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Study of raw cotton and fine debris movement in a pneumatic conveying system and reduction of impurity concentration in bunker cotton

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Abstract

This article analyzes the movement of raw cotton and small debris in the pneumatic conveying system used by cotton pickers. The numerical study was conducted using the Ansys Fluent software package, which offers extensive turbulence modeling capabilities, including RNG k- ϵ , SST k- ω , LES, and other models. These features allow for a detailed examination of the turbulent fluctuations affecting particle trajectories. The numerical calculations revealed that when small debris approaches cotton bundles, some particles cling to and penetrate deeply between the cotton fibers, while others bend around the cotton bundles and continue moving. The study's results indicate that to reduce the contamination of raw cotton with small debris during its passage through the pneumatic conveying system, it is advisable to lower the debris concentration in the air-cotton mixture. Furthermore, it was found that using a U-shaped receiving chamber in the pneumatic conveying system significantly decreases the concentration of cotton debris in the air, leading to a 20–25% reduction in impurities in the bunker raw cotton collected by a vertical spindle cotton harvesting machine.

Keywords: Concentration, Cotton contamination, Pneumatic transport system, Raw cotton, Saturation.

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Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Institutional Review Board Statement: Ethical approval was not required for this study, as it involved the use of a pneumatic transport system to convey cotton to the hopper of a cotton harvester. Therefore, the study only involved inanimate objects.

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1. Introduction

Globally, raw cotton is harvested by cotton pickers. An important requirement for harvesting raw cotton with cotton

pickers is ensuring that the harvested cotton contains no more than 10% impurities, in accordance with state standard GOST UzDst 6152008.

Modern cotton pickers are generally equipped with spindle-type working elements that rotate at high speed and extract cotton fibers from the ripe cotton bolls. As the machine moves through the rows of plants, the spindles penetrate the bolls and wind the cotton fiber around themselves, after which special cleaning discs (doffers) remove the collected cotton from the spindles [1, 2]. The collected cotton is then directed into a conveying system inside the machine, where it is transported to a storage bunker.

One important design feature of modern cotton pickers is the pneumatic cotton conveying system. After separation from the spindles, the cotton enters an airflow generated by fans and is transported through a system of air ducts to the machine's bunker or pressing device [3]. This method of transport ensures the continuous movement of cotton pulp from the working parts to the machine's storage device and significantly reduces the risk of mechanical damage to the fiber and seeds [4].

In the pneumatic conveying system of a cotton picker, airflow serves as the transport medium, moving the air-cotton mixture through the pipelines. The efficiency of cotton transport depends on the airflow velocity, the geometry of the air ducts, and the physical and mechanical properties of the cotton mass. For stable cotton transport, it is necessary to maintain sufficient airflow velocity to prevent clogging or fiber accumulation in the pipelines [5].

However, along with its advantages, mechanized cotton harvesting also has several technological features that affect the quality of the harvested cotton. During the operation of cotton harvesting machines, various plant residues, including leaves, boll parts, stem fragments, and dust, enter the transport system along with the raw cotton. These impurities with cotton, form an air-fiber mixture, which moves through the machine's pneumatic conveying system and enters a storage bunker [6]. The content of foreign matter in mechanized cotton harvesting can vary significantly depending on the condition of plants, the ripeness of bolls, weather conditions, and the technical condition of the harvesting equipment. Research shows that the concentration of foreign matter in cotton harvested by machines can be higher than in manual harvesting, increasing the burden on subsequent cleaning and processing operations [7].

Furthermore, during the transport of cotton within the machine, small foreign matter particles can migrate along with the cotton mass and penetrate the structure of the fibrous material. Aerodynamic forces acting on particles of varying mass and shape lead to differences in their trajectories and settling conditions. Small impurities can readily be captured by the airflow and transported with the cotton to the machine bunker, thereby increasing contamination of bunker cotton [8].

Research shows that the interaction of cotton fibers and small impurities in the airflow of a pneumatic conveying system can lead to the penetration of impurity particles into the cotton pulp. As a result of this process, impurity particles can accumulate within the raw cotton mass, increasing its contamination and complicating subsequent cleaning of the raw material at ginning plants [9].

An additional factor influencing cotton contamination concentration is the design of the receiving chamber and air ducts of the cotton picker's pneumatic conveying system. Imperfect design of individual system components can lead to the suction of contaminated air and the introduction of additional debris into the flow of transported material [10]. Therefore, modern research focuses on improving the design of fans, receiving chambers, and air ducts to ensure efficient transportation of raw cotton with minimal impurity content [11].

Thus, the processes of mechanized harvesting of raw cotton and its transportation within the cotton picker are interconnected stages of the technological cycle. Cotton, extracted from the bolls by the machine's working parts, is transported to the bunker via the pneumatic conveying system, where an air-fiber mixture of cotton and various impurities is formed [12].

Given the increased contamination of machine-harvested cotton and the specifics of its airflow transport, studying the patterns of raw cotton and small debris movement in pneumatic conveying systems is particularly relevant. Such studies enable us to determine the conditions under which it is possible to reduce impurity levels in the transported material and reduce contamination of bunker cotton [13].

Comprehensive study of the movement of raw cotton and debris in the airflow of a pneumatic conveying system is an important area of research aimed at increasing the efficiency of cotton harvesting machines and improving the quality of the harvested raw material. New design solutions and optimization of airflow parameters can reduce the contamination level of cotton entering the machine bunker and improve the efficiency of subsequent processing of raw cotton at ginning plants [14-18].

Many authors Kılıçkan and Güner [19]; Rizaev, et al. [20]; Verma and Mathur [21]; Matchanov, et al. [22]; Kerby, et al. [23]; Baker, et al. [24] and Baker, et al. [25] have studied the influence of field conditions and the technical and design parameters of cotton pickers on raw cotton impurity. Experimental studies by the authors of reference [26] revealed that the morphological composition of small debris amounts to 2.05% in the working area, 2.8% in the harvester's transport corridor, and 4.46% in the bunker. This means that the percentage of small debris increases to 50% from the harvester's transport corridor to the bunker. However, the authors have not fully understood the mechanism by which raw cotton is saturated with small debris, which, under the airflow, move from the picking device to the bunker of the harvester. For the first time, numerical simulations based on the Discrete Phase Model (DPM) implemented in ANSYS Fluent have established the governing patterns of interaction between seed-cotton tufts and fine trash particles in a pneumatic conveying system, taking into account turbulent effects. A novel mechanism of seed-cotton contamination by fine trash particles has been identified, characterized by the advanced motion of particles relative to cotton tufts (by a factor of 1.36), which promotes their penetration into the fibrous structure under the action of aerodynamic forces. It has been shown that the trajectories of trash particles are governed by a combination of factors, including turbulent fluctuations, relative phase

velocity, and flow geometry, which explains both the bypassing of cotton tufts and the partial intrusion of particles into the fiber structure. Based on these findings, a new U-shaped receiving chamber has been proposed, ensuring the elimination of contaminated air entrainment from the soil surface and reducing the concentration of trash particles in the air-cotton mixture. Experimental validation demonstrates that the application of the U-shaped receiving chamber reduces the trash content of bunker seed cotton by 20–25%, significantly outperforming conventional designs. Furthermore, new quantitative relationships have been obtained between airflow parameters, phase velocities, and the degree of cotton contamination, which can be utilized in the design of pneumatic conveying systems for cotton harvesting machines.

2. Materials and Methods

Numerical and experimental studies were conducted to study the patterns of small debris penetration into a cotton bunch as they move through the pneumatic conveying system of cotton pickers. Ansys Fluent software package was used to study process optimization.

Recently, software packages such as Ansys Fluent, Star CCM+, Open Foam, Comsol, and others have been used to study process optimization related to Computational Fluid Dynamics (CFD). Therefore, to study the movement of raw cotton and small debris particles, Ansys Fluent, a leading software package in this field, was chosen. It supports the Discrete Phase Model (DPM), allowing for the simulation of particle motion and interaction with a liquid or gas flow. This is particularly useful for problems where particles experience turbulence, collisions, and adhesion.

Fluent provides a wide range of turbulence modeling capabilities, including RNG k-ε, SST k-ω, LES, and other models. These allow for the incorporation of turbulent fluctuations that impact particle trajectories. The Dynamic Mesh feature enables the simulation of moving objects, such as a cotton bundle, which creates realistic interaction scenarios. Additionally, the program allows for the creation of user-defined functions (UDFs) in C++. This feature extends the program's functionality for specific tasks, such as implementing particle adhesion to surfaces, defining complex boundary conditions, and setting non-standard object velocities.

In accordance with the above, we adopt the Shear Stress Transport (SST) turbulence model based on the k-ω formulation with several modifications [27]. SST uses a switching function, F1, which selects the model: k-ω - near the walls and k-ε - in the main flow. This results in a hybrid scheme that improves the accuracy of calculations of complex turbulent flows, including those with flow separation and intense shear layers (Figure 1).

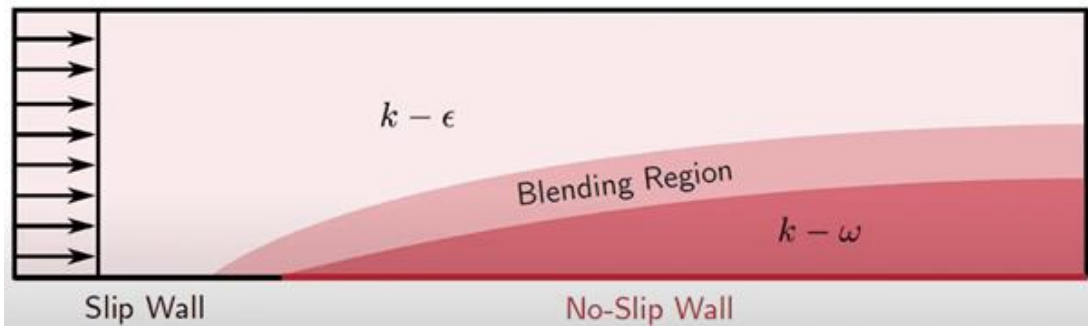


Figure 1.
The SST model switches between k-ω and k-ε turbulence models using a blending function.

Below is the basic two-layer Menter model [28, 29]:

$$\begin{cases} \frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] + P - \beta^* \omega k \\ \frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho U_j \omega)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + \frac{\gamma}{v_t} P - \beta \rho \omega^2 + 2(1 - F_1) \frac{\rho \sigma_{\omega 2}}{\omega} \frac{\partial \omega}{\partial x_j} \frac{\partial k}{\partial x_j} \end{cases}$$

For:

$$P = \tau_{i,j} \left(\frac{\partial u_i}{\partial x_j} \right), \quad \tau_{i,j} = v_t \left(2S_{i,j} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{i,j} \right) - \frac{2}{3} \rho k \delta_{i,j}, \quad S_{i,j} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right).$$

In Menter's model, turbulent viscosity and, consequently, Reynolds stresses are defined similarly to the k-ω model. Menter proposed combining the sets of constants of the two models: the original k-ω model (according to Wilcox) and the transformed k-ε model, using a generalized parameter. Denoting by the generalized parameter φ₁ the set of constants of the original k-ω model with indices 1, and by φ₂ the similar set of constants of the transformed k-ε model, we obtain:

$$\varphi = F_1 \varphi_1 + (1 - F_1) \varphi_2 .$$

The following constants are used: k-ω model constants (Wilcox):

$$\beta^* = 0.09, \beta_1 = 0.075, \sigma_{k1} = 0.85, \sigma_{\omega1} = 0.5, K = 0.41, \gamma_1 = \frac{\beta_1}{\beta^*} - \frac{\sigma_{\omega1} K^2}{\sqrt{\beta^*}}.$$

Model constants of the standard k-ε model:

$$\beta^* = 0.09, \beta_2 = 0.0828, \sigma_{k2} = 1, \sigma_{\omega2} = 0.856, K = 0.41, \gamma_2 = \frac{\beta_2}{\beta^*} - \frac{\sigma_{\omega2} K^2}{\sqrt{\beta^*}}.$$

The weighting function is defined as follows:

$$F_1 = th(\arg_1^4), \arg_1 = \min \left(\max \left(\frac{\sqrt{k}}{\beta^* d \omega}, \frac{500}{d^2 \omega} \right), \frac{4 \sigma_{\omega2} k}{CD_{k\omega} d^2} \right), \quad (1)$$

$$CD_{k\omega} = \max \left(2 \rho \sigma_{\omega2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-20} \right),$$

where d – is the distance to the nearest wall, and $CD_{k\omega}$ - is the stability correction term.

According to Bradshaw's hypothesis, the shear stress in the boundary layer is proportional to the turbulent kinetic energy:

$$\tau = a_1 k \rho, \quad (2)$$

here, $a_1 = const.$

On the other hand, in two-equation models, shear stress is calculated as follows:

$$\tau_{i,j} = H_i \Omega, \quad \Omega = \frac{\partial U}{\partial y}. \quad (3)$$

To match these two approaches, Menter proposed modifying the formula for turbulent viscosity:

$$v_t = \frac{a_1 k}{\Omega}. \quad (4)$$

To extend the model to wall-bounded flows, where Bradshaw's hypothesis may not be fully satisfied, an additional blending function F_2 is used:

$$v_t = \frac{a_1 k}{(a_1 \omega_1, \Omega F_2)}, \quad (5)$$

where:

$$F_2 = th(\arg_2^2), \arg_2 = \max \left(2 \frac{\sqrt{k}}{\beta^* \omega d}, \frac{500}{d^2 \omega} \right). \quad (6)$$

New constants in the inner layer have the following form:

$$\beta^* = 0.09, \beta_1 = 0.075, \sigma_{k1} = 0.85, \sigma_{\omega1} = 0.5, K = 0.41, \gamma_1 = \frac{\beta_2}{\beta^*} - \frac{\sigma_{\omega1} K^2}{\sqrt{\beta^*}}, a_1 = 0.31, \quad (7)$$

in the outer layer, the constants remain unchanged.

The equations in Cartesian coordinates are:

$$\begin{cases} \frac{\partial k}{\partial t} + U \frac{\partial k}{\partial x} + V \frac{\partial k}{\partial y} = \frac{\partial}{\partial x} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x} \right] + \frac{\partial}{\partial y} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial y} \right] + P - \beta^* \omega k \\ \frac{\partial \omega}{\partial t} + U \frac{\partial \omega}{\partial x} + V \frac{\partial \omega}{\partial y} = \frac{\partial}{\partial x} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x} \right] + \frac{\partial}{\partial y} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial y} \right] + \\ + \frac{\gamma}{v_t} P - \beta \omega^2 + 2(1 - F_1) \frac{\sigma_{\omega2}}{\omega} \frac{\partial \omega}{\partial x} \frac{\partial k}{\partial x} + 2(1 - F_1) \frac{\sigma_{\omega2}}{\omega} \frac{\partial \omega}{\partial y} \frac{\partial k}{\partial y} \end{cases} \quad (8)$$

The shape of raw cotton as it moves through the pipeline is based on actual observations during machine harvesting, as illustrated in Figure 2. This figure shows that the cotton bunches travel through the pipeline in an elongated form, maintaining a consistent interval between them. The distance between the cotton plants is 150 mm, which is an essential agronomic requirement for cotton sowing. As a result, raw cotton moves in batches at regular intervals, as observed in flexible, transparent pipelines.



Figure 2.
Raw cotton movement in a flexible transparent pipeline during machine harvesting

Air flow velocity is $V_B = 22\text{m/s}$, raw cotton bunch velocity is $V_x = 16\text{ m/s}$, raw cotton bunch mass is $m = 20\text{ g}$, impurity particle velocity is 21.8 m/s , and impurity particle mass is 1 mg .

3. Results and Discussion

Based on numerical studies, the kinetics of raw cotton and impurity particle movement are shown in Figure 3 (a, b, c, d, e).

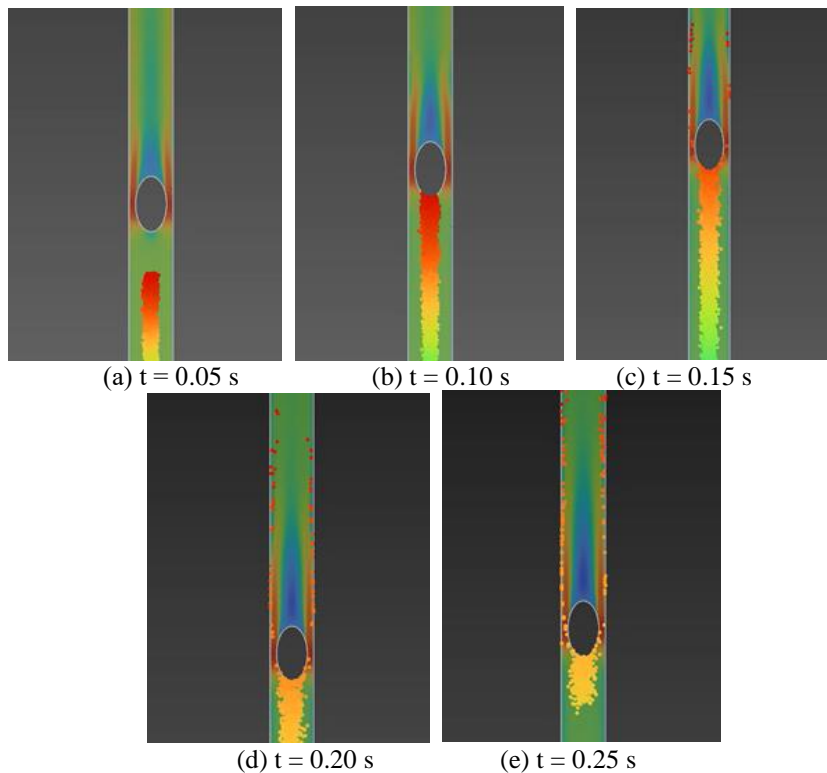


Figure 3.
Movement of raw cotton and impurity particles in a pneumatic conveying system pipeline (red lines show the airflow with impurity particles, and the black ellipsoids show the raw cotton bundles).

The kinetics (Figure 3, b) shows that the impurity particles closely approach the cotton bundle and are then carried by the airflow around the cotton bundle (Figure 3, c, d, e).

Since the speed of small impurity particles moving through the air-cotton mixture in the pipeline is 1.36 times greater than the speed of the raw cotton mass, the impurity particles quickly penetrate cotton fibers, thus saturating raw cotton lobuli with small debris.

To reduce the concentration of small debris in the pneumatic conveying system of the vertical spindle cotton harvester, a U-shaped receiving chamber was developed [30]. Serial and pilot versions of the vertical spindle harvester, shown in Fig. 4, were taken for field testing.

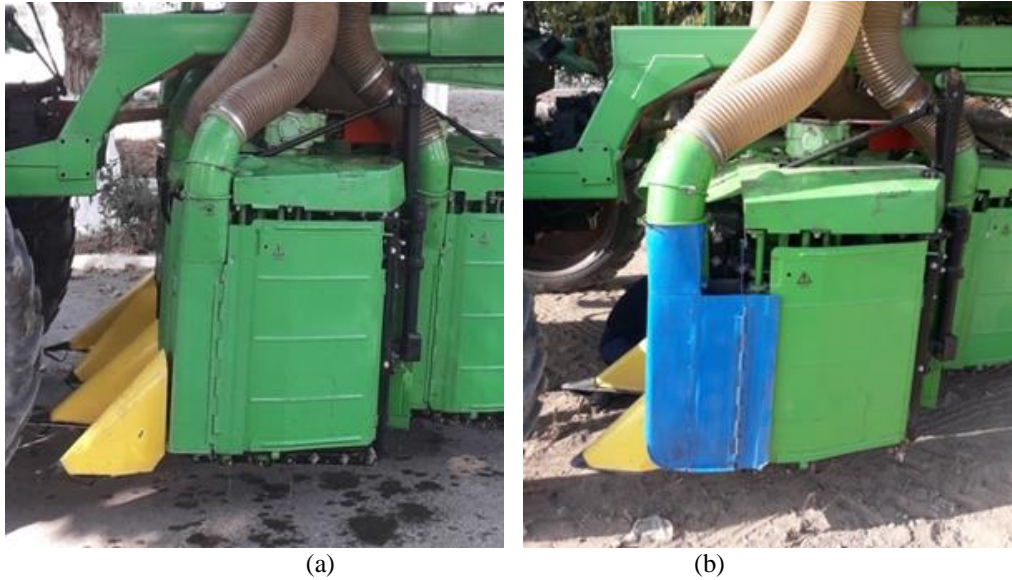


Figure 4. Vertical spindle harvesters with standard (a) and newly developed U-shaped (b) receiving chambers.

It is known that in the standard receiving chamber (Figure 4, a), the lower section is open to allow air to be drawn in. In operating mode, the distance from the bottom of the receiving chamber to the ground surface is 30-50 mm. At this distance, the lower section of the receiving chamber acts like a vacuum cleaner, meaning that debris is sucked up from the ground surface by the receiving chamber, leading to a higher concentration of fine debris in the air-cotton mixture. However, in the new U-shaped receiving chamber (Figure 4, b), there is no air suction of debris from the ground surface.

The harvesting devices, equipped with the standard and new U-shaped receiving chambers, were installed on the MX-1.8 GV cotton picker, shown in Figure 5.



Figure 5. General view of the MX-1.8 GV cotton harvester with the standard (a) and newly developed (b) receiving chambers.

Table 1. Field trial results. Field trials were conducted at a cotton yield of 28 c/ha. The field trial results are presented in Table 1.

Indicators	Standard receiving chamber			New U-shaped receiving chamber		
	30-28	32-28	34-28	30-28	32-28	34-28
Working slit width (mm)	30-28	32-28	34-28	30-28	32-28	34-28
Cotton moisture content, %	8.9	7.6	9.5	7.2	7.4	8.2
Cotton moisture content, %	13.9	11.2	11.5	10.9	10.2	10.0
Cotton moisture content, %	0.2	1.0	0.2	0.4	0.4	0.21

Data obtained from laboratory and field tests show that, with a working slit width of 30-28 mm, the impurity content of harvested raw cotton with standard receiving chambers is 13.9%, and 10.9% with the new receiving chambers.

4. Conclusion

Based on the conducted numerical and experimental studies, it has been established that the intensity of seed cotton contamination in pneumatic conveying systems is largely governed by the concentration of fine trash particles in the air-cotton mixture, as well as by their relative velocity with respect to cotton tufts. It is shown that the advanced motion of particles, identified through DPM-based simulations in ANSYS Fluent, promotes their penetration into the fibrous structure

of cotton under the action of aerodynamic forces, which constitutes the key mechanism of additional contamination. It has been determined that the trajectories and transport behavior of trash particles are controlled by the combined effects of turbulent fluctuations, flow geometry, and phase kinematics, which explains both their bypassing of cotton tufts and their partial intrusion into the fiber structure. It is further demonstrated that reducing the concentration of trash particles in the air–cotton mixture is a decisive factor in minimizing the contamination of bunker seed cotton, which can be achieved, among other approaches, through agronomic measures aimed at improving the efficiency of defoliation prior to mechanical harvesting. The proposed U-shaped receiving chamber, which prevents the entrainment of contaminated air from the soil surface, ensures a significant reduction in the content of trash particles within the flow. Experimental validation confirms that the application of this design reduces the contamination level of bunker seed cotton by 20–25% compared to conventional solutions.

The obtained quantitative relationships between airflow parameters, phase velocities, and the degree of cotton contamination can be effectively utilized in the design and optimization of pneumatic conveying systems for cotton harvesting machines, with the aim of improving the quality of the harvested product.

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