Powder Technology 302 (2016) 333–349

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

The effect of the number of impeller blades on granular flow in a bladed mixer

Veerakiet Boonkanokwong [a,b], Brenda Remy [c], Johannes G. Khinast [d], Benjamin J. Glasser [a,*]

[a] Department of Chemical and Biochemical Engineering, Rutgers, The State University of New Jersey, Piscataway, NJ 08854, United States
[b] Department of Pharmaceutics and Industrial Pharmacy, Faculty of Pharmaceutical Sciences, Chulalongkorn University, Bangkok 10330, Thailand
[c] Drug Product Science & Technology, Bristol-Myers Squibb Co., New Brunswick, NJ 08903, United States
[d] Research Center Pharmaceutical Engineering and Institute for Process and Particle Engineering, Graz University of Technology, Inffeldgasse 21/A, 8010 Graz, Austria

ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form 21 July 2016
Accepted 27 August 2016
Available online 30 August 2016

Keywords:
Impeller blade
Agitated mixer
Discrete element method (DEM)
Granular mixing
Quasi-static flow
Scale-up

ABSTRACT

Simulations of granular flow of monodisperse, cohesionless spherical glass beads in a cylindrical bladed mixer agitated by an impeller were performed using the discrete element method (DEM). The number of impeller blades was varied from 1 to 4 blades, and the impact of the number of blades on granular flow and mixing kinetics was investigated. It was found that particle velocities were influenced by the number of the blades used in the mixing system. Higher radial and vertical velocities of particles were observed in the 1- and 2-bladed mixers, which led to more pronounced three-dimensional recirculation patterns. However, the tangential velocity components of particles in the 3- and 4-bladed cases were larger. Additionally, it was found that using two or three impeller blades provided better mixing performance than using one or four blades, as evaluated by calculation of the relative standard deviation (RSD) and the Lacey index of the systems. Granular temperature and particle diffusivities obtained for the 2- and 3-bladed cases were also higher than those for the 1- and 4-bladed mixers. Solids fraction analysis showed that dilation of the particle bed occurred to the greatest extent in the 2-bladed mixer. Contact force network data and blade-particle force calculations showed that using different numbers of impeller blades led to significant differences in the force distribution. Finally, the effect of scaling up was evaluated by varying the mixer diameter to particle diameter ratio. Increasing the mixer diameter to particle diameter ratio was found to have little impact on flow and mixing behaviors.

1. Introduction

Powders and granular materials occur in everyday life in situations ranging from baking to geophysical flows to industrial processes [1,2]. A large number of industries including chemical, food, pharmaceutical, and cosmetic industries frequently handle powders or granular materials [3]. Compared to fluid processing, our understanding of solids processing lags behind. The lack of fundamental understanding of granular systems can lead to inefficient process development and design, poor identification of critical process parameters, and scale-up problems [4]. A cylindrical mixer mechanically agitated by an impeller blade, which we will refer to as a bladed mixer, is a common geometry in a variety of particle processing technologies. Bladed mixers are used in a number of solids processing operations including blending, agitated drying, high-shear granulation, and during the tablet compaction unit operation to encourage flow in the feed-frame assembly [5,6]. While there has been a significant amount of research on granular flow in bladed mixers, our understanding of bladed mixer operations is incomplete. Problems such as segregation [7], particle attrition [8–11], and agglomeration [12,13] are known to occur in this geometry during processing, but the role of operating parameters and particle properties on the flow behavior remains unclear. A cylindrical mixer agitated by an impeller blade is commonly used for liquid mixing, and it has been observed that the number of blades on the impeller can significantly affect mixing efficiency [14]. The effect of the number of blades on solids flow and mixing in a cylindrical mixer has not been studied in detail.

Previous researchers have experimentally investigated solids flow in a bladed mixer. Measurements of power and torque were carried out in order to understand the force needed to move the blades through a bed of particles [15,16]. Positron emission particle tracking was used to investigate the movement of particles in a bladed mixer [17]. Particle image velocimetry (PIV) was carried out at the free surface and walls of a cylindrical mixer in order to characterize flow behavior [18,19]. These studies found that a periodic three-dimensional (3D) recirculation pattern developed with a frequency corresponding to that of the blade rotation speed. It was also observed that the size of the recirculation zones and the rate of mixing were significantly influenced by the fill level. Additionally, velocity profiles were found to scale linearly with the rotational speed of the blades. Although these experimental studies

* Corresponding author.
E-mail address: bglasser@rutgers.edu (B.J. Glasser).

http://dx.doi.org/10.1016/j.powtec.2016.08.064
0032-5910/

have provided insight into the granular behavior in bladed mixers, they have been limited to the effect of a small set of process parameters and particle properties on the measured variables.

Numerical simulation techniques have the potential of bridging the knowledge gap because information can be obtained on local flow and stresses that are difficult, if not currently impossible, to obtain experimentally. Stewart et al. [20] and Zhou et al. [21,22] performed simulations of bladed mixers with two flat blades using the discrete element method (DEM). They found that the frictional characteristics of particles had an impact on the velocity profiles and mixing kinetics. They also observed that particle size and density affected segregation patterns. Remy et al. [23] carried out DEM simulations of cohesionless spherical glass beads in a cylindrical vessel agitated by a four-bladed impeller. The effect of two different blade configurations (acute or obtuse blade pitch) and the effect of particle friction on granular flow behaviors were investigated. It was found that the obtuse blade pitch orientation generated a strong 3D recirculation zone and promoted vertical and radial mixing. An increase in the sliding friction coefficient of particles led to a rise in granular temperature and an increase in diffusive mixing. Furthermore, Remy et al. [24] studied the effects of fill level and mixer properties (wall friction, blade position, and the ratio between mixer and particle diameters) on granular flow in a bladed mixer. The granular material behavior followed some simple scaling relations when the ratio of mixer size to particle diameter was increased above a critical ratio. They noticed that particle velocities and diffusivities scaled linearly with the mixer size and the blade speed. They also found that normal and shear stress profiles scaled linearly with the total weight of the granular bed. An additional study on the effect of blade speed was carried out by Havlica et al. [25] using DEM simulations.

Remy et al. [26] experimentally examined torque and shear stresses and found that they scaled linearly with the total weight of the bed as predicted by DEM simulations. Comparisons between experiments and simulations for granular flows in agitated mixers have been carried out by varying parameters including surface roughness of particles [27], polydispersity [28], and moisture content in wet systems [29]. Hare et al. [30], Zafar et al. [31], and Chandratilleke et al. [32] reported granular flow behaviors of cohesive particles in a bladed cylinder and found good agreement between experiments and DEM simulations. Although granular flows in agitated mixers have been experimentally and computationally investigated by a large number of researchers, none of these studies have examined the effect of the number of impeller blades on granular flow and mixing behavior.

Mixing of solid particles in various types of blenders has been widely studied by means of the discrete element method. Alizadeh et al. [33] analyzed DEM simulation results for flow and mixing of granules in a rotating drum. They found that the Young's modulus and the static friction coefficient were the important particle properties that affected particle dynamics. Tahvildarian et al. [34] explored the effects of rotational speed and fill level on the circulation intensity and the axial dispersion coefficient of non-cohesive, monodisperse solid particles in a V-blender via DEM simulations. It was shown that the circulation intensity increased with an increase in the rotational speed and a decrease in the fill level. They also reported that the axial dispersion coefficient of the particles was a linear function of the rotational speed of the V-blender.

Alizadeh et al. [35] compared mixing efficiency of a V-blender to that of a tetrapodal blender utilizing discrete element simulations. Higher axial and radial mean velocity profiles were observed in the tetrapodal blender compared to the V-blender. They found that the tetrapodal blender provided better diffusive axial and convective radial mixing and showed a shorter mixing time compared to the V-blender due to more efficient mixing mechanisms. Further analysis demonstrated that the tetrapodal blender was less susceptible to segregation of granules than the V-blender.

DEM simulations of the mixing process of particles in a six-blade plough shear mixer and in a slant cone mixer with an intensifier bar were conducted by Alian et al. [36,37]. They studied the effect of operating conditions on mixing performance by computing the Lacey mixing index. In the plough shear mixer, they compared top-bottom loading to side-side loading and found that the rate of increase of the mixing index was larger for the side-side loading. They also showed that the mixing time decreased with an increase in the rotational speeds and that lower fill levels resulted in higher mixing indices. For the slant cone mixer, the side-side and top-bottom loading patterns led to faster mixing compared to the back-front loading. It was observed that increasing the rotational speed of the vessel enhanced the mixing index and that the kinetic energy of particles increased proportionally with the drum speed. In the slant cone mixer, the effect of the rotational direction of the agitator with respect to the direction of the drum was also analyzed, and it was shown that the mixing rate obtained in the co-rotating mode was higher than that in the counter-rotating mode.

With the current trend of moving from traditional batch manufacturing methods used in the pharmaceutical industry, continuous powder blending processes have been extensively studied in recent years. Gao et al. [38,39] characterized and optimized a continuous mixing process by means of experimental residence time distribution (RTD) measurements and DEM simulations in order to develop a predictive model for the output mixture variance. Combined with the DEM model, Sen and Ramachandran [40] developed a new multi-dimensional population balance model (PBM) to quantify the dynamics of a continuous powder mixing process. Gao et al. also proposed a scale-up strategy for a continuous powder blender that can be used for different types of materials [41]. Although a number of research papers have studied the influence of various operating conditions on the mixing performance, only little have they focused on the number of the blades used in the blender.

Bladed mixers are a relatively simple geometry – a cylinder with an impeller – and thus provide an opportunity for research on particulate flow and mixing. As discussed above, the effect of the number of blades on solids flow and mixing in a bladed mixer has not been studied in detail. In contrast to particulate systems, the effect of the number of impeller blades in liquid stirred tanks has been extensively investigated in a number of papers. Wu et al. [14] conducted experiments to determine the effect of the number of impeller blades on the turbulent velocity fields and the minimum speed required to suspend solids. Kumaresan and Joshi [42] investigated the effect of the number of blades in stirred tanks using computational fluid dynamics and found that increasing the number of blades from four to six led to an increase in the power consumption and the average normal stress. Jirout and Rieger [43] carried out experiments to investigate the effect of the number of blades on a suspension of solids. They reported that the minimum speed necessary for particle suspension for three, four, and six blades decreased with the increasing number of blades. They also observed that the impeller with the lowest number of blades had the lowest torque value.

In this work, DEM simulations have been carried out to examine the effect of the number of impeller blades on granular flow behaviors including particle velocities, mixing kinetics, granular temperatures, particle diffusivities, bulk density, blade-particle contact forces, and normal contact force network. In addition, the impact of scaling up the system size was investigated. This paper is organized as follows: in the next section we describe the details of DEM simulations, and we then discuss results for the base case agitated mixers. This is followed by results for scaling up of the agitated mixer, and we then present conclusions.

2. Numerical method

2.1. Discrete element method

The discrete element method (DEM) integrates Newton's equations of motion for each particle starting from an initial system configuration. If the time-step for integration is sufficiently small, it can be assumed that the state of a particle is only affected by contact with its neighbors