Mixing and Segregation in a Rotating Cylinder: CFD Simulation and Experimental Study

Sumudu S. Karunarathne, Chameera K. Jayarathna, and Lars-Andre Tokheim

***Abstract*—In this study, the mixing and segregation of two particle phases in a horizontal rotating cylinder were investigated via simulations and experiments. Two-dimensional CFD simulations were carried out to simulate the particle behavior in a transverse plane of a rotating cylinder. The Eulerian approach with the kinetic theory of granular flow was used to simulate granular phases with different particle size and density under the rolling mode. Experiments were done in an in-house built transparent rotary drum. The experiments revealed that the fine particles tend to move into the particle bed and form a kidney during rotation. Particle dynamics in the active layer initiate the segregation according to the trajectory mechanism. Further, percolation brings small particles through the voids of larger particles under gravity and get concentrated at the midsection of the particle bed in the transverse plane. The simulated results matched well with the experimental data.**

***Index Terms*—Active layer, granular flow, rotating drums, rolling mode, segregation.**

I. INTRODUCTION

Particle mixing is a key operation in some industrial applications, for example pharmaceutical, cement and food industries. Achieving a homogeneous mixture of particles is essential in many applications, and conditions facilitating good mixing are crucial. Several mixing techniques have been practiced in particle mixing, and fluidized beds, rotating cylinders, ribbon mixers and tumbling mixers are all widely used in the industry [1], [2].

A rotary kiln is a slightly inclined rotating cylinder, in which a powder material and a gas flow in counterflow, typically exchanging heat and mass, and usually involving chemical reactions in both the solids phase and the gas phase. Such a unit can also be categorized as a particle mixer [3]. In a rotary kiln, mixing is vital since it impacts the heat transfer performance from the freebody to the particle bed as well as the heat transfer in the bed itself. Knowledge of the particle dynamics and heat transfer is important to optimize the kiln operation in order to have higher process efficiency.

Rotary cylinders experience six regimes of particle bed behaviors, depending on the Froude (Fr) number of the rotating system [4]. Those regimes are slipping, slumping, rolling, cascading, cataracting and centrifuging. Uniform and good intermixing within the particle bed is possible in rolling mode [5] and industrial rotating cylinders are generally operated in both of rolling and cascading modes [6], [7].

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However, particles can also get segregated when subjected to movement, i.e. while being processed in the processing equipment. This is often a major drawback in particle handling, and it originates from differences in particle characteristics such as density, size, shape, roughness and resilience [8], [9].

In a rotary kiln, particle segregation occurs frequently in both radial and longitudinal directions. Such segregation can be explained through several mechanisms. Trajectory segregation may occur in the flow regimes of slumping, rolling and cataracting. Particles segregate at the active layer due to size variation, and finer particles will be concentrated at the mid-chord section [8]. The distance that the particles move from the top along the surface is proportional to the square of the particle diameter [10]. In percolation, fine particles move into the voids among the larger particles. Condensation is a density dominant segregation in that less dense particles will move upwards in a particle flow. Careful selection of particle size and density is therefore necessary to obtain a homogeneous mixture in the particle bed. Fig. 1 shows a schematic of redial segregation under different particle sizes in a rotary kiln. Further, it clearly shows the "kidney" (or tongue) with the majority of the fine particles concentrated in the middle of the transverse particle bed.

Many studies have been conducted to understand the dynamics of granular beds in rotating drums. Both experiments and CFD simulations have been done to investigate the segregation under different process conditions. Theoretical analysis of particle dynamics in rotating drums can be classified under three categories, depending on the mathematical approach used. The first category covers models developed based on geometrical and stochastic analysis and well-mixed tank theory. In the second category there are models based on the Eulerian approach considering the granular material as a continuum. The third category is the approach of DEM in a Lagrangian frame of reference [11]. Boateng and Barr [8] discussed a mathematical model to evaluate segregation in rotary kilns. The model was developed considering the segregation mechanism of percolation in the active layer and was able to determine the extent of fine particle segregation. A three-dimensional CFD rotary drum simulation in the Eulerian frame was done by Santos et al. [12] to investigate the effect of density and particle size on particle mixing and segregation. The simulation results compared well with the experiments, and it was concluded that particle segregation is affected by particle initial loading, physical properties and drum operating conditions. The DEM approach was used by Yamamoto et al. [13] to understand the influence of particle density on mixing behavior and found that larger density ratios strongly affected

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the mixing behavior in rotary drum. Soni et al. [14] also performed a DEM simulation to study the formation of dead zones and the degree of mixing under different mixing parameters. Simulations were done with more than 50 % filling degree, and results predicted that the packing arrangement and the particle size considerably impacted the dead zone formation while the drum speed and the geometry had less impact.

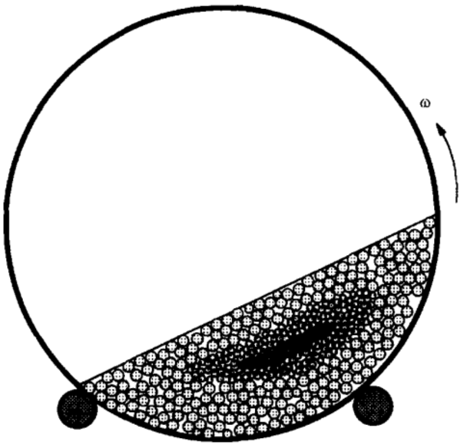

Fig. 1. Schematic of radial segregation of particles of different size in a rotary kiln [8].

In the current work, the transverse particle motion in a rotary kiln is studied in order to understand the mixing and segregation of two granular phases in the particle bed. Two-dimensional (2D) numerical simulations are carried out using the Euler-Euler approach along with the kinetic theory of granular flow, applying Ansys Fluent version 16.2, and the simulation results are compared with experimental data generated in a lab-scale horizontal rotating drum.

II. Model Description

This work has been carried out using the Eulerian approach, which can be used to simulate systems with several (N) phases. The dynamic behavior of a multiphase system with air and solids can be described through a system of equations derived from continuity and momentum equations and the kinetic theory of granular flows.

A. Governing Equations in the Euler-Euler Method

1) Continuity equations

Continuity equations represent the mass conservation of the gas phase and the solid phases:

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g v_g\right) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\varepsilon_S \rho_S\right) + \nabla \cdot \left(\varepsilon_S \rho_S v_S\right) = 0 \qquad (2)$$

Here, ρ is density [kg/m³], v is velocity [m/s], ε is volume fraction [m³/m³] and t is time [s]. The indices S and g refer to the solids phase and the gas phase, respectively.

2) Momentum equations

The particle motion is affected by the forces applied on the particle. The forces of friction, pressure and gravity govern the dynamic behavior of the flow. The relation between the fluid flow and forces applied on the flow is described by momentum equations which are written for all the phases in the system. The momentum equations for the gas phase and the solid phases are written as [6], [15]:

$$\frac{\partial}{\partial t}\left(\varepsilon_g \rho_g v_g\right) + \nabla \cdot \left(\varepsilon_g \rho_g v_g v_g\right) = -\varepsilon_g \nabla P_g + \varepsilon_g \rho_g g - \sum_{s=1}^{N} k_{gs}(v_g - v_s) + \nabla \cdot \left(\varepsilon_g \tau_g\right) \qquad (3)$$

$$\frac{\partial}{\partial t}\left(\varepsilon_s \rho_s v_s\right) + \nabla \cdot \left(\varepsilon_s \rho_s v_s v_s\right) = -\varepsilon_s \nabla P_g + \varepsilon_s \rho_s g + k_{gs}\left(v_g - v_s\right) + \sum_{n=1, s\neq n}^{N} k_{ns}\left(v_n - v_s\right) + \nabla \tau_s \qquad (4)$$

Here, P_g, k_{gs}, k_{ns}, τ_g and g are the fluid pressure [Pa], gas-solid momentum exchange coefficient between the gaseous and solids phases [kg/(m³s)], solid-solid momentum exchange coefficient [kg/(m³s)], the viscous stress tensor of the gas phase [kg/(ms²)] and the gravity constant [m/s²], respectively.

The Newtonian form of the viscous stress tensor for the gas phase, τ_g in Eq.(3), and for the solids phase, τ_s in Eq.(4), are given by [16]:

$$\tau_g = v_g\left[\nabla v_g + \left(\nabla v_g\right)^T - \frac{2}{3}\mu_g\left(\nabla \cdot v_g\right)\right]I \qquad (5)$$

$$\tau_s = \left(-P_s + \zeta_s \nabla \cdot v_s\right)I + \mu_s\left\{\left[\nabla v_s + \left(\nabla v_s\right)^T\right] - \frac{2}{3}\left(\nabla \cdot v_s\right)I\right\} \qquad (6)$$

Here P_s, μ_s, ζ_s and I are the solids pressure [Pa], the solids viscosity [Pa·s], the solids bulk viscosity [Pa·s] and the unit tensor, respectively.

P_s represents the solid pressure (normal forces) [Pa] created due to particle-particle collisions in a flow due to presence of several solid phases [17]

$$P_s = \varepsilon_s \rho_s \Theta_s + \sum_{n=1}^{N} 2\frac{d_{ns}^3}{d_s^3}\left(1 + e_{ns}\right) g_{0,ns} \varepsilon_n \varepsilon_s \rho_s \Theta_s \qquad (7)$$

e_{sn} is the particle-particle restitution coefficient between phase s and n [-], d_s is the particle diameter [m], d_{ns} is the mean diameter of the particles in phase n and s [m], $g_{o,ns}$ and Θ_s are the radial distribution function [-] and the granular temperature respectively [m²/s²].

The bulk viscosity of the solids, ζ_s in Eq (6), is given by [18]:

$$\zeta_s = \frac{4}{3}\varepsilon_s^2 \rho_s d_s g_{0,ss}\left(1 + e_{ss}\right)\sqrt{\frac{\Theta_s}{\pi}} \qquad (8)$$

The solids shear viscosity in Eq (6) is given as [19]:

$$\mu_s = \frac{4}{5}\varepsilon_s^2 \rho_s d_s g_{0,ss}\left(1 + e_{ss}\right)\sqrt{\frac{\Theta_s}{\pi}} + \frac{10\rho_s d_s\sqrt{\pi\Theta_s}}{96\left(1 + e_{ss}\right)\varepsilon_s g_{0,ss}}\left[1 + \frac{4}{5}\varepsilon_s g_{0,ss}\left(1 + e_{ss}\right)\right]^2 \qquad (9)$$

Wen and Ergun [20] proposed that the exchange coefficient k_{gs} between the gas and the solids phase given in Eq (4) and (5) could be calculated by:

$$k_{gs}\Big|_{Wen\ \&\ Yu} = \frac{3}{4} C_D \frac{\rho_s \varepsilon_s \left|v_g - v_s\right|}{d_s} \varepsilon_g^{-2.65} \qquad \varepsilon_g > 0.8 \tag{10}$$

$$k_{gs}\Big|_{Ergun} = 150 \frac{\left(1-\varepsilon_g\right)\varepsilon_s \mu_g}{\left(\varepsilon_g d_s\right)^2} + 1.75 \frac{\rho_g \varepsilon_s \left|v_g - v_s\right|}{\varepsilon_s d_s} \qquad \varepsilon_g \le 0.8 \tag{11}$$

The drag coefficient C_D [-] depends on the value of the Reynolds number, Re [-]:

$$\begin{cases} C_D = \dfrac{24}{\mathrm{Re}}\left(1 + 0.15\,\mathrm{Re}^{0.687}\right) & \mathrm{Re} < 1000 \\ C_D = 0.44 & \mathrm{Re} \ge 1000 \end{cases} \tag{12}$$

$$\mathrm{Re} = \frac{\rho_g \varepsilon_g \left|v_g - v_s\right| d_s}{\mu_g} \tag{13}$$

3) The kinetic theory of granular flow

This theory considers that collisions between the particles can predict the physical properties which affect the dynamic behavior of the particle flow. A variable called granular temperature, Θ, is introduced in the kinetic theory, see Eq. (7). It is a measure of the kinetic energy of the granular flow. One-third of the mean square velocity of the random motion of the particles is considered as the granular temperature, $\Theta = v_s'^2/3$, where $v_s'^2$ is the square of the fluctuating velocity of the particle. A transport equation for the granular temperature can be written as [21]:

$$\frac{3}{2}\left[\frac{\partial}{\partial t}\left(\varepsilon_s \rho_s \Theta_s\right) + \nabla \cdot \left(\varepsilon_s \rho_s \Theta_s\right) v_s\right] = \left(\nabla PI + \varepsilon_s \nabla \tau_s\right) : \nabla v_s + \nabla \cdot \left(k_s \nabla \Theta_s\right) - \gamma_s + \Phi_s + D_{gs} \tag{14}$$

Here, γ_s is dissipation of turbulent kinetic energy [kg/(s³m)], Φ_s is energy exchange between gas and particle [kg/(s³m)] and D_{gs} is energy dissipation [kg/(s³m)].

The turbulent kinetic energy dissipation, γ_s in Eq (14), is given as [18]:

$$\gamma_s = 3\left(1 - e_{ss}^2\right)\varepsilon_s^2 \rho_s g_{0,ss} \Theta_s \left(\frac{4}{d_s}\sqrt{\frac{\Theta_s}{\pi}} - \nabla \cdot v_s\right) \tag{15}$$

The radial distribution for N solid phases can be expressed as [22]:

$$g_{o,ss} = \frac{1 + 2.5\varepsilon_s + 4.59\varepsilon_s^2 + 4.52\varepsilon_s^3}{\left(1 - \left(\dfrac{\varepsilon_s}{\varepsilon_{s,\max}}\right)^3\right)^{0.678}} + \frac{1}{2} d_s \sum_{n=1}^{N} \frac{\varepsilon_n}{d_n} \tag{16}$$

$$\varepsilon_s = \sum_{n=1}^{N} \varepsilon_n \tag{17}$$

n are solid phases only, and d_s is the diameter of a particle in the s^{th} phase.

The energy exchange between the gas and the solids phases in Eq (14) is defined as:

$$\Phi_s = -3 k_{gs} \Theta_s \tag{18}$$

The rate of energy dissipation per unit volume is expressed in the following equation:

$$D_{gs} = \frac{d_s \rho_s}{4\sqrt{\pi \Theta_s}} \left(\frac{18 \mu_g}{d_s^2 \rho_s}\right)^2 \left|v_g - v_s\right|^2 \tag{19}$$

III. Simulation

Simulations were performed with a Froude number below 9×10^{-4} to maintain the rolling mode. Accordingly the rotational speed of the cylinder was set at 3 rpm. The cylinder and the particles rotate in the counterclockwise direction. The drum was simulated with different values for the degree of filling: 10, 15, 20 and 25 % of the drum height.

A. Physical Properties of Materials and Model Parameters

Two granular phases (A and B) with different particle size and density were used in the simulations, see Table I.

TABLE I: Physical Properties of Materials

Parameter	Description	Value
ρ_A (kg/m³)	Particle density	2537
ρ_B (kg/m³)		2417
d_A (µm)	Particle diameter	1500
d_B (µm)		3000

B. Geometry and Mesh

The transverse plane was represented by a circular geometry with a diameter of 0.19 m. The mesh contains 3500 elements to calculate transport properties of the governing equations. Fig. 2 shows the mesh of the transverse plane.

C. Initial and Boundary Conditions

The boundary condition of a rotating cylinder characterize the relative motion between the solid particles and the cylinder wall. At the cylinder wall, particles are subjected to wall friction and gravity forces. In the rolling mode, particles are moving with the wall. There, the relative velocity between the particles and the wall at the cylinder wall is zero. Therefore, a no-slip condition was assumed, meaning that the relative velocities of the gas and the particles at the wall are set to zero.

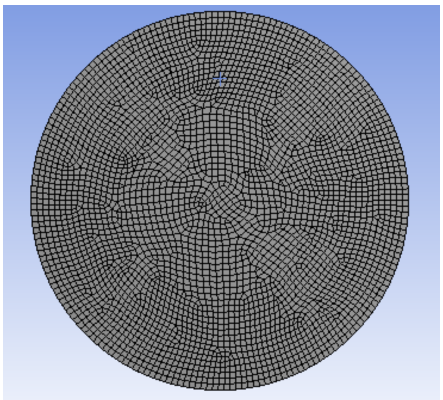

Fig. 2. Mesh of the transverse plane.

D. Solution Strategy and Convergence Criteria

The governing equations of the multiphase flow model were numerically solved by using the finite volume approach. Fluids were considered as incompressible and a pressure-based solver was used. The coupling between pressure and velocity was done by the “SIMPLE” algorithm [23]. Discretization of the model equation was done considering the second order upwind scheme [24], and the volume fraction was discretized according to the “QUICK” scheme [25]. The time step of the simulation was 10^{-3} s, and the residual values for convergence were set to 10^{-3}.

IV. Experiments

A drum made of Lexan with dimensions of 19 cm diameter and length of 29 cm was used for the experimental study. Two types of spherical particles with yellow (A) and blue (B) colours were used for the experiments. The physical properties of the particles are shown in Table 1. The particle diameters were examined through a microscope and tested using sieves. The true density of the particles was measured using an autopycnometer of model 1320 from micromeritics. The experiments were done under a constant rotational speed of 3 rpm to maintain the particle motion in the rolling mode, as explained above. Further, during the experiments, the degree of particle filling of the drum was varied from 10 to 25 % to observe its effect on particle mixing or segregation. Fig. 3 shows the lab scale experimental rig used for the particle mixing and segregation.

Fig. 3. Lab scale experimental setup.

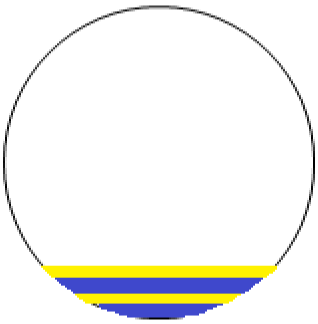

Fig. 4. Schematic of initial particle fill.

Fig. 4 illustrates the initial packing arrangement of the particles in the cylinder at t=0. In all the experiments a rotational time of 25 s was applied, corresponding to 1.25 rotation. The final state of the particle mixture at the front transverse plan was photographed to be able compare with the CFD simulation results.

V. Results

The simulations revealed that particle segregation occurs in the particle bed, see Fig. 5. The fine particles are segregated into the midsection of the transverse plane, whereas the coarser particles were collected at the bottom of the rotating drum. Segregation occurred even in the rolling mode. This can be attributed to the difference in particle size. Different degrees of particle filling had no significant impact on the particle behavior in the rotating drum.

All simulations were carried out up to 25 s, and it was observed that the volume fraction distribution had become constant after that time.

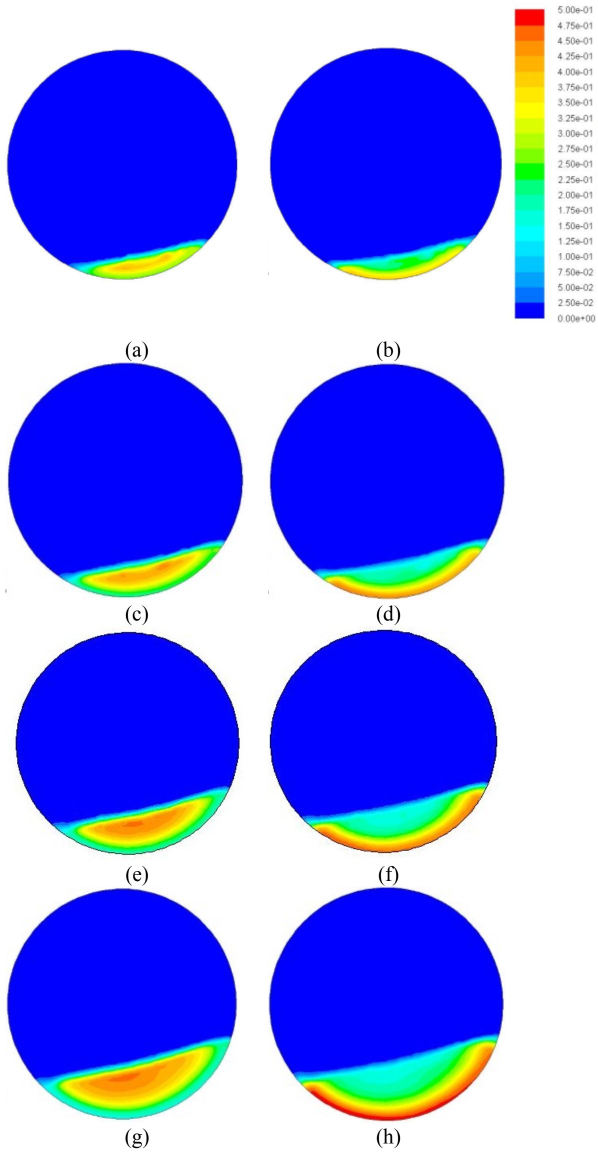

Fig. 5. Volume fractions of the two granular phases “A” (a, c, e, g) and “B” (b, d, f, h) for different filling degrees: 10 % (a, b), 15 % (c, d), 20 % (e, f) and 25 % (g, h).

The lab experiments revealed that the fine particles moved into the particle bed and formed a kidney during the drum rotation. Small particles travel through the voids between the big particles and get concentrated at the midsection of the particle bed in the transverse plane. Percolation occurs due to the variation of particle size among the materials in the drum. Since the densities of the two different granular phases are almost the same, segregation due to condensation is not significant in this setup.

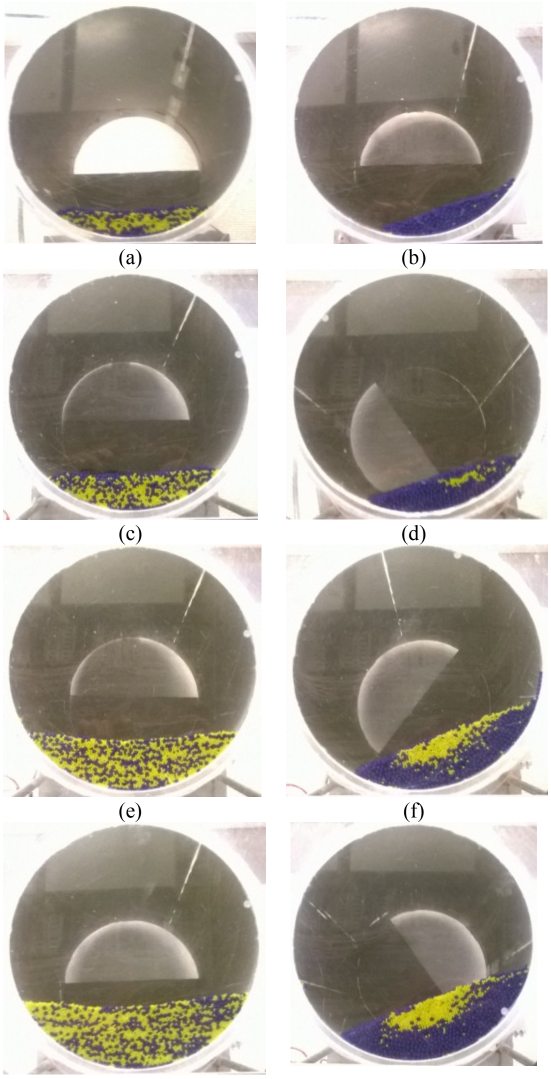

Fig. 6. State of the two granular phases at t = 0 s (a, c, e, g) and t = 25 s (b, d, f, h) for four different filling degrees: 10 % (a, b), 15 % (c, d), 20 % (e, f) and 25 % (g, h). Yellow = "A", blue = "B".

Fig. 6 shows the front view of the rotating drum at the beginning and the end of the drum rotation with different particle fillings. Segregation in the longitudinal direction is also present in a three dimensional rotating drum. As a result of this, some of the fine particles migrated away from the front solid wall of the cylinder. The end wall effect was very significant for the low degree of particle filling. This caused deviations between experimental results and simulation results. Further, the experimental results confirmed that the influence of degree of particle filling on mixing is not very significant.

VI. CONCLUSION

The Euler-Euler approach can be used to investigate mixing and segregation in a rotating cylinder. The model predictions agree with the experimental results when the degree of particle filling is 20-25 %. Segregation along the longitudinal direction causes deviations between simulations and experiments when the degree of particle filling is 10-15 %. Particle mixing in a transverse plane may be improved by selecting materials of similar particle size and density.

REFERENCES

[1] M. Halidan, "Particle mixing study in different mixers," PhD, School of Materials Science and Engineering, University of New South Wales, 2014.

[2] R. H. Nielsen, "Particle mixing and circulation in gas fluidized beds of flour and starch," PhD, Chemical Engineering and Nuclear Engineering, Iowa State University, 1974.

[3] W. Z. Chen, C. H. Wang, T. Liu, C. Y. Zuo, Y. H. Tian, and T. T. Gao, "Residence time and mass flow rate of particles in carbon rotary kilns," *Chemical Engineering and Processing: Process Intensification,* vol. 48, pp. 955-960, 4// 2009.

[4] H. Yin, M. Zhang, and H. Liu, "Numerical simulation of three-dimensional unsteady granular flows in rotary kiln," *Powder Technology,* vol. 253, pp. 138-145, 2// 2014.

[5] J. Mellmann, "The transverse motion of solids in rotating cylinders—forms of motion and transition behavior," *Powder Technology,* vol. 118, pp. 251-270, 8/28/ 2001.

[6] H. B. M. Y. Demagh, M. Lachi, L. Bordja, "Surface particle motion in rotating cylinders: Validation and similarity for an industrial scale kiln," *Powder Technology,* vol. 224, pp. 260-272, 2012.

[7] A. A. Boateng, *Rotary Kilns: Transport Phenomena and Transport Processes* USA: Butterworth-Heinemann publications, 2008.

[8] A. A. Boateng and P. V. Barr, "Modelling of particle mixing and segregation in the transvers plane of a rotary kiln," *Chemical Engineering Science,* vol. 51, pp. 4167-4181, 1996.

[9] H. Henein, J. K. Brimacombe, and A. P. Watkinson, "Experimental study of transverse bed motion in rotary kiln," *Metallurgical Transactions B,* vol. 14B, pp. 191-205, 1983.

[10] J. Bridgwater, "Fundamental powder mixing mechanisms," *Powder Technology,* vol. 15, pp. 215-236, 1976/11/01 1976.

[11] Y. L. Ding, J. P. K. Seville, R. Forster, and D. J. Parker, "Solid motion in rolling mode rotating drums operated at low to medium rotational speeds," *Chemical Engineering Science,* vol. 56, pp. 1769-1780, 2001.

[12] D. A. Santos, C. R. Duarte, and M. A. S. Barrozo, "Segregation phenomenon in a rotary drum: Experimental study and CFD simulation," *Powder Technology,* vol. 294, pp. 1-10, 6// 2016.

[13] M. Yamamoto, S. Ishihara, and J. Kano, "Evaluation of particle density effect for mixing behavior in a rotating drum mixer by DEM simulation," *Advanced Powder Technology,* vol. 27, pp. 864-870, 5// 2016.

[14] R. K. Soni, R. Mohanty, S. Mohanty, and B. K. Mishra, "Numerical analysis of mixing of particles in drum mixers using DEM," *Advanced Powder Technology,* vol. 27, pp. 531-540, 3// 2016.

[15] M. Azadi, "Multi-fluid Eulerian modeling of limestone particles' elutriation from a binary mixture in a gas solid fluidized bed," *Journal of Industrial and Engineering Chemistry,* vol. 17, pp. 229-236, 2011.

[16] H. Liu, H. Yin, M. Zhang, M. Xie, and X. Xi, "Numerical simulation of particle motion and heat transfer in a rotary kiln," *Powder Technology,* vol. 287, pp. 239-247, 2016.

[17] D. Gidaspow, *Multiphase flow and fluidization*. California: Academic press, INC, 1994.

[18] A. Neri and D. Gidaspow, "Riser hydrodynamics: Simulation using kinetic theory," *AIChE Journal,* vol. 46, pp. 52-67, 2000.

[19] H. Arastoopour, "Numerical simulation and experimental analysis of gas/solid flow systems: 1999 Fluor-Daniel Plenary lecture," *Powder Technology,* vol. 119, pp. 59-67, 9/24/ 2001.

[20] L. Huilin and D. Gidaspow, "Hydrodynamics of binary fluidization in a riser: CFD simulation using two granular temperatures," *Chemical Engineering Science,* vol. 58, pp. 3777-3792, 8// 2003.

[21] L. Huilin, D. Gidaspow, and E. Manger, "kinitic theory of fluidized binary granular mixtures," *Phys. Rev* vol. E. 64, pp. 61301-61309, 2001.

[22] G. Ahmadi and D. Ma, "A thermodynamical formulation for dispersed multiphase turbulent flows—1," *International Journal of Multiphase Flow,* vol. 16, pp. 323-340, 1990/03/01 1990.

[23] S. V. Patankar and D. B. Spalding, "A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows,"

International Journal of Heat and Mass Transfer, vol. 15, pp. 1787-1806, 1972/10/01 1972.
[24] J. W. Banks and W. D. Henshaw, "Upwind schemes for the wave equation in second-order form," *Journal of Computational Physics* vol. 231, pp. 5854–5889, 2012.
[25] H. K. Versteeg and W. Malalasekera, *An Introduction to Computational Fluid Dynamics*, second ed. England: Pearson Education Limited 2007.

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