Conference Article

Mixing Performance Analysis of Cohesive Granular Particles in a Planetary Concrete Mixer Containing Two Different Mixing Units via DEM

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Abstract

In this paper, the mixing behavior of two different types of planetary concrete mixers is analyzed and evaluated in terms of homogeneity and granular particle velocity flow regimes. For this, the Hertz-Mindlin contact law, constant directional torque, and Simplified Johnson-Kendall-Roberts (SJKR) models are utilized via the Discrete Element Method (DEM). The Lacey mixing index was employed to calculate the mixing degree of granular particles to assess the mixing performance of planetary concrete mixers. Comparing the mixing degree, we have achieved a 45,5% improvement in the mixing period of high-quality homogeneous mixture in the model B mixer.

Keywords: Discrete Element Method (DEM), Planetary Concrete Mixer, Granular Particles

1. Introduction

Until now, there has been a lot of research on particle mixing in a variety of mixer types such as vertical rotating mixers (High-shear, Bohle Tote, etc.) and horizontal rotating mixers (Twin-shaft, Continuous, Ribbon, etc.). However, the number of research that has been done on planetary concrete mixers is very few. Jin et al [1] investigated the effect of fill level, blade speed, and material properties on the mixing behaviors in an industrial-scale U-shaped ribbon mixer via DEM analysis. They realized the significant roles of fill level, blade speed, and particle diameter as well as the insignificant role of particle density in affecting the final mixing degree. Sarkar et al [2] considered the results from numerical simulations studying fill level and blade rotational speed on flow and mixing in a continuous mixer. In addition, the DEM simulations and statistical analysis were performed by Jadidi et al [3] to assess the mixing performance of a twin-shaft mixer. The relative standard deviation analysis revealed that the initial loading pattern and impeller speed had crucial influences on the mixing efficiency of the mixer. Valigi et al [4] studied the transient and regime phases of the mixing cycle to calculate the forces exchanged between the concrete mixture and the mixing organs and the power consumption in twin-shaft mixers. Arratia et al [5] performed three-dimensional (3D) DEM simulations using soft particle methods to study granular flow patterns, mixing, and segregation mechanisms in a Bohle blender. Moreover, Sato et al [6] illustrated the numerical simulation of particle motion in a high-shear mixer using DEM to analyze agitator blade torque, velocity profiles, and forces acting on a particle under various agitator rotational speeds. Also, Valigi et al [7] presented the wear of mixing blades used in planetary concrete mixers and proposed a new improved blade design with longer durability.

In this work, the Discrete Element Method (DEM) has been used to analyze and evaluate the mixing performance of two different agitator units in a planetary concrete mixer. The agitator and mixing units are powered by a 9PLC09 cobra planetary gearbox, specifically designed for the stationary planetary type of concrete mixing plant application. Also, the planetary concrete mixer is equipped with specially designed robust blades to mix the granular particles with high homogeneity. The Lacey [8] mixing index is utilized to calculate and evaluate the mixing degree. To ensure the consistency of the comparison, the two different mixing units have been analyzed with the same simulation conditions (period, rotation speed, same mixture, and mixer). Numerical simulations are realized via LIGGGHTS 3.0, open-source DEM Particle Simulation Software, to simulate and analyze the mixing performance. LIGGGHTS stands for "LAMMPS Improved for General Granular and Granular Heat Transfer Simulations" and is based on LAMMPS ("Large Atomic and Molecular Massively Parallel Simulator"), an open-source molecular dynamics code by Sandia National Laboratories for massively parallel computing on distributed memory machines [9,10]. The raw data produced by LIGGGHTS are analyzed using qualitative and quantitative techniques in ParaView which is an open-source multi-platform application for interactive scientific visualization.

2. Materials and Methods

2.1. Mathematical Model

In the continuum approach, the behavior of individual particles is ignored. However, discrete methods model granular particles by taking the behavior of individual particle interactions. The DEM was first developed by Cundall and Strack [11] to characterize the mechanical behavior of disks and spheres by explicitly solving particle trajectories. In addition, the discrete element method can provide information related to the position, velocity, acceleration, forces, and torques of particles. Equations (1) and (2) demonstrate the translational and rotational motion of each granular particle in a system exposed to particle-particle, particle-wall, cohesive forces, and gravity as well.

$$m_i \frac{d\mathrm{V}_i}{dt} = \sum_{j=1}^{K_i} (F_{c,ij}^n + F_{d,ij}^n + F_{c,ij}^t + F_{d,ij}^t) + \sum_{j=1}^{N_i} (F_{v,ij}) + m_i g \quad (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{K_i} (T_{ij}^t + T_{ij}^r) \quad (2)$$

Here, m_i, I_i, V_i, ω_i, K_i , N_i, and g are mass, moment of inertia, translational velocity, angular velocity, number of particles in contact with particle i, number of particles in the immediate neighborhood of particle i, and acceleration due to gravity respectively. The contact and damping forces in the normal direction are represented by $F_{c,ij}^n$ and $F_{d,ij}^n$ along with $F_{c,ij}^t$ and $F_{d,ij}^t$ which are the contact and damping forces in the tangential direction. $F_{v,ij}$ is the cohesive force between particles i and j. Also, T_{ij}^t and T_{ij}^r are torques resulting from the tangential force and rolling friction consecutively.
To investigate the mixing performance of planetary concrete mixers, the Hertz-Mindlin contact law, constant directional torque model, and SJKR contact model have been applied in the simulations via LIGGGHTS UDF codes. SJKR is a modified simplified Johnson-Kendall-Roberts cohesion model, which is used to simulate the cohesion of particles. The detailed mathematical formulations can be found in our previous publication and literature [12,13].

2.2. Physical Model and Simulation

As shown in Figure 1, the planetary concrete mixers consist of two side scrapers, mixing arms, mixing stars (P1), agitators (P2), whirler (P3), and hybrid mixing star (P4). The two side scrapers and one mixing arm rotate at 9,1 rpm which have the same geometry and position for both models. In addition, mixing stars (P1), agitators (P2), whirler (P3), and hybrid mixing star (P4) are powered by planetary gears of the gearbox which are rotating

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at 30,8 rpm while also rotating around a central point at 9,1 rpm leading to cover the entire mixer floor in a few revolutions.

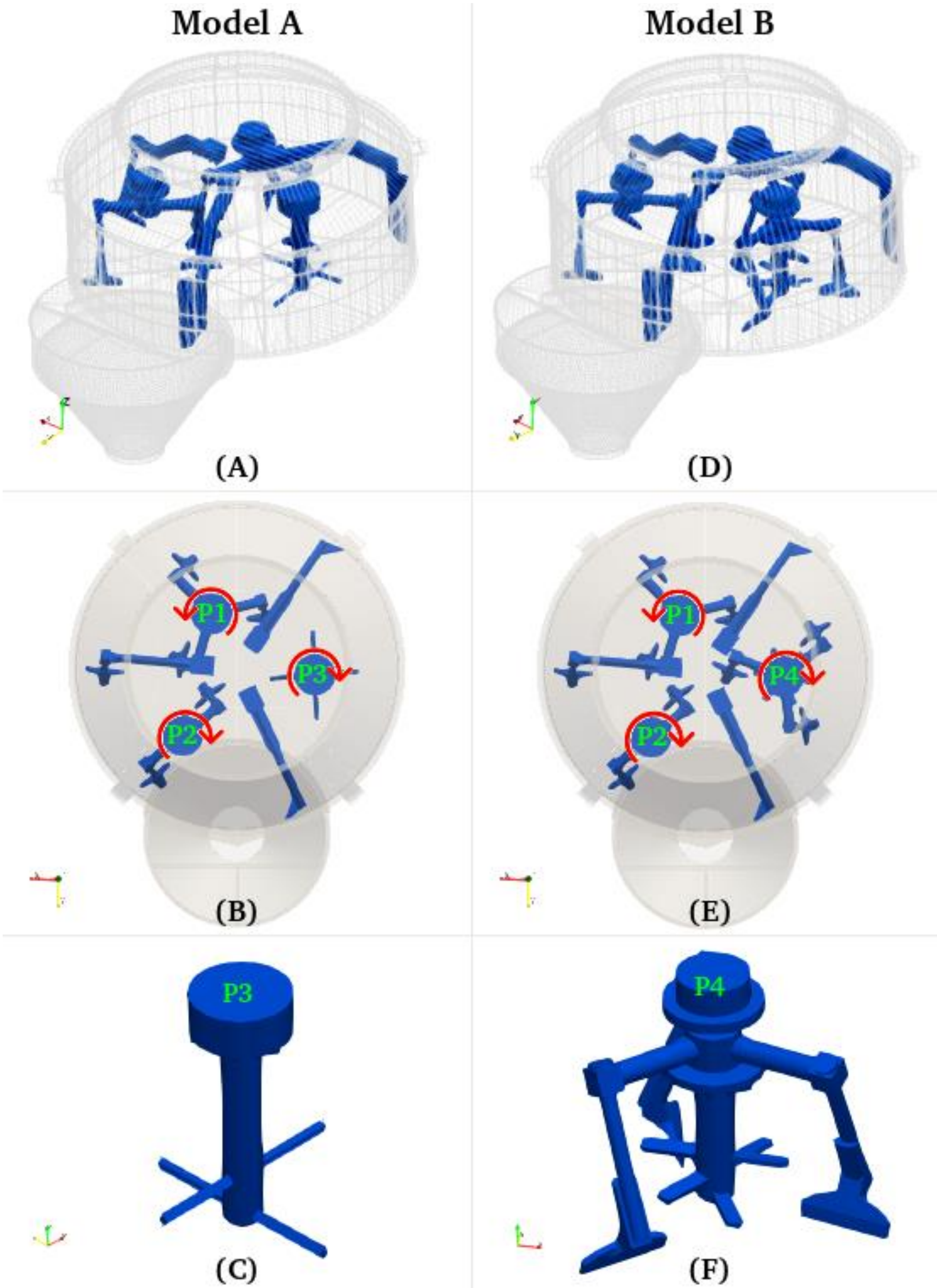

Figure 1. Geometric views of two planetary concrete mixers from top to bottom for each type with their distinct mixing units.

The three-dimensional (3D) geometries of planetary concrete mixers are designed and faceted using the ANSYS SpaceClaim module. Then, the 3D models were converted to STL files, and the mixers' rotational speed and material properties were set in LIGGGHTS UDF codes. Also, a minimum time step for reliable simulation is realized according to the Rayleigh time step criterion [12]. In this study, two different colors of solid granular particles with specific physical and mechanical properties are generated inside the planetary concrete mixers. The following Table 1 shows the set of input parameters used in the simulations.

Table 1: Properties of particles and walls in planetary concrete mixer used in the simulation

Material Properties	**Particle**	**Wall**
Density(kg/m^3)	2400	7800
Radius (mm)	12.5	-
Young's Modulus (N/m^2)	10×10^6	210×10^9
Poisson Ratio	0.30	0.32
Contact Properties	**Particle-Particle**	**Particle-Wall**
Sliding Friction Coefficient	0.30	0.20
Rolling Friction Coefficient	0.10	0.01
Coefficient of Restitution	0.25	0.25
Cohesion (kJ/m^3)	100	100

2.3. Simulation Characterization Analysis

Several mixing indices are introduced for the determination and evaluation of mixtures [14]. The quality of mixing can be analyzed by studying the degree of mixing of granular particles in the planetary concrete mixer. Here, the Lacey mixing index method was realized to calculate the degree of mixing during the mixing period. The Lacey mixing index can be defined as

$$MI = \frac{S_0^2 - S^2}{S_0^2 - S_r^2} \tag{3}$$

where S^2 is the variance of the mixture, S_0^2 and S_r^2 is the variance of a fully segregated system and a fully mixed system. The mixing index value range is between zero to one which has a zero value for a fully segregated system and rise to one for a fully mixed system. The S^2, S_o^2, and S_r^2 are calculated by

$$S^2 = \frac{1}{N}\sum_i^N (x_i - x_m)^2 \tag{4}$$

$$S_o^2 = x_m(1 - x_m) \tag{5}$$

$$S_r^2 = \frac{x_m(1-x_m)}{n} \tag{6}$$

in which N is the total number of sample sets, while x_i, x_m, and n are the number fraction of marked particles in each sample set, the average number fraction of marked particles, and the average number of particles in the sample sets.

3. Result

In this simulation, 240000 monosized particles with two different colors under the effect of gravitational force are injected into the planetary concrete mixer. The particles are generated according to the physical and mechanical properties shown in Table 1. Also, the mixer charging is realized via the Hertz-Mindlin contact law and constant directional torque model while in the mixing stage, the SJKR model is added to simulate the cohesion of granular particles. The total simulation time is 60 sec comprised of 8,5 sec of filling with the mixing stage and 51,5 sec of pure mixing time.

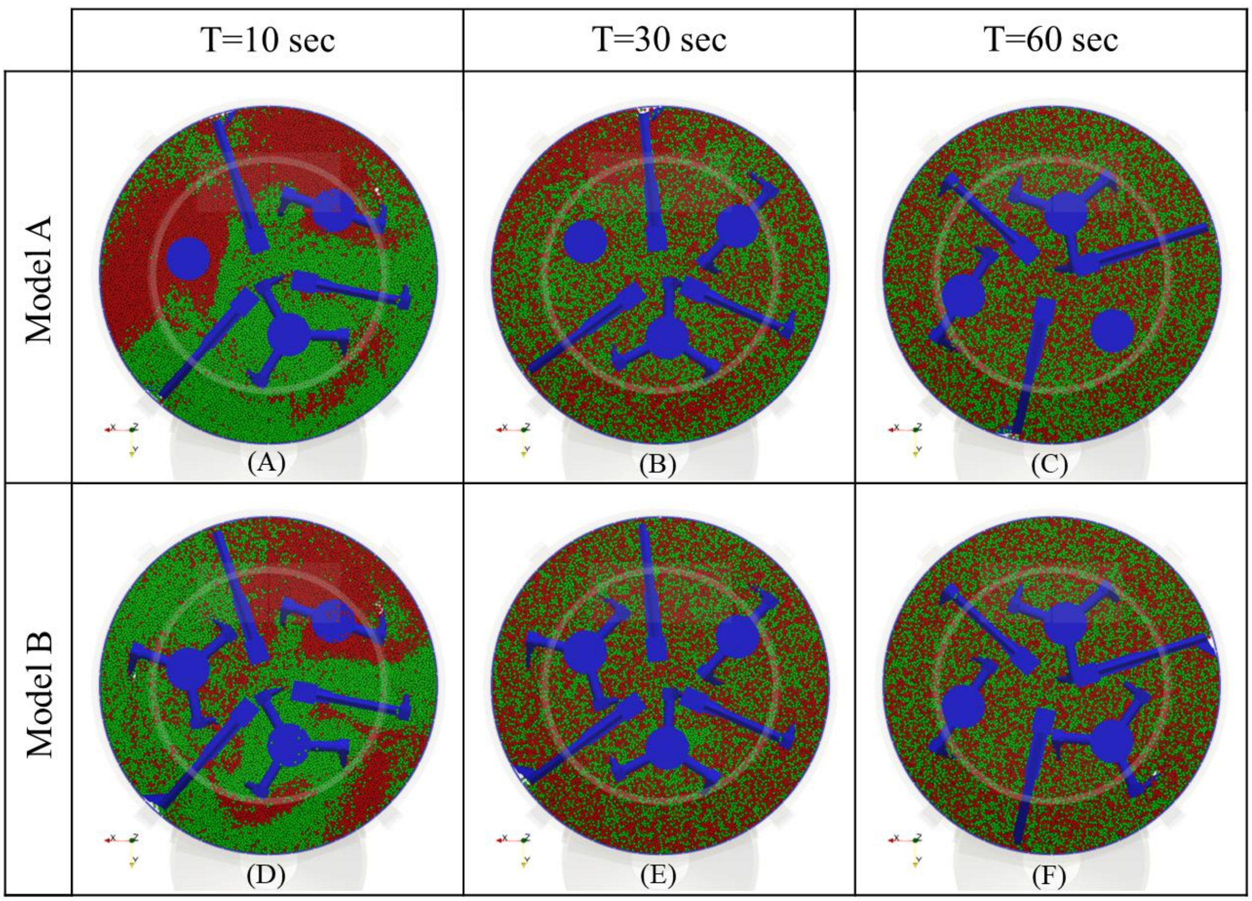

Figure 2. Comparison of simulation snapshots from the top view of planetary concrete mixers at different time instants.

Figures 2 and 3 demonstrate a series of simulation snapshots from the top view and cross-sectional view of planetary concrete mixers at different mixing times respectively. To attain a homogeneous mixture, planetary rotation of mixing units leads to the creation of active flow regimes by different mixing mechanisms such as convection, diffusion, and shearing. As time passes, the particles are mixed continuously but visual homogeneity perception on the mixture at T=10 sec and T=30 sec for model B is leading in comparison with model A. However, at the end of the simulation, the mixing quality for both models is in the acceptable range.

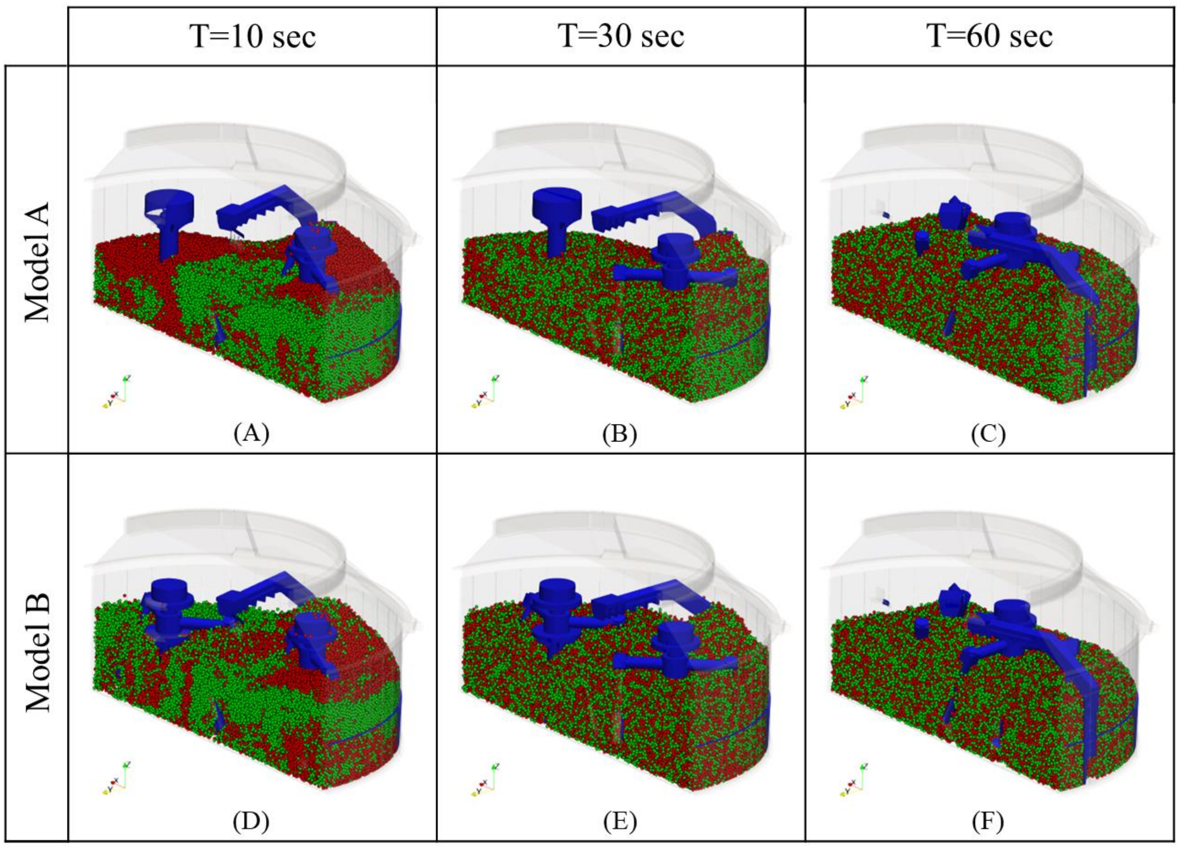

Figure 3. Comparison of simulation snapshots from the cross-sectional view of planetary concrete mixers at different time instants.

The Lacey mixing index was employed to study the mixing efficiency of planetary concrete mixers. Figure 4 presents the mixing index versus time for two models. The results illustrate that the mixing index for model A raised at the beginning and reached a steady state after 33 sec. On the other hand, there was a sharp increase in the mixing index for model B at the first stages of simulation and reached a plateau after 18 sec. As a result, there is a 45,5% improvement in the mixing time of acceptable homogenous mixture in model B mixer which is achieved via a hybrid mixing star (P4) unit.

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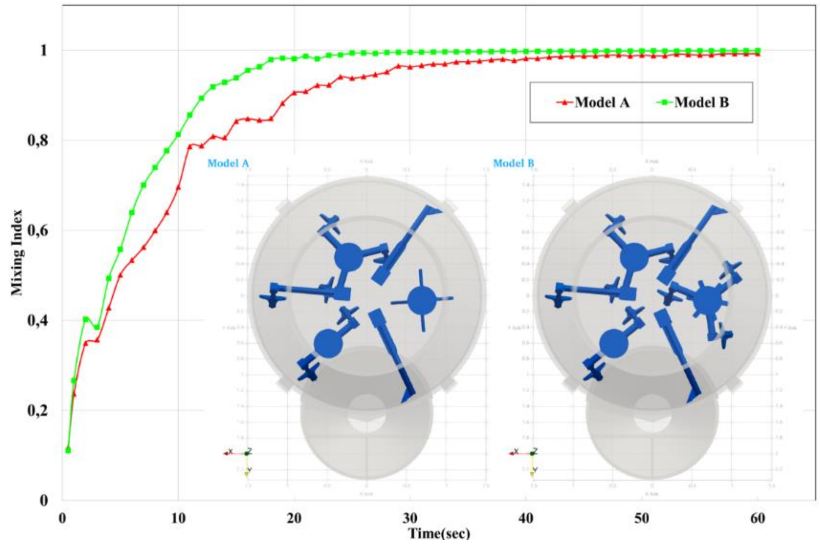

Figure 4. Comparison of the mixing index versus time for two models of planetary concrete mixers.

Figure 5 shows the velocity vectors of the granular particles qualitatively and quantitatively at different time instants for both models. The particle's velocity vectors consist of active and passive regions. Noticeably, the velocity values of granular particles

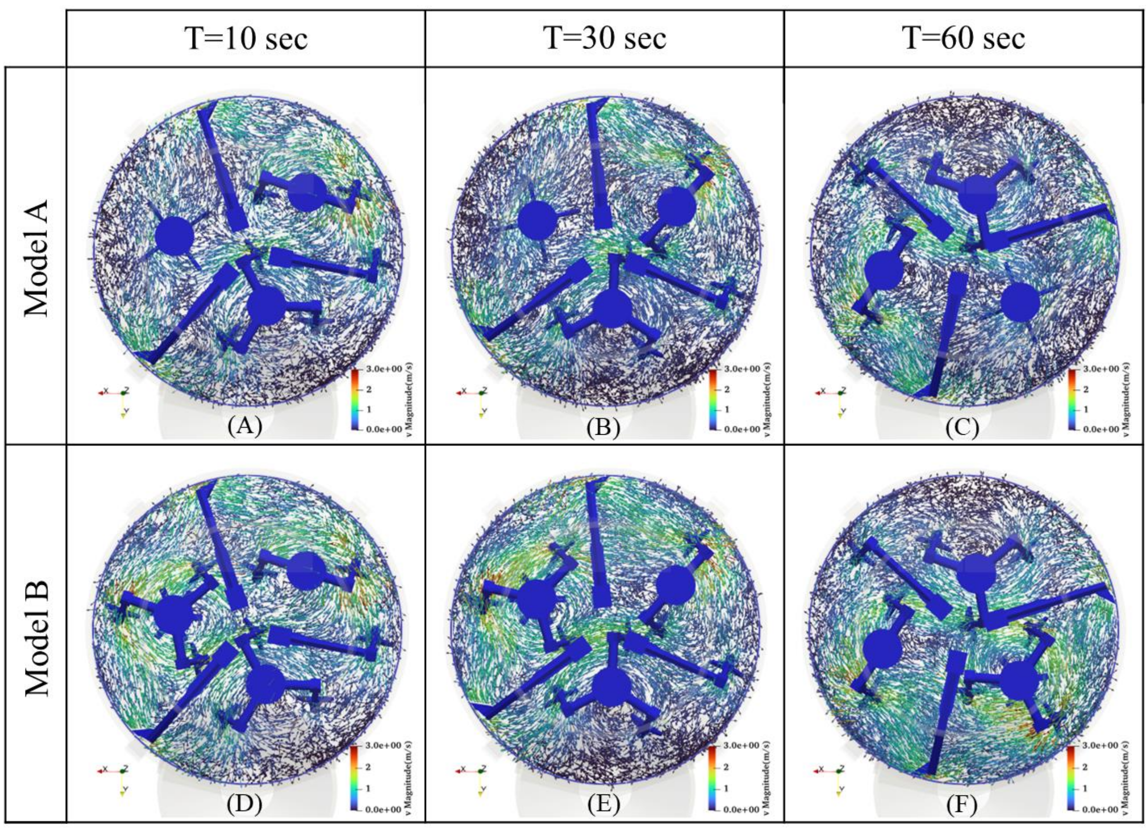

Figure 5. Comparison of simulation snapshots from velocity vectors of particles for model A and model B planetary concrete mixers at different time instants.

around the hybrid mixing star in model B are greater than the whirler mixing unit in model A at all time instants. Consequently, it is worth indicating that the mixing performance of Model B is higher than Model A planetary concrete mixer.

4. Discussion and Conclusion

The DEM is used to analyze and evaluate the mixing performance of two different models of planetary concrete mixer. Accordingly, the mixer charging simulations are realized via the Hertz-Mindlin contact law and constant directional torque model while the mixing stage is realized via the SJKR model. After 60 sec of continuous mixing, the particles are homogeneously mixed inside the mixers and the mixing index at the first stages of model B is far higher than model A. Correspondingly, the hybrid mixing star unit (P4) has improved the mixing period by 45,5% to produce high-quality homogenous mixtures.

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