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Original Research Paper

Mixing assessment of non-cohesive particles in a paddle mixer through experiments and discrete element method (DEM)

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ABSTRACT

In this study the mixing kinetics and flow patterns of non-cohesive, monodisperse, spherical particles in a horizontal paddle blender were investigated using experiments, statistical analysis and discrete element method (DEM). EDEM 2.7 commercial software was used as the DEM solver. The experiment and simulation results were found to be in a good agreement. The calibrated DEM model was then utilized to examine the effects of the impeller rotational speed, vessel fill level and particle loading arrangement on the overall mixing quality quantified by the relative standard deviation (RSD) mixing index. The simulation results revealed as the impeller rotational speed was increased from 10 RPM to 40 RPM, generally a better degree of mixing was reached for all particle loading arrangements and vessel fill levels. As the impeller rotational speed was increased further from 40 RPM to 70 RPM the mixing quality was affected, for a vessel fill level of 60% and irrespective of the particle loading arrangement. Increasing the vessel fill level from 40% to 60% enhanced the mixing performance when impeller rotational speed of 40 RPM and 70 RPM were used. However, the mixing quality was independent of vessel fill level for almost all simulation cases when 10 RPM was applied, regardless of the particle loading arrangement. Furthermore, it was concluded that the particle loading arrangement did not have a considerable effect on the mixing index. ANOVA showed that impeller rotational speed had the strongest influence on the mixing quality, followed by the quadratic effect of impeller rotational speed, and lastly the vessel fill level. The granular temperature data indicated that increasing the impeller rotational speed from 10 RPM to 70 RPM resulted in higher granular temperature values. By evaluating the diffusivity coefficient and Peclet number, it was concluded that the dominant mixing mechanism in the current mixing system was diffusion.

1. Introduction

Particle mixing is a crucial operation in a variety of industries including chemicals, food, cosmetics, mining, agriculture and pharmaceuticals [1]. In most particle processing applications, powder mixing plays a significant role on the quality of the final product [2]. Most of the powder based products should achieve a uniform blend in order to meet quality control and performance standards. A wide variety of particle mixers have been used in industry [2]. Depending on the process requirement, these mixers generally operate in batch or continuous mode. One of the most common types of batch mixers, which is of critical importance to the powder processing industry is the agitated powder blender [2]. The wide applicability of agitated blenders is associated with their high operating capacities. An agitated powder blender is composed of a stationary vessel (vertical or horizontal) and a shaft (single or twin) which has an agitating device attached to it [1–7]. Depending on the impeller shape, some common types of this blender include Paddle, Plow, Ribbon, and Screw mixers. The performance of agitated powder blenders has been commonly investigated in literature both quantitatively and qualitatively through experiments, and numerical simulations [8,9]. Numerous experimental techniques such as visual assessment, positron emission particle tracking (PEPT), radioactive particle tracking (RPT) [10–14], Particle Image Velocimetry (PIV) [15,16], and Near Infrared Spectroscopy (NIR) [17,18] have been previously applied in agitated blender studies. The main advantage of implementing the aforementioned types of experimental methods is the non-intrusive nature of the techniques. The mixture is not physically disturbed in order to attain information about the position and velocity of the particles. However, in PEPT and RPT a single/multi tracer particles are tracked within the mixer to draw specific information however, it may not accurately represent the entirety of the mixing system.

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Nomenclature

RSD	relative standard deviation (%)
K	total number of samples (–)
n_i	number of one type of particle in ith sample (–)
P	overall proportion of one type of particle (–)
N_i	total number of particles in ith sample (–)
k	number of the model obtained for each particle loading arrangement (–)
l	number of levels for impeller rotation speed (–)
q	number of levels for vessel fill level (–)
A	impeller rotation speed parameter (–)
B	vessel fill level parameter (–)
C	particle loading arrangement parameter (–)
A^2	quadratic effect for impeller rotation speed parameter (–)
B^2	quadratic effect for vessel fill level parameter (–)
AB	impeller rotation speed-vessel fill level interaction parameter (–)
AC	impeller rotation speed-loading arrangement interaction parameter (–)
BC	vessel fill level-loading arrangement interaction parameter (–)
ABC	impeller rotation speed-vessel fill level-loading arrangement parameter (–)
a	parameter coefficient for A (–)
b	parameter coefficient for B (–)
a^2	quadratic parameter coefficient for A (–)
b^2	quadratic parameter coefficient for B (–)
ab	parameter coefficient for AB (–)
ac	parameter coefficient for AC (–)
bc	parameter coefficient for BC (–)
abc	parameter coefficient for ABC (–)
E	error (–)
I_j	moment of inertia of particle j $(\mathrm{kg \cdot m^2})$
m_j	mass of particle j (kg)
v_j	velocity of particle j $(\frac{m}{s})$
t	time (s)
F_{jh}^N	normal force resulting from the contact of particle j with particle h (N)
F_{jh}^T	tangential force resulting from the contact of particle j with particle h (N)
F_j^g	gravitational force for particle j (N)
M_{jh}^T	tangential torque resulting from the contact of particle j with particle h (N m)
M_{jh}^r	rolling friction torque resulting from the contact of particle j with particle h (N m)
Y_{eq}	equivalent Young's modulus (Pa)
R_{eq}	equivalent radius (m)
R_j	radius of particle j (m)
R_h	radius of particle h (m)
Y_j	Young's modulus of particle j (Pa)
Y_h	young's modulus of particle h (Pa)
e	coefficient of restitution (–)
m_{eq}	equivalent mass (kg)
m_h	mass of particle h (kg)
G_{eq}	equivalent shear modulus
G_j	shear modulus of particle j (Pa)
G_h	shear modulus of particle h (Pa)
T	granular temperature $\left(\frac{m^2}{s^2}\right)$
U	localized fluctuation velocity$(\frac{m}{s})$
Δt	time step for Diffusivity calculations (s)
D_{fg}	diffusivity coefficient in the f direction due to gradient in g direction $\left(\frac{m^2}{s}\right)$
Δx_f	particle displacement in the f direction relative to particle's initial position (m)
$\overline{\Delta x_f}$	mean particle displacement in the f direction relative to particle's initial position (m)
Δx_g	particle displacement in the g direction relative to particle's initial position (m)
$\overline{\Delta x_g}$	mean particle displacement in the g direction relative to particle's initial position (m)
R	radius of mixer (m)
U_f	average particle speed in the f direction $(\frac{m}{s})$
Pe_{fg}	Peclet number in the f direction due to gradient in g direction (–)

Greek letters

σ^2	variance of samples (–)
μ	overall mean concentration of one type of particle (–)
β	overall average of response variable (–)
ρ	particle density $\left(\frac{kg}{m^3}\right)$
ω_j	angular velocity of particle j $(\frac{rad}{s})$
ω_h	angular velocity of particle h $(\frac{rad}{s})$
δ_n	normal overlap (m)
ϵ_h	poisson ratio of particle h (–)
ϵ_j	poisson ratio of particle j (–)
δ_t	Tangential overlap (m)
μ_r	rolling friction coefficient (–)
μ_s	sliding friction coefficient (–)

PIV and NIR on the other hand, can only provide information regarding free surface and regions close to the wall of the mixer. Mixing kinetics of particles can also be assessed through direct sampling of the mixture under investigation. In this method, samples with specific sizes are taken from various regions of the mixture as representative of the whole system. These samples are then statistically analyzed to reveal the mixing characteristics of the system [19]. The most common technique utilized for sampling is the use of a thief probe [19,20]. The main advantage of using such devices is that numerous samples of various sizes can be obtained to represent the whole mixture. However, these devices are highly intrusive and can therefore, introduce errors in the sample composition. The experimental methods alone do not however, provide an in depth understanding of the mixing mechanisms and interactions involved [21]. Experimental data can only provide information regarding the general behaviour of mixing and cannot fully address the underlying mixing phenomena. Numerical simulations, on the other hand, can reveal critical information about the behaviour and interaction of particles which would otherwise be experimentally difficult or impossible to obtain. The accurate models, which are validated with experimental data could potentially be used to reveal critical information on both the mechanisms and kinetics of mixing within various powder blenders [21]. The granular flows are often simulated by Discrete Element Method (DEM) [6,22]. The DEM technique has enabled engineers and scientists to quantify mixing of powders based on their fundamental behaviours. In the DEM approach, Newton's equations of motion are solved in order to track the position of each individual particle defined within the system [23,24]. The DEM method has been utilized in numerous studies to analyze the flow and dynamics of particle assemblies in various agitated mixers [16,25–27].

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