

Article

Numerical Investigation of Force Network Evolution in a Moving Bed Air Reactor

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Abstract: In spite of extensive research on macroscopic solid movements in the dense granular system of a moving bed air reactor, research on the evolution characteristics of the mesoscale inter-particle contact force network is still lacking. In this work, discrete element simulations are conducted to investigate the force chain structure properties in a moving bed air reactor. The results show that during the particle discharging process, the force chain network exhibits great anisotropy, and force chain contacts account for only about 13–14% of all inter-particle contacts, while the strong particle–particle contacts account for about 37–41% of all the particle–particle interactions. The collimation coefficients of force chains are more stable at the early stages and then decrease sharply over time. Both particle–particle and particle–wall friction coefficients affect the number, strength, collimation coefficient, and direction of force chains but have little influence on the length distribution of force chains. An in-depth analysis of the evolution of the force network provides new insights for further understanding dense granular flow in a moving bed air reactor for chemical looping combustion.

Keywords: force network; discrete element method; dense granular system; moving bed



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1. Introduction

Dense granular systems have extensive applications in chemical engineering, environmental science, mining, the pharmaceutical industry, and grain transport [1]. Moving beds, silos, and hoppers are all typical dynamic dense granular systems. In our previous studies [2–4], a moving bed, a typical dense granular system, was used as the air reactor in a chemical looping combustion system for carbon capture. Despite the advantages of low-pressure drop and stable running performance compared to fluidized bed reactors, the operation of a moving bed reactor shows a tendency for oxygen carrier sintering at high temperatures, primarily due to heterogeneous particle movements. The flow of granular materials exhibits complex self-organizing and non-homogeneous behaviors, which cannot be easily categorized as either classical fluids or solids [5]. Despite their ubiquitous presence, achieving a better operation of a moving bed reactor requires a deep understanding of dense granular systems, which are still in the early stages of exploration to a certain extent [6].

The dense granular system in a moving bed air reactor is intrinsically multiscale, including the microscale of single particles, the macroscale of the bulk of granular materials, and the mesoscale of inter-particle contact mechanics. The mesoscale contact mechanics serve as a bridge between single particles and the granular system. Within the system, some strong inter-particle forces form a cross-linked network of anisotropic and filamentary structures known as force chains. These force chains are crucial to the overall kinetic and mechanical properties of granular materials [7]. Mesoscale structures terminate at the particle scale, with particles within force chains accommodating the majority of body forces and externally applied forces. The force chain network is spatially inhomogeneous,

and its properties are influenced by both the granular material characteristics and the boundary conditions.

Understanding the behavior and properties of these force chains is essential for comprehending the mechanical behavior of dense granular systems. Tian and Liu [8] investigated the effects of particle shape and confining pressure on the spatial distribution and length of force chains under a 2D biaxial loading. The influence of particle shape was also studied by Zhou et al. [9] and Antony et al. [10]. Meng et al. [11] investigated the force chain characteristics of dense particles in a parallel plate particle flow friction system, and the influence of pressure load and shear velocity was discussed. From the above research, it is evident that the mesoscale mechanics of granular materials is an exciting field with many fundamental problems yet to be explored. However, current research primarily focuses on ideal quasi-static systems.

Currently, most existing investigations of dense granular materials in moving beds focus on macroscale features such as solid flow rate [12,13], flow velocity [14,15], solid residence time [16,17], and the distribution of tracking particles [18]. Zhang et al. [19] systematically studied the time intervals between consecutive particle discharges under a series of geometrical and operating conditions, utilizing their probability density function. Liu et al. [18] tracked the particle flow around an obstacle in a quasi-2D flow channel by a stained particle image velocimetry technique and numerical simulation. The influence of the reactor angle, outlet position, orifice size, and internals was also widely investigated in recent research [20,21].

Despite extensive studies on the macroscale flow patterns, deep insights into the fundamental mechanical behaviors underlying these macroscopic phenomena remain limited due to the complexity and difficulty of extracting dynamic force chain information during the operation of dense granular systems like silos, moving beds, and hoppers. Zhang et al. [22] validated that the common clogging–collapsing events occurring in the hoppers were closely related to the coordinated evolution of the entire force chain system. Xu et al. [23] investigated the effects of wall friction on the force network in a rectangular hopper. Liu et al. [18] examined the formation of the contact force network near the outlet. A recent comprehensive analysis of flow behaviors during funnel and mixed flow discharges [24] reported that the “shaking” feature of particle velocity could be attributed to the force disturbance, but a detailed investigation of the source and propagation of these force disturbances was still lacking. To the authors’ knowledge, existing research does not provide a detailed quantitative analysis of the force chain network evolution characteristics in a dynamically dense granular system, even though it is widely accepted that macroscopic solid flow patterns depend greatly on mechanical behaviors. One of the existing studies on dense granular flow in a hopper showed that frictional forces on the side walls support most of the weight of the particle bed above a certain height [25]. Additionally, it has been reported that the coefficients of inter-particle friction and particle–wall friction influence the discharge rate, flow pattern, and stress distributions [26,27]. However, more detailed work is needed to understand how coefficients of friction change the mesoscopic properties of the force chain network.

The discrete element method (DEM), based on the research work of Cundall and Strack [28], is widely used for the simulation of dense granular systems. In the method, each particle is tracked, and collisions between particles are directly resolved [29,30]. This allows for the extraction of detailed information on the evolution characteristics of contact forces, overcoming the limitations of experimental approaches. However, the DEM approach is generally constrained to relatively small systems because of the high computational cost consumed by the neighbor search algorithm [31]. Thus, there may be deviations between the simulation results and actual operating results in industrial-scale systems to a certain degree.

Although many studies have focused on macroscopic flow properties, the mechanical behaviors, especially the quantitative description of the mesoscale force chain network in dynamic dense granular systems like moving beds, still remain open. This study aims to fill

the gap by conducting a quantitative analysis of the contact force network using the DEM approach. The main work is organized as follows: (1) the model validation is first carried out to ensure the feasibility of the DEM model by comparing the simulation results with the experimental data in a moving bed; (2) the spatial–temporal distributions and directions of the inter-particle contact force network are compared with those of the force chain network; and (3) the evolution characteristics of the force chains are statistically investigated, focusing on parameters such as number, length, strength, and collimation coefficient. We believe this study will provide profound insights into the complex distributions of flow patterns, transition laws, and reactor optimization in moving bed air reactors for chemical looping combustion.

2. Numerical Solution Approach

2.1. Discrete Element Numerical Model

The basic principle of the DEM approach is to treat particles as discrete elements. According to Newton's second law, the relationship between the force acting on a particle and its displacement is expressed as follows:

$$\frac{d\mathbf{X}}{dt} = \mathbf{v} \quad (1)$$

$$m\mathbf{g} + \sum \mathbf{F}_i = m \frac{d\mathbf{v}}{dt} \quad (2)$$

$$\sum \mathbf{F}_i \mathbf{r}_i = I \frac{d\boldsymbol{\omega}}{dt} \quad (3)$$

where m is the mass of the particle; $\mathbf{F}_i$ is the contact force between the target particle and i th particle; $\mathbf{v}$ is the linear velocity; $\boldsymbol{\omega}$ is the angular velocity; I is the rotational inertia; and $\mathbf{r}_i$ is the vector between the i th inter-particle contact and the center of the target particle.

The interactions between particles are described by a linear spring dashpot model. The spring component represents the elastic collision, while the dashpot component accounts for the energy loss due to inelastic inter-particle collisions. The inter-particle contact force is the sum of the normal contact force $\mathbf{F}_{in}$ and the tangential contact force $\mathbf{F}_{it}$:

$$\mathbf{F}_{in} = k_n \delta_n \mathbf{n} - \gamma_n \mathbf{v}_n \quad (4)$$

$$\mathbf{F}_{it} = k_t \delta_t \mathbf{t} - \gamma_t \mathbf{v}_t \quad (5)$$

where δ_n and δ_t represent the normal and tangential displacement, respectively; γ_n and γ_t are the damping coefficient in the normal and tangential directions, respectively; and $\mathbf{n}$ and $\mathbf{t}$ are the unit vector in these directions; the elastic coefficients in the two directions, k_n and k_t , are set to the same value in this work.

When the tangential contact force is larger than the maximum static friction force, i.e., $|\mathbf{F}_{it}| > \mu |\mathbf{F}_{in}|$, the static friction force at the contact point changes to sliding friction force. The Coulomb yield criterion is used to limit the magnitude of the tangential contact force, which is expressed as [26]

$$\mathbf{F}_{it} = \mu |\mathbf{F}_{in}| \mathbf{t} \quad (6)$$

where μ is the friction coefficient. In this study, the friction coefficients between particles and between particles and walls are varied between 0.2 and 0.8 to investigate their effects on force distribution characteristics. A more detailed description of the DEM approach can be found elsewhere [16].

2.2. Definition of Force Chain and Search Algorithm

A force chain is defined as a physical structure consisting of a quasi-linear chain of particles. To form a force chain, the following conditions must be met:

The particle–particle contact force must exceed the average contact force $\bar{F}$ in the entire system, as specified in Equation (7).

The angle θ between two adjacent normal contacts should not exceed the threshold θ_c to ensure the stability of the force chain. θ_c is correlated with the average coordination number of the particles, as shown in Equation (8). In DEM simulation, connections between the central points of particles can be treated as contacts. For instance, in Figure 1, there are two contacts among particles 1, 2, and 3. The normal vectors of the contact between particles 1 and 2 are (x_{12}, y_{12}) , while those between particles 2 and 3 are (x_{23}, y_{23}) . Hence, the angle θ between the two contacts can be expressed as shown in Equation (9).

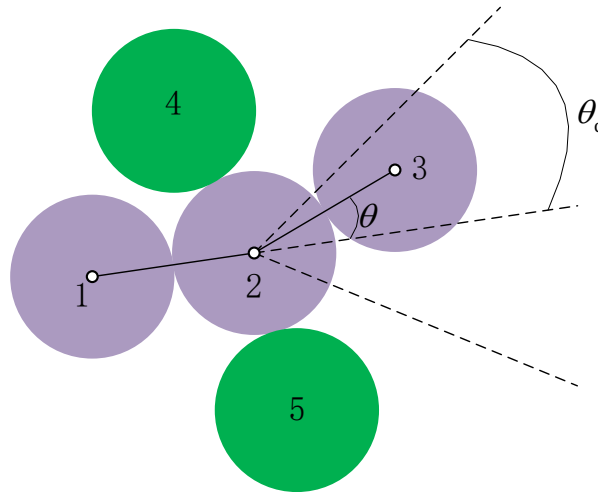


Figure 1. Contact between adjacent particles.

The number of particles forming the force chain should not be less than three, implying that the number of contact points should not be less than two.

$$\bar{F} = \frac{\sum F}{N} \quad (7)$$

$$\theta_c = \frac{180}{\langle Z \rangle} \quad (8)$$

$$\theta = \arccos \frac{|x_{12}x_{23} + y_{12}y_{23}|}{\sqrt{x_{12}^2 + y_{12}^2} \times \sqrt{x_{23}^2 + y_{23}^2}} \quad (9)$$

where $\bar{F}$ is the average contact force in the entire system; N is the number of particles; $\sum F$ is the total inter-particle contact force in the entire system; $\langle Z \rangle$ is the average coordination number of the particle in the system.

In each time step, the force chain search algorithm is shown as follows:

First, the information about particles and their contacts is recorded, and the average contact force $\bar{F}$ and threshold θ_c are calculated. Inter-particle contacts that do not meet Condition 1 are removed. Then, the algorithm searches for force chains based on direction and length conditions. Finally, through iterative searching, repeated force chains are removed. In each time step, the algorithm extracts information such as the direction, length, strength, and collimation coefficient of each force chain, as well as the total number of force chains.

2.3. Quantitative Statistics of Force Chain Network

To quantitatively describe the force chain distributions in the moving bed, information on the direction, number, length, strength, and collimation coefficient of force chains is extracted from the complex network. The number of force chains is determined using the force chain search algorithm described in Section 2.2. The length of a force chain is determined by its particle count N . The strength of a force chain, reflecting its load-carrying

capacity, is defined as the average contact force of the particles within the force chain. The force chain strength is calculated as follows:

$$P_i = \frac{\sum_{k=1}^s F_k}{s \times d} \quad (10)$$

where P_i is the strength of the i th force chain; F_k is the magnitude of the k th contact force in the i th force chain; s is the total number of particle–particle contacts in the i th force chain, which is $N_i - 1$, where N_i is the number of particles in the i th force chain; and d is the particle diameter.

The collimation coefficient of a force chain reflects the degree to which the force chain forms a linear structure. The collimation coefficient varies between 0 and 1. A force chain with a larger collimation coefficient indicates better stability and alignment, while a force chain with a smaller collimation coefficient is more prone to breaking. The collimation coefficient φ_i for the i th force chain can be calculated as follows:

$$\varphi_i = 1 - \frac{\sum_{p=1}^M \gamma_p}{180^\circ \times M} \quad (11)$$

where γ_p is the p th angle between two adjacent normal inter-particle contacts in the i th force chain, and M is the total number of these angles, which is equal to $N_i - 2$, where N_i is the number of particles in the i th force chain.

The direction of a force chain is defined as the angle between the centroid connection line of the starting particle and the ending particle in the force chain and the positive direction of the X-axis. When this angle approaches 0° , the force chain direction is closer to the horizontal direction. Conversely, when the angle approaches 90° , the direction is closer to the vertical direction.

In the analysis, the length, strength, and collimation coefficient of each force chain are calculated for the entire system, and the average values are determined. The reported length, strength, and collimation coefficient of the force chains in the following sections are the average values.

2.4. Simulation Conditions

The parameters used in the DEM simulation are listed in Table 1. To achieve a naturally packed particle state, the bottom side of the reactor is initially closed, as depicted in Figure 2. Particles are randomly generated and then moved downwards by gravity. Subsequently, the bottom side of the reactor is set as the outlet condition, and the contact force and force chain evolution characteristics are analyzed during the particle unloading process. In the reference condition, the particle diameter is 6 mm, while the inter-particle and particle–wall friction coefficients are set to 0.5. The reference condition is used to compare the simulation results and experimental data in the model validation section shown in Section 4.1.

Table 1. The parameters for the DEM simulation.

Parameter	Value
Particle diameter (mm)	6~8, 6 (Reference condition)
Particle density (kg/m ³)	2460
Inter-particle friction coefficient μ_p	0.2~0.8, 0.5 (Reference condition)
Particle–wall friction coefficient μ_w	0.2~0.8, 0.5 (Reference condition)
Normal damping coefficient	0.12
Tangential damping coefficient	0.12
Time step (s)	$8 \times 10^{-5} \sim 9 \times 10^{-5}$

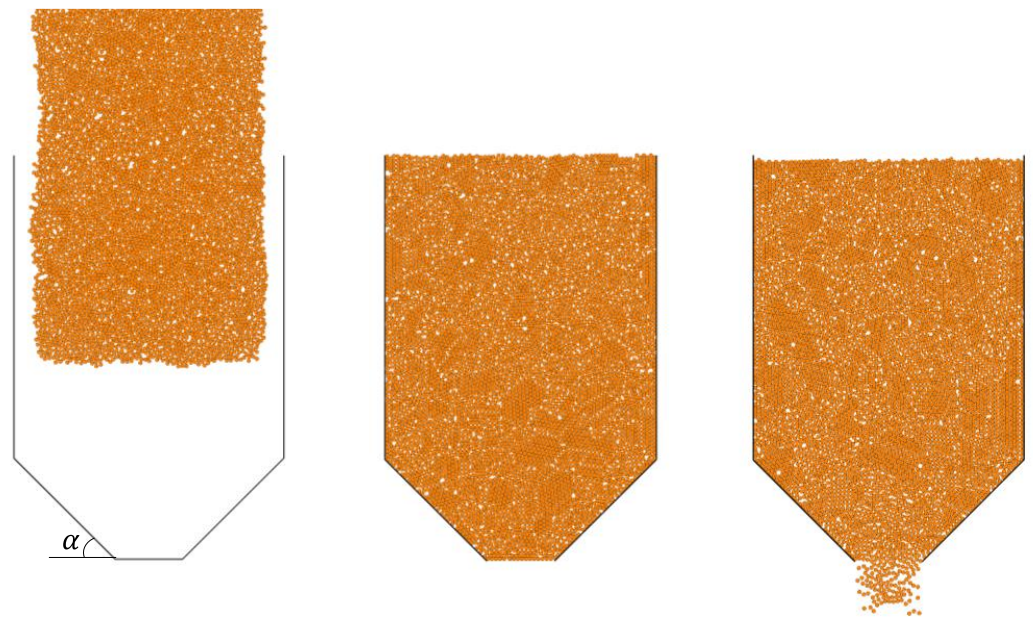


Figure 2. The discrete element model of a dense particle system in a moving bed.

3. Experimental Method

An experimental system was constructed to validate the feasibility of the DEM numerical model. Figure 3 illustrates a schematic diagram of the moving bed, which was the same as the configuration established in the numerical model. The moving bed had a length of 400 mm and a height of 600 mm. In the bottom section, the inclination angle was set to 45° in the reference condition, and the orifice length was 100 mm. Given the narrow width of the moving bed (15 mm), it was reasonable to assume uniform solid velocities in the width direction. An electronic scale was used for real-time recording of the mass of particles leaving the reactor. Additionally, a high-speed camera was used to capture macroscopic flow patterns during the unloading process. The particles had different colors for visualization of the flow pattern.

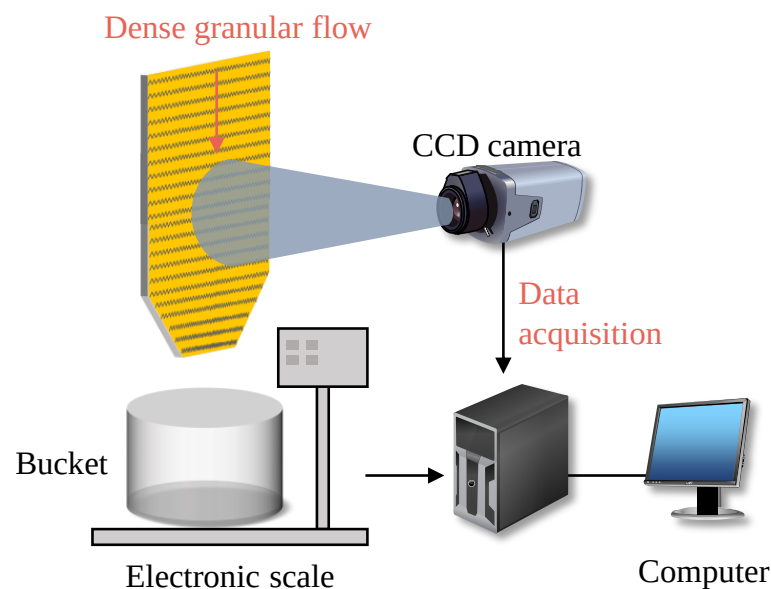


Figure 3. A schematic diagram of the experimental apparatus of a moving bed.

4. Results and Discussion

4.1. Model Validation

The selection of parameters is crucial for accurate simulation. In DEM simulation, the contact stiffness governs the relationship between particle overlap and the resulting normal force [32]. Reducing stiffness can accelerate the simulation process, and its impact on particle movements has been confirmed in previous studies [33]. The normal spring stiffness and tangential spring stiffness are generally related to the material properties of Young's modulus and Poisson's ratio. Figure 4 illustrates the comparison of the mass of particles leaving the reactor over time under different normal spring stiffness k_n and tangential spring stiffness k_s . In Figure 4a, particles with a diameter of 6 mm are shown, while Figure 4b presents particles with diameters of both 6 mm and 8 mm. It is observed that as k_n and k_s increase, the mass of particles discharged from the reactor decreases. When the k_n and k_s of inter-particle contacts are set to 5×10^5 N/m and the k_n and k_s of particle–wall contacts are set to 1×10^6 N/m, the simulation results agree well with the experimental data.

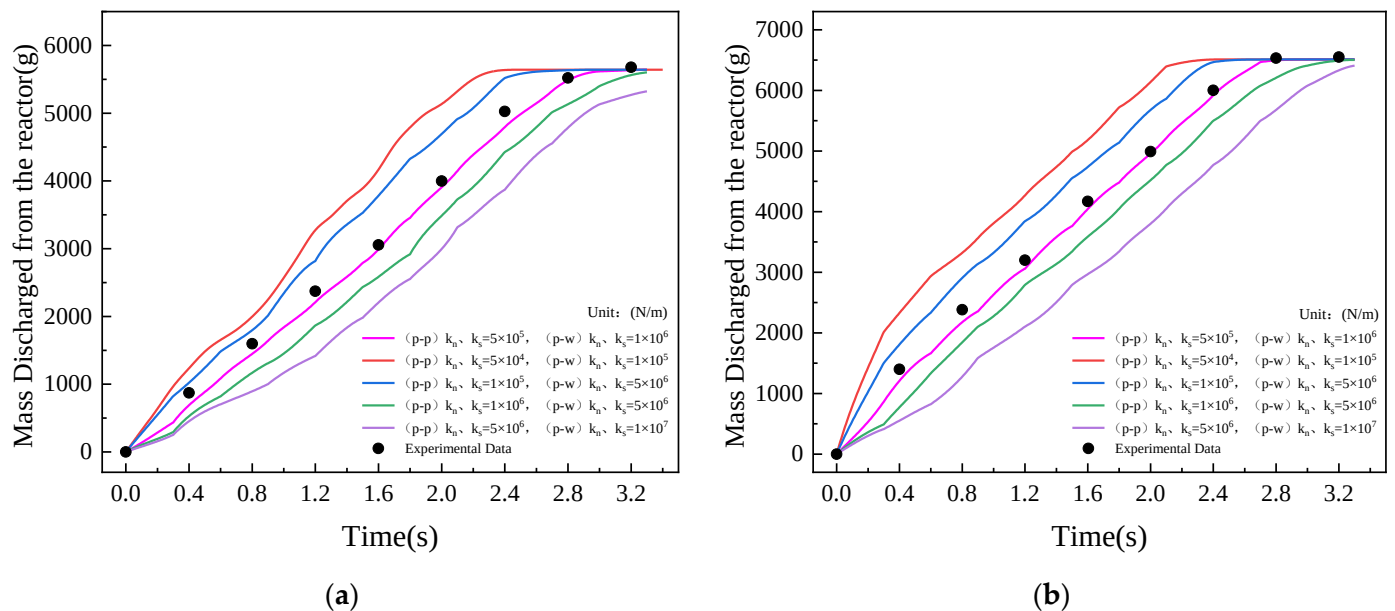


Figure 4. A comparison of the mass of particles leaving the moving bed between simulation results with different normal and tangential stiffness and experimental data: (a) all particles have a uniform diameter of 6 mm; (b) the particles colored in yellow have a diameter of 8 mm, while all other particles have a diameter of 6 mm.

Figure 5 displays the comparison of flow patterns obtained from numerical simulation and experiments at the time of 1 s and 2 s. In Case 1, all particles have a uniform diameter of 6 mm, which is regarded as the reference condition. In Case 2, the particles colored in yellow have a diameter of 8 mm, while all other particles have a diameter of 6 mm. The particles with different colors are used to track and visualize the particle movements. It can be seen that particles move faster in the central zone and slower in the near-wall zone, and the simulation results agree well with the experiment, which further validates the feasibility and accuracy of the numerical model. The detailed solid velocity distributions in the different directions are not provided here since they have been discussed a lot in different types of reactors in previous research.



Figure 5. Comparison of flow patterns obtained from numerical simulation and experiments.

4.2. Comparison of Contact Force Network and Force Chain Network

4.2.1. Spatial and Temporal Distribution of Contact Force Network

Figure 6 displays the instantaneous contact force distribution in the moving bed as particles leave the reactor. At the beginning stage, the equilibrium of the network is disturbed when the bottom side is opened. In most areas, the contact force is smaller than 30 N. As particles continue to leave the reactor, the network becomes sparse in the middle and lower parts due to the increased solid velocity and the resulting less dense packing in these zones. Side branching chains exist in the particle unloading process because particles remain densely packed and frequently contact surrounding particles near the walls. Additionally, strong contact forces exhibit directionality, which are mainly perpendicular to the side walls. Similar side branching chains were observed in the experimental study of a convergent hopper by Vivanco et al. [34]. In their study, chains connecting both side walls, known as arches, were detected when the dimensionless opening size (the ratio of bottom opening size to particle diameter) was about 5, and the inclination angle of the wedge section was 25° [34]. Xiao et al. [35] indicated that to prevent the formation of stable arches above the discharge port, the size of the discharge port should be at least 6–8 times greater than the particle diameter. Avoiding arching phenomena is essential, as it can lead to velocity fluctuations and unstable system operation. In the current simulation, stable arches are not prominently observed due to a larger ratio of bottom opening size to particle diameter.

Figure 7 presents the distribution of contact force directions in polar coordinates. The circle is divided into 36 intervals, with the contact direction probability accumulated in each interval. At the initial stage ($t = 0.4$ s), the distributions of force chain directions are relatively uniform, and anisotropy is not significant. As particles continue to unload from the moving bed, the directions of contact forces tend to align more along the vertical direction, and the anisotropy of contact force direction becomes increasingly evident. Additionally, the probability of contact forces in the direction of 30° increases with time. The main reason is that the side walls at the bottom of the reactor greatly constrain the particle movements in the horizontal direction, which further leads to an increase in the inter-particle contact force. The angles of the side walls are 45° , while the direction in which the probability increases is 30° because gravity also greatly influences the contact force distributions.

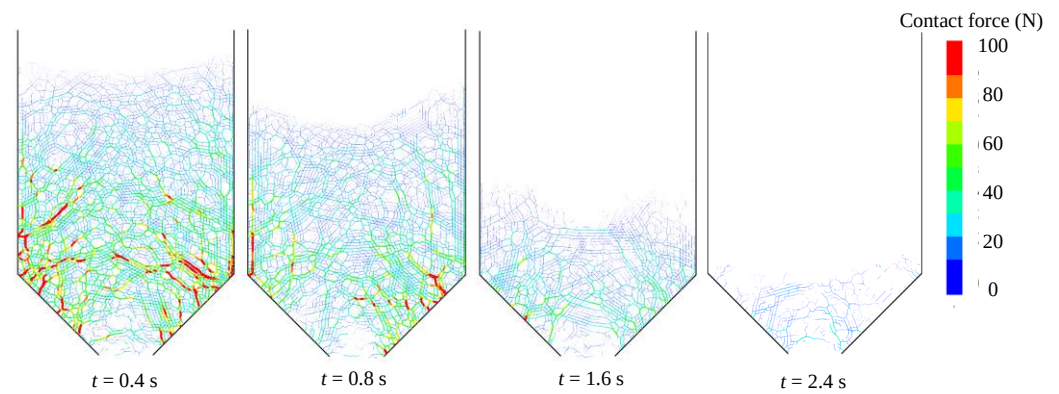


Figure 6. Distributions of inter-particle contact forces over time.

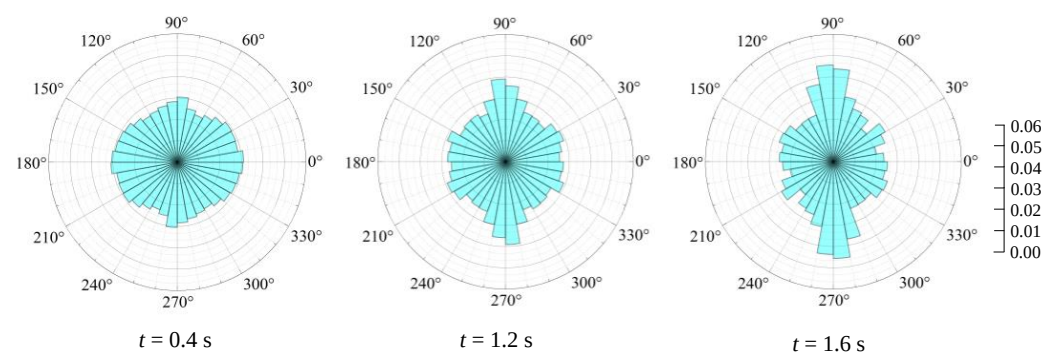


Figure 7. Distributions of contact force directions in polar coordinates over time.

4.2.2. Spatial and Temporal Distribution of Force Chain Network

As described in Section 2.2, a force chain is defined as a physical structure consisting of a quasi-linear chain of particles. Only strong contact forces, which exceed the average contact force in the system, have the potential to be part of a force chain. Figure 8 illustrates the percentages of strong contacts and force chain contacts in the total solid contacts during the particle unloading process. It can be observed that the percentage of strong contact fluctuates between 37% and 41% over time, while the force chain contact accounts for about 13–14%. Initially, both the proportions of strong contacts and force chain contacts decrease, followed by a slight increase after 1.6 s. The initial decreasing trend can be attributed to the decreasing number of particles and the presence of more free particles in the center of the moving bed during the unloading process. The subsequent increasing trend after 1.6 s is due to particles moving slowly and potentially becoming stuck near the two side walls at the bottom of the reactor. Particles in the center behave like a gas-like phase, while those in the near-wall section at the bottom of the reactor exhibit solid-like behavior.

Figure 9 illustrates the distribution of force chain directions in polar coordinates during the particle discharging process. Compared with Figure 9, it is evident that the distribution of force chain directions differs significantly from that of contact force directions. The anisotropy of the force chain direction distribution is more pronounced. Unlike contact forces between only two particles, force chains represent force transmission among at least three particles. This highlights the importance of investigating force chain evolution characteristics. Although the coefficient of friction affects the distribution of force chain directions, the degree of orderliness is not remarkable. Therefore, the specific results are not presented here for brevity.

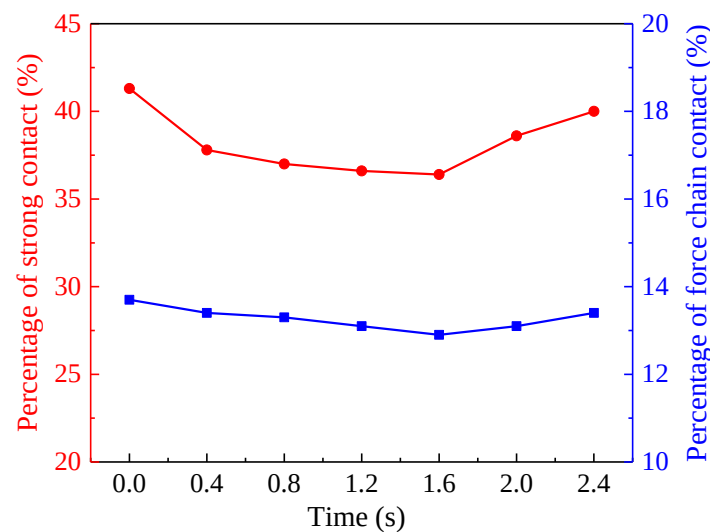


Figure 8. The proportions of the strong contacts and force chain contacts in the total inter-particle contacts during the unloading process.

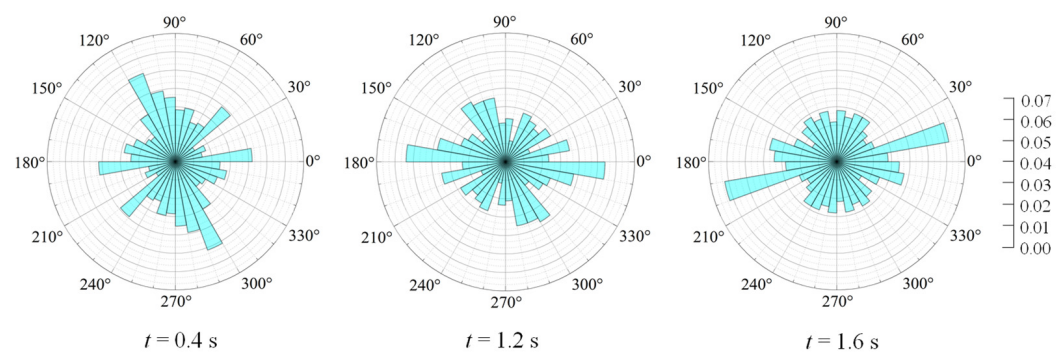


Figure 9. The distributions of the force chain directions in the polar coordinates in the particle discharging process.

4.3. Quantitative Characteristics of Force Chain Networks

4.3.1. Number of Force Chains

Figure 10a illustrates the effects of the inter-particle friction coefficient on the number of force chains in the moving bed. The number of force chains decreases almost linearly with time because more particles leave the reactor, leading to an increase in the number of free particles without strong contact with others. With an increase in the inter-particle friction coefficient, the number of force chains also increases. A smaller coefficient of friction indicates a smoother surface of the particle, which may result in less stable contact between particles. Particles with smoother surfaces are more easily rearranged, increasing the difficulty of forming a stable force chain network and consequently causing a decrease in the number of force chains. The decrease in the number of force chains can also be explained by previous research findings, which show that a decrease in the particle–particle friction coefficient may result in an increase in solid flow rates. Figure 10b demonstrates the effects of the particle–wall friction coefficient on the number of force chains during the particle discharging process. The number of force chains increases with an increase in the particle–wall friction coefficient. The particle–wall friction primarily affects particle movements in the near-wall zone rather than particles in the entire reactor. Therefore, the influence of the particle–wall friction coefficient on the number of force chains is less pronounced than that of the inter-particle friction coefficient. In the research conducted by Anand et al. [25], it was reported that the particle–particle friction played a much more

significant role in discharge rates than particle–wall friction, which is consistent with the findings in the current simulation.

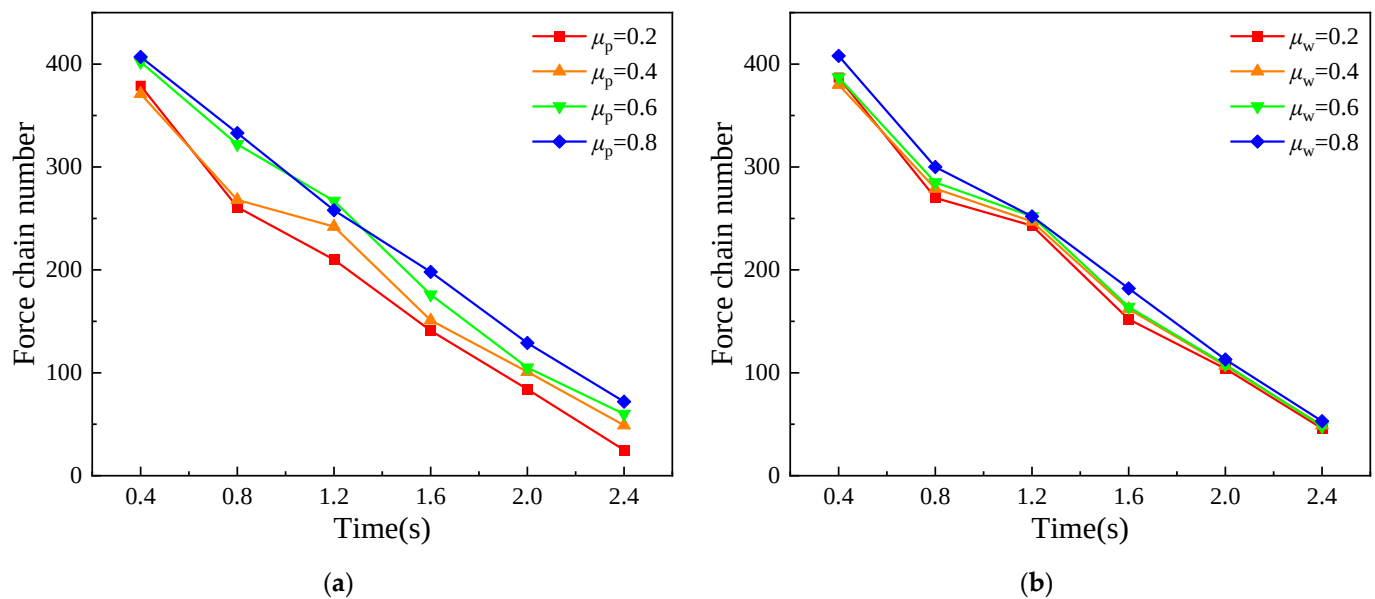


Figure 10. Effects of coefficient of friction on number of force chains during particle discharge: (a) inter-particle friction coefficient; (b) particle–wall friction coefficient.

4.3.2. Length of Force Chains

Figure 11a shows the probability distribution of the length of force chains over time. It can be observed that most force chains consist of 3–6 particles. The number of force chains decreases as the length of the force chain increases. The probability distributions of force chain lengths at different times are similar, and the probability decreases exponentially with an increase in the length of the force chain. To better visualize the probability distribution of force chain lengths, the force chains are divided into three groups based on length, as shown in Figure 11b. Force chains with three particles account for about 45% of all the force chains, and this proportion decreases over time. Force chains with 4–6 particles make up about 40% of all the force chains, and the proportion fluctuates. Force chains with more than six particles account for only about 12% of all the force chains, and the proportion increases over time. When the particle unloading process begins, some particles become free particles. The initial long-length force chains break into shorter-length force chains, resulting in most force chains containing only three particles. As the particle unloading proceeds, the probability of force chains with more than six particles slightly increases. This can be explained from two perspectives: on the one hand, the force chain network is continuously updated, and the system becomes more stable, allowing some short force chains to recombine into new long-length force chains; on the other hand, particles in the near-wall section at the bottom of the reactor leave the reactor in the later stages of the discharging process, where long force chains play a leading role.

Figure 12 illustrates the effects of coefficients of friction on the number of force chains at 0.4 s. It can be observed that both the inter-particle and particle–wall friction coefficients have little impact on the probability distribution of force chain lengths under the given conditions. Long force chains are prone to breaking and are difficult to stabilize, whereas short force chains consisting of 3–6 particles constitute the majority of the network. The probability of force chains decreases exponentially with increasing length, which remains consistent with different friction coefficients.

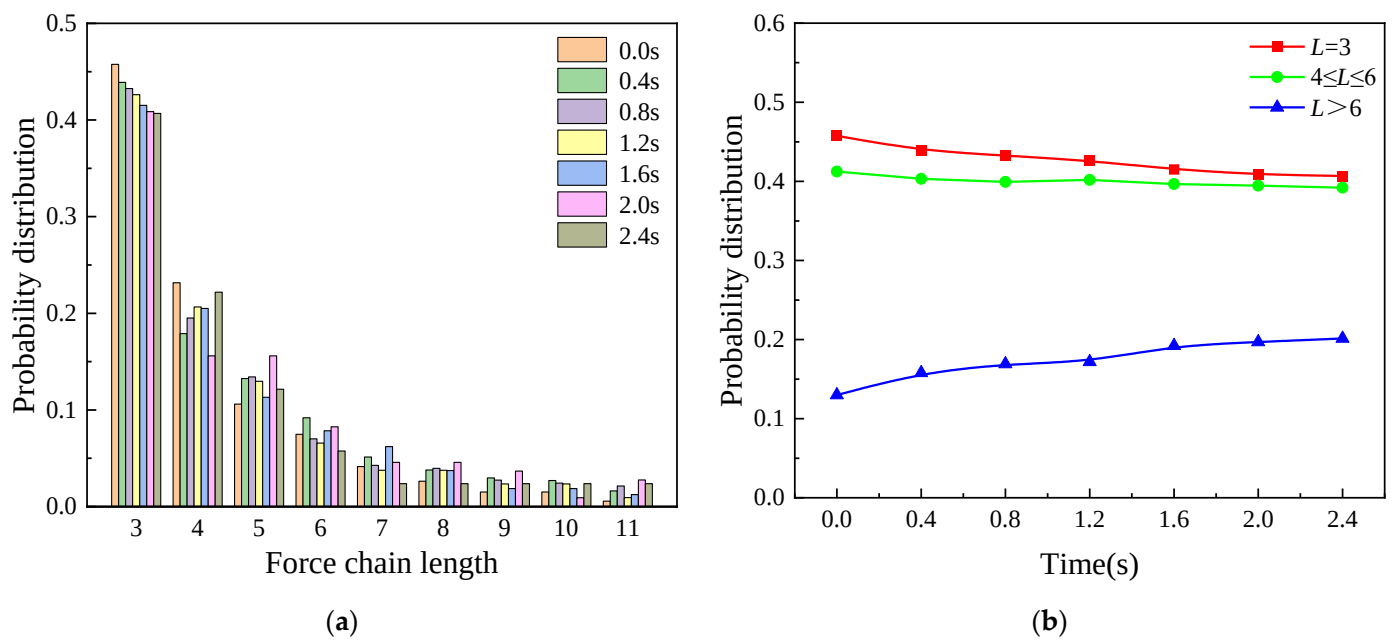


Figure 11. Probability distribution of length of force chains over time: (a) probability distribution of the force chains with the length between 3–11; (b) probability distribution of short, medium and long force chains.

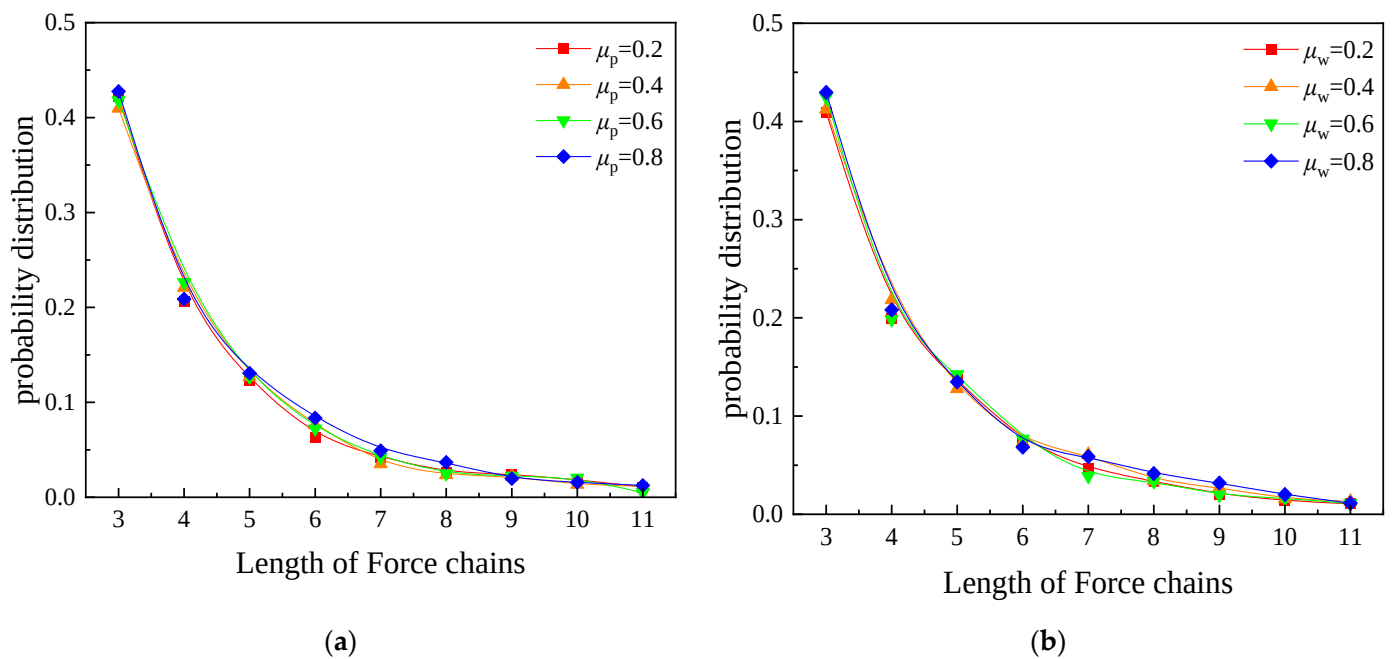


Figure 12. Effects of friction coefficient on probability distributions of length of force chains at 0.4 s: (a) inter-particle friction coefficient; (b) particle–wall friction coefficient.

4.3.3. Strength of Force Chains

The strength of a force chain reveals the bearing capacity of the particle system. Figure 13 shows the influence of the particle–particle friction coefficient on the strength of the force chain during the particle discharging process. The strength of the force chain decreases over time. Initially, particles are densely packed, and the force chain is relatively stable in the reactor. When the outlet is open, this stable state is disrupted, causing the force chain network to break and reorganize repeatedly. Consequently, the strength of the force

chain quickly decreases. Additionally, as more particles discharge from the reactor, the overall force acting on the particles at the bottom decreases, further reducing the strength of the force chain. The strength of the force chain increases with the particle–particle friction coefficient. A higher friction coefficient means a rougher particle surface, making particle rearrangement in a force chain more difficult compared to conditions with a lower friction coefficient. Figure 13b indicates that the effects of the particle–wall friction coefficient on force chain strength are less significant than those of the particle–particle friction coefficient. With an increase in the particle–wall friction coefficient, the strength of the force chain increases slightly.

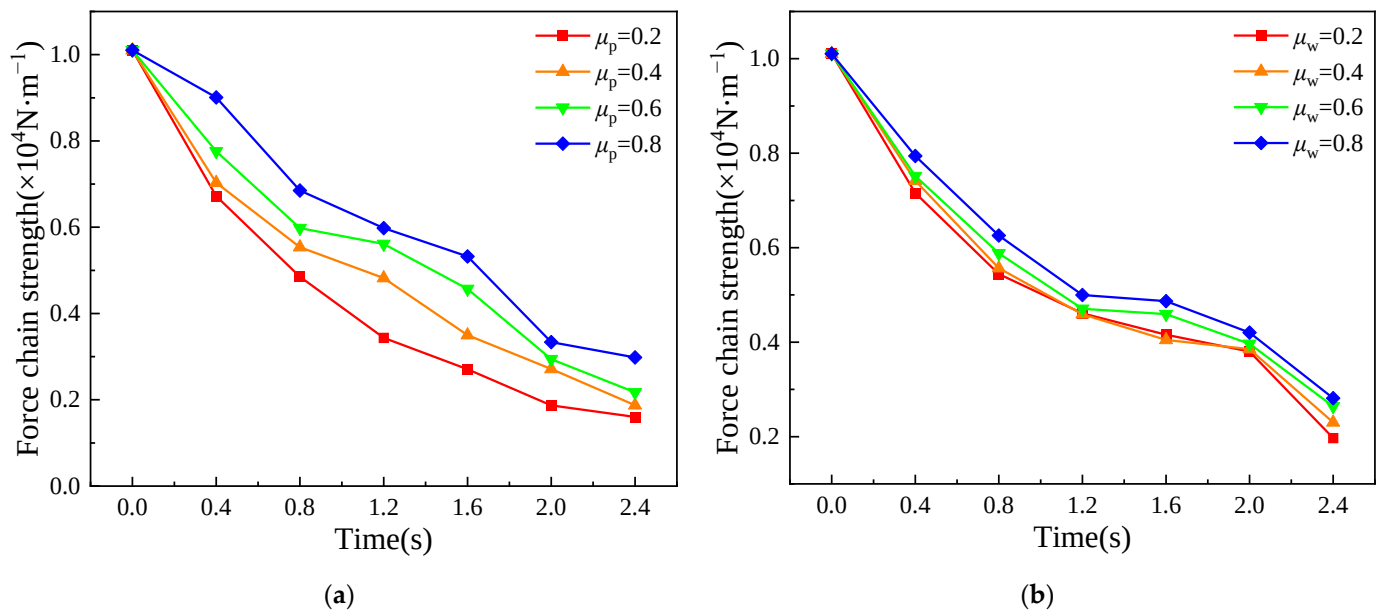


Figure 13. Effects of the friction coefficient on the strength of the force chains at 0.4 s: (a) inter-particle friction coefficient; (b) particle–wall friction coefficient.

4.3.4. Collimation Coefficient of Force Chains

The collimation coefficient reflects the linearity of the force chain. Collimation ensures that the force chain does not buckle easily, which improves the stability of the entire force chain network. Figure 14 illustrates the effects of the inter-particle friction coefficient on the collimation coefficient of the force chain. Overall, the collimation coefficient decreases with time during the particle discharging process. In the initial 1.2 s, the collimation coefficient remains relatively large and stable, indicating a more stable supporting structure. However, between 1.2 s and 2.4 s, there is a sharp decrease in the collimation coefficient, indicating a rapid organizational process of the force chain and a decrease in the stability of the supporting structure. Generally, shorter force chains exhibit better straightness. The increasing proportion of short force chains over time can also explain the decrease in the collimation coefficient to a certain extent. With a decrease in the inter-particle friction coefficient, the collimation coefficient increases. This decrease in inter-particle friction coefficient leads to a decrease in the strength of the force chain and further causes a decrease in the load-carrying capacity of the force chain. To maintain maximum load-carrying capacity, the force chain tends to automatically form a straight-line structure. Figure 14b depicts the effects of the particle–wall friction coefficient on the collimation coefficient of the force chain. As the particle–wall friction coefficient mainly affects particle movements in the near-wall zone; its influence is less pronounced than that of the particle–particle friction coefficient.

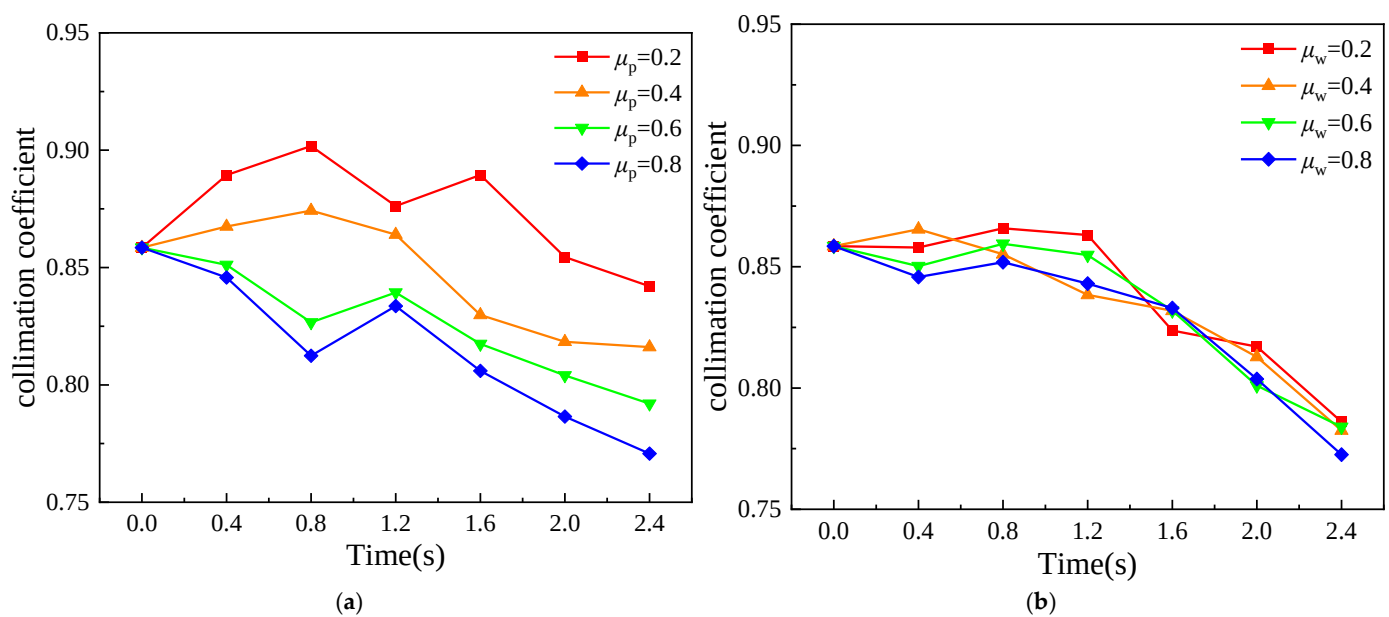


Figure 14. Effects of the friction coefficient on the collimation coefficient of the force chains at 0.4 s: (a) inter-particle friction coefficient; (b) particle–wall friction coefficient.

5. Conclusions

In this work, the qualitative and quantitative aspects of the contact force network and force chain characteristics are explored, and the impact of inter-particle and particle–wall friction coefficients, as well as the moving bed angle on the particle discharging process within a moving bed, are also studied. The aim is to elucidate the mechanical mechanisms underlying the particle movements, which will provide a foundational understanding of various flow patterns, such as funnel flow and mass flow, as well as dense granular flow behaviors around different types of internals in a dynamic dense granular system. Key conclusions obtained from this study are given as follows:

- (1) The contact forces tend to align in a vertical direction. However, the distribution of force chains shows significant variation, with the network being less densely distributed and exhibiting greater anisotropy.
- (2) During the particle discharge process in the given moving bed, the strong particle–particle contacts account for about 37–41% of all the particle–particle interactions, while force-chain contacts account for only about 13–14% of all the particle–particle interactions. Most force chains consist of 3–6 particles, and the number of force chains decreases with increasing chain length. The strength of the force chains decreases over time, while the collimation coefficient remains stable for the first 1.2 s before sharply decreasing.
- (3) Both particle–particle and particle–wall friction coefficients affect the number, strength, collimation coefficient, and direction of force chains but have little influence on the length distribution of force chains. Since the particle–wall friction coefficient primarily affects particle movements in the near-wall zone; its influence is less pronounced than that of the particle–particle friction coefficient.

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