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Research Article

Theoretical Model of Cotton Fiber Waste Cleaning Process Using A Peg Screw and Mesh Surface

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Abstract

The article provides a theoretical analysis of the operating process of a spiked screw and hole-mesh cleaner used in the final stages of cotton ginning to remove small impurities from the lint, lint, and cyclone fluff. Based on the power-kinematic interaction of the working element with fibrous waste and a model of statistical (probable) separation of impurity particles along the fibrous flow, a unified engineering formula was obtained that links the cleaning efficiency with the structural and kinematic parameters of the working element: pile diameter, mesh hole size, rotation speed, working slit, and screw pitch. Numerical calculation results showed that for the experimental sample with a peg diameter dk = 12 mm, a mesh hole of 6×50 mm, and a rotation speed n = 160 rpm, the cleaning efficiency ηo ≈ 92%; meanwhile, fiber loss is practically absent. The model quantitatively confirmed the existence of a technological optimum for hole size—decreasing it reduces efficiency, while increasing it sharply increases fiber loss.

Keywords

Pin screw, mesh mesh, cotton fiber waste, cleaning efficiency, statistical model, probability multiplier, fiber loss.

Introduction

At the final stages of cotton ginning production, cleaning secondary fibrous products, such as lint, lint, and cyclone fluff extracted from raw cotton, is an important technological task. For this purpose, continuous-action fibrous material cleaners of the OVM-A-1 and OVM-A-2 types are widely used, the working element of which consists of a mesh with holes and a rotating pin screw wound into the shell [7]. Unlike the drum-type spike cleaners used in the main flow of raw cotton for cleaning large and small impurities [1, 2, 6], the spike screw performs two functions simultaneously: axially transporting the fibrous mass along the working zone and loosening it through the impact-abrasive action of the spikes on the mesh surface. The compactness of the screw-shaped working element creates convenience for installation in the unit's exhaust ducts, but at the same time complicates the theoretical description of the cleaning process, as the process of loosening and separating impurities occurs continuously along the length of the screw rather than within a strictly defined workload, as in the drum design.

In previous studies [3, 4], as well as in subsequent works [1, 2, 6, 8], it was established that the main factors determining the intensity and degree of cleaning of fibrous material with peg working elements are the geometric parameters of the pegs (diameter, shape, number, placement density), the radial distance between the pegs and the grating, the size and shape of the mesh holes, as well as the rotation frequency of the working element [2, 3]. At the same time, work [6] notes a significant drawback of certain designs: when the geometric and kinematic parameters of peg drums remain constant, the impact of pegs on the fibrous material is monotonous in magnitude and direction, which reduces the cleaning effect and thereby increases fiber damage. This necessitates a rational choice of the combination of peg diameter and mesh size, rather than a purely empirical one.

Practice and preliminary technological observations show that for the peg screw of the type under consideration, there is an optimal combination of the following parameters: a peg diameter dk = 12 mm and a mesh hole size of 6×50 mm. Reducing the hole width (for example, up to 4×50 mm) reduces the degree of cleaning of fibrous waste from fine impurities, as some of the impurity particles separated from the fiber return to the stream before they can pass through the narrowed holes. Increasing the hole width (for example, up to 8×50 mm) increases the probability of leakage, but at the same time increases the loss of fibrous material through excessively large holes. The content of these observations has not yet been quantified, and the purpose of this article is to develop a theoretical model of the cotton fiber waste cleaning process using a peg screw, link it with the geometric and kinematic parameters of the peg, the mesh size, and the working gap, and derive a working formula based on the obtained model that can be directly applied in engineering calculations.

Methodology

1. Design diagram and kinematic characteristics of the working element

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The working element consists of a shaft with fixed rows of pegs with a diameter dk, positioned radially with a pitch s along the screw line (Fig. 1, a). The cylindrical surrounding surface of the pile ends has a radius Rk = Dsh/2, where Dsh is the screw diameter along the piles. Under the screw, a grid with fixed holes of rectangular dimensions b×l is installed along the entire working length L (Fig. 1, b); the radial working distance between the ring surrounding the pegs and the grid is δ. Fibrous waste is fed from one end of the screw and moves along the axis due to the axial component of the screw's motion, while the layer of material pressed against the mesh by centrifugal forces is subjected to multiple impact-abrasive actions of the pegs.

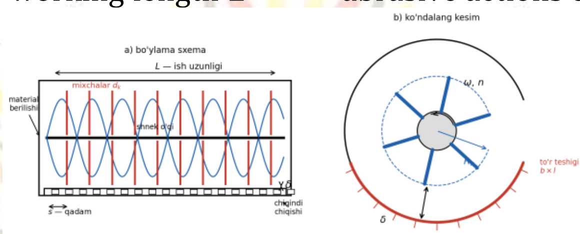

Figure 1. Calculation diagram of a peg screw with a perforated mesh: a — longitudinal diagram; b — cross-section

The angular velocity at the screw rotation speed n (rpm) and the rotational speed of the peg tip are determined by the following formulas:

$$\omega = \pi n/30 \qquad (1)$$

$$vk = \omega Rk = \pi n Dsh/60 \qquad (2)$$

where ω is the angular velocity of the screw, rad/s; vk is the rotational speed of the pile tip, mm/s. When substituting n in rpm and Dsh in mm into formulas (1) – (2), ω is determined in rad/s, and vk in mm/s; they indicate that the rate of strong impact of the peg on the material increases linearly with the screw rotation speed n, which determines the governing role of this parameter in further analysis.

2. Forces acting on a particle and its equation of motion

Let us consider an individual impurity particle located in a layer of fibrous material above the mesh. A normal reaction FN acts on the particle from the network and the fiber surrounding it, and the friction force between the particle and the fiber layer obeys Coulomb's law: Ftr = f·FN, where f is the friction coefficient. Considering the particle as a mass with mass mc, elastically bonded to the surrounding fiber layer with stiffness c, and having a damping coefficient β, we write the equation of motion in the direction perpendicular to the mesh in the following form:

$$mc\cdot\ddot{y} + \beta\cdot y + c\cdot y = \Sigma i\ J0\cdot\delta\ (t - iTk) \qquad (3).$$

where J0 is the momentum of the force against the particle, N·s; Tk = 60/ (n·z) is the period of successive transitions of a single row of stakes, s (z is the number of stakes in a single transverse row). In the interval between impacts (when the right side is zero), this equation represents the damping free oscillations of the particle with a rotational frequency $\omega 0 = \sqrt{}(c/mch - \beta 2/4mch2)$ (4). The coefficients mt, c, β characterize the elastic-dissipative properties of the impurity particle and the fibrous layer supporting it and must be determined experimentally.

3. Multiplying model of separation probability

The separation rate of the impurity particle v0 after the pile is driven is determined as follows:

$$v0 = k\mu\cdot (dk/Dsh)\cdot vk\cdot (1 + e) \qquad (5)$$

where kμ is the efficiency coefficient for transmitting pulse to the particle; e is the collision recovery coefficient (0...1). The particle will be able to pass through the mesh hole if the velocity v0 exceeds the critical value vkr, which is determined by the adhesion forces to the fiber. Since the collision velocities in the actual flow have a propagation, the probability of separation is expressed by a saturable function:

p1 (n) = 1 − e^[− (v0/vkr) 2] (6)

Similarly, the probability of the particle passing through a mesh hole of width b and the geometric capture coefficient with pegs are written as follows:

p3 (b) = 1 − e^[− ((b − bmin) /bσ) 2], b ≥ bmin (7)

pk = z·dk/ (π·Dsh) (8)

The combined effect of geometric capture, impact intensity, and penetration through the hole yields a partial probability of particle escape from the mesh during a single contact: p′ = pk·p1 (n) ·p3 (b) (9). The calculation performed using the initial data of the experimental sample (L = 8000 mm, Dsh = 450 mm, s = 500 mm, n = 160 rpm, z = 8, dk = 12 mm, δ = 20 mm, kμ = 0.5, e = 0.5, vkr ≈ 31.4 mm/s, bmin = 1 mm, bσ = 3 mm) yields: vk (160) ≈ 3.77 m/s, v0 (160) ≈ 75.4 mm/s, Tk ≈ 46.9 ms, pk ≈ 0.068.

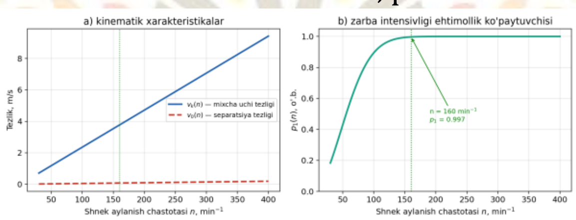

Figure 2. a — rotational speed of the peg vk (n) and particle separation speed v0 (n); b — probability factor of impact intensity p1 (n);

The solution to equation (6) shows that the p1 (n) factor reaches saturation at n ≈ 150–200 rpm (p1 (160) ≈ 0.997), i.e., the assumed value of the experimental sample n = 160 rpm practically corresponds to the beginning of the saturation region of the p1 (n) curve. This confirms the rationality of the adopted design solution n = 160 rpm.

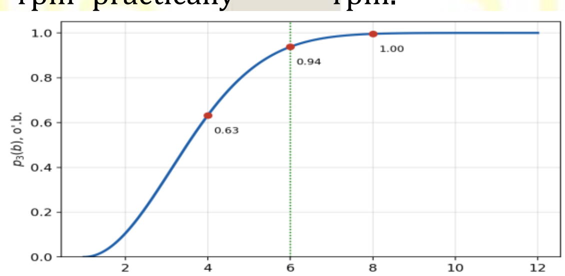

Figure 3. The probability of the impurity particle passing through the mesh hole during a single contact with the pile row is p3 (b).

The solution of equation (7) in the range b = 1...12 mm yields the values p3 (4) ≈ 0.63; p3 (6) ≈ 0.94; p3 (8) ≈ 0.996: a 6 mm hole significantly increases the probability of exit compared to a 4 mm hole, while a further increase to 8 mm leads to a very small (only 0.06) increase in p3. However, the function p3 (b) has the same monotonic saturation property as p1 (n) and does not have an internal optimum—the practical optimum of the hole size occurs only as a result of the accumulation of action along the entire length of the screw, which requires statistical modeling of the process along the axis.

4. Correspondence between the pile diameter and the working hole

If the pile diameter dk is small compared to the gap δ, the impact is "slippery" and weak, and insufficient energy is generated to separate the particle; if dk is the same or larger than δ, the pile practically blocks the working channel, resulting in the material becoming compacted instead of softening. This qualitative consideration is expressed through the peak-like (unimodal) function of the dk/δ ratio:

$$p_2(d_k, \delta) = \left(d_k / (\gamma_{opt} \cdot \delta)\right) \cdot e^{\left[1 - d_k / (\gamma_{opt} \cdot \delta)\right]} \quad (11)$$

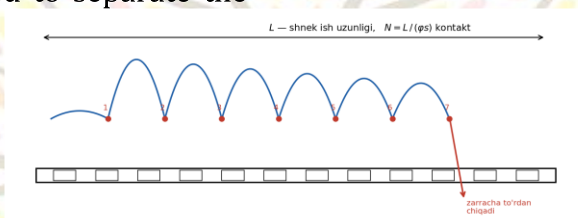

Figure 4. Scheme for the probability model of a particle passing through a mesh hole

where $\gamma_{opt} \approx 0.6$ is the optimal coefficient for filling the working gap of the pile, determined experimentally. The function (11) reaches a maximum value of $p_2 = 1$ at $d_k = \gamma_{opt} \cdot \delta$ and deviates from this value in both directions. Combining the partial probability with the correspondence factor, we get the total probability of a particle exiting the mesh hole during a single contact:

$$p = p' \cdot p_2 = p_k \cdot p_1(n) \cdot p_2(d_k, \delta) \cdot p_3(b) \quad (12)$$

5. Statistical model: decrease in impurity concentration along the screw length.

Such a process represents the classical scheme of Bernoulli's independent tests. If the material moves along the screw with a fill (slip) coefficient $\varphi \le 1$, the number of stakes passed after passing the x-coordinate is $N(x) = x / (\varphi s)$ (10). When moving from one row to the next, the mass of the impurities decreases according to the probability in formula (12):

$$m_s(x + \Delta x) = m_s(x) \cdot (1 - p) \quad (13).$$

Moving to a continuous approximation, we obtain a first-order linear homogeneous differential equation:

$$dm_s/dx = -k \cdot m_s(x), \; k = p / (\varphi s) \quad (14)$$

The solution of this equation with the initial condition $m_s(0) = m_{s0}$ is in the form $m_s(x) = m_{s0} \cdot \exp(-kx)$ (15), from which the law of change in cleaning efficiency along the length of the screw follows: $\eta_o(x) = 1 - m_s(x) / m_{s0} = 1 - \exp(-kx)$ (16). A similar model describes fiber losses through the mesh: the probability factor of losses $q_3(b)$ (17) and the differential equation for fiber losses $d\Delta P/dx = k_{pot} \cdot (\Delta P_{max} - \Delta P(x))$, $k_{pot} = p_k \cdot p_1(n) \cdot q_3(b) / (\varphi s)$ (18) are introduced, the solution of which is $\Delta P(x) = \Delta P_{max} \cdot [1 - e^{(-k_{pot} \cdot x)}]$ (19). Consequently, both cleaning efficiency η_o and fiber loss ΔP increase along the screw according to the same exponential pattern in shape, but are characterized by different velocity constants (k and k_{pot}) and depend differently on the mesh hole size b—this

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difference accounts for the presence of a technological optimum for hole size.

6. Initial data for numerical calculation

The parameters adopted for the nominal calculation mode are presented below (Table 1); some of them correspond to the technical specifications of the experimental sample, while the rest were adopted for illustration due to the lack of precise technical data.

Parameter	Symbol	Value	Unit of measurement
Working length	L	8000	mm
Screw diameter	Mon	450	mm
Screw pitch	p	500	mm
Frequency of rotation	n	160	rpm
Number of stakes in a row	z	8.	pieces
Stake diameter	dк	12	mm
Working clearance	δ	20	mm
Filling coefficient	φ	0.40	—
Reticulum	b	6.	mm
Coefficient of conformity	γopt	0.6	—

Results

Substituting x = L into the solution in formula (16) and expressing the coefficient k through formula (12), a single calculation dependence was obtained that links the cleaning efficiency of the peg screw with all its geometric and kinematic parameters:

$$\eta o\ (n, dk, b, \delta, s, \varphi, L) = 1 - \exp\{-N\Sigma \cdot pk \cdot p1\ (n) \cdot p2\ (dk, \delta) \cdot p3\ (b)\} \quad (21)$$

where NΣ = L/ (φs) is the total number of contacts of the particle with the pile rows along length L; for the received data, NΣ = 8000/ (0.40·500) = 40. For the nominal mode (dk = 12 mm, b = 6 mm, δ = 20 mm, n = 160 rpm), p2 (12; 20) = 1,000 (since 12 = 0.6·20), the absolute probability of a single contact was p = 0.068·0.997·1.000·0.938 ≈ 0.0635 and the velocity constant was k = p/ (φs) = 0.0635/ (0.40·500) ≈ 0.000317 mm−1.

1. Changes in cleaning efficiency along the length of the screw

The analytical solution of formula (16) was compared with the results of numerical integration (Euler's method) with a step Δx = 200 mm. The results for several characteristic points are presented in Table 2.

x, mm	ms/ms0 (number)	ηo, % (numerical)	ηo, % (analytical)
0	1,000	0.0	0.0
1600	0.592	40.8	39.8

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3200	0.350	65.0	63.8
4800	0.207	79.3	78.2
6400	0.123	87.7	86.9
8000	0.073	92.7	92.1

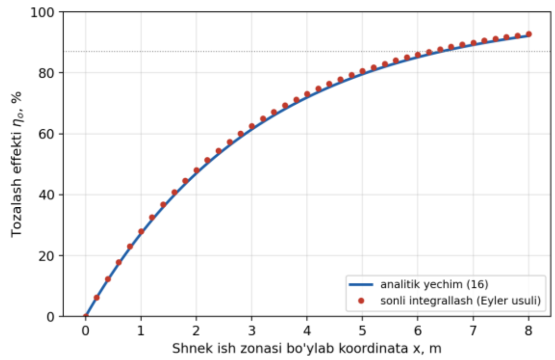

Figure 5. Change in cleaning efficiency ηo along the length of the screw working zone: continuous line — analytical solution; points — numerical integration using the Euler method

The discrepancy between the open numerical scheme and the analytical solution does not exceed 1–1.5 percentage points and is explained by the finiteness of the integration step; At $\Delta x \to 0$, the numerical solution approaches the analytical solution, which confirms the correctness of the transition from the discrete model to the differential equation. At a full length of L = 8000 mm, ηo ≈ 92.1% is achieved, while an efficiency of 87% is achieved at approximately 6.4 m of the working length.

2. Influence of mesh size

The results obtained under the condition of changing the mesh width b from 2 to 10 mm (n = 160 rpm, dk = 12 mm, δ = 20 mm, L = 8000 mm without changing the values) are presented in Table 3.

Hole size b×l, mm	ηo (L), %	ΔP (L), %
4×50	81.9	0.0
6×50 (Optimal)	92.1	0.0
8×50	93.3	3.6

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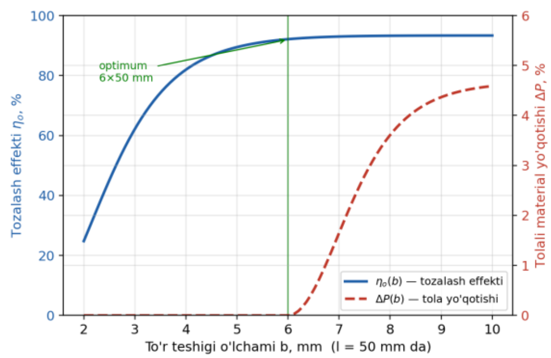

Figure 6. Dependence of cleaning efficiency ηo and fiber loss ΔP on mesh size b.

The results showed that when the hole size is reduced to 4×50 mm, the cleaning efficiency significantly decreases (from 92.1% to 81.9%), while fiber loss is practically absent; when the hole size is increased to 8×50 mm, the cleaning efficiency increases by only 1.2 percentage points, but the loss of fibrous material increases sharply to 3.6%. With a hole size of 6×50 mm, the ηo (b) function is already approaching saturation, while the losses ΔP (b) function corresponds to a region that has not yet begun to increase significantly—that is, this size is close to the practical equilibrium between cleaning completeness and fiber retention.

3. Influence of pile diameter and working clearance

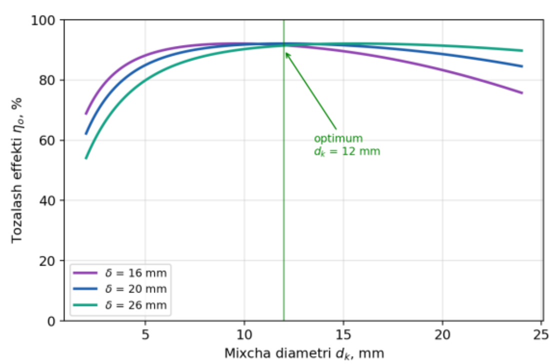

Fig. 7. Dependence of cleaning efficiency ηo on the pile diameter dk at various working clearance δ values (n = 160 rpm, b = 6 mm, L = 8000 mm).

Each curve has an obvious maximum at dk = γopt·δ: at δ = 20 mm, the maximum corresponds exactly to dk = 12 mm. A deviation of the pile diameter from the optimal value by 4 mm in both directions leads to a decrease in cleaning efficiency by 3–5 percentage points; a significant decrease or increase in dk compared to δ = 20 mm leads to a decrease in efficiency by more than 15 percentage points. As the working clearance δ increases, the pile diameter optimum shifts toward larger values proportional to γopt·δ; i.e., the pile diameter and the working clearance should be determined not separately, but in coordination with each other.

Conference

The resulting formula (21) characterizes the cleaning efficiency of the peg screw using four independent probability factors: geometric coverage by the pegs (pk), impact intensity (p1 (n)), the correspondence of the peg diameter to the working gap (p2 (dk, δ)) and mesh hole permeability (p3 (b)). This composition well reflects the physical nature of the process: the rotation frequency and hole size are influenced by monotonic functions with saturation properties starting from certain values, while the correspondence of the pile diameter and the working hole is characterized by a peak-like function with an internal maximum.

The model shows that the reason for the existence of a practical technological optimum for the mesh hole size is the different dependence of the useful cleaning efficiency p3 (b) and fiber loss q3 (b) functions on b: the former is quickly saturated as the hole increases, while the latter begins to grow faster as it approaches the characteristic fiber size. It is the difference between these two dependencies that distinguishes the 6×50 mm size as a practical optimum: at this point, the cleaning efficiency is almost at its maximum value, while fiber loss has not yet increased significantly. This conclusion fully confirms the preliminary technological observations presented in Section 1.

The result obtained for the rotation frequency—the saturation of p1 (n) within the range of n ≈ 150–200 rpm—leads to an important practical conclusion: transitioning to frequencies higher than the adopted value of n = 160 rpm in the experimental sample does not significantly increase cleaning efficiency, but increases the impact intensity of the pegs and thereby the risk of fiber damage. This conclusion is also confirmed by the results of experimental-statistical research, which will be presented in the next section, in which the linear coefficient of rotation frequency has the smallest magnitude relative to the other two factors.

The theoretical substantiation of the compatibility condition between the pile diameter and the working gap (dk ≈ γopt·δ) is of practical importance: it indicates that when designing a structure, these two parameters must be selected together rather than independently. According to the model, the coefficient γopt remains the only binding parameter that must be clarified experimentally; similarly, the exact values of the coefficients kμ, vkr, bmin, and bσ must also be calibrated through additional experiments. Nevertheless, the model, even in its current form, provides qualitatively correct trends in structural and technological parameters and can be used for preliminary assessment at the design stage.

Conclusion

1. A theoretical model of the cotton fiber waste cleaning process using a spiked screw has been developed, combining force analysis and a statistical flow separation model into a single formula.
2. The separation of impurities is determined by four independent factors: the geometric coverage of the pegs (pk), the rotation frequency (p1 (n), the correspondence of the peg diameter to the working gap (p2 (dk, δ)) and the permeability of the mesh holes (p3 (b)).
3. For the parameters of the experimental sample (L = 8000 mm, Dsh = 450 mm, s = 500 mm, n = 160 rpm, dk = 12 mm, δ = 20 mm, b = 6×50 mm), the model yields a cleaning efficiency ηo ≈ 92%, where 87% efficiency is achieved at approximately 6.4 m of the working length, and fiber loss is practically not observed.
4. The technological optimum of the mesh size has been quantitatively confirmed: a mesh size of

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4×50 mm reduces the cleaning efficiency by 81.9%, while an 8×50 mm mesh increases fiber loss by 3.6%, while the efficiency increases by only 1.2 percentage points.

5. A unified engineering tool has been developed for the design of the pin auger. The coefficients kμ, vkr, γopt, bmin, bσ, and dv must be determined experimentally; the energy-power calculation of the drive is not considered in this article.

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