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RESEARCH OF HYDRODYNAMICS OF GAS FLOW FILTRATION THROUGH A STATIONARY LAYER OF CRUSHED COTTON STALKS (WILD COTTON)

The object of this research is the hydrodynamics of the stationary layer of crushed cotton stalks. One of the most problematic areas is the influence of the physical and mechanical characteristics of the stationary layer of crushed cotton stalks on the hydrodynamics of filtration drying.

In the course of research, methods of physical and mathematical modeling are used. Sieve analysis is used to determine the granulometric composition of the polydisperse mixture of crushed cotton stalks.

The granulometric composition of the crushed stalks of cotton is determined and the graphical dependence of the percentage of each fraction is presented. The hydrodynamics of gas flow filtration through a stationary layer of crushed cotton stalks are experimentally investigated, and a graphical dependence of pressure losses on the fictitious rate of gas flow filtration is presented. It is found that pressure losses in the stationary layer of crushed cotton stalks are parabolic, which indicates the influence of both inertial and viscous components on pressure losses. The unknown coefficients of the modified Ergun equation are determined on the basis of experimental data. The correlation dependence between the experimental and theoretically calculated values is presented and it is shown that the maximum relative error is 9.6 %, which is quite acceptable for practical calculations. The results of experimental studies are also presented in the form of a graphical dependence of the Euler number on the Reynolds number. Based on the generalization of the experimental data, the calculated dependences are obtained in the form of dimensionless complexes, which describe the hydrodynamics of the gas flow filtration through a stationary layer of crushed cotton stalks. This makes it possible to predict the energy costs for creating a differential pressure, with an accuracy sufficient for practical calculations. The ratio of the experimental values of pressure losses to the theoretically calculated ones, depending on the Reynolds number, is graphically presented. It is shown that the maximum relative error does not exceed 8 %. The proposed generalizations of experimental data will make it possible to determine the energy consumption for creating a pressure drop at the design stage of the drying equipment, as well as to calculate the optimal process parameters and predict its economic feasibility.

Keywords: *cotton stalks, particle size distribution, porosity, pressure loss, stationary layer, fibrous particles.*

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1. Introduction

The increase in capacities in agricultural production creates favorable conditions for the expansion and modernization of processing industries for regions with favorable natural and climatic conditions for agricultural production.

The integrated use of industrial waste and the attraction of secondary resources for reuse in the production process is aimed at optimizing the resource potential. Depending on the nature of the technology and the combination of individual stages in the production process in the system of the agricultural sector, the integrated use of waste provides for the maximum use of all useful components of raw materials. Let's consider this issue on the example of Kazakhstan.

According to the State Program for the Development of the Agroindustrial Complex of the Republic of Kazakhstan for 2017–2021 [1], by 2021 the sown area of cotton in the South-Kazakh region should increase by 100 thousand hectares, the yield – up to 30 centner/ha, and cotton production up to 300 thousand tons/year. Therefore, the modernization of cotton processing is extremely important for the development of the economy of Kazakhstan. At the same time, large-tonnage waste of cotton stalks (wild cotton) is generated annually, which is one of the promising secondary sources of cellulose-containing raw materials of organic origin. Some of the cotton stalks are used by local residents as cheap fuel, but a significant part of the cotton stalks are not used effectively. Often, cotton stalks are burned directly in the fields, harming the environment or plowing, which threatens the transmission of diseases to new cotton plantations. Therefore, the problem of their rational use requires a technical solution. With appropriate technical solutions, this waste could become a secondary raw material for:

– production of lightweight construction concrete [2];
– inexpensive heat-insulating structural and building material [3, 4];
– lightweight composite wood-plastic boards [5, 6];
– adsorbents [7];
– obtaining biologically active compounds and polysaccharides [8, 9];
– solid environmentally friendly biofuel [10, 11].

To use cotton stalks as a secondary raw material, it must be crushed and dried to the final moisture content $\omega_f^c = 10 \div 12$ kg H_2O/kg dry matter.

One of the highly efficient methods for drying wet materials is filtration drying, the essence of which is the filtration of a thermal agent through a stationary layer of dispersed material due to a pressure drop. Energy costs in this case consist of pressure losses in the stationary layer of dispersed material and energy for heating the thermal agent.

The movement of a gas flow through a porous stationary layer of material largely determines the kinetics of filtration drying of the material [12]. There is a close relationship between the rate of drying of wet material during filtration drying and the hydrodynamics of the process. This process is significantly influenced by the nature of the velocity field of the gas flow that washes individual particles of dispersed material, determines the mode of movement, and, accordingly, the heat transfer and mass transfer coefficients. In addition, the gas flow rate affects the thickness of the boundary layer around the particle, which determines the intensity of the process, both heat transfer and moisture mass transfer.

The influence of hydrodynamics of gas and dispersed material flows in continuously operating shaft-type dryers, in which the authors take into account the inhomogeneity of the gas flow velocity field on the rate of drying of polymer materials, given in [13]. The study of the hydrodynamics of a stationary layer of various dispersed materials is devoted to the work [14]. It analyzes a large number of experimental research results of many scientists. The coefficient of hydraulic resistance of the stationary layer of dispersed material was determined when filtering the gas flow in the direction of «perforated partition – dispersed material» within the gas velocity, did not exceed the rate of fluidization of the layer. The results obtained by various authors are given in dimensionless form. At the same time, this work shows a large discrepancy between the calculated dependencies proposed by the authors, as well as the boundaries of their application with respect to the modes of gas flow. The calculated dependences obtained in these works cannot be used to predict pressure losses during filtration drying of crushed cotton stalks for two reasons. Firstly, the perforated partition on which the dispersed material is located determines the shape of the gas flow, which is filtered through a stationary layer of dispersed material. That is, the open area of the perforated partition, the shape, size and number of holes will determine the velocity field of the gas flow in the stationary layer of dispersed material. Secondly, for a mathematical description of the hydrodynamics of the gas flow through a stationary layer of dispersed material, it is necessary to numerically determine the physical and mechanical characteristics of the layer. At the same time, there are currently no generally accepted methods for determining the average sizes of irregularly shaped particles that form a stationary layer.

In [15], to calculate the pressure loss in a stationary layer of a polydisperse material (granular polyacrylamide, superphosphate, sand, etc.), a modified Ergun equation was used. But this method [14] for the theoretical, in comparison with the experimental data, gives an error of 36 to 58 %, which is certainly unacceptable for practical calculations. This discrepancy is explained by the polydispersity, heterogeneity and spontaneity of the formation of a stationary layer of dispersed material. The authors of [16, 17] investigated the pressure loss in a stationary layer of peat, sand and zeolite and presented generalizations of the results of experimental studies in the form of the linearized Darcy-Weisbach equation. However, the calculated dependences obtained by them relate exclusively to the materials they study and it is impossible to apply them to other materials due to the above reasons. Justification of the limited application of the obtained calculated dependences for predicting pressure losses in a stationary layer for specific dispersed materials are given in [18, 19]. Each dispersed material is characterized by specific physical and mechanical features, such as shape, size and surface roughness of particles, polydispersity, porosity of the stationary layer, equivalent diameter and curvature of channels between particles. The use of known calculated dependencies to predict pressure losses for other materials that are not similar in structural structure, materials or other modes of gas flow, or in apparatuses with other geometric dimensions, is extremely difficult.

Thus, *the object of research* is the hydrodynamics of a stationary layer of crushed cotton stalks. *The subject of research* is the influence of the physical and mechanical characteristics of the stationary layer of crushed cotton stalks on the hydrodynamics of filtration drying. *The aim of this research* is to experimentally study the effect of the physical and mechanical characteristics of the stationary layer of crushed cotton stalks on pressure losses during filtration drying.

2. Methods of research

Experimental studies of the movement of a gas flow in the direction «stationary layer of dispersed material – perforated partition» were carried out according to a technique approved by many authors, which is described in detail in [12].

To determine the pressure loss in a stationary layer of dispersed material, the Darcy-Weisbach dependence is also used [20]:

$$\Delta P = \lambda_l \cdot \frac{H_e}{d_e} \cdot \frac{\rho \cdot \upsilon^2}{2}, \qquad (1)$$

where λ_1 – coefficient of layer resistance; H_e – equivalent length of the channels through which the gas flow moves, m; d_e – equivalent diameter, m; ρ – density of the gas flow, kg/m^3; υ – true velocity of movement of the medium, m/s.

Taking into account that the coefficient of hydraulic resistance λ_1 is a function of the Reynolds number, equa-

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tion (1) can be represented as a two-term equation that takes into account friction losses and local resistance losses:

$$\Delta P = A \cdot \frac{\mu \cdot a^2}{32 \cdot \varepsilon^3} \cdot H_e \cdot \upsilon_0 + B \cdot \frac{\rho \cdot a}{8 \cdot \varepsilon^3} \cdot H_e \cdot \upsilon_0^2, \quad (2)$$

where A and B are unknown coefficients that are determined experimentally; μ – coefficient of dynamic viscosity of the gas flow, Pa·s; a – effective specific surface area of all particles of the stationary layer of dispersed material, which is washed by the gas flow, m^2/m^3; ε – share of voids per unit volume of a stationary layer of dispersed material (porosity), m^3/m^3; υ_0 – fictitious gas filtration rate, m/s.

To determine the unknown coefficients A and B, equations (2) should be linearized with respect to the fictitious rate of filtration of the gas flow and presented in the form:

$$\frac{\Delta P}{H \cdot \upsilon_0} = A^* + B^* \cdot \upsilon_0, \quad (3)$$

where

$$A^* = A \cdot \frac{\mu \cdot a^2}{32 \cdot \varepsilon^3}$$

and

$$B^* = B \cdot \frac{\rho \cdot a}{8 \cdot \varepsilon^3}.$$

The first component of this equation is a constant (for specific conditions of the experiment), in the second component, the variable is only a fictitious velocity.

The unknown coefficients of equation (3) for cotton stalks were determined experimentally under the conditions of the experiment and can be used for practical calculations of drying equipment. It is possible to predict the pressure loss during filtration drying only in a given course of the experiment, the range of gas flow rates.

However, in practice, it is quite convenient to use the calculated dependences presented in dimensionless form, taking into account the mode of gas flow and the influence of the geometric parameters of the drying unit on the pressure loss in the stationary layer of dispersed material. In this case, the pressure loss is presented in the form of a functional dependence of the Euler criterion on the Reynolds criterion and the geometric simplex, that is:

$$Eu = f(Re, \Gamma) = A \cdot Re^x \cdot \Gamma^y,$$

or

$$Eu = A \cdot Re^x \cdot \left(\frac{H_e}{d_e}\right)^y, \quad (4)$$

where Eu – Euler criterion;

$$Eu = \frac{\Delta}{\rho \cdot \upsilon^2},$$

Re – Reynolds criterion:

$$Re = \upsilon \cdot d_e \cdot \frac{\rho}{\mu}.$$

The unknown values of the constant A and the exponents x and y are determined experimentally. This form of presentation of the generalization of experimental data makes it possible, using the theory of similarity, to predict pressure losses in filtration drying installations under similar regimes of gas flow.

3. Research results and discussion

The object of experimental research was crushed cotton stalks. Cotton stalks were crushed on a DKU-M crusher (Ukraine). Crushed cotton stalks weighing 6 kg were sieved through a sieve with round holes 10 mm in diameter. The particles that passed through the holes of the sieve with a diameter of 10 mm and a mass of 4 kg were divided into 7 fractions. The rest of the material that remained on each subsequent feed was weighed using an AXIS-AD3000 analytical balance (Poland) with a measurement accuracy of up to 0.01 g, and the content was calculated by weight. The results of the sieve analysis are shown in Table 1 and Fig. 1.

Table 1

Fractional composition of crushed cotton stalks

Fraction $d \cdot 10^3$, m	0.25–0.5	0.5–1.0	1.0–2.0	2.0–3.0	3.0–5.0	5.0–7.0	7.0–10.0	Total
G, kg	0.188	0.268	0.372	0.724	1.088	0.584	0.776	4.0
%, mass	4.7	6.7	9.3	18.1	27.2	14.6	19.4	100

Note: G – mass of fraction, kg; % mass – mass percent

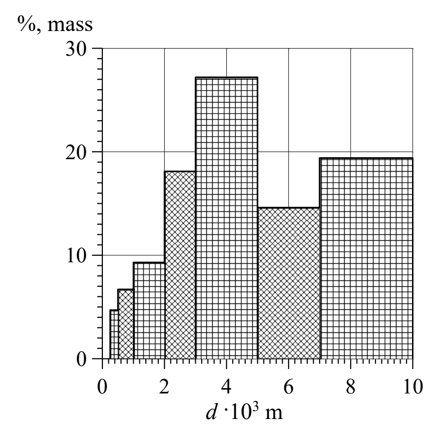

Fig. 1. Granulometric composition of crushed cotton stalks

Experimental studies of the hydrodynamics of gas flow filtration through a stationary layer of crushed cotton stalks were carried out according to the method described in [12]. The results of experimental studies of pressure losses as a function of fictitious velocity for material layer heights of 60, 80, 100, 120, 140, and 160 mm are shown in Fig. 2.

Analysis of Fig. 2 shows that an increase in the height of the stationary layer of crushed cotton stalks from 60 to 160 mm leads to an increase in pressure losses at a velocity of υ_0=1.5 m/s from 3000 to 7400 Pa and at a velocity of 2.5 m/s will not exceed 15000 Pa. Therefore, given the insignificant pressure loss in the stationary layer of crushed cotton, the filtration drying method can be recommended for use as one of the highly efficient and energy-saving methods. At the same time, the curves shown are parabolic. This means that the hydraulic resistance of the material under study is due to both inertial and viscous components.

To generalize the results of experimental studies shown in Fig. 1, le’ts use the Darcy-Weisbach dependence presented in the form of a two-term equation (3). For this, let’s present the results of experimental studies shown in Fig. 1, in the form of a functional dependence in Fig. 3.

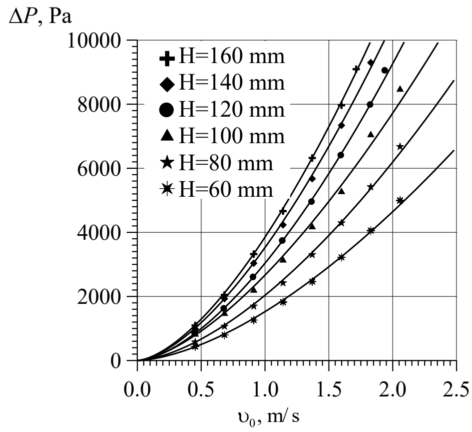

Fig. 2. Dependence of the pressure loss ΔP in a stationary layer of various heights H of crushed cotton stalks, depending on the fictitious rate of filtration of the gas flow υ_0

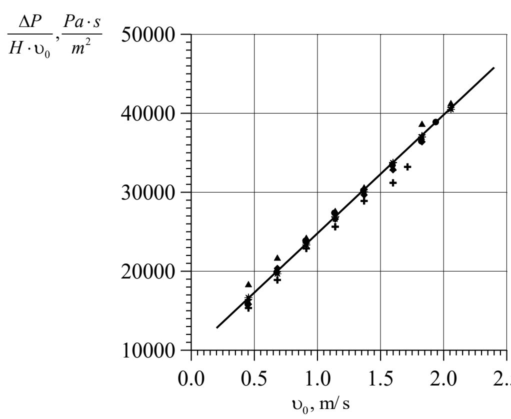

Fig. 3. Dependence $\Delta P/(H\cdot\upsilon_0)=f(\upsilon_0)$ for crushed cotton stalks (designations correspond to Fig. 1)

The experimental data approximated by a linear dependence is the value:

$$A^*=A\cdot\frac{\mu\cdot a^2}{32\cdot\varepsilon^3}$$

determined by the segment that directly cuts off on the ordinate axis, and the value:

$$B^*=B\cdot\frac{\rho\cdot a}{8\cdot\varepsilon^3}$$

beyond the tangent of the angle of inclination of the straight line to the abscissa axis.

Then equation (3) can be represented as:

$$\frac{\Delta P}{H\cdot\upsilon_0}=9800+15000\cdot\upsilon_0. \qquad (5)$$

The obtained dependence can be used to predict pressure losses in the stationary layer of crushed cotton stalks during practical calculations of drying equipment within the studied filtration rates of the gas flow.

Fig. 4 shows a comparison of the experimental values with those calculated on the basis of dependence (5).

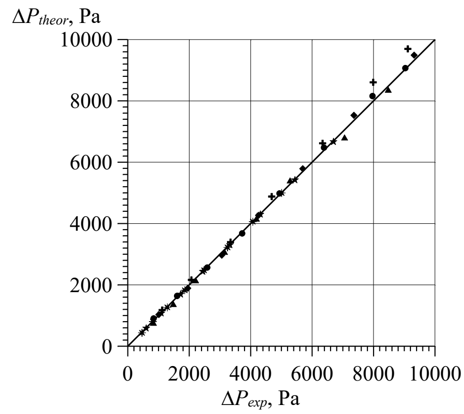

Fig. 4. The correlation dependence between the experimental values shown in Fig. 1, and calculated on the basis of dependence (5) (designations correspond to Fig. 1)

The absolute value of the relative error between the experimental data and the calculated values was calculated based on the equation:

$$\delta=\left|\frac{\Delta P_{\exp}-\Delta P_{theor}}{\Delta P_{\exp}}\right|\cdot 100\ \%. \qquad (6)$$

Analysis of Fig. 4 shows that the absolute value of the relative error between the experimental data and those calculated on the basis of dependence (5) does not exceed 9.6 %. This is acceptable for practical use in the design of new drying equipment.

To obtain the calculated dependences in the form of dimensionless complexes, the experimental results are shown in Fig. 2, were presented in the form of the dependence of the Euler number on the Reynolds number (Fig. 5).

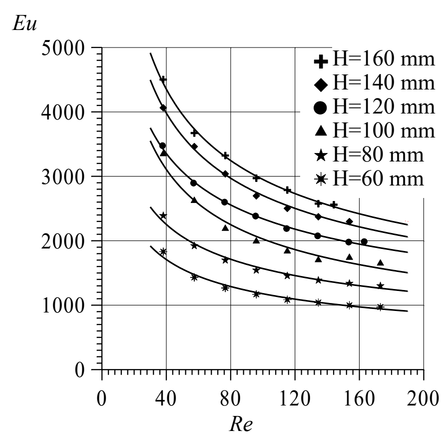

Fig. 5. Dependence of the Euler number on the Reynolds number for different heights of the stationary layer of crushed cotton stalks

Analysis of Fig. 5 shows that the Euler number depends on the height of the stationary layer of the material, and the experimental points are fairly well approximated by a power law. The curves for all heights are practically parallel to each other, and the distance between the curves is proportional to the height of the stationary layer.

Approximation of the experimental data shown in Fig. 5, the power function made it possible to determine the exponent of the Reynolds number, which for all heights is 0.4, and the unknown coefficient A for each height has a different value. The results of the study are shown in Table 2.

Table 2

Dependence of unknown coefficients and exponents on the height of the stationary layer of crushed cotton stalks

H, m	0.16	0.14	0.12	0.10	0.08	0.06
$H_e = 1.5 \cdot H$ m	0.24	0.21	0.18	0.15	0.12	0.09
H_e/d_e	187.06	163.68	140.29	116.91	93.53	70.15
A^*	18800	17200	14700	13000	9800	7400
n	0.4					

In order to obtain a generalizing dependence for all investigated heights in Fig. 6 shows the dependence $A = f(H_e/d_e)$. As it is possible to see, the unknown coefficients A^* determined for each layer height fall on a straight line, but approximating these values by a power function will allow to determine the unknown coefficient A and the exponent of the geometric simplex (H_e/d_e), which is equal to one. The research results are shown in Table 2.

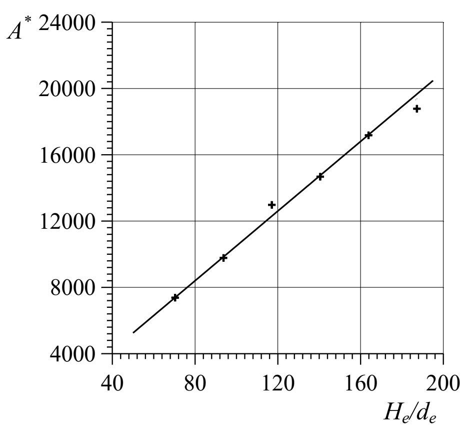

Fig. 6. Dependence of the coefficient A^* on the geometric simplex H_e/d_e

Based on the generalization of the experimental data shown in Fig. 2, the calculated dependence (4) can be represented as:

$$Eu = 105 \cdot Re_e^{-0.4} \cdot (H_e/d_e). \qquad (7)$$

This dependence is valid in the value of the Reynolds number $40 \ll Re \ll 180$.

Fig. 7 shows the correlation dependence between the dependence $\Delta P_{\exp}/\Delta P_{theor}$ on the Reynolds number in the stationary layer of crushed cotton stalks. The theoretical values of pressure losses are calculated based on dependence (7).

Analysis of Fig. 7 shows that the absolute value of the maximum error between the experimental data on pressure losses in the stationary layer of crushed cotton stalks and those calculated on the basis of dependence (7) does not exceed 8 %. It is quite acceptable for using dependence (7) for design calculations of pressure losses in the design of new drying equipment.

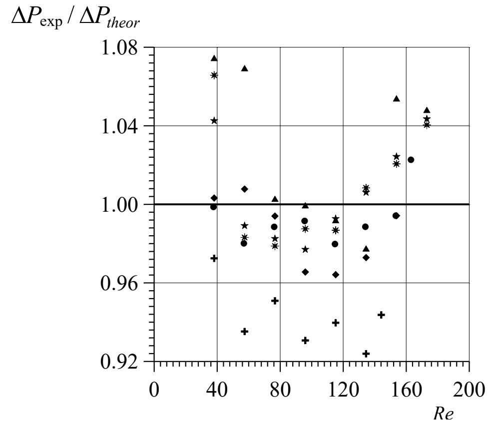

Fig. 7. Dependence of $\Delta P_{\exp}/\Delta P_{theor}$ on the Reynolds number (designations correspond to Fig. 2)

The presented calculated dependences of the righteous within the Reynolds numbers $40 \ll Re \ll 180$ for cotton stalks, crushed on a GKU-M crusher, and with a granulometric composition, are shown in Fig. 1.

4. Conclusions

A generalization of the experimental data in the form of dimensionless complexes is proposed:

$$Eu = A \cdot Re^x \cdot \left(\frac{H_e}{d_e}\right)^y,$$

and also the unknown coefficients of this equation are determined: $A = 105$, $x = -0.4$, $y = 1$.

Comparison of experimental and theoretically calculated data showed that the absolute value of the maximum relative error does not exceed 10 %, which is acceptable for design calculations of filtration drying installations.

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