addition, slight asymmetry is exhibited in the PDF wide tails under G_s=7.4 kg/(m^2·s) in Figure 11(d), which may be related to the sudden increase of wavelet flatness factor under G_s=7.4 kg/(m^2·s) in Figure 7(d).

To further demonstrate the variation tendencies of the PDF curves with the solids flux, Figure 12 compares the PDF of wavelet coefficients under U_g=4.5 m/s, G_s=4.0 kg/(m^2·s) and U_g=4.5 m/s, G_s=7.4 kg/(m^2·s) at h=1850 mm and h=1870 mm, respectively. These two heights are focussed on owing to the stronger influence of coherent structures on the flow field in the upper part of the riser, as stated above. Similar to Figure 11, the wide tail probability at a certain scale increases with the solids flux, despite less significant non-smoothness and asymmetry are shown in the PDF curves in Figure 12.

Figure 13 compares the PDF of wavelet coefficients under U_g=4.5 m/s, G_s=19.4 kg/(m^2·s) and U_g=5.1 m/s, G_s=19.0 kg/(m^2·s). As the solids fluxes under U_g=4.5 m/s and 5.1 m/s are kept basically unchanged, G_s=19.4 kg/(m^2·s) is adopted here for ease of comparison. At all the heights investigated, the wide tail probability at a certain scale significantly decreases with the superficial gas velocity, and the non-smoothness and asymmetry of the wide tails are also weakened. This is due to the reduction of the formation and motion of coherent structures at a higher superficial gas velocity. However, the wide tails and the corresponding asymmetry under U_g=5.1 m/s in Figure 10(c) and (d) are slightly stronger than those in Figure 13(a) and (b), indicating stronger flow intermittency in the upper part of the riser under this condition, which is basically consistent with the variation tendencies of wavelet flatness factors shown in Figure 7.

Figure 14 further compares the PDF of wavelet coefficients under U_g=4.5 m/s, G_s=7.4 kg/(m^2·s) and U_g=5.1 m/s, G_s=7.4 kg/(m^2·s). Similar to Figure 13, the wide tail probability at a certain scale basically decreases with the superficial gas velocity, except for that at r=256 in Figure 14(b). This indicates similar effects of the coherent structures on the flow field at h=1870 mm under the two operation conditions.

4.4. EXTRACTION OF COHERENT STRUCTURE SIGNALS

To further prove the existence of coherent structures and their influence on the flow hydrodynamics in the CFB, the characteristic signals of coherent structures were extracted from the electrostatic signals though a conditional sampling method. The ESS scaling law was then applied to the signals before and after the extraction for the comparison of flow intermittency. The extraction strategy and the ESS scaling law have been elaborated in our previous work and are only briefly introduced here for the sake of clarity[17].

When an energetic coherent structure passes through a certain position, singularity will appear in the electrostatic signal. As a result, the first indicator of the coherent structure is the local intermittency expressed as,

$$I(r,t)=\frac{\left(w^{(r)}(t)\right)^2}{\left\langle\left(w^{(r)}(t)\right)^2\right\rangle} \tag{11}$$

where r represents the scale, $w^{(r)}(t)$ the wavelet coefficient at scale r and time t, and $\langle\ \rangle$ the average over the time. The second indicator is the wavelet flatness factor at each scale ($FF(r)$), as given in Eq.(4). By implementing the following algorithm on the electrostatic signals, the coherent structure signals are extracted and excluded from the original signals:

(1) The electrostatic signals are firstly resampled to 2.5 kHz and then decomposed into 64 scales based on the Mexican hat.

(2) For $FF(r)>3$, a threshold T with an initial value of $12r$ is exerted on $I(r, t)$, and the wavelet coefficients resulting in $I(r, t)>T$ are set to 0.

(3) Recalculate $FF(r)$. If $FF(r)>3$, T is lowered and the above two steps are repeated until $FF(r)$ at all the scales are equal to or less than 3.

The ESS scaling law in the form of wavelet coefficients is expressed as,

$$\left\langle\left|w^{(r)}(t)\right|^p\right\rangle \propto \left\langle\left|w^{(r)}(t)\right|^3\right\rangle^{\zeta(p)} \tag{12}$$

where p is any positive integer and $\zeta(p)$ the scaling index representing the flow intermittency. When no intermittency is exhibited in the signal,

$$\zeta(p)=p/3 \tag{13}$$

Otherwise $\zeta(p)$ will deviate from $p/3$[41]. In this work, p was set to 4 and the wavelet coefficients at the scales 2, 4, 8, 16, 32 and 64 were used to fit the ESS scaling law curves. When the wavelet coefficients at a certain scale all became 0 after the extraction processing, such scale was excluded from the curve fitting. Figure 15 and Figure 16 show the relationships between $\ln\left\langle\left|w^{(r)}(t)\right|^3\right\rangle$ and $\ln\left\langle\left|w^{(r)}(t)\right|^4\right\rangle$ under different operation conditions and heights before and after the extraction of coherent structure signals, with $\zeta(p)$ represented by the slopes of the curves. Before the extraction, the ESS curves under different operation conditions show different variation tendencies, while after the extraction they coincide with each other very well. Table 3 lists $\zeta(p)$ before and after the signal extraction, compared to the ideal value computed from Eq. (13). $\zeta(p)$ is found to deviate from the computed value of 1.33 before the extraction, indicating intermittency in the solids flow field. However, after the extraction $\zeta(p)$ becomes equal or highly close to 1.33 under all the operation conditions and heights. This demonstrates that the coherent structures leading to flow intermittency do exist in the riser, and the signal extraction approach employed in this work is valid.

Table 3 $\zeta(p)$ under different operation conditions before and after the extraction of coherent structure signals

Operation condition	Height	Before signal extraction	After signal extraction	$\zeta(p)$ from Eq.(13)
U_g=3.9 m/s, G_s=7.4 kg/(m^2·s)	h=560 mm	1.18	1.34	1.33
U_g=4.5 m/s, G_s=7.4 kg/(m^2·s)		1.30	1.31	1.33
U_g=4.5 m/s, G_s=19.4 kg/(m^2·s)		1.27	1.33	1.33
U_g=5.1 m/s, G_s=4.0 kg/(m^2·s)		1.20	1.34	1.33
U_g=5.1 m/s, G_s=7.4 kg/(m^2·s)		1.20	1.34	1.33
U_g=5.1 m/s, G_s=19.0 kg/(m^2·s)		1.31	1.33	1.33
U_g=3.9 m/s, G_s=7.4 kg/(m^2·s)		1.20	1.33	1.33
U_g=4.5 m/s, G_s=7.4 kg/(m^2·s)		1.31	1.33	1.33

U_g=4.5 m/s, G_s=19.4 kg/(m^2·s)	h=1850 mm	1.29	1.33	1.33
U_g=5.1 m/s, G_s=4.0 kg/(m^2·s)		1.20	1.33	1.33
U_g=5.1 m/s, G_s=7.4 kg/(m^2·s)		1.20	1.33	1.33
U_g=5.1 m/s, G_s=19.0 kg/(m^2·s)		1.29	1.32	1.33

5. CONCLUSIONS

A multi-channel electrostatic measurement system based on arc-shaped sensing electrodes has been employed on a CFB test rig. Cross correlation, statistical analysis, wavelet transform and probability density function have been applied to the electrostatic signal processing for the characterisation of solids motion, flow intermittency and coherent structure behaviours. Strong correlation has been shown between the upstream and downstream electrostatic signals, and the flow pattern has been indicated by the time-averaged solids velocities. Particle clusters and particle vortices have been regarded as coherent structures in the CFB. It has been found that the flow intermittency and influence of coherent structures are enhanced with the solids flux and weakened with the superficial gas velocity. By comparing the ESS scaling law curves before and after the extraction of coherent structure signals, the influence of coherent structures on the flow intermittency has been further confirmed. The results presented in this paper have demonstrated that the electrostatic signals generated in the CFB contain important information about the complex flow field. By applying the intermittency analysis methods to the electrostatic signals, the intermittent hydrodynamic behaviours have been appropriately characterised, leading to an in-depth understanding of the fluidisation process.

AUTHOR INFORMATION

Corresponding Author

* Email: J.Sun@kent.ac.uk

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Newton International Fellowships provided by the British Academy and the Royal Society. Dr. Lijuan Wang is particularly thanked for her help in electrostatic measurement. Dr. Jian Ye is also thanked for his suggestions and discussions in preparing the manuscript.

REFERENCES

(1) Upadhyay, M.; Park, J. H. CFD simulation via conventional, Two-Fluid Model of a circulating fluidized bed riser: Influence of models and model parameters on hydrodynamic behavior. *Powder Technol.* **2015**, *272*, 260-268.

(2) Li, T. W.; Gel, A.; Pannala, S.; Shahnam, M.; Syamlal, M. CFD simulations of circulating fluidized bed risers, part I: Grid study (Reprinted from Powder Technology, vol 254, pg 170-180, 2014). *Powder Technol.* **2014**, *265*, 2-12.

(3) Zhang, Z. S. *Turbulence*. National Defense Industry Press: Beijing, China, **2002**.

(4) She, Z. S.; Jackson, E.; Orszag, S. A. Intermittent vortex structures in homogeneous isotropic turbulence. *Nature* **1990**, *344*, 226-228.

(5) Zhang, J. P.; Jiang, P. J.; Fan, L. S. Flow characteristics of coal ash in a circulating fluidized bed. *Ind. Eng. Chem. Res.* **1998**, *37*, 1499-1509.

(6) Du, B.; Warsito, W.; Fan, L. S. Behavior of the dense-phase transportation regime in a circulating fluidized bed. *Ind. Eng. Chem. Res.* **2006**, *45*, 3741-3751.

(7) Lungu, M.; Wang, J. D.; Yang, Y. R. Numerical simulations of a bubbling fluidized bed reactor with an energy minimization multiscale bubble based model: effect of the mesoscale. *Ind. Eng. Chem. Res.* **2014**, *53*, 16204-16221.

(8) Brereton, C. M. H.; Grace, J. R. Microstructural aspects of the behavior of circulating fluidized-beds. *Chem. Eng. Sci.* **1993**, *48*, 2565-2572.

(9) Issangya, A. S.; Grace, J. R.; Bai, D. R.; Zhu, J. X. Further measurements of flow dynamics in a high-density circulating fluidized bed riser. *Powder Technol.* **2000**, *111*, 104-113.

(10) Camussi, R.; Guj, G. Orthonormal wavelet decomposition of turbulent flows: intermittency and coherent structures. *J. Fluid Mech.* **1997**, *348*, 177-199.

(11) Chen, W.; Zhou, H. B. Levy–Kolmogorov scaling of turbulence. *Eprint <arXiv:math-ph/0506039>* **2005**.

(12) Onorato, M.; Camussi, R.; Iuso, G. Small scale intermittency and bursting in a turbulent

channel flow. *Phys. Rev. E* **2000**, *61*, 1447-1454.

(13) Jiang, N.; Zhang, J. Detecting multi-scale coherent eddy structures and intermittency in turbulent boundary layer by wavelet analysis. *Chin. Phys. Lett.* **2005**, *22*, 1968-1971.

(14) Farge, M. Wavelet transforms and their applications to turbulence. *Annu. Rev. Fluid Mech.* **1992**, *24*, 395-457.

(15) Li, H. Identification of coherent structure in turbulent shear flow with wavelet correlation analysis. *J. Fluids Eng.-Transactions of the ASME* **1998**, *120*, 778-785.

(16) Sun, J. Y.; Zhou, Y. F.; Ren, C. J.; Wang, J. D.; Yang, Y. R. CFD simulation and experiments of dynamic parameters in gas-solid fluidized bed. *Chem. Eng. Sci.* **2011**, *66*, 4972-4982.

(17) Sun, J. Y.; Wang, J. D.; Yang, Y. R. CFD simulation and wavelet transform analysis of vortex and coherent structure in a gas-solid fluidized bed. *Chem. Eng. Sci.* **2012**, *71*, 507-519.

(18) Zhang, W. B.; Cheng, Y. P.; Wang, C.; Yang, W. Q.; Wang, C. H. Investigation on hydrodynamics of triple-bed combined circulating fluidized bed using electrostatic sensor and electrical capacitance tomography. *Ind. Eng. Chem. Res.* **2013**, *52*, 11198-11207.

(19) Zhang, W. B.; Yan, Y.; Yang, Y. R.; Wang, J. D. Measurement of flow parameters in a bubbling fluidized bed using electrostatic sensor arrays. *IEEE International Instrumentation and Measurement Technology Conference*, Pisa, Italy, **2015**.

(20) Dong, K. Z.; Zhang, Q.; Huang, Z. L.; Liao, Z. W.; Wang, J. D.; Yang, Y. R.; Wang, F. Experimental investigation of electrostatic effect on particle motions in gas-solid fluidized beds. *AIChE J.* **2015**, *61*, 3628-3638.

(21) Yang, Y.; Huang, Z. L.; Zhang, W. B.; Wang, J. D.; Lungu, M.; Liao, Z. W.; Wang, F.; Yang, Y. R.; Yan, Y.; Yang, J. Effects of agglomerates on electrostatic behaviors in gas-solid fluidized beds. *Powder Technol.* **2016**, *287*, 139-151.

(22) Feng, G. M.; Zhu, L. R.; Wu, Z. W. Wavelet transform applied on vehicle air flow meter (AFM) signal de-noising. *Appl. Mech. Mater.* **2012**, *188*, 287-291.

(23) Yan, Y.; Byrne, B.; Woodhead, S.; Coulthard, J. Velocity-measurement of pneumatically conveyed solids using electrodynamic sensors. *Meas. Sci. Technol.* **1995**, *6*, 515-537.

(24) Qian, X. C.; Yan, Y. Flow measurement of biomass and blended biomass fuels in pneumatic conveying pipelines using electrostatic sensor-arrays. *IEEE Trans. Instrum. Meas.* **2012**, *61*, 1343-1352.

(25) Qian, X. C.; Yan, Y.; Shao, J. Q.; Wang, L. J.; Zhou, H.; Wang, C. Quantitative characterization of pulverized coal and biomass-coal blends in pneumatic conveying pipelines using electrostatic sensor arrays and data fusion techniques. *Meas. Sci. Technol.* **2012**, *23*, 085307.

(26) Qian, X. C.; Huang, X. B.; Hu, Y. H.; Yan, Y. Pulverized coal flow metering on a full-scale

power plant using electrostatic sensor arrays. *Flow Meas. Instrum.* **2014**, *40*, 185-191.

(27) Wang, L. J.; Yan, Y.; Hu, Y. H.; Qian, X. C. Rotational speed measurement using single and dual electrostatic sensors. *IEEE Sens. J.* **2015**, *15*, 1784-1793.

(28) Wang, C. X.; Li, C. Y.; Zhu, J.; Wang, C. X.; Barghi, S.; Zhu, J. A comparison of flow development in high density gas-solids circulating fluidized bed downer and riser reactors. *AIChE J.* **2015**, *61*, 1172-1183.

(29) Jin, Y., Zhu, J.X., Wang, Z.W., Yu, Z.Q. *Fluidization Engineering Principles*. Tsinghua University Press: Beijing, China, **2001**.

(30) Bai, D. L.; Kato, K. Saturation carrying-capacity of gas and flow regimes in CFB. *J. Chem. Eng. Jpn.* **1995**, *28*, 179-185.

(31) Hussain, A. K. M. F. Coherent structures - reality and myth. *Phys. Fluids* **1983**, *26*, 2816-2850.

(32) Sun, J. Y.; Yan, Y. Computational characterisation of intermittent hydrodynamic behaviours in a riser with Geldart A particles. *Powder Technol.* **2016**, revision submitted.

(33) Echim, M. M.; Lamy, H.; Chang, T. Multi-point observations of intermittency in the cusp regions. *Nonlinear Processes in Geophys.* **2007**, *14*, 525-534.

(34) Bruno, R.; Carbone, V. The solar wind as a turbulence laboratory. *Living Rev. Solar Phys.* **2013**, *10*, 2.

(35) Kulkarni, J. R.; Sadani, L. K.; Murthy, B. S. Wavelet analysis of intermittent turbulent transport in the atmospheric surface layer over a monsoon trough region. *Boundary-Layer Meteorol.* **1999**, *90*, 217-239.

(36) Mangeney, A.; Salem, C.; Veltri, P. L.; Cecconi, B. Intermittency in the solar wind turbulence and the Haar wavelet transform. *Sheffield Space Plasma Meeting: Multipoint Measurement Versus Theory, Proceedings* **2001**, *492*, 53-64.

(37) Xia, Z. Y. Experimental research on controlling coherent structures in wall turbulence by periodic blowing and suction from streamwise slit. *Ph.D Thesis,* Tianjin University, **2007**.

(38) Ruiz-Chavarria, G.; Ciliberto, S.; Baudet, C.; Leveque, E. Scaling properties of the streamwise component of velocity in a turbulent boundary layer. *Phys. D* **2000**, *141*, 183-198.

(39) Chen, J.; Hu, F. Coherent structures detected in atmospheric boundary-layer turbulence using wavelet transforms at Huaihe River Basin, China. *Boundary-Layer Meteorol.* **2003**, *107*, 429-444.

(40) Wavelet Toolbox. *In Matlab Help Documentation,* The MathWorks, Inc. **2014**.

(41) Benzi, R.; Ciliberto, S.; Baudet, C.; Chavarria, G. R.; Tripiccione, R. Extended self-similarity in the dissipation range of fully-developed turbulence. *Europhys. Lett.* **1993**, *24*, 275-279.

FIGURE CAPTIONS

Figure 1. Layout of the gas-solid CFB test rig

Figure 2. Typical voltage signals from the upper sensor array, U_g=4.5 m/s, G_s=19.4 kg/(m^2·s) (after filtering and wavelet de-nosing)

Figure 3. Typical correlation function between the upstream and downstream signals, U_g=4.5 m/s, G_s=19.4 kg/(m^2·s) (after filtering and wavelet de-nosing)

Figure 4. Variations of the solids velocities near the wall with time under typical operation conditions, (a) h=570 mm, (b) h=1860 mm

Figure 5. Axial profiles of the RMS charge level of electrostatic signals

Figure 6. Variations of wavelet flatness factor with the frequency and height, U_g=4.5 m/s, G_s=19.4 kg/(m^2·s)

Figure 7. Variations of wavelet flatness factor with the frequency and solids flux, U_g=4.5 m/s, (a) h=1850 mm, (b) h=1870 mm

Figure 8. Variations of wavelet flatness factor with the frequency and solids flux, U_g=5.1 m/s, (a) h=1850 mm, (b) h=1870 mm

Figure 9. Variations of wavelet flatness factor with the frequency and superficial gas velocity, G_s=7.4 kg/(m^2·s), (a) h=1850 mm, (b) h=1870 mm

Figure 10. Typical PDF of wavelet coefficients from the electrostatic signals, h=1850 mm, U_g=4.5 m/s, G_s=19.4 kg/(m^2·s)

Figure 11. PDF of wavelet coefficients from the electrostatic signals under U_g=4.5 m/s, G_s=7.4 kg/(m^2·s) and U_g=4.5 m/s, G_s=19.4 kg/(m^2·s), (a) h=560 mm, (b) h=580 mm, (c) h=1850 mm, (d) h=1870 mm

Figure 12. PDF of wavelet coefficients from the electrostatic signals under U_g=4.5 m/s, G_s=4.0 kg/(m^2·s) and U_g=4.5 m/s, G_s=7.4 kg/(m^2·s), (a) h=1850 mm, (b) h=1870 mm

Figure 13. PDF of wavelet coefficients from the electrostatic signals under U_g=4.5 m/s,

G_s=19.4 kg/(m^2·s) and U_g=5.1 m/s, G_s=19.4 kg/(m^2·s), (a) h=560 mm, (b) h=580 mm, (c) h=1850 mm, (d) h=1870 mm

Figure 14. PDF of wavelet coefficients from the electrostatic signals under U_g=4.5 m/s, G_s=7.4 kg/(m^2·s) and U_g=5.1 m/s, G_s=7.4 kg/(m^2·s), (a) h=1850 mm, (b) h=1870 mm

Figure 15. ESS scaling law curves under different operation conditions before and after the extraction of coherent structure signals, h=560 mm, p=4, (a) before extraction, (b) after extraction

Figure 16. ESS scaling law curves under different operation conditions before and after the extraction of coherent structure signals, h=1850 mm, p=4, (a) before extraction, (b) after extraction