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New constructions of dryers for production of environmentally safe cereal products at reduced specific energy consumption

***Abstract**. The design of an energy-efficient block grain dryer with evaporative-condensing energy supply systems has been developed. The dryer contains a drying shaft, a condenser, a steam generator that comprise an evaporative-condensing module, and a fan. Design features of the dryer enable to carry out the drying process without direct contact of combustion gases and the product. Analytical modeling of the grain drying process has been carried out. It is based on a two-component model of heat transfer between thermosiphons and a layer of bulk material, taking into account evaporation of moisture from the grain. The efficiency of the developed structure has been evaluated according to such indicators as coefficients of heat transfer to grain flow; specific energy consumption. The values of coefficients of heat transfer to grain flow are 60 W·m^{-2}·K^{-1}. An increase in the grain flow rate leads to an increase in the heat transfer coefficient. Energy costs approach the minimum when drying at the temperature of the surface of thermosiphons T_s=140 °C for different grain consumptions. Energy consumption is 3.3...5.15 MJ/kg, depending on the surface temperature and air consumption.*

***Streszczenie.** Opracowano projekt energooszczędnej blokowej suszarni zbożowej z wyparno-kondensacyjnymi układami zasilania energią. Suszarka zawiera szyb suszący, skraplacz, wytwornicę pary, która zawiera moduł wyparno-skraplający oraz wentylator. Cechy konstrukcyjne suszarni umożliwiają przeprowadzenie procesu suszenia bez bezpośredniego kontaktu gazów spalinowych z produktem. Wykonano modelowanie analityczne procesu suszenia ziarna. Opiera się on na dwuskładnikowym modelu wymiany ciepła pomiędzy termosyfonami a warstwą materiału sypkiego, z uwzględnieniem odparowywania wilgoci z ziarna. Sprawność opracowanej struktury oceniono na podstawie takich wskaźników jak współczynniki przenikania ciepła do przepływu ziarna; określone zużycie energii. Wartości współczynników przenikania ciepła do przepływu ziarna wynoszą 60 W·m^{-2}·K-1. Wzrost prędkości przepływu ziarna prowadzi do wzrostu współczynnika przenikania ciepła. Koszty energii zbliżają się do minimum przy suszeniu w temperaturze powierzchni termosyfonów T_s=140 °C dla różnych zużycia ziarna. Zużycie energii wynosi 3,3...5,15 MJ/kg w zależności od temperatury podłoża i zużycia powietrza. (**Nowe konstrukcje suszarni do produkcji bezpiecznych dla środowiska produktów zbożowych przy obniżonej jednostkowej energochłonności**)*

Keywords: drying, grain, thermosiphons, energy consumption.
Słowa kluczowe: suszenie, ziarno, termosyfony, zużycie energii.

Introduction

Grain drying occupies up to 25% of industrial energy costs in developed countries. Convective dryers used for drying grain have low thermal efficiency. In order to minimize grain losses, obtain high-quality products, and reduce the burden on the environment, new designs of grain dryers are required. Modern grain drying is characterized by two problems, namely high energy consumption and grain contamination by combustion products. Globally, 10–12% of all energy is spent on drying processes [1]. Energy costs for grain drying are higher than energy costs for grain production. It is advisable to search for reserves to reduce energy costs in grain drying. There is growing interest in the use of thermosiphons (TS) in drying systems for solar collectors and heat exchangers [2]. TSs are able to transfer heat with a specific capacity of 3...6 kW·m-^{2} of the heat transfer surface.

In Ukraine, a mixture of combustion gases and air is used as a drying agent. Direct contact of combustion products with grain deteriorates its quality due to the penetration of carcinogenic components into the product. The improvement of drying technologies can be achieved due to the reduction of energy costs for moisture removal, ensuring environmental safety of the product being dried, development of highly efficient grain drying equipment. The process of grain drying with the use of infrared and microwave radiation can also be classified as ecological, but it is still insufficiently studied [3, 4]. There are various methods of drying intensification are used to obtain grain raw materials of conditioned humidity and reduce energy consumption in agricultural production: vibration drying, recirculation drying, preheating, vacuum drying, drying with the use of infrared radiation, drying of grain under the influence of an electric field and many others. Promising in terms of energy consumption and quality of raw materials is the use of vibrating dryers in combination with ozonation technology, which is an additional factor in intensifying the drying process [5].

There have been developed dryers that use available waste heat from the exhaust gases of diesel generators, instead of burning fresh fuel in order to actualize the drying of agricultural products [6]. Application of this energy recovery system for food drying would help to save a significant amount of primary fuel, which is considered a viable means of saving costs and reducing environmental degradation [7]. For small farms, in a sustainable and energy-efficient post-harvest drying process, there has been developed a heat exchanger that uses rice husk biomass energy to convert it into thermal energy. The purpose of using this heat exchanger in the dryer is to avoid contamination of the product with gases coming out of burning husks in the oven and their use [8, 9].

The experience of using TSs in global practice allows us to expect the possibility of creating energy-efficient and environmentally safe devices for heat treatment of grain on their basis [10, 11]. Therefore, it is relevant to develop a scientific base on the mechanisms of heat and mass exchange in devices with TS and creation of dryers based on them as well as methods of their calculation.

The efficiency of convective dryers comprises 40%. The energy consumption of convective dryers reaches 8 MJ/kg of removed moisture, which is almost three times higher than the physically necessary minimum. The content of carcinogens in the drying agent and the product is not controlled.

The goal of further research is to develop energy-efficient devices based on TS for drying grain products, theoretical foundations and methods of their calculation.

Materials and methods

As a result of our preliminary research [3, 12], a block grain dryer with evaporative-condensing systems (ECS) of the energy supply was developed (Fig. 1). In fact, ECS is a branched thermosiphon. The block grain dryer is a fundamentally new construction, in which energy is supplied to the grain layer due to the contact with the heated surface of ECS. The dryer contains a layer heater (1), a drying chamber (2), ECS, a condensation section (3) of which is located inside the layer heater (1), and an evaporation section (4) is located outside the dryer. The condensing section (3) of the ECS is made in the form of torus chambers (5), connected by bundles of pipes (6) with an inclination of 50...60 °. The body of the drying chamber (2) has channels (7) for the removal of the steam-air mixture using a fan (8) connected to the drying chamber (2).

The energy of fuel is transformed into the energy of combustion gases, which in the evaporation section of ECS (4) is transformed into the energy of water vapor, then the steam enters the condensation section of ECS (3), which is located in the drying chamber (2). The steam condenses and gives energy to grain. The condensate returns to the evaporation section.

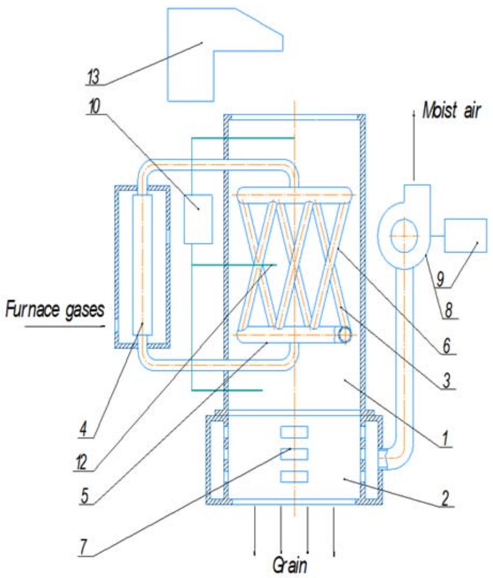

Fig. 1. Experimental stand: 1 – layer heater of grain, 2 – drying chamber, 3 – condensation section of ECS, 4 – evaporation section of ECS, 5 – torus chambers, 6 – bundle of pipes, 7 – channels for the removal of moist air, 8 – fan, 9 – frequency converter, 10 – analog-to-digital converter (ADC), 12 – thermocouple, 13 – grain elevator

The experiments on drying were carried out on wheat (Table 1).

Chromel-Copel thermocouples (12) were used to measure the temperature of the grain flow inside the mine. The data from the primary temperature transducers were fed to the ADC and entered into the PC.

The temperature of the air leaving the dryer was determined using a standard psychrometer. Air velocity and temperature were also determined using a Benetech GM816 anemometer. Air consumption was determined as the product of air velocity by the cross-sectional area of the air channel. Ambient air parameters were determined using a VIT-2 psychrometric hygrometer.

Table 1.The range of values measured

Crop	Air consumption at the dryer outlet	Grain moisture content	Product consumption	Grain flow temperature	Pressure in ECS module	Heater power, N	Duration of drying
	$m^3 \cdot s^{-1}$	%	$kg \cdot s^{-1}$	°C	MPa	kW	min
Wheat	0.01…0.03	12…25	0,02..0,4	20…100	0.1…0.4	1…4	0…180

The following experimental technique was used to determine the coefficients of heat transfer from the surface of the ECS to the grain flow of the layer heater.

The product was loaded into the dryer, the test time was measured using an electronic stopwatch. A sample of the product was taken for time τ. The sample was weighed on the laboratory electronic scale. The weight of the product *m*, kg was obtained. Mass consumption G_{gr}, $kg \cdot s^{-1}$ was determined as the ratio of product weight *m* to time τ.

Thermocouples were placed at the height of the layer heater (Fig. 1). The data from the primary temperature transducers were fed into the ADC, converted into a digital signal and entered into the PC. The data registration interval was 10 s. The temperature of ECS was measured with an interval of 100 s. The surface temperature of ECS was determined by thermocouples mounted in the surface.

The heat exchange process was studied at the grain moisture content close to the equilibrium humidity of the surrounding air at a given temperature.

Coefficient of heat transfer from the condensation sections of ECS of the layer heater to the grain flow was determined by the formula:

$$(1) \quad \alpha = \frac{Q_{ht}}{F \cdot \Delta t_a}$$

where: *F* – the surface area of the condensation sections of ECS, m^2; Q_{ht} – heat flow transmitted to grain, W; Δt_a – average temperature difference.

Moisture content of grain ω_{gr} % was determined with a Wile 65 digital moisture meter. During the drying process, grain samples were taken. Moisture content was measured when the temperature of the samples became the same. In this way, the influence of temperature error was reduced when measuring humidity.

Specific energy consumption for the drying process *E*, $MJ \cdot kg^{-1}$ was determined as the ratio of the total energy consumption for the process to the amount of moisture removed.

Results and discussion

A two-component model of heat transfer between ECS and the grain flow was developed, taking into account moisture evaporation from the grain.

The grain flow in the layer heater is considered as a discrete two-component “air – grain” system that washes the surface of ECS. Heating of the vaporized areas of ECS is performed by fuel combustion gases. For each component, heat transfer is described as for a solid medium, and the equations are written in a simplified differential form.

where $R_{tev} = \alpha_r^{-1} + R_1 + R_2 + \alpha_{ev}^{-1}$ – total thermal resistance of ECS;

At the condensation sections of ECS for grain:

$$(2)\ G_{gr} c_{sgr} \frac{dt_{gr}}{dz} + \left(a_{agr}\left(t_a - t_{gr}\right) + q_m\right) F_c = \frac{N_t}{V_{gr}} F_c F_a \left(t_a - t_{gr}\right) \frac{1}{\frac{1}{a_{gr}} + \frac{1}{a_c}},$$

for air:

$$(3)\quad G_a c_{sa} \frac{dt_a}{dz} - \left(a_{agr}\left(t_a - t_{gr}\right) + q_m\right) F_c = \frac{N_t}{V_{gr}} F_c F_a \left(t_a - t_{gr}\right) \frac{1}{\frac{1}{a_{ca}} + \frac{1}{a_c}},$$

on the evaporation section of ECS for gas:

$$(4)\quad G_g c_{sg} \frac{dt_g}{dz} = \frac{N_t}{V_{gr}} F_{gr} F_c \left(t_{ev} - t_s\right) \frac{1}{R_{tev}},$$

where $R_{tev} = \alpha_g^{-1} + R_1 + R_2 + \alpha_{ev}^{-1}$ – general thermal resistance of ECS;

G_a – air consumption; G_{gr} – grain consumption; G_g – gas consumption;

F_c – surface of the condenser; F_{ev} – evaporator surface; F_{gds} – the surface of the gas duct section;

N_t – the number of ECS tubes;

V_{grs} – the volume of the section with a grain layer; V_{gs} – the volume of the gas duct section.

q_m – the flow of water vapour removed from grain.

t_a – temperature of air; t_{gr} – temperature on the grain surface; t_{ev} – temperature of the evaporator; t_s – temperature of steam saturation in ECS;

c_{sgr} – specific heat capacity of grain; c_{sa} – specific heat capacity of air; c_{sg} – specific heat capacity of gas;

α_{agr} – coefficient of intercomponent heat exchange "air – grain"; α_{gr} – coefficient of heat transfer from grain flow; α_c – coefficient of heat transfer from ECS condenser; α_{ca} – coefficient of heat transfer at the condenser-air interface.

In the heater, in real operating conditions, the air from the environment enters the mine at almost the same temperature as the grain, as a result of which the intercomponent heat exchange is very small. The intensity of heat transfer during the movement of the grain layer is largely determined by its speed and flow conditions. Therefore, the study of this mechanism will enable to establish the ranges of parameters that vary during the experimental study of heat transfer, to determine the parameters of the beams that are rational for setting up experiments.

To take into account the intercomponent heat and mass exchange, it is possible to use the model of interaction of the grain layer and moist air, based on the model of a thin layer, which consists of three zones.

It is assumed that each zone is characterized by the same temperature and moisture content. Evaporation of moisture occurs from the 3rd (external) zone.

Heat and mass exchange of grains with the surrounding air can be expressed in the following way:

(5) $q = \alpha_{gr}(t_k - t_{gr}) - (\alpha_{agr}(t_a - t_{gr}) + q_m \cdot r)$,

(6) $q_m = \beta(p_{grs} - p_a) \quad p_{grs} = A_w \cdot p,$

Where: β – the mass transfer coefficient from the grain layer to the air; p_{grs}, p_a – partial pressure of water vapour above the grain surface and in the air; p_s – pressure of saturated water vapour at the grain temperature; A_w – water activity coefficient.

Heat and mass transfer between zones is described by the equations of heat conduction and diffusion.

(7) $G_{12} = K_{12}(W_1 - W_2)$; $G_{23} = K_{23}(W_2 - W_3)$;

(8) $Q_{12} = (T_1 - T_2)/R_{z1}$; $Q_{23} = (T_2 - T_3)/R_{z2}$,

where

W_1, W_2, W_3 – moisture content of the corresponding zone;

K_{12}, K_{23} – coefficient of mass conductivity between zones;

T_1, T_2, T_3 – temperature of the corresponding zone;

R_{z1}, R_{z2} – total thermal resistance to transfer between the corresponding zones;

G_{12}, G_{23} – mass flow between zones;

Q_{12}, Q_{23} – heat consumption between zones;

The value of the coefficient of heat transfer α_c, W·m^{-2}·K^{-1} from the condensing sections of the ECS layer heater to the grain flow was obtained experimentally. The dependence of the heat transfer coefficient on the average grain flow rate υ_{gr}, mm·s^{-1} and air consumption G_a, m^3·s^{-1} at the surface temperature T_s =142,9 °C was obtained (Fig. 2). As the average grain flow rate increases, the value of the average heat transfer coefficient increases. In the dryer, the values of the heat transfer coefficients vary within 28…60 W·m^{-2}·K^{-1} at the corresponding flow rates of 2,5…8 mm·s^{-1}. Air flow was varied within 0,01…0,03 m^3·s^{-1} using a frequency converter installed on the fan drive.

In the experiments, wheat with equilibrium initial moisture content was heated at given initial temperature and air humidity. The values of heat transfer coefficients were obtained taking into account the developed model (2-4).

In the layer heater, the ECS tubes are installed at an angle, the value of heat transfer coefficients when flowing around an inclined pipe is higher due to the fuller use of the pipe surface, mixing of the flow.

Energy consumption E, MJ·kg^{-1} of the developed grain dryer (Fig. 3) is presented in the form of the dependence on the grain flow consumption G_{gr}, kg·s^{-1} and the surface temperature of ECS condenser T_s.

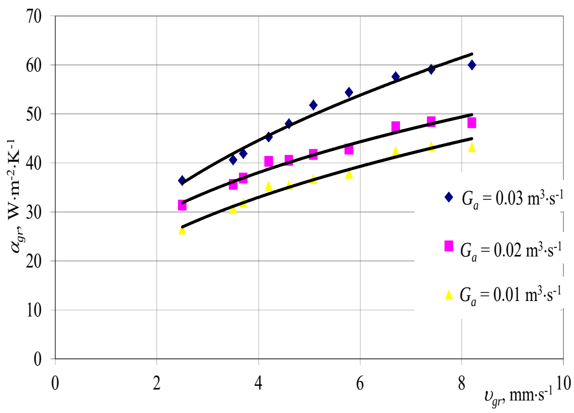

Fig. 2. The influence of average speed of grain flow and air on the coefficient of heat transfer from ECS

The nature of the dependence obtained shows that the combined effect of temperature and grain flow rate leads to a decrease in energy consumption. The energy consumption for drying under the surface temperature of ECS T_s=142,9 °C for grain consumption G_{gr}=0,2 kg·s^{-1} and air consumption G_a =0.05 m^3·s^{-1} is minimal and amounts to 3.3 MJ·kg^{-1}. An increase in the air speed leads to acceleration of the drying process, an increase in the grain flow rate and surface temperature of ECS leads to intensification of the heat exchange process. Due to this, a significant reduction in energy consumption is achieved.

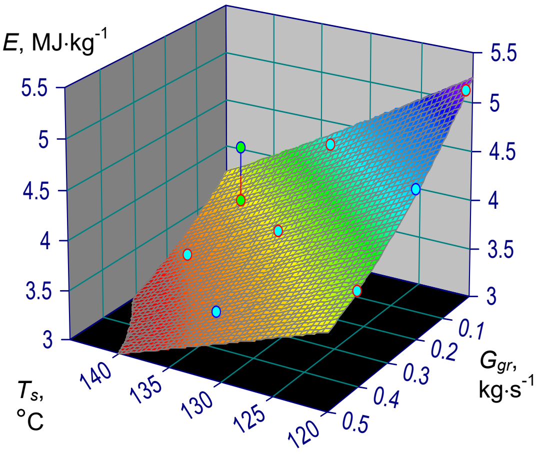

Fig. 2. The influence of average speed of grain flow and air on the coefficient of heat transfer from ECS

Conclusions

1. The experimental design of the block grain dryer was developed and tested. Features of the dryer allow the drying process to be carried out without direct contact of combustion gases and the product. Hence, it was possible to create a dryer that provides environmentally friendly drying of grain products with increased energy efficiency.

2. The efficiency of the developed structure was evaluated according to the following indicators: coefficients of heat transfer to the grain flow, specific energy consumption. The values of coefficients of heat transfer to the grain flow reach 60 W·m^{-2} K^{-1}. An increase in the grain flow rate leads to an increase in the coefficient of heat transfer. The results of experimental studies show that energy consumption of a block grain dryer is lower than existing convective dryers and amounts to 3.3...5.15 MJ·kg.

3. The research data are of practical value for agricultural enterprises and farmers who grow and store grain products.

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