Pneumatic system of a seeder with pneumatic sowing

Vladimir Konovalov¹, Artem Kravtsov¹, Vladimir Zaitsev¹, Alexander Petrov² and Svetlana Petrova²

¹Penza State Technological University, travel Baidukova / st. Gagarina, 1a / 11, Penza, 440039, Russia
²Samara State Agrarian University, st. Training, 2, P.g.t. Ust-Kinelsky, Samara Region, 446442, Russia

E-mail: ssaariz@mail.ru

Abstract. The aim of the study is to develop a mathematical model of linear calculation of the pneumatic system of a seeder with a pneumatic sowing system, implemented in the MathCAD computer algebra system. The description of the pneumatic transport system of a typical seeder with pneumatic sowing is presented, its design scheme is given. Based on the provisions of the mechanics of continuous media, a methodology for calculating the parameters of a pneumatic system to verify the adopted design decisions has been developed. A computer model of a pneumatic transport system with series-parallel arrangement of sections has been developed. Linear calculations with structurally implemented recounting of indicators were performed. The obtained value of the standard deviation between the calculated average values and the velocities of the flow core in the sections does not exceed 14% for the values of the velocities and 0.5% for the pressure over the sections. When implementing the proposed analytical modeling in the MathCAD 8.0 system, the error in mass flow rate is 1.152×10⁻¹⁴%, which allows limiting the number of conversion cycles of indicators to two – three cycles.

1. Introduction

Crop yield is largely determined by compliance with the requirements for the technology of growing this type of plant and by ensuring proper distribution of seeds along the bottom of the furrow or the surface of the field to ensure the necessary nutrition area [1, 2]. At the same time, it is not possible to achieve seeding units with pneumatic sowing of high uniformity when sowing plant seeds and fertilizer granules [3].

Therefore, the solution of issues directly related to the stability and accuracy of the values of seed supply through the coulters and with an increase in the uniformity of seed distribution by pneumatic sowing systems can be considered relevant [4,5].

The main directions of improving the technology of sowing and design of seeders is the use of granular small seeds [2], precision sowing systems [6], the improvement of metering mechanisms [7] and various devices [1, 8], the improvement of the pneumatic system of the seeder [9]. In recent years, computer control of the seeders [10], the use of a computer to simulate its work [11] and the workflow of individual nodes and systems [4, 12] have become widespread. Simulation is widely used, especially in 3D systems [13, 14].

Given that the length of the hoses connecting the distributor to the coulters is different for the seeder, and during the movement of seeds and granules through the pneumatic conveying pipeline there are conditions that displace particles of these materials from a central location in the pipeline to
the walls, it is difficult to achieve uniform distribution of seeds and granules across the coulters excluding air flow. This requires a theoretical analysis of the distribution system of pneumatic transport on the example of specific seeders for air flow and pressure losses in the pneumatic system.

In the process of product design, a number of measures are envisaged, which include, inter alia, outline design and development of a technical project. If a technical design requires analysis of a specific product design (using the modules of engineering analysis of computer-aided design systems - CAD systems), then at the outline design level, a preliminary justification of the main parameters of the designed structure is necessary.

For these purposes, widely distributed computer algebra systems (CAS), such as MathCAD, Matlab, SciLab, etc., are well suited because they allow quick enough initial calculations and also do not require the development and preparation of object models.

The development of a computational model on the basis of verifying the correspondence of average flow velocities to the recommended interval of motion velocities for different spatially located sections using the computer algebra system for economy class computers was not carried out.

The purpose of the study is to develop a mathematical model of linear calculation of the pneumatic system of a seeder with a pneumatic sowing system, implemented in the MathCAD computer algebra system.

When conducting surveys, the research tasks were previously set and solved: a description, based on the known provisions of continuum mechanics, of a method for calculating the pneumatic system of a seeder with a pneumatic sowing, incorporating parallel bends for supplying the air mixture from the distributor to the coulters; drawing up a methodology for linear calculation of a pneumatic system and its implementation in the MathCAD system; verification of calculation results based on the data of a three-dimensional flow model obtained in the NXThermal/Flow engineering analysis system.

2. Materials and methods

Analysis of the seeder designs of several well-known manufacturers [15, 16, 17] made it possible to choose one of the schemes of pneumatic systems of seeders with pneumatic sowing (Figure 1). The pneumatic system of one of the seeders produced in Russia is taken as a basis.

The analysis of existing designs of pneumatic seeders made it possible to design some typical scheme of the pneumatic system of a seeder (Figure 1), which includes all the key elements characteristic of seeders with a vertical distributor. The geometric parameters of the nodes are obtained based on measurements.

The pneumatic sowing system of the seeder includes: fan 1 driven by the tractor PTO, air duct 2, ejector 3 for grain and granules, horizontal 7 and vertical 9 sections of the pipeline and bend 8 between them, the distributor 11 of the material flow with a guide 10, and branches, each of which is made up of: a branch pipe of the distributor 12, a seed tube (flexible hose) 13 and a coulter 15 with a sleeve 14 and a nozzle 16. Seed material and granules of mineral fertilizers are loaded into its respective hoppers 4 and 6. Under the hoppers are dispensers 5 of the sowing apparatus. The dispensers are driven from the support wheel of the seeder. The metered particles of the material enter the ejector 3 of the pneumatic seeding system. The seed material is dispersed with the help of air and separated in the distributor 11 along the outlet branch pipes (z, pcs). Further, the material moves with air through the vas deferens and coulters 15 to the coulter nozzles 16. From the nozzle 16, the material is directed by air to the groove 17. The position of the coulters 15 relative to the groove 17 is provided by special parallelogram mechanisms.

The research methodology was developed on the basis of the known principles of continuum mechanics for modeling the calculation of the distribution pneumatic transport system of a seeder with pneumatic sowing. The use of the MathCAD system for the analytical determination of the relationship between the structural and operational parameters of the pneumatic system based on a linear calculation is provided. The basis of any calculation and modeling is: input of initial data, calculation methodology and output of calculation results in the form of numerical values, tables or graphic material.
Figure 1. Pneumatic transport system of a seeder with pneumatic sowing.

Where: (a) – structural and technological scheme; (b) – layout diagram of structural objects and sizes; 1 – fan; 2 – air duct; 3 – ejector; 4, 6 – hopper for bulk material (seeds or granules of mineral fertilizers); 5 – sowing apparatus (dispenser) of the material; 7 – horizontal section of the pipeline; 8 – pipe bend; 9 – vertical section of the pipeline; 10 – guide; 11 – distributor; 12 – branch pipe of the distributor; 13 – vas deferens (flexible hose); 14 – coupling; 15 – coulter; 16 – coulter nozzle; 17 – furrow; \( \vec{V}_v \) – air velocity; \( \vec{V}_m \) – material velocity from the batcher; \( \vec{V}_p \) – velocity of air mixture; \( D_0 \) – diameter of the hole of the central duct, m; \( D_e \) – diameter of the pipeline ejector, m; \( D \) – diameter of the horizontal pipeline, m; \( D_v \) – diameter of the vertical pipeline, m; \( D_d \) – diameter of the distributor guide, m; \( D_{D,H} \) – diameter and height of the common hole of the distributor, m; \( d_p \) – diameters of the holes of the inlet and outlet of the distributor pipe, m; \( d_d \) – coulter diameter, m; \( F_s \) – coulter nozzle hole area, m\(^2\); \( L_0 \) – duct length, m; \( L_1 \) – length of the horizontal pipeline, m; \( L_2 \) – length of the vertical pipeline, m; \( l_1 \) – length of the flexible hose, m; \( l_2 \) – length of the air channel of coulter, m; \( \Delta H \) – height difference between the distributor and the ejector, m; \( H_{ot} \) – difference in height of the coulter nozzle and distributor, m; \( \lambda_0, \lambda_1, \lambda_2, \lambda_{21}, \lambda_{22} \) – resistance coefficients, respectively: air duct ejector, rotary pipe bend, guide, distributor, branch pipe of the distributor, hose and coulter connections, coulter nozzle; \( \lambda_{01}, \lambda_{12}, \lambda_{23} \) – local resistance coefficients, respectively: of the duct, horizontal and vertical piping, hoses, coulter inlets.

The source data for the presented model is determined by the following information:
- initial conditions (for example, gravitational acceleration \( g \), m/s\(^2\), atmospheric pressure \( p_a \), Pa);
- technological operating conditions of the sowing unit (seeder width / or its sections operating from one fan / \( B_p \), m; seeder working velocity \( V_c \), m/s; seed rate of material – seeds \( H_s \) and granules \( H_G \) of mineral fertilizers, kg/ha);
- physico-mechanical properties of the material (velocity of material particle whirl \( V_{wh} \), m/s; density of the grain material \( \rho_G \) and granules \( \rho_G \) of mineral fertilizers, kg/m\(^3\); \( \rho_{Air} \) – density of air / kg/m\(^3\) / at normal atmospheric pressure \( p_a \), Pa / and temperature \( T=15 \) °C, and gas constant of air \( R \), J/(kg·K) /, corresponding to the external working conditions of the seeder);
- design and operational parameters of the pneumatic transport system of the seeder (number of coulters \( z \), pcs; length of the duct \( L_0 \), m; length of the horizontal \( L_1 \) and vertical \( L_2 \) sections of the pipeline, m; length of the hose \( l_1 \) and coulter \( l_2 \) of each branch /, respectively, \( l_{1,i} \) and \( l_{2,i} \), m; coulter
duct area $F_s$, m$^2$; pressure loss in the loading device $\Delta P_3$, Pa; air velocity $V_{vis}$ at the outlet of the coulter nozzle, m/s; empirical coefficient $k'$ of reducing the air flow rate at the outlet of the coulter; height difference $H_0$ of the outlet from the coulter of the redistributor, m; height difference from the ejector to the distributor $\Delta H$, m; the coefficient of resistance of the accelerated section $K_p$, which takes into account the fraction of the material to be accelerated to air velocity. Some parameters can be calculated in the estimated module or taken by already determined values. In the proposed model are already known: coefficient of air friction on the walls of the restrictive structures (respectively, duct pipes $\lambda_0$, horizontal $\lambda_1$ and vertical $\lambda_2$ pipes, hoses $\lambda_{21}$ and opener ducts $\lambda_{22}$); coefficients of local resistance of the pipeline $\xi$ (coefficients of local resistance of the ejector (s) $\xi_{el}$, bend (s) $\xi_{el1}$, guide $\xi_{el2}$, distributor $\xi_{el13}$, branch pipe $\xi_{el21}$ of the distributor / with replaceable branch pipes of different sections – $\xi_{el21}$/, the transition from the hose to the coulter $\xi_{el22}$, nozzles and the zone of contact of the coulter with the furrow $\xi_{el23}$).

The determining condition for transportation is the velocity of the whirl. The average velocity of the air-product stream [4] for vertical lifting sections is desirable in the range of 1.5-2.0 whirlvelocities; for horizontal sections – not less than 1.1 velocity of whirling. Descent plots may have lower values.

3. Research results

The calculated part of the methodology and computer model includes several points.

3.1. Technological calculations of the total part of the sowing unit and pneumatic transport system

At the beginning of the calculation, the mass productivity (kg/s) of the seeder (or its section operating from one fan) is determined by the seed to be sown (by the seeds and granules of mineral fertilizers):

$$Q_m = 0.0001 \cdot B_p \cdot V_c \cdot (H_S + H_G).$$  \hspace{2cm} (1)

Comparing the set values of the whirl velocity of the seed and granules, their highest value is selected – $V_{wh}$.

Volumetric flow rate of sowing material with a seeder, m$^3$/s:

$$W_m = 0.0001 \cdot B_p \cdot V_c \cdot \left( \frac{H_S}{\rho_S} + \frac{H_G}{\rho_G} \right).$$  \hspace{2cm} (2)

Estimated air volumetric flow rate at the outlet of the coulter nozzle, m$^3$/s:

$$W_k = V_{vis} \cdot F_s \cdot k.$$  \hspace{2cm} (3)

Estimated concentration of material relative to air, kg/kg:

$$\mu = \frac{Q_m}{W_k \cdot \rho_{Air}}.$$  \hspace{2cm} (4)

For different pressure values in the nozzle $p_k$, Pa (Figure2.a) for j–th values, will correspond a different velocity $V_j$, m/s. The required air velocity is $V_{vis}$, m/s. The general solution of the functions $V(p_k)$ and $V_{vis}(p_k)$ corresponds to the point of their intersection along the coordinate $p_k$. Based on the graph, the pressure $p_k$ is taken and the value of the air velocity $V_k$ is immediately specified to correspond to the value of the indicator $V_{vis}$.

The velocity of air flow from the coulter ($V_k = V$), m/s:

$$V_k = k' \sqrt{\frac{2k}{\lambda_1} R \cdot T \cdot \left( 1 - \frac{p_k}{p_a} \frac{\lambda_1}{\lambda_2} \right)}.$$  \hspace{2cm} (5)

Volume fraction of air relative to air mixture (flow porosity):
ε=\frac{W_k}{(W_k + W_m)z} \quad (6)

Volumetric air consumption at the outlet of the branch (coulter), m³/s:

W_k = V_k \cdot F_s \cdot \varepsilon \quad (7)

The volumetric air flow rate at the exit of the coulter in terms of atmospheric pressure, m³/s:

W_{iz} = \frac{W_k}{P_k} \quad (8)

We specify the concentration of the material relative to air (Formula 4).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Change in air velocity from the nozzle.}
\end{figure}

Where: (a) – depending on the pressure in the nozzle of the coulter \( p_k \), Pa; (b) – depending on the number (index) of the \( j \)-th estimated pressure point: \( V, V_j \) – estimated velocity of air flow from the coulter, m/s; \( V_{vix}, V_{vixj} \) – required air velocity in the nozzle, m/s.

We calculate the estimated diameter of the holes of the duct, ejector, pipeline, hose and coulter, by analogy with the hose, m:

\[ d = \sqrt{\frac{4k(W_k + W_m)z}{3.14V_k}} \quad (9) \]

We accept the diameter of the holes of the duct \( D_0 \), ejector \( D_e \), sections of the horizontal pipe \( D \) and vertical \( D_v \), hose \( d \) and coulter \( d_s \), m.

3.2. Aerodynamic calculation of parallel sections of pneumatic transport

Preliminary estimated air velocity over sections of the pneumatic conveying system (Figure 1.b), using the example of a coulter nozzle, m/s:

\[ V_k = \frac{(W_k + W_m)z}{F_{v,c}} \quad (10) \]

Estimated pressure loss along the \( i \)-th branches, Pa:

\[ \Delta P_{ot} = \rho_{Air} \cdot (1+\mu) \cdot \left( \frac{k_p}{2} \frac{(4W_k)^2}{\pi d^2 \cdot \varepsilon} + \xi_1 + \frac{2}{d_1} + \xi_2 + \frac{2}{d_2} + \frac{2}{d_s} + \xi_3 \right) \frac{k(4W_k)^2}{2g} + gH_{ot} \quad (11) \]

The average pressure in the coulters, Pa (the function "mean" considers the average value):

\[ P_{av} = \text{mean}(\Delta P_{ot}) + p_k \]

Pressure at the outlet of the distributor, Pa: (the function "max" considers the maximum value):
Velocity of air flow as a function of pressure (Pa) in the coulter:

\[ V_{ki} = k' \sqrt{\frac{\Delta P_{ot}}{k+1}} \left(1 - \frac{p_k}{(P_{p} - \Delta P_{ot})} \right)^{k+1}. \] (12)

The intermediate concentration of the material relative to air, kg/kg:

\[ \mu = \frac{Q_m F_s \cdot \varepsilon \rho_{Air} p_k}{W_k} \] (13)

We recalculate the volumetric air consumption \( W_k \) at the outlet of the coulter nozzle (Formula 7), pressure loss along the outlets \( \Delta P_{ot} \) (Formula 11), etc. – that is, we repeat the calculation cycle, using the calculated values of the previous cycle in the calculation.

An example of calculating a part of the above indicators for sections I and II:

\[ \Delta P_{ot} = p_Air(1+\mu) \left( \frac{k'}{2} \left( V_{oi} - V_{i} \right)^2 + \left( \xi_{23} \right) \frac{k' \left( \frac{4W_k}{\pi d_{ki}^2} \right)^2}{2g} + g'0 \right); \]

\[ \Delta P_{ot} = p_Air(1+\mu) \left( \frac{k'}{2} \left( V_{i} - V_{ii} \right)^2 + \left( \xi_{23} 2l_2 \right) \frac{k' \left( \frac{4W_k}{\pi d_{ki}^2} \right)^2}{2g} + g'l_2 \right); \]

\[ P_i = p_k + \Delta P_{ot}; \quad P_{ii} = p_k + \Delta P_{ot} + \Delta P_{ot}; \quad \text{etc.} \ldots; \] (14)

\[ V_{0i} = k' \sqrt{\frac{\Delta P_{ot}}{k+1}} \left(1 - \frac{p_k}{(P_{p} - \Delta P_{ot})} \right)^{k+1}; \quad W_{0i} = V_{oi} \cdot F_{s}; \quad W_{i} = W_{0i} \cdot \frac{p_k}{p_k}; \quad W_{ri} = W_{0i} \cdot \frac{p_k}{p_k}; \quad V_{li} = \frac{4W_{li}}{\pi d_{ki}^2}; \quad V_{vi} = \frac{4W_{vi}}{\pi d_{ki}^2}. \]

The average air velocity in the coulter, and it is also calculated in terms of atmospheric pressure, m/s:

\[ V_f = \frac{\sum V_i}{Z_i}; \quad V_{rf} = \frac{\left( \sum (V_{ki} \cdot P_k) \right)}{\left( X \cdot p_k \right)}. \] (15)

Let us plot the pressure change over the coulter nozzles taking into account the length of the hoses at the coulters (Figure 3).

**Figure 3.** Graph of compliance: (a) – hose lengths \( l_{i}, \) m; (b) – pressure in the nozzle \( p_{ki} \) (Pa×10^5) of the coulter, depending on the number \( (1 \leq i \leq 16) \) of the coulter nozzle.

The unevenness of pressure on the coulters will be 8.978×10^{-5}%, with unevenness length of the hoses – 1.492%. The unevenness air flow in this case is 2.876×10^{-4}%. The unevenness of the air...
velocity is $3.766 \times 10^{-4}$%. That is, the unevenness of the lengths of the elements of the branches is smoothed out during the operation of the air mixture flow.

### 3.3. Aerodynamic calculation of seriar sections of pneumatic transport

Volumetric air consumption through the distributor, $m^3/s$:

$$W_{VII} = z \cdot W_{VII}^2$$

Losses of pressure in the sections, air velocities and costs on the example of sections IX and X:

$$\Delta P_{IX} = \rho_{air} \left(1 + \mu \right) \left( \frac{k_p}{2} \left(V_{IX} - V_{VII} \right)^2 + \frac{k}{g} \left(\frac{4W_{VII}}{p_{IX} D_v^2 \varepsilon_p} \right)^2 \right) + 0 \cdot g$$

$$\Delta P_{X} = \rho_{air} \left(1 + \mu \right) \left( \frac{k_p}{2} \left(V_{X} - V_{IX} \right)^2 + \frac{1}{2 \varepsilon_p} \left(\frac{4W_{IX}}{p_{IX} D_v^2 \varepsilon_p} \right)^2 \right) + \frac{g}{2} \cdot \Delta H$$

The results of calculating the volumetric air consumption (in terms of atmospheric pressure) and mass consumption based on the law on the conservation of matter in all sections of pneumatic transport should be a constant value, which is a way to control data output. When implementing the proposed simulation, the error in air consumption (at atmospheric pressure) in the pneumatic transport sections is 1.594%, and for the mass consumption it is $1.152 \times 10^{-14}$%, which is quite acceptable for linear calculation and allows to limit the number of recount cycles to two to three cycles.

### 3.4. Definition of calculation indicators and construction of graphic material

A graph of air pressure changes over sections is presented in Figure 4. As you move away from the nozzle and closer to the fan, the pressure rises. In the ejector, a real drop in the flow pressure occurs (v.13 - XIII) due to the transition of potential energy into kinetic (Figure 4.5). Since the pressure loss by points is analytically calculated, there are no jumps on the graph (Figure 4).

![Graph of pressure changes determined analytically](image)

**Figure 4.** Graph of pressure changes determined analytically $P_{anV}(Pa)$ and by the finite element method $P_{3DV}(Pa)$ over $jj$–th ($0 \leq jj \leq 15$) pneumatic transport sections.
The graph of the air velocity changes over the sections is shown in Figure 5.a. Also for control, velocities are given: whirling particles of air mixture $V_{wh}$, recommended values of velocity for horizontal $(1.1 \times V_{wh})$ and velocity zone $((1.5-2.0) \times V_{wh})$ vertical air mixture. Based on the indicated zone (at its center), the calculated air velocity in the pneumatic pipeline $V_p$ is taken as a guideline.

Analyzing the graph of the average velocity over the cross section of the pipeline (Figure 5.a), we see that in the pipeline the average velocity corresponds to the recommended zone of air velocities. In the distributor (v. 7 - VII) and the hose (v. 3-4 – III–IV), the average velocity in sections is less than required for a horizontal section. However, taking into account the slope of the hose (Figure 6), there is no risk of disruption of the pneumatic conveying system.

Figure 6. Velocity graph of pneumatic transport system of a seeder with pneumatic sowing: 1 – fan installation site; 2 – air duct; 3 – ejector; 4 – metering devices; 5 – horizontal section of the pipeline; 6 – pipe bend; 7 – vertical section of the pipeline; 8 – guide; 9 – distributor; 10 – vas deferens (flexible hose); 11 – coulter; 12 – coulter nozzle.
A drop in velocity in the distributor can contribute to the formation of congestion and crushing of particles from an impact on its walls. However, one can finally determine the indicated disadvantages of the distributor only by analyzing its internal structure.

Comparing the values along the jj-th section of the average velocity $V_{anj}$ and the velocity of the flow core $V_{3D}$ determined by the finite element method (Figure 5. b), we see a slight excess of the flow core velocity relative to the average values. This corresponds to the general principles of the theory of media motion. The standard deviation does not exceed 14% for the values of velocities and 0.5% for pressure.

Analyzing the above expressions in the form of a calculation implemented on the computer, graphs of pressure changes, air velocity and air consumption over the sections of the pneumatic conveyor, we can conclude.

4. Conclusion
Based on the well-known principles of continuum mechanics, a methodology for calculating the pneumatic system of a seeder with pneumatic sowing through parallel bends to the coulters has been developed, implemented as a computer model of a linear calculation of pneumatic systems with series-parallel sections. The standard deviation between the calculated mean values and the velocity of the flow core in the cross sections in the NX Thermal/Flow package does not exceed 14% for the values of velocities and 0.5% for the pressure over the cross sections. This indicates sufficient accuracy of the proposed calculation.

When implementing the proposed analytical modeling in the MathCAD 8.0 system, the error in mass flow rate is $1.152\times10^{-14}$%, which is quite acceptable for linear calculation and allows to limit the number of recount cycles of indicators to two to three cycles.

The unevenness (coefficient of variation) of the lengths of the hoses as elements of parallel arranged seeder branches is 1.492%; during the movement of the air mixture flow, it is smoothed and mutually compensated, as a result of which the calculated unevenness of pressure along the coulters amounts to $3.5\times10^{-3}$%, air flow and air velocity – up to 0.039%.

References
[1] Bagautdinov I, Gryazin V, Kozlov K, Belogusev V 2018 Engineering for Rural Development 17 pp 350-355 DOI:10.22616/ERDev2018.17.N409
[2] Doğan T, Zeybek A 2009 African Journal of Biotechnology 8 22 pp 6120-6126 DOI:10.5897/AJB09.176
[3] Petaev M 2013 Vestnik CSA 65 pp50-55 https://elibrary.ru/item.asp?id=21025466
[4] Mudarisov S, Khasanoz E and others 2017 Journal of Mechanical Engineering Research and Developments 404 pp 706-715 DOI: 10.7508/jmerd.2017.04.018
[5] Saitov V, Kurbanov R, Suvorov A 2016 Procedia Engineering 150 pp 107-110 https://doi.org/10.1016/j.proeng.2016.06.728
[6] Litvinov M, Moskovskii M, Smirnov I 2018 Proceedings of 2018 IEEE East-West Design and Test Symposium EWDT 8524657 DOI:10.1109/EWDT.2018.8524657
[7] Ibrahim J, Liao Q, Wang L, Liao Y, Yao L 2018 International Journal of Agricultural and Biological Engineering 115 pp 116-123 http://www.ijabe.org/index.php/ijabe/article/view/3544
[8] Yang R, Zhang X, Li J, Shang S, Chai H 2016 Transactions of the Chinese Society of Agricultural Engineering 323 pp 6-13 https://www.ingentaconnect.com/content/tcsae/tcsae/2016/00000032/00000003/art00002#
[9] Zubrilina E, Vysochikina L, Danilov M, Maliyev V 2017 Open AccessEngineering for Rural Development 6 pp772-778 DOI:10.22616/ERDev2017.16.N158
[10] Ding Y, Yang J, Zhu K, Zhang L 2017 Transactions of the Chinese Society of Agricultural Engineering 339 pp 29-36 DOI:10.11975/j.isss.1002-6819.2017.09.004
[11] Zhang J, Liu H, Gao J, Lin Z 2018 Transactions of the Chinese Society for Agricultural
Machinery 499 pp 66-72 DOI: 10.6041/j.issn.1000-1298.2018.09.007
[12] Bourges G, Medina M 2013 Acta Horticulturae 1008 pp 259-264
DOI: 10.17660/ActaHortic.2013.1008.34
[13] Bourges G, Eliach J, Medina M 2017 Chemical Engineering Transactions 125 pp 571-576
DOI: 10.3303/CET1758096
[14] Sun Y, Shen J, Dou Q, Chen G 2018 Transactions of the Chinese Society for Agricultural Machinery 498 pp 50-58
http://www.j-csam.org/jcsam/ch/reader/viewabstract.aspx?doi=10.6041/j.issn.1000-1298.2018.08.006
[15] http://www.amazone.ru/97.asp
[16] https://www.vaderstad.com/ru/zernovye-seyalki/
[17] https://www.horsch.com/ru/produkty/