

Article

Motion Characteristics and Distribution Laws of Particles in the Launching System with a Sequence-Change Structure

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Abstract: There is a fundamental issue in the launching system with the modular charge technology, which is an unsteady gas–solid flow in the sequence-change space within a short period of time. It leads to complex particle behavior, causing the strong pulsation of particle energy released during the combustion process. As a result, a large initial pressure wave is generated, which damages the launching stability. In this work, a 3D gas–solid flow model is developed based on the computational fluid dynamics–discrete element method (CFD–DEM) model to analyze the particle behavior in the launching system with different numbers of modules. The rationality of the model is verified through the experiment. It is found that the particles near the cover of the rightmost module move out of the module rapidly and collide with the right face of the chamber, forming a retained particle layer. When particles are stationary, the distribution of particles consists of slope accumulations and horizontal accumulation. With the increase in the module number, the position changes of all tracer particles are decreased, both the thickness and the length of the horizontal shape are increased, the variation laws of the slope stack height change from exponential to linear, and the distribution of particles becomes uniform.

Keywords: particle behavior; unsteady gas–solid flow; sequence-change space; CFD–DEM; launching system



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1. Introduction

The issue of unsteady gas–solid flow is a widespread challenge in the launching system, involving the intricate interaction between gas and particles. This includes factors such as the gas turbulence effect, the multidirectional movement of particles, the gas–solid interphase interaction, and the particle–particle collision. When the modular charge technology is adopted, the process is in a sequence-change space within a short period of time. In the modular charge technology, energetic modules are charged as the power source, comprising a flammable module box and a center core igniter. The module box is filled with energetic particles, and the igniter is internally bound with a bag containing black powder. The number of energetic modules that are charged in the launching system corresponds with the velocity of the vehicle. During system operation, the ignition gas is injected into the modular box through radial holes of the igniter, causing a rise in pressure within the module. Once the pressure in the module reaches the threshold value, the modules are broken in sequence due to the ignition delay of the black powder, forming a sequence-change structure. This exacerbates the complexity of the gas–solid flow and the nonuniform particle distribution, resulting in a strong pulsating release of the energetic particle energy in space and time. Consequently, this phenomenon leads to the formation of substantial initial pressure waves in the chamber, which damages the launching stability. Therefore, it is of great significance to research the particle behavior in the initial launching process of modular charge.

Previous studies on the gas–solid flow in the launching system loaded with different numbers of modules have been carried out to develop the initial pressure wave based

on the Eulerian–Eulerian method [1]. Ma et al. [2] enhanced the one-dimensional (1D) two-phase flow model for the modular charge, and the simulation studies on the interior ballistics for the six-module charge and the four-module charge were conducted. It was observed that there were strong pressure fluctuations during the interior ballistic process. Dong et al. [3–5] developed a double 1D two-phase flow model to research the effects of combustible cartridge energy, propellant mass, and arc thickness on interior ballistic characteristics for the bimodular charge. They discovered that the obvious pressure wave is generated in the chamber due to the high burning rate of the module box with high energy density. Based on the two-dimensional (2D) interior ballistic two-phase flow model, Woodley [6,7] considered the convection, radiation, and heat transfer processes between the combustion products of the ignition powder and the propellant. Sen et al. [8] established a 2D two-phase flow model to simulate the ignition process of the one-module charge using the space–time conservation element and solution element (CE/SE) method. In addition, a 2D axisymmetric two-phase flow interior ballistic model was developed in different regions according to the characteristics of the modular charge. Based on the monotonic upwind scheme for conservation laws (MUSCL) with high-order accuracy, Ma et al. [9,10] simulated the ignition process of the one-module charge. The research indicates that the ignition powders in different modules are not ignited simultaneously, the module boxes are not broken simultaneously, and a large pressure fluctuation occurs in the chamber. However, the space–time distribution characteristics of energetic particles in the flow field were not accurately obtained in the previous studies, making it difficult to analyze the mechanism of the initial pressure wave during the launching process. This is primarily due to the complex two-phase flow and nonuniform particle dispersion after the module rupture, which are the primary factors contributing to the formation of the initial pressure wave.

In the launching process of the modular charge, a complex unsteady gas–solid flow is created by the sequence change of the space structure where the energetic particle groups are located. The sequence-change space is caused by the nonsimultaneous gas source, which only exists for a while. In addition, it leads to the complex behavior of particles in a short period of time. To describe particle behavior characteristics after module rupture in detail, it is necessary to establish the mathematical models from the particle scale. Recently, the CFD-DEM coupling method has been widely used for studying the particle-scale behavior in the two-phase flow with fixed spatial structures [11–13]. Mu, Han, Vijayan, et al. [14–16] employed the CFD-DEM method to investigate the gas–solid flow with the continuous gas flow. The low-speed gas flowed from the bottom to the top of the cube chamber. The effects of superficial gas velocity and other parameters on the flow characteristics of monodisperse and polydisperse particle groups were analyzed from particle scale. Xi, Wu, Zhao, et al. [17–19] simulated the motion of particle groups in a cylindrical space under uniform low-speed airflow using the CFD-DEM method. The gas was sprayed into the cylindrical chamber through a circular hole on the side wall, and the factors affecting the generation and distribution of bubbles within the particle group in two-phase flow were analyzed. Based on the CFD-DEM method, Yue, Breuninger, Batista, et al. [20–22] researched the particle-scale details of the gas–solid flow in a conical space, in which the particle group was located at the bottom of the space in the initial state. Additionally, Zhao, Swasdisevi, et al. [23,24] studied the particle motion details in the funnel-shaped space with different jet laws, where the gas flowed from the small end face of the funnel-shaped gas chamber into the large end face. They made predictions regarding particle-scale information such as distributions of particle drag force and particle concentration. Yang et al. [25] investigated the particle–fluid dynamics process in a space consisting of two parallel connected funnel-shaped spaces, in which particle groups moved under the action of airflow sprayed from two small end faces. Furthermore, CFD-DEM has been applied to the study of multiphase flow problems in special engineering structures [26,27]. The gas–solid flows in the above works are in the fixed space within a long time, and the particle has a low speed. This differs from the gas–solid flow in the modular charge launching

system. However, some mathematical models from these works can still be referenced for this study.

Nowadays, there are few reports on the research of the motion characteristic and the distribution law in the launching system with a sequence-change space. In this study, an efficient 3D unsteady gas–solid flow model is established based on CFD-DEM. The research focuses on the particle-scale analysis of the unsteady gas–solid flow in the launching system with different numbers of modules. The spatiotemporal distribution characteristics and the motion details of particles in the flow field are accurately obtained. Furthermore, the effect of the number of energetic modules on the particle behavior is described. The research results can provide a foundation for further analysis of the formation mechanism of the initial pressure wave in the launching system.

2. Methods

2.1. Basic Assumption

The theoretical model of the gas–solid flow in the sequence-change space is established at the particle scale, and the simplified assumptions are as follows:

- (1) The ignition gas is treated as an ideal compressible gas.
- (2) The modules filled with energetic particles are destroyed in turn under the action of high-pressure gas, and the particle combustion is not considered.
- (3) The cylindrical energetic particle is treated as the sphere by the equivalent volume method.

2.2. Governing Equations

2.2.1. Gas Phase

In the CFD-DEM coupled calculation, the fluid motion is solved based on the Euler method

$$\frac{\partial(\varepsilon_g \rho_g)}{\partial t} + \frac{\partial(\varepsilon_g \rho_g \mathbf{u}_{g,i})}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\varepsilon_g \rho_g \mathbf{u}_{g,i}) + \frac{\partial(\varepsilon_g \rho_g \mathbf{u}_{g,i} \mathbf{u}_{g,j})}{\partial x_j} = -\varepsilon_g \frac{\partial p_g}{\partial x_i} + \rho_g \varepsilon_g \mathbf{g} + \frac{\partial}{\partial x_j} \left[\varepsilon_g (\mu + \mu_t) \left(\frac{\partial \mathbf{u}_{g,j}}{\partial x_i} + \frac{\partial \mathbf{u}_{g,i}}{\partial x_j} \right) \right] - \mathbf{S} \quad (2)$$

$$\frac{\partial}{\partial t}(\varepsilon_g E_g) + \frac{\partial[\varepsilon_g (E_g + p/\gamma M^2) \mathbf{u}_{g,j}]}{\partial x_j} = -\frac{1}{\text{PrRe}(\gamma - 1)M^2} \frac{\partial}{\partial x_j} \left(\varepsilon_g k \frac{\partial T_g}{\partial x_j} \right) + \frac{1}{\text{Re}} \frac{\partial(\varepsilon_g \mathbf{u}_{g,i} \tau_{ij})}{\partial x_j} + E \quad (3)$$

where ε_g is the voidage; ρ , $\mathbf{u}$, and p are the mean density, velocity, and pressure, respectively; subscript g represents the gas; $\mathbf{S}$ is the momentum exchange source term and E is the energy exchange source term; E_g is the total energy of the gas; and τ_{ij} is the viscous stress tensor.

The transport equations of the realizable $k - \varepsilon$ turbulence model [28] are as follows:

$$\frac{\partial}{\partial t}(\rho_g k) + \frac{\partial}{\partial x_i}(\rho_g k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho_g \varepsilon - Y_M \quad (4)$$

$$\frac{\partial}{\partial t}(\rho_g \varepsilon) + \frac{\partial}{\partial x_i}(\rho_g \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho_g C_1 S \varepsilon - \rho_g C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b \quad (5)$$

where μ is the dynamic viscosity and ν is the kinematic viscosity; G is the change of turbulent kinetic energy; σ is the turbulent Prandtl number; C_2 , $C_{1\varepsilon}$ is an empirical constant; and k , ε , and subscript b mean the turbulent flow energy, the turbulent dissipation rate, and the effect of buoyancy, respectively.

2.2.2. Solid Phase

The particle motion follows the Newtonian dynamic equation based on the Lagrange method. The particle–gas density ratio is large, thus only the gravity, drag force F_d , collision force F_c [29], and pressure gradient force F_p are considered in this work [30]

$$m_s \frac{dv_s}{dt} = m_s g + F_d + F_c + F_p \quad (6)$$

$$I_s \frac{d\omega_s}{dt} = \sum_{j=1, j \neq i}^N (\mathbf{R} \times \mathbf{f}_{\tau,ij}) \quad (7)$$

where m_s , v_s , ω_s , and I_s are the mean mass, velocity, angular velocity, and the rotational inertia of the particle; and $\mathbf{R}$ is the radius vector.

In the above equations,

$$I_s = m_s d_s^2 / 10 \quad (8)$$

$$\mathbf{F}_p = -V_s \nabla p_g \quad (9)$$

$$\mathbf{F}_c = \sum_{j=1, j \neq i}^N (\mathbf{f}_{n,ij} + \mathbf{f}_{\tau,ij}) \quad (10)$$

$$\mathbf{f}_{n,ij} = -[k_n \delta_n + \eta_n (\mathbf{v}_{ij} \cdot \mathbf{n})] \mathbf{n} \quad (11)$$

$$\mathbf{f}_{\tau,ij} = \min(-k_\tau \delta_\tau \mathbf{t}_{ij} - \eta_\tau \mathbf{v}_{ct}, -\mu_s |\mathbf{f}_{n,ij}| \mathbf{t}_{ij}) \quad (12)$$

where $\mu_s |\mathbf{f}_{n,ij}|$ is the maximum static friction force; subscripts n and τ represent the normal and the tangential direction; k_n and k_τ are the mean the normal and tangential elastic coefficients, respectively; η is the damping coefficient; δ is the relative displacement; and $\mathbf{v}_{ct}$ is the slip vector velocity, and its expression is

$$\mathbf{v}_{ct} = \mathbf{v}_{ij} - (\mathbf{v}_{ij} \cdot \mathbf{n}) \mathbf{n} + R_i \omega_i \times \mathbf{n} + R_j \omega_j \times \mathbf{n} \quad (13)$$

2.3. Drag Force

The momentum exchange between the gas and the solid is mainly reflected in the drag force. The calculation of the drag force is of great significance for the accurate reduction of gas–solid flow [31]. The calculation formula is as follows:

$$\mathbf{F}_{d,i} = \frac{\beta V_s}{\varepsilon_s} (\mathbf{u}_{g,i} - \mathbf{v}_{s,i}) \quad (14)$$

where V_s is the particle volume, $\mathbf{u}_{g,i}$ is the fluid velocity interpolated to particle i , and β is the momentum exchange coefficient.

In this work, the relative velocities between gas and particles are large to generate high Reynolds numbers. Therefore, Gibilaro and Gidaspow's model [32] for the high Reynolds number is used in this work, which is written as follows:

$$\beta = \frac{3}{4} C_D \frac{\rho_f |\mathbf{u}_g - \mathbf{v}_s|}{\rho_s d_s} \quad (15)$$

$$C_D = \begin{cases} \frac{24}{Re_s} \left[1 + 0.15 (Re_s)^{0.687} \right] \alpha^{-1.8} & Re_s < 1000 \\ 0.44 \alpha^{-1.8} & Re_s \geq 1000 \end{cases} \quad (16)$$

$$Re_s = \frac{d_s \rho_g |\mathbf{v}_s - \mathbf{u}_g|}{\mu_g} \quad (17)$$

where d_s is the particle diameter and Re_s is the Reynolds number.

2.4. Model Verification

In this work, a visual simulation experiment system is designed and built, as shown in Figure 1a. It consists of a simulation experiment device, a pressure measurement system, and a high-speed video camera system. The energetic module used in the experiment is shown in Figure 1b. It is composed of the module box, energetic particles, the igniter, and the ignition packet. On this basis, the simulation experiment can be carried out on the early launching process of the modular charge. In this process, the high-temperature and high-pressure gas jet produced by the combustion of the ignition powder is sprayed into the module box through the hole of the igniter side wall. The signal is amplified by a charge amplifier and input to the computer, which is stored as the pressure data. The experimental device is equipped with a transparent viewing window. The high-speed video camera system consists of the FASTCAM Mini AX-50 and a computer. The computer is used to control the switch of high-speed video instruments and the storage of video data.

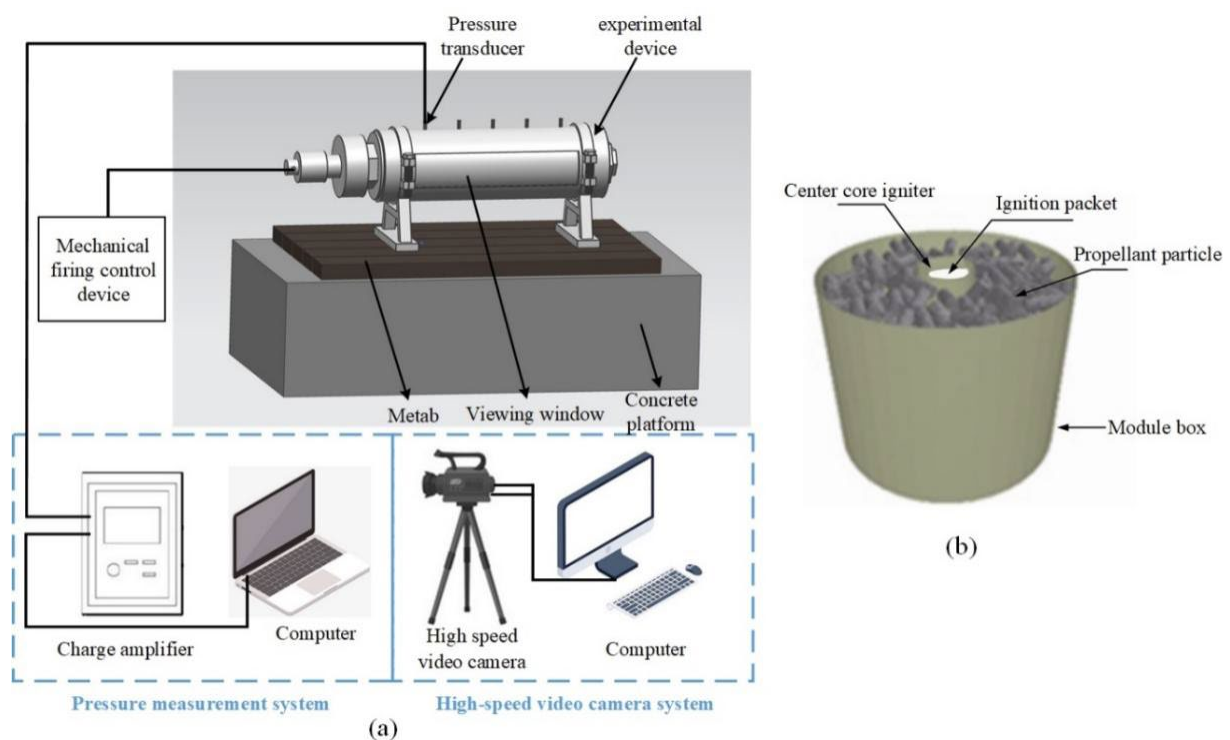


Figure 1. The visual experiment system: (a) test system; (b) internal composition of the energetic module.

The experimental study on the early launch process of the two-module charge is carried out. Thereinto, the distance between modules is 50 mm, and the distance between the module and the left surface of the chamber is 60 mm. The “cold simulation method” is adopted to observe the motion of particles, module rupture, and particle accumulation, in which the simulated particles made of incombustible inert materials are used to replace the propellant particles. During the experiment, the simulated particles move violently by the high-pressure, high-temperature gas after the module is destroyed. At last, the particle final accumulation is measured. The center of the left surface of the chamber is set as the zero point, and the axis of it is set as the X-axis. Finally, most of the particles accumulated in the area of 310~500 mm in the axial direction with a steep slope distribution. In addition, the calculated particle stack height is compared with the experimental one, as presented in Figure 2. The average error is about 8.5%, indicating that the model is reasonable.

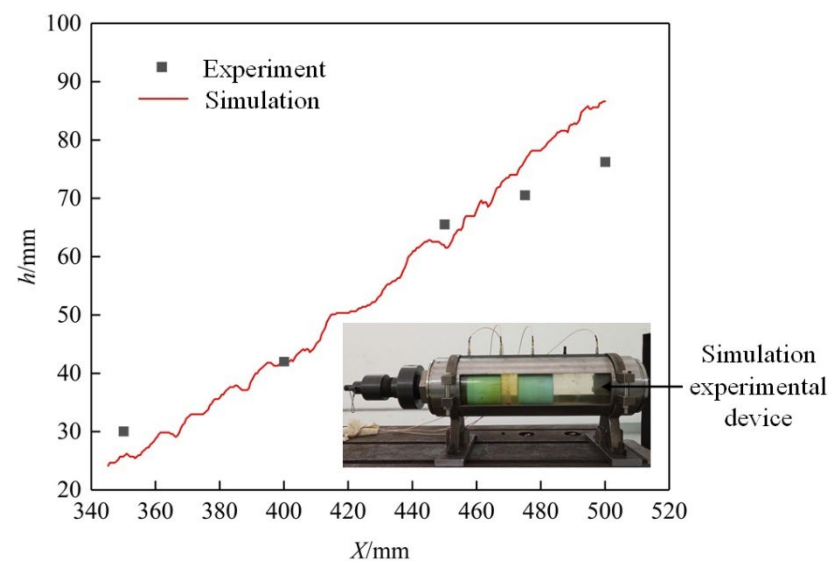


Figure 2. Comparison between the calculated and measured particle stack height.

2.5. Calculation Model

In this work, the two-module (2 M) charge, three-module charge (3 M), and four-module (4 M) charge are studied. In the three working conditions, module 1 is 40 mm away from the left end, and the spacing between the modules is 0. Thereinto, the diameter of the chamber is 135 mm and its length is 500 mm. The inner diameter of the module is 30 mm and the length is 100 mm. For the CFD-DEM method, the flow field information is obtained from CFD by solving the governing equations, which is transferred to DEM in each time step. Next, the particle information is updated using DEM by solving the motion equations, and then the updated particle information is transferred to CFD to calculate the flow field at the next time step. In this work, the gas is compressible, the specific heat of it is 1800 J/kg·K. The particle diameter is 8 mm, the particle density is 1600 kg·m⁻³, Young's modulus is 2.75×10^9 Pa, and Poisson's ratio is 0.4.

The condition with three energetic modules is taken as an example to show the geometric structure of the calculation model for energetic particle groups with the sequence-change space, as illustrated in Figure 3a. The 3D rectangular coordinate system presented in Figure 3 is established to carry out the numerical analysis of particle motion and dispersion. In the numerical calculation, both initial velocities of gas and solid are 0, the initial gas pressure in the chamber is the atmospheric pressure, and the initial temperature is 300 K. Both walls of the module and the chamber are fixed boundaries. The wall adopts nonslip boundary conditions. The computational domain is divided by the structural grid. Due to the large pressure gradient in the area near the igniter, the grids in the area near the central core igniter are refined during grid division, as shown in Figure 3b.

In the CFD-DEM method, the mesh size should be larger than the particle size. Three groups of structured grids with main dimensions of 9 mm (fine grid), 12 mm (mediate grid), and 13.5 mm (coarse grid) are used to divide the computational domain. Then, point A (X = 90 mm, Y = 0, Z = 66 mm) in the module is selected as the monitoring point. The comparison of pressure change curves at point A calculated by the three groups of grids is illustrated in Figure 4. The average error between mediate grid data and fine grid data is 1%, and the average error between coarse grid data and fine grid data is 4.5%. There is no systematic difference between the three grid calculation results. Considering the efficiency and accuracy of calculation, the mediate grid is used for numerical calculation.

In this work, the pressure–velocity coupling model is the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE). The convection-term and diffusion-term in the equations are discretized by the second-order upwind scheme, the time-term is discretized by the first-order implicit scheme, and the gradient in spatial discretization is solved by the

least-squares cell-based scheme. In the DEM collision calculation, the time step of the solid phase should be smaller than the Rayleigh time 1.7×10^{-5} s. Therefore, the time step of the solid phase is 1×10^{-6} s. The time step of the gas phase is 10 to 100 times the particle calculation time step. In order to ensure the optimal configuration of calculation efficiency and calculation accuracy, the gas phase calculation time step of the gas phase is set as 2×10^{-5} s.

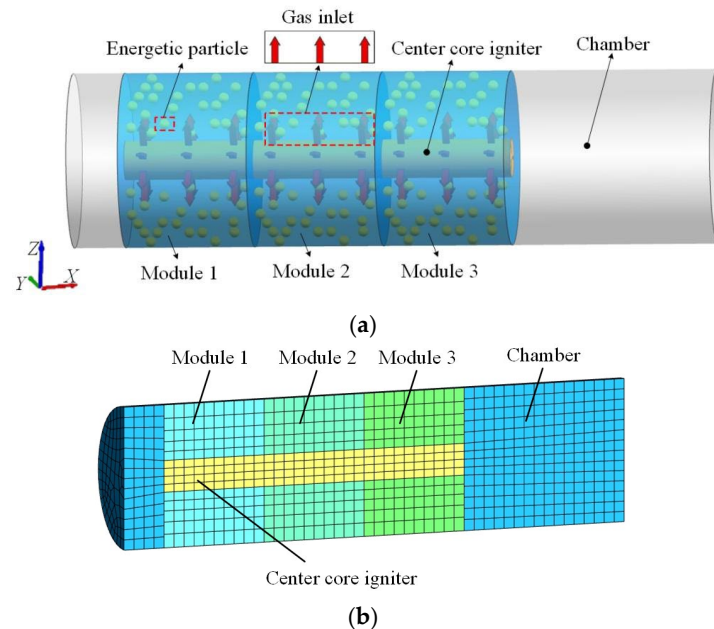


Figure 3. The computational domain and the grid division: (a) geometric structure diagram of the calculation model with the three-module charge; (b) the internal mesh of the computational domain.

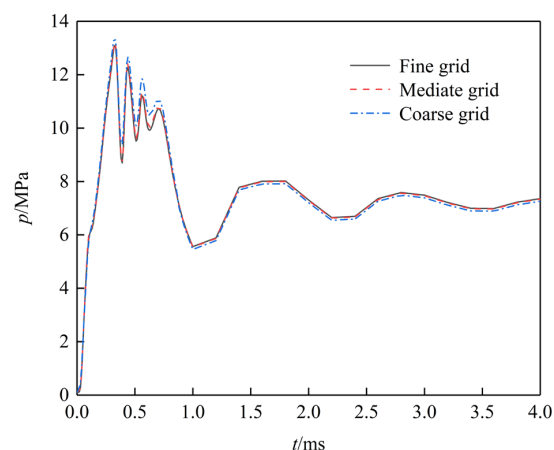


Figure 4. Pressure–time curves at point A in three groups of grid.

3. Results and Discussions

In the launching process, the high-pressure, high-temperature gas generated by combustion is radially sprayed into the module from the igniter, causing the pressure in the module to rise. The gas source in each module is turned on successively from left to right considering the ignition delay of the black powder bags. The mechanical strength of the module box is reduced due to its partial combustion. When the pressure in the module rises to the threshold value, the end face of it is broken. In the 2 M charge, two end faces between module 1 and module 2 are broken first, and then the cover of module 2 is opened. In the 3 M charge, two end faces between module 1 and module 2 are broken first, then two end faces between module 2 and module 3 are broken, and finally, the cover of module 3

is opened. In the 4 M charge, the end face of the module is broken from left to right in a sequence similar to the above process.

The tracer particles are selected near the igniter in the three working conditions. The motion paths of tracer particles are shown in Figure 5. From Figure 5a, the particles near the bottom of module 1 only move radially under the effect of the blocking of the right particle group. The particles in the middle part of module 1 move in the module with a small axial displacement. When two modules are charged, two particles near the cover of module 1 move to the chamber with a large axial displacement. With the increase in the module number, the axial displacement of that particle is decreased. The time–space release of propellant in the launching system is more uniform because the distribution of particles is relatively uniform when the axial displacement is small. When four modules are charged, these particles do not move out of module 1. The particles near the cover of the rightmost module move rapidly to the right end of the chamber at a large speed and stay in the area near it after the collision. With the increase in the module number, the displacements of all tracer particles are decreased. According to the main characteristics of the particle behavior and the space change, the moving process is divided into three stages as follows: the in-module stage, the out-module stage, and the accumulation stage.

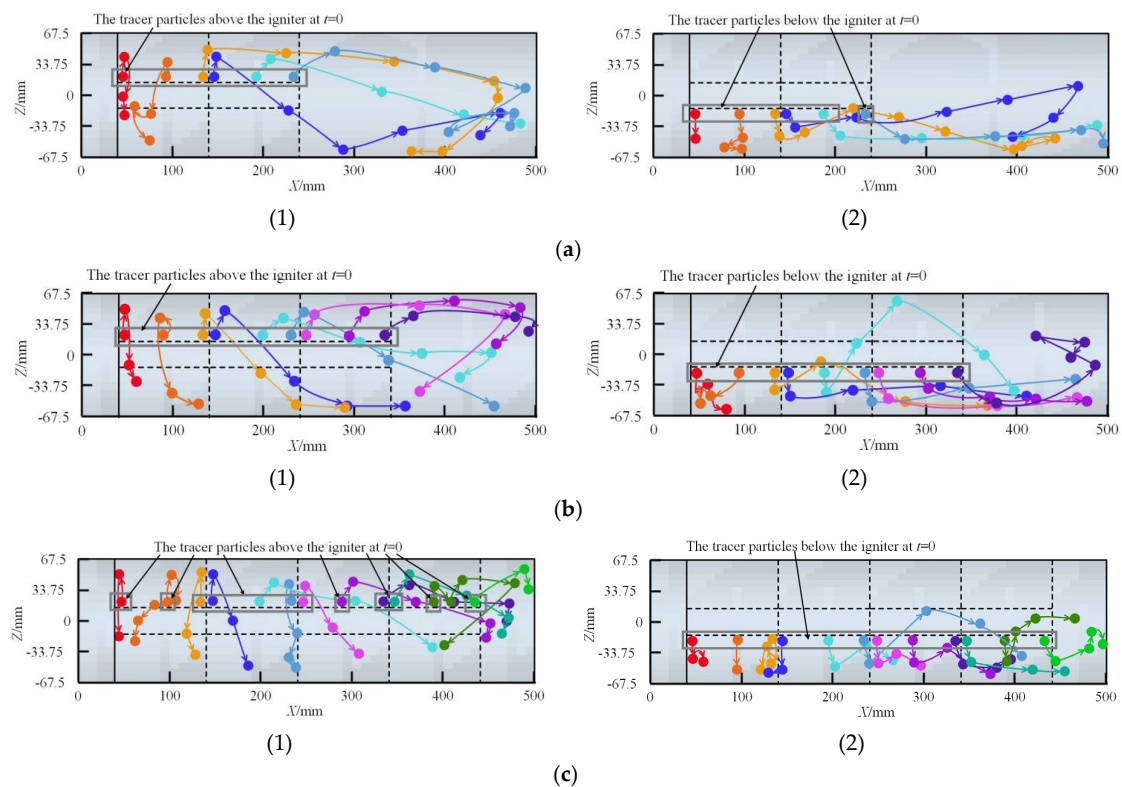


Figure 5. The motion path of the tracer particles in the three working conditions: (1) the tracer particles above the igniter; (2) the tracer particles below the igniter; (a) the motion path of the tracer particles in the two-module charge; (b) the motion path of the tracer particles in the three-module charge; (c) the motion path of the tracer particles in the four-module charge.

3.1. In-Module Stage

In this stage, the motions of particles in the three working conditions are shown in Figure 6. From the figure, the particles in module 1 are accelerated first under the action of the radially input gas, and the speed of the particle near the igniter is the highest. Then, particles in module 2, module 3, and module 4 begin to accelerate successively. This is because the gas sources inside modules are generated from left to right. During this process, the inner diameters of particle groups in modules are increased, as illustrated in Figure 6c. After particles move radially for a while, some particles collide with the wall of the module,

the particle velocity is decreased, and the direction of motion changes to antiradial. This part of particles with the opposite motion direction collided with those with the original direction. After the collision, the velocities of both particles are decreased, and the motion directions of those change.

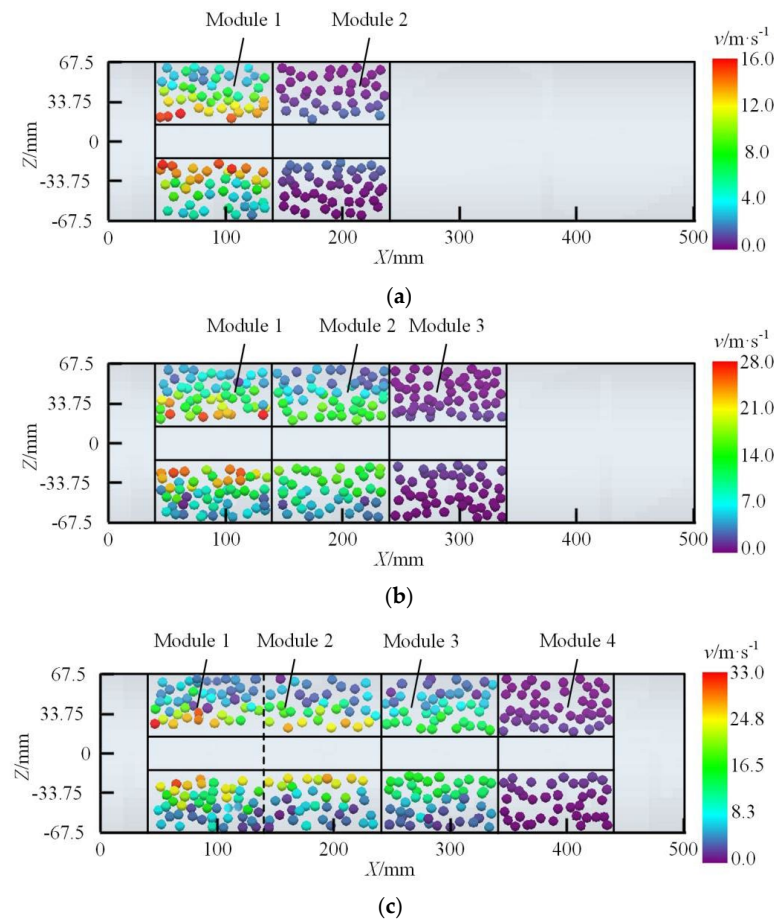


Figure 6. The front view of $Y = 0$ slices in the three charging conditions: (a) the velocity and position of particles in the two-module charge at $t = 0.1$ ms; (b) the velocity and position of particles in the three-module charge at $t = 0.2$ ms; (c) the velocity and position of particles in the four-module charge at $t = 0.3$ ms.

The in-module stage ends when the cover of the rightmost module is opened. In this process, modules are destroyed in turn. The space of the modules is divided into the unit slices equally along the axis with a length of 10 mm to analyze the variation of the average value of the particle axial velocity with the axial position. The changes of the average axial velocity in the three working conditions are shown in Figure 7. For the 2 M charge, the end faces between module 1 and module 2 are broken at $t = 0.28$ ms. At this moment, the axial velocity of particles in module 1 is larger than that of particles in module 2, and the maximum value is in the area ($40 \text{ mm} < X < 50 \text{ mm}$). The axial motion direction of particles is irregular. The cover of module 2 is opened at $t = 0.33$ ms. The closer the particle is to the end faces between module 1 and module 2, the greater the axial velocity. The maximum value exists in the area ($130 \text{ mm} < X < 140 \text{ mm}$), as presented in Figure 7a. For the 3 M charge, the end surfaces between module 1 and module 2 are destroyed at $t = 0.28$ ms. At $t = 0.38$ ms, the end faces between module 2 and module 3 are broken. Thereafter, the spaces of module 1, 2, and 3 are axially connected, and the axial velocities of particles change by the gas. From Figure 7b, the particle near the cover in module 1 and particles in module 2 and 3 move to the right. When the cover of module 3 is destroyed, the particle axial velocity in module 3 is decreased along the axial direction, while that in module 1

is increased. The axial velocity of particles in the middle of module 2 is smaller than that near both end faces, as illustrated in Figure 7b. For the 4 M charge, the change law of the axial velocity is similar to the above two working conditions. After the end faces between modules are destroyed, the particles near the end faces obtain the positive axial velocity. When the cover of module 4 is opened, the maximum value of axial velocity exists in the area ($230 \text{ mm} < X < 240 \text{ mm}$) near the cover of module 2. In the three working conditions, the axial velocity of particles in the connected module increases from both sides to the middle. When the rightmost module is opened, the particle axial velocity increases with the increase in the number of modules.

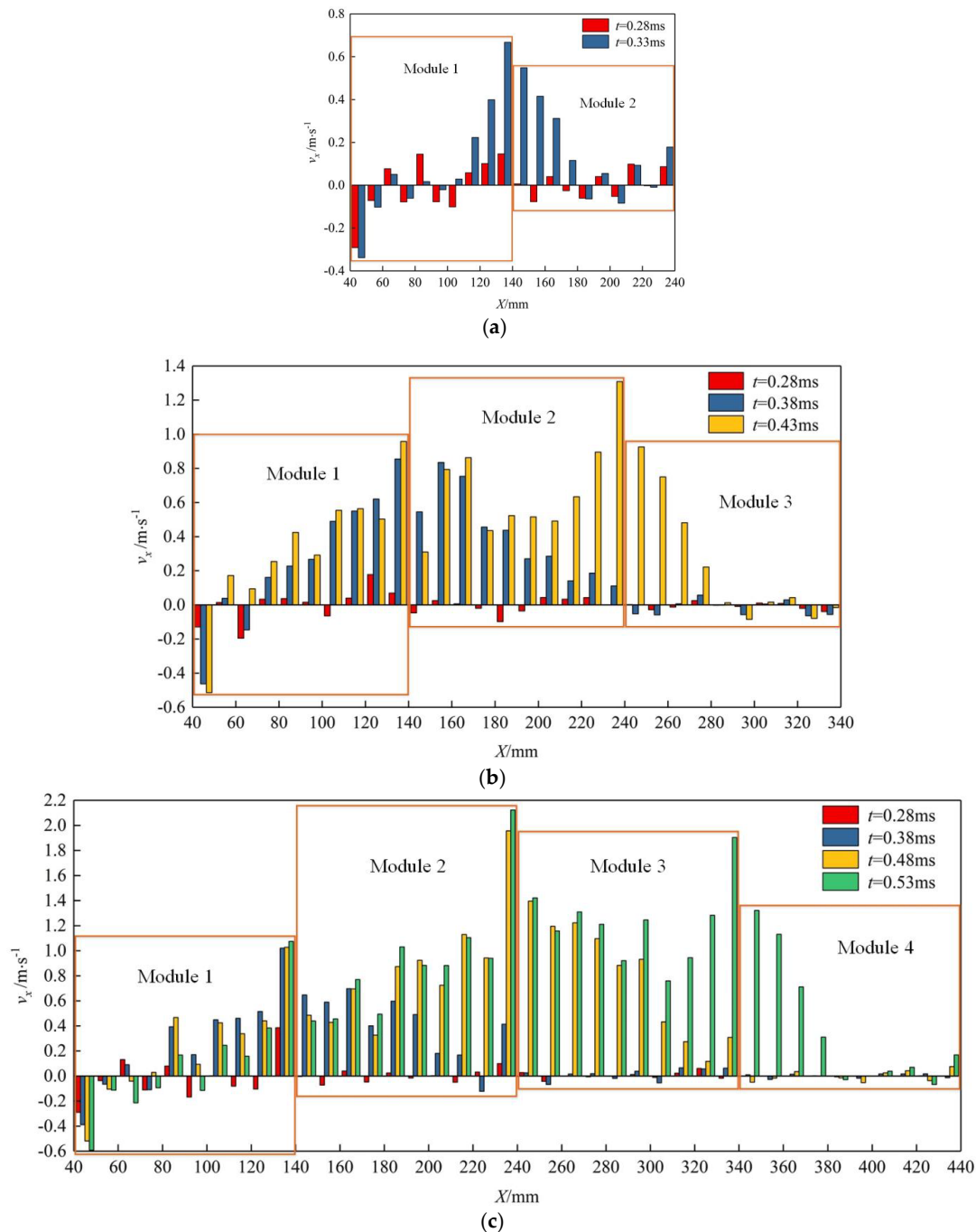


Figure 7. Histogram of the axial velocity of the particles in three charging conditions: (a) the axial velocity of the particles in the two-module charge; (b) the axial velocity of the particles in the three-module charge; (c) the axial velocity of the particles in the four-module charge.

3.2. Out-Module Stage

After the cover of the rightmost module is opened, the space of the gas–solid flow is changed from a multiple-connected module box to a chamber. Most of the particles move out from modules to the chamber right face by the gas phase force. The moment when a particle has moved to the right face of the chamber and has not collided with it is the end of this stage. The motions of particles at this moment in the three working conditions are shown in Figure 8. The color of the arrow represents the particle speed in the figure, and the direction of the arrow represents the motion direction. From the figure, the particle velocity in the chamber gradually increases along with the axis in three conditions. The end times of this stage are $t = 8$ ms for the 2 M charge, $t = 5.85$ ms for the 3 M charge, and $t = 4.2$ ms for the 4 M charge, respectively. It can be seen from the figure that the particle behavior can be divided into three regions as follows: the disordered motion region, the transition region, and the ordered motion region at this moment. With the increase in the module number, the transition region moves to the right, the number of particles moving disorderedly is increased, while the number of particles moving orderly to the right is decreased. The maximum particle velocity is decreased.

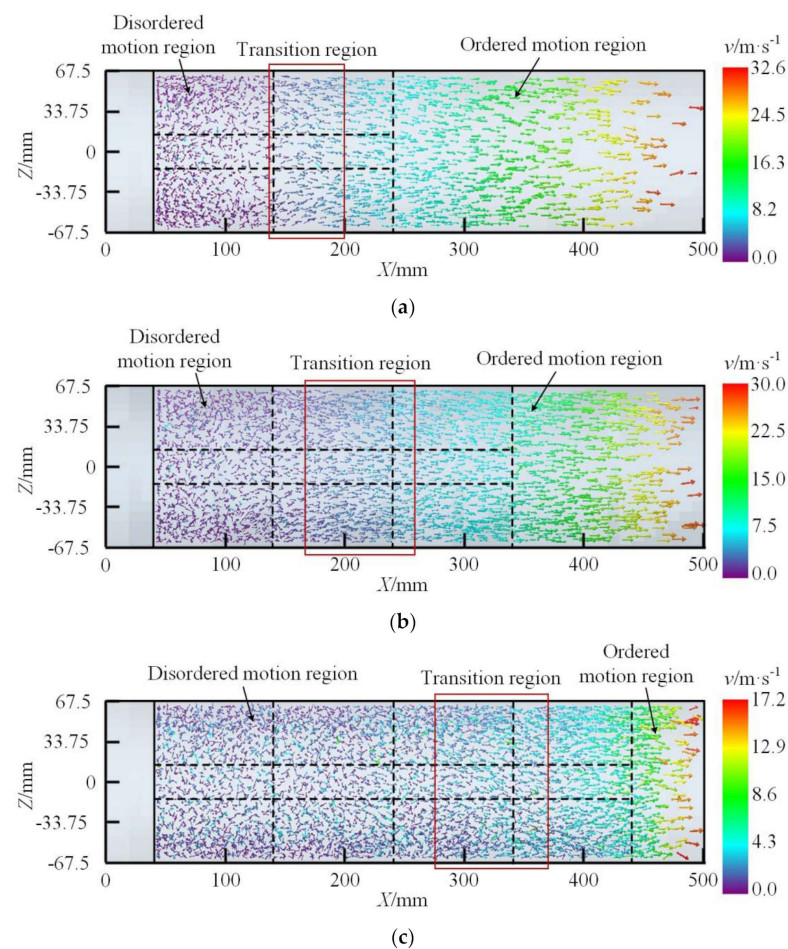


Figure 8. Front view of the particle velocity vector in the out-module stage: (a) the vector of the particle velocity in the two-module charge at $t = 8$ ms; (b) the vector of the particle velocity in the three-module charge at $t = 5.85$ ms; (c) the vector of the particle velocity in the four-module charge at $t = 4.2$ ms.

3.3. Accumulation Stage

After the particles collide with the right face of the chamber, the motion and distribution of particles in the $Y = 0$ slice (the thickness is 20 mm) during the accumulation stage of the three working conditions are shown in Figure 9. In this stage, the velocities of particles,

which have collided, are decreased and the axial motion directions of those are reversed. After the collision, particles moving in the opposite direction collide with particles moving to the right. Most of the particles collide in the area near the right face of the space and remain near the surface, forming a retained particle layer, as illustrated in Figure 9. The thickness of the particle group increases with time. At $t = 40$ ms, the particles near the left surface of module 1 move in opposite directions in both radial and axial directions for the 2 M charge. For the 3 M charge, the particle motion in module 1 is disordered. For the 4 M charge, the particle motion in module 1 and module 2 is disordered. With the increase in the module number, the particle motion in the left part of the chamber changes from reverse motion to disordered motion, and the area where the disordered moving particles are located is increased. At $t = 80$ ms, the particles have begun to move downward. For the 2 M charge and the 3 M charge, the particles near the bottom move to the right and collide with the right retained particle group. For the four-module charge, two hill-like retained particle groups are formed near the bottom of the chamber. With the increase in the module number, the thickness of the particle layer near the bottom of the chamber is increased, and the particle behavior changes from orderly motion to accumulation. At this moment, the retained particle layer in the 3 M charge is larger than that in the 4 M charge.

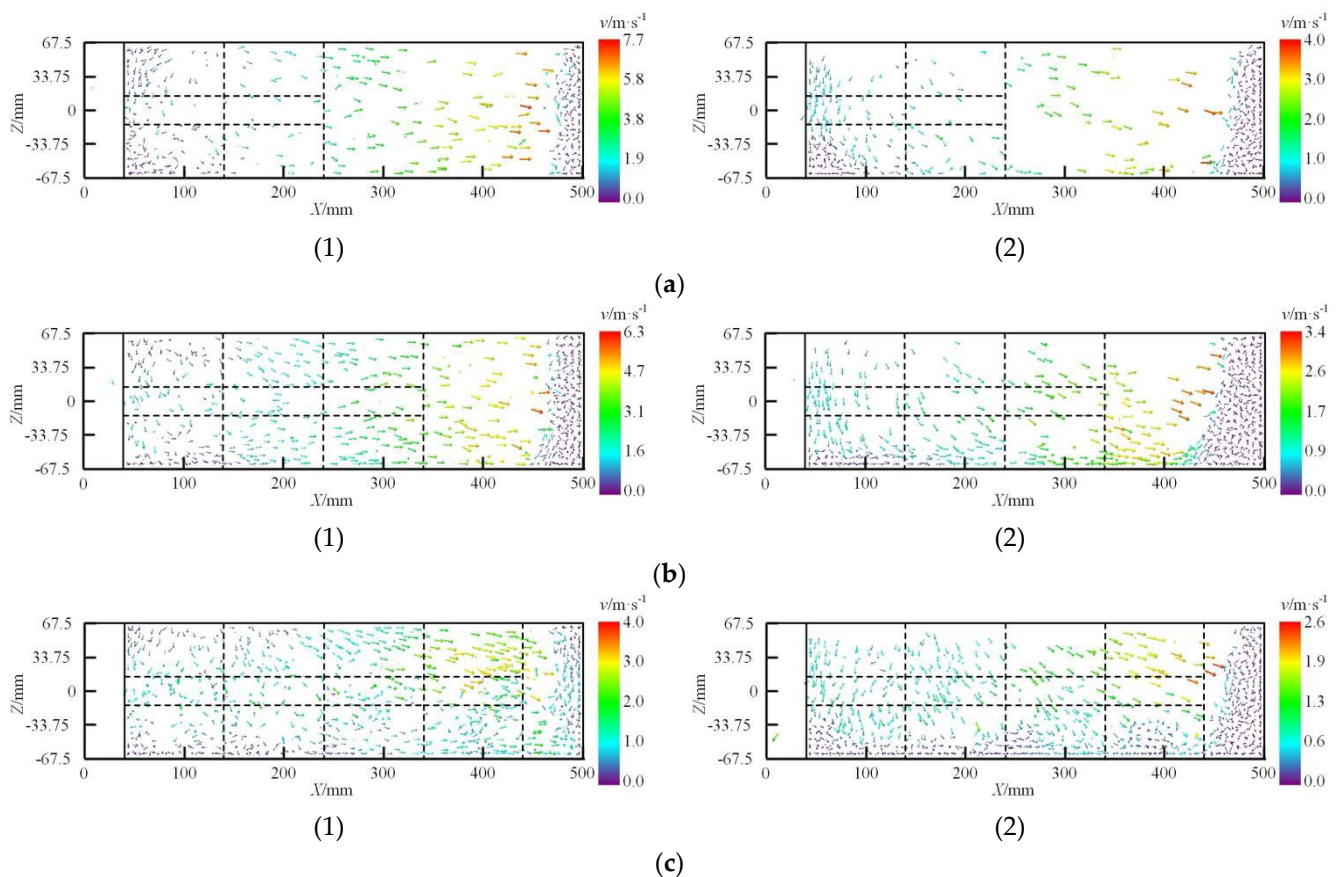


Figure 9. Front view of the particle velocity vector in the stage of particle accumulation and sedimentation: (1) $t = 40$ ms; (2) $t = 80$ ms; (a) the velocity vectors of particles in the two-module charge; (b) the velocity vectors of particles in the three-module charge; (c) the velocity vectors of particles in the four-module charge.

When particles have been stationary, the particle distributions in the three working conditions are shown in Figure 10. The step point of the particle stacking height is taken as the dividing point of the distribution form. All three particle distributions consist of the gentle-slope shape, the horizontal shape, and the steep-slope shape accumulations. From Figure 10(a2), the particles in the gentle slope and the horizontal shape are from module 1,

and the particles in the steep slope are from module 2. From Figure 10(b2), the particles in the gentle slope are from module 1, most of the particles in the horizontal accumulation are from module 1, and a few are from module 2. The particles from module 2 are located below those from module 3 for the steep slope. From Figure 10(c2), the particles in the gentle slope are from module 1. The horizontal accumulation consists of a mixture of particles from modules 1, 2, and 3, and the particles from module 3 are located below those from module 2. And the particles from module 3 are located below those from module 3 in the steep slope. With the increase in the module number, the axial distribution of particles from module 1 is shortened.

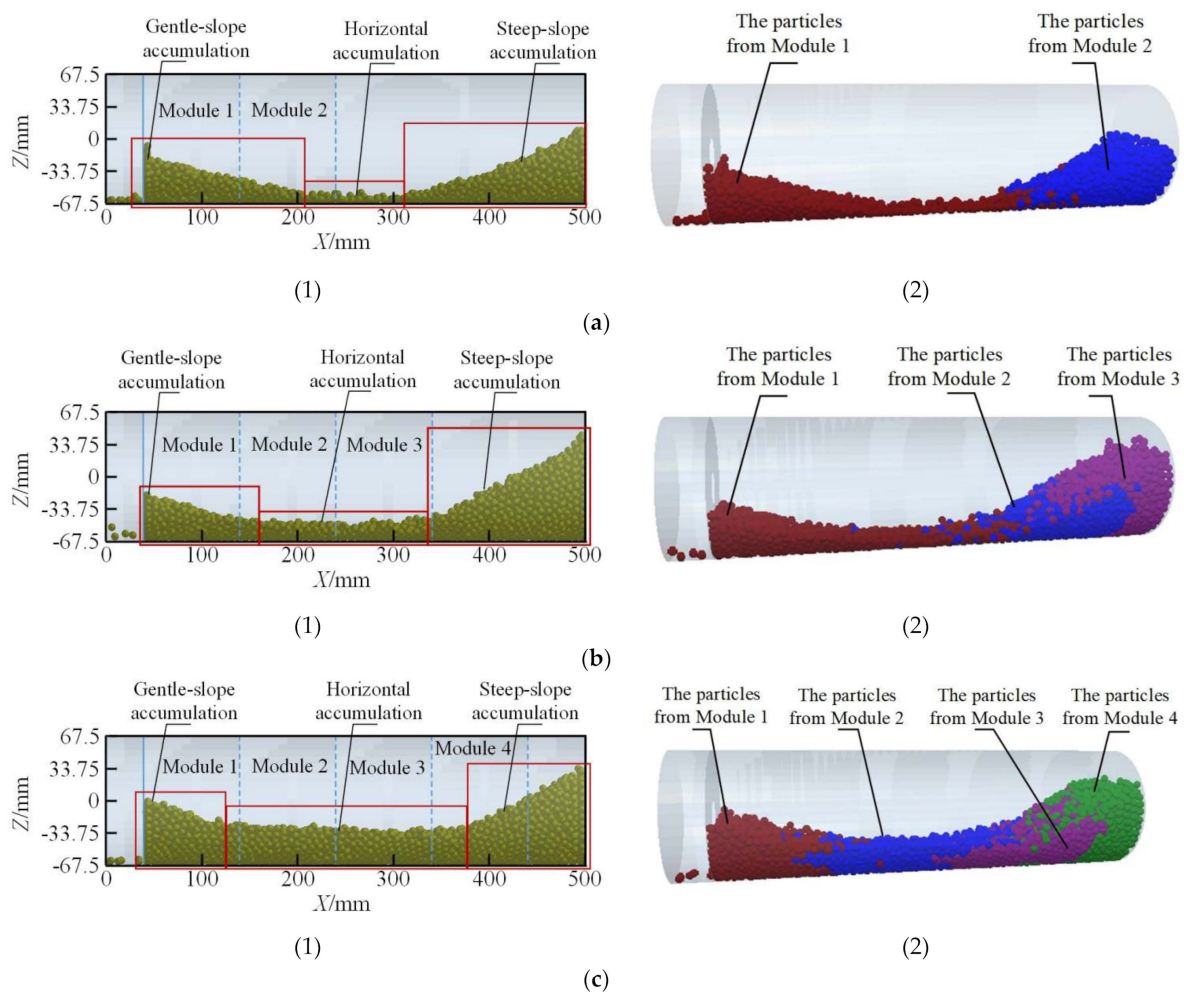


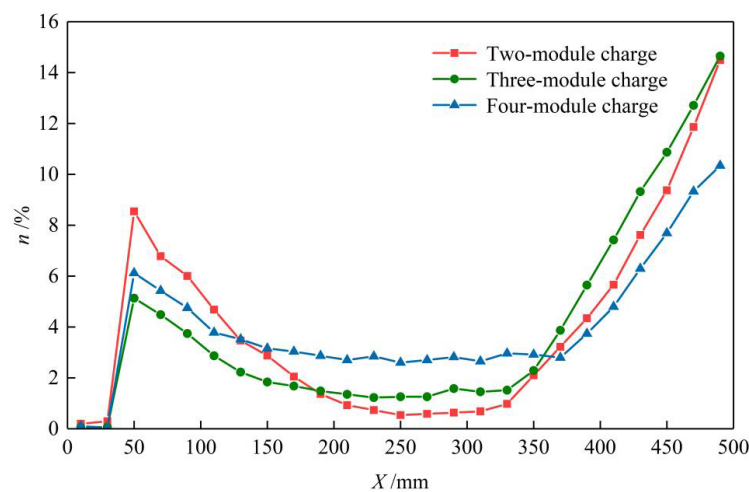
Figure 10. The final particle accumulation in the three working conditions: (1) the front view of the particle accumulation; (2) the 3D particle distribution; (a) particle distribution in the two-module launch system; (b) particle distribution in the three-module launch system; (c) particle distribution in the four-module launch system.

The parameters of three shape accumulations in the three working conditions are presented in Table 1. It can be seen from the table that both the length of the gentle-slope shape and the steep-slope shape accumulation are decreased with the increase in the module number, while the length of the horizontal shape is increased. The angle of the gentle slope is increased with the increase in the module number. And the thickness of the horizontal shape is increased.

Table 1. The parameters of the three shape accumulations.

Particle Accumulation Parameters	Gentle-Slope Shape		Horizontal Shape		Steep-Slope Shape	
	Length L_g (mm)	Slope Angle θ (°)	Length L_h (mm)	Thickness δ (mm)	Length L_s (mm)	Slope Angle θ (°)
Two-module charge	167	12.5	108	10.7	185	19.0
Three-module charge	123	14.6	173	21.9	164	27.0
Four-module charge	87	19.6	250	40.0	123	26.8

The space is divided into 25 units with a height of 20 mm, and the percentage of particle number in the unit to the total particle number is calculated as n to study the uniformity of particle axial distribution. The changes of n along the axis when two to four modules are loaded, respectively, are shown in Figure 11. For the 2 M charge, the minimum proportion in the chamber $n_{\min}$ is 0.537%, the maximum proportion in the gentle slope n_g is 8.541%, and the maximum proportion in the chamber $n_{\max}$ is 14.495%. For the 3 M charge, $n_{\min} = 1.226\%$, $n_g = 5.129\%$, and $n_{\max} = 14.645\%$. For the 4 M charge, $n_{\min} = 2.604\%$, $n_g = 6.123\%$, and $n_{\max} = 10.342\%$. As can be seen from the figure, the particle proportion is increased along the axial from the middle to both ends and that near the left end of the chamber is increased slowly, while that near the right end of the chamber is increased rapidly. With the increase in the module number, the change curve of particle proportion along the axis gradually becomes gentle. When four modules are loaded, the distribution of particle proportion along the axis is the most uniform.

**Figure 11.** The proportion of particles changes along the axis.

From Figure 11, most of the particles in the three working conditions are located in the slope accumulation, and the axial distributions in the area are nonuniform. It is necessary to analyze the axial variation of slope shapes. By fitting the axial variation of the height of slope shapes, the subsection relationship between stack heights and axial positions is established as follows:

Two-module charge

$$h = \begin{cases} 82.985e^{(X/-140.85)} - 5.0076 & 40\text{mm} \leq X \leq 207\text{mm} (R^2 = 0.9639) \\ 5.2047e^{(X/166.67)} - 23.147 & 315\text{mm} \leq X \leq 500\text{mm} (R^2 = 0.9936) \end{cases} \quad (18)$$

Three-module charge

$$h = \begin{cases} 71.570e^{(X/-147.06)} - 2.0226 & 40\text{mm} \leq X \leq 163\text{mm} (R^2 = 0.9772) \\ 0.50843X - 147.54 & 336\text{mm} \leq X \leq 500\text{mm} (R^2 = 0.9925) \end{cases} \quad (19)$$

Four-module charge

$$h = \begin{cases} 0.35701X + 85.836 & 40\text{mm} \leq X \leq 127\text{mm} (R^2 = 0.9739) \\ 0.50466X - 149.69 & 377\text{mm} \leq X \leq 500\text{mm} (R^2 = 0.9930) \end{cases} \quad (20)$$

From the fitting formulas, it can be seen that the particle stack height in the slope shape changes exponentially along the axis in the two-module charge. The particle stack height in the slope shape changes linearly along the axis in the 4 M charge. With the increase in the module number, the variation law of the slope stacking height changes from exponential to linear.

4. Conclusions

In this study, the particle behavior in the unsteady gas–solid flow within the sequence-change space structure is studied using the CFD-DEM method under the background of the modular charge launching system. The effect of the module number on the particle behavior under the action of the thermal jet flow in the sequence-change space is analyzed. The conclusions are as follows:

1. In the launching process, the space structure where the particle group is located first changes from disconnected modules to a connected module structure, and then to the cylindrical chamber structure. The particles in the left part of module 1 move in the module with a small axial displacement. The particles near the cover of the rightmost module move rapidly to the right end of the chamber at a large speed and stay in the area near it after the collision. With the increase in the module number, the displacements of all tracer particles are decreased. The moving process of particles in the sequence-change space can be divided into the following three stages according to the main characteristics of the particle behavior and the space change: the in-module stage, the out-module stage, and the accumulation stage.

2. In the in-module stage, particles are accelerated in turn according to the axial position of the module in which they are located, and the speed of the particle near the igniter is the highest. This is because the gas sources inside modules are generated in sequence from the left module to the right module. During the sequence-change process of the space, the particles near the end faces obtain the positive axial velocity after the end faces between modules are destroyed. When the cover of the rightmost is opened, the particle axial velocity increases with the increase in the number of modules, and the maximum value of axial velocity exists in the area near the cover of module 2. This moment is the end of the stage. In the three working conditions, the axial velocity of particles in the connected module increases from both sides to the middle at this moment.

3. In the out-module stage, the space of the gas–solid flow is changed from the connected module box to the chamber. Most of the particles move out from modules to the chamber right face. The moment when a particle has moved to the right face of the chamber and has not collided with it is the end of this stage. At this moment, the chamber can be divided into the disordered motion region, the transition region, and the ordered motion region according to the particle behavior. With the increase in the module number, the transition region moves to the right, the number of particles moving disordered is increased, while the number of particles moving orderly to the right is decreased. The maximum particle velocity is decreased.

4. In the accumulation stage, particles move in the opposite direction after the particles collide with the right face of the chamber. Most of these particles collide with particles moving to the right in the area near the right face of the space and remain near the surface, forming a retained particle layer. The thickness of the retained particle layer in the three-module charge is larger than that in the four-module charge. With the increase in the module number, the particle motion in the left part of the chamber changes from reverse motion to disordered motion, the area where the disordered moving particles are located becomes larger, and the thickness of the particle layer near the bottom of the chamber is

increased. The behavior of particles near the chamber bottom changes from orderly motion to accumulation.

5. When the particles are stationary, all particle accumulations in the three working conditions present a combination of gentle-slope shape, horizontal shape, and steep-slope shape accumulation. With the increase in the module number, both the thickness and the length of the horizontal stack are increased, while the axial lengths of the slope shape accumulations are decreased. The variation laws of the slope stack height change from exponential to linear. According to the proportion distribution of particles along the axis, the particle axial distribution in the cylindrical space became uniform with the increase in the module number. In the four-module charge launch system, the gentle-slope stack height changes with the axial position as $h = 0.35701X + 85.836$, and the steep-slope stack height changes with the axial position as $h = 0.50466X - 149.69$.

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References

1. Zhang, L.K.; Yu, Y.G.; Lu, X. Interior ballistics simulation of modular charge gun system using Matlab. *Appl. Mech. Mater.* **2012**, *195–196*, 834–839. [\[CrossRef\]](#)
2. Ma, C.J.; Zhang, X.B. Interior ballistic modeling and simulation for different charge zones in modular charge system. *J. Appl. Mech-T ASME* **2013**, *80*, 031404. [\[CrossRef\]](#)
3. Wang, Y.W.; Guo, Y.H.; Wei, J.G.; Li, J.; Dong, Y.C. Study of propellant characteristic effects on pressure waves for low-zone of a bi-modular charge. In Proceedings of the 29th International Symposium on Ballistics, Edinburgh, Scotland, 9–13 May 2016.
4. Wang, Y.W.; Guo, Y.H.; Dong, Y.C.; Zhang, H.H. Study of combustible case effects on pressure waves for low-zone of bi-modular charge. *J. Gun Launch Control* **2016**, *37*, 31–35+45. [\[CrossRef\]](#)
5. Dong, Y.C.; Wang, Y.W.; Guo, Y.H.; Zhang, H.H.; Liu, W. Effect of random factors of charge on interior ballistic performance. In Proceedings of the 31st International Symposium on Ballistics, Hyderabad, India, 4–8 November 2019. [\[CrossRef\]](#)
6. Woodley, C. On the use of accurate ignition and combustion models in internal ballistics gun codes. *Chin. J. Explos. Propell.* **2018**, *41*, 117–121. [\[CrossRef\]](#)
7. Woodley, C. Modeling the effects of non-gaseous igniter combustion products on the ignition of gun propellant. In Proceedings of the 26th International Symposium on Ballistics, Miami, FL, USA, 12–16 September 2011; Volume 17.
8. Sen, S.Y.; Wang, H.; Tao, R.Y. Numerical simulation and characteristics analysis on ignition and flame-propagation process of modular charge based on CE/SE method. *Chin. J. Energ. Mater.* **2022**, *30*, 744–751. [\[CrossRef\]](#)
9. Ma, T.Y.; Tao, R.Y.; Sen, S.Y. Experiment and simulation of flow field characteristics for single modular artillery charge system. *Chin. J. Energ. Mater.* **2023**, *31*, 70–82. [\[CrossRef\]](#)
10. Ma, T.Y.; Wang, H.; Tao, R.Y. Investigation of combustion process in a modular charge system with a primer gap. *AIP Adv.* **2023**, *13*, 115018. [\[CrossRef\]](#)
11. Vångö, M.; Pirker, S.; Lichtenegger, T. Unresolved CFD–DEM modeling of multiphase flow in densely packed particle beds. *Appl. Math. Model.* **2018**, *56*, 501–516. [\[CrossRef\]](#)
12. Hirche, D.; Chew, J.W.; Hinrichsen, O. CFD-DEM study of geometry changes in an AnFMBR towards particle momentum. *Chem. Eng. J.* **2020**, *379*, 122336. [\[CrossRef\]](#)
13. Wang, H.; Wu, J.; Fu, P.; Qu, Z.; Zhao, W.; Song, Y. CFD-DEM study of bridging mechanism of particles in ceramic membrane pores under surface filtration conditions. *Processes* **2022**, *10*, 475. [\[CrossRef\]](#)
14. Mu, L.J.; Buist, K.A.; Kuipers, J.A.M.; Deen, N.G. Hydrodynamic and heat transfer study of a fluidized bed by discrete particle simulations. *Processes* **2020**, *8*, 463. [\[CrossRef\]](#)
15. Han, C.; Bai, L.; Zhou, C.; Sun, W.L.; Zhou, L. CFD-DEM simulation and experimental study of flow pattern transition in a rectangular spouted bed. *Powder Technol.* **2022**, *399*, 117179. [\[CrossRef\]](#)

16. Vijayan, A.; Joy, B.; Annabattula, R.K. Fluid flow assisted mixing of binary granular beds using CFD-DEM. *Powder Technol.* **2021**, *383*, 183–197. [[CrossRef](#)]
17. Xi, K.; Kovar, T.; Fullmer, W.D.; Penn, A.; Musser, J.; Boyce, C. M CFD-DEM study of bubble properties in a cylindrical fluidized bed of Geldart Group D particles and comparison with prior MRI data. *Powder Technol.* **2021**, *389*, 75–84. [[CrossRef](#)]
18. Wu, G.; Li, Y. CFD-DEM simulation of slugging and non-slugging fast fluidization of fine particles in a micro riser. *Processes* **2023**, *11*, 2977. [[CrossRef](#)]
19. Zhao, Y.P.; Wang, C.X.; Shi, X.G.; Gao, J.S.; Lan, X.Y. Gas-solid flow characteristics in turbulent fluidized bed with variable gas velocity. *Powder Technol.* **2022**, *402*, 117358. [[CrossRef](#)]
20. Yue, Y.H.; Shen, Y.S. CFD-DEM study of spout incoherence phenomena in a conical spouted bed. *Powder Technol.* **2022**, *406*, 117529. [[CrossRef](#)]
21. Breuninger, P.; Weis, D.; Behrendt, I.; Grohn, P.; Krull, F.; Antonyuk, S. CFD-DEM simulation of fine particles in a spouted bed apparatus with a Wurster tube. *Particuology* **2019**, *42*, 114–125. [[CrossRef](#)]
22. Batista, J.N.M.; Santos, D.A.; Béttega, R. Determination of the physical and interaction properties of sorghum grains: Application to computational fluid dynamics–discrete element method simulations of the fluid dynamics of a conical spouted bed. *Particuology* **2021**, *54*, 91–101. [[CrossRef](#)]
23. Zhao, X.L.; Li, S.Q.; Liu, G.Q.; Qi, Y.; Maeshall, J.S. DEM simulation of the particle dynamics in two-dimensional spouted beds. *Powder Technol.* **2008**, *184*, 205–213. [[CrossRef](#)]
24. Swasdisevi, T.; Tanthapanichakoon, W.; Charinpanitkul, T.; Kawaguchi, T.; Tanaka, T. Investigation of fluid and coarse-particle dynamics in a two-dimensional spouted bed. *Chem. Eng. Technol.* **2004**, *27*, 971–981. [[CrossRef](#)]
25. Yang, S.L.; Luo, K.; Zhang, K.; Qiu, K.Z.; Fan, J.R. Numerical study of a lab-scale double slot-rectangular spouted bed with the parallel CFD-DEM coupling approach. *Powder Technol.* **2015**, *272*, 85–99. [[CrossRef](#)]
26. Su, S.Y.; Xi, Y.; Dai, Y.; Liu, H.J.; Wang, H.L. Motion characteristics and residence time of particles in the new cross structure under constant pulse condition. *Numer. Heat Transf. A Appl.* **2024**, *85*, 467–490. [[CrossRef](#)]
27. Wéry, F.; Vandewalle, L.A.; Marin, G.B.; Heynderickx, G.J.; Geem, K.M.V. Hydrodynamic CFD-DEM model validation in a gas–solid vortex unit. *Chem. Eng. J.* **2023**, *455*, 140526. [[CrossRef](#)]
28. Shih, T.H.; Liou, W.W.; Shabbir, A.; Yang, Z.G.; Zhu, J. A New $k-\epsilon$ Eddy Viscosity Model for High Reynolds Number Turbulent Flows. *Comput. Fluids* **1995**, *24*, 227–238. [[CrossRef](#)]
29. Hou, Q.F.; Zhou, Z.Y.; Yu, A.B. Computational Study of Heat Transfer in a Bubbling Fluidized Bed With a Horizontal Tube. *AIChE J.* **2012**, *58*, 1422–1434. [[CrossRef](#)]
30. Bates, R.B.; Ghoniem, A.F.; Jablonski, W.S.; Carpenter, D.L.; Altantzis, C.; Garg, A.; Barton, J.L.; Chen, R.; Field, R.P. Steam-air blown bubbling fluidized bed biomass gasification (BFBBG): Multi-scale models and experimental validation. *AIChE J.* **2017**, *63*, 1543–1565. [[CrossRef](#)]
31. Gao, X.; Li, T.W.; Sarkar, A.; Lu, L.Q.; Rogers, W.A. Development and validation of an enhanced filtered drag model for simulating gas-solid fluidization of Geldart A particles in all flow regimes. *Chem. Eng. Sci.* **2018**, *184*, 33–51. [[CrossRef](#)]
32. Papadakis, K.; Gu, S.; Fivga, A.; Bridgwater, A.B. Numerical comparison of the drag models of granular flows applied to the fast pyrolysis biomass. *Energy Fuels* **2010**, *24*, 2133–2145. [[CrossRef](#)]

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