Enhancing the fluidization quality of nanoparticles using external fields

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1. Introduction

Fluidized beds have many industrial applications due to their superior properties, such as effective fluid-solid contact, high heat and mass transfer rates, low bed pressure drop, and absence of temperature gradient throughout the bed. These advantages make fluidized beds attractive for being employed in chemical, biochemical, petrochemical and food industries [1–4]. Nanoparticles also have been used for the production of catalysts, plastics, foods, drugs, micro electro mechanical systems, hydrogen storage as well as in nanofluids and fuel cells [4–6]. Therefore, developing large-scale units in which various processes like particle mixing, surface modification of nanoparticles and transporting of particles occur is essential [4]. For this purpose, nanoparticles can be dispersed in the gas stream to establish nanoparticle fluidized beds. When designing large scale fluidize beds for processing nanoparticles in various applications, hydrodynamic characterization and real-time monitoring of the fluidization condition is essential [7].

Particle properties strongly affect the hydrodynamics. Cohesive forces (especially van der Waals force) become dominant as the particles size decreases, the reason for finding nanoparticles in agglomerates form. Size of nanoparticles agglomerates varies from a few hundred micrometers to nano-scales and it depends on nanoparticle properties, fluid properties and operating conditions [8]. Wang et al. [9] studied fluidization of six types of silica nanoparticles and recognized two types of fluidization regime based on size and shape of nanoparticle agglomerates. These regimes are Agglomerate Bubbling Fluidization (ABF) and Agglomerate Particulate Fluidization (APF). In the ABF regime, gas phase can be found in form of distinct bubbles rising in the column and nanoparticle agglomerates forming a dense phase, called emulsion. In the APF regime, light and porous agglomerates of nanoparticles are fluidized to form a homogeneous bed. The bed expansion in the APF is higher than that in the ABF and agglomerates size distribution is more uniform in the APF regime.

Agglomeration of nanoparticles is a challenge in fluidization. The pronounced cohesive forces among agglomerates brings some difficulties in fluidization of the nanoparticles [7,10–12]. Thus, it is usually necessary to apply external forces to improve the fluidization quality of cohesive nanoparticles [13,14]. These external...
forces can be mechanical vibration [15,16], sound waves [17,18], electric field [19,20], centrifugal force [21], micro jets [22], and magnetic field [21,22]. Applying these forces can increase bed expansion, bed component intermixing, breakage of nanoparticle agglomerates and decrease the minimum fluidization velocity.

Among various assisting methods for enhancing the fluidization quality, vibration and magnetic field have shown good effects. The magnetization field was first used in fluidized beds for fluidizing a mixture of magnetic and non-magnetic particles [23]. It is common to use the oscillating magnetic field for this purpose [23–25]. Zeng et al. [26] investigated the effect of magnetic field on APF and ABF regimes in the presence of coarse magnetic particles. Their results indicated that the difference between the minimum fluidization velocity and minimum bubbling velocity (called stability area) decreases as the fraction of ferromagnetic particles increases in the bed. Zhu and Li [27] studied the effect of magnetic field on fluidization of Geldart group C powders mixed with ferromagnetic particles. They showed that the bubbles size highly depends on the intensity of the magnetic field. Increasing the intensity at a constant frequency leads to formation of smaller bubbles. On the other hand, by increasing the frequency at constant field intensity, bubbles become smaller.

Utilization of magnetic field is effective when ferromagnetic nanoparticles exist in the bed [28]. Ferromagnetic nanoparticles (such as iron oxide) rapidly gain acceleration in the presence of a magnetic field in the direction of the field. In an oscillating magnetic field, in which direction of the field changes at a high frequency (50 Hz in this work), direction of this acceleration, and hence direction of the motion of particle, changes at the same pace [29]. Such an external field can act as a very effective agent to break large agglomerates of non-ferromagnetic nanoparticles.

Monitoring the hydrodynamics of the nanoparticle fluidized bed requires proper techniques which can detect the agglomerates behavior in each instant. Many mathematical methods have been employed for analysis of time-series in the time domain. However, the most common methods in processing the time-series signals are in frequency domain and state space. As fluidized beds are non-linear systems, their characterization by linear methods does not reveal proper information. Therefore, using analysis techniques in the state space provide more details about their hydrodynamics and fluidization behavior. Many nonlinear methods are used for processing pressure signals in the state space [30–35]. These methods are based on transforming a system variable into the multi-dimensional state space. Dynamical trajectories are constructed by this transformation and these trajectories become attracted to an attractor [36–38]. Recurrence Plot (RP) is a method in which the proximity of trajectories in the state space is examined and plotted in a 2-D square plot. The concepts of RP and Recurrence Quantitative Analysis (RQA) were first initiated by Eckmann et al. [39]. These methods were developed for characterizing the dynamics of complex systems. Fluidized bed is a complex dynamical system, in which linear methods cannot disclose its hydrodynamics. Therefore, RP and RQA were used for characterizing the fluidization hydrodynamics. Tahmasebpoor et al. [40] used the RQA for investigating the hydrodynamic structures in fluidized beds and also determining the frequency ranges of each structure. Babaei et al. [41] discussed the effect of superficial gas velocity on the hydrodynamic structures of fluidized beds and showed that finer structures become dominant in the bed by increasing the superficial gas velocity. Sedighikamal and Zarghami [42] used the RP technique for detecting regime transition in a fluidized bed. Savari et al. [43] showed that water injection into a spotted bed brings the bed into a deterministc status. Norouzi et al. [44] used the multi-scale wavelet transform in combination with the RQA to investigate the effect of internal tubes on the bed hydrodynamics.

Wang et al. [45] used analyzed the pressure fluctuations using RQA to investigated various spouting regimes.

In the present study, various mixtures of alumina and ferromagnetic iron oxide nanoparticles were fluidized in a cylindrical fluidized bed. A magnetic coil was attached to the bed wall provided both vibration and oscillating magnetic field induced into the bed, providing two assisting forces for fluidization enhancement. Expansion and pressure fluctuations of the bed were recorded and used to characterize and monitor the fluidization quality. The pressure fluctuations were processed in frequency and state space domains by Fourier transform and recurrence analysis, respectively. The main goals in this work were to identify which method can effectively reveal the fluidization condition as well as transition from ABF to APF, and to determine how the assisting methods affect the hydrodynamics of fluidization.

2. Experiments

Fig. 1 shows the experimental set-up used in this study. The column was made of quartz to minimize the electrostatic charge accumulation in the bed. The column diameter was 28 mm and its height was 800 mm. A sintered glass disc with 2 mm thickness and average pore diameter of 20 μm was placed at the bottom of the bed to act as the gas distributor. To obtain a better gas distribution across the bed, a wind box with the height of 50 mm was placed under the distributor and was filled with 2.8 mm glass beads. To minimize the inter-particle forces due to gas moisture, nitrogen with a purity of 99.98% was used as the fluidizing gas. The gas was delivered to the bed through a mass flow controller (MFC, Alicat scientific, Inc.). A filter (Wafergard GT-Plus gas filters) was placed at the top of column to prevent losing particles from the bed.

![Fig. 1. The schematic of experimental set-up. A: magnetic coil; B: wind box filled with glass beads; C: sintered glass plate; D: ports for sampling and pressure measurements; E: filter.](image-url)
The nanoparticles used in this work were aluminum oxide (Al2O3) and iron oxide (Fe3O4) as ferromagnetic particles, supplied by TECNAN© company. The average size (before agglomeration) of alumina particles was 25 nm with a standard deviation of 4 nm and that of iron oxide particles was 17 nm with a standard deviation of 5 nm. Bulk density of alumina was 65 kg/m³ and iron oxide was 850 kg/m³. The size of nanoparticle agglomerates was measured using the method proposed by Tamadonard et al. [46]. The average size of alumina nanoparticle agglomerates was 332 µm with a standard deviation of 105 µm and the average size of iron oxide nanoparticles was 246 µm with a standard deviation of 85 µm.

A Piezoresistive barometer (model 7261, Kistler© company) was used for measuring pressure fluctuations of the bed. The probe was placed at 14 mm above the distributor. The sampling frequency for pressure fluctuations signals was 6250 Hz. The measured signals were band-pass filtered (hardware) at lower cut-off frequency of 0.017 Hz and upper cut-off Nyquist frequency (100 Hz).

The magnetic source consisted of a steel core of 5 cm and a bundle of copper wires (0.35 mm diameter) was coiled around the steel core. A 50 Hz–220 V electricity was used to produce the oscillating magnetic field with frequency of 50 Hz and intensity of 0.8 T. Several experiments were carried out for studying the hydrodynamics of the fluidized bed of nanoparticles. In each test, pressure fluctuations and bed expansion measurements were performed for 110 s and the magnetic field was applied in the last 20 s. First, the bed was filled with 1 g of alumina nanoparticles (28 mm high). The iron oxide nanoparticles were added to the bed, as the ferromagnetic agent, to investigate the effect of magnetic force on the hydrodynamics of the bed. Tests were repeated after adding 0.5, 1, and 2 gr iron oxide nanoparticles (equivalent to 33 wt%, 50 wt %, and 67 wt%) to the bed of alumina nanoparticles. The superficial gas velocity was varied between 2.7 and 13.5 cm/s and the experiments were carried out in atmospheric pressure and ambient temperature. In this velocity range the bed operates above the minimum fluidization and before particle entrainment. Each set of experiments was performed two times and all reported values are averaged based on these repeated measurements.

3. Theory

3.1. Discrete Fourier transform

A time series signal of pressure fluctuations can be decomposed into constituent sines and cosines of various frequencies by the Discrete Fourier Transform (DFT). The Fourier transform of a time series \( x(i) \) consisting of \( N \) points can be calculated by:

\[
X(f) = \sum_{i=1}^{N} x(i) \exp(-j2\pi if)
\]

where \( f \) is the sampling frequency and \( j \) is the unit imaginary number.

Squared \( X(f) \) represents the power spectrum of the signal at frequency \( f \). The power spectrum at each frequency demonstrates its relative power to the overall power of the whole signal [47]. The Welch method is a common method in estimating the power spectrum [48]. In this method, the signal is divided into \( L \) segments with individual length of \( N \), and the power spectrum is defined by:

\[
P_x(f) = \frac{1}{N} \sum_{i=1}^{N} w(i) x(i) \exp(-j2\pi if)
\]

In which, \( w(i) \) is the window function. Hanning, Hamming, Blackman and rectangular are examples of the window function [49]. In the presence study, the Hanning window function was used. In Eq. (2), \( U \) is the normalized factor of \( w(i) \):

\[
U = \frac{1}{N} \sum_{i=1}^{N} w^2(i)
\]

The averaged power spectrum is calculated by:

\[
P_{avg}(f) = \frac{1}{L} \sum_{l=1}^{L} P_x(f)
\]

3.2. Recurrence plot

Recurrence plot is a 2-D plot which demonstrates the dynamic behavior of a system qualitatively. The theory of RP was started based on the Poincare’s theory [50]. Eckmann et al. [39], assuming that the time series is much longer than the characteristic time of the dynamic system, developed some methods to illustrate the m-dimensional trajectory of the system into a 2-D graph by comparing the proximity of trajectories. After reconstructing the attractor in the state-space, the RP can be plotted based on the recurrence matrix whose elements are obtained by:

\[
R_d(i, j) = \Theta(e - || \vec{x}_i - \vec{x}_j ||), i, j = 1, ..., N
\]

where \( N \) is the number of data points, \( x_i, x_j \in \mathbb{R}^d \) are ith and jth points in the d-dimensional space state trajectory, \( || \cdot || \) shows the norm, \( e \) is the threshold distance, and \( \Theta \) represents the Heaviside function. If the distance between two points in the trajectory is less than the threshold, \( R_d = 1 \) in the recurrence matrix and a black dot is shown on its place in the plot. On the contrary, if the distance is more than the threshold, \( R_d = 0 \) which is presented by a white dot on the plot [39]. March et al. [51] indicated that RPs can be generated without embedding parameters. Nevertheless, according to the Takens’ theorem [52], using at least one parameter for displaying RPs can reveal more valuable information about the system dynamics.

3.3. Recurrence quantification analysis (RQA)

Three geometric structures can be identified in a RP: single dots, diagonal lines and vertical/horizontal lines. These geometric structures reveal dynamic information about the fluidized bed. However, visual inspection of a RP does not reveal proper details about the system dynamics. Therefore, the RQA is used to quantify dynamic behavior of the system. In the present study, determinism (DET) was used.

\[
DET = \frac{\sum_{l=1}^{L} \text{L}_P(l)}{\sum_{l=1}^{L} \text{L}_P(l)}
\]

Babaei et al. [53] showed that the value of 2 for the minimal length of diagonal lines, \( l_{min} \), the fraction of diagonal lines which are equal or longer than \( l_{min} \) is known as the determinism. \( DET \) is calculated from

\[
DET = \frac{\sum_{l=1}^{L} \text{L}_P(l)}{\sum_{l=1}^{L} \text{L}_P(l)}
\]

Babaei et al. [53] showed that the value of 2 for the minimal length of diagonal lines provides the largest difference in the determinism of the Lorenz system and hence this value is the best choice for the minimal length. Therefore, the same value was considered for \( l_{min} \) in this study. Determinism shows the predictability of a system. It assumes a high value in a deterministic systems and is very small in a stochastic system [50]. It is the lowest value for random systems and the highest value (around 100) for periodic systems.

4. Results and discussion

As mentioned earlier, the magnetic coil produces vibration on the bed wall and also induces a magnetic field. When alumina nanoparticles are loaded into the bed, the only external assisting
force is vibration and when iron oxide nanoparticles are added to the bed, the magnetic field exerts an additional force on the ferromagnetic particles. In the experiments, bed expansion and pressure fluctuations of the bed were measured during fluidization of various mixtures of alumina and iron oxide nanoparticles.

Regime transition from ABF to APF involves reduction in the number of bubbles while bubbles and agglomerates become smaller [1]. As the regime approaches APF, the bed expansion \( (H/H_0) \) increases. According to previous observations, the bed expansion is very high in the APF regime [3], while the bed expansion remains very low in the ABF regime. Therefore, the bed expansion is a visual identification of fluidization regime and it increases from low to high values (for example, from 1 to 10) during the fluidization transition from ABF to APF.

Fig. 2(a) and (b), respectively, show the time series of pressure fluctuations in the bed of alumina nanoparticles and the bed of a mixture of 67 wt% alumina and 33 wt% iron oxide nanoparticles at gas velocity of 8.1 cm/s. In both cases, the coil was turned on after 90 s from the start of fluidization. In the bed of alumina particles only, vibration is the sole assisting force when the coil is turned on, and in the bed with the mixture of alumina and iron oxide, both vibration and magnetic forces are the assisting forces. Fig. 2 shows that the amplitude of pressure fluctuations increases in both beds when the magnetic field is turned on. A comparison between the two signals before 90 s reveals that the amplitude of pressure fluctuations is slightly higher in the bed of mixed nanoparticles in compassion with the bed of alumina nanoparticles. This increase can be attributed to the addition of ferromagnetic particles. In the presence of ferromagnetic particles in the bed, the magnetic cohesion force between particles results in a more stable and larger nanoparticle agglomerates and hence presence of larger bubbles in the bed. Larger bubbles in the bed produce larger pressure fluctuations. The same trend was observed for other gas velocities examined in this study and results are not discussed for the sake of brevity.

To better illustrate changes in the frequency of pressure fluctuations before and after applying the magnetic field, pressure signals are demonstrated in an enlarged scale in Fig. 3. This figure shows the pressure fluctuations for the 0.5-second periods before and after turning on the magnetic coil. In Fig. 3(a1) and (a2), the bed was filled with alumina nanoparticles only (effect of vibration on pressure fluctuations). In Fig. 3(b1) and (b2), the bed was a mixture of alumina (67 wt%) and iron oxide (33 wt%) nanoparticles (combined effect of vibration and magnetic field). As can be seen in these figures, the amplitude of pressure fluctuations increases when the magnetic coil is switched on. Also, frequency of the fluctuations becomes higher and the signal becomes closer to periodic. When the magnetic coil is on, energy is transferred to the bed via vibration of the wall and due to the magnetic force acting on the ferromagnetic nanoparticles. Combination of these two effects transfers much more energy into the bed which increases the intensity of pressure fluctuations almost 10 times the original ones. This increase in the pressure fluctuations also reveals that the fluctuations caused by external field are dominant in comparison with other sources of pressure fluctuations in the bed (motion of bubbles and agglomerates). Since vibration of the bed wall and oscillation of magnetic field were periodic, the pressure fluctuations become close to periodic when applying the external field.

In order to extract information about the changes of dominant frequency in the bed before and after applying the external fields, discrete fast Fourier transform was performed on the pressure signals of an empty column with the magnetic coil on. The Power Spectrum Density Function (PSDF) is shown in Fig. 4. As can be seen in this figure, a strong peak exists at 100 Hz. This frequency is related to the vibration of the column. Since the column was empty in this case, the measured pressure fluctuations do not contain information about the fluidization hydrodynamics. Therefore, if a low-pass filter is applied on the measured pressure fluctuations of the fluidized bed at 100 Hz (low-pass digital filter using Hamming window), the information originated from the wall vibration

![Fig. 2. Pressure fluctuations measured at 14 mm above the distributor at gas velocity of 8.1 cm/s: (a) fluidization of alumina nanoparticles, (b) fluidization of mixture with 67 wt% alumina and 33 wt% iron oxide nanoparticles.](image-url)
would be excluded from the signal. Tamandondar et al. [46] showed that all hydrodynamic information of the bed is within the range of 0–80 Hz in the pressure fluctuations. Consequently, this filtration does not eliminate any hydrodynamic information [46]. In this way, it is possible to obtain a more precise view of the hydrodynamic changes in the fluidized bed when external field is applied.

For better understanding the changes in the hydrodynamics of the fluidized bed, RP analysis was also used in this work. The RPs of unfiltered pressure fluctuations (at the same operating conditions of Fig. 3) are shown in Fig. 5. Fig. 5(a1) and (b1) correspond to when the magnetic coil is off and in Fig. 5(a2) and (b2) the coil is on. Black dots on the RP show the recurrences of the dynamic state of the bed. The patterns observed in this plot illustrate the contribution of various flow structures in the whole dynamic behavior of the fluidized bed. When the external force was applied, a significant increase in the number of recurrence states (black dots) can be witnessed. In addition, repeated diamonds have appeared in the RP of the bed with external field (a2 and b2) which indicate strong periodic behavior of the bed, since it is very similar to the RP of a sine (or cosine) signal [54]. It can be claimed that these diamonds in the RP are a result of application of the external field, effect of which is reflected in the pressure fluctuations. In other words, the regular wall vibration transfers energy to the bed and causes close to periodic pressure fluctuations. The pressure fluctuations originated from wall vibration is so strong that can mask the fluctuations resulted from bed hydrodynamics (i.e., bubbles and agglomerates).

By filtering pressure fluctuations at 100 Hz, the filtered signal contains only the hydrodynamic information of the bed. In this way, it is possible to track the changes in the hydrodynamics before and after applying the external field. RPs of the filtered pressure fluctuations of the bed filled with a mixture of alumina and iron oxide nanoparticles (33 wt% iron oxide) before and after applying the external magnetic field are shown in Fig. 6(a) and (b). Operating conditions in these figures were those of Fig. 5(b1) and (b2), respectively. It can be seen in Fig. 6(b) that characteristic diamonds of the oscillating signal have vanished after filtration. The large white areas in the RP shown in Fig. 6(a) are related to high contribution of large structures in the bed (like bubbles), as explained by Tahmasebpour et al. [55]. By applying the external field, the large white areas of Fig. 6(a) are replaced by smaller white areas in Fig. 6(b). Smaller white areas in the RP indicate the high contribution of smaller structures (like small bubbles or agglomerates) in the bed [55]. Therefore, by applying the external field, bubbles become smaller and the bed expands more to form a more homogenous bed of suspended agglomerates. Visual observation in the experiments of this work also confirmed this trend. In fact, when the coil was turned on, bubbles start to disappear and bed gradually expands to its final state (ABF to APF). It should be noted that the similar results were obtained for other gas velocities and the discussion on these results is omitted here for the sake of brevity.

The RP only represents a qualitative view of the hydrodynamics of the bed. To obtain a quantitative state of fluidization behavior, a quantitative tool should be used. Here, determinism was used. DET
shows the predictability of the dynamic system. Fig. 7 shows the variation of determinism of pressure fluctuations of the bed between 70 and 110 s after start of fluidization (20 s before and after turning the magnetic coil on) at the superficial gas velocity of 8.1 cm/s for various mixtures of alumina and iron oxide nanoparticles. Fig. 7(a) is generated using unfiltered pressure fluctuations while the signal is filtered in Fig. 7(b). It can be seen in Fig. 7(a) that the determinism of the bed starts changing after activating the magnetic coil and reaches to the highest value (almost 100) in all experiments. Increasing the determinism to 100 is due to the fact that pressure fluctuations in this case are influenced by vigorous wall vibrations caused by the magnetic coil. As explained in discussions of Fig. 4, these vibrations transfer a high amount of energy to the bed materials. Since the vibration occurs at a constant frequency, it acts as a periodic system with a very high determinism. In Fig. 7, transition of determinism starts

Fig. 5. RPs of the unfiltered pressure fluctuations of the bed at gas velocity 8.1 cm/s with (a1) pure alumina nanoparticles when the magnetic coil is off, (a2) when the magnetic coil is on, (b1) the mixture of alumina (67 wt%) and iron oxide (33 wt%) nanoparticles when magnetic coil is off, and (b2) when the magnetic coil is on.

Fig. 6. RPs of pressure fluctuations in the bed filled with a mixture of alumina (67 wt%) and iron oxide (33 wt%) nanoparticles at gas velocity 8.1 cm/s when the magnetic coil is (a) off and (b) on.
right after applying the external field and reaches to its new value in few seconds. This transition time is the longest for bed of pure alumina nanoparticles (0 wt% iron oxide in which the magnetic force is absent) and is the lowest for the bed with 33 wt% of iron oxide nanoparticle (in which both vibration and magnetic force work alongside). This trend shows that the magnetic force can significantly enhance the fluidization quality of the particles and reach particulate fluidization in a shorter time. Nevertheless, adding more iron oxide nanoparticles (50 and 60 wt%) makes this transition slower which indicates that increasing the concentration of iron oxide nanoparticles in the bed do not enhance the fluidization quality of the bed, but acts in the opposite direction.

To better track the hydrodynamic changes of the bed due to magnetic field, the filtered pressure signals was used to evaluate determinism of pressure fluctuations of the beds with various mixtures of alumina and iron oxide nanoparticles at superficial gas velocity 8.1 cm/s and is shown in Fig. 7(b). It can be seen in this figure that the determinism of the bed without iron oxide nanoparticles does not exhibit a meaningful change after turning the magnetic field on. This trend indicates that this bed is not affected by the magnetic field and vibration is the only enhancing force. In order to confirm this claim, the bed expansion measurements of the same beds are shown in Fig. 8. The change of expansion of bed of alumina nanoparticles in the absence of iron oxide is the
least when magnetic field is applied which also implies that the fluidization regime has not significantly changed compared to the condition when the magnetic coils was off. However, in beds containing iron oxide nanoparticles, difference in the bed expansion before and after applying the magnetic field is more. Fig. 7 (b) also illustrates that determinism decreases after turning the coil on when the bed contains iron oxide nanoparticles. The decrease in determinism confirms that contribution of macro-structures (like bubbles) decreases in the bed and smaller structures (like agglomerates) are formed [55]. The high expansions of these beds, shown in Fig. 8, also confirm this trend. The change in the determinism of the bed (before and after turning on the external field) is the highest for the bed containing 33 wt% iron oxide nanoparticles, followed by the beds with 50 wt%, 60 wt% and 0 wt%. The bed expansion also follows the same trend. This trend suggests that determinism of the filtered pressure fluctuations is a good candidate for monitoring the changes of the fluidization from ABF to APF.

To support the discussion on RP and DET in previous figures, the PSDFs of pressure fluctuations of the beds were compared. PSDFs of the filtered pressure fluctuation signals of the bed with various mixtures of alumina and iron oxide nanoparticles are illustrated in Fig. 9. The peaks are observed in 30–40 Hz and 60–70 Hz intervals.

According to Letzl et al. [56], the peak frequency around 40 Hz corresponds to small bubbles (or bubble swarms) as well as large agglomerates of nanoparticles and the peak frequency greater than 50 Hz is related to small nanoparticle agglomerates. Tamadondar et al. [46] also showed, the frequency range between 25 and 50 Hz belongs to meso-structures (agglomerates and small bubbles) and the frequency range higher than 50 Hz is related to micro-structure phenomena (particle scale motions and noises) in the bed of silica nanoparticles. Since the intensity of the peak near 35 Hz is noticeably increased by applying the external field, we can conclude that the meso-structures are more affected by the field. In addition, we can see that the bed containing 33 wt% iron oxide nanoparticles showed the most changes in the presence of external field. This increase in the intensity of 35-Hz peak means the number/share of small bubble and agglomerates to the bed hydrodynamics is increased which is equivalent to a bed with smaller flow structures and more homogenous regime (APF).

In fact, incorporating ferromagnetic nanoparticles along with magnetic field is a powerful method for enhancing the fluidization quality and is effective in breaking agglomerates. However, there is an optimum value for adding ferromagnetic particles and this effect is not increased by increasing the amount of ferromagnetic nanoparticle. The bulk density of the iron oxide nanoparticles is much higher than that of alumina nanoparticles. It seems that the adding too much heavy iron oxide to the bed results in the denser bed (with higher weight) which acts in the opposite direction to the bed expansion.

5. Conclusions

Fluidization quality of various mixtures of alumina and iron oxide nanoparticles (0–60 wt% iron oxide) was monitored in the absence and presence of a combination of vibration and magnetic field. All mixtures exhibited ABF regime before applying the assisting forces to the bed. To assess and track the fluidization behavior, the bed expansion and pressure fluctuations were measured.
Pressure fluctuations were analyzed by FFT, RP and RQA. Using FFT, it was shown that the peak frequency of 100 Hz with a high amplitude in the PSDF of pressure fluctuations originates from the wall vibration. Therefore, the pressure signals were filtered by a proper low-pass filter to obtain a better view of the hydrodynamic changes in the bed. A comparison between RP of pressure fluctuations before and after applying the assisting forces showed that the white areas in the plot decreased in the presence of vibration and magnetic field which confirms that in this condition the contribution of small structures (like agglomerates and small bubbles) increases in the bed hydrodynamics. The transition in the equilibrium bed hydrodynamics, between the condition in which assisting forces are not applied and condition in which they are applied, was tracked. It was shown by determinism of pressure fluctuations that when the iron oxide nanoparticles exist alongside with alumina nanoparticles, this transition to the new equilibrium condition was reached in a shorter time. In addition, beds containing iron oxide nanoparticles has greater bed expansion. Determinism of pressure fluctuations decreases after applying the assisting forces. This reduction confirms that large bubbles disappear in the bed and are substituted by smaller structures, like agglomerates and smaller bubbles, when assisting forces are applied to the bed. In this condition, the fluidization behavior approaches to ASF. The bed expansion measurements also confirmed the results obtained from determinism. Finally, results show that the quality of fluidization of the mixture containing 33 wt% iron oxide in the presence of assisting forces is improved the most and higher quantities of iron oxide nanoparticles has reversed impact.

References


