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Numerical flow simulation of fresh concrete in mixing truck

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HIGHLIGHTS

- A numerical method was developed to simulate flow of fresh concrete in mixing drum.
- The screw pitch and height of blade have an effect on discharge uniformity.
- Increasing the screw pitch of blade at the posterior cone can increase discharge speed.

GRAPHICAL ABSTRACT

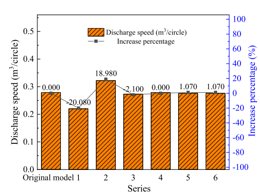

Fig. 1. Discharge speed and increase percentage of series 1-6

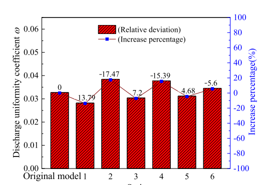

Fig. 2. Discharge uniformity and increase percentage of series 1-6

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ABSTRACT

The structure of concrete truck not only affects the homogeneity of fresh concrete but also influences the construction efficiency. The repeatability of fresh concrete's test is worse and its cost is high. With this in mind, the simulation of fresh concrete flowing in concrete truck was conducted. The effects of screw pitch and height of blade on discharging speed were analyzed. The numerical results shown that increasing the screw pitch of blade at posterior cone can significantly promote the discharging speed. The discharging uniformity was also investigated. It is shown that increasing the height of blade or decreasing the screw pitch of blade can improve the homogeneity.

1. Introduction

As the most important building materials, concrete is mainly composed of sand, stone and cementitious materials. Concretes include printed concrete, previous concrete and ordinary concrete [1,2], and their rheology is controlled by the rheology of their pastes [3]. With the extensive application of concrete in the field of infrastructure, the traditional field mixing concrete is gradually replaced by commercial

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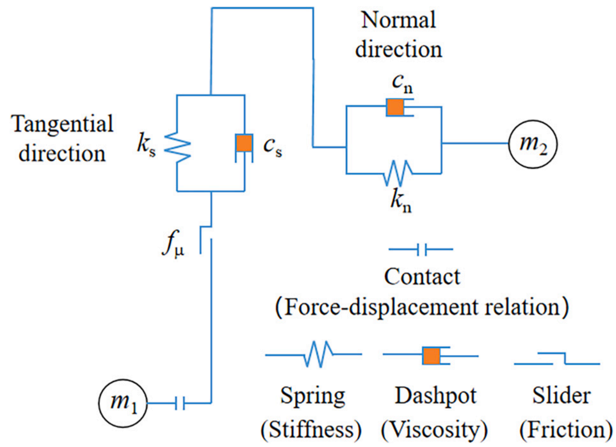

Fig. 1. General contact model in DEM (k is the stiffness of the linear spring, c is the damping coefficient of the damper, f_μ is sliding friction coefficient.)

concrete, which is generally produced by professional mixing plant and then transported to the construction site [4]. In this process, the concrete mixer is used as the main tool of transportation, which is mainly composed of spiral blade and mixing drum. The structural parameters of spiral blade affect the working performance of concrete mixer.

The flow of fresh concrete in the mixing drum is a complex process [5]. Due to the differences in the size, shape and density between mortar and coarse aggregate, they are easy to separate and lead to segregation [6], which seriously affects the strength and durability of concrete structure [7]. In addition, the rheology of fresh concrete also affects the segregation [8]. The concrete mixer truck mainly mixes the fresh concrete through its internal spiral blade, which will break the particle contact and slow down the setting of the fresh concrete to make the coarse aggregate evenly distributed [9]. The concrete mixer is large and opaque, so it is inconvenient to observe the internal particle state [10], it is difficult to evaluate the influence of the internal structural parameters of the concrete mixer on the discharge efficiency, and the test cost is expensive. The discrete element method (DEM) can visualize the flow of concrete in a mixing drum and understand the particle movement [11]. Liu et al. used DEM to study the mixing performance of drum. Particles had quick been mixed in the transverse plane and the well mixed state was achieved within a few revolutions, however, the presence of the capillary force in general reduced mixing performance [12]. The cohesion of particles is not conducive to their mixing [13]. Deng et al. studied on the axial segregation of particles through the change of coarse aggregate content. They found that the segregation of particles was mainly caused by the shape and size of particles and the structure of mixing drum. The segregation is a proportional function of the relative movement of particles. The greater the torque, the greater the axial segregation speed [14]. The tilt angle of the mixing drum, the discharge speed and the mixing time before discharge have a important effect on the discharge uniformity. The discharge uniformity is inversely proportional to the discharge speed and tilt angle [15], and the maximum discharge rate can be obtained at the discharge speed of 8 rpm [16]. Due to the thixotropy of fresh concrete, its apparent viscosity increases. The early segregation speed in the mixer is fast, and the later segregation speed is obviously slow [17]. However, there are few studies on the influence of concrete truck structure on the discharge performance.

In order to understand the flow behavior of fresh concrete in the concrete mixing truck, a numerical method was developed via a commercial software EDEM in this paper. A discharge uniformity coefficient and discharging speed were respectively calculated as the measurement index of discharge uniformity and discharging efficiency. The numerical results of discharging process were compared with experimental results. And then 12 series of screw pitch and height of blade varying in the front cone, middle cone and posterior cone respectively were designed. The influences of structural parameters of blade on discharge uniformity and efficiency were numerically analyzed. The results will provide guidance for the optimal design of concrete mixing truck.

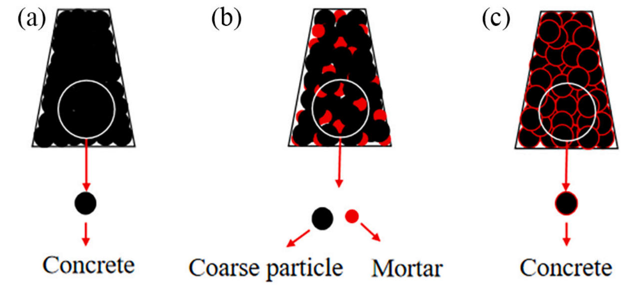

Fig. 2. Fresh concrete in DEM.

2. Numerical method

2.1. DEM

DEM proposed by Cundall (1971) is a recognized numerical tool in the field of rock mechanics. This method regards the research object as a particle element and solves its movement by Newton's law of motion and Force-Displacement law. Different physical relations between discrete particles are reflected by the connector, mainly including spring, dashpot and slider [18], as shown in Fig. 1.

2.2. Fresh concrete in EDEM

Fresh concrete is mainly composed of cement, sand and coarse aggregate etc., which have great differences in size, and relevant literature shows that DEM can be used for numerical simulation of fresh concrete [19]. Considering the calculation scale, capacity and efficiency, the treatment of fresh concrete is particularly important. There are usually three types in DEM: single-phase elements, separated single-phase elements and biphasic elements [20], as shown in Fig. 2. In this paper, the discharge uniformity will be calculated, so that the separated single-phase element model is selected, that is to say, fresh concrete is divided into mortar and coarse aggregate that are respectively described by two types of spherical particles with different size and properties. (See Fig. 2.)

(a)Single-phase element (b)Separation of single-phase elements (c) Biphasic element.

The interaction of fresh concrete is described by the contact model between coarse aggregate and mortar particles as well as theirselves. Fresh concrete is of viscosity due to cement. Therefore, the Hertz Mindlin with JKR contact model in EDEM, which is suitable to viscosity material, was selected as the contact model between particles. An important parameter of Hertz Mindlin with JKR contact model is the contact surface energy, which is the work done by particles to particles. JKR model has cohesion force to make particles agglomerate together [21].

3. Calibration

3.1. Raw materials

The parameters of contact model are calibrated to ensure that the numerical simulation results are consistent with the test results. In this

Table 1
Mix proportion (bulk density 2400 kg/m^3).

Water(kg)	Cement(kg)	Water reducing agent(kg)	Sand(kg)	Gravel(kg)
214.4	466.0	1.4	722.3	997.4

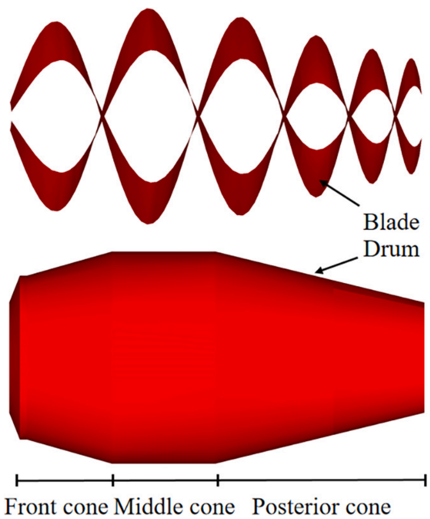

Fig. 3. Concrete mixing truck model.

Fig. 4. Field diagram of discharging test.

paper, the discharge test of concrete mixing truck was used, and the measurement indexes are discharge speed and discharge uniformity. The mix proportion of fresh concrete is shown in Table 1. Sand and gravel were purchased locally. 42.5 ordinary Portland cement was used. The addition amount of naphthalene sulfonate water reducer was 0.2%, the water binder ratio was 0.46 and the sand ratio was 42%. The slump is 180 mm.

3.2. Discharging test

A concrete mixing truck with maximum loading of 7m^3 was used. The concrete mixing truck and blade is shown in Fig. 3. The concrete mixing truck contains three parts: front cone, middle cone and posterior cone. The loading volume was 6m^3 and rotate speed of drum was 6 rpm, from beginning to end of discharging, the concrete mixing truck rotated 20 cycles in total. The field test is shown in Fig. 4. Therefore, the discharge speed of the concrete mixing truck was 0.3 m^3/circle.

In discharging process, 15%, 50% and 85% of the total mass (6m^3) of fresh concrete were respectively sampled. The coarse aggregate content Ω_i is calculated by Eq. (1).

$$\Omega_i = \frac{m_i^a}{m_i^c} \quad (1)$$

where, *ma i* and *mc i* are the total mass of sample *i* and the mass of coarse aggregate in sample *i*, respectively.

The discharge uniformity coefficient ω is expressed Eq. (2). The smaller the coefficient, the better the discharge uniformity [22].

$$\omega = 0.5\left(\frac{|\Omega_1 - \Omega_2|}{\Omega_1 + \Omega_2} + \frac{|\Omega_3 - \Omega_2|}{\Omega_3 + \Omega_2}\right) \quad (2)$$

where, $i = 1,2,3$ respectively the sample at 15%, 50% and 85%.

After sampled, the fresh concrete was washed to select the coarse aggregate. The average masses of fresh concrete and coarse aggregate of three times are shown in Table 2. The experimental discharge uniformity is 3.35.

Table 2
Discharge uniformity test.

Sample	Fresh concrete(kg)	Coarse aggregate(kg)	Discharge uniformity
15%		3.30	
50%	7.1	2.97	3.35
85%		3.07	

Table 3
Physical parameters of materials.

Category	Parameter	Value
Coarse aggregate	Diameter(mm)	20
	Density(kg/m^3)	2560
	Shear modulus(N/m^2)	8e+07
	Poisson's ratio	0.35
Mortar	Diameter(mm)	10
	Density(kg/m^3)	2100
	Shear modulus(N/m^2)	8e+06
	Poisson's ratio	0.35
Steel	Density(kg/m^3)	7850
	Shear modulus(N/m^2)	8e+08
	Poisson's ratio	0.3

Table 4
Particle contact parameters.

Category	JKR contact parameters (J/m^3)
Mortar-mortar	3.6
Mortar-aggregate	3.2
Aggregate-aggregate	2.8
Mortar-wall	0.25
Aggregate-wall	0.2

3.3. Comparison of simulations and experiments

Due to the capacity of computer, the concrete mixing truck and blade

Table 5
Standard deviation of coarse aggregate content before discharge.

Series	Mixing time (s)	Standard deviation of coarse aggregate content (%)
Original model	30s	2.90
1	25	2.92
2	54	3.00
3	26	2.92
4	38	2.96
5	40	2.94
6	50	2.90
7	20	2.92
8	44	2.81
9	44	2.88
10	36	2.86
11	35	2.93
12	35	2.94

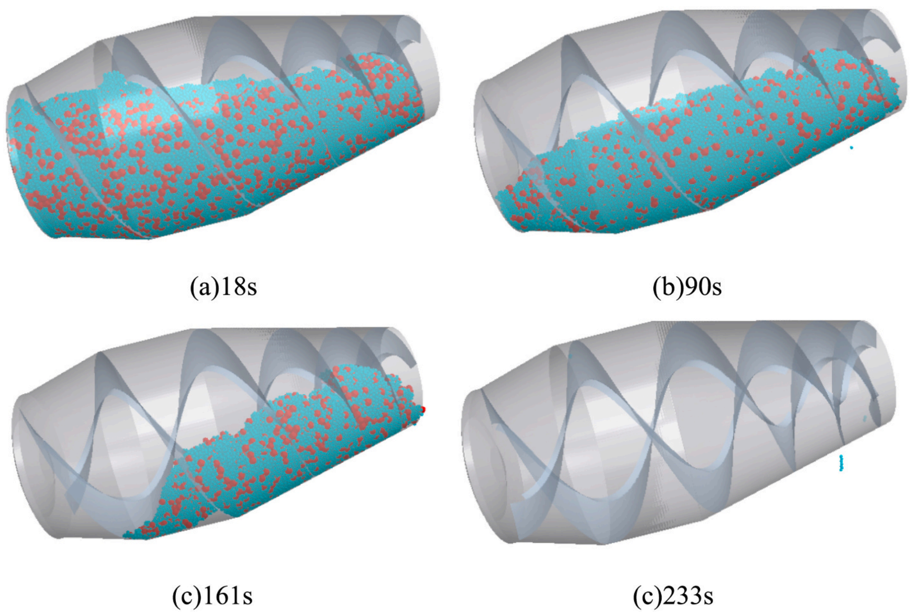

Fig. 5. Diagram of concrete mixing truck discharging process.

Table 6
Experimental and numerical results of discharge speed.

	Discharging volume (m^3)	Number of circles	Discharge speed (m^3/Circle)	Error
Test	6	20	0.30	6.7%
Simulation		21.5	0.28	

Table 7
Experimental and numerical results of discharge uniformity.

	Test	Simulation	Error (%)
Discharge uniformity coefficient	3.35	3.27	2.4

was scaled 64 times. Fresh concrete is represented by two types of particles with diameter of 10 and 20 mm, the physical parameters of materials are shown in Table 3. The concrete mixing truck rotated at -2 rpm, particles with a total mass of 147.71 kg and volume of 6m^3 were generated at the middle cone, there were 5756 coarse particles and 77,714 mortar particles. The values of contact parameters are shown in Table 4.

In order to guarantee the uniformity in mixing drum, we calculated the standard deviation of coarse aggregate content before discharge. If the index is less than 3%, we regard the fresh concrete is uniform. Otherwise, the mixing truck is rotated with a high speed of −10 rpm till the index is less than 3%. The standard deviations of coarse aggregate content in the drum of 12 series are shown in Table 5.

3.3.1. Discharge speed

The concrete mixing truck rotated at 6 rpm for discharging. As stated above, the drum rotated quickly before discharge to guarantee the uniformly in mixing drum, the mixing time was different (Table 5). To compare discharge speed, 0 s is reset at the beginning of drum rotating at 6 rpm. At 18 s, the particle begins to flow out. At 233 s, the last particle flows out of the concrete mixing truck. The concrete mixing truck turned 21.5 circles in discharging process. The discharging processes are shown in Fig. 5. The numerical results of discharge speed is 0.28 m^3/circle. The error between simulation and test is 6.7%, as shown in Table 6, which indicates that the numerical simulation results under these contact parameters are close to the experimental ones and meet the simulation requirements.

Table 8
Change of screw pitch.

Series	Posterior cone (mm)	Middle cone (mm)	Front cone (mm)
Original model	600–2000	2000–2000	2000–2000
1	480(−20%)-2000	2000–2000	2000–2000
2	720(+20%)-2000	2000–2000	2000–2000
3	600–2000	2000–1600 (−20%)	(−20%) 1600–2000
4	600–2000	2000–2400 (+20%)	(+20%) 2400–2000
5	600–2000	2000–2000	2000–1600 (−20%)
6	600–2000	2000–2000	2000–2400 (+20%)

3.3.2. Discharge uniformity

Every 5% discharging concrete, the coarse aggregate content was calculated according to Eq.(1). As the same with experiment, the discharge uniformity was also evaluated by the Eq. (2). As shown in Table 7, The experimental and numerical discharge uniformity is respectively 3.35 and 3.27, the error is 2.4%.

4. Effect of blade on discharge process

In order to investigate the effect of blade's structural parameters on discharge process, 6 series blades of different screw pitches and 6 series blades of different heights were taken into account. Their effects were discussed as follows.

4.1. Discharge speed

4.1.1. Screw pitch

Screw pitch of blade refers to the axial distance between two corresponding points of adjacent blades on the central diameter line. It is one of the key parameters characterizing the spiral blade in the concrete mixing truck. The screw pitch of different positions has different effects on the concrete mixing truck. The change of screw pitch is shown in Table 8. The screw pitch of original model is linear change at posterior

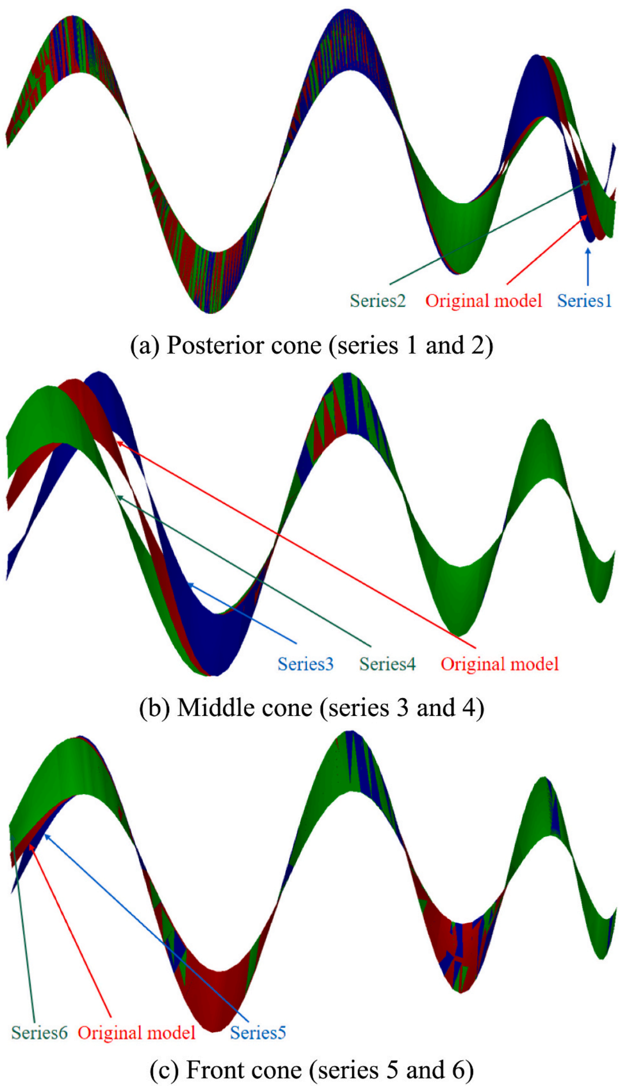

Fig. 6. Change of screw pitch.

cone, and is constant (2000 mm) at middle cone and front cone. The screw pitch of series 1 at posterior cone is reduced by 20% and is increased by 20% in series 2. The connection between front cone and middle cone needs to be consistent, so the screw pitch at middle cone and front cone should simultaneously change. The screw pitch of series 3 is decreased by 20%, and the screw pitch of series 4 is increased by 20%. The screw pitch of series 5 at front cone is reduced by 20% and is increased by 20% in series 6. The model diagram is shown in Fig. 6.

According to the numerical results of the above series 1–6, the relationship curve between discharge quality and time is obtained, as shown in Fig. 7, it can be seen that the change of screw pitch at posterior cone has a significant effect on the discharge speed, which is shown in Fig. 8, it can be seen that increasing the screw.

pitch at posterior cone (series 2) can increase the discharge speed by 18.98%, while reducing the screw pitch at posterior cone (series 1) can reduce the discharge speed by 20.08%. However, the change of screw pitch at middle cone and front cone has no significant difference on the discharge speed. The reason for this phenomenon is that the discharge speed is positively correlated with the screw pitch at posterior cone, when the particles move to the outlet, they will have a larger

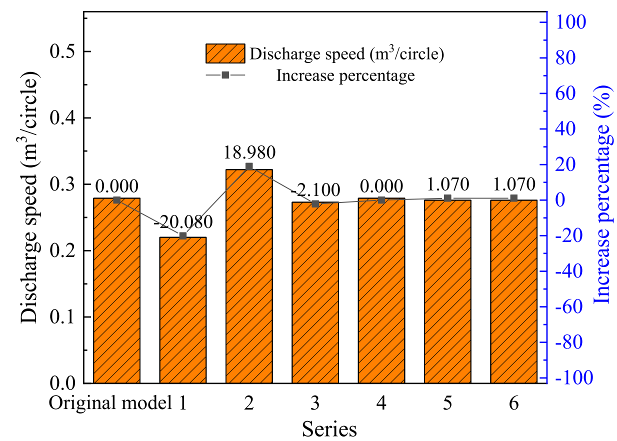

Fig. 8. Effect of screw pitch on discharge speed.

Table 9
Change of blade's height.

Series	Posterior cone(mm)	Middle cone (mm)	Front cone (mm)
Original model	260–510-440	440	440–410
7	234(−10%)-510–440	440	440–410
8	286(+10%)-510–440	440	440–410
9	260–510-396	396(−10%)	396(−10%)-410
10	260–510-484	484(+10%)	484(+10%)-410
11	260–510-440	440	440–451(+10%)
12	260–510-440	440	440–369(−10%)

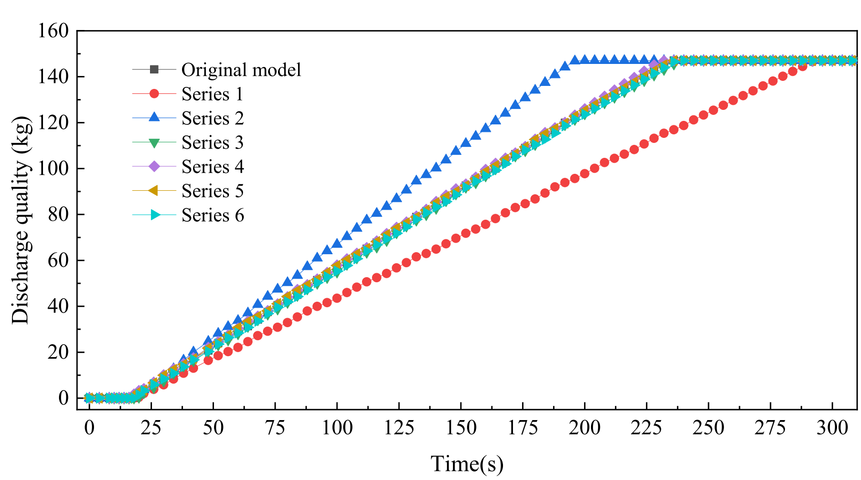

Fig. 7. Relationship between discharge quality and time of series 1–6.

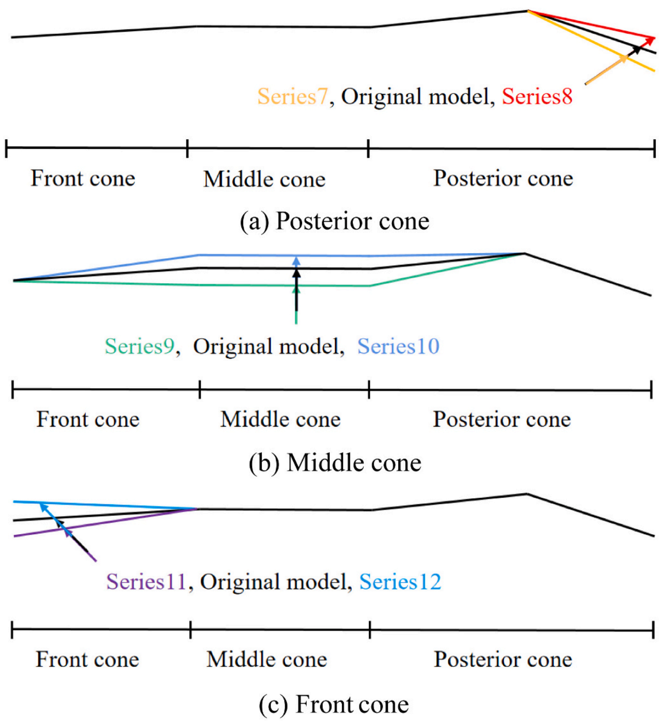

Fig. 9. Schematic diagram of blade's height.

displacement along the axial direction of cone, so their velocities increase.

4.1.2. Height

In order to investigate the influence of blade's height on the working process of concrete mixing truck, 6 series blades of different heights were designed, as shown in Table 9. The height of blade at posterior cone is limited by the feeder unit and maximum loading, so it is low at the beginning of posterior cone and is high at the middle position. The height of series 7 at posterior cone is reduced by 10% and is increased by 10% in series 8. The height of series 9 is decreased by 10%, and the height of series 10 is increased by 10%. The height of series 11 at front cone is reduced by 20% and is height by 20% in series 12. The schematic diagram of blade's heights are shown in Fig. 9.

Figs. 10 and 11 show the effect of blade's height on discharge speed. Decreasing the height of blade at middle cone has a slight influence on discharge speed. Other series do not has obvious effect. The reason is that the blade at the middle position of posterior cone is enough high, it can guarantee the fresh concrete near the outlet is almost the same. Hence, the discharge speed has little change.

4.2. Discharge uniformity

4.2.1. Screw pitch

Fig. 12 shows the influence of the screw pitch of spiral blade on the coarse aggregate content in the discharging process. It can be seen that the coarse aggregate content fluctuates greatly at the beginning and end of the discharging process. Discharge uniformity of series 1–6 is shown in Fig. 13. It can be seen that reducing the screw pitch of blade (Series 1, 3 and 5) can improve the discharge uniformity. On the contrary, increasing the screw pitch of blade (Series 2, 4 and 6) reduces the discharge uniformity. Due to the effect of gravity, the coarse aggregate slides toward to the bottom of cone and result in segregation. The movement of coarse aggregate is prevented by the blade. The degree of segregation increases with the displacement of coarse aggregate. Decreasing the screw pitch lead to a smaller displacement. At posterior cone, the tilt angle is largest, its effect is most obvious.

4.2.2. Blade's height

Fig. 14 shows the influence of blade's height on the coarse aggregate content in the discharging process. As the same in Fig. 12, the coarse aggregate content fluctuates greatly at the beginning and end. Discharge uniformity and increase percentage of series 7–12 is shown in Fig. 15. It can be seen that increasing the height of spiral blades at posterior cone,

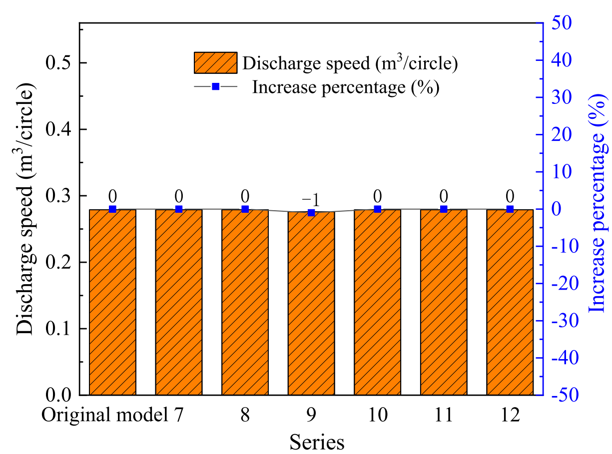

Fig. 11. Effect of blade's height on discharge speed.

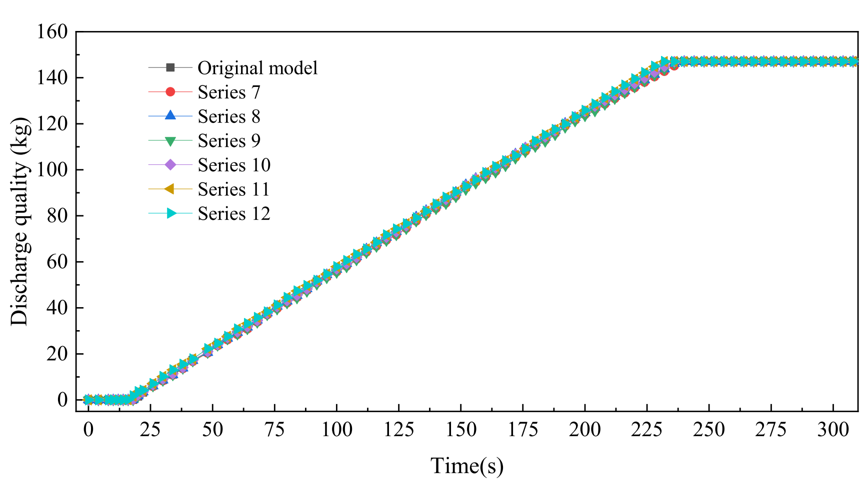

Fig. 10. Relationship between discharge quality and time of series 7–12.

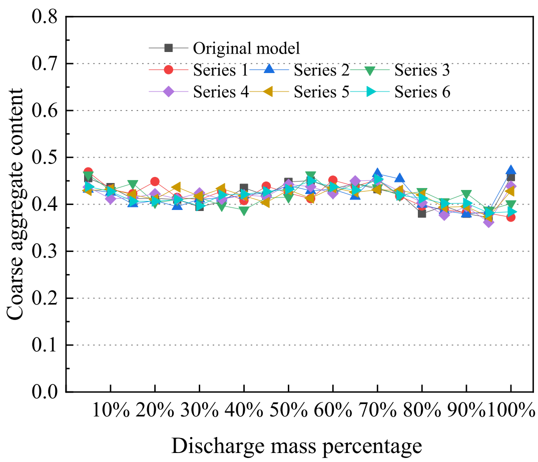

Fig. 12. Relationship between Coarse aggregate content and time of series 1–6.

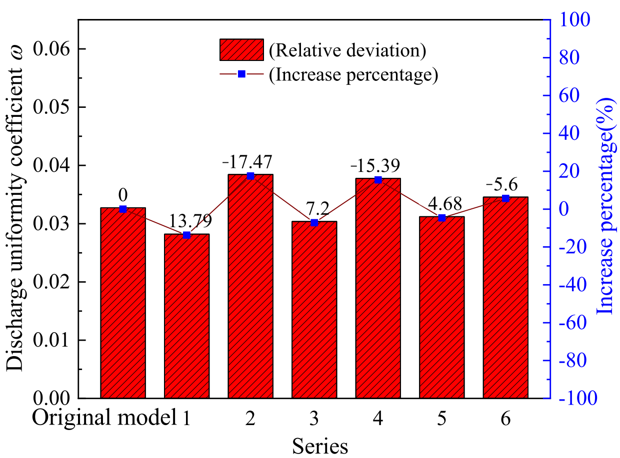

Fig. 13. Effect of screw pitch on discharge uniformity.

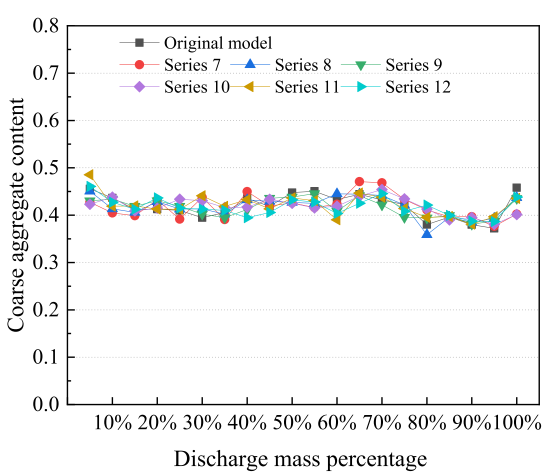

Fig. 14. Relationship between coarse aggregate content and time of series 7–12.

middle cone or front cone (Series 8, 10 and 12) can slightly improve the discharge uniformity. On the contrary, reducing their height of spiral blades (Series 7, 9 and 11) reduces the discharge uniformity. The uniformity of fresh concrete in mixing cone is dependent on mixing effect and its viscosity. The higher the height of blade, the better the mixing

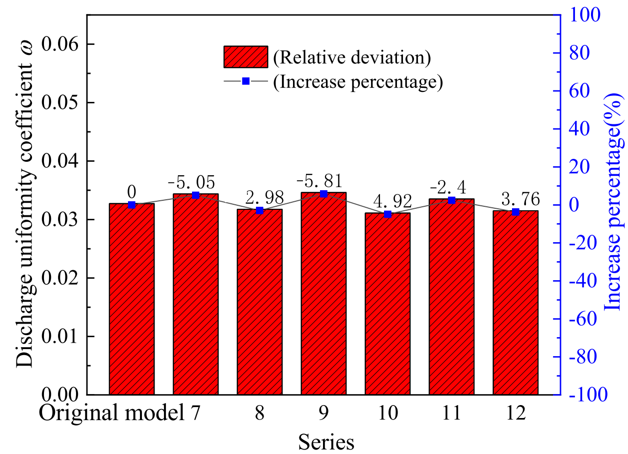

Fig. 15. Effect of blade's height on discharge uniformity.

effect, which is necessary for the uniformity. When fresh concrete is homogeneous, the discharge uniformity is relatively better. Therefore, the discharge uniformity increases with height of blade.

5. Conclusion

The working performance of the fresh concrete mixing truck mainly depends on the structure of spiral blade. In this paper, a numerical method based on EDEM was proposed. 12 series simulations of different screw pitch and blade's height were conducted. The numerical results of discharging test were well agree with the experimental results.

Based on the simulation, it is found that increasing the screw pitch of blade at posterior cone can increase the discharge speed of 18%, and decreasing the screw pitch of blade will reduce the discharge speed of 20%. However, the changes of screw pitch at other positions have no obvious effect on the discharge speed. The change of blade's height has slight effect on discharge speed.

For discharge uniformity, decreasing the screw pitch is beneficial, the increase of blade height can be significantly improved within 3% ~ 5%.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Data availability

The data that has been used is confidential.

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