Early agglomeration monitor of coarse cohesive particles

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Abstract. This paper established a three-dimensional visualization experimental system. Paraffin particles were chosen as a test of raw material to simulate the movement and bonded process of coarse cohesive particles. Experimental study on fluidization process of coarse cohesive particles has been done by high-speed camera. The study shows that: from the normal fluidization to shut-down, it can be divided into two phases. The former is a slower phase of the bond and the formation of core grew up phase; the second stage is the huge bonded core turn to bridge fast and shut-down happens with great velocity. Then, comparison of different methods has been done to deal with the experimental date of pressure, the results show that: Compared to the average pressure and pressure deviation method, S attractor method that is based on chaotic theory could monitor the agglomeration much earlier, reflect the degrees of bond with the specific numerical value and also demonstrate the velocity of agglomeration. Thus, it could be applied to the early monitor of agglomeration of coarse cohesive particles.

1. INTRODUCTION

Fluidization technology as a basic technology has penetrated into the national economy in many sectors. It has been widely used and has very good prospects for industry. According to the Gerldart’s classification of particles, particles can be divided into four types by size and density of material, namely type A, B, C and D. Type D particle generally refers to the particles larger than 1 mm in diameter and is too coarse or spray used particle. With big bubbles, it is difficult to stabilize operations, so agglomeration and shut-down often happens in the actual industry production. The research on Type D particle is still in the trial of a simple description and does not receive relatively common laws. Furthermore, the research on coarse cohesive particles in high temperature is rather small and different scholars in the same issue come to the different conclusions (ZHOU Yong-min et al., 2005; Aihua Chen. Hsiaotao T.Bi., 2003). Although many scholars have done a lot of research on the influence of temperature to the behaviour of particle fluidization, many of them concentrated in the Type B particle and did more research on the impact of fluid flow by temperature, rarely considering the viscosity of particles(B.Formisani et al., 1998; GUO Qing jie et al., 2002). In view of the fluidized operation must be done against coarse cohesive particles in actual industrial production, it is of great theoretical and practical value to establish the general law of fluidization and agglomeration of coarse cohesive particles as well as the method for early monitor of agglomeration.
2. Experimental System and the Process

2.1 Experimental System
The three-dimensional visualization experimental system of coarse cohesive particles is shown in Figure 1. It consists of three-dimensional fluidized bed body, measurement system and power system. The fluidized bed body is a 3-D cylinder made from plexiglas, whose diameter is 156 mm and height is the 1200 mm, in order to make visual observation to the flow of material and bonded process in bed. Bed material is supported in bed screen. A total of four measuring points, as shown in Figure 2, are: the measuring point 1 at the top of the exit in the centre of the bed, the measuring point 2 above the screen at 10 cm in the centre of the bed, the measuring points 3 above the screen at 1 cm and the measuring point 4 below the screen at 7 cm in the side wall of the bed. They are used to measure pressure information in order to better study the pressure fluctuation in different locations with different flow state and bonded status. To control the temperature of bed, there is also a measuring point below the screen to measure the temperature of fluid by thermocouples. Rotor flowmeter is used to flow measurement. To measure accurately, pressure sensor calibration has been done. The experimental system also includes blower, high-speed camera and electric heater.

![Fig. 1 Sketch of Experimental System](image1)

![Fig. 2 The Layout of Measuring Points](image2)

2.2 The Raw Material used in Experiment
To be able to simulate the movement and bonded process of coarse cohesive particles, paraffin particles with the average size of 5 mm and the melting point of 58 °C were chosen as a test of raw material. Compared with cement, it can be softened at a lower temperature (nearly 40 °C) and has a good cohesive to meet the needs of experimental research purpose. With this raw material, visual observation of the bonded process of coarse cohesive particles in low temperature can be easily realized.

2.3 3-D Experimental Process
3-D experimental process as follows: First add to paraffin particles in bed. Then start blower and set a fixed speed with the rotor flowmeter. When the movement of the fluidized bed has stabilized, record the pressure information with pressure sensors. The computer sampling frequency of pressure signal is 500 Hz and the effective time of each sample is 60 s. Then, stop data collection and use vacuum cleaners to aspirate the paraffin particles from bed. Heat up the gas by electric heater without closing blower until the temperature is up to pre-set value. After the system is in stable, put paraffin particles into bed. At the same time, pressure sensors begin to record pressure information in bed, until shutdown happens.
Figure 3 shows the flow state in slugging of coarse cohesive particles. It can be seen from the figure that there is only one big bubble throughout the bed cross-section, in the recycling course of generating, rising and rupturing in entire bed. Particles at the bottom of the bubble are almost static. It shows that the gas-solid contact with bad conditions in the flow state of coarse cohesive particles, causing the flow of deterioration easily. If the flow parameters are selected unreasonable, it will have a bonded slugging and make shut-down happen, as shown in Figure 4. Therefore, the flow parameters must select the appropriate scope to make sure the flow state is in normal fluidization.

![Fig. 3 Flow State in Slugging](image1)

![Fig. 4 Bonded Block in Shut-down State](image2)

3. The General Law of Agglomeration of Coarse Cohesive Particles
When the temperature is up to pre-set value and the system is in stable, paraffin particles in room temperature are put into bed. In the early stages of the flow, paraffin particles are dispersed in bed and the flow state is in a normal fluidization. As the increase of the stay time in bed, heat exchange between the paraffin particles and the gas is becoming more and stronger, so that the temperature gradually increases and paraffin particles viscosity also increases. Paraffin particles in movement collide with each other constantly. When the cohesive force comes to a certain value with the increasing viscosity, some paraffin particles bond together and no longer separate, forming a bigger particle. While the gravity of them overcomes the other forces, they will be at the bottom of the bed and be static. They will continue growing up and have great influence in bonded process, so they are called bonded core. As more obvious side effect of the wall, agglomeration is very likely to happen in the area where the gas velocity is slow, such as the area near the wall. The bond often starts from the low-speed zone of side wall and extends to the centre of bed, showing layers. When the viscosity of paraffin particles reaches a certain value, particles suddenly bond together, land to the centre of bed and a large number of particles quickly adherence to the surface of bonded core, so the material in bed collapse to make shut-down happen. Figure 5 is the sketch of bonded process.
4. The Analysis of Pressure Information

If it can predict in advance that the deteriorative trend of flow state, it would be possible to avoid the occurrence of the shut-down phenomenon by taking certain methods, such as; changing the bed temperature or increasing the apparent wind speed of gas to prevent further reunion. Therefore, it is very necessary to monitor the flow state of fluidized bed. Pressure fluctuation signals are often used to analyze and judge the flow state of bed. Many research on early monitor of agglomeration with different methods scholars have been conducted (Jaap C. Schouten., 1998; Kai. T et al., 1985). In this paper, research and comparison of these methods have been done by using them to deal with the experimental date of pressure, judging whether the method can be used for early monitor of agglomeration of coarse cohesive particles.

4.1 The Average Pressure Method

The average pressure method is often used in the first experimental study, so this paper also uses this method to analyze bed pressure information in different flow state primarily. Figure 6 shows the pressure information of different measuring points. As the constraints of experimental system, the pressure information of four measuring points comes from different experiments. Therefore, this paper only has a qualitative analysis to laws that exist in a large number of experiments. From the curve of the changes in Figure 6, it can be seen that the average pressure change of the measuring point 2 is on a declining trend and the average pressure changes of the measuring point 1 and point 4 are irregular with the different bonded state. Although the average pressure change of measuring point 3 shows a declining trend, shut-down has been formed before the average pressure decrease. It can not reflect the changes of bonded state in due course. Therefore, after choosing the right measuring point, it has applicability to the average pressure method to realize the early monitor of agglomeration of coarse cohesive particles.
From this figure, pressure information of different measuring points has different sensitivity to the flow and bonded state. Measuring point 2 near the top of the material is very sensitive to the change of bonded state. Its pressure information can accurately reflect the bonded state of paraffin particles in bed. This is mainly because the changes of pressure are influenced by the recycling course of the bubbles’ generating, rising and rupturing in entire bed. A high degree of material will be reduced due to the bonded deterioration, so it is very sensitive to the change of pressure. At the same time, It has enough distance to weaken the impact of the pressure fluctuation for measuring point 1, so the pressure fluctuation is rather small. Measuring point 3 is in the bubbles’ generating area, so the bubble is relatively small and moves quickly and the point is not sensitive to pressure changes. Measuring point 4 under the screen is almost not influenced by the bubbles, so the pressure fluctuation is small, either. Thus, the point which is very sensitive to the change of pressure is the point which is higher in the impact range of material. It can distinguish between different flow state and bonded state conveniently.

4.2 The Standard Deviation Method
In this paper, the standard deviation method is used to analyze the pressure information of different measuring points, and the results are shown as below. With the bond increasing, the changes of standard deviation of measuring point 1 and point 2 are in certain regularity, except for measuring point 3 and point 4. As mentioned above, it is because pressure information of different measuring points have different sensitivity to the flow and bonded state. After choosing the right measuring point, it can realize the early monitor of agglomeration of coarse cohesive particles, either.
4.3 The Wavelet Analysis Method

Wavelet analysis method is based on Fourier analysis. The basic idea is to express or approach signal with function family. This function family is composed of the parallel movement and flex of basic wavelet function $\Psi(t)$ with different scales. There are still some shortcomings with wavelet analysis, such as the wavelet is unsound theoretically. This paper attempts to use wavelet analysis, and the results are shown in Figure 8. The components of characteristics vector from 1 to 5 got by wavelet analysis are on a declining trend and the components of characteristics vector 6 and 7 got by wavelet analysis are irregular with the different bonded state. In addition, each of the changes in the law is not the same components of characteristics vector. The components of characteristics vector got by wavelet analysis cannot show a pattern of changes accompanying the progressive deterioration of the situation or ease, so it is very difficult for using wavelet analysis in early monitor of agglomeration of coarse cohesive particles.

4.4 S Attractor Method

4.4.1 Introduction of S Attractor Method

Many non-linear methods are based on a so-called state-space projection of a dynamical system, such as a fluidized bed. In general, the state of a fluidized bed at a certain time can be determined by projecting all variables governing the system into a multi-dimensional space; the collection of the
successive states of the system during its evolution in time is called the attractor and can be considered as a characteristic measure for a dynamical system. It has been shown by Takens (Takens F., 1981) that the dynamic state of a system can be reconstructed from the time series of only one characteristic variable such as the local pressure in a fluidized bed. Using so-called time-delay coordinates it is possible to convert a pressure time series consisting of N values into a set of N – m delay vectors P with m elements. The subsequent delay vectors can be regarded as points in an m-dimensional state space yielding a reconstructed attractor, for which Takens has proven that it has the same dynamic characteristics as the true attractor, obtained from all variables governing the system. The attractor can therefore also be seen as a characteristic measure of the hydrodynamics of a fluidized bed.

The 6th International Symposium on Measurement Techniques for Multiphase Flows IOP Publishing
Journal of Physics: Conference Series 147 (2009) 012075 doi:10.1088/1742-6596/147/1/012075

S attractor method (van Ommen JR et al., 2000; Malte Bartels et al., 2008) is an attractor comparison method that is based on chaotic theory. It is a step beyond the short-term predictability in state space and has been applied to monitoring agglomeration effects in fluidized beds. The principle of this method consists of reconstructing and comparing attractors of the system. One first has to record a reference attractor representing a desired (e.g. well-fluidized) state of the system. Subsequently, the attractor of the current operating state is reconstructed and compared to the reference attractor. This comparison is based on a statistical test developed by Diks et al. (Diks C et al., 1996), which evaluates the dimensionless squared distance $S$ between two attractors. The $S$-value is defined as

$$S = \frac{\hat{Q}}{\sqrt{V_c(\hat{Q})}}$$

with $\hat{Q}$ is the estimator of the squared distance between the two smoothed distributions of the two attractors and $V_c$ is the variance of $\hat{Q}$.

For attractors being generated by the same mechanism, $S$ has an expectation of 0 and a standard deviation of 1. An $S$-value larger than 3 indicates with at least 95% confidence that the two attractors have been generated by a different system. As the test is in fact one-sided, the actual confidence is even higher, 98–99%, as shown in numerical simulations by Diks et al.(1996). The principle is shown in Figure 9.
4.4.2 The Correlative Preferences

In the reconstruction phase space, there are four important parameters that is Delay Time $\tau$, Embedding Dimension $m$, Segment Length $L$ and Length Scale $d$. These preferences are of great significance which has a direct impact on the quality of S attractor. Many selection methods have been studied by many scholars (Lin Jiayu et al., 1999; Huang E N., 1998; Liangyue Cao., 1997; van Ommen JR et al., 2000). In this paper, appropriate method has been chosen.

(1) Delay Time $\tau$

Multiple autocorrelation method without excursion (Lin Jiayu et al., 1999) has been adopted. It has a strong theoretical basis, simple mathematical expression, and moderate complexity. Most importantly, the demand of its data length is not strong. The expressions is:

$$R_{xx} = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})(x_{i+\tau} - \bar{x})$$  \hspace{1cm} (2)

Where $N$ is the number of samples, $\bar{x}$ is the average value of sequence. When $R_{xx}$ falls to the initial value of $1 - 1/e$ with the increasing of $\tau$, $\tau$ is the delay time of the reconstruction phase space. This paper establishes a procedure to calculate this parameter. The result is 1 which is same to references (Huang E N., 1998). A pressure time-series in actual experiment is chosen to calculate the delay time, and the result is also 1.

(2) Embedding Dimension $m$

Cao method (Liangyue Cao., 1997) is used widely at present to calculate this parameter. The method overcomes the shortcomings of the other methods. It is shown as below. Suppose that there is a time series:

$$x_1, x_2, x_3, ..., x_N$$  \hspace{1cm} (3)

The time-delay vectors can be reconstructed as follows:
\( y_i(d) = (x_i, x_{i+r}, \ldots, x_{i+(d-1)r}), i = 1,2,\ldots, N - (d - 1)r \) \hspace{1cm} (4)

Where \( d \) is the embedding dimension and \( r \) is the time delay. Define

\[
a(i,d) = \frac{\left\| y_i(d+1) - y_{n(i,d)}(d+1) \right\|}{\left\| y_i(d) - y_{n(i,d)}(d) \right\|}, i = 1,2,\ldots, N - d \tau \quad (5)
\]

\[
\left\| y_k(m) - y_i(m) \right\| = \max_{0 \leq j < m - d} \left| x_{k+jr} - x_{i+jr} \right|
\]

\( y_i(d+1) \) is the \( i \)th reconstructed vector with embedding dimension \( d + 1 \).

\( y_i(d+1) = (x_i, x_{i+r}, \ldots, x_{i+(d+1)r}), 1 \leq n(i,d) \leq N - d \tau \) \hspace{1cm} (7)

The \( n(i,d) \) in the numerator of Eq. (5) is the same as that in the denominator. If \( y_{n(i,d)}(d) \) equals \( y_i(d) \), the second nearest neighbour is taken instead of it.

To get more accurate results, the value of \( m \) is determined by \( E1(d) \) instead of \( a(i,d) \).

\[
E(d) = \frac{1}{N - d \tau} \sum_{i=1}^{N-d\tau} a(i,d) \quad (8)
\]

\[
E1(d) = E(d+1)/E(d) \quad (9)
\]

It is found that \( E1(d) \) stops changing when \( d \) is greater than some value \( d_0 \) if the time series comes from an attractor. Then \( d_0 + 1 \) is the minimum embedding dimension looking for.

This paper use 1000 points to compare the results with this reference. From the Figure 10, the difference of E1-value between them is rather small. That is to say, the procedure in this paper can calculate this value correctly. In this experiment, the m-value is 6.
The E1-value in actual experiment with a pressure time-series

Fig. 10 The E1-value in different situation

(3) Segment Length $L$

The selection of L-value is to ensure that the vectors in the reconstruction phase space are unrelated. It is better that a time series contains at least not less than eight fragments, and each fragment contains a number of signals in the cycle of the pressure information. The method in this reference (van Ommen JR et al., 2000) is chosen. When $S$ begins to fall with the increasing $L$, $L$ is the suitable value. According to this method, $L$-value of pressure information in this experiment is 80.

Fig. 10 The Selection of L

(4) Length Scale $d$

$d$ is the length scale to compare the two vectors. Optimal value depends on the number of research object and decreases with the increasing data quantity. The method in this reference (van Ommen JR et al., 2000) is chosen, either. When $S$ begins to rise with the increasing $d$, $d$ is the suitable value, as shown in Figure 11. According to this method, $d$-value of pressure information in this experiment is 0.5.
4.4.3 The Calculation Process

The process of the procedure is shown as follows:

First get a time series of pressure information from normal fluidization, setting as a reference sequence.

\[ P_1, P_2, P_3, \ldots, P_N \quad (10) \]

In order to eliminate the impact of the apparent wind speed, standardization has been made to this sequence.

\[ x_k = \frac{P_k - \bar{P}}{\sigma_P} \quad (11) \]

The vectors come from the construction of its space:

\[ X_i = (x_{(i-1)m+1}, x_{(i-1)m+2}, \ldots, x_{im})', \quad N_k \text{ vectors Matrix A} \quad (12) \]

Similarly, get the Matrix B of the vectors to be detected. Matrix A and B form a new Matrix Z. Then calculate h function:

\[ h(Z_i, Z_j) = e^{-\frac{1}{4d^2} \| Z_i - Z_j \|^2} \quad (13) \]

To eliminate the relevance of the vectors, get the average value of \( h(Z_i, Z_j) \) in every L vectors of Matrix Z:
\[ H_{pq} = \frac{1}{L} \sum_{i=1}^{L} \sum_{j=1}^{L} h(Z_{(p-1)L+i}, Z_{(q-1)L+j}) \] (14)

Then, S Attractor can be calculated as follows:

\[ \tilde{Q} = \frac{2}{N_1(N_1 - 1)} \sum_{1 \leq p, q \leq N_1} H_{pq} + \frac{2}{N_1(N_1 - 1)} \sum_{1 \leq p, q \leq N_1} H_{pq} \sum_{N_1 + 1 \leq p, q \leq N_2} H_{pq} \sum_{N_1 + 1 \leq p, q \leq N_1 + 1} H_{pq} \] (15)

\[ V(\tilde{Q}) = \frac{4(N - 1)(N - 2)}{N_1(N_1 - 1)N_2(N_2 - 1)N(N - 3)} \sum_{1 \leq p, q \leq N} \psi_{pq}^2 \] (16)

\[ \psi_{pq} = HH_{pq} - g_p - g_q \] (17)

\[ g_p = \frac{1}{N - 2} \sum_{q \neq p} HH_{pq} \] (18)

\[ S = \frac{\tilde{Q}}{\sqrt{V_C(\tilde{Q})}} \] (19)

To test the accuracy of this procedure, comparison has been done between this paper and this reference (C. Diks et al., 1996). Two time series come from Henon function of different coefficient.

\[ X_{n+1} = 1 - aX_n^2 + bX_{n-1} \] (20)

The first time series is:

\[ a = 1.35, b = 0.31 \] (21)

The second time series is:

\[ a = 1.4, b = 0.3 \] (22)

\[ L = 18, d = 0.0025, \tau = 1, m = 3 \]

The results show that the more differences between the two series are, the greater the S-value is, in line with the reference. When the coefficient of time series is the same, S-value is less than 3. So it is credible for using this procedure to calculate S-value.

4.4.4 The Impact of the Number of Points
As shown in Figure 12, the more the number of points is, the greater S-value is. The procedure can
detect changes in the flow state more easily. If the conditions permit, it is better to use more points.
Considering computer performance and sensitivity, it is enough to use 3000 points in this experiment.

![Figure 12: The S-value in Different Calculation Points](image)

**4.4.5 The Comparison of Different Pressure Analysis Method**

Figure 13(a) shows the change of S-value in the same experiment. According to experimental records,
the bond begins gradually. The bond has a certain scale at 150 seconds. At 300 seconds the bond is
already very serious. S-value has the corresponding changes which can be seen from Figure 13(a). S-
curve is rising gradually, reflecting the particles begin to bond. S-curve rises very quickly from 150
seconds to 300 seconds, reflecting particles bond have a certain scale and are at a faster bonded
velocity. After 300 seconds, bond is relatively stable and shut-down happens. Therefore, the use of S
Attractor Method not only reflects the particles from the beginning when to bond, but also reflects
the velocity and trend of agglomeration.

![Figure 13: Comparison of Different Methods](image)

The results in Figure 13 come from the same experiment as mentioned above. The average pressure
and the standard deviation method can show a pattern of changes when bond begins, but the results of
the bond changes in the specific numerical value are difficult to determine. When S-curve shows a
significant change, the trends in Figure 13(b) and (c) are not obvious, so it cannot quickly determine
these changes whether indicate the occurrence and degrees of bond; Compared to the average pressure
and pressure deviation method, S-value is about 3 at 104 seconds. It shows that the current state is
different from normal fluidization, which is consistent with the experimental phenomenon. That is to
say, S attractor method could monitor the agglomeration much earlier, reflect the degrees of bond with the specific numerical value and also demonstrate the velocity of agglomeration.

5. CONCLUSIONS
This paper established a three-dimensional visualization experimental system to monitor the bonded process of coarse cohesive particles and study the method of early monitor of agglomeration. The conclusions are shown as follows:

(1) From the normal fluidization to shut-down, it can be divided into two phases. The former is a slower phase of the bond and the formation of core grew up phase; the second stage is the huge bonded core turn to bridge fast and shut-down happens with great velocity. Through the research of general law of agglomeration, it lays the foundation to early monitor of agglomeration.

(2) Through the study on pressure information of different points, the point which is very sensitive to the change of pressure is the point which is higher in the impact range of material. It can distinguish between different flow state and bonded state conveniently. After choosing the right measuring point, it has applicability to the average pressure method to realize the early monitor of agglomeration of coarse cohesive particles.

(3) For the pressure information of different bonded degrees, the components of characteristics vector got by wavelet analysis cannot show a pattern of changes accompanying the progressive deterioration of the situation or ease, so it is very difficult for using wavelet analysis in early monitor of agglomeration of coarse cohesive particles; The average pressure and the standard deviation method can show a pattern of changes with all the different degrees of bond, but the result of the bonded changes in the specific numerical value is difficult to determine, so it cannot quickly determine these changes whether indicate the occurrence and degrees of bond.

(4) Compared to other methods, S attractor method that is based on chaotic theory could monitor the agglomeration much earlier, reflect the degrees of bond with the specific numerical value and also demonstrate the velocity of agglomeration. Thus, it could be applied to the early monitor of agglomeration of coarse cohesive particles more conveniently.

ACKNOWLEDGEMENTS
This project is funded by The National Natural Science Foundation Projects (NO. 50432040).

NOMENCLATURE

\( S \)  the dimensionless squared distance \( S \) between two attractors
\( \hat{Q} \)  the estimator of the squared distance
\( V_{\hat{Q}} \)  the variance of \( \hat{Q} \)
\( m \)  Embedding Dimension
\( L \)  Segment Length
\( d \)  Length Scale
\( N \)  the number of samples
\( \bar{x} \)  the average value of sequence
\( y(d) \)  the reconstructed vector

Greek Letters
\( \tau \)  Delay Time

Subscripts
\( i \)  \( i \)-th coordinates
\( j \)  \( j \)-th coordinates
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