Experimental and numerical study on gas-solid flow system of plastic pellets using recurrence quantification analysis of pressure sensor measurements

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Abstract

The recurring dynamics of fully developed gas-solid flow patterns are characterised using recurrence quantification analysis measure in horizontal pneumatic conveying of plastic pellets. This measure was applied to recurrence plots, developed from phase spaces (attractors) reconstructed from pressure signals to characterise the recurring dynamics of flow patterns: stratified flow, pulsating flow, moving dunes and blowing dunes. The recurrence plot is a representation of the recurring dynamics in the attractor. Recurrence plots were analysed for flow patterns which showed different qualitative structures. The qualitative structures of recurrence plots at different operating parameters are measured using recurrence quantification analysis such as recurrence rate (RR). The RR measure was correlated with the state diagram, indicating that the recurring dynamics of pressure signals can detect the change between moving dunes and blowing dunes at a specific range of operating conditions.

Keywords: *Pneumatic conveying; Attractor; Recurrence plot*

1. Introduction

Dilute phase, transition phase and dense phase flows are the main modes of operation in a horizontal pneumatic conveying system. The state diagram describes the pressure drop characteristic curve of the gas-solid flow transition spectrum from dilute to dense phase flow operations for specific particulate material [1]. The pressure drop directly relates to the air velocity in dilute phase flow operation and shifts to an indirect relationship for dense phase flow. The air velocity at the centre of this shifting curve is the optimal pneumatic conveying condition for minimum energy consumption, known as minimum conveying air velocity (MCAV). While the pressure drop line connecting the MCAV at different solid mass flow rates is known as the mínimum pressure drop minimum curve (PMC).

The instabilities of horizontal gas-solid flow patterns in the transition phase from dilute to dense phase flow increase as the operating conditions approach the PMC. The flow patterns in the transition phase near the PMC are rich with complex nonlinear dynamics. These complex dynamics can quantitatively be explored using high-dimensional phase spaces (attractors) reconstructed from time-series state measurements using the time-delay coordinate embedding method [2]. A phase space reconstructed from one time-series state measurement of a system can be topologically equivalent to the full state space of the system. The recurrence plot (RP) is used to visually observe this topology, initially introduced by [3], and its morphology is quantified using the recurrence quantification analysis, such as the recurrence rate [4]. This extended abstract presents recurrence plots analysis for different horizontal gas-solid flow patterns of plastic pellets developed using pressure sensor signals acquired at different operating parameters, air mass flow rate and solids mass flow rate. The recurrence plots are quantified using the recurrence rate measure and correlated with the observed flow patterns and the PMC in the state diagram.

2. Problem description

Experimental tests have been conducted in a close-loop pneumatic conveying system to capture fully developed gas-solid flow behaviour in a horizontal pipeline. Figure 1 shows a schematic of the industrial-scale pneumatic conveying system and its main components, including a 0.1 m inner diameter pipeline with a total length of 127 m, receiving hopper and blow tank with a 1.5 m^3 capacity, a screw feeder, and a nozzle bank. Two screw-type compressors are used to compress air in tanks at 5.2 bar, which is then regulated and introduced in the pipeline cycle from the blow tank to receiving hopper using the nozzle bank at two locations: the screw feeder and the pipeline inlet, which can be adjusted per the requirement. The solid mass flow rate is measured using a load cell at the receiving hopper and controlled by choosing a suitable air ratio between the blow tank and supplementary air and screw feeder motor speed. The air mass flow rate at the inlet of the pneumatic conveying pipeline system is controlled using the nozzle bank. The nozzle bank consists of two sets of eight nozzle sizes, which can incrementally control the air mass flow rate at the blow tank exit and pipeline inlet using different combinations of nozzles for each set, each with a maximum limit of 0.38 kg/s.

Cubical shape plastic pellets with a total batch mass of 800 kg are used, having a mean diameter of 3.6 mm, particle density of 910 kg/m3 and bulk density of 560 kg/m3. The pressure drop in the state diagram is developed using eight pressure sensors installed along a horizontal pipeline downstream of the third bend, as shown in Figure 1. The first pressure sensor is installed 8 m downstream of the third bend to ensure gas-solid flow is transitioned from accelerating to fully developed. The data used for the analysis is from the first pressure sensor, acquired at a high frequency of 525 Hz, while the load cell and the rest of the pressure sensors are sampled at 1 Hz, which is sufficient for the state diagram representation.

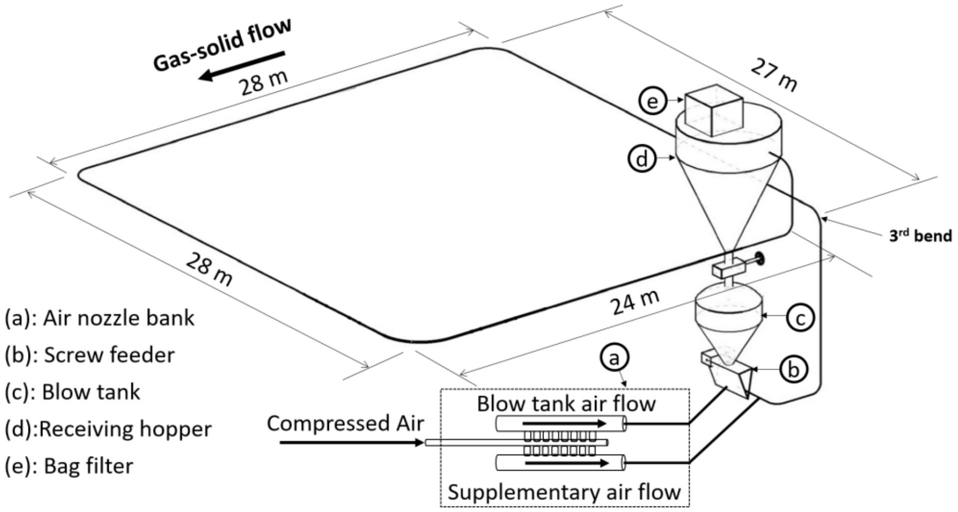


Figure 1. A schematic of the pneumatic conveying system setup.

Phase spaces are reconstructed using the time-delay coordinate embedding method from time-series measurements of air-wall pressure using a pressure sensor installed 8 m downstream of the third bend in the pneumatic conveying pipeline. Time-delay coordinate embedding method requires two parameters - time delay and embedding dimension. Consider a signal $X(t) = (x(t_1) \dots x(t_n))$, where n is the number of points acquired at constant sampling periods. Equation 1 shows the phase space data is in the form of a vector Y represented in the matrix form, where m is the embedding dimension, τ is the time delay, and N is the number of points in phase space ($N = n - (m-1)\tau$).

$$Y = \begin{bmatrix} x(t_1) & x(t_{1+\tau}) & x(t_{1+2\tau}) & \cdots & x(t_{1+(m-1)\tau}) \\ x(t_2) & x(t_{2+\tau}) & x(t_{2+2\tau}) & \cdots & x(t_{2+(m-1)\tau}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x(t_N) & x(t_{N+\tau}) & x(t_{N+2\tau}) & \cdots & x(t_{N+(m-1)\tau}) \end{bmatrix} \tag{1}$$

The recurrence plot is represented in a square matrix (RP) relating pairs of times at which phase points meet in a fixed hypersphere with radius r, as shown in Equation 2. The subscripts i and j are the index of the matrix for each pair of phase points. RPs have a main diagonal line that is black, separating two identical triangles, known as the line of identity (LOI). The identical triangles contain a geometric arrangement of recurrent points, denoted as typology, capable of revealing several global dynamic characteristics, such as periodic structure.

The periodic structure has repeated dense local structures and long diagonal lines separated at equal distances, describing a cyclic process.

$$RP = \Theta\left(r - \left\|Y_i - Y_j\right\|\right) \tag{2}$$

The recurrence rate (RR) measure is the ratio of recurrent points to the total number of points, as shown in Equation 3.

$$RR = \frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N} RP \tag{3}$$

3. Numerical results

The recurrence plots (RPs) of pressure signals are developed using phase spaces reconstructed using an embedding dimension of 10, a time delay of 1 and a hypersphere radius threshold r is selected at 10% of the máximum distance between phase points. Figure *2* (a), (b) and (c) shows 30s pressure sensor signals and their recurrence plots (RPs) for three different flow patterns, including the stratified flow, the moving dunes and near the blowing dunes transition to the settled layer. These distributions reveal various local white areas (LWA) and local bolt areas (LBA), providing qualitative information on pressure signal fluctuations. The RPs show dissipative structures with decreasing LWA values and, consequently, LBA increases, evolving from stratified flow to blowing dunes. Although the LWA increases, their occurrence and irregularity increase, meaning that the disruptions are due to more frequent but rare extreme events occurring in pressure signals.In stratified flow, individual plastic pellets are in suspension mode and are dispersed with high solid concentrations at the bottom section of the pipeline, having minimal effect on the complexity of pressure signals. The pressure signal behaviour of stratified flow is periodic, observed in the RPs shown in Figure *2* (a), through the consistency of diagonal lines parallel to the LOI, and repeated structure of LWA. As the flow evolves from stratified flow to moving dunes, as shown in Figure *2* (b), the thickness of the diagonal lines decreases and, in some instances, converges to thin lines. The moving dunes flow pattern has more influence on the complexity of pressure fluctuations than stratified flow, which is caused by airflow redirections around and through the dunes creating high pressure in the luff and low pressure on the lee side of the dune. This complexity is magnified even further in blowing dunes as dunes size increases, forcing the air to flow through smaller areas. This event of high and low-pressure pulses around the dunes depends on its shape, size, and interaction with the dispersed particles on top and the pipeline wall at the bottom. The chance of having these interactions repeated in a short period is rare, reflected in the increased number and complexity of LWA from stratified flow to blowing dunes.

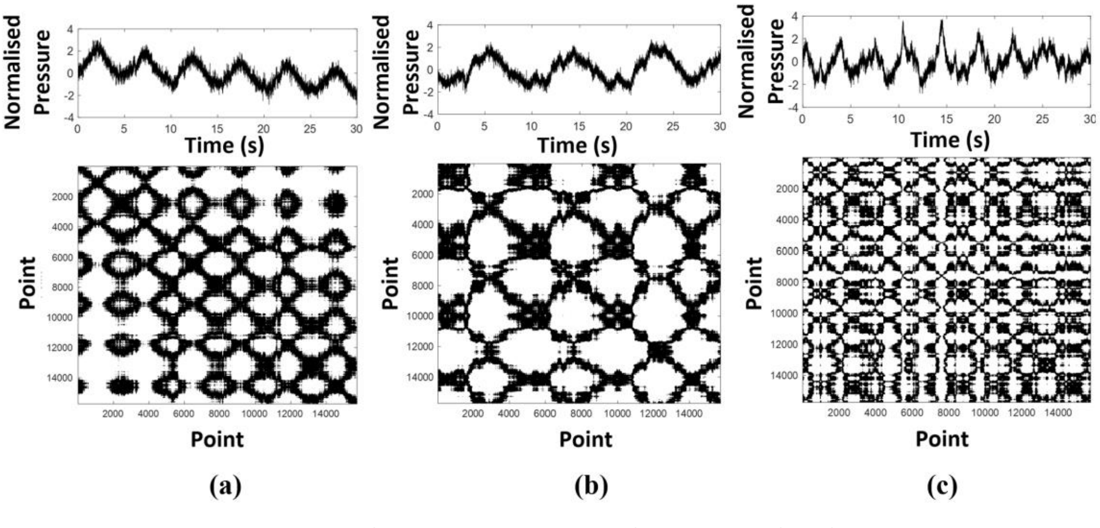
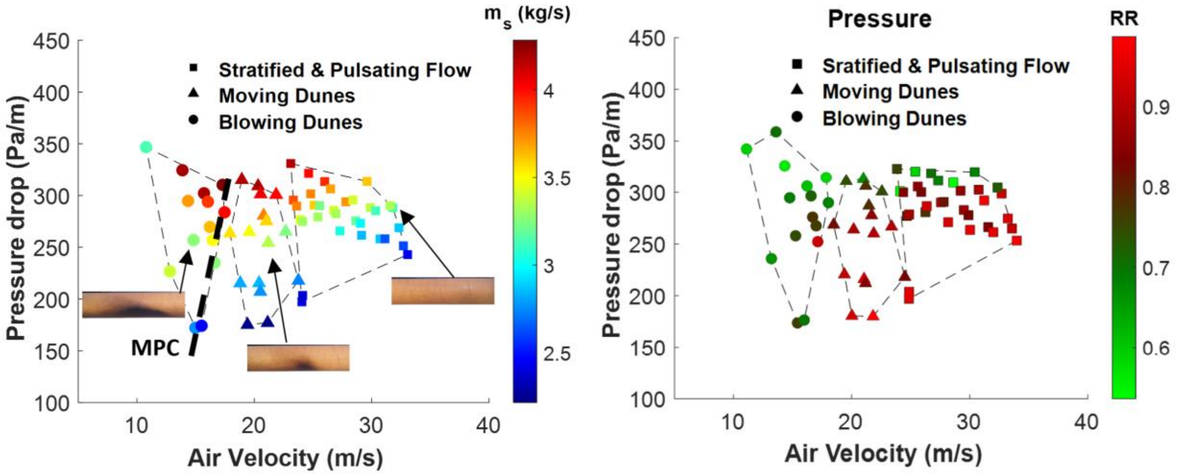


Figure 2. Recurrence plot developed from pressure signals for (a) stratified flow, (b) moving dunes and (c) blowing dunes at air velocities 33.5, 20 and 16 m/s and solid mass flow rates = 2.6, 2.2 and 2.5 kg/s.

Figure 3 (a) shows a state diagram with classified flow patterns developed from the horizontal pneumatic conveying of the plastic pellets. The superficial air velocity is calculated based on the mean pressure and pipe diameter using the ideal gas law at ambient temperature and plotted as a function of the pressure drop per unit length of pipe. The superficial air velocity in stratified, pulsating and moving dunes directly relates to the pressure drop. While the superficial air velocity of blowing dunes has an indirect relationship with the pressure drop, indicating that the PMC is between moving dunes and blowing dunes. Figure 3 (b) shows the RR of pressure signals correlated with the operating conditions in the state diagram. The RR profile can identify the PMC by distinguishing between moving dunes and blowing dunes flow patterns at a low solid mass flow rate ranging from 2.2 to 3.5kg/s. The RR at high solids mass flow rate above 3.5 kg/s is no table to detect changes between moving dunes and blowing dunes.



(a) (b)

Figure 3. State diagrams for horizontal pneumatic conveying of plastic pellets with classified flow patterns regions showing the profile of (a) solids mass flow rate and (B) the recurrence rate.

4. Conclusions

Recurrence plots are developed from pressure sensor signals in horizontal pneumatic conveying of plastic pellets to analyse the recurring dynamics of gas-solid flow in the transition phase between dilute and dense phase conveying conditions. The recurrence plot is quantified using the recurrence rate, and its profile can distinguish between moving dunes and blowing dunes at a low solid mass flow rate ranging from 2.2 to 3.5kg/s, with no apparent change in the RR between the flow patterns operating at solids mass flow rates higher than 3.5 kg/s.

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References

[1] A. B. Makwana, A. Patankar, and M. Bose, “Effect of dune formation on pressure drop in horizontal pneumatic conveying system,” *Particulate Science and Technology*, vol. 33, no. 1, pp. 59–66, 2015, doi: 10.1080/02726351.2014.936541.

[2] F. Takens, “Detecting strange attractors in turbulence Dynamical Systems and Turbulence,” *Dynamical Systems and Turbulence*, vol. 898, pp. 366–381, 1981, [Online]. Available: http://dx.doi.org/10.1007/bfb0091924

[3] J. P. Eckmann, O. Oliffson Kamphorst, and D. Ruelle, “Recurrence plots of dynamical systems,” *Europhys Lett*, vol. 4, no. 9, pp. 973–977, 1987, doi: 10.1209/0295-5075/4/9/004.

[4] J. P. Zbilut and C. L. Webber Jr, “Embeddings and delays as derived from quantification of recurrence plots,” *Phys Lett A*, vol. 171, no. 3–4, pp. 199–203, 1992, doi: 10.1016/0375-9601(92)90426-M.