ARTICLE IN PRESS

Advanced Powder Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Flow of granular materials in a bladed mixer: Effect of particle properties and process parameters on impeller torque and power consumption

Veerakiet Boonkanokwong [a,b], Rohan P. Frank [a], Pavithra Valliappan [a], 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 27 February 2018
Received in revised form 1 July 2018
Accepted 26 July 2018
Available online xxxx

Keywords:
Impeller torque
Shear rate
Bladed mixer
Particulate flow regime
Granular material

ABSTRACT

The torque and power needed to drive an impeller are important quantities that can indicate flow behavior and can be used to control processes, especially mixing and granulation in the pharmaceutical industry. In this study, experiments were conducted on monodisperse spherical glass beads flowing in a cylindrical bladed mixer agitated by an impeller. The impeller torque was measured using a rotating platform and a data recording device, and the power draw for the motor driving the impeller was measured using a power meter. The effect of various impeller blade designs and material properties on the torque and power were investigated as a function of the impeller blade rotation rate. It was found that the torque exerted on a granular bed and the power consumption were a strong function of the impeller blade configuration, the position of the blades in a deep granular bed, the fill height of the glass beads, and the size and friction coefficient of the particles. It was observed that the time-averaged torque and power consumption for different particle sizes qualitatively scaled with particle diameter. A scale-up relationship for a deep granular bed was developed: the time-averaged torque and average adjusted power consumption scaled with square of the material fill height.

1. Introduction

Mixing is a unit operation that is widely used in a variety of production processes ranging from catalytic to chemical, cosmetic, food, and pharmaceutical industries [1,2]. In pharmaceutical manufacturing, mixing is one of the steps of critical importance that needs to be carefully controlled. Homogeneity of a mixture of excipients and an active pharmaceutical ingredient (API) needs to be achieved to ensure that the drug concentration in a finished product is consistent and that all dosage units produced are of uniform potency [3]. There are several different types of mixers (also called blenders) used in the pharmaceutical industry. Examples of mixers include rotating drums [1], bladed mixers [3], high-shear mixers [4], agitated filter beds/dryers [5,6], and fluidized beds [7,8]. Bladed mixers and high-shear mixers have advantages that they are simple in construction and that they take a relatively short time to complete the mixing operation [9]. The degree of uniformity of dosage units and the resulting quality of finished products are functions of the material properties, the design of the mixer, and the operating conditions [10–12]. Process monitoring and control are therefore important to maintain stable product quality and improve process efficiency.

Monitoring of the mixing process can be carried out by various methods, such as employing the particle image velocimetry (PIV) technique [13], measuring agitation torque, and recording power consumption of the mixer [9]. While getting mixed, solid particulate matter exerts a load on agitator blades and vice versa, thus, giving rise to the agitation torque [14]. Changes in powder characteristics and flow behaviors in the mixer are reflected by changes in the value of the impeller torque, e.g., when the endpoint of granulation is reached [9]. The torque required to turn an impeller in a particle bed depends on a number of factors, including blade design, agitator rotational speed, material fill level, and mixer size [15–17]. In the case where agglomeration is being carried out in a high shear mixer, torque measurement helps in control and monitoring of the granulation process [18–20]. Since torque is sensitive to changes in operating conditions, with rapid measurement and

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

https://doi.org/10.1016/j.apt.2018.07.022
0921-8831/

Please cite this article in press as: V. Boonkanokwong et al., Flow of granular materials in a bladed mixer: Effect of particle properties and process parameters on impeller torque and power consumption, Advanced Powder Technology (2018), https://doi.org/10.1016/j.apt.2018.07.022

Nomenclature

List of variables

d	diameter of particles (m)
D	diameter of a mixer (m)
$\underset{\rightarrow}{f}$	frequency of torque signals (Hz)
$\vec{F}$	force that a lever arm exerts on a load cell (N)
g	gravitational acceleration (m/s^2)
H	fill height of particle bed (m)
H/D	material fill height to mixer diameter ratio (–)
ℓ	length of a lever arm (m)
L	length of blades (m)
m	mass of particle bed (kg)
P	actual power (W)
P_{emp}	power measured from an empty mixer (W)
P^*	adjusted power (W)
P	normal stress (Pa)
R_{cyl}	radius of mixer (m)
$\underset{\rightarrow}{t}$	time (s)
$\vec{T}$	instantaneous torque at each time step (Nm)
$\langle T \rangle$	time-averaged torque (Nm)
$\vec{T}^*$	normalized torque (–)
V_{tip}	tip speed of blades (m/s) where $V_{tip} = \omega L$
W	work done by impeller blades (J)

List of subscripts

0, 1, 2	subscripts for D and H in Table 1 which denote each part of the schematic in Fig. 2

List of Greek letters

$\mathring{\gamma}$	shear rate (s^{-1})
γ^*	dimensionless shear rate (–)
μ	macroscopic/bulk friction coefficient (–)
ρ_{bulk}	bulk density of particle bed (kg/m^3)
ρ_p	density of particles (kg/m^3)
τ	shear stress (Pa)
$\langle \tau_{\theta r} \rangle$	time-averaged shear stress (Pa)
ω	angular velocity of impeller blades (rad/s)

good precision, it can be used as a parameter to probe the efficiency of mixer designs [18]. In addition, impeller torque measured from a laboratory scale mixer can be used to characterize and predict the risk for agglomeration in powder beds with varying degrees of moisture content at industrially relevant scales. Bulk friction coefficient can also be measured for wet powder beds using torque data [21].

Impeller torque measurements can be implemented to monitor not only mixing and agglomeration/granulation processes, but also agitated drying processes. Drying of API crystals can be carried out in an agitated filter-bed dryer, which has advantages over tray dryers as it reduces operation time by improving heat and mass transfer. In an agitated dryer, torque data can provide a correlation between shear stress experienced by a powder bed and the degree of attrition of particles [5]. Impeller torque at the laboratory scale can also be used to obtain an estimate of the amount of work done per unit mass by the impeller at larger scales. This relationship can help improve scale up of the agitated drying process [5]. The ability to predict attrition and to obtain uniform size distribution of API particles results in better critical quality attributes of the finished dosage forms including content uniformity, dissolution rate, bioavailability, and stability.

Besides the impeller torque measurement, recording power consumed by the impeller motor can also be employed to monitor and control mixing processes. Previous research by Ritala et al. [22] demonstrated that power consumption during rotation of the blades was a function of intra-granular porosity and surface tension of a binder solution in wet mixing operations. Additionally, a correlation existed between power consumption and the strength of the moist agglomerates. An increase in cohesiveness or tensile strength of the moist granule mass resulted in a change in power consumption, indicating that the liquid solution characteristics, such as surface tension and contact angle, had an influence on power consumption [22]. Jirout and Rieger [23] illustrated that, in the case of suspending solids in liquid systems, the power consumption required for off-bottom suspension of the solid particles could be used to compare the efficiency of different types/configurations of impellers for the mixing operation. Although power consumption measurement has been extensively carried out in previous research on the liquid mixing process, there has been limited work for monitoring mixing of solids systems.

With the current interest of moving from batch to continuous manufacturing in the pharmaceutical industry, continuous mixing processes have been extensively studied in recent years [24–26]. Vanarase et al. [27,28] conducted experiments on a continuous powder mixer to examine the effects of operating conditions, design parameters, and material flow properties of pharmaceutical mixtures as a function of shear rate. Relative standard deviation (RSD), one of the most common mixing indices, was used to characterize mixer's performance and in turn the efficiency of the mixing process. RSD is a measure of blend homogeneity, and for a continuous process they found RSD depended on several factors such as blade rotation rate, material flow rate, and mixer blade configuration. They demonstrated that the number of blade passes, a measure of the strain, was a function of the blade rotational rate. Although there is interest in the pharmaceutical industry in continuous manufacturing, most products are still manufactured in batch mode. Thus, there is still a need to better understand batch operations.

Campbell [29,30] and Campbell and Brennen [31] outlined a theoretical method for calculating collisional stresses within a granular bed from the total contact force between particles, particle diameter, and volume of a sampling cell. The important stress tensor components in the area of granular material flows are the average normal stress and the shear stress. Knowing the normal stress values, the pressure inside a granular bed can be calculated. According to a granular rheological model [32,33], a number of experimental and numerical studies suggested that the mass density and the macroscopic (bulk) friction are functions of the inertial number, which can be computed from the shear rate, the particle diameter and density, and the compressive pressure. Stresses and torque can be measured from the macroscopic friction coefficient and the inertial number. In previous work, Cavinato et al. [34] conducted experiments on the mixing and flow behaviors of cohesive pharmaceutical powders in lab-scale and pilot-scale high shear mixers. They proposed a scaling relationship based on a dimensionless torque number which was a function of the mass fill and the square root of the impeller Froude number. It was found that the mass fill was one of the important parameters that had an impact on the powder flow patterns during the high shear mixing process.

In spite of some previous research in this area, the roles of material properties, blade and equipment configurations, and operating parameters on the impeller torque and power consumption in a batch mixer are still poorly understood. In this paper, we