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Quantitative comparison of image analysis methods for particle mixing in rotary drums

Xiaoyan Liu [a,b,*], Chaoyu Zhang [a], Jiesi Zhan [a]

[a] College of Electrical and Information Engineering, Hunan University, 410082 Changsha, China

[b] State Key Laboratory of Synthetical Automation for Process Industries, Northeast University, 110004 Shenyang, China

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ABSTRACT

Optical imaging is a powerful tool for the study of particle mixing dynamics in rotary drums because it offers abundant choices of image analysis methods. However, little effort has been made to investigate the compatibility of the results obtained by those different methods, and the magnitude of deviations between them remains unclear. The present work contributes to quantitative comparison of two classic image analysis methods (Variance and Contact), with special attention to the procedures for measuring the mixing time which is an important parameter describing the mixing efficiency of drum equipments. For conditions tested in our experiment (red/white binary mixing in a drum of ID 206 mm captured by a camera with 25 fps), a relative deviation of 20%–36% was found between mixing times determined by different image processing algorithms and regression models. Compared to Variance, Contact can improve the measuring accuracy by 20% but requires 40% more computing time. An increase of the number of cells shows no significant effect on the processing speed of Variance. For regression analysis of the data, the second-order model is shown to be more reliable than the first-order model. Based on the comparative results of the present work, we would suggested that image analysis procedures for particle mixing be standardized so that reasonable conclusions can be drawn from measurements of different resources.

1. Introduction

Particle mixing in rotary drums is a fundamental operation in pharmaceutical and metallurgical industries, with the objective of obtaining a defined homogeneity in the particles within a shortest possible mixing time. However, the underlying kinematics of mixing has not been fully understood [1–3]. In order to attain more information, several non-invasive measuring techniques have been developed in the past years to monitor the transient mixing process, including positron emission tomography (PEPT) [4,5], magnetic resonance imaging (MRI) [6] and optical imaging [7–9]. PEPT permits the trajectory measurement of a single positron-emitting tracer particle but does not reveal concentrations; MRI is well suited for determining structure of the mixture but hard to use outside specialized laboratory studies [1]. In comparison, optical imaging has the advantages of relative simplicity, low costs and potential use on process plant [8]. It allows rapid recording of images at a surface of the particle bed from a camera with flexible adjustment of contrast and image size. The change of mixing quality over the time, and the time allotted to reach certain homogeneity of the mixture (mixing time) can be obtained conveniently by using image processing algorithms, such as Variance [1], Contact [10], Entropy [11], Gray-Level Co-occurrence Matrix (GLCM) and Discrete Wavelet Transform (DWT) [12]. However, little effort has been devoted to investigate the compatibility of those measured results which are sometimes puzzling and even contradictory. Contributive work was done by Gosselin et al. in [12] where the mixing of black and white particles was followed by a camera (frame rate = 0.5 fps, drum diameter D ≤ 75 mm) and analyzed separately using Entropy, Contact, GLCM and DWT. It was reported that Entropy overestimates the state of mixing, while the other three methods provide good results among which GLCM is best suitable in terms of speed and reliability. However, a quantitative comparison of the mixing times determined based on these different methods were not investigated. Aissa et al. [9] improved GLCM in combination with RGB color analysis so that it can be applied to systems of different colors, but the whole image processing speed has to be sacrificed.

With the rapid development of digital image processing technology which offers abundant choices of algorithms, there is no doubt that optical imaging will become a powerful tool for the study of mixing dynamics. The question left is, "are the results compatible when one applies different image analysis methods and what is the magnitude of the deviation of the results?" Such a question is frequently raised by drum designers and users who are concerned mostly on the mixing efficiency of the drum equipment. The present work tries to answer this question through experimental study in which the particle mixing of a

* Corresponding author. Tel.: +86 731 88822224.
E-mail address: xiaoyan.liu@hnu.edu.cn (X. Liu).

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binary system in a relatively larger drum (D = 206 mm) is followed by a fast camera (25 fps), and the mixing times determined by two different image analysis methods (Contact and Variance) are compared. The comparisons are limited to Contact and Variance because they belong to classic image analysis methods that are widely used in practice due to their good interpretability and simplicity.

2. Experimental

A steel rotary drum of diameter 206 mm was used in the experiment. It is covered with a glass plate on the front end and another glass plate fixed inside the drum, as shown in Fig. 1. Glass plate is chosen because it has good transparency for visual observation as well as low friction for reduction of the end-effects. Two layers of colored particles, consisting of 500 red ones on the bottom and 500 white ones on the top (plastic balls, d = 6 mm, bulk density = 1.414×10^3 kg/m^3) were put into the space between the two glass plates (with an axial depth of 26 mm). The free surface of the particle bed was horizontally positioned before the drum was rotated. The drum speed was configured at 5.74 rpm so that the bed motion was restricted to the rolling pattern where the surface flow is in the rolling regime [13]. The transverse mixing was followed by a video camera fixed perpendicularly to the front glass plate, at a frame rate of 25 fps with a resolution of 720 × 480 pixels. To ensure that the details of particle-to particle interactions be captured, the space resolution is configured relatively high with around 177 pixels for each particle in the image. In order to obtain good color contrast between particles and to reduce light disturbances, a black background was placed behind the drum and a lamp was used for illustration. The video of transverse mixing was later de-framed as image sequences using Adobe Premier. Fig. 2 shows some raw images of particle mixing at different time stages. It can be seen that transverse mixing is rather fast and tends to settle down on macroscopic level in about 30 s. It is therefore reasonable to use only those images in the first 70 s (1750 images in total) for further analysis so that calculation time can be reduced.

3. Image analysis of the mixing dynamics

3.1. Pixel classification

To investigate the mixing between white and red particles, the pixels in each image should be classified. To achieve this, RGB color analysis was performed using Image Processing Toolbox provided by Matlab. The thresholding was selected since the particles and background were well contrasted in our case. With color histogram analysis, a threshold of 128 was found appropriate for pixel classification in our case, as shown in Fig. 3 where pixels with (R > 128) & (G > 128) & (B > 128) were classified as white particles and pixels with (R > 128) & (G < 128) & (B < 128) as red ones, while other pixels were treated as black background. It can be seen from Fig. 2 that the classification method is effective in identifying the red and white particles which lie just against the front glass plate of the drum (the first layer of particles), and the particles in the second layer were mostly filtered as background. This is actually advantageous in the analysis of transverse mixing which requires that the particles to be analyzed should be in the same cross section of the drum (two dimensional).

Based on the classified image, the degree of particle mixing can be described using Variance or Contact image analysis method.

3.2. Variance method

This method requires that the bed region in the image be subdivided into a certain number of cells. The mixing quality is quantified using the concentration variance of the system defined by [1]

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(c_i - c)^2 \tag{1}$$

where n is the number of cells and, c_i is the concentration of a certain component in cell i calculated by area fraction as

$$c_i = \frac{\text{number of red pixels}}{\text{number of red pixels} + \text{number of white pixels}} \tag{2}$$

and c is the average value calculated as

$$c = \frac{1}{n}\sum_{i=1}^{n} c_i. \tag{3}$$

Theoretically, c should be equal to 0.5 since the number ratio of the red and white particles is 1:1. Due to the quasi-2D drum configuration and inevitable measuring error, the value of c is around 0.48 in our case.

By applying the above calculation procedure to each image, the change of concentration variance σ^2 with time (mixing curve) can be obtained. For convenience, the square-root of the concentration variance will be used in the following discussions, as shown in Fig. 4 where the change of σ with time is illustrated. It is shown that σ begins with a high value at $t = 0$ where the bed is totally segregated and then decreases sharply in the first 10 s with the rapid transverse mixing of particles and then tends to settle down at around 15–30 s. A decrease

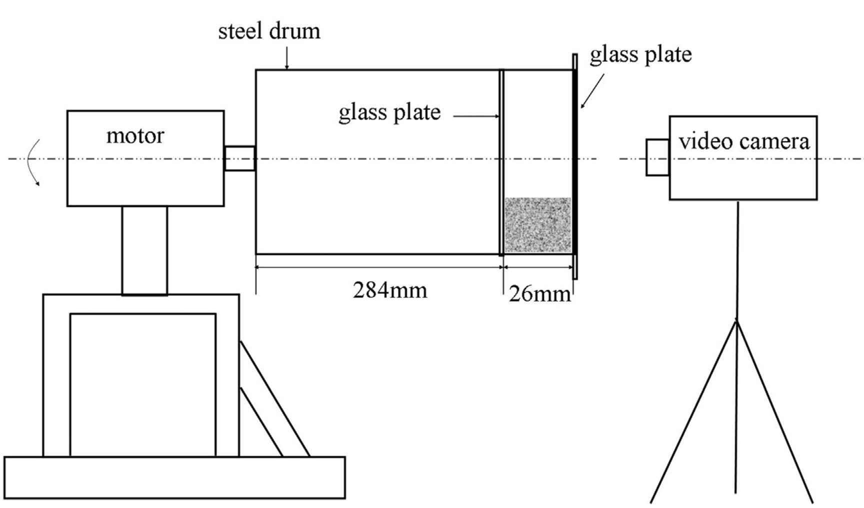

Fig. 1. Schematic representation of the experimental set-up.

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