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Original Research Paper

The joint mixing action of the static pre-mixer and the rotating drum mixer – Discrete element method approach

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A B S T R A C T

In this study, the mixing performance of coupled mixing action of the Komax static mixer (which is used as a pre-mixer) and rotating drum (applied as the final mixer) was explored in the maize meal mixing operation. The main objective of this paper was to predict the behaviour of the previously grinded maize particles, during the mixing process in static mixer and drum mixer, and to explore the possibilities to shorten the mixing time in the main mixer (in order to reduce the energy consumption).

Three different experiments were performed: in the first experiment, possibilities of static mixer were explored, second experiment showed the mixing performance of rotating drum, and the combination of these two mixing devices was investigated in the third experiment. Homogeneity of the obtained mixtures was determined experimentally, by the "Microtracers" method.

The Discrete Element Method was used for modelling of granular flow in the pre-mixing and final mixing applications, and to predict the inter-particle mixing quality within a static mixer and the rotating drum mixer. The results of the numerical simulation are compared with appropriate experimental results. The possible industrial application of this model could be the optimization of parameters of mixing systems taking into account the quality and the duration of the mixing process.

1. Introduction

The mixing of granular and powder materials are used in different areas of industry such as energy sector, food, pharmaceutical, agricultural, chemical and process industry. These materials can be found in various shapes, concentrations, and amounts.

The mixing of granular materials consists of simultaneous diffusion, convection and shear processes, which represent the main mechanisms of the homogenization [1].

Understanding these mechanisms and the behaviour of materials is important for a correct design and construction of processing units such as static mixers and rotating drums.

The most effective way to optimize the mixing process is to use mathematical modelling.

Modelling of flow and particle motions in the rotating drums has been a research topic in the previous researches. The mathematical modelling seems to be a very suitable tool to find the best method of operation, or to determine how the system responds to changes in mixing conditions, otherwise this investigation would require many experiments. The numerical simulation results are reflected in the reduction of labour costs and reducing the time required for the experiments.

The discrete element method (DEM), introduced by Cundall and Strack [2] has proven to be a capable tool for predicting the mechanism and behaviour of particles mixing in various mixing devices. The most comprehensive review about the applications, possibilities and opportunities of discrete element method in recent years was given in the paper by Zhu et al. [3]. DEM can provide plenty of valuable information about the mechanism in rotating drums and static mixers, the physical mechanisms of granular flows and the operating conditions. A detailed review of previous results in the area of mathematical modelling and numerical simulation using DEM for granular materials is given in the paper by Bridgwater [4].

In the study performed by Xiao et al. [5], the parameters of the particles being mixed were determined by a series of tests such as high rebound test, friction and wear test, stacking angle test. The

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mixing behaviour of particles in a rotating drum mixer was analysed by experiment and DEM simulation in order to discuss the effect of particle density in the paper by Yamamoto, Ishihara and Kano [6].

The effects of particle shapes on the mixing process in a rotating drum mixer were investigated by Höhner, Wirtz and Scherer [7], and the application of the DEM was introduced. The spherical shapes were mixed more easily than the polyhedral elements, and the increase of particle angularity leads to an increase of the dynamic angle of repose. The spherical and non-spherical particle dynamics during mixing operation, and the effects of angle of repose was also investigated by Norouzi, Zarghami and Mostoufi [8]. Modelling of the flow of ellipsoidal particles in a horizontal rotating drum mixer, based on DEM simulation was analysed in the study performed by Ma and Zhao [9]. The effects of the aspect ratio and the rotation speed on the mixing process were concerned. Mixing results in the horizontal rotating drum are presented and discussed in terms of mixing times and mixing numbers, that means numbers of revolutions necessary for uniform mixing of the solids [10].

A particle dynamics simulation of granular systems in differently shaped mixing systems has been investigated by Ayeni et al. [11]. Within this work, segregation was used as a method of quantifying the quality of mixing. An attempt to understand the mechanism of the dead zone formation during the mixing process, and the degree of mixing of varying mixing parameters was performed by Soni et al. [12]. The investigation performed by Xu et al. [13], indicated that higher rotation speed can significantly enhance mixing. The various effects on mixing process, such as rotational velocity, filling degree and presence of an inner tube amidst the particles were investigated by Tada et al. [14]. In this study, the image analysis technique was used to evaluate the mixing quality. The velocity fields are investigated for the rotating drums and the numerical simulations based on the DEM was conducted using graphics processing units in the works by Qi et al. [15] and Santos et al. [16]. These numerical simulations showed that an alternative to experiments could be provided by appropriate DEM studies.

Combined modelling of the particle mixing in the rotating drum by using DEM and Population Balance model was investigated in the study by Kumar et al. [17]. The authors showed that the combined modelling approach is much faster than only using DEM and that the results of the modelling can be compared with the experimental results in the satisfactory manner.

Static mixer can be added in-line, as a pre-mixing device to shorten and improve the final mixing process. The static mixers are low cost, low energy devices which use energy from gravitational force as driving force to produce the desired mixing results in the process [18–21] Static mixer is made as a channel with a specific geometric construction and has influence on the flow characteristics enabling mass and heat transfer in the cross-section [19].

The focus of this paper was to predict the behaviour of previously grinded maize meal in Komax static pre-mixer and rotating drum, which is used for the final mixing process. Three mixing tests were conducted: in the first experiment the outcomes of static mixer were analysed, in the second experiment demonstrated the rotating drum mixer capabilities, while the third experiment dealt with the results of the combination of these two mixing methods.

The mixing quality was determined using "Microtracer" method. The results of this study can be applied in industrial processes to reduce total mixing time by shortening the final mixing step. In this study, the DEM is used for mathematical modelling of granular flow in the multiple Komax mixing device and rotating drum mixer. The numerical simulation results are compared with appropriate experimental results, demonstrating that this model gives the streamlining of parameters of mixing systems taking into account the quality of the mixing process and the cost of the final product.

2. Materials and methods

2.1. Material properties determination

The experimental procedures shown within this investigation, present a study which was performed in "Feed to Food" pilot plant, in the Institute of Food Technology, Novi Sad, Serbia.

The water content in maize (9.74% wb) was determined in three repetitions, according to the standard method (after drying at 105 °C, to a constant weight), and as such falls within the limits prescribed by the Serbian standards [22–24], which is less than the maximum allowed level of 14% for raw material for feed.

Maize was grinded in a laboratory hammer mill (Model 11, ABC Engineering, Pančevo, Serbia). The hammer mill was equipped with a screen with the openings of 3 mm.

Maize meal granulometric composition was determined on laboratory Endecott's sieving shake, (Minor, Endecotts Ltd., London, UK), with a screen size of 3150, 2500, 2000, 1600, 1000, 630, 250, 125 and 63 μm, according to ANSI/ASAE standard S319.3 [25]. The averaging of each sample was done in three repetitions with a sample weight of about 100 g. After screening, the mass of the material was measured at each sieve at bottom and the particle size distribution obtained was measured. The results of the granulometric analysis of the maize meal are shown in Fig. 1.

The geometric mean diameter (GMD) and the geometric standard deviation (GSD) were calculated according to the following equations [26]:

$$GMD = \log^{-1}\left[\frac{\sum_{i=1}^{n}(W_i \cdot \log d_i')}{\sum_{i=1}^{n} W_i}\right] \quad (1)$$

$$d_i' = \sqrt{d_i \cdot d_{i+1}} \quad (2)$$

$$GSD = \log^{-1}\left[\frac{\sum_{i=1}^{n}(\log d_i' - \log GMD)}{\sum_{i=1}^{n} W_i}\right] \quad (3)$$

where

d_i (μm) - diameter of the i-th sieve opening

d_i' (μm) - the geometric mean of the particle diameter on the i-th sieve

W_i - mass of material on the i-th sieve.

The GMD value of the maize meal in the conducted experiments was 694.73 μm, which corresponds to the values for mixtures commonly used in animal nutrition [27–29]. The obtained GSD value was 2.42 μm, which indicates a wide particle size distribution of the size of the maize meal particles, and also corresponds to the values usually obtained in the animal feed mixtures [25].

The bulk density of the material was determined using Bohme's apparatus (according to ASTM C29/C29M-09 standard [30]), as 639 g/dm^3, while the angle of repose was 39°, indicating a satisfactory flow of particles [31].

The coefficients representing the inter-particle and particle-to-wall collision phenomena which were used in the numerical analysis of this study were developed by various authors [32–34]. The experimental determination of the restitution coefficient was performed using the method by Smith and Liu [32]. The friction coefficient for particles was determined using the method explained in the work of Mohsenin [35]. The particle to wall friction coefficient was obtained using the method explained in the work of Stahl [36].

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