

# Application of Two-fluid Mode

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In two-fluid model (TFM), the granular flows are modeled as continuous fluid flows. The random motions of particles resulting from the interactive collisions of particles has a dominant effect on the flow behavior. The granular interactions are commonly modeled based on the kinetic theory of granular flow (KTGF).

Keywords: dense granular flow ; rotating drum ; flow and mixing ; two-fluid model

## 1. Introduction

Granular matter are ubiquitous in the daily lives and in industries, but they behave differently from other familiar forms of matter, such as solids, liquids and gases <sup>[1]</sup>. Some researchers have even suggested that granular medium be considered as an additional form of substance existence <sup>[2]</sup>. The science of granular media has a long history <sup>[3]</sup>, but the description of granular flow still remains an open issue due to its intriguing range of complex, nonlinear behavior. Because of their practicability and complexity, knowledge of the dynamics of particles is of high interest in engineering and academia. Among the many varieties of particle processing equipment, the rotating drum is a typical one with dense granular flow inside, and it is widely used in the industry for mixing, drying, milling, coating, or granulation/agglomeration <sup>[4]</sup>. Particle flow in rotating drums exhibits a range of complex phenomena, such as avalanche, segregation, and convection <sup>[5]</sup>. Therefore, the current paper focus on dense granular flow in rotating drums.

The diameter of the rotating drum used in the industry ranges from a few meters to tens of meters, and the number of particles in it is huge. Therefore, the cost of industrial-scale experimental research is quite high. Moreover, it is difficult to get the particle scale information accurate in experiments <sup>[6]</sup>. With the rapid development of computers, numerical methods provide an effective and cost-saving alternative way to study particle flow behavior in rotating drums. The two common numerical methods are the discrete element method (DEM) and the two-fluid model (TFM). DEM has been applied in this area since the 1990s <sup>[7]</sup>. DEM calculates the motion and force equation of individual particles, so it can provide valuable particle scale information, such as coordinate number, collision velocity, and collision frequency <sup>[8]</sup>.

## 2. Model Application

The behavior of particle flow is affected by many variables related to system geometry, operational condition, and material properties <sup>[9]</sup>. Rotational speed, which is an important operating parameter of the rotating drum, has attracted the attention of researchers for a long time. Ingram et al. <sup>[9]</sup> summarized the flow of dense particles in the rotating drum without flights at different rotational speeds into six patterns: sliding, collapsing, rolling, cascading, cascading, and centrifuging. In addition, the particles in the rotating drum are usually different in size, density and shape in practical application. However, only uniform particles with the same properties and binary particles with different sizes in rotating drums were found, as seen in **Table 1**.

**Table 1.** Summary of the simulation condition.

Year of Publication	Focus of the Study	Validation Basis	Rotation Method	D (mm)	L (mm)	Flight or Not	Particle Type	d (mm)	$\rho_s$ (kg/m <sup>3</sup> )	Particle Shape
2012 <sup>[10]</sup>	Dynamic characteristics and the rheology of a granular viscous flow scale up	Particle velocity and dimensionless active layer thickness	-	400	-	No	Uniform	1.5	2900	Spherical
2013 <sup>[11]</sup>	Particle dynamic behavior	Solid flow regime and velocity distribution	-	195	500	No	Uniform	1.09/3.68	2460	Spherical

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2015 <sup>[12]</sup>	The effect of operating conditions on solids flow	Solids hold up in the flight	moving mesh	108	500	Yes	Uniform	1.09/1.84/2.56 2.56	2455 2090	Spherical
2016 <sup>[13]</sup>	Predict the transverse and axial solid-flow patterns, the fluid-flow profile, and particle residence time	Particle and fluid velocities and residence time	moving wall	390	450	No	Uniform	4.25	1370	Spherical
2016 <sup>[14]</sup>	Heat transfer and mixing characteristics	Velocity and temperature of particles	-	203	-	No	Uniform	2.5	2627	Spherical
2017 <sup>[15]</sup>	Boundary condition effects on the particle dynamic flow	Solids hold up in the flight, the bed height and solid volume fraction distribution	moving mesh	108	500	Yes	Uniform	1.09	2455	Spherical
2017 <sup>[16]</sup>	The effects of specularly and restitution coefficients under different solid-flow regimes	Solid volume fraction distribution	moving mesh	300	450	Yes	Uniform	25	7890	Spherical
2017 <sup>[17]</sup>	The effects of parameters on heat transfer characteristics	Average temperature of granular materials	moving wall	300	350	Yes	Uniform	1	3900	Spherical
2018 <sup>[18]</sup>	The effects of parameters on the hydrodynamic and granular temperature of particles	Particle velocity	moving wall	215	-	No	Uniform	6.2	1164	Spherical
2018 <sup>[19]</sup>	Irregular particle (non-spherical) dynamics	Rice grains velocities and drum transverse plane	moving wall and moving mesh	390	20/30/40	No	Uniform	3.44 *	1465	Non-spherical
2019 <sup>[20]</sup>	The effects of parameters on the charge of solid in the flight	Solids hold up in the flight and solid volume fraction distribution	moving mesh	108	500	Yes	Uniform	1.09 1.02	1551 963	Spherical
2020 <sup>[21]</sup>	Solid frictional viscosity and wall friction	Particle velocity and flow pattern	moving mesh	100	-	No	Uniform	3	2500	Spherical
2021 <sup>[22]</sup>	The comparison between the Eulerian (CFD) and the Lagrangian (DEM) approaches	Solids hold up in the flight and solid volume fraction distribution	moving mesh	108	500	Yes	Uniform	1.09	2455	Spherical
2007 <sup>[23]</sup>	Main features of solids motion and segregation	Particle velocity and concentration	-	240	1000	No	Binary	1.5/3	2600	Spherical
2013 <sup>[24]</sup>	Particle segregation and model of granular viscosity	End-view bed profile	-	45	50	No	Binary	0.385/0.775	2500	Spherical
2016 <sup>[25]</sup>	Quantitatively and qualitatively evaluates the mixture and segregation processes	Drum transverse plane	-	220	500	No	Binary	6.35/1.13	2460	Spherical
2017 <sup>[26]</sup>	Particle segregation and model of granular viscosity	End-view bed profile	-	500	500	No	Binary	0.385/0.545/0.775	2500	Spherical
2017 <sup>[27]</sup>	Effects of specularly coefficient on particle segregation	End-view bed profile	-	500	500	No	Binary	0.385/0.545/0.775	2500	Spherical
2020 <sup>[28]</sup>	Mixing and segregation of particles	The evolution of the degree of mixing and mixing process	-	150	10	No	Binary	3/1.5	2600	Spherical

An important step before using a model is validation. Usually, the model is validated by comparison with experiment results. Therefore, before the analysis of model application, how the model is validated is worthy of attention. A column

named validation basis is given in **Table 1**. It is easy to see that for the drum with flights, solids holdup in the flight is often used as a comparison object. While for the drum without flight, the velocity distribution of particles is used the most, especially for drums with uniform particles. End-view bed profiles are used for rotating drums with binary particles inside because there is often a core structure of segregation, or other clear structures can be found, and it is easy to make qualitative comparison. It should be noted that the comparison using granular temperature is not found, although it is the most direct way for the validation of the model.

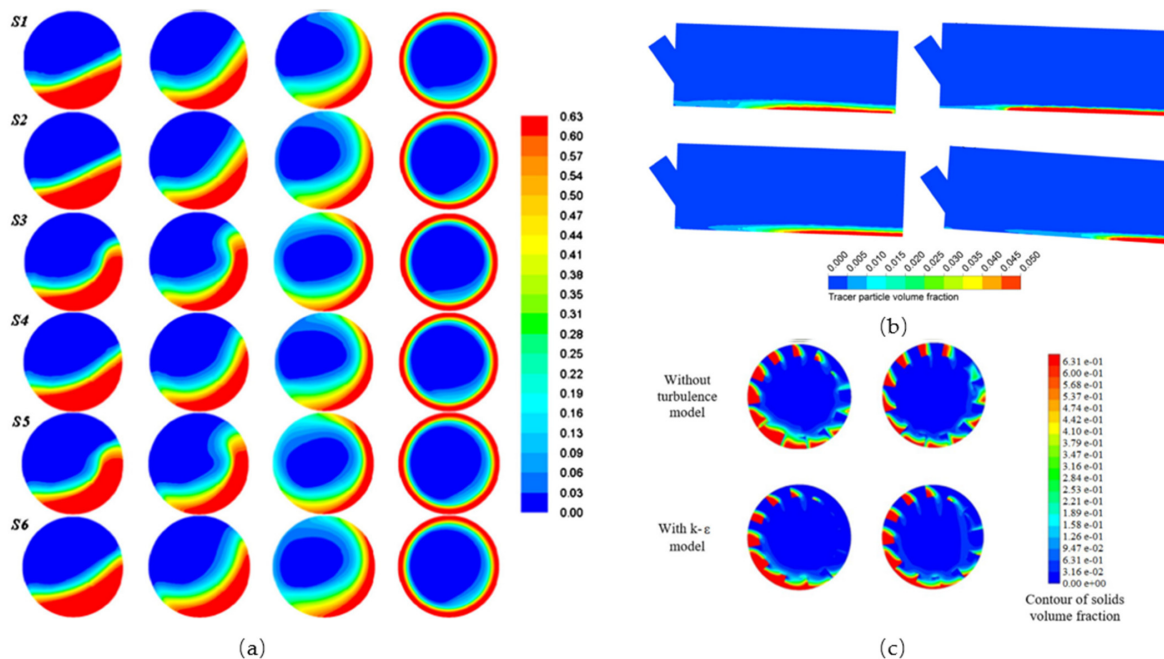
## 2.2. Study on the Flow of Dense Uniform Particles

In order to simplify the simulation, uniform particles are assumed in most studies, even though they are rarely found in practice. Under this assumption, the model is verified by comparing it with laboratory-scale experiments in which uniform particles are used [21][18].

For the dense uniform particle flow in the rotating drum without flights, Demagh et al. [10] studied the particle flow characteristics in the two flow states of rolling and cascading, and found that the particle velocity direction on the particle bed surface is not always parallel to the bed surface, and there are included angles in some positions, indicating that the particles will not slide or roll, but jump when moving. Santos et al. [11] identified different regimes (rolling, cascading, cataracting and centrifuging) of solids in motion in a rotating drum. Furthermore, Delele et al. [13] used the model to study the effects of rotational speed, filling level, feed speed, and drum inclination angle on particle flow, and found that the particle flow near the surface of the particle bed has a strong entrainment effect on the transverse air flow. Similarly, the effects of rotational speed, restitution coefficient and particle size on the hydrodynamics of the particle was investigated by Taghizadeh et al. [18]. It is worth mentioning that the effects of these parameters on the granular temperature of particles was also studied. They found that the particle–particle restitution coefficient and rotational speed play a significant role in the granular temperature, and consequently on the hydrodynamic behavior of the bed. Moreover, the TFM-coupled KTGF and diverse heat transfer models were used to predict heat transfer in a rotating drum, and it was revealed that the bed surface velocity characteristic peak is located at the center and down the edges [14].

For the dense uniform particle flow in the rotating drum with flights, the configuration of flights plays an important role on the granular flow. The effects of the number of flights [20], flight folding angle [20] and flight shape [15][17][22] on particle flow behavior were analyzed. The solid-hold-up in the flight was well predicted. Similar to the rotating drum without flights, the particle flow pattern, the effects of the operational parameters, the effects of the model parameters, and the heat transfer were also analyzed [12][16][17].

Moreover, Nascimento et al. [22] proposed for the first time that considering the turbulence effect in the model can better predict the active region and passive region of the particle bed. **Figure 1** gives representative results.

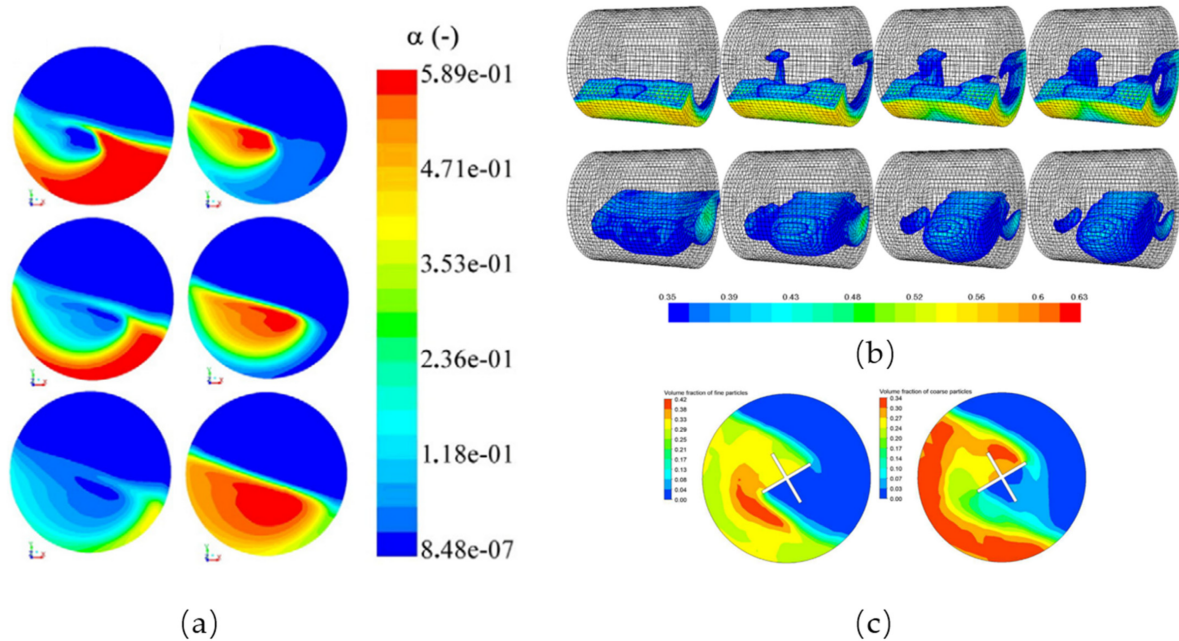


**Figure 1.** (a) Volume fraction of the granular solid phase of 3.68 mm and fill level of 31.40% for drum rotating at 1.45, 4.08, 8.91 and 16.4 rad/s from the left to the right [11]; (b) axial distribution of the tracer particle volume fraction after an injection time of 60 s for different operating conditions of the drum [13]; (c) solid volume fraction distributions (passive phase) without and with the k-ε-turbulence model [22]. (Note: all the legends indicate volume fraction of particles).

It is about at spherical particles, while the flow process of uniform non-spherical particles in a rotating drum was studied by Benedito et al. [19]. It was found that by giving appropriate parameters, the model could be verified by comparing the rice grain velocities and the drum transverse plane with the experimental results. It is worth noting that this verification is accidental, because the parameters are given by the trial-and-error method instead of experimental measurement. In essence, the numerical model for non-spherical particles has not been developed.

### 2.3. Study on Mixing and Segregation of Dense Binary Particles

Compared with uniform particles in rotating drums, the mixing and segregation of binary particles occur due to different particle properties, which are more complex. There are generally two types of mixing in horizontal rotating drums: longitudinal and transverse. Similar to mixing, there are also two types of segregation: radial and axial segregation. He et al. [23] first used the TFM coupled with KTGF to simulate binary particle segregation with different sizes in a rotating drum, which confirmed the predict applicability of the model. A clear core-shell structure in the transverse plane of the drum, in terms of the concentration of small and large particles, was predicted and an initial attempt was made to simulate the axial particle segregation. Santos et al. [25] conducted simulations to predict the mixing and segregation of particles in a rotating drum due to the different particle diameters. The predicted particle segregation was in good agreement with the experimental results. The internal structure of the bed material inside the drum which consisted of a symmetrical wing-shaped extension of small particles towards the drum end plates was observed. However, Huang et al. [24][29] observed that the TFM coupled with KTGF failed to predict the mixing and segregation of the particles in the rotating drum they investigated; then, they proposed the dynamic angle of repose fitting (DARF) and bed surface fitting (BSF) to modify the kinetic viscosity of the model. The results showed that the modified model was useful for analyzing the radial and axial segregation of particles in the rotating drum. Although these studies predict the typical mixing and segregation of particles using the model, the degree of particle mixing or segregation was not quantified. Referring to mixing indices in DEM simulation and experimental research, a mixing index based on sampling information from the computational grids was established [28]. The index was used for the quantitative analysis of the segregation degree of binary particles with different sizes in a rotating drum without a baffle, and drums with baffles of different shapes. It was found that the enhancement effect of the baffle on particle mixing was not obvious, and the mixing speed was too fast compared with the experimental results. Therefore, the TFM coupled with KTGF is applicable for predicting the mixing and segregation of binary particles in rotating drums, but the accuracy needs further discussion. The representative results are shown in Figure 2.



**Figure 2.** (a) Simulated drum transverse plane for the radial segregation analysis [25]; (b) the surface of the 0.775 mm solid phase (top row) and 0.385 mm solid phase (bottom row) [30]; (c) the mixing process of binary particles in the drum with "+" baffle [28]. (Note: all the legends indicate volume fraction of particles).

**Table 1** summarizes the relevant studies including the representative model applications described above. It can be seen that TFM coupled with KTGF has been used for modeling dense granular flow in rotating drums since 2007. It has been used for only 14 years. Zhu et al. [7] has given a detailed review of DEM used for granular flow in rotating drums; it can be easily noticed that DEM has a longer history and has been more popular in this area than TFM. However, they indicated that the number of particles that can be dealt with at the moment is limited. Moreover, although there are model



advantages of TFM compared with DEM, such as low computing resources and suitability for industrial-scale modeling, the model is still used for a laboratory-scale rotating drum (diameter less than 0.5 m), and no simulation for an industrial-scale rotating drum was found.

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