THEORETICAL SUBSTANTIATION OF THE PHYSICAL AND MECHANICAL PROPERTIES AND LAWS OF MOTION OF WOOL IN A WASHING BATH

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Introduction. This article theoretically analyzes the physical and mechanical properties of wool in a washing bath and the laws of its movement in a liquid environment. The physical properties of wool fiber, moisture absorption, elasticity, hydrodynamic resistance, Archimedes' force and the influence of friction forces on the washing process are studied. Also, the processes of wool displacement, lifting and mixing using a baronet working body are evaluated based on mathematical models. The theoretical results obtained serve to increase the efficiency of wool washing machines and reduce energy consumption.

Key words: wool fiber, wool washing machine, washing bath, hydrodynamic resistance, Archimedean force, friction force, physical-mechanical properties, storm, theoretical analysis, law of motion.

Аннотация. В статье выполнен теоретический анализ физико-механических свойств шерсти в моечной ванне и закономерностей её движения в жидкой среде. Исследовано влияние физических свойств шерстяного волокна, влагопоглощения, упругости, гидродинамического сопротивления, силы Архимеда и силы трения на процесс промывки. Также рассмотрены процессы перемещения, подъема и перемешивания шерсти под действием рабочего органа барабанного типа на основе математических моделей. Полученные результаты могут быть использованы для повышения производительности шерстомоечных машин и снижения энергозатрат.

Ключевые слова: шерсть, шерстомоечная машина, моечная ванна, гидродинамическое сопротивление, сила Архимеда, сила трения, физико-механические свойства, рабочий орган, теоретический анализ.

Introduction

This section theoretically analyzes the physical and chemical changes in the washing process of wool fiber, its structural structure and resistance to external environmental influences.

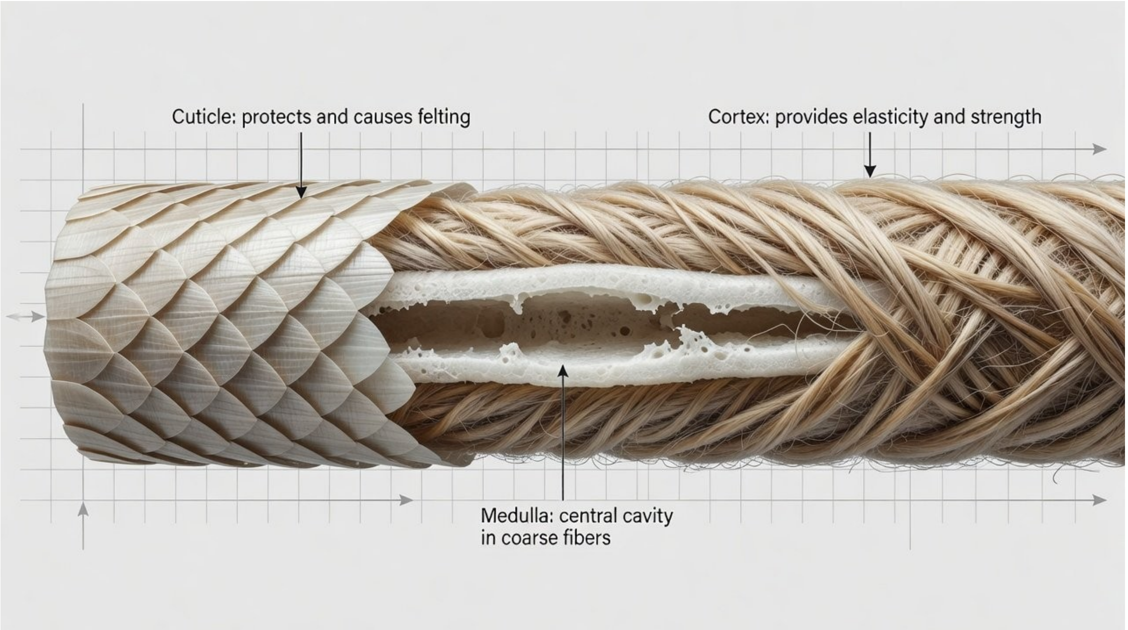
1. Physical and mechanical properties of wool fiber

Wool fiber is a natural polymer consisting of a complex protein substance - keratin. Its structure consists of three main layers:

• Cuticle (coin-shaped layer): It is the outer protective shell of the fiber, which determines its friction coefficient in the washing bath and its feel.

• Cortex (bark layer): It makes up 80-90% of the fiber and provides mechanical strength and elasticity.

• Medulla (core layer): It is found only in coarse wool and affects the heat retention ability of the fiber.



The strength of the fiber is associated with the disulfide bonds $(-S-S-¿)$. The preservation of these bonds during the washing process is a key factor determining the quality of the fiber.

2. The effect of water and washing solution on wool fiber

When wool fiber interacts with water, it undergoes changes at the molecular level:

• Swelling phenomenon: When fibers absorb water, their cross-sectional area $25-30\%$ga increases, and the change in length is less $(1-2\%)$.

• Chemical effect: The pH of the washing bath plays an important role. Wool is stable in an acidic environment, but in an alkaline environment $(pH>9)$, keratin chains are hydrolyzed, and the fiber becomes brittle.

• Hydrophobicity: The wool oil (lanolin) contained in raw wool prevents the fiber from absorbing water. Surfactants (SFM) break down this barrier and allow the fiber to be fully wetted with water.

3. Density, moisture absorption and elasticity of wool $\rho\approx1.30-1.32\,\mathrm{g}\cdot\mathrm{cm}^{-3}$

The following quantities are taken into account when calculating the condition of wool in the wash bath:

• Density: It is the average density of clean wool$\rho\approx1.30-1.32\,\mathrm{g}\cdot\mathrm{cm}^{-3}$. Since it is higher than the density of water, it causes wool fibers without air bubbles to sink in the bath.

• Moisture absorption (Hygroscopicity): Wool has moisture under normal conditions $15-17\%$. When fully saturated, it can absorb water of its own weight $30-40\%$igacha. The moisture content W is determined by the following formula:

$$W=\frac{m_{\mathrm{nam}}-m_{\mathrm{quruq}}}{m_{\mathrm{quruq}}}\cdot100\%$$

$$m_{\mathrm{quruq}}=1.00\,kg$$

$$m_{\mathrm{nam}}=1.35\,kg$$

$$W=\frac{1.35-1.00}{1.00}\cdot100\%=35\%$$

In most scientific literature, the relative humidity is given as 33-35%. [1]

• Elasticity: In an aqueous environment, the Young's modulus of wool decreases, i.e. the fiber becomes softer and more flexible. This condition, while reducing the risk of mechanical damage to the fiber in the bath, can increase its tangling.

4. Position and deformation of the wool layer in the bath

The wool layer in the bath is considered to be a non-homogeneous porous medium. The balance of forces acting on the wool layer can be expressed as follows:

1. Hydrodynamic pressure: The wool layer is compressed under the influence of the flow rate of the washing solution.
2. Compressive deformation: The density of a layer varies with height. The relationship between compressive strength $P$and layer height is often exponential:

$$\epsilon \wedge ¿ \frac{h_0 - h}{h_0}$$

$$P \wedge ¿ k \cdot \epsilon^n$$

where ϵ is the relative deformation, k is the proportionality coefficient, n is an indicator expressing the porosity of the material.

1. Felting: Under the influence of mechanical action and high temperature in the bath, the fibers of the fibers become entangled with each other, leading to irreversible deformation, i.e. felting. To reduce this, it is recommended that the temperature in the washing bath does not exceed.

Conclusion: Theoretical analysis of the wool washing process shows that in order to achieve effective cleaning, an optimal balance between hydrodynamic forces and the physical and mechanical strength of the fiber is necessary. In this case, the swelling and elasticity of the fiber are the main parameters of the technological process.

Theoretical justification of the laws of wool movement in a washing bath

In a washing bath, wool fibers and wool mass move in a fluidized bed of water or washing solution. The main purpose of this movement is to separate fat, sweat, dust, mineral impurities and other impurities from the wool. The efficiency of the process depends on the speed of the liquid flow, the effect of the working body, the physical properties of the wool and the balance of forces acting on it.

The behavior of wool in a liquid environment

When wool is immersed in a bath, it appears as individual fibers, tufts, and a porous wool layer. Liquid enters the spaces between the wool, the fibers become wet, and the bulk density changes. Therefore, the behavior of wool differs from the behavior of a simple solid: the liquid passes through the wool layer, while the fibers bend, compress, and move relative to each other.

The behavior of wool in a liquid is generally described by Newton's second law:

$$m \frac{d\vec{v}}{dt} = \vec{F}_{\text{ish}} + \vec{F}_A + \vec{G} + \vec{F}_{\text{q}} + \vec{F}_{\text{ishq}}$$

Here:

- m – effective mass of wool mass;
- $\vec{v}$ – speed of movement of wool;
- $\vec{F}_{\text{ish}}$ – force generated by a working body, flow, or mixer;
- $\vec{F}_A$ – Archimedes force;
- $\vec{G}$ – gravity;
- $\vec{F}_{\text{q}}$ – hydrodynamic resistance force;

- $\vec{F}_{\text{ishq}}$ – friction force between wool fibers and equipment surfaces.

In practice, the wool movement is often uneven and complex. This is caused by eddy currents in the bath, fiber entanglement, liquid penetration into the wool layer, and external mechanical influences.

The movement, lifting and mixing of wool under the action of the harrow

When the working body of the baron or washing machine moves, it creates a forced flow in the liquid. This flow imparts momentum to the wool mass, lifting it from the geometric bottom, moving it forward and mixing it again.

The movement of wool usually occurs in the following stages:

1. **Sliding.** The wool moves horizontally through the bath as a result of the pushing action of the working body. The movement helps to loosen the impurities between the fibers..
2. **Ascension.** The mass of wool moves upward under the influence of the geometric flow created by the working body and the lifting force of the fluid. The lifting of the wool depends on its weight and hydrodynamic resistance.
3. **Interference.** The wool is repeatedly raised and lowered, coming into geometric contact with the washing solution in the bath. As a result, the solution penetrates between the wool fibers and lifts dirt from the surface.

If the agitation is too strong, the wool fibers may be damaged or tangled. On the contrary, if the agitation is not sufficient, the washing solution will not penetrate well into the inner layer of the wool. Therefore, the speed of the working element must be optimally selected.

Hydrodynamic resistance forces

When a fluid moves in a straight line, it is affected by a hydrodynamic resistance force in the opposite direction. This force increases as the velocity of the fluid increases.

At high speeds and in turbulent flow, the resistance force is approximately determined as follows:

$$F_{\text{q}} = \frac{1}{2} C_d \rho S v_{\text{nisb}}^2$$

Here:

- C_d – resistance coefficient;
- ρ – density of the washing solution;
- S – surface of a wool tuft perpendicular to the flow;
- v_{nisb} – surface of a wool tuft perpendicular to the flow.

Since wool is a porous, flexible, and non-permanent material C_d, it is not a fixed value S. When wool is compressed, its surface area of resistance to flow decreases, and when it is expanded, it increases. In addition, internal hydraulic resistance occurs as the fluid passes through the wool layer. At low speeds, that is, when the flow is laminar, the resistance force is approximately proportional to the speed:

$$F_{\text{q}} \sim v_{\text{nisb}}$$

At high speeds, resistance depends mainly on the square of the speed.:

$$F_{\text{q}} \sim v_{\text{nisb}}^2$$

The interaction of gravity, Archimedes, and friction forces

The downward force of gravity on wool:

$$G = mg$$

is expressed as. Here is g the acceleration of free fall.

The mass of wool immersed in a liquid is also affected by the upward Archimedes force:

$$F_A = \rho g V$$

where is V the external volume occupied by the wool. Since the wool contains air voids, its initial volume may be large. During wetting, air escapes, the wool becomes denser, and the relative effect of the lifting force decreases.

The friction force arises from the mutual displacement of wool fibers, the contact between wool and the walls of the bath, nets, or surfaces of the working body. It is conditionally expressed as follows:

$$F_{\text{ishq}} = \mu N$$

Here:

- μ – coefficient of friction;
- N – normal compressive strength.

On the one hand, friction helps to properly mix the wool mass and separate dirt from the fibers. On the other hand, excessive friction can lead to breakage, felting, and deterioration of the wool fibers.

Conclusion

The movement of wool in the washing bath is determined by the combined effect of gravity, Archimedean force, hydrodynamic resistance, friction, and the forced flow created by the working body. For effective washing, the wool mass must be constantly moving, rising, and mixing in the bath. The flow rate and mechanical action must be selected so that the dirt is effectively separated, but the wool fibers are not damaged and felted.

Rotation frequency: n = 6 rpm

Radius: R = 0.67 m

Pile length: L = 0.25 m

Pile diameter: d = 0.012 m

Liquid density: ρ = 1310 kg/m^3

Resistance coefficient: Cd = 1

Number of piles: N = 260 ta

Wool weight: m=8kg

Cam angular velocity:

$$\omega = \frac{2\pi n}{60} = \frac{2*3,14*6}{60} = 0,628 \text{ rad/s}$$

3.5. Linear speed:

v = ωR

v = 0.628·0.67 = 0.42 m/s

Linear acceleration:

$$a = \omega^2 \times R = 0.628^2 \times 0.67 = 0.264 \text{ m/s}^2$$

Frontal area:

A = L·d = 0.25·0.012 = 0.003 m^2

Hydrodynamic resistance force:

$$F_q = \frac{1}{2} C_d \rho A v_{\text{nisb}}^2 = F_q = \frac{1}{2} \cdot 1 \cdot 1310 \cdot 0.003 (0.42)^2 = 0.346\, N$$

$F_q = 0.346\, N$ - this is for 1 pile

For a total of 260 piles:

$Fu = F_q \cdot N =$ ¿ 0.346·260 = 90 N

The downward force of gravity of wool:

$G = mg = 8{\cdot}9.81 = 78.48\text{N}$

Archimedes force:

$$F_A = \rho g V$$

$V = \frac{m}{\rho} = \frac{8}{1350} = 0.0059$

$F_A = \rho g V = 1310{\cdot}9.81{\cdot}0.0059 = 75.82\text{N}$

Normal compressive strength:

$\text{N} = \text{G} - F_A = 78.48 - 75.82 = 2.66\ \text{N}$

Friction force:

$F_{\text{ishq}} = \mu N = 0.25{\cdot}2.66 = 0.665\ \text{N}$

The motion of wool in a fluid is generally governed by Newton's second law.:

$$m\frac{d\vec{v}}{dt} = \vec{F}_{\text{ish}} + \vec{F}_A + \vec{G} + \vec{F}_{\text{q}} + \vec{F}_{\text{ishq}}$$

$\text{m}{\cdot}\text{a} = \vec{F}_{\text{ish}} + \vec{F}_A - \vec{G} - \vec{F}_{\text{q}} - \vec{F}_{\text{ishq}}$

$\vec{F}_{\text{ish}} = m{\cdot}a + \vec{G} + \vec{F}_{\text{q}} + \vec{F}_{\text{ishq}} - \vec{F}_A = 8 \cdot 0.264 + ¿78.48 + 90 + 0.665 - 75.82 = 95.44\text{N}$

The force generated by the working body:

$\vec{F}_{\text{ish}} = 95.44\text{N}$

Moment:

$\text{M} = \vec{F}_{\text{ish}} {\cdot} \text{R} = 95.44{\cdot}0.67 = 63.94\ \text{N}{\cdot}\text{m}$

Power:

$\text{P} = \text{M}{\cdot}\ \omega = 63.94{\cdot}0.628 = 40.15\ \text{W}$

Conclusion.

As a result of the theoretical analysis, it was determined that the physical and mechanical properties of wool in the washing bath and the laws of its movement in a liquid medium are the main factors determining the efficiency of the washing process. During the study, the interaction of moisture absorption, elasticity, density, hydrodynamic resistance, Archimedes' force and friction forces of wool fiber was scientifically substantiated. The calculation results showed that the hydrodynamic effect created by the working body ensures effective displacement, lifting and mixing of the wool mass in the bath. In this case, the optimal selection of the rotation frequency, geometric dimensions of the working body and fluid parameters allows to increase the washing quality, reduce energy consumption and prevent damage and felting of wool fibers. Thus, the theoretical results obtained serve as a scientific basis for improving the design and technological parameters of wool washing machines. The results of the study can be used in the design and production of modern wool washing equipment with high productivity, energy efficiency and high-quality washing.

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