

GRANULAR FLOW IN STATIC MIXERS - DEM/CFD APPROACH

PROTOK GRANULISANOG MATERIJALA U STATIČKOJ MEŠALICI, DEM/CFD PRISTUP

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ABSTRACT

The mixing process greatly influence the quality of the intermediate and/or the final product, moreover, the parameters of the mixing process and the design of used equipment have a strong impact on mixing efficiency, the quality and the price of the product. In this article, Discrete Element Method is used for modeling of granular flow in multiple static mixer applications (Komax and Ross configurations were utilized). Computational Fluid Dynamic method was chosen for fluid flow modeling, using Eulerian multiphase model. Coupling of these two methods provides reliable, sufficiently correct and adequate results of proposed model compared to experimental measurements. The aim of this article is to predict the behavior of granules in different mixer configuration and to optimize parameters of the mixing process taking into account the duration of the mixing process and the quality of mixture, as well as the price of final product.

Keywords: DEM/CFD, Static mixer, Komax, Ross, Particle tracking.

REZIME

Proces mešanja veoma utiče na kvalitet krajnjeg poluproizvoda i/ili krajnjeg proizvoda, a parametri procesa mešanja i dizajn opreme veoma utiču na efikasnost mešanja, kvalitet proizvoda i cenu proizvoda. U ovom radu, prikazana je upotreba metode diskretnih elemenata (engl. Discrete Element Method - DEM) na modelovanje mešanja granula u različitim konfiguracijama statičkih mešaća (korišćene su različite Komax i Ross konfiguracije za mešanje). Za modelovanje protoka fluida primenjena je metoda računске dinamike fluida (engl. Computational Fluid Dynamic - CFD), korišćenjem Ojlerovog višefaznog modela. Povezivanjem rezultata ove dve metode dobija se pouzdan, dovoljno tačan i adekvatan model koji daje rezultate koji odgovaraju eksperimentalnim merenjima. Praćene su i analizirane trajektorije, brzine i ubrzanja čestica, u cilju procene kvaliteta procesa mešanja. Dobro poznati kriterijum za kvalitet mešanja, pod nazivom relativna standardna devijacija (RSD) je korišćen za ovu svrhu. Optimizacija dimenzija i parametara mešanja u statičkoj mešalici je izvedena korišćenjem matematičkog modeliranja. Cilj ovog rada je bio da se predvidi ponašanje granulamog materijala u različitim konfiguracijama mešalica i da optimizuje parametre procesa uzimajući u obzir trajanje procesa mešanja, kvalitet mešavine i cenu finalnog proizvoda mešanja. U istraživanju je primećeno da su Komax elementi primenljiviji, u poređenju sa Ross elementima, posebno kada je visina instalacije mala. Međutim, upotreba Ross je finansijski prihvatljivija, zbog njegove jednostavnije geometrije. Dodatna pregrada sa kvadratnim otvorima, koja se postavlja na izlazu iz statičke mešalice, koristi se da bi se umirilo kretanje granula na obodu cevi, kao i da smanji segregaciju granula.

Ključne reči: DEM/CFD, statički mikser, Komax, Ross, trajektorije čestica.

INTRODUCTION

Static mixers are low energy consuming and efficiently mixing devices that can handle a wide range of applications. Detailed review on static mixers, concerning the mechanisms, applications and characterization methods focusing on mixing and mass transfer performance is given by Bridgwater, 2012; Ghanem et al., 2014; Nikolić et al., 2014; Jovanović et al., 2014, Bukurov et al., 2014. Models based on DEM (Discrete Element Method) have been developed in the past and shown to be reliable and efficient in catching particle interactions and predicting mixing process for investigation of solids mixing. The soft-sphere method originally developed by Cundall and Strack, 1979, was the first granular dynamics simulation technique published in the open literature. They developed the linear spring and dashpot model whereby the magnitude of the normal force between two particles was the sum of spring force and damping

force. Lagrangian tracking techniques have been used in many studies in order to characterize the mixing performance in different systems, Kumar, et al., 2008. A detailed review and definitions of the quality of a mixture, the mixing mechanisms, the possibilities for the choice of solid mixer, the experimental assessment of homogeneity and mixing indexes are presented in Poux et al., 1991. In this paper, experimental and numerical comparison between various multiple Komax and Ross mixing configurations has been performed. The fluid is treated as a continuum while the solid phase is modeled using the DEM. The fluid (air) velocity and pressure are computed by using the CFD approach. In the DEM, particle-particle and the particle-wall interactions are resolved and the time integration is performed using Newton's second law of motion. The quality of the mixing process is analyzed using relative standard deviation (RSD) criteria, Lemieux, 2008. The focus of this paper was to optimize the geometry and to compare different static mixer devices.

Komax and Ross are commercial products, with known geometry, used widely in various branches of industry.

MATERIAL AND METHOD

Mathematical model

This paper studies the flow in two types of twisted-blade static mixers, (Komax or Ross mixing elements, linked in series of 1, 2 or 3 pieces). It evaluates the mixing performance by calculating the trajectory of suspended particles through the mixer. The mathematical model is solved in two stages, first the fluid velocity and pressure are computed by CFD, and then, using a separate study, the particle trajectories of the granular materials are computed by DEM. The conservations of mass and momentum in terms of the local mean variables over a computational cell are given by Navier-Stocks equations, Patankar, 1980:

$$\frac{\partial(\rho_f \varepsilon)}{\partial t} + \nabla(\rho_f \varepsilon u) = 0 \quad \text{and}$$

$$\frac{\partial(\rho_f \varepsilon u)}{\partial t} + \nabla(\rho_f \varepsilon u \cdot u) = -\nabla p - F_{p-f} + \nabla(\varepsilon \tau) + \rho_f \varepsilon g \quad (1)$$

where ε , u , t , ρ_f , p , F_{p-f} , τ and g are: porosity, mean fluid velocity, time, fluid density, pressure, volumetric fluid – particle interaction force, fluid viscous stress tensor, and acceleration due to gravity. Fluid particle interaction force is defined by:

$$F_{p-f} = \frac{1}{V_{cell}} \sum_{i=1}^{k_i} \rho_{p-f,i} \quad (2)$$

where $F_{p-f,i}$ is the total fluid force on particle i and k_i is the number of particles in a CFD cell. The solid phase is treated as a discrete phase and described by the so-called Discrete Element Method, Lemieux, 2008. According to this model, the translational and rotational motions of a particle at any time, t , can be described by Newton's law of motion:

$$m_i \frac{dv_i}{dt} = f_{p-f,i} + \sum_{j=1}^{k_i} (f_{c,ij} + f_{d,ij}) + m_i g \quad \text{and}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{k_i} (T_{ij} + M_{ij}) \quad (3)$$

where m_i , I_i , v_i and ω_i are: the mass, moment of inertia, translational and rotational velocities of particle i , respectively. The fluid flow field can be obtained by solving Eqs. (1) by use of a standard CFD method. Solid flow field can be obtained by solving Eqs. (3) by an explicit time integration method. The modelling of the fluid flow by CFD is performed at the computational cell level, whilst the modelling of the solids flow by DEM is accomplished at the individual particle level. Coupling DEM and CFD is achieved as follows: DEM gives information about positions and velocities of individual particles at each time step, for the evaluation of porosity and volumetric fluid–particles interaction force in a computational cell. Incorporation of the resulting forces into DEM will produce information about the motion of individual particle for the next time step, Chu et al., 2011. Numerical evaluations were performed for various static mixer configurations. The first segment of the mixer is filled with 30,000 particles, diameter 2.5

mm. The scheme of the mixer is presented on Fig. 1a: inlet compartment filled with 15,000 red particles and second compartment filled with 15,000 blue particles, outlet-pressure outlet (atmospheric pressure) and wall - the other side of the mixer and the blades of the mixer (Fig. 1a). No slip condition is adopted at the wall. The adiabatic conditions at the walls are applied. It is assumed that the surface roughness is ideal with fresh surface. The influence of the gravity is taken into account and it represents the force which leads the particles to the bottom. The density of the particles released is normalized to the magnitude of the fluid velocity at the inlet. This means that there are more particles released where the inlet velocity is highest. It is assumed that the gas (air) velocity is close to zero, and the impact of fluid on particle movement is minimal. Particle density was 650 kg/m^3 , fluid density was 1.2 kg/m^3 , viscosity $1.8 \times 10^{-5} \text{ kg/ms}$, particle friction coefficient was 0.3, Young's modulus was 10^7 , Poisson's ratio of particles was 0.25, while CFD time step was $5 \times 10^{-5} \text{ s}$ and DEM time step was $5 \times 10^{-6} \text{ s}$.

Experimental method

The experimental apparatus consists of a static mixer, made from transparent Plexiglas. The different experiments were performed with 1, 2 or 3 Komax or Ross mixer elements, linked in one column in the diameter 60 mm, 280 mm long. Fig. 1a presents the 3 pieces Ross static mixer. The upper segment is divided into two compartments with a barrier and a mobile panel. Small spherical painted zeolite granules are placed in both compartments (red granules in first and blue granules in second). The material used for these experiments are zeolite in a spherical shape. The conditions under which the experiments were conducted are the same as in the numerical simulation conditions.

Numerical model

The set of balance equations (Eq. (1) – Eq. (3)) is solved by using the control volume based finite difference method. SIMPLE (Semi Implicit Method for Pressure-Linked Equations) numerical method is used for solving pressure-correction equation from the momentum and mass balance equations, Patankar, 1980. The three-dimensional flow field is discretized in Cartesian coordinates. Numerical grids are made from 109,540 to 111,320 control volumes, as shown in Fig. 1b (this figure shows 3 Komax elements static mixer configurations used for numerical simulation). The optimization of numerical grid was performed, and grid refinement tests showed that there is no significant change in the results of the simulation for larger number of cells in control volume. The elements used in numerical mesh are tetrahedral and size of element is less than 10^{-8} m^3 . A discretization of partial differential equations is carried out by their integration over control volumes of basic and staggered grids. The convection terms are approximated with upwind finite differences, while diffusion and source terms are approximated with central differences, Patankar, 1980. The calculation error for every balance equation and every control volume is kept within limits of 10^{-5} by iterative solution of sets of linear algebraic equations. CFD time step is ten times larger than DEM time step. The DEM time step is limited by natural oscillation period of spring-mass system used to model contacting particles. It should satisfy the following equation (m is particle mass and k is stiffness coefficient):

$$\Delta t_{DEM} \leq \frac{1}{10} 2\pi \sqrt{\frac{m}{k}} \quad (4)$$

RESULTU AND DISCUSSION

The results of the DEM/CFD simulation are compared with experimental results. The mechanical properties of zeolite granules are taken from *Lin et al., 2005*. The model is solved in two stages, first the fluid velocity field and pressure field are computed, and then, using a separate study, the particle trajectories are computed. In the following, we consider two different representative cases (1, 2 and 3-segment Ross configuration and 1, 2 and 3-segment Komax elements configuration). The velocity and the pressure field for the fluid phase were obtained via CFD calculations, Fig. 1c. Figure 1d (upper) presents the mixing experiment results, performed with three-segmented Ross configuration, while the processed photo was presented on Fig. 1d (lower). Color images of experimental results were captured by a Sony PowerShot A550, which is a common digital camera for home use. The macro function of the digital camera has been used, to cover a scene area of approximately Ø60 mm. Samples were placed on a white paper napkin set on a flat white painted surface, inside the closed chamber, 15 cm below the digital camera. Paper napkins were used in order to avoid undesired reflection effects from chamber's walls. With this setup, it was possible to capture

images with negligible shadows and without specular reflections. Fig. 1f and Fig 1g shows cross-sections (Poincare plot) along the particles routes of mixer and only the last figure represents the results of the whole mixing process. The locations of particles at 11 Poincare sections are shown. The color parameter is logical expression used to mark the initial color of particles at positions $x < 0$ (red) and $x > 0$ (blue). Overall particle trajectory for three-segmented Komax and Ross configurations, gained by numerical simulations were: 436 and 430 mm, respectively. In this work, RSD was used to follow the evolution of mixing uniformity for the static mixers with different configurations, explained above, *Poux, et al., 1991*:

$$RSD = \frac{\sigma}{\bar{x}} \cdot 100\% , \quad \sigma = \sqrt{\frac{\sum_{i=1}^M (\bar{x} - x_i)^2}{M - 1}} \quad (5)$$

where: M is the number of samples, x_i the concentration of sample i , and \bar{x} the average concentration of all samples. For instance, concentration of red particles in a sample is calculated as the ratio of the number of red particles and the total number of particles. The results of numerical simulations and experimental mixing processes are presented on Fig. 1e. Mixing begins after

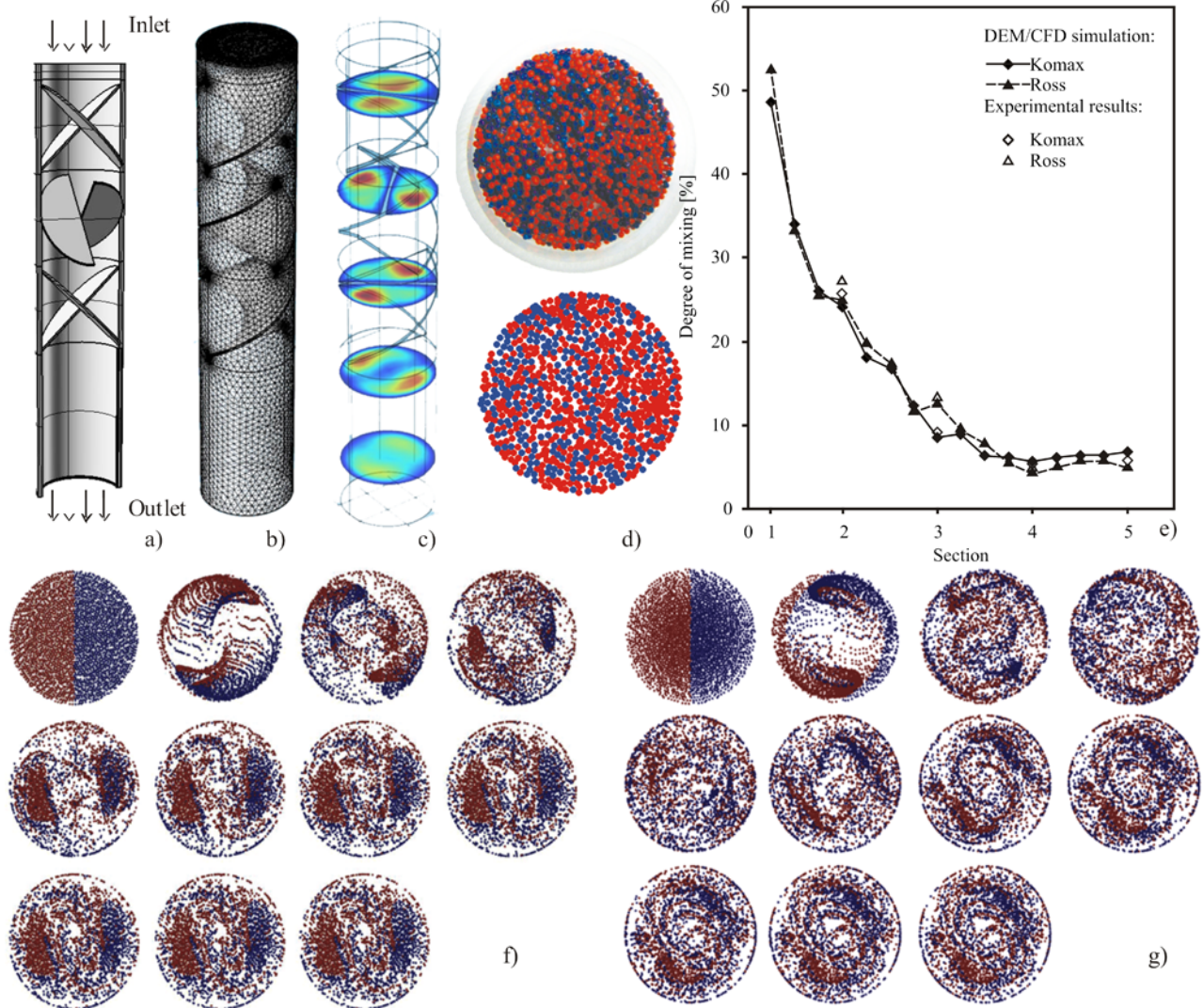


Fig. 1. a) Boundary conditions of experimental mixer, b) Numerical mesh used for simulation, c) The velocity field in the fluid phase, d) The mixing results for three-segmented Ross configuration - experimental (upper) and processed photo (lower), e) RSD mixing criteria for Ross and Komax mixers, Poincare maps of the particle trajectories at different Poincare sections, f) 3-segment Komax configuration and g) 3-segment Ross configuration

particles leave the upper segment, between section 0 and 1 on Fig. 1e (as soon as the mobile panel is removed, enabling the granules to fall toward the static mixer). The particles are rapidly blended in the first section, as seen from the figure, reaching the mixing degree of 20-27 % at the outlet. Komax mixing element shows better blending results in this section (20-22 %, for DEM/CFD simulation and experimental results) compared to Ross (24-27 %), which is expected concerning its twisted surface geometry. Komax mixing elements remained more effective after second and third section, reaching the mixing degree of 6-8 % and 4-5 % at the outlets, while the mixing quality of 11-13 % and 5-6 % were obtained at the outlets of section 2 and 3, using Ross elements. The small, but steady decrease in the mixing degree was observed for both Komax and Ross blending elements during DEM/CFD simulation, which can be seen in Fig. 1e (between section 4 and 5). This is due to centrifugal force affecting the motion of granules that exit the mixing compartment. The decrease in quality is even more evident for Komax configuration, as seen in Fig. 1e, due to its specific geometry. The use of the quadratic grid divider could enable the mixing degree to remain constant after granules left the third mixing element.

CONCLUSION

Coupled DEM/CFD approach was used to investigate mechanisms of fluid flow and particle tracking for granular flow. In the DEM, particle-particle and the particle-wall interactions are resolved and the time integration is carried out using Newton's second law of motion. CFD analysis was used for the determination of velocity and pressure field for the fluid phase by using mixture model. The particle trajectories with particle positions were tracked and analyzed in order to estimate the quality of the mixing process. A well-known mixing criterion, named relative standard deviation is used for this purpose. Optimization of the dimension and mixing parameters in static mixer was done by using mathematical modeling. The aim of this study is to predict the behavior of granules in different mixer configuration and to optimize parameters of mixing process taking into account the price of the final product, duration of the mixing process and the quality of mixture. Komax mixing elements are more applicable, compared to Ross, especially when the height of installation is low. However, the use of Ross is more financially acceptable, due to its simpler geometry. The additional quadratic grid divider, installed after a static mixer outlet, is used to quench the motion of the granules on the rim of tubes, and to lower the segregation of granules.

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