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Design and Optimization of Feeding Device for Pneumatic Seeder of Legume-Gramineae Mixed Sowing

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Abstract: To address the problems of uneven velocity and seed separation during the mixed feeding of alfalfa and smooth brome, which have significant differences in physical properties, a dedicated feeding device was designed based on the Venturi principle. The EDEM-Fluent gas-solid two-phase flow coupled simulation method was adopted to explore the effects of nozzle cross-sectional size, nozzle length and air inlet velocity on seed motion characteristics and flow field distribution. Multiple sets of simulation tests were carried out with the outlet velocity difference between the two grass seeds and airflow energy loss as evaluation indexes. The results show that the optimal parameter combination is a nozzle cross-section of 26 mm × 16 mm, a nozzle length of 30 mm, and an air inlet velocity of 14 m/s. Under this working condition, the outlet velocity difference between alfalfa and smooth brome is only 0.29 m/s, featuring high airflow conveying efficiency, low pressure loss and excellent gas-solid mixing performance. The research results can provide a theoretical reference for the structural design and operating parameter matching of the feeding device of legume-gramineae mixed pneumatic seeders.

Keywords: Feeding device, Venturi structure, Gas-solid two-phase flow, Simulation optimization.

1. Introduction

Mixed sowing of alfalfa and smooth brome is the dominant cultivation pattern for artificial grasslands in northern China. The two grass seeds have obvious differences in particle size, density and flow characteristics. As the core component connecting the independent seed feeding mechanism and seed conveying pipeline of a pneumatic seeder, the feeding device mainly realizes the thorough mixing of seeds and high-speed airflow based on the Venturi effect [1]. Its structural and operating parameters directly determine the stability and uniformity of gas-solid two-phase flow [2]. Most existing feeding devices for pneumatic seeders are designed for single crops. When applied to mixed sowing of legume and gramineous grass seeds, they are prone to defects such as velocity separation of two types of seeds and insufficient gas-solid mixing, which will eventually lead to inaccurate sowing ratios [3, 4]. To solve the above problems, this paper designs a special feeding device for mixed sowing based on the Venturi structure according to the motion characteristics of alfalfa and smooth brome. The EDEM-Fluent coupled simulation technology is adopted to analyze the influences of nozzle structure and airflow velocity on the internal flow field and seed motion rules, and the optimal structural and operating parameters are obtained through optimization. This research aims to improve the feeding quality for legume-gramineae mixed sowing.

2. Model Establishment and Simulation Analysis

2.1. Simulation Method

In the EDEM-Fluent coupled simulation, Fluent 2022 R1 and EDEM 2.0 are used to conduct calculations based on Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM) respectively [5, 6]. The fluid inside the pneumatic device is regarded as incompressible fluid. The flow field is solved by the Fluent solver, and the fluid resistance, gravity, buoyancy and other forces acting on particles are calculated via the EDEM-Fluent coupling approach to simulate the particle motion state at each time step [7]. To ensure the synchronous data exchange of the gas-solid two-phase flow, the time steps of EDEM and Fluent must follow an integer multiple relationship. In this study, the time steps of EDEM and Fluent are set to 1×10^{-6}s and 1×10^{-3}s respectively. The iterative calculation of flow field and particle motion within each time step continues until the total simulation time reaches the preset value.

2.2. Structural Design and Mesh Generation

As a core component for achieving efficient mixing of seeds and airflow in pneumatic seeders for legume-gramineae mixed sowing, the feeding device is structurally designed based on the Venturi effect. Its primary function is to fully blend alfalfa and smooth brome, which are quantitatively delivered by the seed feeder, with high-speed airflow to form a uniform and stable gas-solid two-phase flow, laying a solid foundation for subsequent pneumatic conveying [8, 9]. The feeding device consists of four parts: mixed seed inlet, air inlet, nozzle (gas-solid two-phase flow mixing zone) and gas-solid two-phase flow outlet. Its key structural parameters include the diameters of the air inlet and outlet, as well as the length and cross-sectional area of the rectangular nozzle. The cross-sectional area is mainly determined by its width and height. This study optimizes the cross-sectional area and length of the nozzle to prevent seed blockage and uneven gas-solid mixing from a structural perspective, enabling smooth passage of the two types of seeds and sufficient contact between seeds and airflow. The working principle is described as follows. Alfalfa and smooth brome enter the nozzle chamber through the seed inlet, while high-speed airflow flows in from the air inlet. Thanks to the flow channel characteristics of the Venturi structure, the airflow accelerates and pressure drops as it passes through the contracted nozzle, creating a highly turbulent flow field. This keeps seed particles suspended and achieves primary mixing with the airflow. The gas-solid two-phase flow then travels to the outlet, which is composed of a conical diffuser and a cylindrical pipe. The flow channel expands gradually from the nozzle to the outlet, resulting in a decrease in airflow velocity. This creates a favorable flow environment for thorough mixing and ensures stable conveying of the gas-solid two-phase flow. Apparently, the distribution of airflow velocity and pressure serves as the core indicator of seed conveying efficiency and gas-solid mixing performance. The inlet and outlet diameters, air inlet velocity, as well as the cross-sectional area and length of the nozzle are the key parameters affecting flow field distribution and mixing quality. According to the parameter calculation results of the pneumatic conveying system obtained in the previous work, the initial diameters of the air inlet and outlet are set to 38 mm.

The mixed seed inlet acts as the connecting structure between the seed feeder and the feeding device. Given the obvious differences in particle size, shape and density between the two types of seeds, the inlet is designed as a rectangular opening to reduce collision impact against the wall and initial retention of seed flow before entering the nozzle. Its length is set to 24 mm and width to 18 mm. As the mixing zone for gas-solid two-phase flow, the nozzle is defined by its length, width and height. The device achieves efficient gas-solid mixing via the Venturi effect by reducing the cross-sectional area of the flow channel along the airflow direction to accelerate the airflow and lower the pressure. Accordingly, the effective cross-sectional area of the nozzle must be smaller than that of the upstream circular air inlet pipe. This guarantees sufficient variations in airflow velocity and pressure inside the nozzle to meet the flow field requirements for gas-solid mixing. The nozzle width is fixed at 26 mm, with the height ranging from 12 mm to 20 mm and the length ranging from 20 mm to 35 mm.

The mesh generation module of Workbench 2022 R1 was used to discretize the fluid domain. Block-structured tetrahedral meshes with a global size of 2 mm were adopted throughout the computational domain. The nozzle is a critical region for airflow acceleration and seed mixing, where sharp flow field gradients occur. Hence, local mesh refinement with a refinement ratio of 2 was applied to this area. The final mesh of the fluid domain is presented in Figure 1. The air inlet was defined as Velocity Inlet, while both the seed inlet and gas-solid two-phase flow outlet were set as Pressure Outlet. The air inlet delivers high-speed airflow, the seed inlet serves as the passage for continuous feeding of mixed seeds, and the outlet discharges the gas-solid two-phase flow consisting of seeds and airflow.

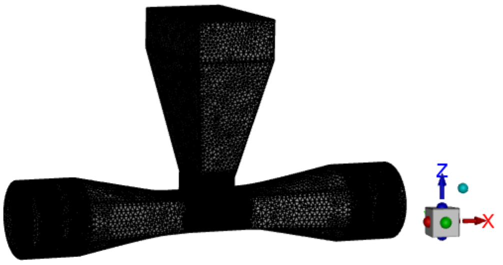


Figure 1. Mesh structure of the feeding device

2.3. Mesh Independence Verification

To verify mesh independence, the computational domain was divided with an initial mesh count of 140,000. The mesh number was increased stepwise by 20,000, and the airflow velocity at the outlet was monitored. Figure 2 presents the variation of outlet airflow velocity when the mesh number ranges from 140,000 to 240,000.

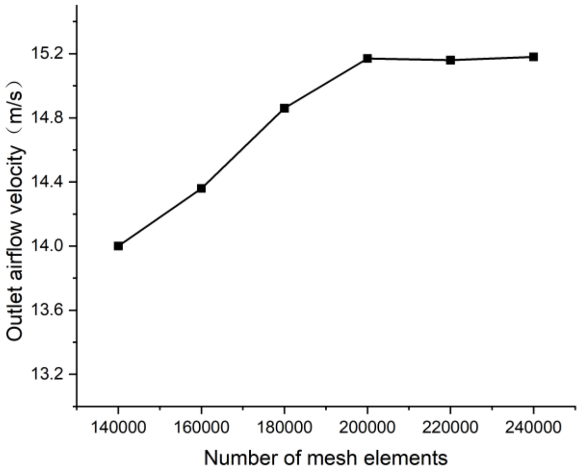


Figure 2. Trend plot of simulation results with the number of meshes

It can be seen that when the mesh number reaches 200,000, further increasing the mesh quantity leads to negligible variation in airflow velocity, and the calculation results tend to be stable. Therefore, 200,000 meshes are finally selected for the simulation of the feeding device. This mesh scheme can ensure calculation accuracy while effectively improving the overall simulation efficiency.

2.4. Simulation Scheme

To explore the effects of nozzle structure on seed conveying and mixing processes, simulation tests were conducted to analyze the combined performance of nozzles with different cross-sectional areas and lengths. Three types of nozzles with varying cross-sectional dimensions were selected for simulation analysis, and the specific parameters are listed in Table 1. Four levels of nozzle length were set, namely 20 mm, 25 mm, 30 mm and 35 mm. Except for the above variables, all other key geometric dimensions and operating conditions were kept constant: the distance from the air inlet to the contraction section and the distance from the expansion section to the gas-solid two-phase flow outlet were both 85 mm, the air inlet velocity was set to 14 m/s, and the pressure at both the seed inlet and gas-solid two-phase flow outlet was atmospheric pressure.

Table 1. Structural parameters of different nozzle cross-sectional areas

Scheme	$W_W \times H_W$ (mm)	L_W (mm)
1	26×12	30
2	26×16	30
3	26×20	30

2.5. Simulation Results and Analysis

2.5.1. Influence of Nozzle Cross-section on Airflow and Seed Motion Characteristics

As analyzed from the pressure and velocity curves in Figure 3 and Figure 4, Scheme 1 exhibits remarkably higher pressure loss than Scheme 2 and Scheme 3. While maintaining a relatively high airflow velocity, Scheme 2 effectively suppresses pressure loss, and its flow field distribution is closer to the optimal working condition for gas-solid mixing and stable conveying [10]. In summary, the nozzle cross-section of Scheme 2 achieves an excellent balance between efficient flow acceleration and low pressure loss, and delivers superior performance in gas-solid two-phase flow conveying and mixing. Thus, it is selected as the preferred solution for the subsequent structural optimization of the feeding device.

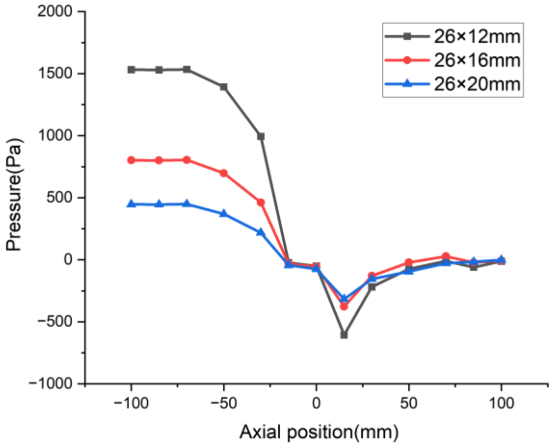


Figure 3. Influence of nozzle cross-sectional area on air pressure

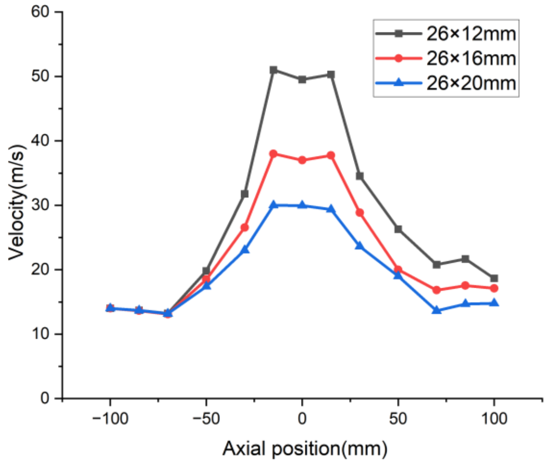


Figure 4. Influence of nozzle cross-sectional area on air velocity

2.5.2. Influence of Nozzle Length on Airflow and Seed Motion Characteristics

Under the operating conditions where the air inlet was set as Velocity Inlet at 14 m/s, the seed feeding ratio was 1:1, and the feeding rate of alfalfa and smooth brome was both 4.5 g/s, the effects of different nozzle lengths on the gas-solid flow field and seed motion characteristics were investigated. The nozzle cross-section adopted the parameters of the aforementioned Scheme 2. As shown in Figure 5 and Figure 6, nozzle length has little influence on air pressure and airflow velocity. Nevertheless, Table 2 indicates that nozzle length exerts a significant impact on seed velocity and the velocity difference between the two seeds. In terms of outlet velocity, when the nozzle length is 30 mm, the outlet velocities of alfalfa and smooth brome are 7.91 m/s and 8.20 m/s respectively, which are higher than those of the other three schemes. A too short nozzle results in inadequate acceleration of seeds in the flow field, making them fail to acquire sufficient kinetic energy. An excessively long nozzle, by contrast, intensifies friction and collision between seeds and the wall, increases energy dissipation and reduces the kinetic energy transfer efficiency between gas and solid phases [11], which eventually causes a drop in seed outlet velocity. Reducing the velocity difference between the two seed varieties and between seeds and airflow is essential to guarantee uniform sowing and prevent patchy distribution. At the nozzle length of 30 mm, the velocity difference between the two seeds is only 0.29 m/s, and the velocity differences between alfalfa, smooth brome and airflow are 7.26 m/s and 6.97 m/s respectively, all lower than those of other schemes. Considering the kinetic energy acquisition efficiency of seeds and mixed sowing uniformity, 30 mm is determined as the optimal length for the nozzle with the cross-section of Scheme 2.

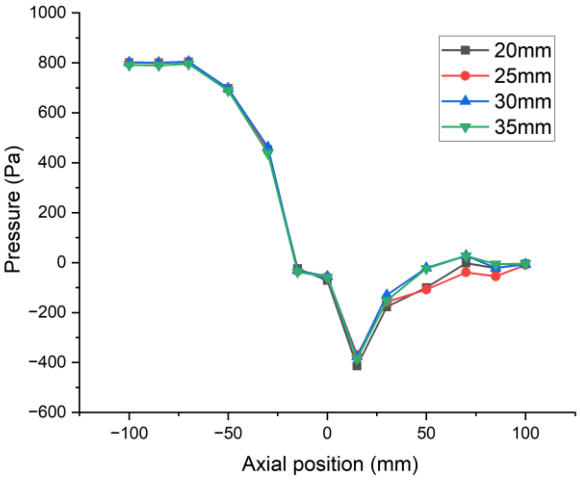


Figure 5. Influence of nozzle length on air pressure

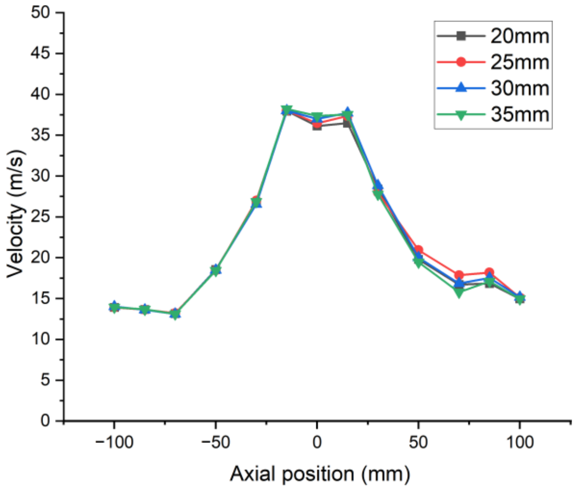


Figure 6. Influence of nozzle length on air velocity

Table 2. Motion characteristics of different nozzle lengths

Nozzle length/mm	Alfalfa outlet velocity (m/s)	Smooth brome outlet velocity (m/s)	Velocity difference between the two seeds (m/s)	Airflow velocity (m/s)	Velocity difference between alfalfa and airflow (m/s)	Velocity difference between smooth brome and airflow (m/s)
20	7.06	8.09	1.03	14.96	7.90	6.87
25	7.44	8.13	0.69	15.11	7.67	6.98
30	7.91	8.20	0.29	15.17	7.26	6.97
35	7.39	8.17	0.78	14.95	7.56	6.78

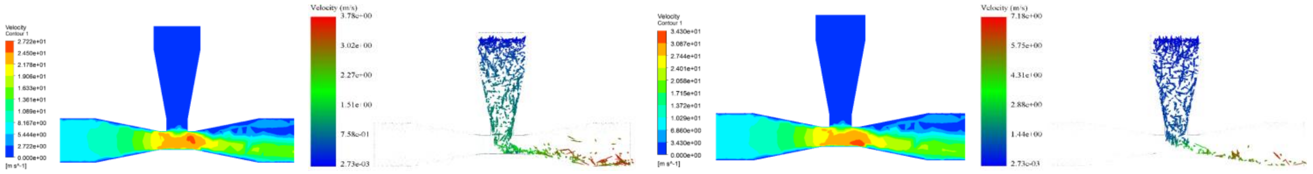
2.5.3. Influence of Air Inlet Velocity on Seed Motion Characteristics

To further reveal the effects of air inlet velocity on the air pressure inside the feeding device and seed motion characteristics, a single-factor experiment was carried out. Five velocity levels were set as 8 m/s, 10 m/s, 12 m/s, 14 m/s and 16 m/s, while all other structural and operating parameters remained consistent with the above conditions.

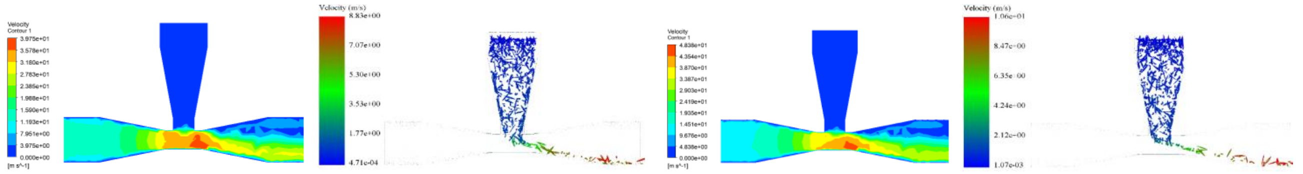
Table 3. Motion characteristics of different airflow velocities

Airflow velocity (m/s)	Alfalfa outlet velocity (m/s)	Smooth brome outlet velocity (m/s)	Velocity difference between the two seeds (m/s)	Airflow velocity (m/s)	Velocity difference between alfalfa and airflow (m/s)	Velocity difference between smooth brome and airflow (m/s)
8	3.07	3.42	0.35	9.41	6.34	5.99
10	5.29	5.71	0.42	11.71	6.42	6.00
12	6.82	7.70	0.88	14.56	7.74	6.86
14	7.91	8.20	0.29	15.17	7.26	6.97
16	7.83	8.34	0.51	16.85	9.02	8.51

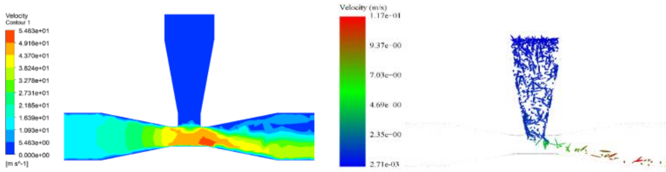
As shown in Table 3, within the airflow velocity range of 8–14 m/s, the outlet velocities of the two types of seeds increase with the rise of airflow velocity, and the velocity of smooth brome is always slightly higher than that of alfalfa. When the airflow velocity rises to 16 m/s, the seed velocities stop increasing. The velocity difference between the two seeds reaches a peak of 0.88 m/s at 12 m/s and falls to a minimum of 0.29 m/s at 14 m/s, demonstrating the best motion synchronization of the two seeds at this velocity. Overall, the velocity difference between seeds and airflow increases with the inlet velocity, with only a slight drop at 14 m/s, which means the airflow achieves the highest kinetic energy transfer efficiency to seeds under this working condition. Combined with Figure 7, seeds cannot obtain sufficient kinetic energy at low airflow velocities. They tend to settle toward the pipe wall under gravity and inertia, bringing risks of seed-wall collision and pipeline blockage. At the velocity of 16 m/s, the increase of seed velocity is limited, the velocity difference between seeds and airflow rises remarkably, and the kinetic energy transfer efficiency decreases greatly. Meanwhile, the airflow pressure loss and energy consumption inside the pipeline are aggravated. Therefore, 14 m/s is selected as the optimal air inlet velocity for gas-solid two-phase flow conveying.



(a) Airflow velocity 8m/s (b) Airflow velocity 10m/s



(c) Airflow velocity 12m/s (d) Airflow velocity 14m/s



(e) Airflow velocity 16m/s

Figure 7. Pressure nephograms and grass seed distribution diagrams at different air velocities

3. Conclusion

Based on the Venturi principle, a dedicated feeding device for legume-grass mixed sowing was designed. By adopting the EDEM-Fluent coupled simulation method for gas-solid two-phase flow combined with the drag model for non-spherical particles, the movement and mixing processes of alfalfa and smooth bromegrass inside the device can be accurately simulated.

The optimal parameters of the feeding device are determined as follows: nozzle cross-section of 26 mm × 16 mm, nozzle length of 30 mm, and air inlet velocity of 14 m/s. Under this working condition, the outlet velocity difference between the two seeds is only 0.29 m/s. The gas-solid mixture is uniform and the flow field remains stable, which can well meet the requirements of legume-grass mixed sowing.

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