Numerical and experimental study of the raw cotton saturation with fine trash in the pneumatic conveyor system of a cotton harvester

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Abstract. The article presents a numerical study of the impurity content in raw cotton during machine harvesting, considering the features of the formation of fine trash. An analysis is given of the change in the content of fine trash particles depending on the overall impurity content, starting from the conveyor corridor of the working apparatus to the hopper of the cotton picker. A mathematical model of the process of bringing together fine trash particles with cotton lobules in a pneumatic conveyor system was developed. Numerical studies were conducted to determine the approach distance considering the influence of the parameters of the air-cotton mixture. An analysis of the results of numerical studies is presented. Recommendations are given on factors affecting the saturation of cotton lobules with fine trash particles during transportation in a pneumatic conveyor system. Theoretical studies were conducted based on classical methods for modeling processes in a pneumatic conveyor system using the MathCad 15 programming environment.

1 Introduction

In recent years, in connection with the transition to machine harvesting of cotton, special attention has been paid to the issues of technologies for the primary processing of raw cotton. The content of impurity of raw cotton during machine harvesting is higher than when picked by hand and the state norm for the impurity according to GOST 16298-81 is no more than 10%. During the primary processing of raw cotton, multiple ginning is conducted due to the high content of fine trash. As a result, the number of short fibers increases, and thereby the strength of the yarn decreases [1-10]. Therefore, reducing the impurity amount in raw cotton (especially, fine trash) during machine harvesting is relevant. The features of the formation of fine trash and the reduction of impurities in raw cotton

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cotton during machine harvesting were analyzed in numerous publications by well-known scientists [11-20].

Based on many years of research, the data on the morphological composition of impurities of raw cotton during machine harvesting is presented in Table 1 [20].

**Table 1.** Impurities in raw cotton during machine harvesting, obtained in different years (in morphological composition, %).

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Cuttings</td>
<td>0.13±0.07</td>
<td>0.122±0.05</td>
<td>0.115±0.08</td>
<td>0.108±0.08</td>
</tr>
<tr>
<td>Valves</td>
<td>13.63±3.67</td>
<td>16.6±4.55</td>
<td>21.34±8.94</td>
<td>12.3±2.52</td>
</tr>
<tr>
<td>Leaf stalks</td>
<td>9.42±2.03</td>
<td>8.36±1.24</td>
<td>8.32±1.93</td>
<td>7.38±1.40</td>
</tr>
<tr>
<td>Branches</td>
<td>12.25±4.20</td>
<td>1.42±0.30</td>
<td>1.64±1.52</td>
<td>1.17±1.27</td>
</tr>
<tr>
<td>Seed-buds</td>
<td>-</td>
<td>1.3±0.46</td>
<td>0.88±0.67</td>
<td>1.37±1.13</td>
</tr>
<tr>
<td>Flowers</td>
<td>-</td>
<td>0.653±0.28</td>
<td>0.37±0.43</td>
<td>0.763±0.74</td>
</tr>
<tr>
<td>Weeds</td>
<td>-</td>
<td>1.83±0.81</td>
<td>1.94±1.64</td>
<td>1.05±0.79</td>
</tr>
<tr>
<td>Soil</td>
<td>1.01±0.85</td>
<td>0.672±0.96</td>
<td>0.743±0.82</td>
<td>1.05±0.86</td>
</tr>
<tr>
<td>Fine trash</td>
<td>63.93±7.54</td>
<td>68.9±5.67</td>
<td>64.65±12.9</td>
<td>75.1±4.8</td>
</tr>
</tbody>
</table>

The table shows that fine trash on average accounts for 68.14% of the total impurity of raw cotton. The results of experimental studies of the content of raw cotton impurities in various zones are shown in Table 2 [11].

**Table 2.** Impurities in raw cotton samples in different zones (according to A.I. Komogortseva), %.

<table>
<thead>
<tr>
<th>Morphological composition</th>
<th>Working area</th>
<th>Conveyor corridor</th>
<th>Hopper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cuttings</td>
<td>0.12</td>
<td>1.29</td>
<td>0.94</td>
</tr>
<tr>
<td>Branches</td>
<td>0.01</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Leaf stalks and cuttings</td>
<td>0.36</td>
<td>0.85</td>
<td>0.82</td>
</tr>
<tr>
<td>Dry leaves and flowers</td>
<td>0.59</td>
<td>1.26</td>
<td>0.84</td>
</tr>
<tr>
<td>Bust fiber</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Fine trash</td>
<td>2.05</td>
<td>2.98</td>
<td>4.46</td>
</tr>
<tr>
<td>Soil</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Seed-buds</td>
<td>0.08</td>
<td>0.25</td>
<td>0.42</td>
</tr>
<tr>
<td>Weeds</td>
<td>0.95</td>
<td>0.34</td>
<td>0.50</td>
</tr>
<tr>
<td>Total</td>
<td>4.16</td>
<td>7.04</td>
<td>8.03</td>
</tr>
</tbody>
</table>

In the morphological composition, the content of fine trash in the working area is 2.05%, in the conveyor corridor - 2.98%, in a raw cotton hopper - 4.46%. That is, the amount of fine trash on the way from the conveyor corridor to the hopper increases to 50% [11]. However, the authors of that article have not fully studied the mechanism of saturation of raw cotton with fine trash.

Previous studies have shown that when using a U-shaped receiving chamber (Figure 1), a 30% reduction in clogging is achieved; the results are shown in Table 3 [20].
Fig. 1. Vertical spindle devices with serial (a) and U-shaped receiving chambers with elbow bend (b).

Table 3. Field test results.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Serial receiving chamber</th>
<th>New U-shaped receiving chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working slot width (mm)</td>
<td>30-28</td>
<td>32-28</td>
</tr>
<tr>
<td>Cotton moisture content, %</td>
<td>8.9</td>
<td>7.6</td>
</tr>
<tr>
<td>Cotton seed impurity, %</td>
<td>13.9</td>
<td>11.2</td>
</tr>
<tr>
<td>Cotton seed crushing, %</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The authors confirmed that the reduction in the amount of raw cotton impurities when using a U-shaped receiving chamber is explained by the fact that the suction of dirty air from the lower part of the receiving chamber is eliminated, and as a result, the concentration of dust particles in the air-cotton mixture is reduced. The mechanism of saturation of raw cotton with fine trash particles in a pneumatic conveyor system was not fully studied.

The purpose of the study is to conduct a numerical study of the process of the approach of small trash particles with cotton lobules with further penetration inside the cotton fiber by simulating the movement of raw cotton lobules and trash particles in the pneumatic conveyor system of a cotton harvester.

2 Materials and methods

Calculation studies of the saturation of raw cotton with fine trash particles were conducted based on modeling the movement of cotton lobules and impurities in a pneumatic conveyor system using the MathCad 15 programming environment.
3 Results and Discussion

To determine the approach of cotton lobules with fine trash particles, the model shown in Figure 2 is considered.

![Fig. 1. Model of movement of cotton lobules and fine trash particles.](image)

We accept the following indices: $L$ – the distance from the receiving chamber to the hopper ($L = 4.5 \pm 5.0$ m); $\ell$ – the distance of approach of trash particles with cotton lobules; $\Delta \ell$ – the distance from trash particles to a cotton lobule ($\Delta \ell = 0.5 \pm 1.2$ m); $m_d$ – mass of a cotton lobule according to [18] $m_d = 1.0$ g; $m_{ci}$ – mass of trash particles according to [1] $m_{ci} = 1$ mg; $\vartheta_v$ – air flow velocity, m/s; $\vartheta_d$ – cotton lobule velocity, m/s; $\vartheta_{ci}$ – trash particles velocity, m/s; $\vartheta_{sd}$ – soaring velocity of a cotton lobule, m/s; $\vartheta_{sci}$ – soaring velocity of fine trash particles, m/s.

The velocities of cotton lobules and fine trash particles are determined as:

$$\vartheta_d = \vartheta_v - \vartheta_{sd} \tag{1}$$

$$\vartheta_{ci} = \vartheta_v - \vartheta_{sci} \tag{2}$$

According to the author of [20], the experimental soaring velocity of a stretched cotton lobule in a wind tunnel is $\vartheta_d = 4.69 \pm 5.02$ m/s. In the cotton ginning industry, the lag coefficient is experimentally determined; it equals the ratio of the cotton velocity to the air velocity [2]:

$$k = 0.7 \div 0.75 \tag{3}$$

Based on the above calculated and experimental data on the soaring velocity of a cotton lobule, in the computations, we accept $\vartheta_{sd} = 3 \div 6$ m/s. When developing a model of fine trash particles, we determine its dimensions based on the following data.

The soaring velocity is the velocity in a vertical pipeline in which the body is in suspension and oscillates within certain limits of its equilibrium position.

According to [20], the lifting force $R$, equal to the weight of body $G = V \gamma M$ is determined by the following formula
\[ R = \phi \cdot f_M \cdot \frac{V_s^2 \cdot \gamma}{2g} \]  

(4)

Where: \( V \) – is the volume of the body, \( m^3 \); \( \gamma_M \) – is the specific gravity of the material, \( \text{kg/m}^3 \); \( f_M \) – is the midsection area (the area of projection of the body onto a plane perpendicular to the direction of air velocity), \( m^3 \); \( \gamma \) – is the specific gravity of air, \( \text{kg/m}^3 \); \( g \) – is the gravity acceleration, \( \text{m/s}^2 \); \( \phi \) – is the coefficient depending on the shape and fluffiness of the raw cotton components and the properties of the flow itself; with an increase in flow turbulence, the value of \( \phi \) increases (according to CNIIKKhprom data, \( \phi \approx 1 \)); \( V_s \) – is the air velocity relative to the material (soaring velocity), i.e. \( V_s = V - V_M, \text{m/s} \).

\[ V \cdot \gamma_M = \phi \cdot f_M \cdot \frac{V_s^2}{2g} \]  

(5)

\[ V_s = \sqrt{\frac{2 \cdot V \cdot \gamma_M \cdot g}{\phi \cdot f_M \cdot \gamma}} \]  

(6)

As they move through the air, raw cotton lobules change their shape and size. Depending on the change in the shape and size of cotton lobules, the soaring velocity changes. Based on this, we study the pattern of soaring velocity, considering changes in the shape and size of cotton lobules moving in the airflow direction. The dimensions of the lobule picked by vertical spindle devices are (according to [12]): weight of the cotton lobule \( G_d = 1.0 \text{ g} \), length in the form of a stretched cylinder \( l = 7.5 \text{ cm} \), diameter \( d = 3.3 \text{ cm} \). The specific weight of the stretched cotton lobule is determined in the following form:

\[ G_d = \frac{\pi \cdot d^2 \cdot l \cdot \gamma_x}{4}, \text{ (kg)} \]  

(7)

Where: \( d \) – is the diameter of the cylinder, \( m \); \( l \) – is the length of the cylinder, \( m \); \( \gamma_x \) - is the specific weight of cotton, \( \text{kg/m}^3 \).

Therefore, the specific gravity of a cotton lobule is:

\[ \gamma_x = \frac{4 \cdot G_d}{\pi \cdot d^2 \cdot l} = \frac{4 \cdot 1 \cdot 10^{-3}}{3.14 \cdot (3.3 \cdot 10^{-2})^2 \cdot 7.5 \cdot 10^{-2}} = 15.6 \text{ kg/m}^3. \]

The raw cotton lobules entering the slot receiving chamber from the working unit under the action of suction air are arranged in three types, shown in Figure 3. The soaring velocity of raw cotton lobules for three options is determined according to expression (6). We assume that the raw cotton lobules are cylindrical in shape and the airflow affects the minimum midsection area (Figure 3, a).
Here, the midsection area is \( f_M = \pi \cdot R^2 \), the volume of the lobule is \( V = \pi \cdot R^2 \cdot L \).

Considering the flow turbulence, the value of \( \phi \) increases (according to CNIIKKhprom data, \( \phi \approx 1 \)). The specific gravity of air is \( \gamma = 1.2 \text{ kg/m}^3 \). According to (6), the soaring velocity is determined by the following formula:

\[
V_S = \sqrt{16.3 \cdot L \cdot \gamma_M} = \sqrt{16.3 \cdot 0.075 \cdot 15.6} = 4.37 \text{ m/s}.
\]

Let us assume that a raw cotton lobule moves in the air (Figure 3, b). Then, according to expression (6), we determine the soaring velocity of a cotton lobule:

\[
V_S = \sqrt{16.3 \cdot L \cdot \gamma_M} = \sqrt{16.3 \cdot 0.0165 \cdot 15.6} = 2.05 \text{ m/s}.
\]

We assume that a raw cotton lobule has a spherical diameter \( d_M \) (Figure 3, c). We determine the diameter of the sphere when a raw cotton lobule changes its shape from cylindrical to spherical \( d_M \):

\[
\pi \cdot R^2 \cdot L = \frac{\pi \cdot d_M^3}{6} \quad (8)
\]

\[
d_M = \sqrt[3]{6 \cdot \left(\frac{0.033}{2}\right)^2} \cdot 0.075 = 0.0497 \text{ m} = 4.97 \text{ cm}.
\]

We determine the midsection area \( f_M = \frac{\pi \cdot d_M^2}{4} \) and the volume of the sphere \( V = \frac{\pi \cdot d_M^3}{6} \).

According to expression (6), we calculate the soaring velocity:
Analysis of the results obtained shows that the soaring velocity of a raw cotton lobule reaches its maximum value when the airflow acts along the minimum midsection. According to [1], the mass of fine trash is taken equal to \( m_{Ci} = 1 \text{ mg} \). The specific gravity of dry leaves of cotton shrubs and their thickness is assumed to be \( \gamma_{C} = 1.5 \text{ mg/mm}^3 \), \( \delta = 0.25 \text{ mm} \) [18]. Based on the proportion, we determine the volume of 1 mg of fine trash [18]:

\[
V = \frac{1 \text{ mg} \cdot 1 \text{ mm}^3}{1.5 \text{ mg}} = 0.66 \text{ mm}^3.
\]

The model of fine trash particles is taken in the form of a square with side “\( a \)” and thickness “\( \delta \)”. Then the total volume of impurity is \( V = a^2 \cdot \delta = 0.66 \text{ mm}^3 \). Hence, we define:

\[
a = \sqrt{\frac{V}{\delta}} = \sqrt{\frac{0.66}{0.25}} = 1.62 \approx 1.6 \text{ mm}.
\]

The soaring velocity of fine trash particles is determined experimentally. Fine trash is sifted through a mesh (36 \text{ mesh/cm}^2). Next, the soaring velocity of fine trash particles is determined according to the scheme of the experimental setup (Figure 4).

As a result of the experiment, the soaring velocity of fine trash particles was \( V_{S_{Ci}} = 0.3 \text{ m/s} \). Based on the data presented above, we derive an equation to determine the path of approach of fine trash particles and cotton lobules (Figure 1).

Let \( t_0 \) be the time of approach of small particles with cotton lobules when passing distance \( \ell \) from the receiving chamber to the hopper; the distance to the hopper is \( L \).

Approach time \( t_0 \) for the lobule is:

\[
\frac{\ell}{V_{\theta}} = t_0,
\]

For fine trash particles:

\[
\frac{\Delta \ell}{V_{C_{i}}} + \frac{\ell}{V_{C_{i}} - V_{\theta}} = t_0
\]
Equating expressions (10) and (11), we obtain:

$$\frac{\ell}{V_\delta} = \frac{\Delta \ell}{V_{C_i}} + \frac{\ell}{V_{C_i} - V_\delta},$$  \hspace{1cm} (12)

Hence:

$$\ell = V_\delta \cdot \Delta \ell + V_\delta (V_{C_i} - V_\delta) \frac{\ell}{V_{C_i} + (V_{C_i} - V_\delta)},$$  \hspace{1cm} (13)

Or:

$$\ell = \frac{(V_a - V_{SC}) \cdot \Delta \ell + (V_a - V_{SC}) ([V_a - V_{SC}] - (V_a - V_{SC}))}{(V_a - V_{SC}) + [V_a - V_{SC}] - (V_a - V_{SC})},$$  \hspace{1cm} (14)

Using the MathCad 15 programming environment, the results of the numerical solution to equation (14) were obtained in the form of graphs presented in Figures 5 and 6.

**Fig. 5.** Graph of changes in the approach distance $\ell$ (m) of trash particles with cotton lobules depending on the air flow velocity $V_a$ (m/s) at different values of the soaring velocity of raw cotton lobules $V_{Sd}$ (m/s): 1 – $V_{Sd} = 2$ m/s, 2 – $V_{Sd} = 3$ m/s, 3 – $V_{Sd} = 4$ m/s.

**Fig. 6.** Graph of changes in the approach distance $\ell$ (m) of trash particles with cotton lobules depending on the distance $\Delta \ell$ (m) from the trash particles to the cotton lobule at different values of the soaring velocity of raw cotton lobules $V_{Sd}$ (m/s): 1 – $V_{Sd} = 4$ m/s, 2 – $V_{Sd} = 5$ m/s, 3 – $V_{Sd} = 6$ m/s.
As seen from Figure 5, with an increase in air flow velocity from 20.0 m/s to 25.0 m/s and an increase in the soaring velocity of cotton lobules from $V_{sd} = 2$ m/s to $V_{sd} = 6$ m/s, the distance of approach of trash particles with cotton lobules varies from $\ell = 1.85$ m to $\ell = 3.876$ m. With an increase in velocities of air flow and soaring of cotton lobules, the probability of saturation of cotton lobules with fine trash particles as they move in the pneumatic conveyor system of a cotton harvesting machine decreases.

From Figure 6, it can be seen that with an increase in the distance ($\Delta \ell$) between the trash particles and the cotton lobules at the soaring velocity of the cotton lobules from $V_{sd} = 2$ m/s to $V_{sd} = 6$ m/s, the distance between the trash particles and the cotton lobules changes from $\ell = 3.7$ m to $\ell = 4.3$ m. This means that an increase in ($\Delta \ell$) and $V_{sd}$ helps reduce the probability of saturation of cotton lobules with fine trash particles as they move in the pneumatic conveyor system of the cotton harvester.

4 Conclusion

- The results of numerical studies confirmed that changes in air velocity $V_{a}$, the soaring velocity of cotton lobules $V_{sd}$, and the distance of approach of trash particles to cotton lobules $\ell$ in the pneumatic conveyor system of a cotton picker have a significant impact on the degree of saturation of cotton lobules with fine trash particles.
- According to the graphs shown in Figures 5 and 6, it can be seen that the smaller the distance $\ell$, the faster fine trash particles reach the cotton lobules, and the higher the probability of deep penetration of fine trash particles into cotton lobules. Deep penetration is explained by the fact that the time for small particles to overcome the residual distance increases; this time is expressed as the difference in distances from the receiving chamber to the hopper and the approach of fine trash particles to cotton lobules: $(L - \ell)$.

References


12. A.D. Glushchenko, A.P. Fedotov, Models of cotton lobule and bolls for harvesting devices of cotton pickers (UzNIINTI, Tashkent, 1992)


