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Characterization of mixing of binary particles in a continuous colliding static mixer

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ABSTRACT

The mixing of particulate solids in a continuous colliding static mixer was studied by using binary particles with different colors and properties. A method of image analysis was used to measure the contrasting colors in a sample picture in order to quantify the component concentration, thus to evaluate the mixing homogeneity of different particles. Experiments were conducted to investigate the effect of the number of mixing internals, feeding mass ratio, particle size and falling height on mixing performance of the mixer. The results showed that mixing homogeneity seemed to stabilize at certain standard deviations after colliding with four mixing internals. Large size particles were easier to be mixed than that of small particles, which indicated that a continuous colliding static mixer was suitable for mixing binary inhomogeneous particles in millimeter scale with salient difference in particle sizes. There was an optimal mixture surface position in the falling height. For large particles, the optimal mixture surface position was only a small distance in the falling height. The predicted model proposed in our study was able to describe the mixing characteristics in the continuous colliding static mixer quantitatively.

1. Introduction

The mixing of particulate solids is a ubiquitous and important unit operation in many industrial processes, such as, chemical, pharmaceutical, fertilizer, ceramic and food. Especially, in the fuel pyrolysis process with solid heat carriers, good mixing of particles with different properties plays a very important role in the transfers of heat and mass among particles, the pyrolysis reaction, and pyrolysis oil yield and quality. It is hence of high theoretical and practical value to investigate mixing process of particulate solids. Static or motionless mixers are commonly applied in process technologies for solid mixing. Comparing with common mechanical mixers, there are a number of advantages of the static mixer, e.g., rapid and continuous operation, energy and labor efficiency, minimum space requirement, low manufacturing and maintenances costs, and less particle wearing and so on [1–3].

There are two types of particle static mixer frequently used in process industry. One of them is splitting, shifting, shearing, rotating, accelerating, decelerating and recombining of different parts of materials which resembles fluid flow [3], namely the analogously fluid flow static mixer (hither to refer to as AFFSM). The flow regime is a quasi-static dense flow. The movements of particles are sliding with a slow velocity and the inter-particle interactions by frictional contact. The other one is the gravity induced collision of particulate solid materials when they flow through the channel, which is named as continuous colliding static mixer (hither to refer to as CCSM) [4]. The flow regime is a rapid dilute flow. The movements of particles are almost free falling with a rapid velocity and inter-particle interacts by collisions [5]. Fig. 1 shows the differences between the two kinds of static mixers. Previous studies [1,6] revealed that segregation would occur if there was a free area to form a hollow flow cone or a moving surface in AFFSM. However, CCSM can avoid such segregation during mixing and has wide operation flexibility. As opposed to a variety of studies on AFFSM with DEM simulations and experiments [7,8], research to date has failed to bring sufficient data in quantitative researches on CCSM.

The typical industrial application of a CCSM is in the solid fossil fuel pyrolysis process. Solid fossil fuel and solid heat carriers are mixed by the mixing internals [9–15] with rapidity in the upper mixing section and those homogeneously distributed mixtures subsequently drop down on the bottom section where reactions take place and the resultant mixture is discharged slowly. The particle systems in solid fossil fuel pyrolysis process industry belong to binary inhomogeneous systems in the millimeter or submillimeter scale. The mechanical motion behavior of this range particle system is mainly manipulated by gravity. Besides, the mixing process is profoundly influenced by the physical properties of solid materials. Free flowing particles with differences in size, shape and density subject to the risk of inhomogeneity and poor quality in mixture [1,16–18]. The mixing may result in migration of smaller particles downwards and of larger ones upwards, and the migration of heavier particles downwards and of lighter ones upwards. The approximate spherical particles can be easily mixed than those with irregularity shapes [6,8]. The mixing of granular materials of different particle properties is generally accompanied by segregation which is reported by several researchers in AFFSM [19,20]. However, little

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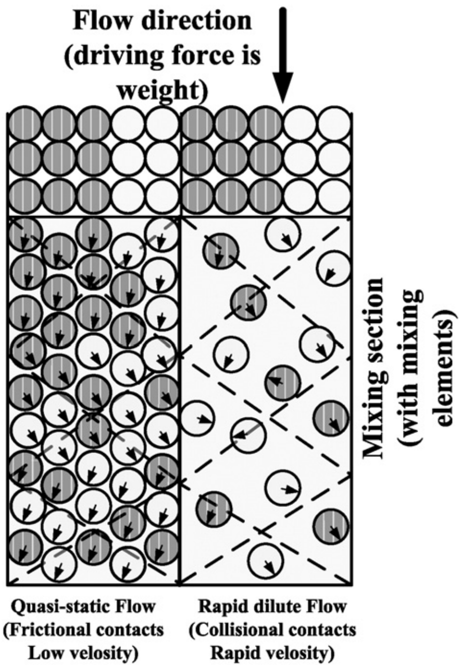

Fig. 1. Characteristic flow regimes in two different static mixers.

published investigations on the mixing of solids with different properties in CCSM are available.

The measurement of mixture quality plays an important role in assessment of the performance of mixing process. Thief sampling [21] is a direct means to detect the mixture composition inside the mixer. The number, size and position of samples directly affect the accuracy of measurement. Another method is sampling during discharge [22]. However, this method could not determine the truly mixture composition inside the mixer. There are also researchers by using differences of products to assessment mixing quality indirectly [11,12]. Thus, rapid, reliable and accuracy method of measurement is needed for assessment of mixture quality. Recently, with the development of image analysis, immediate and rapid scan sampling method is suitable for evaluating mixture quality.

In this study, we design a typical pyrolysis process industrial applicable CCSM apparatus for solid fuel particles, such as coal and oil shale. The binary particle systems with different properties are chosen as the experimental materials. "Frozen cutting method" is used in this experiment to determine the mixing state. In order to investigate the mixing performance inside the mixer, every mixing state is frozen (namely rapid suspend the mixing at a certain position) and recorded by using a digital camera of the cutting cross-section. The sample picture of mixture state is qualified by image analysis. The objective of the present work devotes to investigating the effect of several governing process factors and evaluating the mixing characteristics in a CCSM quantitatively.

2. Experimental

2.1. Static mixing set-up

A schematic of the experimental setup of CCSM is shown in Fig. 2. It consists of three parts: feeding section, mixing section, and collecting section. Two volumetric hoppers feed materials into the static mixer through a rotary feeder. Its mixing zone is a tube of 400 mm in diameter, in which conical baffle type structure internals are inserted as mixing elements (see Fig. 2). The mixing element is installed from the top of the mixing zone, and as many as five mixing elements can be installed in the whole mixing zone. The collecting zone is a tube with the same diameter as the mixing zone, with mixture discharged through a rotary discharger on the bottom. The speed of all the rotary devices in the experiment is regulated by a frequency converter, which functions to charge the accurate amount of materials.

2.2. Particulate systems

In order to study the mixing of particles in CCSM for a typical industrial application, binary particles in pyrolysis process industry were chosen as the experimental materials. Solid heat carriers with high hardness and thermal conductivity are often used to heat up solid fossil fuel particles in pyrolysis process. With heat provided by solid heat carriers, solid fossil fuel can be heated up to around 500 °C and converted into semi-char, tar and gaseous products [23,24]. In this study, the ceramic ball (white) was referred as the solid heat carriers, and oil shale (black) was chosen as fuel material (see Fig. 3). The properties of materials are shown in Table 1, with differences in particle size, shape and density. Such a broad materials system is typical in industry.

2.3. Methods

"Frozen cutting method" was used in this experiment to sample and measure the mixing state. Before mixing, each of the hoppers was filled with enough materials. Then, the two feeding rotary were opened at the same time, and the bottom discharging rotary was closed during the mixing process. In order to investigate the mixing performance inside the mixer, every mixing state was frozen (namely rapid suspended the mixing at a certain position) and a picture was taken by using a digital camera of this cutting cross-section (see Fig. 4). The position of the cutting cross-section was regulated by the bottom discharging rotary so that the mixture state of different fall height was recorded by this method. When investigating the effect of other factors on mixing performance expect for falling height, the position of the cutting cross-section was fixed in the collecting zone with 150 mm distance from mixing zone.

Gray scale image analysis technique in quantifying the component concentrations in binary mixtures of contrasting colors is a simple and immediate method to study mixing process [16,25]. Based upon this technique, a method of image analysis was used to measure black and white particles in a given sample picture. The cross-section picture was divided into nine areas of interesting (AOI) which was shown in Fig. 4. The resulting image was processed using the Photoshop image software package to calculate pixels, and subsequently the approximately particle areas in each AOI. Therefore, the concentration of black particle (C_b) can be defined as:

$$C_b = \frac{S_b}{S_{AOI}}$$

where S_b is the area of black particle and S_{AOI} is the area of the whole AOI.

The mixture homogeneity can be expressed as the function of the concentration standard deviation σ, and the definition is as follows:

- the mean of the concentration of black particles can be expressed as:

$$\overline{C_b} = \frac{1}{n}\sum_{i=1}^{n} C_{bi}$$

- the standard deviation of the concentration of black particles:

$$\sigma_b = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(C_{bi} - \overline{C_b}\right)^2}.$$