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Development of a Model of the Mechanism of Saturation with Small Impurity Particles of Raw Cotton During Movement in the Pneumatic Conveying System of Cotton Harvesting Machines

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Abstract: This article analyzes the contamination of machine-picked raw cotton. It focuses on how small particles of impurities saturate raw cotton during transportation within the pneumatic conveying system of a cotton harvester. A model was developed to understand how these small impurity particles approach the clusters of raw cotton as they move from the receiving chamber to the harvester's hopper. Using the MathCAD-15 programming environment, we created graphs based on this model. Additionally, another model was constructed to illustrate how small particles penetrate the fiber strands. Numerical calculations conducted with the developed model revealed that an increase in the concentration and mass of these small impurity particles leads to a deeper penetration into the fiber strands. The results from these numerical studies confirmed the reliability of the experimental findings. Based on the analysis, we provide recommendations to reduce the contamination of raw cotton in the hopper.

Keywords: model development, small impurity particles, fiber strands, contamination of raw cotton, air flows, concentration, pneumatic conveying system, programming environment, saturation of cotton segments, numerical studies.

Introduction. One of the most important tasks in machine harvesting is to improve the quality of the collected raw cotton, that is, to reduce its contamination. With an increase in the contamination of raw cotton, the frequency of cotton processing in the ginning industry increases, leading to a rise in the cost of the resulting fiber. In addition, due to the great amount of short fibers, the staple length decreases, also leading to a decrease in the purchase price of the final product.

Mechanical damage to seeds takes the following forms: seeds damaged to the skin, through which the seed kernel is visible (punctures in the skin, shell), seed crushing, and cracking. Mechanical damage to seeds presents an undesirable defect, since when ginning raw cotton, fiber defects increase (seed skins mixed with fibers) and are difficult to clean.

The main task of cotton-harvesting machine designers is to preserve the natural properties of raw cotton during its collection. The inevitable mechanical effects of the working parts of the machines on cotton plants lead to an increase in weed infestation of the crop during machine harvesting. Moreover, the higher the degree of mechanical impact on cotton plants, the higher the weed infestation. The initial weed infestation of raw cotton significantly affects the quality of products in the cotton ginning and textile industries. In this regard, state standards GOST UzDst 6152008 set the maximum contamination level of machine-harvested raw cotton at 10%.

According to GOST, the percentage of mineral and organic impurities is taken into account when determining the contamination level of raw cotton. Mineral impurities include soil, sand, and dust. Organic impurities include particles of leaves, periapts, flowers, boll flaps, stems, and dried, rotten, and brittle pieces of raw cotton with weak fibers. The contamination level of machine-harvested raw cotton is influenced by several factors, including those related to the cotton-harvesting machine and the agricultural background of the cotton field.

Scientists from SAIME, TashPI, TIIIMSH, TITLP, GSKB for cotton-growing machines, IMSS of the Uzbekistan Academy of Sciences, and other institutions studied the contamination of machine-picked cotton. However, the problem of reducing contamination of raw cotton during machine picking has not lost its relevance to this day.

Recently, the authors of references [1 - 14] have published studies related to improving the quality of machine-picked raw cotton.

In [15], the dynamics of changes in contamination of raw cotton during its collection by a harvesting machine and subsequent transportation to a hopper were studied. It was shown that saturation of raw cotton with foreign impurities occurs mainly in the working zone of capturing and extracting cotton segments from bolls (51.98%), when parts of cotton plants collected in the space between the drum shield and the moving surface of the spindle drum enter the hopper (35.59%), and when part of the debris is sucked in by the receiving chambers (11.19%). The authors found that in the morphological composition of debris, the content of small impurities in the working area is 2.05%, in the conveying corridor, it is 2.18%, and in the machine hopper, it is 4.46%.

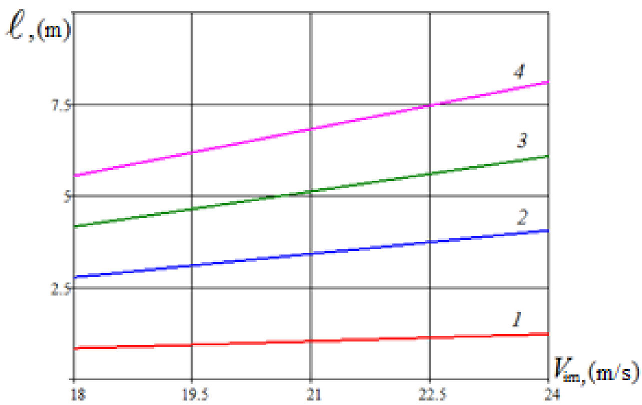
The study aims to develop a model for the approach and penetration of small litter particles into a cotton bunch during movement in a pneumatic conveying system, to conduct numerical studies, and to issue recommendations for reducing the overall contamination of raw cotton.

Materials, methods, and object of study. Calculation and numerical studies of the patterns of approach and penetration of small weed particles into a cotton bunch during movement in a pneumatic conveying system of cotton harvesters were performed. The MathCAD-15 programming environment was used to conduct numerical calculations and plot graphs.

Results and discussions. To determine the approach of cotton pieces with small impurities, we consider the following model [16]:

$$\ell = \frac{(V_a - V_{Sd}) \cdot \Delta\ell}{(V_a - V_{SC_i}) - (V_a - V_{Sd})}. \qquad (1)$$

To conduct a numerical study according to expression (1), we take the following values of air velocity V_a = 18÷24 m/s, the hovering speed of waste particles V_{SCi} = 0.3 m/s, the hovering speed of cotton fiber V_{Sd} = 4.69÷5.02 m/s, and the distance from waste particles to cotton fiber $\Delta\ell$ = 0.3÷2 m [17]. Taking into account the above data, a graph was plotted in the MathCAD 15 programming environment, shown in Fig. 1.



1 – $\Delta\ell = 0.3$ m, *2* – $\Delta\ell = 1.0$ m,

3 – $\Delta\ell = 1.5$ m, *4* – $\Delta\ell = 2.0$ m

Fig. 1. Graph of the change in the distance of approach ℓ (m) of impurity particles to cotton fibers depending on the air velocity $V_в$ (m/s) for different values of the distance from impurity particles to the raw cotton fibers $\Delta\ell$ (m)

Analyzing the graphs in Fig. 1, we see that when the airflow velocity is V_a = 18÷24 m/s and the distance of small impurity particles to the raw cotton fiber is $\Delta\ell$ = 0.3÷2 m, the distance of approach of small particles to the raw cotton fiber is ℓ = 0.83 ÷ 8.08 m. If the length of the pneumatic conveying system is chosen equal to 4 m, then at an airflow velocity of V_a = 24 m/s, impurity particles located at a distance of 1 m from the cotton fibers reach the surface of the raw cotton, and thereby, saturating the raw cotton, increase the contamination of raw cotton in the hopper.

To develop a model of the penetration of small particles into cotton fiber, it is necessary to determine the speed of approach of small waste particles moving towards a bunch of raw cotton.

It is known that the velocity of moving small impurity particles V_{ip} in the air is determined by the following formula:

$$V_{ip} = V_a - V_{SCi}, \text{ m/s} \qquad (2)$$

The velocity of small impurity particles with a mass of 1 mg, according to experimental data [17], is V_{SCi} = 0.2÷0.3 m/s. We determine the velocity of the moving bunch V_{mb} of raw cotton:

$$V_{mb} = V_a - V_{sx}, \text{ м/с} \qquad (3)$$

where: V_{sx} – is the velocity of the hovering bunch of cotton, m/s.

We determine the speed of approach of impurity particles ΔV_{im} to the bundle of raw cotton:

$$\Delta V_{im} = V_{\text{ip}} - V_{mb} = (V_a - V_{SCi}) - (V_a - V_{sx}) = V_{sx} - V_{SCi} \text{ m/s} \qquad (4)$$

According to the experimental data obtained in [17], ΔV_{im} = 4.7 ÷ 6.8 m/s. In the model, small impurity particles are taken in the form of a parallelepiped with a mass of 1 mg, a density of debris $\gamma_c = 1.5$ g/cm^3 [18], which move in an air medium with a smaller cross-section opposite to the air flow direction.

The model of the calculation scheme of the fiber strands and approaching impurity particles is shown in Fig. 2. Consider the bundle of fibers as an elastic element with a mass uniformly distributed along its length.

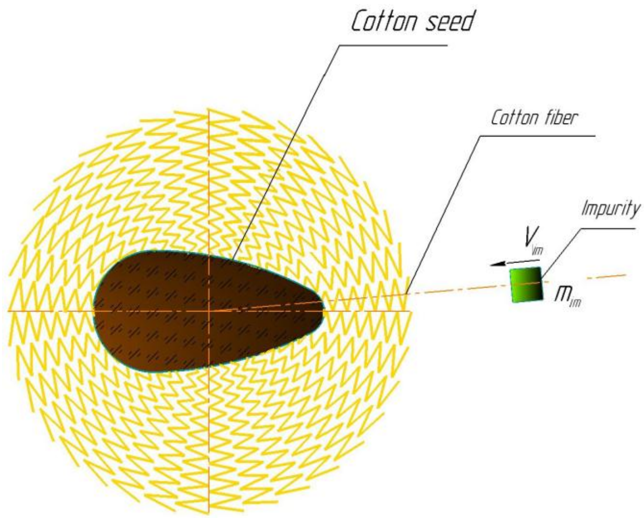


Fig. 2. Model of the calculation scheme of the cotton fiber strand and approaching impurity particles

Fig. 3 shows cotton fiber strands with impurity elements penetrated in them. The depth of impurity penetration into the fiber strand is determined as:

$$\Delta x = \sqrt{\frac{(m \cdot V_{im}{}^{2})}{k}}, \text{ m} \qquad (5)$$

where V_{im} – is the velocity of impurities approaching the cotton strand, equal to V_{im} = 1÷8 m/s;

m is the mass of impurities, equal to *m* = 1÷20 mg; *k* - is the stiffness coefficient, which, due to impurity admixture with fibrous material, is in a wide range (from 10 to 200 N/m) [19], in calculations, we take *k* = 30 N/m, since the stiffness of the fibers increases as the cotton fiber approaches the seeds.

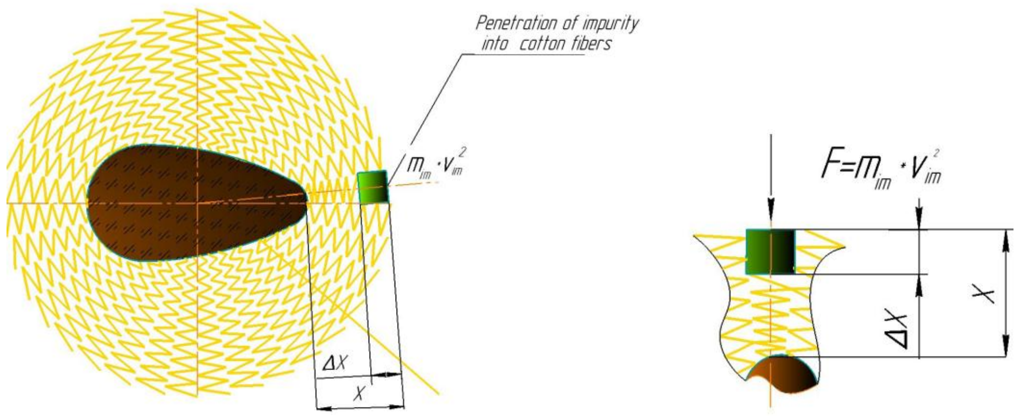


Fig. 3. Fiber strands with penetrated impurity particles of the specified cross-section

Figure 4 shows the influence of impurity particle velocity on the penetration depth into fiber strands. The following values were taken according to expression (5): *m* = 1 mg, *k* = 30 N/m, V_{im}= 1 ÷ 8 m/s.

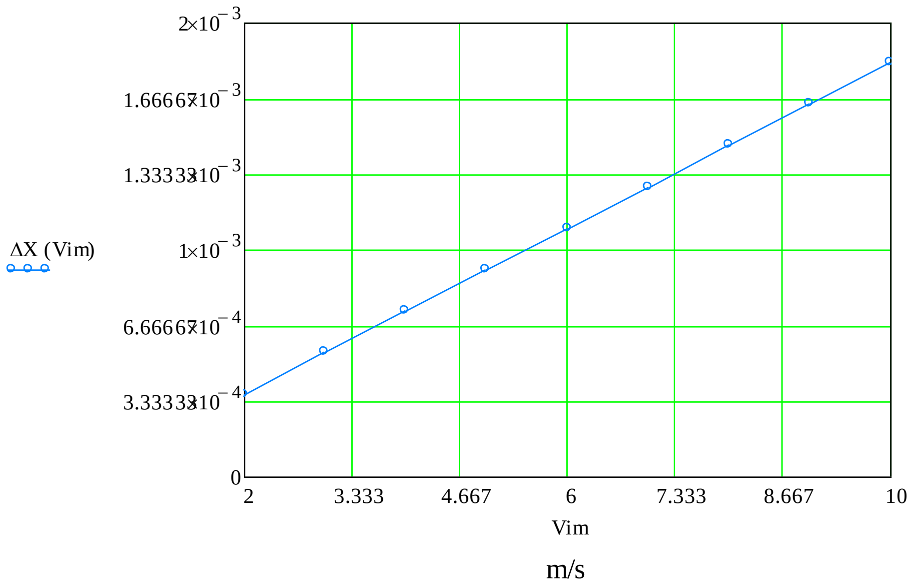


Figure 4. The influence of impurity particle velocity on the penetration depth into fiber strands

Figure 4 shows that with an increase in the impurity particle velocity, their penetration into fiber strands increases proportionally.

Taking the following values: ΔV_{im} = 6 m/s, *k* = 30 N/m, *m* = 1 ÷ 20 mg, and according to expression (4), we construct a graph of the influence of impurity particle mass on the penetration depth into fiber strands, shown in Figure 5.

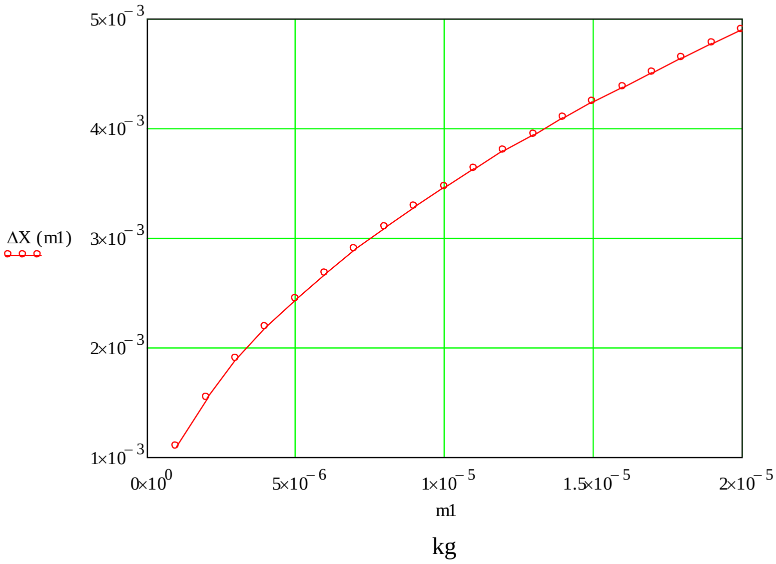
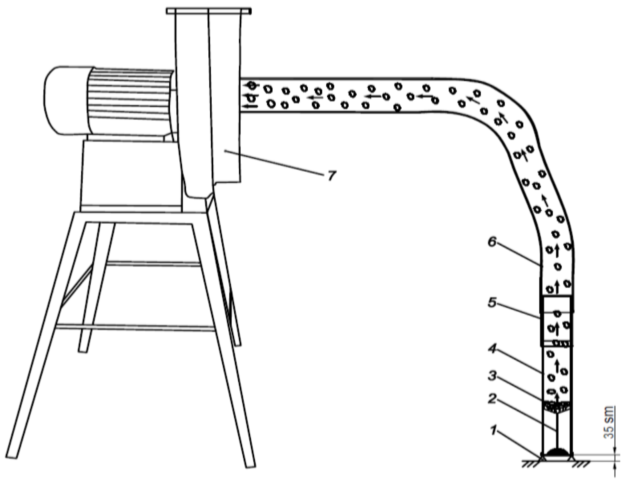


Figure 5. Effect of the mass of impurity particles on the depth of penetration into fiber strands

From Fig. 5, it is clear that with an increase in the mass of impurity particles, the depth of penetration into fiber strands also increases.

Experimental studies were conducted to confirm the results obtained according to the developed model.



1 – pipe stand for air suction, 2 – holder of raw cotton strands and small debris, 3 – strands of raw cotton, 4 – glass pipe, 5 – plastic pipe, 6 – corrugation, 7 – centrifugal fan

Fig. 6. Schematic representation of a glass pipe for studying the convergence of debris with raw cotton

Figure 6 shows a schematic representation of a glass pipe for studying the convergence of debris with raw cotton. On this stand, the research methodology is realized in the following order: in glass pipe 4, a strand of raw cotton with small debris is placed, the distance between particles is 0.15 m, and air suction is provided due to the gap in stand 1. Before starting the centrifugal fan, video filming (telephone) of the movement of raw cotton and debris is prepared. Then the centrifugal fan is started, under the action of which raw cotton and small impurity particles are sucked into the glass tube. Using the special program MOVAVI Video Editor Plus 20.4.0, the video recording of the approach of raw cotton to small particles is analyzed.

The analysis of photographs of the kinetics of the approach of small debris to cotton fiber confirms the adequacy of the developed models of the mechanism of saturation of cotton fibers with small impurity particles during movement in the pneumatic conveying system of a cotton harvesting machine.

Conclusions. As a result of the conducted computational and experimental studies, the following conclusions can be drawn:

1. The developed model of the convergence of impurity particles with raw cotton segments in the pneumatic conveying system of a cotton picker confirmed that particles located 1.0 m away from the cotton segments, having approached them by the airflow, saturate the cotton, easily penetrating its internal area, thereby increasing the contamination of raw cotton in the hopper.

2. To reduce the saturation of raw cotton with small debris, it is necessary to reduce the concentration of small impurity particles in the air-cotton mixture as they travel through the pneumatic conveying system.

3. The newly developed design of the receiving chamber allows for the elimination of contaminated air suction from the lower part of the chamber, ensuring a decrease in the concentration of small debris in the air-cotton mixture.

4. Performing high-quality defoliation before machine harvesting of cotton reduces the concentration of small impurity particles in the air-cotton mixture during its movement through the pneumatic conveying system, resulting in decreased contamination of raw cotton in the hopper.

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