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Comparison of computational fluid dynamics-based simulations and visualized seed trajectories in different seed tubes

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Abstract: The objective of this study was to compare computational fluid dynamics (CFD)-based simulations and visualized seed trajectories in different seed tubes that can provide seed incorporation into the soil with enhanced seed spacing. The other objective was to determine the relation between the seed trajectories and peripheral speed of the vacuum disk. In order to meet the first objective, 2 different seeds (corn and cotton) and artificial spherical material (Ø10 mm) were tested under laboratory conditions. The seeds and artificial material were released by free fall into the semitransparent seed tubes (seed tubes A and B) from different release points, and their trajectories were recorded using a video camera. For the second objective, corn seeds were used and released from a vacuum-type metering unit equipped with a semitransparent seed tube (seed tube A) at 3 different peripheral speeds of the vacuum disk, as a function of 3 forward speeds of the seeder. For both objectives, the seed tubes were modeled and release of the seeds into the seed tubes was simulated and analyzed using ANSYS Fluent for CFD. The results obtained from the captured video and simulations were compared. As a result of the comparisons, it was found that the seed release point was an effective parameter on both the seed trajectory and seed spacing, since seed bouncing and skating in the seed tube, based on the release point, may occur. The results also showed that the lab tests and simulations were found to be very similar in terms of the seed trajectories and seed spacings. It is believed that this study, using CFD, will be an example and enable the development and design of new seed tubes in order to obtain better seed distribution uniformity.

Key words: Analysis, computational fluid dynamics (CFD), design, precision seeding, simulation, uniformity

1. Introduction

Seeders may vary depending upon the seeding techniques. Seeders equipped with a runner opener are generally used for conventional row-crop seeding, while seeders with a disk-type opener are preferred for direct seeding or ridge seeding. These 2 types of seeders differ from each other in terms of the seed drop configuration and seed incorporation into the soil. Seeds are dropped directly into the soil in runner openers, while seeds are dropped through a seed tube and then incorporated into the soil in disk-type openers (Figure 1).

Additionally, these 2 types of seeders meter the seeds from different heights from the soil surface. The release height and velocity of the seed may affect the incorporation of the seedin to the soil and seed spacing uniformity performance of the seeder. Yazgı (2013) found that the seed distribution uniformity of precision seeders equipped with a high metering unit was lower than that in those with a low metering unit.

Since a disk-type precision seeder has a seed tube following the metering unit, seeds are released from the vacuum disk first, and then pass through the seed tube, and finally, they are incorporated into the soil. The seed tube should have such good geometry that it provides a continuous and smooth flow to obtain the desired performance. Otherwise, seed bouncing through the seed tubes may detrimentally affect the seed placement, even if the metering unit performs optimally.

The number of studies on the effect of seed tubes on seed spacing uniformity performance is limited. Smith and Kocher (2008) studied seed spacing accuracy using sunflower planters equipped with 3 basic metering systems that were sensitive to adjustments, such as a vacuum, vacuum disk or finger option, seed size/shape, forward speed, and new/used seed tubes on a greased belt. One of their findings was that new seed tubes had greater coefficient of precision values than that of used seed tubes.

In a study conducted by Kocher et al. (2011), new and worn seed tubes were tested and compared in laboratory experiments using round- or flat-type corn seeds at a theoretical seed spacing of 17.7 cm. They found that the new seed tubes had better seed spacing accuracy than the

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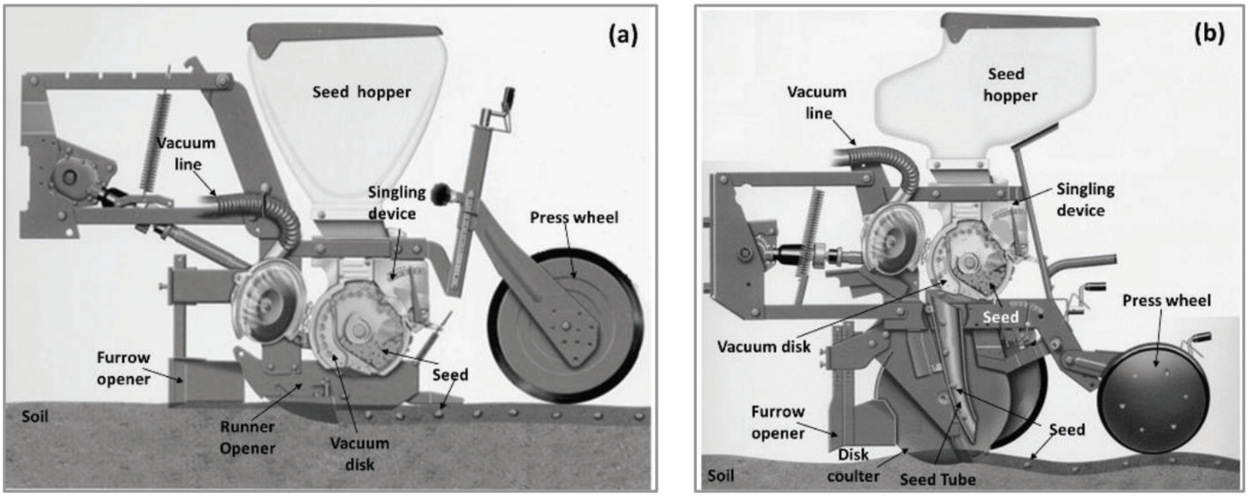

Figure 1. Seeding system (a) seeder with runner type opener (Gaspardo, 2007a) and (b) seeder with disk type opener (Gaspardo, 2007b) (courtesy of Gaspardo-Maschio).

worn tubes and round-type corn seeds had better seed spacing accuracy than the flat type.

Yazgi (2016) conducted a study to find the effects of seed tubes on seed spacing uniformity. A precision metering unit for corn was used with 5 seed tube treatments comprising no seed tube and 4 different seed tubes in different alternative designs. Statistically significant differences were found in all 5 seed spacing parameters due to the use of various seed drop tube treatments. The study pointed out that the design of the seed tube was important and the seed tube geometry had a significant impact on seed spacing uniformity.

Yazgi et al. (2017) aimed to develop prediction performance functions and determine the seed releasing characteristics of seed meter disks based on the metering rate and pitch angle at different levels using corn seeds of 2 different shapes. Seed release characteristics determined at the seed tube outlet of interest included the side and rear angles, and time between the seeds. Based on the experimental results, the maximum side angle ranged from 33.5 to 48.3° for the flat seed disk and 33.4 to 47.6° for the round seed disk. The maximum rear angle ranged from 5.1 to 15.1° for the flat seed disk and 6.4 to 17.6° for the round seed disk. The maximum time between seeds varied from 0.120 to 0.297 s for the flat seed disk and 0.088 to 0.248 s for the round seed disk. Model equations were also developed to predict the quality of feed index, side and rear angles, as functions of metering rate, and the pitch angle.

Taylor et al. (2015) conducted a study on the seed orientation of corn under field conditions. They applied 3 different seed rates and orientation degrees. They found that the plot level yield did not provide an advantage for orienting the corn seed at planting. However, the by-plant regression showed some potential advantage, but the seed and leaf angles parameter estimates were in direct conflict.

Computational fluid dynamics (CFD) is a method that is commonly used for the determination and improvement of product performance in the design and manufacturing of final products with optimal performance. Providing the lowest number of prototype productions for the tests, and decreasing investment and time requirements are considered the primary advantages of CFD applications. Studies conducted using the CFD method in seeding are limited, and these studies are specifically focused on multi grain flow in the seed metering unit.

Lei et al. (2016) used the discrete element method (DEM) and CFD coupling approach to investigate gas-solid flow in a seed drill equipped with a seed feeding device comprised of an air-assisted centralized metering seeding system. The effects of the throat area, throat length, airflow inlet velocity, and seed feed rate were studied and analyzed in terms of the gas field and seed movement. They used rapeseed and wheat and found that the increase in the throat area resulted in a decrease in seed velocity and pressure loss at a certain range. Seeds moved slowly and generated the phenomenon of bounce and concentration for low airflow inlet velocities. When the airflow inlet velocity was increased, resultant force and seed velocity developed.

Bayati and Johnston (2017) investigated the clustering effect of seeds to improve the future air seeder design using the DEM-CFD approach. The clustering effect was found to be largely due to obstructions in the flow, causing the seeds to drop into Geldart's spouted bed fluidization regime, resulting in periodic bursts of seeds after localized pressure build-up. They also compared simulation-based and experimental results and found that the results were in good agreement.

Han et al. (2018) conducted a study to simulate the gas-solid flow in an inside-filling air-blowing maize precision seed-metering device using the DEM-CFD coupling approach. In their study, effects of the positions, the width, and the average arc length of the lateral hole were examined and analyzed in terms of the gas field and seed movement.

The results of the CFD-based studies stated above showed that the DEM-CFD coupling approach was a reliable instrument for simulating the physical phenomenon of seed movement in a seed metering unit.

Beyond the limited number of studies on seed tubes, researchers have generally investigated machine performance using standard seeders by changing the seed varieties or operational parameters (vacuum pressure, forward speed, seed spacing, etc.), while CFD-based seeding studies have focused on gas-solid multigrain flow and seed movement in a seed metering unit.

The objective of this study was to compare CFD-based simulations and visualized seed trajectories in different seed tubes that can provide seed incorporation into the soil with enhanced seed spacing. The other objective was to determine the relation between the seed trajectories and peripheral speed of the vacuum disk.

2. Materials and methods

Seed tubes in disk-type precision seeders may have different shapes and curvatures, and be made out of different materials, along with different accessories, as provided by manufacturers. The properties of the seed tubes used in this study are tabulated in Table 1.

Two different seeds (corn and cotton) and spherical material (Ø10 mm) were released by free fall into the semitransparent seed tubes (seed tubes A and B) from different release points, and the seed trajectories were recorded from the side and back view using video camera with a resolution of 12 MP, frame rate of 30 fps and 16 bits. Physical properties of the seeds and spherical material are given in Table 2.

The seed release points, marked on cardboard, were used for guiding and releasing the seeds from the same point. The release points were chosen as 4 corner points (C1–C4), 4 midpoints (M1–M4), and the center (C) of the seed tube entry, as depicted in Figure 2. Each seed release was triplicated.

The seed tubes used in the experiments were also modeled using the SolidWorks CAD program (Waltham, MA, USA). The release of the seeds and the artificial spherical material into the seed tubes was simulated and analyzed using CFD ANSYS Fluent 16.2 (Canonsburg, PA, USA) software (ANSYS, 2016). The modeled and meshed seed tubes are given in Figure 3. The number of nodes and elements in this mesh structure were more than 6.8×10^5 and 1.3×10^5, respectively, for seed tube A, and more than 8.7×10^4 and 2.5×10^4, respectively for seed tube B.

The flow can be described by the mass and momentum conservation equations. In the Newtonian, incompressible, and steady-state flow conditions, the density of the fluid is the constant, and the conservation of the mass, or continuity equation, is defined as:

$$\nabla \cdot \mathrm{v}=0 \tag{1}$$

Similarly, an incompressible Newtonian fluid with constant viscosity, in the vector notation of the Navier-Stokes equations, is defined as:

$$\rho\left(\frac{\partial \mathrm{v}}{\partial t}+(\mathrm{v}\cdot\nabla)\mathrm{v}\right)=-\nabla p+\rho \mathrm{g}+\mu\nabla^2\mathrm{v} \tag{2}$$

In Eqs. (1) and (2), ∇ is the vector operator ($\nabla=\partial/\partial x+\partial/\partial y+\partial/\partial z$), p is the mean velocity vector (ms^{-1}), r is the density of the fluid (kgm^{-3}), p is the static pressure (Pa), g is the acceleration of the gravity vector (ms^{-2}), and m is the viscosity of the fluid (Pa s) (White, 2001; ANSYS, 2016).

Table 1. Technical properties of seed tubes used in the study.

Technical properties	Seed tubes			
	A		B	
Material	Plastic		Plastic	
Vertical height of the seed tube (mm)	400		380	
Length of the seed tracing where the seed slides (mm)	420		415	
Cross-section of the outlet (mm^2)	1100		900	
Seed tube release angle (°)	53		59	

Table 2. Physical properties of the seeds and artificial material.

Physical properties	Seeds		
	Corn	Cotton	Spherical material
Length (l, mm)	10.7	8.2	Ø = 10 mm
Width (w, mm)	7.8	4.7	
Thickness (t, mm)	6.2	4.1	
Sphericty (Φ, %) ($\Phi = \frac{\sqrt[3]{lwt}}{l} \times 100$)	75.0	65.9	100.0
Thousand seed weight (m_{1000}, g)	343.75	90.55	490.75
Projected area (A_p, mm^2)	17.29	7.38	78.50
Geometric mean particle diameter (D_p, mm) ($D_{p=}\sqrt[3]{lwt}$)	8.03	5.41	10.00
Dimensions of the seeds were measured with a caliper at an accuracy of ±0.1, for a total of 10 samples, and each sample that consisted of 100 seeds was weighed for determination of the thousand seed weight, while 100 seeds were scanned and used to calculate the projected areas using UTHSCSA Image Tool version 3.0.			

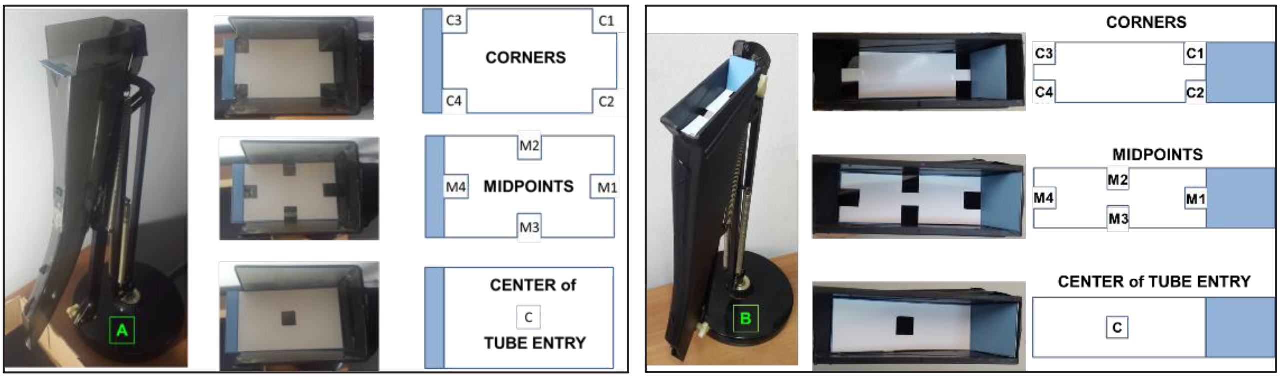

Figure 2. Seed release points for A- and B-type seed tubes.

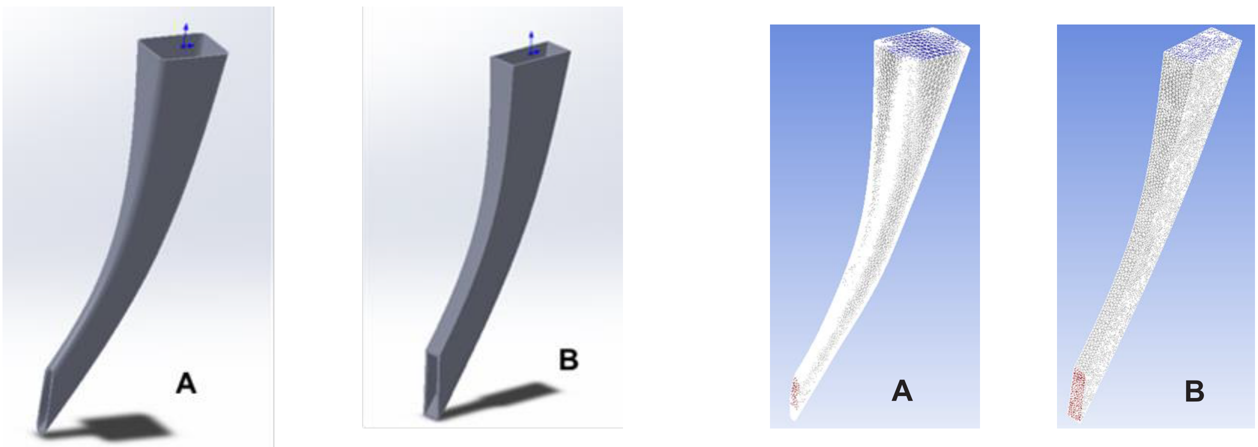

Figure 3. Modeled and meshed seed tubes.

The trajectory of the seeds in 2 and 3 dimensions, elapsed time in the seed tube, and velocity of the seeds were determined in the simulations. The results obtained from the experiments and simulations were compared to determine whether or not they were in harmony with each other.

In the ANSYS Fluent analysis, the fluid was chosen as air, and it was assumed to be incompressible and viscous. The gravity effect was also considered. The inlet boundary condition was set as the seed initial velocity of 0.1 ms^{-1} in order to eliminate the convergence issue in the simulations, and the outlet boundary condition was set as the outflow (outlet flow rate weighting 1). Surface roughness height was not considered because of the quite low roughness height of the plastic producing material. In the CFD simulations, the Reynolds stress model, semi-implicit pressure-linked equation salgorithm, second-order upwind, and discrete phase model (DPM) were utilized, and it was assumed that the seeds were released from seed tube one after another. The solution convergence accuracy was accepted as 1×10^{-5}. The DPM reflection coefficients and reflect type were accepted as polynomial (normal = 0 and tangent = 1) for the wall sections for the DPM model conditions.

Additionally, the corn seeds were released from a vacuum-type metering unit equipped with a completely semitransparent seed tube (type A) at 3 different peripheral speeds during the sticky belt tests (Figure 4). The seed plate, with a pitch diameter of 190 mm, with 36 holes and a 4-mm hole diameter, were used in the experiments. The seed spacing was set to 140 mm.

Some experiments prior to those simulated in the CFD were performed and based on these experiments; the release point of M4 that caused the least bouncing was chosen to determine the effect of the releasing point on the seed trajectory.

The seed tube was positioned under the metering unit, so that the seeds were released from the M4 point of the tube. The metering unit was run at 3 different forward speeds and videos were recorded to compare the trajectories with those obtained from the CFD simulations.

The seeding system, which included the seed tube and environment in which the seeds could be moved, was modeled (Figure 5) using SolidWorks. The system was meshed, simulated, and analyzed using ANSYS Fluent 16.2. All of the simulations were performed similar to the method described above.

While travelling in the tube, the seed met the air first, and then dropped onto the soil surface as it was influenced by environmental factors. This was the other critical point; to determine the boundaries for the simulations. In this evaluation process, the trajectory of the seed andparticle residence time in the seed tube were determined using simulations and experiments under working conditions.

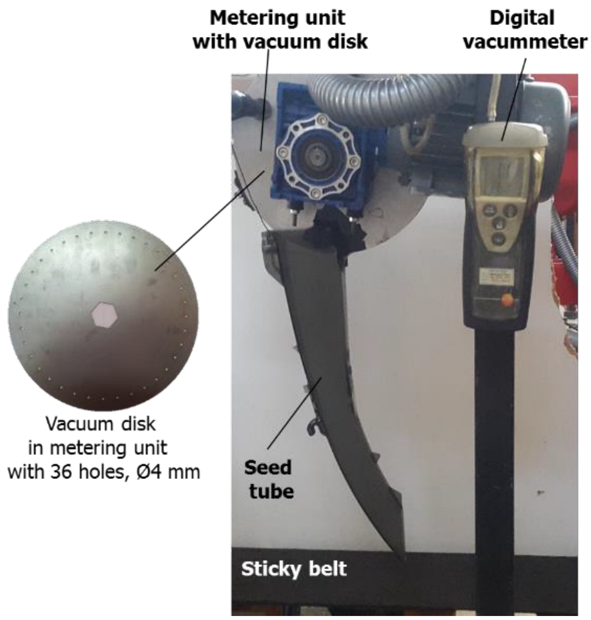

Figure 4. Sticky belt test stand.

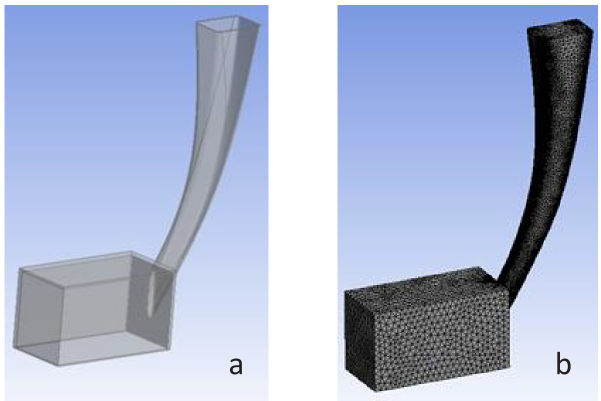

Figure 5. Modeled (a) and meshed (b) views for the combination of the seed tube and environment.

The experiment and simulation results were also compared to determine whether or not they were in good agreement.

One of the important issues in the seed trajectories in seed tubes is vibration, since the level of vibration during field operations will change the seed trajectory. However, in this lab-based study, this variable was not considered.

Precision planter forward speeds of 1.0, 1.5, and 2.0 ms^{-1}, which correspond to the peripheral speeds of 0.14 ms^{-1} (13.7 rpm), 0.21 ms^{-1} (20.5 rpm), and 0.28 ms^{-1} (27.4 rpm) of the vacuum disk, were applied for both the simulations and sticky belt tests. The vacuum pressure for holding the seeds in the hole in vacuum disk was provided by the fan driven by the power take-off of the tractor. The vacuum pressure was kept at 6.0 kPa for all of the tests. The sticky belt and vacuum disk were driven separately, and special care was taken to provide synchronization of the forward and belt speeds.

3. Results and discussion

The results obtained from the comparison of the CFD-based simulations and visualized seed trajectories in the seed tubes are given under different headings below.

3.1. Results of the experiments and simulations for the seeds release from the center of the tube entry (C)

The visualized seed trajectory was developed as a picture by cutting and combining the snapshots of the video recording of a seed chosen randomly in the seed tube. The comparison of the CFD-based simulations and visualized seed trajectories in the seed tubes are depicted in Figures 6–8 for the corn, cotton, and spherical material, respectively.

Based on the results, it was found that the seed tube geometry affected the seed trajectory. In seed tube B, all of the seeds met the sliding side of the seed tube earlier when compared to seed tube A. At that point, all of the seeds had a bounce, with at least 1 bounce before the seeds left the tube. The bounce point was similar in the experiments and simulations for each seed tube (Figures 6–8). Moreover, the seed trajectories were also similar for all of the seeds in the same seed tube, even though the physical properties of the seeds were different (Figure 9). The seeds skated depending upon the curvature of the seed tube.

3.2. Results of the seed release from the corners (C1–C4)

Based on the detailed analysis of the experiments and CFD simulations, it was found that the seed release from different corner points varied the seed trajectories. However, the seed released from the same point had a similar trajectory for the corn, cotton, and spherical material when the same seed tube was used (Figure 10).

The results showed that release points C1 and C2 caused symmetrically similar trajectories for all of the seeds in the same seed tube. Release from points C3 and C4 also resulted in symmetrically similar trajectories. This finding is depicted in Figure 11, using the example of the spherical material results for seed tube A. Moreover, the trajectories obtained from the simulations were in harmony with the captured videos. The experimental and CFD simulation results of the spherical material released from center points C1 and C3 are given as examples in Figures 12 and 13, respectively. Based on the results, when the seeds were released from points C1 or C2, they skated on the bottom side of the seed tube without any bouncing (Figure 12). However, for points C3 and C4, the seeds first landed on the skating side of the seed tube and bounced, and then skated (Figure 13). This bouncing caused a change in the trajectory of the seeds.

3.3. Results of the seed release from the midpoints (M1–M4)

Similar to the results obtained for the seed release from the corner points, it was found that, while different seeds released from the same point in the same tube had similar trajectories, the seed bouncing point changed when the curvature and geometry of the seed tube changed (Figure 14). Different midpoints caused different seed trajectories (Figure 15). Moreover, the trajectories were found to be in good agreement once the experiments and CFD simulations for each seed tube were compared (Figure 16).

Based on the results, when the seed was released from point M1, it skated on the bottom side of the seed tube without any bouncing (Figure 15). However, for points M2–M4, the seed had at least 1 bounce (Figure 13), and this bouncing resulted in a change in the trajectory. This finding is important because when the seed has a bounce, it may cause a change in trajectory, and when the trajectory changes, it may cause a change in the seed residence time in the seed tube. When the residence time varies for any seed in the tube, this may cause a change in the seed spacing. As a result, point M1 may be suggested as the appropriate point that provides the best seed spacing.

The results showed that releasing points M2 and M3 caused symmetrically similar trajectories for all of the seeds in the same seed tube. This finding was supported by the back view videos (Figure 17). Moreover, the trajectories determined in the CFD simulations and experiments were also in good agreement, as seen in Figure 17.

3.4. Results obtained from thes ticky belt tests

In the experiments, seed tube A was used and release point M4, which caused the least seed bouncing, was chosen to determine whether or not the trajectories varied at different forward speeds of the vacuum-type precision seeder (1.0, 1.5, and 2.0 ms^{-1}).

The results of the simulations (Figure 18) and captured videos (Figure 19) were compared, and it was found that they were very similar in terms of the seed trajectory at different forward speeds for the corn seeds. The similarity of the contact point of a seed on the sticky belt in the simulations and experiments supported this finding (Figures 18 and 19).

The results of the simulations and captured videos, in terms of the residence time of the corn seeds in the seed tube, were found to be similar. The residence time decreased as the forward speed increased (Figures 20 and 21). From the captured videos, the residence time of the seed in the seed tube was observed as 0.195, 0.190, and 0.185 s at forward speeds of 1.0, 1.5, and 2.0 ms^{-1}, respectively, while these values were 0.228, 0.223, and 0.216 for the simulations. Based on the forward speed variation, the

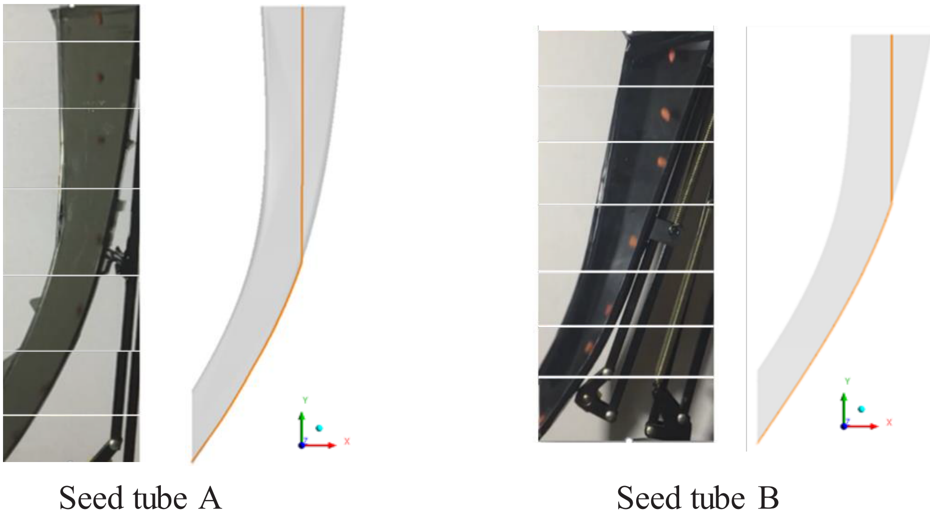

Figure 6. Trajectory of the corn released from the center point (C) in seed tubes A and B.

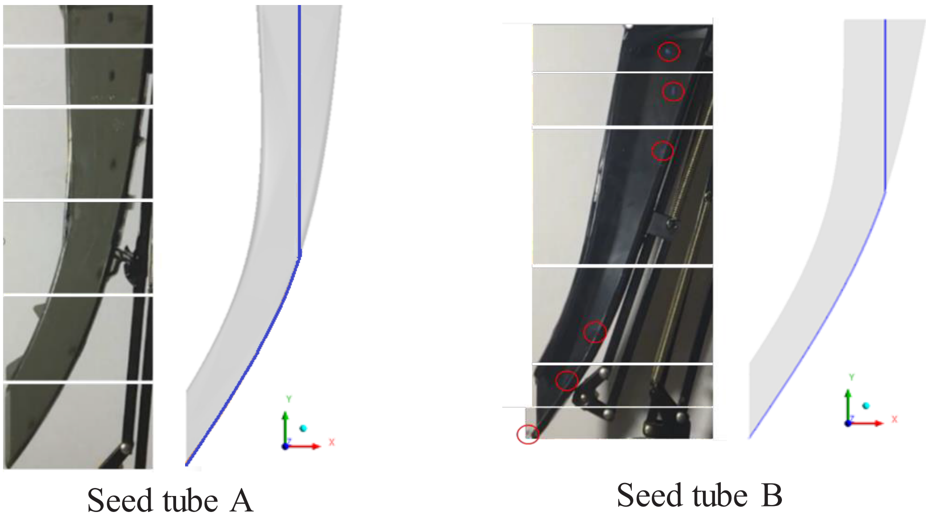

Figure 7. Trajectory of the cotton released from the center point (C) in seed tubes A and B.

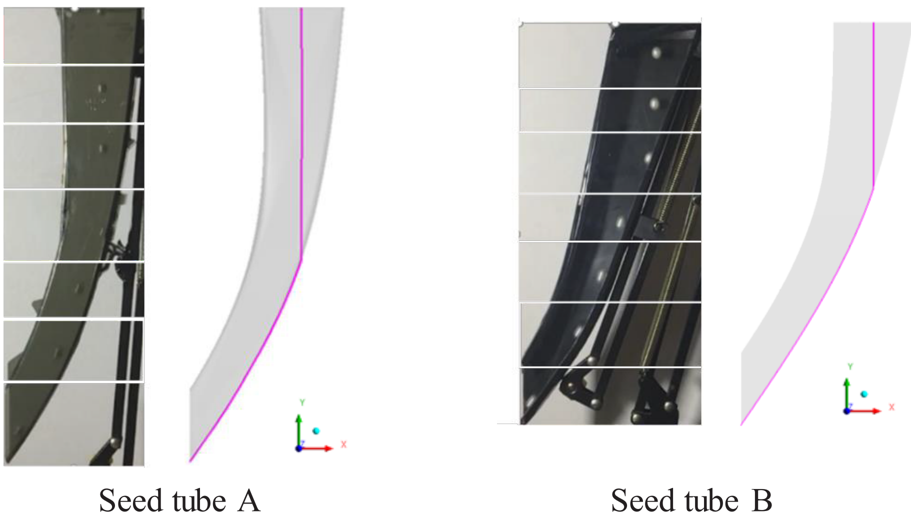

Figure 8. Trajectory of the spherical material released from the center point (C) in seed tubes A and B.

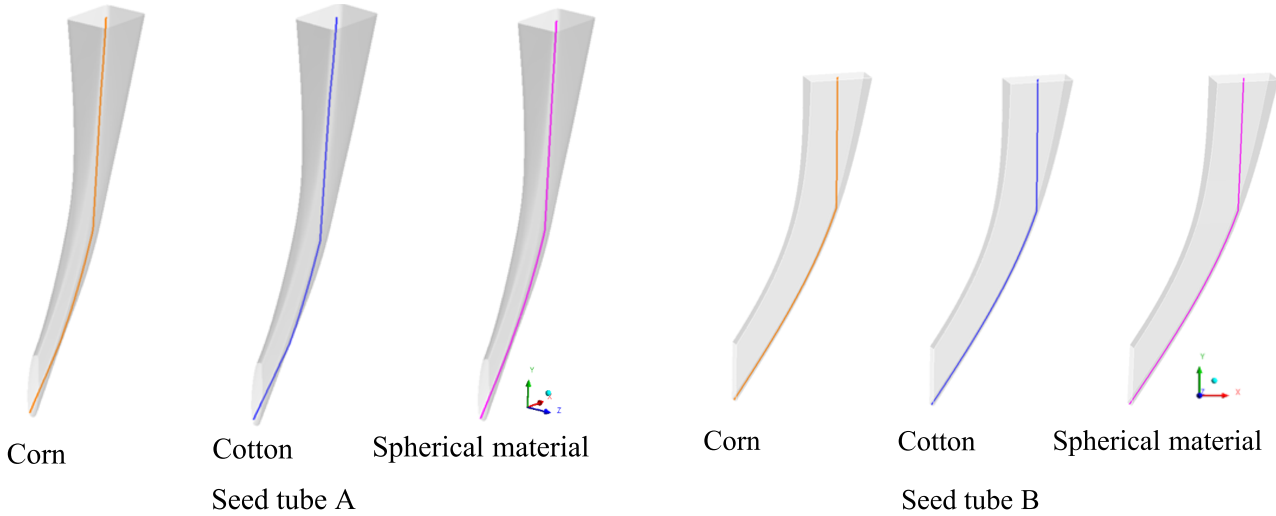

Figure 9. Trajectory of the center point (C) in seed tubes A and B in perspective views.

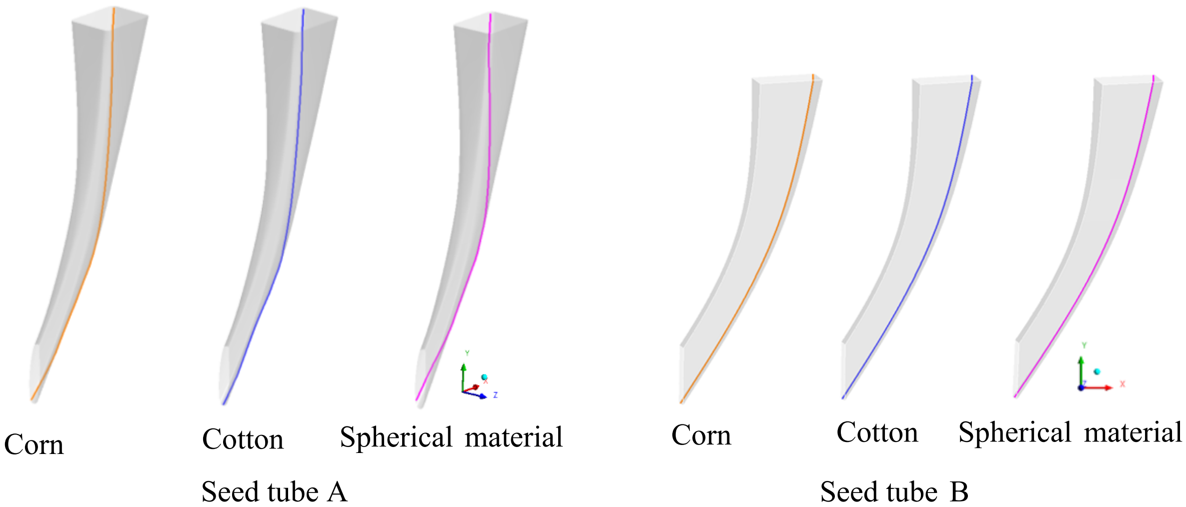

Figure 10. Trajectories of the corn, cotton, and spherical material for the corner point of C1 in seed tubes A and B.

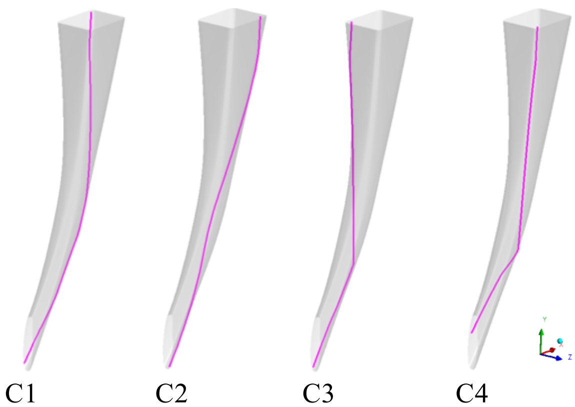

Figure 11. Trajectory variation on the corner points of C1–C4 in seed tube A for the spherical material.

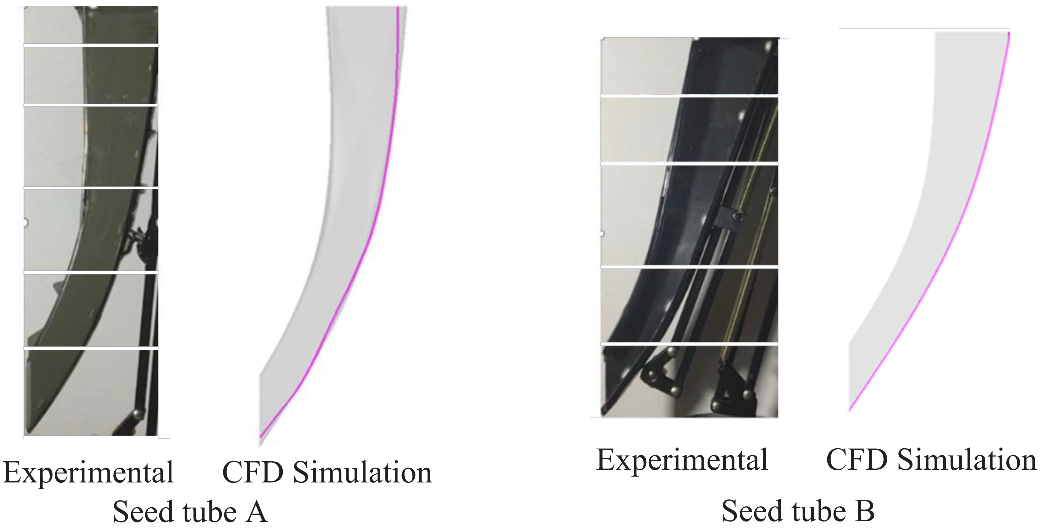

Figure 12. Experimental and CFD simulation trajectories of the spherical material on the corner point of C1 in seed tubes A and B.

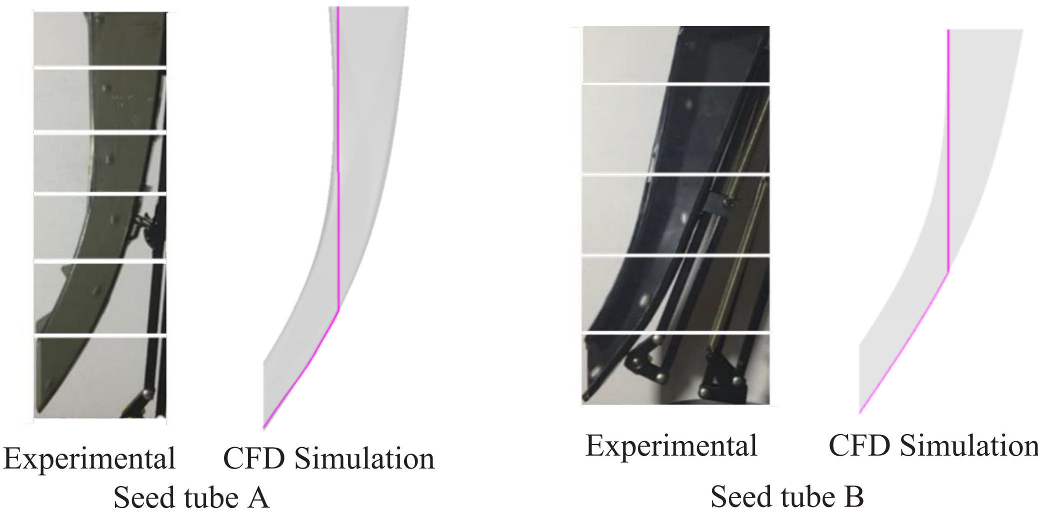

Figure 13. Experimental and CFD simulation trajectories of the spherical material on the corner point of C3 in seed tubes A and B.

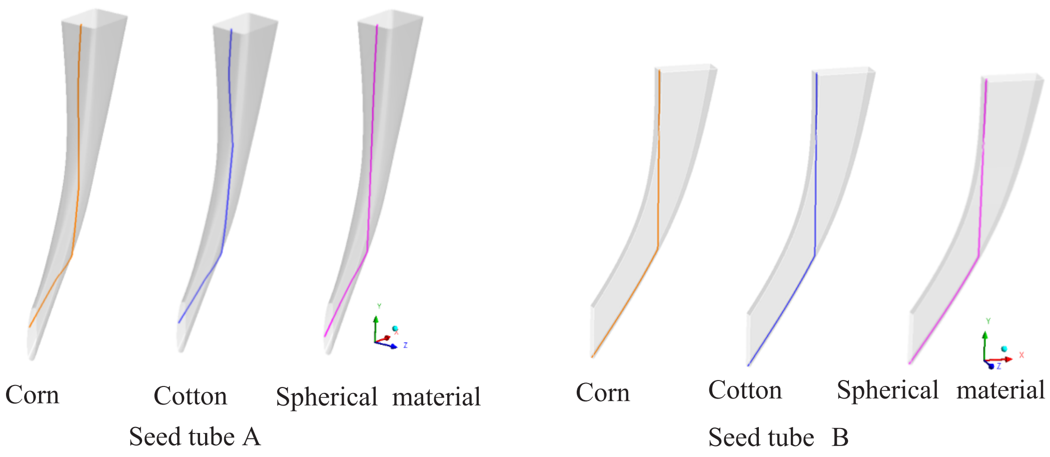

Figure 14. Seed trajectories of the corn, cotton, and spherical material released from the midpoint of M4 in seed tubes A and B.

differences between the captured videos and simulations were similar. The differences in the residence time between the experiments and simulations were approximately 17%.

The seed spacings were also measured on the sticky belt and the results are tabulated in Table 3. The measurements were conducted from a 10-ml ength of the belt. Based on the results, when the forward speed increased, the seed spacing increased, whereas the seed spacing accuracy decreased.

The comparison of the experimental and CFD simulation results of the free fall of the seeds showed that the releasing point was an important parameter for the seed trajectory, and the trajectories were similar for all of the seeds released from different points in the same seed tube.

The sticky belt test results showed that the residential time of the seeds varied based on the releasing point and peripheral speed of the vacuum disk. The residential time of the seed variation affected the seed spacing.

The CFD-based simulations and visualized seed trajectories in the seed tubes were similar. As a result, it could be said that CFD is a useful method for the determination of the seed trajectory in a seed tube. The appropriateness of CFD usage in the seeding phenomena has also been reported in other studies (Lei et al., 2016; Bayati and Johnston, 2017; Han et al., 2018).

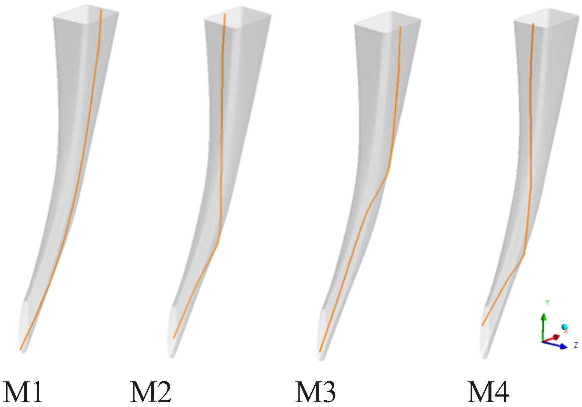

Figure 15. Trajectory variation for the corn seeds released from the midpoints of M1–M4 in seed tubes A.

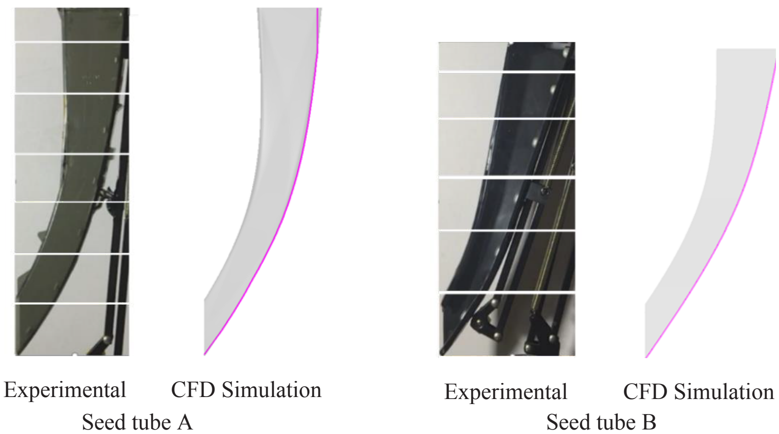

Figure 16. Comparison of the experimental and CFD simulation trajectories of the spherical material released from the midpoint of M1 in seed tubes A and B.

Table 3. Seed spacing results of the corn at different forward speeds on the sticky belt.

Forward speeds (ms^{-1})	1.0	1.5	2.0
Seed spacing (cm)	14.5 ± 0.2	15.0 ± 0.4	17.1 ± 0.6

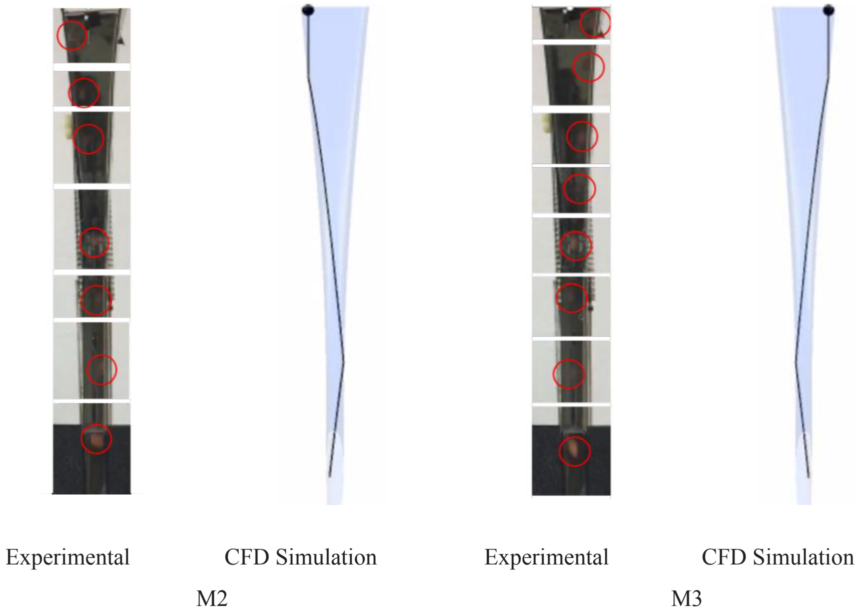

Figure 17. Trajectory variation between the midpoints of M2 and M3 in seed tube A from the backside view.

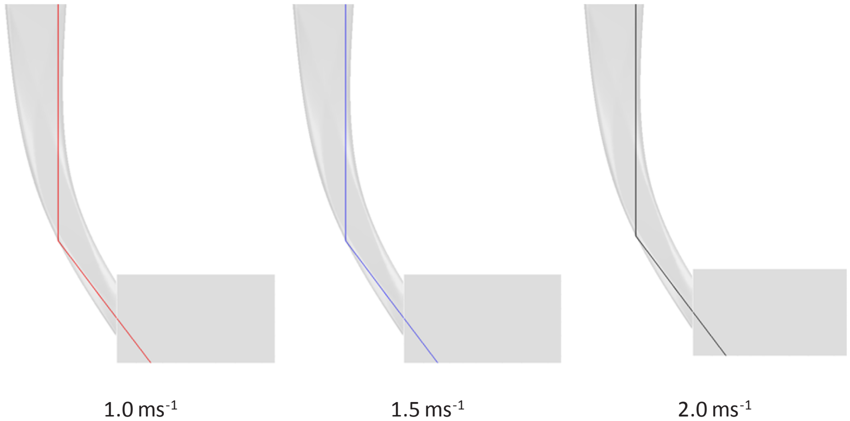

Figure 18. Seed trajectories at different forward speeds in the CFD simulations.

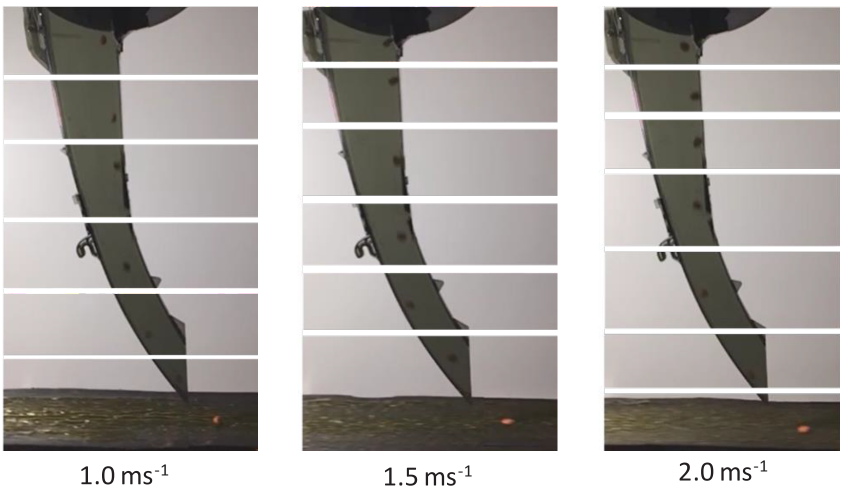

Figure 19. Seed trajectories at different forward speeds in the experiments.

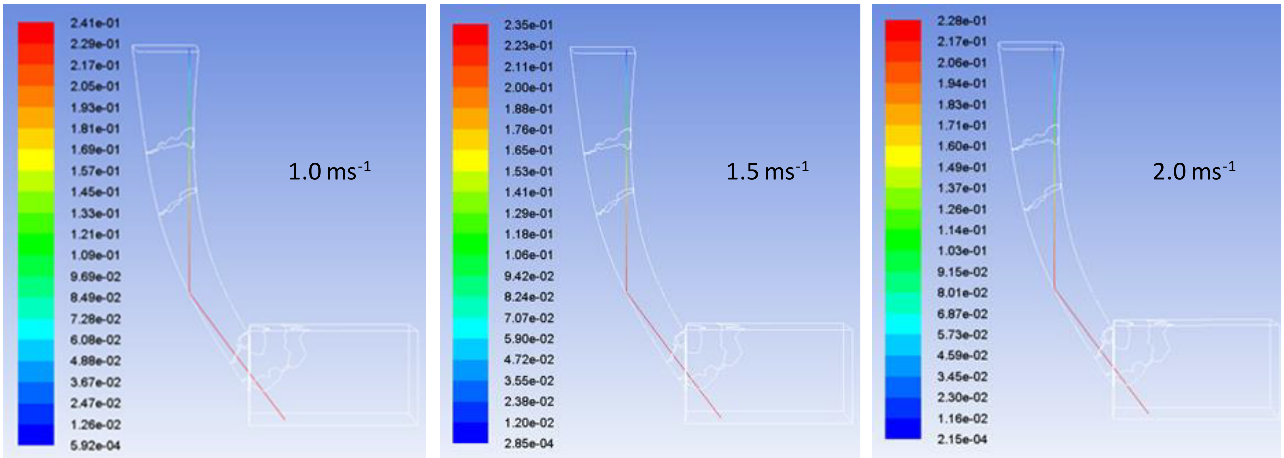

Figure 20. Residence time variation at different forward speeds in the simulations.

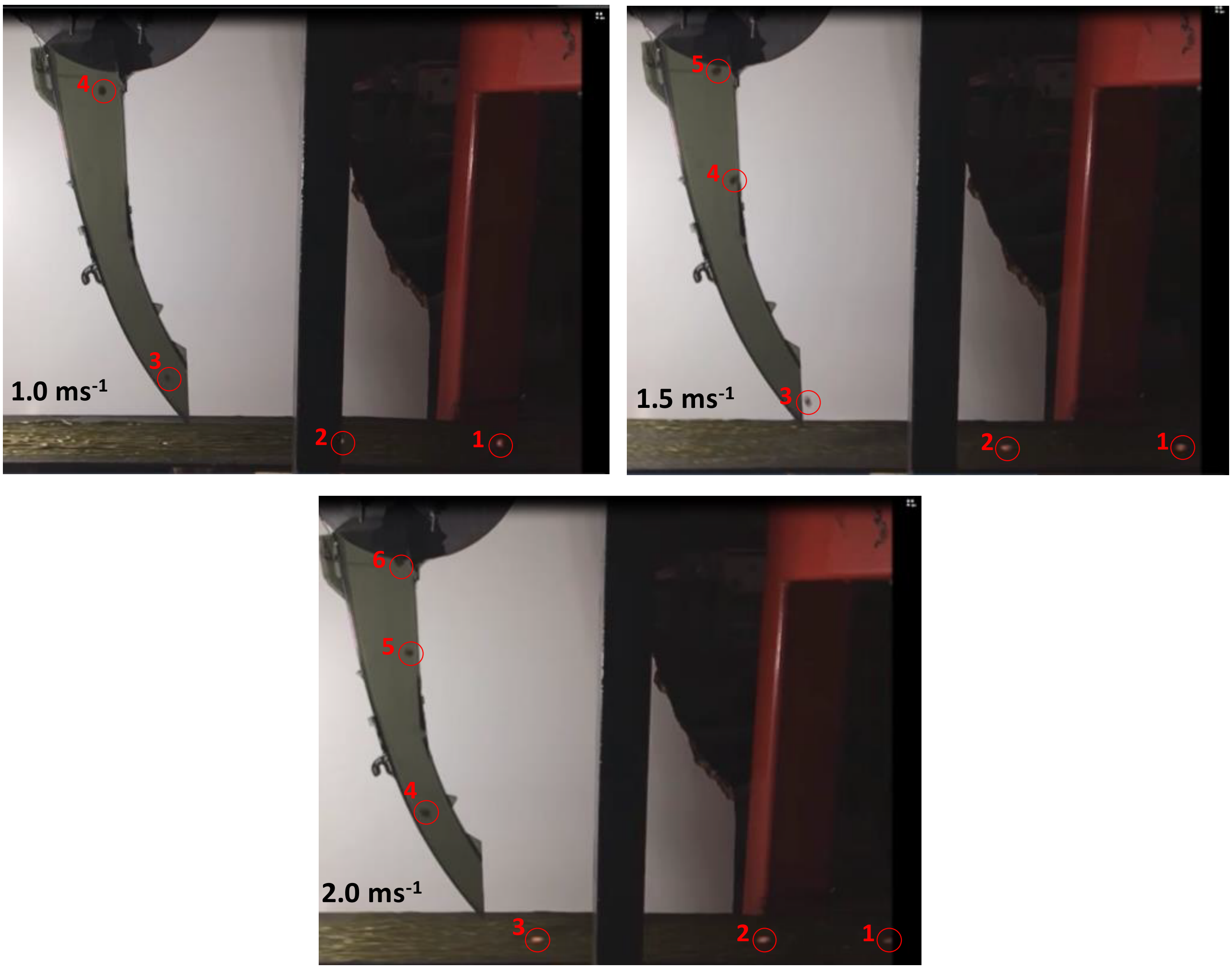

Figure 21. Residence time at different forward speeds and effects on the seed spacing.

4. Conclusion

The following conclusions can be drawn from the study conducted:

· Seeds follow the same path (similar trajectories) if they are released from the same point.

· The seed release point is an effective parameter that causes bouncing.

· Bouncing results in variations in the seed trajectories.

· The appropriate release point was found to be the midpoint (M1).

· Seed tubes should have a certain curvature that provides a trajectory for the seed without bouncing.

· The seed trajectories for cornwere similar in the sticky belt tests and CFD simulations at different forward speeds.

· The residence time decreases as the forward speed increases, and this was proven to be the case in both the simulations and sticky belt tests.

· It is believed that CFD simulations can be further used to develop new seed tubes that optimize seed trajectory and seed spacing.

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