Powder Technology 258 (2014) 324–330

Contents lists available at ScienceDirect

Powder Technology

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

CFD simulation of transient particle mixing in a high shear mixer

Duy Nguyen [a], Anders Rasmuson [a,*], Ingela Niklasson Björn [b], Kyrre Thalberg [b]

[a] Department of Chemical Engineering, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
[b] Astra Zeneca Pharmaceutical Development R&D Mölndal, SE-431 83 Mölndal, Sweden

ARTICLE INFO

Article history:
Received 22 May 2013
Received in revised form 10 February 2014
Accepted 1 March 2014
Available online 16 March 2014

Keywords:
Particle mixing
High shear
Multiphase flow
Transient

ABSTRACT

Particle mixing is one of the key operations in pharmaceutical processing. In this work, an Eulerian–Eulerian multiphase framework has been employed to model and simulate particulate flow and mixing behaviour in the blending of dry powders for inhalation. The kinetic theory of granular flow and the frictional stress model are used to close the transport equations of dense particulate flow in a high shear mixer. The transient mixing dynamics, including start-up, within the mixer are captured by adding a scalar transport equation as a tracer. The solid velocity profile at the wall is experimentally determined by using a high speed camera and particle image velocimetry (PIV) evaluation. The evolution of a tracer movement is experimentally tracked using an imaging technique that is processed in the Matlab image toolbox to obtain the local particle concentration. The model can capture the main features in granular flow motion, e.g. bed height and the dominating flow direction. The mixing mechanism is found to be a combination of azimuthal, axial and radial mixing at the same order of magnitude. Rapid mixing is captured in the simulation and is in agreement with experimental data. Even though the continuum-based model can predict well some flow features and the transient mixing time, there is a need for further development of the continuum description of dense particulate flows.

1. Introduction

Particle mixing is an important unit operation and widely used in food and pharmaceutical industries. For instance, a dry mixing step is employed to form a homogeneous mixture of active substances and excipients prior to binder addition in wet granulation. The blending of dry powder for inhalation is also governed by dry mixing to form an adhesive mixture. The purpose of mixing is to obtain a homogenous mixture; however, many researchers have pointed out that the local mixing as well as the flow pattern has significant effects on the properties of the final products. It was found that the granule size is controlled by breakage and agglomeration that are sensitive to the flow pattern within the mixer [1]. It has also been reported that both the homogeneity and adhesion of drug particles on the carrier surface in DPI depend on the movement and collision of particles induced by the impeller [2]. There is a need for better understanding of granular flow structure and mixing behaviour to improve mixer design and mixing process control.

One common approach for the numerical simulation of multiphase particulate flow is the discrete element method (DEM) where the motion of every single particle is tracked by integrating Newton's second law equation [3]. Although DEM is a promising method since it reflects the granular flow structure at particle level, the limitation of computational power makes it not applicable for large-scale processes. Instead of following the motion of individual particles, the Eulerian–Eulerian approach treats the particulate phase as a continuous medium with properties that are averaged over a control volume and derived from closure models [4]. The use of the continuum approach in dilute particulate flows, e.g. in fluidized beds, in which the kinetic theory of granular flow (KTGF) is used to model the particle–particle interaction, is well established [5,6]. For the dense flows in a high shear mixer where sustained particle–particle contacts occur, the use of KTGF in combination with a frictional stress model to describe additional particle stresses can be found in the work of [7,8]. Although the Eulerian multiphase framework seems promising for investigating the structure of granular flows at larger scales, the use of this continuum-based model for evaluating mixing mechanisms and mixing degree is not earlier reported.

The aim of this study is to investigate the mixing behaviour and local flow structure in a high shear mixer that is used for blending of adhesive mixtures. This process is comprised of a dry mixing step of three particle classes, i.e. carrier, drug, and fine particles. As a first phase of study, the Eulerian multiphase framework with KTGF and frictional stress models is employed to obtain a quantitative image of the granular flow structure and macro mixing behaviour of the carrier particles. The motivation for this work is based on the experimental finding that the granular flow and mixing degree are dominated by carrier particles. The solid velocity profiles are experimentally validated by using a high speed camera and PIV evaluation. A scalar transport equation is added to the model as a tracer to capture transient mixing dynamics. This approach is commonly applied for liquid mixing, but has not been used for particle mixing. The

* Corresponding author. Tel.: +46 31 772 2940; fax: +46 31 81 46 20.
E-mail address: rasmuson@chalmers.se (A. Rasmuson).

http://dx.doi.org/10.1016/j.powtec.2014.03.041
0032-5910/

evolution of tracer concentration and mixing behaviour is evaluated and compared with experimental data obtained using imaging techniques.

2. Model description

2.1. Eulerian multiphase framework

The Eulerian–Eulerian approach treats the particulate phase as a continuous medium with averaged properties. The two phases (solid (s) and gas (g)) are described separately by mass and momentum equations with shared pressure and interaction terms [4].

$$\frac{\partial\left(\alpha_g\rho_g u_g\right)}{\partial t}+\nabla\cdot\left(\alpha_g\rho_g\boldsymbol{u}_g\boldsymbol{u}_g\right)=-\alpha_g\nabla P+\nabla\cdot\left(\alpha_g\bar{\bar{\tau}}_g\right)-\beta\left(\boldsymbol{u}_g-\boldsymbol{u}_p\right)+\boldsymbol{F} \quad (1)$$

$$\frac{\partial\left(\alpha_g\rho_g\right)}{\partial t}+\nabla\cdot\left(\alpha_g\rho_g\boldsymbol{u}_g\right)=0 \quad (2)$$

$$\frac{\partial(\alpha_s\rho_s\boldsymbol{u}_s)}{\partial t}+\nabla\cdot(\alpha_s\rho_s\boldsymbol{u}_s\boldsymbol{u}_s)=-\alpha_s\nabla P-\nabla P_s+\nabla\cdot\left(\alpha_s\bar{\bar{\tau}}_s\right)-\beta\left(\boldsymbol{u}_g-\boldsymbol{u}_p\right)+\boldsymbol{F} \quad (3)$$

$$\frac{\partial(\alpha_s\rho_s)}{\partial t}+\nabla\cdot(\alpha_s\rho_s\boldsymbol{u}_s)=0 \quad (4)$$

where α_g represents the volume fraction of gas, ρ_g is the intrinsic gas density and $\boldsymbol{u}_g$ is the gas velocity. P is the pressure, τ_g is the viscous stress tensor and β is the coefficient for the interphase momentum exchange term, $\boldsymbol{u}_s$ is the solid phase velocity and $\boldsymbol{F}$ represents all external forces acting on the system. The closure equations are given in Table 1.

2.2. Transient mixing model

A general scalar transport equation is used to model the tracer distribution in the vessel. This approach is usually employed for modelling liquid mixing in stirred tanks [15,16] but to the best of the author's knowledge, no corresponding study for particle mixing has been reported. The tracer is treated as a property of the particulate phase and transported in the system by convection only.

$$\frac{\partial(\alpha_s\rho_s C)}{\partial t}+\nabla\cdot(\alpha_s\rho_s\boldsymbol{u}_s C)=0 \quad (13)$$

where C is the tracer concentration and is defined as the mass ratio of marked particles to the total number of particles corresponding to experimental setting.

The evolution of tracer concentration is computed simultaneously with the transient start-up of the granular flow (i.e. particles are initially at rest).

2.3. Boundary conditions

Different boundary conditions for the particulate phase can be found in the literature, e.g. free slip [17], no slip [8], and partial slip [7,18]. In this study, the linear Navier wall slip model is employed

$$\left(\frac{\partial u}{\partial\eta}\right)_w=l\left(u_w-u_{slip}\right) \quad (14)$$

where l is the slip coefficient, u_{slip} is the slip velocity of the particles, and w indicates the solid wall.

No slip condition ($l=0$) is used for the continuous air phase. For the solid phase, both no slip and partial slip are considered. The slip length for the partial slip condition is evaluated experimentally by approximating the Navier wall slip model to

$$u_{slip}=l\left(\frac{\Delta u}{\Delta\eta}\right)_w. \quad (15)$$

u_{slip} is obtained through PIV evaluation of particle velocity at the bed surface close to the wall. $\left(\frac{\Delta u}{\Delta\eta}\right)$ is the differential of particle velocity at wall and at the bed surface close to the wall.

The Neumann boundary condition of zero flux is applied for the tracer concentration at all boundaries.

3. Numerical simulation framework

The pre-processor GAMBIT was used to generate the mesh from the geometry model based on the MiPro mixer (Procept, Belgium) installed with a 1900 ml vessel and a three-bladed bevelled impeller. For transient modelling of the rotation of the impeller, the sliding mesh approach is the primary choice and employed in this work. Due to the large velocity gradients, a high mesh density with tetrahedral cells was constructed for the rotational zone. In order to resolve the velocity gradient at the wall and impeller boundary, the grid was refined at these regions using size functions to improve the accuracy of the simulation. A

Table 1
Closure equations.

Viscos stress tensor	$\bar{\bar{\tau}}_k=\left(\mu_{k,col}-\frac{2}{3}\mu_k\right)(\nabla\cdot\boldsymbol{u}_k)\bar{\bar{I}}+2\mu_k\bar{\bar{S}}_k$	Eq. (5)
Interphase momentum exchange [9]	$\beta=\frac{3}{4}C_D\frac{(1-\alpha_s)\alpha_s\rho_g\lvert\boldsymbol{u}_g-\boldsymbol{u}_s\rvert}{D_p}(1-\alpha_s)^{-2.65}$	Eq. (6)
Drag coefficient for a single-sphere particle [10]	$C_D=\begin{cases}24\frac{\left(1+0.15((1-\alpha_s)Re_p)^{0.687}\right)}{Re_P(1-\alpha_s)} & \text{if } Re_P(1-\alpha_p)<1000\\ 0.44 \quad \text{if } Re_P(1-\alpha_p)\geq 1000\end{cases}$	Eq. (7)
Solid viscosity $\mu_s=\mu_{s,col}+\mu_{s,kin}+\mu_{s,fr}$	$\mu_{s,col}=\frac{4}{3}\alpha_s^2\rho_s D_p(1+e)\sqrt{\frac{\bar{T}}{\pi}}$ [11]	Eq. (8)
	$\mu_s=\frac{4}{5}\alpha_s^2\rho_s D_p g_0(1+e)\sqrt{\frac{\bar{T}}{\pi}}+\frac{1}{15}\sqrt{T\pi}\rho_s D_p g_0\frac{(1+e)(\frac{3}{2}e-1/2)}{\left(\frac{3}{2}-e/2\right)}\alpha_s^2+\frac{1}{12}\frac{\alpha_s\sqrt{T\pi}\rho_s D_p}{\left(\frac{3}{2}-e/2\right)}$ [12]	Eq. (9)
	$\mu_{s,fr}=\frac{P_f sin\varphi}{2\sqrt{I_{2D}}}$ [13]	Eq.(10)
Solid pressure	$P_s=\rho_s\alpha_s T+2g_0\rho_s\alpha_s^2 T(1+e)$ [11]	Eq.(11)
	$P_f=Fr\frac{(\alpha_s-\alpha_{s,min})^n}{(\alpha_{s,max}-\alpha_s)^q}$ [14]	Eq.(12)