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Development Of An Energy-Efficient Multi-Stage Cotton Drying System

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Abstract. This paper investigates the operating principles and engineering characteristics of a multi-stage cotton drying system designed for industrial cotton processing enterprises. The proposed unit improves the efficiency of thermal treatment through continuous mixing of raw cotton and counterflow movement of heated air. Special attention is devoted to heat and mass transfer processes, energy-saving operating modes, and optimization of drying parameters. The developed approach allows stable reduction of cotton moisture while minimizing fiber damage and thermal losses.

Keywords: cotton drying, heat transfer, moisture reduction, energy efficiency, drying unit, convective drying, textile engineering, automation.

Introduction

The drying of raw cotton remains one of the most critical technological stages in cotton-processing enterprises. Excessive moisture content negatively affects transportation, storage stability, cleaning efficiency, and the quality of the produced fiber. In industrial practice, insufficient drying may lead to microbial degradation, deterioration of fiber characteristics, and unstable operation of processing equipment.

Modern industrial requirements demand the creation of drying systems capable of ensuring high productivity with minimum energy consumption and limited thermal impact on the fiber structure. Traditional chamber and single-drum dryers are often characterized by uneven temperature distribution, incomplete moisture removal, and increased energy losses.

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In recent years, researchers have focused on the development of multi-stage drying technologies based on controlled airflow circulation, turbulence intensification, and repeated mixing of fibrous material. Such systems improve heat exchange conditions and create a more stable moisture removal process.

The purpose of this research is to investigate the operating principles and technological characteristics of a multi-level cotton drying unit designed for continuous industrial operation under variable moisture conditions. The proposed multi-level installation combines staged movement of cotton material with controlled circulation of the heat carrier.

Structural design of the drying unit

The proposed installation consists of interconnected functional sections that jointly ensure continuous drying of raw cotton. The engineering concept is based on the sequential movement of material through several rotating stages with simultaneous exposure to heated airflow.

The main structural elements include:

1. Cotton feeding mechanism;
2. Air supply and heat carrier distribution channel;
3. Multi-tier rotating drum assembly;
4. Intermediate transition guides;
5. Screw conveyor for discharge;
6. Settling and airflow stabilization chamber;
7. Adjustable supporting elements;
8. Protective side walls;
9. Automated monitoring and regulation subsystem.

The feeding section provides uniform delivery of raw cotton into the upper processing chamber. The rotating drum modules are positioned in several levels, creating a cascading movement of material. Each drum is equipped with internal lifting blades that intensify mixing and prevent local overheating.

The heat carrier distribution system supplies heated air into the lower part of the installation. During operation, the airflow moves upward through all technological zones, thereby creating a counterflow interaction with descending cotton material.

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The settling chamber located in the lower section reduces aerodynamic losses and minimizes fiber entrainment into the exhaust system.

Operating principle of the installation

The technological process begins with the delivery of raw cotton into the receiving chamber. After entering the first rotating section, the cotton mass is continuously lifted and redistributed by the drum blades.

Due to cyclic mixing, the following technological effects are achieved:

- equalization of temperature distribution;
- prevention of material agglomeration;
- intensification of evaporation processes;
- increase in contact surface area;
- stabilization of moisture removal.

The heated airflow generated by the thermal source enters the lower zone of the dryer and passes upward through the material layers. Such counterflow organization significantly increases thermal efficiency because the hottest air interacts with the wettest cotton layers.

As the cotton passes through each subsequent drum level, the moisture content gradually decreases. The final stage includes discharge into the screw conveyor and transfer to subsequent technological operations.

Heat and mass transfer analysis

The drying mechanism is based on simultaneous heat transfer from the air medium to the cotton fibers and diffusion-driven moisture removal.

The total heat supplied to the material can be estimated using the classical thermal relationship:

$$Q = mc\Delta T$$

where:

Q — amount of heat transferred to cotton,

m — air flow mass,

c — air heat capacity,

ΔT — temperature difference.

The evaporation intensity depends on the interaction area between air and cotton fibers as well as the vapor pressure gradient.

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The moisture removal process may be represented as:

$$W = kA(P_w - P_a)\tau$$

where:
W — amount of removed moisture,
k — mass transfer coefficient,
A — contact area,
Pw — partial vapor pressure of moisture in cotton,
Pa — partial vapor pressure of moisture in air,
τ — interaction time.

The multi-stage drum configuration increases turbulence intensity and enhances constructive exchange processes. Repeated redistribution of the cotton layer improves temperature uniformity and reduces local overheating risks.

Technological parameters.

The experimental and engineering analysis of the drying system was carried out under industrial operating conditions.

Parameter	Value
Initial cotton moisture	25%
Final moisture content	8–10%
Heat carrier temperature	110–130 °C
Processing capacity	1500 kg/h
Dryer efficiency coefficient	0.70
Average moisture removal	150 kg per 1000 kg

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The obtained indicators demonstrate that the developed installation is suitable for continuous industrial application in cotton-processing enterprises.

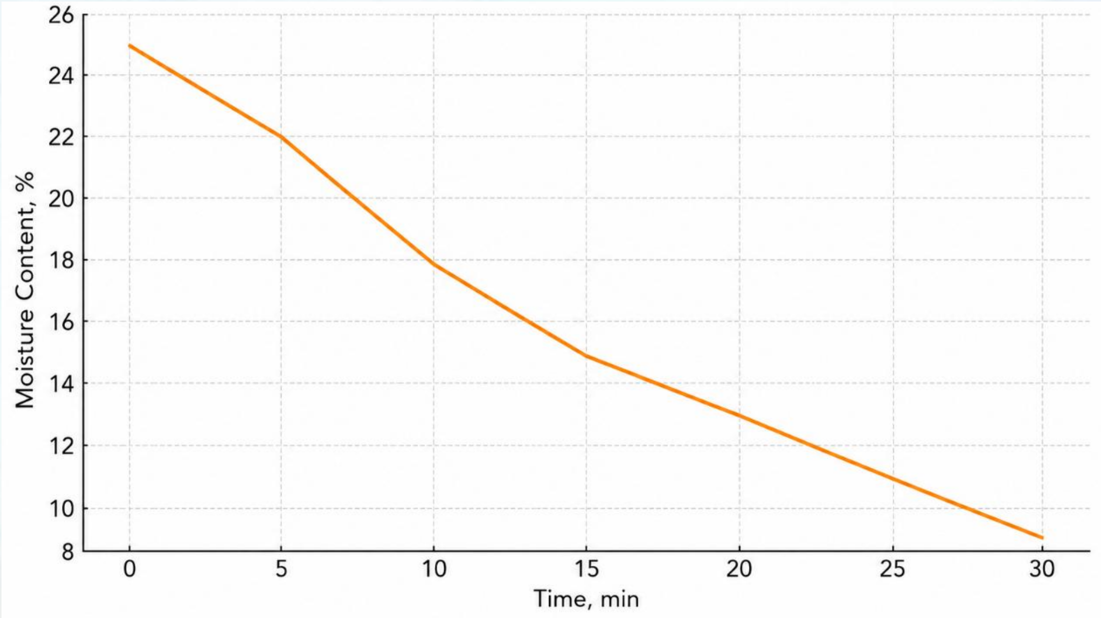

Figure 1. Reduction of cotton moisture over time

Engineering Estimation of Energy Consumption

The evaporation of moisture from fibrous material requires significant thermal energy. For engineering calculations, the latent heat of water evaporation is accepted as 2250 kJ/kg.

For a processing cycle involving removal of 150 kg of moisture from 1000 kg of raw cotton:

$$Q_{used} = 150 \times 2250 = 337{,}500 \text{ kJ}$$

Considering the dryer efficiency $\eta = 0.7$:

$$Qt = Q_{used} / \eta = 481{,}000 \text{ kJ}$$

At an efficiency value of η=0.7, the total required thermal energy reaches approximately 481000 kJ.

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The calculations confirm that optimization of airflow circulation and staged drying significantly reduces overall energy losses compared with conventional drying systems.

Advantages of the proposed system

The developed drying installation possesses several technological and operational advantages:

- improved uniformity of cotton drying;
- reduction of thermal damage to fibers;
- increased interaction surface between air and material;
- stable operation under variable moisture conditions;
- reduced probability of local overheating zones;
- higher productivity due to multi-level organization;
- possibility of automated parameter control;
- improved energy efficiency of the technological process.

The staged arrangement of rotating drums ensures gradual dehydration without abrupt thermal loading, which positively affects fiber preservation.

Prospects for modernization

Further improvement of the system may include the integration of intelligent monitoring technologies and adaptive control algorithms.

Promising modernization directions include:

- installation of distributed moisture sensors;
- automatic regulation of airflow temperature;
- implementation of recirculation channels;
- application of intelligent process control methods;
- digital monitoring of energy consumption;
- integration with industrial SCADA systems.

The application of intelligent automation can significantly improve drying stability and reduce energy expenditure in large-scale industrial facilities.

Conclusion

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The conducted study confirms the efficiency of the proposed multi-stage cotton drying system intended for continuous industrial operation. The developed installation combines counterflow airflow organization, repeated material mixing, and staged moisture reduction, which together ensure improved heat and mass transfer conditions.

The engineering calculations and technological analysis demonstrate that the system provides stable reduction of cotton moisture while maintaining the structural integrity of fibers. The use of rotating multi-level drums increases drying uniformity and contributes to energy savings.

The proposed design can be recommended for implementation at modern cotton-processing enterprises and may serve as the basis for further scientific research related to intelligent process automation and optimization of thermal treatment technologies.

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