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DEM-CFD coupling simulation and optimization of an inside-filling air-blowing maize precision seed-metering device

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ABSTRACT

Simulation of the gas-solid flow in an inside-filling air-blowing maize precision seed-metering device was performed by means of a coupling approach of the discrete element method (DEM) and computational fluid dynamics (CFD). In this model, EDEM software was used to depict the discrete particle phase, and ANSYS Fluent software was used to describe the continuous gas phase. Maize particles were created by EDEM software using the bonded particle model (BPM) to define a single structure of the particles. Effects of the positions, the width and the average arc length of the lateral hole were examined and analyzed in terms of gas field and seed movement. Using an orthogonal experimental design, the primary and secondary factors and parameters of the maximum evaluation index affecting the working performance of a seed-metering device were assessed. The superiority of a lower position of the lateral hole was identified, as both the width and the average arc length of the lateral hole had no effect on the drag force or differential pressure. The area of the lateral hole significantly affected the movement and airflow field of seeds in the hole of a seed-metering device. The drag force, the differential pressure and the pressure loss increase with the expansion of the area of the lateral hole also resulted in a decrease in the upper pressure. The optimized lateral hole, which is 1.5 mm wide and has an average arc length of 10 mm when the position is lower, had a good working performance, with less pressure loss, superior drag force and differential pressure. The qualified rate of the optimized seed-metering device was greater than 93% when the working pressure was above 5.5 kPa with a working speed lower than 10 km/h through experiment. The results showed that the DEM-CFD coupling approach was a reliable instrument for simulating the physical phenomenon of seed movement in the airflow field. DEM-CFD coupling simulation of seed movement can provide a theoretical basis for assessment of the potential working performance of an inside-filling air-blowing seed-metering device.

1. Introduction

Maize is one of the most vital food crops worldwide and is widely used for industrial purposes, such as animal husbandry, medicine and the chemical industry, which has led to increasing demands for its growth all over the world (Yang et al., 2016). Maize has become the largest crop in China, with an annual production of more than 200 million tons due to its multiple uses and high yield (Sun, 2014; Zhang, 2015; Yu et al., 2015). Although there are many factors affecting maize yield, precision planting technology is considered one of the most important factors (Liao et al., 2006). Precision planting technology can reduce seed requirements to 22.5–30.0 kg/hm^2 and increase output up to 1.5 t/hm^2 (Zhao and Meng, 2010). In recent years, the germination percentage and emergence rate of maize seeds have increased with the enhancement of seed quality. As a result, precision planting technology has become the main research direction for enhanced maize cultivation (Zhang, 2014; Li et al., 2012a, 2012b). Seed-metering devices serve as the most crucial component of a planter to ensure sufficient seeding performance. Although there are multiple types of seed-metering devices, each with unique individual working principles, pneumatic seed-metering devices are used more widely because of their high accuracy, preservation of seed integrity and fitness for high-speed operations (Yang et al., 2016).

Inside-filling air-blowing seed-metering devices are a type of pneumatic seed-metering device. They are based on the operational principles of inside-filling and high-velocity airflow cleaning of seeds; via a simple structure, they provide homogeneous seeding and lower seed injury rates. It has been found in previous studies that the effects of

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sowing flat seeds in seed-metering device are better than those of circular seeds when utilizing a seed-metering plate with a half-conical hole. Cui et al. (2017) analyzed the source of this phenomenon and found that the seed-metering device itself must be optimized through further research. Inside-filling air-blowing seed-metering devices are based on the theory that high-velocity airflow cleaning of seeds and differential pressure pressing seeds guarantee a high rate of individual seeds. The movement and interrelationships between fluids and particles coexist simultaneously in the working space of the seed-metering device. Consequently, it is necessary to adopt fluid simulation, particle simulation and coupling simulation methods for fluids and particles to optimize and analyze pneumatic seed-metering devices (Han et al., 2017).

Computational fluid dynamics (CFD) has become an effective tool to simulate fluid flow, describe the characteristics of a flow field and reveal the mechanism of fluid phases with sustainable development (Zhao et al., 2012; Yu et al., 2013). The technologies of computer numerical calculation power and image display are utilized in CFD to analyze the system, which models related physical phenomena such as fluid flow and heat transfer. The distribution of fundamental physical quantities in all positions of the airflow field, as well as the variation in these quantities over time can also be obtained by CFD simulation analysis. The CFD method has been successfully applied to various mechanical structures (Zhou et al., 2016; Lu et al., 2015; Li et al., 2012a, 2012b). The discrete element method (DEM) is used to study fundamental dynamics of particle flow. DEM is an analytical method based on molecular dynamics principles for studying particle dispersion materials and their kinematic pattern of motion, which was first proposed in 1971 by Cundall and Strack (1979). Contact force is calculated according to the overlap between particles based on a soft sphere model (Di Renzo and Di Maio, 2004). The deterministic evolution of the whole granular system is determined by sequentially updating the velocity and location of each particle. A robust modeling process is generated via the display method, which handles dynamic problems, or by the dynamic relaxation method, which solves static problems. To describe detailed dynamic information, including particle velocity, instantaneous forces that act on each particle by airflow and the interactions between gas-solid phases, the computational fluid dynamics and discrete element method (CFD-DEM) techniques have been combined (Mikio and Seiichi, 2009; Ren et al., 2012). Fluid flow and particle motion behavior have been quantitatively studied by means of this CFD-DEM coupling approach, appearing in various industrial applications such as pneumatic particle motion (Lei et al., 2016a,2016b), circulating fluidized beds (Fernández and Nirschl, 2013; Salikov et al., 2015) and air-screen cleaning devices (Li et al., 2012a, 2012b). In these studies, it was found that the simulation results based on the coupled approach of DEM with CFD could adequately explain fluid and particle motion mechanisms, which were consistent with experimental data. Although the coupling method of DEM-CFD has been applied to many mechanical devices, coupling research of seed-metering devices has been limited, and there have been no studies concerning the application of the coupling method of DEM-CFD to pneumatic seed-metering devices.

Currently, studies of seed-metering devices with the sole use of the discrete element method are conducted widely. Shi et al. (2015) employed the DEM method to study the influence of different kinds of seed-metering plates on the seed-filling performance of pneumatic combined-hole seed-metering devices. The normal force was employed as an index for data analysis during simulations at different rotational speeds, and an optimal seed-metering plate was identified. Two-dimensional DEM analysis models of seeds and precision seed-meters with combined inner-holes were built by Yu et al (2008). The feasibility and advantages of analyzing the working performance of precision seed-metering devices via custom two-dimensional DEM software were validated through comparing the results of DEM simulation and experiments. Li et al. (2011) found that the simulation and experimental results were highly coincident. Zhang and Yi (2017) have performed DEM simulations of seed-filling performance of maize seed-metering devices with rollers for air suction. The height of the seed layers, the vibration frequency and the angle of vibration were analyzed via DEM, and the results of real-world experiments were consistent with DEM simulations. Lei et al. (2016a,2016b) used EDEM software to simulate the impact of seed-flow properties and compressive force on the seed-filling performance of a feeding device in an air-assisted centralized metering system, and a high-speed camera was used to verify the simulation results. To increase the qualified index and reduce the re-seeding and miss-seeding indexes, a DEM simulation of a horizontal circular-plate precision seed meter was performed by Shi et al. (2014). In addition, DEM has been utilized in many analyses to study particle dispersion mechanisms in other agricultural machinery (Zhang et al., 2016; Yu et al., 2015; Lei et al., 2016a,2016b; Han et al., 2017). Although there have been several studies of seed-metering devices, most previous studies have not investigated dynamic behavior of particles, especially the seed motion in a pneumatic seed-metering device where the influence of airflow is highly relevant. Detailed flow characteristics inside the pneumatic seed-metering device, such as airflow and particle velocity distribution, airflow pressure and drag force, are difficult to model solely via DEM simulation.

To optimize the structure of pneumatic seed-metering devices, multiphase flow models combining the discrete element method (DEM) and computational fluid dynamics (CFD) were utilized in this study. The model involves various kinds of particle movement and interactions of particles with each other. In the simulations, particles served as discrete phase models based on Newton's law of motion, and the fluid phase was treated as a continuous phase described by local averaged Navier-Stokes equations. The modeling of gas-solid two-phase flow was used to simulate the particle movement process of the seed-metering device. The feasibility and effectiveness of analyzing the cleaning and pressing processes based on DEM-CFD coupling simulation were verified through comparisons between simulation and experimental data. Positions, width and average arc length of the lateral hole, the drag force and the differential pressure of seeds in the hole were studied and analyzed in terms of fluid field and seed movement. A theoretical basis for improving the design of seed-metering device is proposed in this paper. To our knowledge, the simulated study of the working process of pneumatic seed-metering device, from a micro-mechanical perspective, has not been previously performed.

2. Structure and working principles of the seed-metering device

2.1. Structure of the seed-metering device

The inside-filling air-blowing maize precision seed-metering device was composed of a seed-metering device case, a seed-metering plate, combined gas nozzles, a seed-entrance pipe, a seed-protecting device and a seed-retaining plate, as shown in Fig. 1. Combined gas nozzles consisted of a cleaning gas nozzle and a pressing gas nozzle. The seed-entrance mouth and voting mouth are respectively arranged on the seed-metering device case. The working process of the inside-filling air-blowing seed-metering device can be divided into 4 stages, including a seed-filling process, a seed-cleaning-pressing process, a seed-guarding process and a voting process.

In the function of a seed-metering device, the cleaning zone will be filled with high-velocity airflow, which also flows to the seed-filling zone. Seeds will be individually separated from the stock seed population and fill into the hole via the combined action of gravity, centrifugal force, and airflow perturbation. Seeds in the hole are rotated to the cleaning zone with the seed-metering plate, and the seed cleaning and pressing processes will be completed via the effects of high-velocity airflow. The inside-filling air-blowing seed-metering device has the benefits of a simple mechanism, with good seed-filling and cleaning efficacy. The working performance has been analyzed in detail by Cui et al. (2017), with the final results showing that the effect of sowing flat