УДК.631.365 DOI 10.22314/2073-7599-2018-12-6-9-14

Эффективность работы энергосберегающей мини-зерносушилки с комбинированной системой теплоснабжения

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Реферат. Приведены описание и принцип работы энергосберегающей мини-зерносушилки для сушки малых партий зерна в фермерских хозяйствах с применением кондуктивного и конвективного способов сушки и процесса охлаждения зерна, использующей для сушки теплоту, полученную от традиционного источника тепла, и теплоноситель, подготовленный посредством солнечного коллектора или заряженного теплового аккумулятора. (*Цель исследования*) Разработать и изучить малогабаритную энергосберегающую зерновую сушилку, в системе теплоснабжения которой наряду с использованием теплоты традиционного источника предусматривается применение теплоносителя, нагретого с помощью солнечного коллектора или заряженного теплового аккумулятора. (*Материалы и методы*) Выполнили экспериментальные исследования процесса сушки зерна пшеницы для определения эффективности работы разработанного устройства; основным условием экономии энергосбережения принята минимизация суммарных удельных затрат на испарение одного килограмма влаги. (*Результаты и обсуждение*) Провели двухфакторный эксперимент по определению основных оптимальных параметров, влияющих на процесс сушки зерна, – скорости движения зерна в кондуктивной камере и температуры греющей поверхности ее кожуха на основе построенной математической модели. В первом варианте сушку осуществляли только кондуктивным способом с использованием теплоты традиционного источника энергии. Во втором варианте сушку провели последовательным применением кондуктивного и конвективного способов, а также выполнили охлаждение зерна с использованием тепловой энергии, полученной от традиционного источника, теплоты солнечного излучения и теплоты отработанного теплоносителя. (*Выводы*) Выявили, что наиболее эффективный вариант с точки зрения экономии тепловой энергии – сушка зерна при последовательном применении кондуктивного и конвективного способов с последующим охлаждением зерна. Теплоснабжение сушильной установки частично осуществляли за счет использования теплоты солнечного излучения и теплоты, полученной от рециркуляции отработанного теплоносителя. В данном оптимальном варианте затраты теплоты на испарение одного килограмма влаги из зерна минимальны и составили 1,53-2,50 МДж на килограмм при скорости движения зерна в сушилке 0,007-0,011 м в секунду и при температуре греющей поверхности 85-91 градус Цельсия.

Ключевые слова: сушка зерна, сушильное устройство, теплоснабжение, энергосбережение, регрессионный анализ, тепловая энергия.

Для цитирования: Гасанов У.Р., Магеррамова С.А. Эффективность работы энергосберегающей мини-зерносушилки с комбинированной системой теплоснабжения // *Сельскохозяйственные машины и технологии*. Т. 12. N6. С. 9-14. DOI 10.22314/2073-7599-2018-12-6-9-14.

Performance Efficiency of an Energy-Saving Mini Dryer with a Combined Heat Supply System

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Abstract. The paper presents the description and operating principle of energy-saving mini-grain dryers for drying small grain batches on farms using conductive and convective drying methods and the process of grain cooling with heat obtained from a traditional heat source and a heat carrier prepared with a solar collector or a charged heat storage. (*Research purpose*) To develop and study a compact energy-saving grain dryer, with a heat supply system based on both a traditional source and a heat transfer fluid heated by a solar collector or a charged heat storage. (*Materials and methods*) The authors have carried out experimental studies of the drying process of wheat grain to determine the effectiveness of the developed unit for grain drying; the main condition for saving energy has been taken as the minimization of the total unit cost of the evaporation of one kilogram of moisture. (*Results and discussion*) The authors have conducted a two-factor experiment to determine the main optimal parameters affecting the grain drying process - the speed of grain movement in the conductive chamber and the temperature of the heating surface of its casing based on the calculated mathematical model. In the first variant, the drying process was carried out only by the conductive method using the heat from a traditional energy source. In the second variant, the drying was carried out by successive use of conductive and convective methods, and the grain was cooled using both thermal energy received from a traditional source and solar radiation heat along with the heat of the spent heat carrier. (*Conclusions*) The study has revealed that the most effective option in terms of saving thermal energy is grain drying with the consistent use of conductive and convective drying methods followed by grain cooling. The heat supply of the drying unit was partially carried out by using the heat of solar radiation and the heat obtained from the spent coolant recycling. In this optimal variant, the heat consumption for evaporation of one kilogram of moisture from the grain is minimal and amounts to 1.53-2.50 MJ per kilogram with a grain movement speed of in the dryer of 0.007-0.011 m per second and a heating surface temperature of 85-91 degrees Celsius.

Keywords: grain drying, drying device, heat supply, energy saving, regression analysis, thermal energy.

For citation: Gasanov U.R., Magerramova S.A. Effektivnost' raboty energosberegayushchey mini-zernosushilki s kombinirovannoy sistemoy teplosnabzheniya [Performance efficiency of an energy-saving mini dryer with a combined heat supply system]. *Sel'skokhozyaystvennye mashiny i tekhnologii*. Vol. 12. N6. 9-14. DOI 10.22314/2073-7599-2018-12-6-9-14 (In Russian).

To solve the problem of food security, agriculture and the processing industry of the Republic of Azerbaijan face the task of not only increasing food production, but also improving its quality indicators.

In order to avoid losses and ensure the safety of the crops grown, farms widely apply post-harvest processing technologies, including drying and thermal disinfection. Drying of grain crops is a complex and rather energy-intensive technological process, which provides not only the preservation of quality indicators, but in some cases their improvement. According to expert estimates, the share of energy consumption in the cost of grain drying is 75-80%, and the price of energy materials accounts for 80-90% [1]. Therefore, the choice of methods and rational modes of the process should take account of the scientific foundations of drying, from studying the product properties as a drying object to rational designing of a drying unit.

Agricultural development shows that in addition to high-performance drying devices, existing farms also need small-sized energy-saving drying units for drying small batches of grain that meet modern environmental requirements and use the existing thermal potential of the environment [2-4]. To solve this problem, studies have been conducted, the results of which have helped to develop contact-type plants for drying grain with a capacity of up to 0.5 ton/hour [5-8].

The research purpose is the development and study of a compact energy-saving grain dryer, in the heating system of which, along with the use of heat from a traditional source, it is planned to use a heat carrier preheated with a solar collector or a charged heat accumulator.

Materials and methods. When designing a compact grain drying unit, the main criteria were the minimization of heat consumed to evaporate one kg of moisture during grain drying, as well as compliance with all requirements for the quality indicators of dried grain or seed material. *Fig. 1* shows the structural diagram of the developed compact grain dryer with a combined heat supply.

The main structural elements of a compact grain dryer include conductive *6* and convective *14* drying chambers, as well as a cooling chamber *13*. The heating system includes solar collector *1*, heat accumulator *18*, electric heating elements *15* located in duct *16*. The coolant moves through air ducts *4*, *17*, *25* under the action of pressure fan *2*, and the spent coolant is removed through pipe *9*. The circulation circuit is selected with seven shut-off and control valves *3*, *19-23*, *26*. Grain from hopper *5* enters conductive chamber *6*, from where, through transporting body *8* located in casing *7* with actuator *24*, it moves into convection chamber *14*, and then into cooling chamber *13*. The bulk density of the grain in the chambers is regulated by means of weight valves *10* and *12*. Atmospheric air for cooling the grain in the cooling chamber is supplied through compressor *11*.

Grain drying in the proposed dryer is implemented consistently by conductive (direct contact of the grain with the heating surface) and convective (by means of a drying agent) methods, and cooling is done with atmospheric air. Depending on the climatic conditions, heat is supplied to the drying chamber either directly from the heating elements or from the heat carrier preheated in a solar air collector or heat accumulator. Use can be made of a combination of heating elements and a coolant. The drying device provides for the possibility of charging the heat accumulator with thermal energy due to the coolant prepared in a solar air collector, as well as active ventilation of the grain.

To identify the effectiveness of the developed

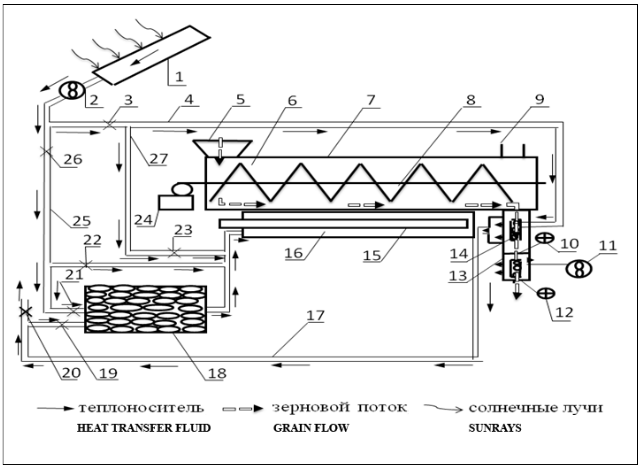

Fig. 1. Design scheme of a compact grain dryer

combined mini-grain dryers, experimental studies have been conducted. The obtained data have been processed using a correlation-regression analysis; the authors have also studied the relationship between the output parameter and the input variable independent factors, and basing on the results, they compiled a mathematical model of the grain drying process in a compact grain dryer with a combined heat supply. The technology has been patented (RF Patent No. 2625589 dated July 17, 2017).

Results and discussion. To determine the minimum heat input needed to evaporate one kg of moisture in the process of wheat drying based on the mathematical model, a two-factor experiment has been conducted to determine the main optimal parameters affecting the grain drying process - the speed of grain movement in the conductive chamber V_3 and the heating surface temperature of its casing $t_{гр.п}$ [9-12]. Experimental studies on the determination of thermal energy needed to evaporate 1 kg of moisture during the drying of wheat grain conducted in the first embodiment, when for conductive drying only the thermal energy of the traditional source, or the thermal energy received from the electric heating elements, has been used. In the second variant, the grain drying was carried out sequentially by conductive and convective methods, where, along with the thermal energy received from the electric heating elements, the thermal energy accumulated by the solar air collector was partially used, after which the grain was cooled with atmospheric air. The limits of changes in the grain movement speed in the conductive chamber V_3 (X_1) = 0.002-0.011 m/s, the heating surface temperature of the conductive chamber $t_{гр.п}$ (X_2) =70-103°C; the coolant speed in the drying unit was 2.63 m/s (zero option).

To determine the regression equations of both options, the authors have performed experimental studies, basing on the results of which, they have constructed orthogonal experiment planning matrices and obtained regression equations in actual values:

option 1:

$$q = 86.92 + 742.06V_3 - 1.97t_{гр.п} - 34074\,V_3^2 + 0.012\,t_{гр.п}^2 - 7.21\,t_{гр.п}; \quad (1)$$

option 2:

$$q = 5.2185 - 513.1041\,V_3 - 0.0293\,t_{гр.п} + 33672.2769\,V_3^2 + 0.00026\,t_{гр.п}^2 - 1.5549\,V_3 t_{гр.п}, \quad (2)$$

where q is specific heat consumption for moisture evaporation, MJ/kg;

V_3 is grain velocity in the conductive chamber of the dryer, m/s;

$t_{гр.п}$ is the heating surface temperature of the dryer's conductive chamber, °C.

Criterion-based estimation of the obtained regression equations is given in the *table*.

$F_р$ and $F_т$ are, respectively, the calculated and tabulated values of Fisher's criterion for determining the adequacy of the obtained regression equation; $t_р$ and $t_т$ 0,5, are, respectively, the calculated and tabulated values of Student's criterion for determining the significance of the regression equation coefficients.

The calculated values of Fisher's criterion

(*for option 1*: $F_t = 2.6 > F_p = 2.48$;

for option 2: $F_t = 2.68 > F_p = 2.41$) indicate the adequacy of the mathematical models obtained, and the comparison of the calculated and tabulated values of Student's criterion

(*for option 1*: $t_p = 5.23$; $t_{t0.5} = 2.06$;

for option 2: $t_p = 2.75$; $t_{t0.5} = 2.06$) confirms the accuracy of the studies performed.

Graphic images of the response surfaces from the interaction of the grain flow rate and the heating surface temperature of the dryer's conductive chamber and their effect on the optimization criteria are shown in *Fig. 2*.

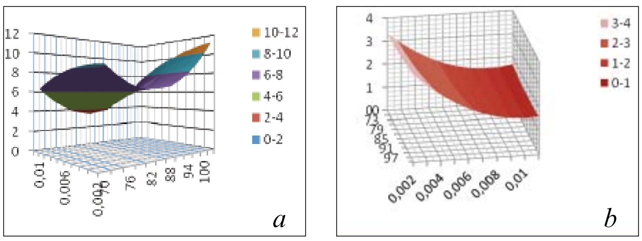

Fig. 2. Graphic interpretation of regression equations (1): a – option 1; b – option 2

The response surfaces represent a hyperbolic paraboloid (saddle) for *option 1*; while an elliptical paraboloid – for *option 2*.

The regression equations (1) in coded values can be represented as:

option 1:

$$Y = 4.25 - 1.47X_1 + 1.38X_2 - 0.69X_1^2 + 3.56X_1^2 - 0.55X_1 \cdot X_2; \quad (3)$$

Table

Criteria estimation of the regression equations

Option number	Correlative relation	Values of Fisher's test		Values of Student's test	
		calculated	tabulated	calculated	tabulated
	R	F_p	$F_т$	t_p	$t_{т\,0,5}$
1	0.964	2.48	2.6	5.23	2.06
2	0.917	2.41	2.68	2.75	2.06

option 2:

$$Y = 1.863 - 0.948X_1 + 0.107X_2 + 0.682X_1^2 + 0.076X_2^2 - 0.119X_1 \cdot X_2. \quad (4)$$

It follows then that the linear term of the equation – the grain flow rate in the dryer (X_1) – has the greatest influence on the optimization parameters, while the smallest effect is offered by the combination of the grain flow rate and the heating surface temperature (X_1 and X_2). Among the nonlinear terms of the equation, the square of the heating surface temperature has a significant effect on the optimization parameter, the increase of which causes a sharp increase in the latter. An analysis of equation (4) shows that, among the linear coefficients, the grain flow rate in the dryer has the greatest influence on the optimization parameters (X_1), and among the nonlinear ones, the flow rate (X_1^2). The least influence is offered by the square of the heating surface temperature (X_2^2).

After determining the types of response surfaces, the authors analyzed them using a two-dimensional section performed with the coded values of factors. To determine the response surface center of the obtained mathematical models, partial derivatives were found for each factor. The resulting expression was equated to zero. After that, a canonical transformation of the second-order model was carried out and the graphical-and-analytical analysis of the resulting expression was performed.

Option 1:

$$\begin{cases} \dfrac{dY}{dX_{1s}} = -1,47 - 1,38X_{1s} - 0,55X_{2s} \\ \dfrac{dY}{dX_{2s}} = 1,38 + 7,12X_{2s} - 055X_{1s} \end{cases} \quad (5)$$

$X_{1s} = -2.06;\ X_{2s} = -0.267$

Option 2:

$$\begin{cases} \dfrac{dY}{dX_{1s}} = -0,948 + 1,364X_{1s} - 0,119X_{2s} \\ \dfrac{dY}{dX_{2s}} = 0,107 + 0,152 - 0,119X_{1s} \end{cases} \quad (6)$$

$X_{1s} = 0.681;\ X_{2s} = -0.171.$

After substituting the values (X_{1S}) and (X_{2S}) into equations (3) and (4), the total unit costs for moisture evaporation in the surface center were determined:

for option 1: $S_{min} = 3.68$ MJ/kg;

for option 2: $V_{Smin} = 1.53$ MJ/kg.

Then the authors performed the canonical transformation of equations (3) and (4) by solving the characteristic equation:

$$f(B) = \begin{vmatrix} b_{11} - B & 0,5b_{12} \\ 0,5b_{12} & b_{22} - B \end{vmatrix} = B^2 - \left(b_{11} + b_{22}\right)B + \left(b_{11}\,b_{22} - 0,25b_{12}^2\right) = 0 \quad (7)$$

After the substitution of values:

for option 1: *for option 2*:

$B^2 – 2.865B – 2.326 = 0;\ B^2 – 0.758B – 0.0119 = 0.$ (8)

The characteristic equation roots:

for option 1: *for option 2*:

$b_{11} = 3.529,\ b_{22} = –0.659;\ b_{11} = 0.731,\ b_{22} = 0.0273.$

The equation in a canonical form can be represented as:

option 1:

$Y_{12} – 3.68 = 3.529X_1^2 – 0.659X_2^2$;

option 2: (9)

$Y_{12} – 1.531 = 0.731X_1^2 – 0.0273X_2^2$.

Checking-up the accuracy of the calculations:

option 1: *option 2*:

$\Sigma b_{ii} = –0.69+3.56=2.87;\quad \Sigma b_{ii} = 0.682+0.076=0.758;$

$\Sigma b_{ii} = 3.529–0.659=2.87;\ \Sigma b_{ii} = 0.731+0.0273=0.758.$

The rotation angle of the reference axes at point S:

option 1:

$$ctg2\alpha = \frac{b_{ii} - b_{jj}}{b_{ij}} = \frac{-0,69 - 3,56}{0,55} = -7,72;$$

option 2: (10)

$$ctg2\alpha = \frac{b_{ii} - b_{jj}}{b_{ij}} = \frac{-0,3125 - 1,2345}{0,2472} = -6,26.$$

The angle α is negative, therefore, the axes are rotated clockwise relative to the center of the two-dimensional section of the response surface. Canonical equations (9), (10) are used to construct the contour curves of the response surface. *Fig. 3* shows two-dimensional sections of the response surface characterizing the total specific heat consumption for moisture evaporation, MJ/kg.

Fig. 3 shows that the parameter X_1 (*option 1*) affects the value of the total specific heat consumption for moisture evaporation more intensively than the parameter X_2. The study revealed that when drying wheat grain with a compact grain dryer using a conductive method and a traditional energy source for heat supply only, the flow rate of a heat carrier in the drying unit is 2.63 m/s and it is possible to achieve a minimum of total specific heat consumption for the evaporation of moisture of 3.68 MJ/kg, and the optimum range of 3.68-4.5 MJ/kg corresponds to the range of the grain flow rate of 0.007-0.011 m/s and a heating surface temperature of the conductive chamber of the drying unit of 85-91°C. In *option 2*, the change in the parameter X_1 influences the value of the total specific heat consumption more intensively than the parameter X_2.

The most effective option in terms of saving thermal energy is associated with grain drying based on the sequential use of conductive and convective methods with subsequent cooling. In this case, to supply heat to the drying installation, use is made not only of solar radiation heat, but also of the heat obtained from recycling the spent coolant. In this optimal variant, when the coolant velocity in the drying unit is 2.63 m/s, the heat consumption for evaporation of 1 kg of moisture from the grain is minimal and equals 1.53-2.50 MJ/kg with the grain flow rate in the dryer of 0.007-0.011 m/s and at the heating surface temperature of 85-91°C.

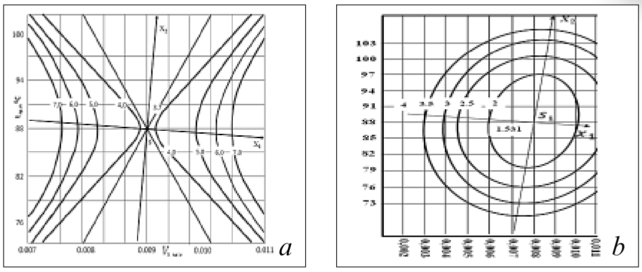

Fig. 3. Two-dimensional cross-sections of the response surface characterizing the total specific heat consumption for moisture evaporation, MJ/kg; a – option 1, b – option 2

Conclusions

The developed mini-grain dryer with a combined heat supply as contrasted to the existing small-sized dryers can significantly reduce energy consumption when using the combined method of grain drying with its subsequent cooling.

The carried out experimental studies have allowed to determine the optimal operation modes of a grain dryer, at which the specific heat consumption of a traditional thermal energy source for moisture evaporation is minimal and amounts to 1.53-2.50 MJ/kg, at a grain flow rate in the dryer of 0.007-0.011 m/s and the heating surface temperature of the conductive chamber of 85-91°C.

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Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Conflict of interest. The authors declare no conflict of interest.

Статья поступила в редакцию 24.10.2018
The paper was submitted to the Editorial Office on 24.10.2018

Статья принята к публикации 19.11.2018
The paper was accepted for publication on 19.11.2018