Journal of Engineering and Applied Sciences 13 (Special Issue 8): 6517-6526, 2018
ISSN: 1816-949X

Modeling the Process of Heap Separation in the Grain Harvester Cleaning System

Ildar I. Gabitov, Ildar D. Badretdinov, Salavat G. Mudarisov, Eduard R. Khasanov,
Ramil L. Lukmanov, Ruslan R. Nasyrov, Marat F. Tuktarov,
Dinar T. Atnagulov, Ildar A. Timeriashev and Viktor A. Pavlenko
Federal State Budgetary Educational Establishment of Higher Education,
"Bashkir State Agrarian University", 50 Letia Octyabrya Street 34, Ufa, Russia

Abstract: The purpose of this study is to substantiate the design and technological parameters of the grain harvester cleaning system as well as the justification of the air-sieve parameters of the grain heap for implementing the mathematical model for describing the technological process of the grain harvester cleaning system operation. We established the flow regimes of the mixture "Air-grain heap-sieve" and "Air-chaff", determined by the Reynolds number and the volume concentration of polydisperse particles. To calculate these parameters, the method is given for determining the speed of air flow to provide air-sieve cleaning of grain heaps and for the separation of light chaff. As a result, the speed of the air flow was determined to provide pneumatic-sieve separation and uniform distribution over the sieve area for different crops 2.3, ..., 6.3 m/sec, mass concentration $M = 0.102, ..., 0.474$, the volume concentration of grain heap $\Phi = 9.2 \cdot 10^{-5}, \ldots, 4.25 \cdot 10^{-4}$, the Reynolds number of the grain heap is 125, ..., 1884; The aerodynamic coefficient of resistance of grain heap is 0.19, ..., 0.59 which are necessary for the implementation of mathematical models of the technological process of the grain harvester cleaning system by the methods of mechanics of two-phase flows.

Key words: Grain combime harvester, cleaning system, heap separation, technological process modeling, mathematical description, Russia

INTRODUCTION

In grain harvesters, the process of separating the grain heap from large chaff (spikelets, straw residues, etc.) and lightchaff (glume, small weed seeds, etc.) occurs by the air-sieve in the cleaning system. However, the existing air-sieve cleaning systems have a number of significant drawbacks in the quality of the technological process of separating the grain heap from chaff. This occurs with increasing flow, uneven maturation of the bread mass, different concentrations of particles (grain and chaff) and uneven grain heap coming into the cleaning system, humidity and content of chaff, during harvesting on the slopes which is due to unevenness or irregularity in the distribution of air flow throughout the entire area of the sieve due to imperfections in existing designs cleaning system and lack of a complete theoretical description of the study and methods for their design and technological parameters (Mudarisov *et al*., 2017; Badretdinov and Nasyrov, 2017).

Yermol'ev and Muratov in their research simulated the process of the fan operation by air-sieve cleaning of the combine harvester using the iteration method and integral dependences describing the air flow velocity and revealed the unevenness of the air flow and its distribution on the sieves (Ermolev and Muratov, 2011).

Alferov developed a mathematical model of the motion of an element of a layer along the surface of the sieves in the form of systems of differential equations, the upward and the downward motion are considered separately. The grain heap is considered by the available coefficient of sailing capacity and the frictional properties of the straw. The direction of the inertia force of the layer element above the sieve from the sieve vibrations is given by the angle which is defined as a function of time.

In his researches Sorochenko when describing the motion of grain heap used the mathematical model of Alferov for the case of a combine harvester on slopes (Sorochenko, 2016, 2017).

Baran and Popov used modern Computer-Aided Engineering (CAE)-technologies to simulate the process of grain and chaff separation into fractions, they considered the movement of two phases of particles (grains and chaff) in the aerodynamic flow of the cleaning system of a combine harvester. Numerical modeling of airflow motion is made on the basis of Navier-Stokes

Corresponding Author: Ildar I. Gabitov, Federal State Budgetary Educational Establishment of Higher Education, "Bashkir State Agrarian University", 50 Letia Octyabrya Street 34, Ufa, Russia

equations and k-aturbulence. The motion of two phases of particles of grain and chaff was described by the method of Lagrangian multiphase.

Modeling of grain separation at a purification unit refers to the mathematical description and quantitative determination of the frequency distribution and cumulative distribution of purified, separated grain through the sieve of a purification unit that is subjected to the vibrational action of the forces created by the airflow of the fan and the gravitational forces influencing the grains. The literature mentions various approaches that extend from physical measurements and empirical equations to analytical systems of equations and more recently, stochastic models. Various differential models describe the influence of the main technological parameters on the separation of grain and grain losses, the cleaning unit (Miu, 2015).

Beck developed a convective-diffusion model of stochastic grain motion through a layer on the upper part of the sieve and explained that the grain separation occurs in a spasmodic process, according to the laws of convection (constant downward motion) and diffusion (random distribution). The model assumes that the grain is concentrated in the upper part of the bulk layer while the layer moves over the sieve at a constant speed, the grain passes through the layer, thus, separation takes place. It is also assumed that the grain distribution in the layer always obeys the normal distribution law (Miu, 2015; Spokas *et al*., 2016; Kutzbach, 2001; Anonymous, 2014).

Kutzbach and Beck conducted a comprehensive study and collected all existing mathematical models of grain separation in the grain harvester cleaning system, starting with the simplest exponential to complex functions (Kutzbach, 2001).

According to the theory of observations (Miu, 2015; Rademacher, 2003), it is assumed by the theory of probability that the free grain will pass through the sieve holes if the grain projection on the surface of the sieve hole is within this region.

Voicu *et al*. (2008) published their research on the adequacy of the description of the experimental grain separation data for various statistical distribution laws (normal, γ-gamma, Weibull and β-beta). According to the results of their research, the best results were obtained for γ-gamma and β-beta distributions with a correlation close to one (Voicu *et al*., 2008). And in the Schreiber and Kutzbach Model, the step gradient corresponding to the separation of the peaks is not considered (Kutzbach, 2001).

Their research was continued by Miu (2015) who used the one-dimensional Weibull distribution and considered that the total grain movement in the layer can be divided into at least a few: grain separation to the upper part of the sieve (the diffusion generated by the sieve vibrations), grain motion along the sieve, the grain passes through the sieve holes (Ermolev and Muratov, 2011; Esfahani *et al*., 2013; Kutzbach, 2001; Miu, 2015; Spokas *et al*., 2016; Anonymous, 2014). To obtain the grain motion function Kundu and Gupta (2014) proposed to use the generalized two-dimensional Weibull distribution.

The accuracy of the mathematical description of the technological process of the combine harvester cleaning system largely depends on how the model takes into account the presence and intensity of the interfacial interaction (particle relaxation time, Froude number), exchange processes, particle concentration and so on. It is needed to establish a regime for the interaction of a “Gas-particle” (air-grain and air-chaff) which is determined by the Reynolds number of the particle Re_p and the volume concentration of the particles Φ as well as the kinematic (structural-technological) parameters of the sieve mill to account for the inertia force. In turn in order to determine these parameters, it is necessary to know the amount of material coming in for cleaning (flow capacity), the speed of airflow and particles and the coefficients of their aerodynamic resistance (Mudarisov *et al*., 2017; Badretdinov and Nasyrov, 2017; Miu, 2015).

Purpose of the study. To substantiate the parameters of the air flow and grain heap (particles with different physical and mechanical properties) for the implementation of the mathematical model of the technological process of the grain harvester cleaning system operation, taking into account its design and technological parameters.

MATERIALS AND METHODS

In the grain harvester cleaning system, the technological process of air-sieve separation of a grain heap from chaff can be mathematically described as a complex system of polydisperse two-phase flow, taking into account the forces of gravity, friction and inertia where one phase is the air created by the fan and the second is the particles. Particles (solid) in this case can be of different concentrations and have suchphysico-mechanical properties as mass, density, geometric dimensions, humidity, elasticity, sailing capacity, etc. The difference in the physico-mechanical properties of the phases determines the nature of the interaction of air and particles. The inertia and sailing capacity of different particles (heavy-seeds, light-chaff, husk) leads to different separation of the trajectories of motion from the air. In such flows, light particles are moved (stratified) by the air flow due to the aerodynamic drag force which exceeds the gravitational forces caused by the difference in air and particle velocities. Heavy particles predominantly move (separated from the light ones) under the action of gravity and inertia of the sieves while the aerodynamic drag force acts insignificantly (Mudarisov *et al.*, 2017; Badretdinov and Nasyrov, 2017; Mudarisov and Badretdinov, 2013; Vasilevskii *et al.*, 2013; Ermolev and Muratov, 2011). The aerodynamic drag force is determined from the expression:

$$\overrightarrow{F_A} = C_D \rho \frac{\pi d_p^2}{4} \left|\overrightarrow{U} - \overrightarrow{V}\right| (U - V) \quad (1)$$

Where:

C_D = The aerodynamic coefficient of the particle drag
ρ = The density of the air (kg/m^3)
d_δ = is the particle diameter (m)
U = The air flow speed by the fan (m/sec)
V = The particle speed (m/sec)

The aerodynamic drag coefficient of the spherical particles C_D is determined according to the Rayleigh curve as a function of the Reynolds number Re (C_D = f (Re)) (Anonymous, 2014; Badretdinov and Nasyrov, 2017). In this case, the Reynolds number is determined by the Eq. 2:

$$Re_p = \frac{d_p \rho_g |U - V|}{\eta} \quad (2)$$

Where:

ρ_g = The desity of the air (ρ = 1.225 kg/m^3)
η = The dynamic viscosity of air, Pa•s (at 200 η = 1.82•10-5 Pa•s)

The coefficient of particle resistance in the environment of other particles differs from the value of $C_D$obtained for a single particle in an unlimited flow, because in confined conditions, the interaction of particles with each other and with the walls limits the flow.

One of the most important functional parameters of the motion of a layer on the surface of a sieve is the Froude number which expresses the ratio of the forces acting on the particle lying on the sieve, the amplitude of sieve vibrations and gravity. This number can be expressed as follows (Miu, 2015):

$$F_r = \frac{A\omega^2 \sin(\beta - \alpha)}{g \cos\alpha} \quad (3)$$

Where:

A = The amplitude of sieve vibrations (A = 0.02 m)
ω = The angle speed of the leading lever shaft (ω = 28 rad/sec)
β = The angle af vibrations directions (β = 8°C,..., 36°C)
α = The sieve inclination angle (α = 7°C)
g = The free fall acceleration (m/sec^2)

Mathematical description of the process of interaction of air flow with grain heap. We consider the case when the main influence on the motion of particles is exerted by the force of aerodynamic drag and the force of gravity, the Lagrangian equations of motion have the form:

$$\frac{dv_i}{dT} = \frac{u_i - V_i}{T_p} \pm g \quad (4)$$

We obtain the equations of pulsational motion of inertial particles. At the basis of the developed approach to the derivation of the pulsation equations of the polydisperse phase is the application of the procedure of averaging the Reynolds number to the actual Lagrangian equations for particles.

Heterogeneous flows have a number of their own specific characteristics. These characteristics of heterogeneous streams are intensive and extensive. Intensive values include physical properties of particles such as their geometric parameters (equivalent diameter) $d_p$and density ρ_δ.

The dynamic inertia of particles (the time of the particle action in the air flow) is determined by the time of their relaxation τ_δ (the time of dynamic particle relaxation) which has the following form:

$$\tau_p = \frac{\rho_p d_p^2}{18\mu C} \quad (5)$$

where, C is the correction function:

$$C = \begin{cases} 1+^{Re_p^{2/3}} / 6 \text{ with } Re_p \leq 10^3 \\ 0.11^{Re_p} / 6 \text{ with } Re_p \leq 10^3 \end{cases} \quad (6)$$

where, μ is the kinematic air viscosity (with 20°Cμ = 1.51•10^{-5} m^2/sec). The inertia of a particle depends on the characteristics of the airflow in which it is moving. The correction function C takes into account the effect of inertia forces on the particle relaxation time. Thus, when the particle moves, its inertia also depends on the Reynolds number of the particle.

The effect of the air flow created by the fan on the grain heap entering the combine harvester cleaning system outside the working surface of the sieve mill will take the following form in general terms on the basis of the Navier-Stokes Eq. 7 (Badretdinov and Nasyrov, 2017):

$$\frac{\partial \rho_g}{\partial t} + \vec{\nabla}.\left(\rho_g U\right) = f_m^p \qquad (7)$$

Where:

$\bar{\nabla}$ = The nabla (Hamilton)

$f^p{}_m$ = The mass inflow of particles (kg/m^3•sec)

In the right part of the Eq. 7the mass inflow of particles if the following:

$$f_{mass}^P = \sum \frac{q}{Q} \qquad (8)$$

Where:

q = The mass inflow of grain heap for cleaning at the unit of time (kg/sec)

Q = The estimated volume of the cleaning system (m^3)

$$q = \frac{\left(m_P^{BX} - m_p^{BbIX}\right)Np}{t} \qquad (9)$$

Where:

$m_p{}^{\hat{a}\tilde{o}}$ = The mass of particles at the entrance (kg)

$m_p{}^{\hat{a}\hat{u}\tilde{o}}$ = The mass of particles at the exit (kg)

N_p = The calculation concentration of particles

t = The time (sec)

Equation of particles motion:

$$\frac{dV_p}{dt} = \frac{\pi d_p^2}{8m} C_D \rho_g \left|U - Vp\right|\left(U - V_p\right) + g\left(I - \frac{\rho_g}{\rho_p}\right) \qquad (10)$$

Mathematical description of the process of interaction of a layer of grain heap on the surface of the sieves (Fig. 1). Let x be the displacement of the sieve. It is given by:

$$x = r\cos\omega t \qquad (11)$$

then x' = -rω sinωt speed and x' = rω^2 cosωt acceleration at the moment of time t (Sorochenko, 2016, 2017). The particle (grain) is acted upon by forces of inertia, air resistance, gravity and friction. The inertia force is:

$$P_{\Pi H} = mr\omega^2 \cos\omega t \qquad (12)$$

where, m is the particle weight. It always has a direction opposite to the direction of movement of the sieve. The

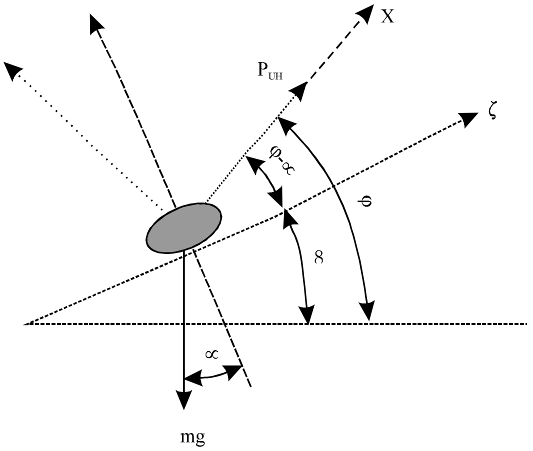

Fig. 1: Calculation diagram of the forces acting on the grain heap on the surface of the sieve

force of air resistance has a direction opposite to the direction of the air flow and is equal in magnitude to:

$$P_B = mk_n U^2 \qquad (13)$$

Where:

k_n = The particle sailing capacity coefficient

U = The air flow speed along the blade of the sieve

Friction:

$$F_{TP} = F_N f \qquad (14)$$

where, f = tgφ is the coefficient of the particle friction against the blade of the sieve in the grain combine harvester cleaning system, F_N is the force acting on the particle along the normal to the blade of the sieve of the cleaning system. This force is defined by equality:

$$F_N = mg.\cos\alpha + P_{\Pi H}.\sin(\varphi - \alpha) \qquad (15)$$

Then the friction force is:

$$F_{TP} = \left[mg.\cos\alpha - mr\omega^2.\sin(\varphi - \alpha)f\right] \qquad (16)$$

Let ζ (t) be the relative displacement of the particle along the blade of the sieve. On the basis of Newton's second law we obtain the following differential equation for the determination of ζ(t):

$$\frac{d^2\zeta}{dt^2} = \left[F_1(t) - F_2(t)\text{sign}\left(\frac{d\zeta}{dt}\right)\right] \qquad (17)$$

Where:

$$F_1(t) = r\omega^2.\cos\omega t.\cos(\varphi-\alpha)+k_{\Pi}U^2-g.\sin\alpha$$

$$F_2(t) = \left[g.\cos\alpha - r\omega^2.\cos\omega t.\sin(\varphi-\alpha)\right]f$$

We note that the initial parameters are $F^2(t)>0$, otherwise the forces of inertia will tear the particle from the surface of the blade of the sieve. In addition, the initial position and the initial velocity of the particle must be given. We accept them as zero:

$$\zeta(t_0) = 0; \zeta'(t_0) = 0 \qquad (18)$$

where, t_0 is the moment of time when the particle fell on the blade of the sieve system of the combine harvester cleaning system.

The process of separation of valuable grains from weed impurities (husk, chaff) is based on a significant difference in their coefficients of sailing capacity for full grains it varies in the range = 0.09, ..., 0.3 and for chaff it is k_{Π} = 0.4, ..., 1.22. For this reason, it is possible to select a certain range of airflow velocities in which the weeds always move up the sieve and the full grains, although they will have stages of slip upward as they move downward in general for the full crank turn will move downward. At the same time, a part of the grains that are caught at the time of their fall onto the blade of the sieve are close to the upper edge of the blade and can slip to the next blade. Separate grains can thus, "Slip" several blades of the sieve system of the combine harvester cleaning system. However, the probability that a full grain on several blades in a row, firstly, falls for the period of the sieve's movement down and secondly, it will have time to reach the top of the blade during this time is very small. In addition, the speed of the air flow decreases on the far blades, this in turn, reduces the slipping of particles up the blade.

If it is possible to achieve the fact that on the first blades of the sieve, the speed of the air flow is such that the weeds do not slip down at all and the full grains will have a general tendency to move downward (over several turns of the crank) then the weeds will slip off the top of the blade and fly with airflow (if $k_{\Pi}U^2$ and the full grains will slip down on the first or subsequent blades of the sieve of the combine harvester cleaning system.

RESULTS AND DISCUSSION

Table 1 and 2 show the main physical and mechanical properties and statistical analysis of the geometric parameters of grains of grain heaps.

As experimental measurements show (Table 1 and 2), the grain heap entering the combine harvester cleaning systemis heterogeneous and has a wide range both in physico-mechanical and geometric parameters (Badretdinov and Nasyrov, 2017). The obtained data are used in the mathematical model of the description of the technological process of the operation of the combine harvester cleaning system.

Determination of the intensity of interfacial interaction (volume and mass concentration of grain heap) and flow regime. The technological process of separating grain from a heap is characterized by a relatively small volume content of grain heaps. At the same time, the total mass of the grain heap exceeds by several times the mass of the air flow created by the fan. So, it is necessary to determine the intensity of the interfacial interaction which is estimated by the volume and mass concentrations of the air-grain mixture. The volume concentration of the mixture (Spokas *et al*., 2016; Kutzbach, 2001):

$$\Phi = \frac{q_{шт}\pi d^3 p}{6.U.S} \qquad (19)$$

Where:

S = The area of the sieve of the combine harvester cleaning system (m^2)
$q_{øò}$ = The piece quantity of grain heap delivered per unit of time (PCs/sec)

Mass concentration of the mixture:

$$M = \frac{\phi.\rho_p}{\rho} \qquad (20)$$

The volume concentration of the mixture is determined by the unit quantity $q_{øò}$ of the supplied grain heap to the combine harvester cleaning system which in turn depends on the flow capacity of the combine harvester and is determined as follows, taking into account the mass of 1000 pieces of seeds m_{1000}:

$$q_{шт} = \frac{q.1000}{m1000} \qquad (21)$$

where, q is the flow capacity (productivity) of the combine harvester cleaning system (kg/sec). Table 3 presents changes in the mass and volume concentrations of grain heap in the combine harvester cleaning system, depending on its productivity.

Table 1: Physical and mechanical properties of grain heaps

	Spring wheat, "Vatan" variety				
Parameters	Terminal velocity (V_g,m/sec)	Absolute mass (mass of 1000 units of grains) (m_{1000}, g)	Grain unit (H, g/L)	Caryopsis mass (g)	Humidity (%)
Minimum value	3.1	29	484	0.0012	17
Maximal value	9.8	38	522	0.08	18
Average value	6.45	33.5	503	0.036	17.5

Table 2: Statistical analysis of geometric parameters of grain heap and pure grain (wheat, "Vatan")

	Grain heap					
Parameter	Min.	Max.	Average (X)	Dispersion (σ^2)	RMS (σ)	Variation(v)
Length l (mm)	1.11	28.1	10.77	39.8	6.31	58.59
Thicknessa (mm)	0.3	9.5	2.11	1.8	1.34	63.57
Width β (mm)	1.4	5.7	3.53	1.02	1.01	28.64
Equiv. diam $d_э$ (mm)	0.72	5.41	2.59	-	-	-
Pure grain						
Length*l* (mm)	5.06	6.92	6.03	0.22	0.47	7.74
Thicknessa (mm)	2.24	3.36	2.70	0.05	0.23	8.62
Widthβ (mm)	2.05	3.63	2.98	0.11	0.34	11.28
Equiv. diam d_3 (mm)	3.12	4.64	3.90	-	-	-

Table 3: Changes in the concentration of grain heap, depending on the flow capacity of the combine harvester (crop: spring wheat "Vatan")

	Volume concentration of grain heap Φ		Mass concentration of grain heap M	
Flow capacity of the grain combine harvester q (kg/sec)	Minimum value	Maximum value	Minimum value	Maximum value
5	0.000092	0.000236	0.102	0.263
6	0.000110	0.000284	0.123	0.316
7	0.000129	0.000331	0.143	0.369
8	0.000147	0.000378	0.164	0.422
9	0.000165	0.000425	0.184	0.474

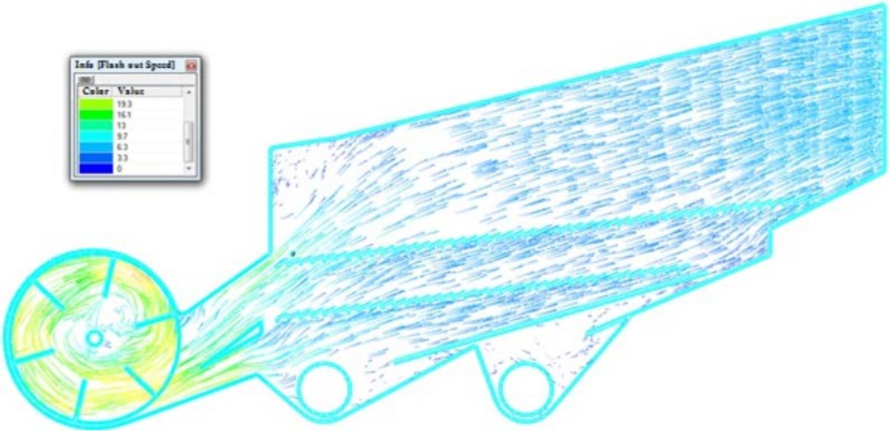

Fig. 2: Trajectories of the motion of air flow velocity vectors

Volume concentration Φ of grain heap during the technological process of the combine harvester cleaning system varies within the limits of $9.2 \cdot 10^{-5}, \ldots, 4.25 \cdot 10^{-4}$. For such limits, the "Air-grain heap"flow regime, according to the accepted classification (Spokas *et al*., 2016), refers to heterogeneous low-dust flows. With this flow regime, the carrier phase (air) affects the movement of solid particles (grain) and their reverse effect on the air flow is negligible. As the concentration increases, the influence of the grain heap on the air flow increases as well as the interaction of the heap components with each other. However, in this case, the process of cleaning is violated. The concentrations obtained by experiment are used for machine modeling of the technological process of the combine harvester cleaning system operation in the flow vision software (Fig. 2).

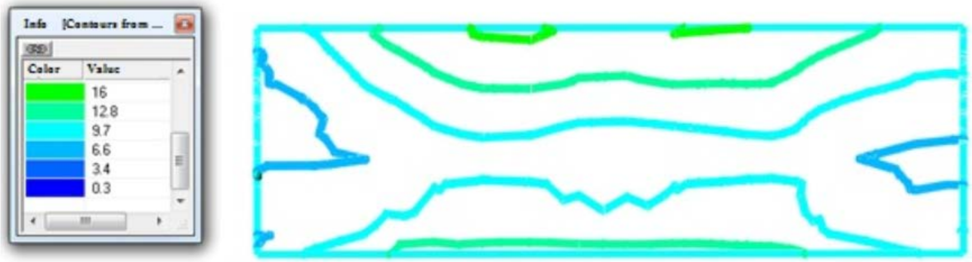

Fig. 3: Isolines of airflow velocity distribution at the exit of the blower channel of the combine harvester fan

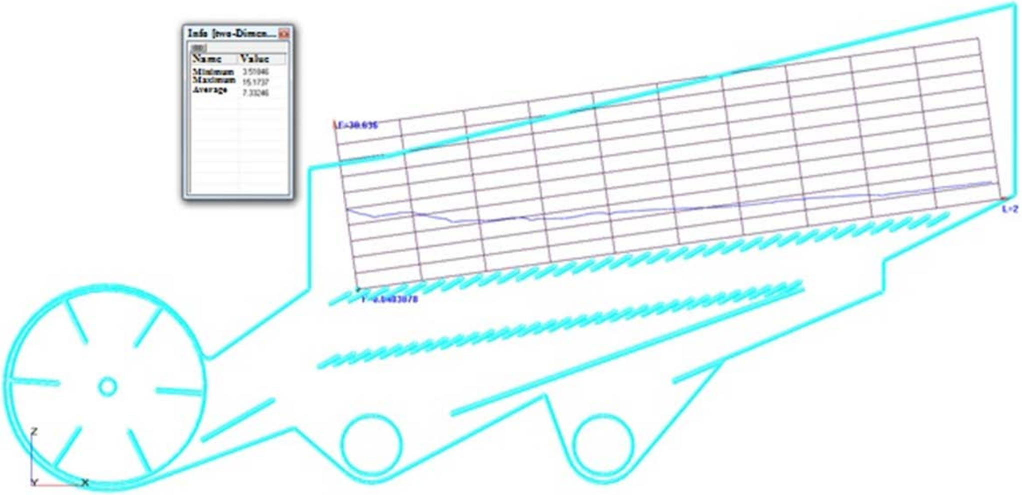

Fig. 4: Diagram of the distribution of the velocity vector of the air flow above the surface of the upper sieve mill of the combine harvester along the length

Visualization of airflow velocity trajectories, obtained from simulation and calculation results in the Flow Vision software package can be seen in Fig. 2.

It can be seen from Fig. 2 that the air flow created by the fan passes through two sieve mills. The main part of the air flow is directed to the upper sieve mill and its small part is cut off by the air flow guide and directed to the lower sieve mill where the airflow velocity is lower (up to 3 m/sec) than the air flow directed to the upper sieve. In the front part of the upper sieve mill (1/3 part of the surface), the speed of the passing air flow is much higher (up to 9 m/sec) than on the remaining surface of the sievemill and is 5, ..., 6 m/sec.

The airflow velocity distribution isolines at the fan exit indicate that the air flow is not evenlydistributed and has a wide variation range of 3, ..., 16 m/sec (Fig. 3 and 4).

Figure 5 that the distribution of the velocity vectors of the air flow over the surface of the upper sieve mill of the combine harvester over the width is uneven. Due to the uneven air flow along the width of the sieve, poor-quality pneumatic-sieve cleaning of the grain heap may occur. At the same time where the speed of air flow has minimum values, light chaff can get to the cleaned grain material and in those areas where the air speed has the maximum values, full grain can be carried away and ejected (lost).

The statistical data for the distribution of airflow velocity (coefficient of variation) over the width and length of the upper sieve (Fig. 6 and 7) were determined experimentally in the production conditions for combine harvesters (Acros, John Deere, Case, New Holland). The airflow velocity was measured by a KIMO digital anemometer.

It can be seen from Fig. 6 and 7 that the air flow over the whole area of the sieve is distributed unevenly, more evenly it is distributed only at the beginning and at the end of the sieve. Strong variation is observed in the middle part of the sieve mill because of the strong interval of air velocity dispersion in this study, the technological process of pneumatic sieve cleaning of the grain heap may be disrupted, so that, light chuff can enter the purified grain material. And on the width of the sieve there

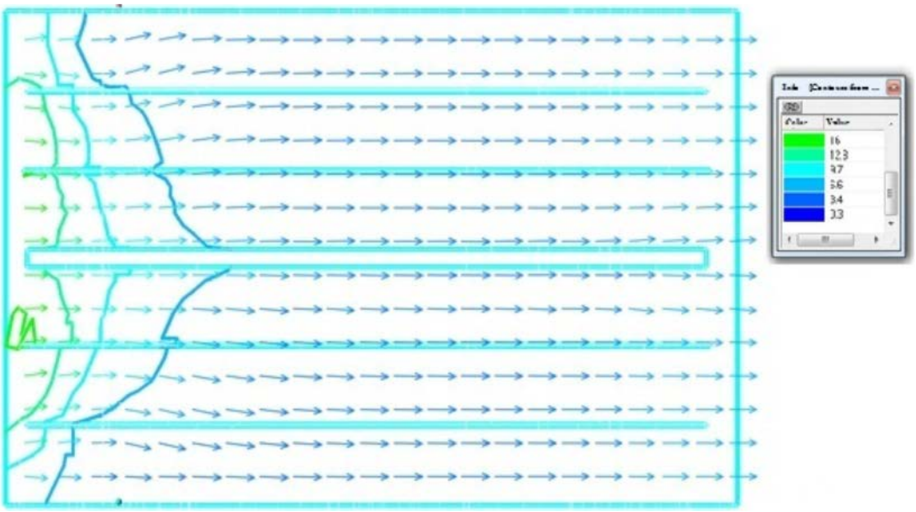

Fig. 5: Distribution of air flow velocity vectors over the surface of the upper sieve mill of the combine harvester over the whole area

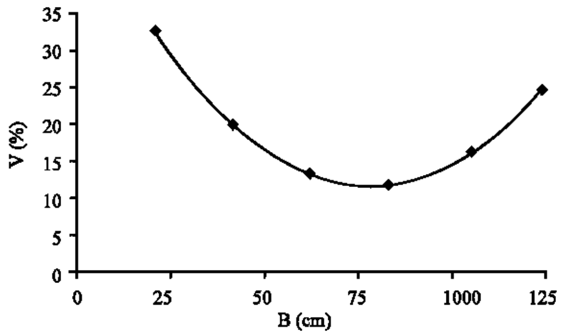

Fig. 6: Graph of the distribution of the coefficient of variation vof the airflow velocity over the width Bon the sieve surface of the combine harvester; y = 0.0047x2-0.8489x+50.256, R^2 = 0.9948

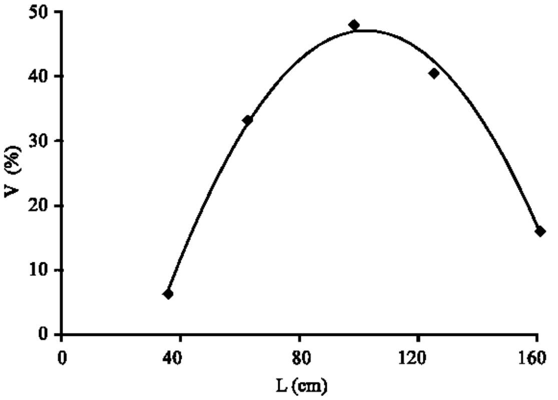

Fig. 7: Graph of the distribution of the coefficient of variation v of the air flow velocity along the length L on the sieve surface of the combine harvester; y = -0.0074x2+1.6852x-49.256 R^2 = 0.9953

Table 4: Speed ranges of air flow

Angle of the sieve α, degrees	20°C	22°C	24°C	26°C
Air flow velocity over the sieve U (m/sec)	With the grain sailing capacity coefficient k_n = 0.3			
	2.3, …, 2.4	2.5, …, 2.8	2.6, …, 3.1	3.0, …, 3.4
	With the grain sailing capacity coefficient k_n = 0.15			
	2.4, …, 3.3	2.9, …, 3.9	3.4…4.4	3.7, …, 4.9
	With the grain sailing capacity coefficient k_n = 0.09			
	2.4, …, 4.2	2.9, …, 5.1	3.4, …, 5.7	3.7,…, 6.3

is an opposite picture in the middle part of the sieve air flow is more leveled and at the edges uniformity is violated.

Table 4 presents the results of calculating the motion of a layer of grain heap on the surface of the sieve of the combine harvester (Acros) in the software product Mathcad and operating ranges of the airflow speed passing through the sieves of the cleaning system of a combine harvester by the example of harvesting a grain heap (wheat "Vatan") in the cleaning system of a combine harvester depending on its design and technological parameters (rotation frequency of the fan is 850 sec^{-1}, the clearance of the upper sieves is 10, ..., 14 mm (α = 20°C, …., 26°C), the angular velocity of the crankshaft of the sieve drive is ω = 28 rad/sec, the coefficient of friction f_1 = 0.3 for grain and f_2 = 0.7 for chaff.

Analyzing Fig. 8, it can be concluded that during a time of 6π revolutions of the crank, the trajectory of the motion of the grain material (the boundaries are shown by a solid linea yellow fill) first, under the influence of the inertial force of the sieve and the aerodynamic force of the air flow is thrown forward along the surface of the sieve and further is thrown downwards by gravity which dominates aerodynamic force.

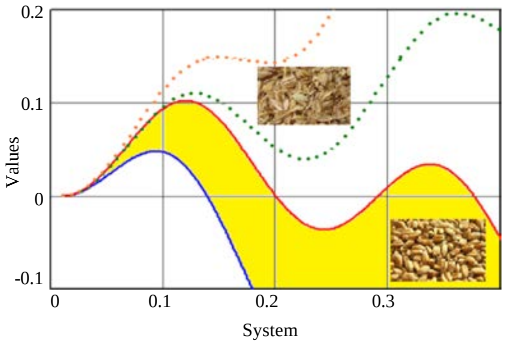

Fig. 8: Trajectories of the grain heap motion on the surface of the sieve in the combine harvester cleaning system with U = 3 m/sec (the boundaries are shown by a solid line a yellow fill)

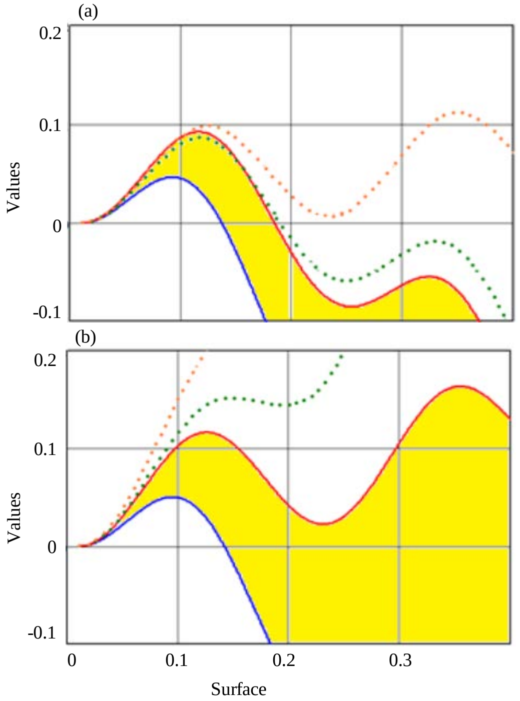

Fig. 9: Trajectories of the grain heap motion on the surface of the sieve at different airflow speeds: a) at U = 2 m/sec and b) at U = 4.5 m/sec, (the boundaries are shown by a solid line a yellow fill)

Weed light chuff (borders are shown by a dotted line) under the influence of the inertial force of the sieve and the force of the air flow are carried away over the surface of the grain heap layer, thereby the necessary condition for air-sieve cleaning of the grain heap in the combine harvester cleaning system is fulfilled.

Figure 9 at various airflow speeds the technological process of air-sieve cleaning of the grain heap in the combine harvester cleaning system is violated. So, at U = 2 m/sec and below, a part of the chaff is added to the cleaned grain material as a result, a highly clogged grain material will appear in the bunker and thereby make further cleaning on the grain cleaning machines more difficult. And at U = 4.5 m/sec and higher part of the full grain material (the frail, loose grains) are carried away by the air flow and there is a loss.

Based on the results of the simulation, it is revealed that the trajectory of the grain heap motion depends heavily on the specific location of contact with the surface of the sieve and specifically where it falls, on the front or the final part of the sieve.

It was shown experimentally that the distribution of airflow velocity of existing modern combine harvesters is uneven over the sieve area and varies over a wide range. This is evidenced by the results of other researchers (Badretdinov and Nasyrov, 2017; Miu, 2015; Spokas *et al*., 2016; Kutzbach, 2001; Sorochenko, 2016; Alferov, 1987). This indicates that the technological process of air-sieve cleaning in the combine harvesters proceeds in violation of agrotechnical requirements. Due to increased productivity and flow capacity, there are problems with the quality of the cleaning system. This can be explained by the complexity of the simultaneous regulation of several design parameters (fan speed and air speed U, the sieve shutter clearance and angular velocity of the sieve drive crank ω) and depending on the crop being harvested on its physical and mechanical properties (geometric parameters, humidity, weediness).

The experimental data were confirmed by theoretical studies of mathematical description and modeling in the form of a polydisperse two-phase flow with allowance for concentration, inertia, relaxation time and drag coefficient. Similar studies were carried out by other scientists which are reflected in the works (Mudarisov *et al*., 2017; Miu, 2015; Ermolev and Muratov, 2011; Voicu *et al*., 2008).

A comparative analysis of theoretical and experimental studies has shown that the level of significance is more than 0.05 according to the t-test of Student which gives grounds to believe that the results can be validated.

Having modeled and calculated the model of a real combine harvester using this method, we identified problem areas of the cleaning system. These problems could be solved by changing design parameters and adding guides to the fan blower channel (patent RU 2621026 C1 and RUS 175203) which contributes to even distribution of the air flow over the entire area of the combine harvester sieve.

The obtained characteristics make it possible to develop recommendations on optimizing the design and technological parameters of the fan and the cleaning system of a combine harvester in general. Using this simulation method, it is possible to improve the cleaning systems of combine harvesters without significant costs and efforts.

CONCLUSION

The following parameters of the air-grain mixture flow regime in the grain harvester cleaning system are substantiated, mass concentration M = 0.102, ..., 0.474, the volume concentration of grain heap $\Phi = 9.2 \bullet 10^{-5}, \ldots, 4.25 \bullet 10^{-4}$, the Reynolds number of the grain heap $Re_p = 125, \ldots, 1884$, the Froude number $F_r = 0.49$ characterizing the ratio between the forces of inertia, gravity and the aerodynamic force in the field of which the motion takes place, acting on the elementary volume of the air flow, this meanscalm flow, the aerodynamic coefficient of grain heap resistance $C_D = 0.19, \ldots, 0.59$, coefficients of sailing capacity for full grains it fluctuates in the range $k_n = 0.09, \ldots, 0.3$ and for chaff it is $k_n = 0.4, \ldots, 1.22$, dynamic inertia of particles of grain heap $\tau_\delta = 1 \ldots 28.5$, recommended speed of air flow in the working zone of the sieve mill to provide pneumatic-sieve separation and even distribution over the sieve area for different crops U = 3.1, ..., 4.0 m/sec. The “air-grain heap” flow regime in the combine harvester cleaning system refers to heterogeneous low-dust flows. The obtained parameters make it possible to establish that for the modeling of the technological process of the combine harvester cleaning system, two-phase “Gas- particle” flows can be used.

REFERENCES

Anonymous, 2014. Crop Trade and markets division of FAO under the global information and early warning system. Food and Agriculture Organization, Rome, Italy.

Badretdinov, I.D. and R.R. Nasyrov, 2017. Reasoning of a two-phase air-grain heap flow to model perfomance of the cleaner for a combine harvester. Bull. Orenburg State Agrar. Univ., 5: 103-105.

Badretdinov, I.D. and S.G. Mudarisov, 2017. Experimental reasoning of a two-phase “air-grain heap” flow to model performance of the air system in the grain cleaner. Bull. Bashkir State Agrar. Univ., 1: 57-61.

Ermolev, I.I. and D.K. Muratov, 2011. Modelling performance of the radial fans in Air-screen cleaning of a grain harvester. Bull. State Tech. Univ., 8: 38-46.

Esfahani, M., M. Emami and H. Tajnesaei, 2013. The investigation of the relation between job involvement and organizational commitment. Manage. Sci. Lett., 3: 511-518.

Kundu, D. and A.K. Gupta, 2014. On bivariate Weibull-geometric distribution. J. Multivariate Anal., 23: 19-29.

Kutzbach, H.D., 2001. [Combine cleaning systems (In German)]. Landtechnik Agric. Eng., 56: 392-393.

Miu, P., 2015. Combine Harvesters: Thery, Modeling and Design. CRC Press, Boca Raton, Florida, USA., ISBN:9781482282375, Pages: 460.

Mudarisov, S., E. Khasanov, Z. Rakhimov, I. Gabitov and I. Badretdinov *et al*., 2017. Specifying Two-phase flow in modeling pneumatic systems performance of farm machines. J. Mech. Eng. Res. Dev., 40: 706-715.

Mudarisov, S.G. and I.D. Badretdinov, 2013. Numerical implementation of a mathematical model for operational performance of a transverse fan in rotating coordinates. Bull. Intl. Acad. Agrar. Educ., 17: 79-83.

Rademacher, T., 2003. [Combine harvester the agony of the right choice]. Getreide Mag., 3: 186-191.

Sorochenko, S.F., 2016. Studies on movement of grain heap particles on the screen of a grain harvester when grain is harvested on slopes. Bull. Altai State Agrar. Univ., 8: 162-168.

Sorochenko, S.F., 2017. Mathematical model of grain separation in the cleaning system of a hillside grain harvester. Bull. Altai State Agrar. Univ., 12: 134-140.

Spokas, L., V. Adamcuk, V. Bulgakov and L. Nozdrovicky, 2016. The experimental research of combine harvesters. Res. Agric. Eng., 62: 106-112.

Vasilevskii, M.V., V.I. Romandin and E.G. Zykov, 2013. Transporting and Depositing Particles in Disperse Material Processing Technologies. Tomsk Polytechnic University, Tomsk, Russia, Pages: 288.

Voicu, G., T. Casandroiu and C. Tarcolea, 2008. Testing stochastic models for simulating the seeds separation process on the sieves of a cleaning system and a comparison with experimental data. Agric. Conspectus Sci., 73: 95-101.