Shannon Entropy Increment Analysis on Dynamic Behavior of A Biomass Fluidized Bed

WQ Zhong, BS Jin, Y Zhang, XF Wang, MY Zhang, R Xiao
School of Energy & Environment, Southeast University, Nanjing 210096, P. R. China
wqzhong@seu.edu.cn

Abstract. Information theory based Shannon entropy increment analysis of the differential pressure fluctuations was successfully developed to recognize dynamic behavior of gas-solid flow and different flow patterns. Experiments were carried out in a biomass fluidized bed with cross-section of 100 mm × 30 mm and height of 500 mm was carried out. Cylinder-shaped biomass particles with the size of 2.6 mm in diameter and 6 mm in length were used to as bed materials. Pressure fluctuations and flow patterns were obtained by a multi-channel differential pressure sampling system and a high-resolution digital CCD camera, respectively. It was found that both Shannon entropy and the present developed Shannon entropy increment analyses were pronounced with the flow patterns and transitions. Besides, Shannon entropy increment analyses, i.e. Shannon entropy increment and Shannon entropy increment rate, are very helpful to obtain the chaotic nature especially the change of chaotic nature with operating condition in gas-solid flow.

1. INTRODUCTION

Pressure fluctuations in multiphase flows contain much dynamic information. Many methods, e.g. statistical analysis (Fan et al., 1984; Bi et al., 1995; Xu et al., 2004), power spectrum analysis (Vaccaro et al., 1997), chaotic analysis (Van den Bleek et al., 1993; Marzocchella et al., 1997; Ellis et al., 2003), fractal analysis (Fan et al., 1993; Lowe et al., 1999) and wavelet analysis (Lu and Li, 1999; Ellis et al., 2003) have been proposed to describe the dynamic behavior of two-phase flow successfully.

Besides, as a measure of the information content or complexity of measurement series, Shannon entropy analysis has been active in the multiphase flows since last decade. Kang et al. (1999) used the Shannon entropy of pressure fluctuations to detect the flow pattern transitions in three-phase fluidized beds. Zhang and Shi (1999) introduced the calculation of Shannon entropy to study the flow characteristics of two-phase flow systems. Shi et al. (2000) used Shannon entropy to characterize the air-water two phase flows in vertical pipes. Cho et al. (1999) studied the heat transfer and temperature fluctuations between an immersed heater and the bed proper in the riser of a three-phase circulating fluidized bed. Shi et al. (2004) employed Shannon entropy to describe the two-phase flow density wave instability for 200MW nuclear heating reactor. Zhong and Zhang (2005) attempted to depict the dynamic behaviors and flow patterns of a rectangular spout-fluid bed at ambient conditions by Shannon entropy. Camesasca et al. (2006) computed the Shannon entropy in order to find a suitable chosen group/complex of particles for a given species at a given location. Besides, measurements of the mixing performance based on Shannon entropy were employed to quantify the mixing of two miscible fluids by Chang and Yang (2006). Liang et al. (2007) analyze the dense-phase pneumatic conveying of pulverized coal with variable moisture content at high pressure by Shannon entropy. These efforts showed that it is promising to grasp the dynamic behaviors of multiphase flows by Shannon entropy analysis of pressure fluctuations.
It is known that entropy increment represents an event that transits from ordered to disorder in the second law of thermodynamics. Thus, we wonder whether the dynamic behavior especially the flow patterns and transitions could be described pronouncedly by Shannon entropy increment. The present work attempted to develop Shannon entropy increment of dynamic behavior of gas-solid flow and different flow patterns. It focused on studying dynamic behavior of gas-solid flow in the aspect of Shannon entropy increment.

2. THEORETICAL

2.1 Shannon Entropy

It is well known that the concept of entropy was firstly used in the second law of thermodynamics. As a state function, entropy reveals that the direction of any un-reversible spontaneous process in an isolated system is the direction of increased entropy. Then, the well-known physical scientist, Boltzmann, investigated the entropy in molecular movement theory and indicated that entropy was the reflection and the measurement of the chaos degree of molecular motion (Araujo et al., 2003). The founder of information theory, Shannon, introduced the concept of entropy into information theory, suggesting entropy is a measurement of the amount of information in a certain information source and the degree of indeterminacy in a certain system (Shannon, 1948), called Shannon entropy resulting in it enriching the meaning of entropy.

Shannon entropy provides a scientific method to the essential state of things (Otwinowski, 2006), which can be utilized to express the degree of uncertainty involved in predicting the output of a probabilistic event (Camesasca et al., 2006). That is to say, if one predicts the outcomes exactly before it happens, the probability will be a maximum value and, as a result, the Shannon entropy will be a minimum value. Besides, if one is absolutely able to predict about the outcomes of an event, the Shannon entropy will be zero.

The Shannon entropy of any differential pressure time series in a fluidized bed can be defined as

\[ S = -\sum_{i=1}^{n} p(x_i) \log[p(x_i)] \quad (1) \]

Where, \( n \) is the length of time series signal, \( p(x_i) \) is the probability of every component in the signal, satisfying the constraint \( \sum p(x_i) = 1 \). \( p(x_i) \) can be estimated by joint probability density formula. The unit of \( S \) is decibels (dB). It can be seen that the more disorder in a system, the larger Shannon entropy, which implies more complex and stochastic chaos nature resulting in turbulent motion of the gas or particles, gas-solid intensive interactions, flow instability, and etc.

2.2 Shannon Entropy Increment and Shannon Entropy Increment Rate

In the second law of thermodynamics, thermodynamics entropy increment represents an event that transits from order to disorder. For Shannon entropy, the value of entropy expresses the degree of uncertainty in a certain system. Similar to the thermodynamics entropy increment, Shannon entropy increment should also represent an event that transits from order to disorder.

The Shannon entropy increment in a multiphase flow system when the operating condition changes from \( i \) to \( j \) is defined as

\[ \Delta S_{ij} = S_j(x) - S_i(x) \quad (2) \]

Where \( S_i(x) \) and \( S_j(x) \) are the Shannon entropy of differential pressure time series at \( i \) operating condition and \( j \) operating condition, respectively.

\[ S_i(x) = -\sum_{i=1}^{m} p(x_i) \log[p(x_i)] \quad (3) \]
\[ S_j(x) = -\sum_{i=1}^{n} p(x_i) \log[p(x_i)] \]  
(4)

in which, \(m\) and \(n\) are the lengths of sampled time series.

In order to study the speed of Shannon entropy increment when operating condition changes, we define the Shannon entropy increment rate here. The Shannon entropy increment rate for the operating condition transiting from \(i\) to \(j\) is defined as

\[ \delta_{ij} = \frac{\Delta S_{ij}}{\Delta C_{ij}} = \frac{S_j(x) - S_i(x)}{C_i(x) - C_j(x)} \]  
(5)

Where \(\delta_{ij}\) is the Shannon entropy increment rate, and \(\Delta C_{ij}\) is the operating condition increment. \(C_i(x)\) and \(C_j(x)\) are the operating conditions \(i\) and \(j\), respectively. The unit of Shannon entropy increment rate \(\delta_{ij}\) is dB/ (unit of operating condition). If the unit of operating condition is m/s, the unit of Shannon entropy increment rate is dB/(m s\(^{-1}\)).

3. EXPERIMENTAL

An experimental setup was established to verify the simulations. The schematic diagram of experimental setup is shown in Fig.1. This set-up consists of a fluidized bed column, a gas supply system and some sampling instruments. The column has a cross-section of 100 mmX30 mm and a height of 500 mm. It was made of 6mm thick Plexiglas. The orifices in the air distributor are 1 mm in diameter, and the total area of all orifices is 1.1% of the gas distributor.

![Fig.1 Schematic diagram of experimental setup](image)

The fluidizing gas was supplied by a compressor supplied. A pressure-reducing valve was installed to avoid pressure oscillations and achieve a steady gas flow. Besides, an air desiccator was installed in the gas supplied pipe to avoid moisture in the gas. The gas flow rates were measured by flow meter. The fluidizing gas was sent into the gas chamber, and then entered the bed via the orifices in the gas distributor.

Pressure fluctuations in the bed were obtained by a multi-channel differential pressure signal sampling system. There were five pressure-measuring holes located on the back wall of the column,
with heights of 30 mm, 70 mm, 110 mm, 160 mm and 260 mm above the bottom of the bed. Every differential pressure sensor has two ports, one was connected to the pressure-measuring hole in the column wall, and the other was connected to a fluidizing gas chamber. The differential pressures were measured and then converted into voltage signals by multi-channel differential pressure signal transmitter. The voltage signals were sent to a computer through an A/D converter. A digital camera (Nikon 5000) was employed to photograph the flow patterns through the transparent wall during the experiments. Two groups of 2000W floodlights were used to enhance the photo definition when photographing.

Branches were cut to the cylinder-shaped particle with the size of 2.6 mm in diameter ($d_p$) and 6 mm in length ($L_p$). They were used as bed materials. The real density ($\rho_p$) of the biomass particle is 850 kg/m$^3$, the initial packed bed height ($H_0$) is 80mm.

4. RESULTS AND DISCUSSION

4.1 Total Pressure Drops with Superficial Gas Velocities

Pressure fluctuations were obtained at various superficial gas velocities. The mean values of total pressure drops with increasing superficial gas velocities are plotted in Fig.2. The total pressure drop sharply increases with increasing superficial gas velocity increasing to about 1.25 m/s, while the increasing of total pressure drop becomes slightly when the superficial gas velocity increases from 1.25 m/s to 2.25 m/s. For the superficial gas velocity increases over 2.25 m/s, the increasing of total pressure drop becomes sharply. The tendency of total pressure drop with increasing superficial gas velocity is similar to the previous report by Abdullah et al.(2003). According to the pressure drops with increasing superficial gas velocities, the minimum fluidizing velocity was determined to be about 1.24m/s.

![Fig.2 The total pressure drop with increasing superficial gas velocity.](image)

4.2 Flow Patterns at Different Superficial Gas Velocities

The flow patterns through the transparent wall were photographed by a digital camera (Nikon 5000) during the experiments. Fig.3 shows the flow patterns at different superficial gas velocities. The flow patterns are distinct with increasing superficial gas velocities. According to the images of flow patterns and the total pressure drop, the gas-solid flows can be divided into three patterns. They are under-fluidization (Fig.3a-e), steady fluidization (Fig.3f-i) and turbulent fluidization (Fig.3j-l).
Fig. 3 Flow patterns different superficial gas velocities: (a) \( u_f = 0 \) m/s; (b) \( u_f = 0.24 \) m/s; (c) \( u_f = 0.54 \) m/s; (d) \( u_f = 0.96 \) m/s; (e) \( u_f = 1.21 \) m/s; (f) \( u_f = 1.37 \) m/s; (g) \( u_f = 1.54 \) m/s; (h) \( u_f = 1.86 \) m/s; (i) \( u_f = 2.03 \) m/s; (j) \( u_f = 2.25 \) m/s; (k) \( u_f = 2.66 \) m/s; (l) \( u_f = 2.97 \) m/s.

For the flow pattern of under-fluidization, the gas-solid flow comes through the flow patterns of fixed bed (Fig.3a, b), bubbling with slugging (Fig.3c, d) and bubbling (Fig.3e) with the increasing of superficial gas velocity. Unlike spherical particles, larger bubbles can be seen in the middle of the bed when fluidizing of non-spherical biomass when the superficial gas velocity is less than the minimum fluidizing velocity. At this time, slugging can be often observed due to the movement of large bubbles. When the superficial gas velocity is beyond the minimum fluidizing velocity, the bed is fluidized. Here, we defined this kind of flow pattern as steady fluidization. Because the bed is not well fluidized but steady according to the phenomena observed in the experiments. Agglomeration of particles can be clear seen in the bed.

In this case, the bed could not be well fluidized. The phenomena agree well with the previous indication that biomass particles are difficult to fluidize due to their peculiar shapes, sizes and densities by Cui and Grace(2007). Besides, large bubbles can be seen in this flow pattern but the bubble size is less and the bed is much steady than those at the superficial gas velocity less than the minimum fluidizing velocity. When the superficial gas velocity is larger than 2.25 m/s, the bed is turbulent. In this case, the particles are fluidized but the interaction of gas and particles are unsteadily turbulent. Thus, we define this kind of flow pattern as turbulent fluidization.

4.3 Shannon Entropy
The Shannon entropies at different superficial gas velocities for three times measurements and their mean values are plotted in Fig. 4. It can be seen that the Shannon entropies increase with superficial gas velocities, implying the fact that the gas-solid interaction in the bed is more and more complex and stochastic when the superficial gas velocity increases, because Shannon entropy reflects the characteristic of dynamic behaviors (e.g. turbulent motion of the gas or particles, gas-solid intensive interactions and flow instability).

Besides, the Shannon entropies are found to be significant different for different flow patterns. In the flow pattern of under-fluidization, the Shannon entropies of pressure fluctuations sharply when the superficial gas velocity increases. While the increasing of Shannon entropy for the flow pattern of steady fluidization becomes slightly with increasing superficial gas velocity. When the flow pattern transits into turbulent fluidization, the increasing of Shannon entropy with increasing superficial gas velocity becomes sharply again. The results indicate that the changes of Shannon entropies of pressure fluctuations were pronounced with the transitions of flow patterns, which is similar to the previous findings (e.g. Kang et al., 1999; Zhong and Zhang, 2005).

![Fig. 4 Shannon entropy derived from pressure fluctuations for three times measurements at various superficial gas velocities.](image)

**4.4 Shannon Entropy Increment**

Fig. 5 plots the Shannon entropy increments for three flow patterns. The Shannon entropy increments were calculated by equation (2). The Shannon entropy increment is found to be larger than zero in all the cases. This means that the chaotic nature occurs in these flow patterns, and a fluidized bed was a deterministic chaos system since the Shannon entropy increment was positive. The Shannon entropy increment of steady fluidization is the lowest, while the Shannon entropy increment of turbulent fluidization is the highest. The pressure fluctuations are much more random in the turbulent fluidization than under-fluidization and steady fluidization, and the system appears a chaotic nature. The gas-solid turbulent motions were clearly observed during the experiments, and sometimes the growth of surface disturbances could be seen. However in the case of steady fluidization, the particles are fluidized steady, the pressure fluctuations are less random. As a result, the Shannon entropy increment is lower.

It can be seen that Shannon entropy increments are also very distinct difference to those flow patterns. For the flow pattern of under-fluidization, the mean Shannon entropy increments is about 0.5 dB. While for steady fluidization and turbulent fluidization, the mean values are about 0.1 dB and 1.4 dB, respectively.
4.5 Shannon Entropy Increment Rate

The changes of Shannon entropy with operating conditions can be described by Shannon entropy increment rate. The Shannon entropy increment rates for the flow patterns of under-fluidization, steady fluidization and turbulent fluidization with increasing superficial gas velocity are plotted in Fig. 6. The Shannon entropy increment rate with the increasing of superficial gas velocity is found to be about 2.5 dB/(m s\(^{-1}\)) from the linear fitting line at the flow pattern of under-fluidization. However, the increment rate of Shannon entropy drops at a low level for about 0.6 dB/(m s\(^{-1}\)) in the flow pattern of steady fluidization. For turbulent fluidization, the increment rate of Shannon entropy is about 4.9 dB/(m s\(^{-1}\)) when the superficial gas velocity increases.

The results indicated that turbulent fluidization appears largest insensitive in the change of chaotic nature at the flow pattern of turbulent fluidization, but least insensitive in change of chaotic nature in the flow pattern of steady fluidization. As a result, Shannon entropy increment analyses, i.e. Shannon entropy increment and Shannon entropy increment rate, are distinct difference to the flow patterns, besides they are very helpful to obtain the chaotic nature especially the change of chaotic nature with operating condition in gas-solid flow.
Fig.6 Shannon entropy increment rate with flow patterns: (a) under-fluidization, (b) steady fluidization, (c) turbulent fluidization.

5. CONCLUSIONS
As a kind of information, pressure fluctuations contain much dynamic information of multiphase flows. Thus, it is conceivable to grasp the dynamic behaviors of multiphase flows by information theory based Shannon entropy analysis. In the present work, information theory based Shannon entropy increment analysis of the differential pressure fluctuations was successfully developed to recognize dynamic behavior of gas-solid flow and different flow patterns. Experiments were carried out in a biomass fluidized bed with cross-section of 100 mm × 30 mm and height of 500 mm was carried out. It was found that both Shannon entropy and the present developed Shannon entropy increment analyses were pronounced with the flow patterns and transitions. Besides, Shannon entropy increment analyses, i.e. Shannon entropy increment and Shannon entropy increment rate, are very helpful to obtain the chaotic nature especially the change of chaotic nature with operating condition in gas-solid flow.

ACKNOWLEDGEMENTS
Financial support from the National Natural Science Foundation of China (50706007) was sincerely acknowledged.
**NOMENCLATURE**

- $C_i(x)$: operating condition $i$
- $d_p$: diameter of particles, [mm]
- $D_i$: diameter of spout nozzle, [mm]
- $D_t$: diameter of bed column, [mm]
- $H_0$: static bed height, [mm]
- $L_p$: length of cylinder-shaped particle, [mm]
- $P$: operating Bed pressure, [MPa]
- $P(x_i)$: probability of certain component in pressure fluctuations
- $Q_s$: spouting gas flow rate, [Nm$^3$/h]
- $Q_f$: fluidizing gas flow rate, [Nm$^3$/h]
- $Q_{mf}$: minimum fluidizing gas flow rate at $i$, [Nm$^3$/h]
- $S$: Shannon entropy, [dB]
- $n$: length of pressure fluctuation time series

**Greek Letters**

- $\Delta C_{ij}$: operating condition increment
- $\Delta S_{ij}$: Shannon entropy increment, [dB]
- $\delta_{ij}$: Shannon entropy increment rate, [dB/(operating condition)]
- $\rho_p$: particle density, [kg/m$^3$]

**REFERENCES**

Abdullah, M.Z. et al. (2003). “Analysis of cold flow fluidization test results for various biomass fuels,” Biomass and Bioenergy, 24, pp.487-494.

Araujo, D.B. et al. (2003). “Shannon entropy applied to the analysis of event-related MRI time series,” NeuroImage, 20, pp.311-317.

Camesasca, M. et al. (2006).“Quantifying fluid mixing with the Shannon entropy,” Macromolecular Theory and Simulations, 15, pp.595-607.

Chang, C. C. et al. (2006). “A particle tracking method for analyzing chaotic electroosmotic flow mixing in 3D microchannels with patterned charged surfaces,” Journal of Micromechanics and Microengineering, 16, pp.1453-1462.

Cho, Y. J. et al. (1999). “Heat transfer and bubble properties in three-phase circulating fluidized beds,” Chem.Eng.Sci., 75, pp.113-119.

Cui, H. et al. (1999). “Fluidization of biomass particles: A review of experimental multiphase flow aspects,” Chem. Eng. Sci., 62, pp.45-55.

Ellis, N. et al. (2003). “Characteristics of dynamic behavior in gas-solid turbulent fluidized bed using chaos and wavelet analyses,” Chem. Eng. J., 96, pp.105-116.

Fan, L.T. et al. (1984). “Analysis of pressure fluctuations in a gas-solid fluidized bed,” AIChE Journal, 30, pp.346-349.

Fan, L.T. et al. (1993). “Fractal analysis of fluidized particle behavior in Liquid-solid fluidized bed,” AIChE Journal, 39, pp.513-517.
Fuhrman, S. et al. (2000). “The application of shannon entropy in the identification of putative drug targets,” BioSystems, 55, pp. 5-14.

Kang, Y. et al. (1999). “Particle flow behavior in three-phase fluidized beds,” Korean Journal of Chemical Engineering, 16, pp.784-788.

Liang, C. et al. (2007). “Flow characteristics and Shannon entropy analysis of dense-phase pneumatic conveying of pulverized coal with variable moisture content at high pressure,” Chem. Eng. & Tech., 30, pp.926-931.

Lu, X. et al. (1999). “Wavelet analysis of pressure fluctuation signals in a bubbling fluidized bed,” Chem. Eng. J., 75, pp.113-119.

Marzocchella, A. et al. (1997). “Chaotic behavior of gas-solid flow in the riser of a laboratory –scale circulating fluidized bed,” AIChE Journal, 43, pp. 1458-1468.

Otwinowski, H. (2006). “Maximum entropy method in comminution modeling,” Granular Matter, 8, pp.239-249.

Shannon, C.E. (1948). “A mathematical theory of communication,” Bell System Tech. J., 27, pp.379-423.

Shi, L. et al. (2000). “Shannon entropy characteristics of air-water two phases flow regimes in vertical pipes,” Chinese Journal of Nuclear Power Engineering, 5, pp.411-415.

Shi, L. et al. (2004). “Shannon entropy characteristics of two-phase flow density wave instability experiments for 200MW nuclear heating reactor,” Chinese Journal of Nuclear Power Engineering, 1, pp.18-21.

Vaccaro, S. et al. (1997). “A technique for measurement of the jet penetration height in fluidized bed by pressure signal analysis,” Powder Technol., 92, pp.223-231.

Van den Bleek, M. et al. (1993). “Deterministic chaos: a new tool in fluidized bed design and operation,” Chem. Eng. J., 53, pp.75-87.

Xu, J. et al. (2004). “Statistical and frequency analysis of pressure fluctuations in spouted beds,” Powder Technol., 140, pp.141-154.

Zhang, Z.Y. et al. (1999). “Shannon entropy characteristics of two-phase flow systems,” Journal of Applied Physics, 85, pp.7544-7551.

Zhong, W. et al. (2005). “Characterization of dynamic behavior of a spout-fluid bed with Shannon entropy analysis,” Powder Technol., 159, pp.121-126.