RESULTS OF LABORATORY STUDIES OF GRAIN DRYING IN FLUIDIZED BED DRYER

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Abstract. A paper presents mathematical modelling and experimental results of grain drying in a dryer with pseudofluidized bed with intermittent drying media supply, working on producer gas. A system of four differential equations that interconnects the grain moisture content and temperature and drying media temperature humidity are presented. Straw and producer gas consumption for grain drying is presented. A multifactor experiment is done, where the drying media temperature, number of sections and sections blowing time are variable factors. Response surfaces are built on these data. Experimental results let us define the optimal calm period to the blow period ratio and drying media temperature that provide the highest grain moisture evaporation tempo. The obtained measurement results are in high correlation with the calculations. It illustrates that using gasifier technologies to supply grain dryers is expedient and provides high indexes of economical, energetic and ecological effectiveness, when using straw with the moisture content range of 10-30 %. Using this dryer lowers specific expenses on after harvesting post processing up to 30 %.

Keywords: fluidized bed, grain drying, gasifier technologies.

Introduction

In Ukraine existing drying modes in installations with periodical and continuous action do not provide substantial during quality and correspondent energy expenditures. The existing dryers have a low coefficient of productivity (CoP) and high specific material consumption [1].

As an alternative for convectional type dryers there are dryers with pseudofluidized bed [2]. Moist product is dried in the pseudofluidized layer that is created by heated drying media provided through the distribution system maintaining a “boiling” layer in the drying chamber [3-5]. Herewith created mode mixes the product effectively that raises the heat transfer coefficient, raising the whole product volume drying effectiveness [4]. While grain is moving in the “boiling” layer through the dryer sections, the used drying media is evacuated through the system of filters and cyclones [2; 6; 7]. For companies that have a surplus of straw, to provide production self-sufficiency and high indexes of ecological and energy efficiency it is expedient to equip dryers with gasifiers [8; 9].

Besides pros such dryers have some disadvantages. Separate grains, because of mixing, spend unequal time in the layer. As a result the grain mass can be processed unequally, that is not good especially for sowing grain. Using the gasifier as an energy supply for the dryer makes the situation even more complicated. Thus, there are sufficient achievements in the area of gasifying, especially agricultural raw material and its mixtures [10], however, there is still a problem of coordination between the thermo-technical modes of the gasifier and the dryer operation [9; 11].

There are quite enough scientific investigations describing the drying process in the pseudofluidized layer [3; 5; 12], although not all of them represent modelling of drying grain material, especially of sowing grain, when feeding the grain dryer with producer gas. Systematization of the grain and bean drying process (not considering the drying methods) modelling methods is rather complicated because of multiple factors that impact the integral effect of this process [3; 4; 7; 13-20]. Scientists tend to analyze these factors in different ways, depending on the type of the system that is investigated: grain properties, process parameters etc. [13; 16; 17]. Assumptions are reviewed (depending on the model) about the type of heat-mass transfer, separate grain movement inside the grain mass, mixing grade, type of the drying media, drying agent temperature ratio inside the grain mass and on the exit from it, the type of experimental kinetics of the process [5] and dried material heating [3; 4; 12; 14-17].

There are a lot of interesting works about modelling complex drying processes in dryers with fluidized bed proposed by scientists from Australia [3; 4; 13], Iran [12], Latvia [16; 17], Argentina [5], Ireland [18], the U.K. [19], Germany [20]. Depending on their aim these models were developed either to optimize the existing processes or to develop a new procedure. Discrete element method and computation fluid dynamics are the most used [13]. Computation fluid dynamics method is a powerful tool for its capacity of in-depth analysis of heat exchange, mass transfer and flow in multi-component systems. However, it is difficult for the computation fluid dynamics method to consider the discrete nature of grains [13; 15]. This problem can be solved with the discrete element method [13; 14]. If we want to describe the processes such as mass, heat transfer in pseudofluidized layer and investigate coupled gas-particle flows, it is better to combine computation fluid dynamics models with discrete element method models [14]. This combined method gives us a possibility to generate detailed grain scale information (to describe the acting forces and trajectory of individual grains) [14]. Many scientific works demonstrated that this combined approach is effective to examine the flow and heat transfer in fluidized systems [13-15]. But every mathematical model should be proved by experiments. It is necessary to investigate the grain drying process in a dryer with pseudofluidized bed and intermittent drying media supply, working on producer gas.

Materials and methods

A mathematical model for convectional drying of grain in a pseudofludized state was developed based on the mass and thermal balance of the dried product and drying media [6]. Drying agent supply was intermittent (blowing – calm period – blowing - …). Drying zone was divided into *n* sections, that were blowing through in series, each one for $\tau^{'}$ seconds. Blowing was removing moisture from the surface of grain, and during the calm period moisture and heat inside the grains were redistributing [13].

We neglected the specific heat capacity temperature coefficient for dry material and water at temperatures around maximum permissible temperature of grain heating according to [6; 21]. Latent heat of evaporation *r* that depends on the initial dried product temperature T_1 was calculated by recommendations [21]. To create a mathematical model of drying a grain product with intermittent drying media supply according to recommendations [6] such assumptions were made. It was assumed that: transportation of dried product particles in vertical direction is ideal, and temperature changes only alongside the machine (*x* axis) from minimum (feeding side) to maximum; drying media temperature that comes out of grain layer is equal to grain average temperature in the layer; mass transfer and heat exchange proceeds only between the drying media and the dried material; when the dried product is in the calm period, its moisture content and temperature do not change.

We obtained the following system of partial differential equations including the grain temperature $T_1(x, \tau)$, its moisture $W(x, \tau)$, the temperature of the drying media (air) $T_2(x, \tau)$ and humidity $d(x, \tau)$ [6; 16]:

$$\frac{\partial W}{\partial \tau} = -k \cdot \left(W - W^{P}\right),\ \tau > 0,\ x > 0, \tag{1}$$

$$\frac{\partial W}{\partial \tau} = -\frac{\rho_2 \cdot \varepsilon}{10 \cdot \rho_1} \cdot \left(\frac{\partial d}{\partial \tau} + V_1 \cdot \frac{\partial d}{\partial x}\right),\ \tau > 0,\ x > 0, \tag{2}$$

$$A \cdot \frac{\partial T_1}{\partial \tau} + B \cdot \frac{\partial W}{\partial \tau} = \frac{\partial T_2}{\partial \tau} + V_1 \cdot \frac{\partial T_2}{\partial x},\ \tau > 0,\ x > 0, \tag{3}$$

$$\lambda \frac{\partial^2 T_1}{\partial x^2} - V_1 \cdot D \frac{\partial T_1}{\partial x} - E \cdot W\left(T_2 - T_2\big|_{\tau=0}\right) = 0,\ \tau > 0,\ x > 0. \tag{4}$$

There:

$$A = -\frac{D}{E \cdot \varepsilon}; \quad B = -\frac{\rho_1 \cdot r}{100E \cdot \varepsilon}; \quad D = \rho_1 \cdot c_1; \quad E = \rho_2 \cdot c_2,$$

where x, τ – variables of space and time.

Equilibrium moisture content W^P was obtained from [17].

Initial and boundary conditions for the system (1) – (4) can be written in the following way.

Initial conditions:

$$T_1(x, 0) = T_1(x) = const; \quad T_2(x, 0) = T_2(x) = const; \quad W(x, 0) = d(x, 0) = const.$$

λ – effective heat conductivity coefficient of the layer in horizontal direction, $kJ\cdot m^{-2}\cdot h^{-1}\cdot K^{-1}$;
k – drying coefficient, h^{-1};
V_1 – grain layer movement velocity along the dryer axis, $m\cdot s^{-1}$;

Boundary conditions:

$$T_1(0,\tau) = const; \quad T_1(l,\tau) = const; \quad \frac{\partial W(l,\tau)}{\partial x} = const; \quad \frac{\partial T_2(0,\tau)}{\partial x} = \frac{\partial T_2(l,\tau)}{\partial x} = 0.$$

where l – dryer length, m.

Equation system (1-4) analytical solution with more variables is complicated.

To solve this problem a stepped calculation method was used that was sequential (in time and space) calculation of the drying process, using the MATLAB version 6.5.

The physical and chemical properties of the dried product (wheat grain) for modelling were: bulk density $\rho_1 = 850\ kg\cdot m^{-3}$, specific heat capacity $c_1 = 1.55\ kJ\cdot(kg\cdot°K)^{-1}$, dried product layer porosity $\varepsilon = 0.4$. The physical and chemical properties of the drying media (air) were: specific heat capacity $c_2 = 1.01\ kJ\cdot(kg\cdot°K)^{-1}$, density $\rho_2 = 0.89\ kg\cdot m^{-3}$. Specific heat of evaporation was $r = 2.26\cdot 10^6\ J\cdot kg^{-1}$. Drying agent had a velocity of $V_2 = 2.5\ m\cdot s^{-1}$. For modelling by recommendations [6] the dried product layer height was set at 0.1 m. The results of modelling for $T_2 = 333$ K are given in Table 1.

Table 1

Results of mathematical modelling of grain drying process

Section number	Dried product temperature T_1, °K			Dried product moisture content W, %			Drying media temperature T_2, °K			Drying media moisture content d, $g\cdot kg^{-1}$ of d.a.		
	Blowing through time of one section τ', s											
	10	30	50	10	30	50	10	30	50	10	30	50
at the entrance	288.0	288.0	288.0	19.0	19.0	19.0	333.0	333.0	333.0	11.0	11.0	11.0
1	288.3	289.8	290.2	18.9	18.8	18.8	321.5	311.0	303.2	18.9	18.8	18.8
2	288.8	291.7	292.7	18.7	18.3	18.2	321.6	311.1	304.3	18.8	18.7	18.6
3	289.3	293.6	295.4	18.5	17.8	17.6	321.7	311.2	305.6	18.7	18.6	18.4
4	289.8	295.2	298.1	18.3	17.4	17.0	321.8	311.3	306.9	18.6	18.5	18.2
5	290.3	296.8	300.8	18.2	17.0	16.5	321.9	311.4	308.2	18.5	18.4	18.0
6	290.7	298.3	303.5	18.1	16.6	16.0	322.0	311.6	309.3	18.4	18.3	17.9
7	291.1	299.9	306.2	18.0	16.2	15.5	322.1	311.8	310.4	18.3	18.2	17.7
8	291.5	301.4	308.7	17.9	15.8	15.1	322.2	313.0	311.6	18.3	18.1	17.6
9	291.9	302.8	311.2	17.8	15.5	14.7	322.3	313.2	312.3	18.3	18.0	17.5
10	292.3	303.9	313.6	17.7	15.2	14.3	322.4	313.4	313.0	18.2	17.9	17.4
11	292.7	304.8	316.0	17.6	14.9	13.9	322.5	313.6	313.4	18.2	17.8	17.3
12	293.1	305.7	318.3	17.5	14.6	13.5	322.6	313.8	314.0	18.2	17.7	17.2
13	293.4	306.6	320.6	17.4	14.3	13.1	322.7	314.0	314.6	18.1	17.6	17.1
14	293.7	307.1	322.8	17.3	14.0	12.7	322.8	314.3	315.2	18.1	17.5	17.0
15	294.1	307.6	325.0	17.2	13.7	12.4	322.9	314.6	315.8	18.1	17.4	16.9
16	294.3	308.0	327.2	17.1	13.5	12.1	323.0	315.0	316.4	18.0	17.3	16.8

The results of modelling say that when the drying media temperature grows, the drying speed also grows, but grain overcomes the maximum permissible temperature the same time.

The specific straw consumption G and medium hour producer gas consumption C_{gas} depend a lot on the type of fuel and its moisture content:

$$G = \frac{10.7\cdot K_1\cdot q\cdot\psi}{K_2\cdot\eta\cdot\left[c_3\cdot T_3 + HHV_{gas}\cdot\eta_f + (k_1+k_2)\cdot\rho_2\cdot\left[T_2\cdot c_2 + \left(r + c_4\cdot T_2\right)d_0\right]\right]}, \tag{5}$$

$$C_{gas} = \frac{(1.07 \cdot q \cdot m) \cdot \psi \cdot 10^{-2} \cdot \Delta W}{\tau \cdot \eta \cdot \left[(c_3 \cdot T_3 + HHV_{gas} \cdot \eta_f) + (k_1 + k_2) \cdot \rho_2 \cdot \left[T_2 \cdot c_2 + \left(r + c_4 \cdot T_2 \right) d_0 \right] \right]}, \quad (6)$$

Setting the values of such parameters as: quantity of heat q, that is needed to evaporate moisture from grain by $\Delta W = 5.5$ % (determined by Mollier h-x diagram of wet air in kJ·kg^{-1}); dryer heat consumption irregularity coefficient during the grain drying cycle $\psi = 0.8$-1.05 (depends on gasification process stability); coefficient K_1, that depends on CO, CO_2, CH_4 content in producer gas, $K_1 = 17.62$-19.4 [9]; coefficient K_2, that shows carbon quantity in gas compared to its initial quantity in fuel considering all its loses $K_2 = 24.8$-38.7 [9]; dryer CoP $\eta = 0.7$; dryer furnace CoP $\eta_f = 0.85$; grain mass m, that needs drying; coefficients $k_1 = 1.57$-1.74 and $k_2 = 10.28$-10.96, that consider air quantity needed to burn producer gas and form drying media respectively [9]; specific producer gas heat capacity $c_3 = 1.05$ kJ·(m^3·K)$^{-1}$; producer gas temperature $T_3 = 673$-873 ºK; specific steam heat capacity $c_4 = 2.2$ kJ·(kg·K)$^{-1}$; higher heating value of gas $HHV_{gas} = f(W_{straw})$, kJ·(m^3)$^{-1}$ the dependence of specific straw consumption G in kg·(ton· %)$^{-1}$ for grain drying was built, Fig. 3.

The investigations let us theoretically substantiate the working process of drying grain in pseudofluidized layer with intermittent drying media supply in a dryer working on producer gas. Technological parameters of the dryer are: drying capacity – 1.3-2 t·h^{-1}; time to reduce the moisture content from 19 % to 13.5 % – 10-13 min.; gas productivity of gasifier $P_{gas} = 120$-136 m^3·h^{-1} (for dryer drying capacity 2 t·h^{-1}) when using straw with 8…30 % moisture content. The paper dedicated to gasifier design development for the grain dryer is [9].

The investigation was made by multifactor experiments. Design of a proposed dryer, Fig. 1a, Fig. 1b, equipped with the gasifier, Fig. 1c, features pseudofludizing grain material not by the whole drying surface, but gradually by sections. In every moment of time grain is blow through with hot air on one part of the drying zone. Here it appears in pseudofluidized state. An intense drying is held and a wave is created that helps transporting grain along the drying chamber. At the same time the rest of grain stays in calm state. Heat redistributes equally within the layer as well as moisture redistributes inside each grain moving from inner to outer layers by capillaries.

Fig. 1. **Grain dryer (a), dryer working zone (b) and gasifier (c) views**

Drying media temperature was measured with K-type thermocouple, installed in the gas distributor chamber, Fig. 1b. Grain temperature was measured with the method [21; 22] measuring temperature of a suddenly released layer (after stopping drying media supply). Namely, it was measured, when grain was in the calm period by putting in a thermocouple into the grain layer (3...4 points). Initial and final moisture content was measured with a moisturemetre Aqua-15 Etalon, and evaporated moisture was controlled with electronic laboratory scales AXIS ADGS. Anemometer GM-18 is used to meashure the air flow velosity. The velocity of drying media was measured at the entrance (in the gas distribution chamber) and at the outlet – in the recirculation channel, then the values were averaged.

The goals of the investigation were to determine the optimal blowing period $\tau^{'}$ to the calm period ratio $\tau^{''}$ in the dryer, equiped with a gasifier, and to determine the optimal drying media temperature that provides the fastest grain moisture evaporation tempo. The grain should not be heated above maximum permissible temperature $T_1 = 50$ ºC [21; 23].

The variable factors of the experiment were: drying media temperature T_2, number of sections of grates of the dryer n and grates' opening period τ'. The mentioned parameters were changing between limits: T_2 from 30 to 54 ºC; n from 4 to 16; τ' from 10 to 50 s. Factors coding were: $X_1 = T_2$, $X_2 = n$, $X_3 = \tau'$. To receive process models in form of quadratic polynomial a Box-Behnken type quadratic plan was used [22; 23]. For experimental data certainty repetition of experiments under the same conditions equals $k = 3$. Eight original experiments were made according to the planning matrix and polynomial`s linear part coefficients were calculated according to [22]. The values of the model relative error for all experiments according the plan of the multifactor analysis are lower than 3 % [22]. The values of mean relative deviation are lower than 2.11 % [22]. As it can be seen, the relative error values less than 10 % are considered acceptable in modelling of the drying process [22]. Therefore, it can be concluded that the presented model predicts drying processes with a high accuracy.

Results and discussion

After calculating the correlation polynomial coefficients regression equations for drying exposition τ (7) and temperature increment ΔT_1 (8) were received:

$$\tau = 5280 - 186.02 \cdot T_2 + 168.5 \cdot n - 30.42 \cdot \tau' - 3.33 \cdot T_2 \cdot n - 0.134 \cdot n \cdot \tau' + 2.2 \cdot T_2^2 + 6.21 \cdot n^2 , \qquad (7)$$

Equation adequacy characteristics are: R^2=0.985; F=19.03; p=1.88·10^{-3}.

$$\begin{aligned} \Delta T_1 = 20.66 + 0.08 \cdot T_2 - 0.0375 \cdot n + 0.025 \cdot \tau' - 0.07 \cdot T_2 \cdot n + 0.062 \cdot T_2 \cdot \tau' + \\ + 0.07 \cdot n \cdot \tau' - 0.034 \cdot T_2^2 + 0.017 \cdot n^2 - 0.025 \cdot (\tau')^2 \end{aligned} , \qquad (8)$$

Equation adequacy characteristics are: R^2=0.99; F=18.3; p=2.03·10^{-3}.

The surfaces, Fig. 2a, and equation (7) analysis shows that while drying the media temperature lowers, drying exposition rises. It gains minimum with minimal sections number. The coefficients of the equation (7) show that among the linear terms of the equation, the drying media temperature T_2 and the number of sections n have the greatest influence on the optimization parameter τ. Grates' opening period τ' and combination of the parameters $T_2 \cdot n$ have less influence on this parameter. Equation analysis (7) shows that while the grates' opening period τ' decreases the drying exposition τ rises. According to equation analysis (8) grain has higher temperature, if the drying media has higher temperature and it rises when the blowing time τ' rises. Grain temperature increment is the lowest for the number of sections 13-16, Fig. 2b.

Therefore, a program was written to make optimization of polynomials (7) and (8). Investigations showed that for the drying media temperature of 60 ºC the drying process proceeds with the highest tempo between the sections 6 to 10. On practice, maximum productivity is reached with maximum grain material drying tempo and when the number of sections equals 14.

Drying process kinetic dependencies were developed experimentally. Following them, depending on initial grain moisture content, we can define the optimal drying time. This index was found for the design dryer by the method of checking all combinations of the experimental data by means of "Statistics 10" software by the calm period τ'' to blow through the period τ' ratio. The calm period was $\tau'' = \tau' \cdot n - \tau'$. The highest drying tempo was achieved for $\tau'' \cdot (\tau')^{-1}$ ratio values 0 to 8 depending on the drying media temperature. Also we observed lowering moisture evaporation tempo from the grain layer with further drying media temperature rising. This regularity is explained by the phenomenon of grain quenching under high drying media temperature that makes moisture evaporation from the grain surface difficult.

Analyzing the experimental data we see that the grain dryer productivity was rising, while the drying media temperature was rising till 60 ºC, but then it was lowering. Maximum dryer productivity at drying media temperature 60 ºC was reached for $\tau'' \cdot (\tau')^{-1}$ = 1:13 ratio. Thus, the highest drying tempo and productivity are reached for different $\tau'' \cdot (\tau')^{-1}$ values, nevertheless, it should be admitted that, when rising the number of sections, the productivity rises sharply, though the moisture evaporation tempo lowers.

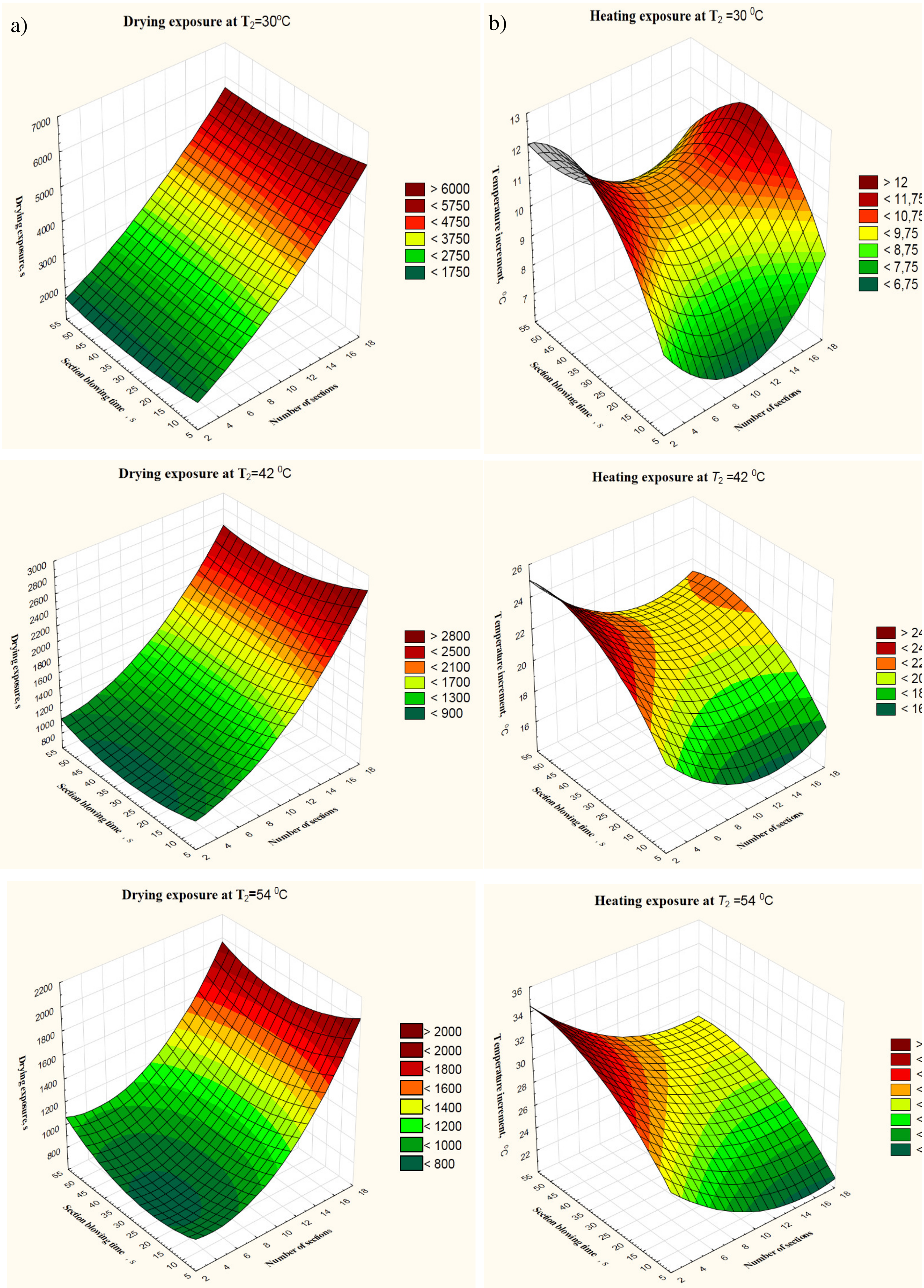

Fig. 2. **Grain drying (a) and heating (b) exposition against number of sections and blowing trough time for different T_2 values**

So, the grain dryer was designed and made by maximum productivity criteria that were obtained experimentally with such rational values of the parameters: $T_2 = 60$ ºC, $n = 14$, $\tau' = 30$ s. Technical-economical specifications of the dryer are as follows: drying capacity 1.5 t·h^{-1}; initial grain moisture content – 19 %, final moisture content – 13.5 %; drying media temperature 60 ºC; drying exposition – 12 min; drying media supply – 2600 m^3·h^{-1}; fuel consumption (chopped straw) 50-56 kg·h^{-1} specific energy consumption – 4.28·10^6 J·kg^{-1}. This dryer with gas feeding is made at "Vibroseparator" plant.

Experiments on using gasifier technologies for feeding the grain dryer show that specific consumption of chopped straw G for drying grain depends greatly on its moisture content W_{straw}. Rising the straw moisture content by 5 % leads to lowering the dryer specific productivity by 18-20 %. So, rational straw moisture content range is W_{straw} = 10-30 %. When using straw with the moisture content more than 30 %, the dryer specific productivity lowers by 25-30 %, thereby using gasifier technologies is inappropriate. Comparing the designed dryer with similar type dryers [4; 5; 12; 23] we can see that this dryer not only fulfils the necessary grain drying technological modes, but also provides high indexes of economical, energetic and ecological effectiveness.

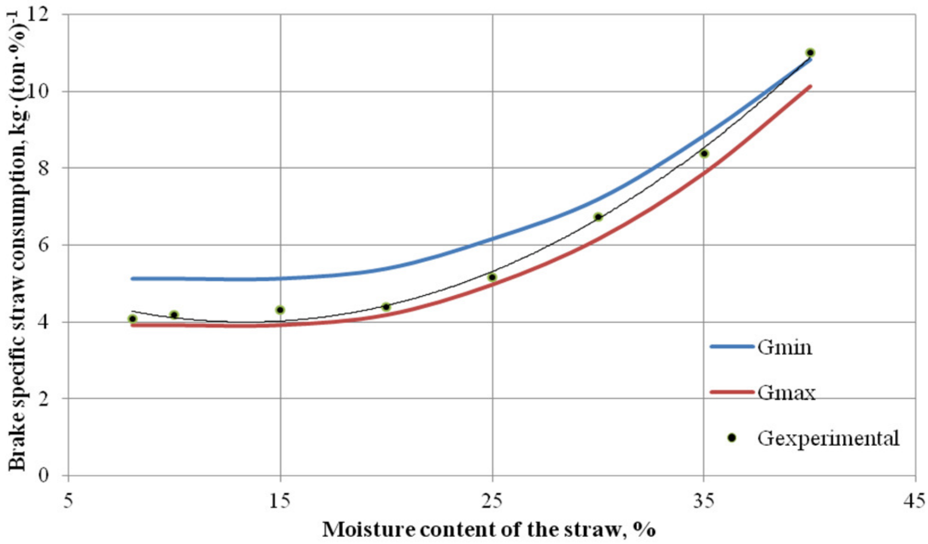

Fig. 3. **Specific chopped straw consumption *G* for grain drying process against straw moisture content W_{straw}**

Conclusions

The experimental study, mathematical modelling and numerical simulation of the grain drying process in the dryer with pseudofluidized bed working on producer gas have led to the following conclusions.

1. A mathematical model of a convective grain drying process in pseudofluidized layer is proposed. It was developed on the basis of material and heat balance of the dried product and drying media. Yet, this model needs further development, because it does not fully take into account the possible movement of separate grains inside the layer, temperature ratio between the drying media inside the grain volume and outside of it, heat loses for unorganized air exchange.
2. With help of multifactor experiments with further data analysis a rational design and technological parameters of the designed dryer were set up: maximum dryer productivity 1.5 t·h^{-1} is reached, when the drying media temperature is 60 ºC; number of sections is 14 with blowing time of one section 30 s; drying media supply – 2600 m^3·h^{-1}; fuel consumption (straw) 50-56 kg·h^{-1}; specific energy consumption – 4.28·10^6 J·kg^{-1}.
3. Using gasifier technologies to supply grain dryers is expedient and provides high indexes of economical, energetic and ecological effectiveness, when using straw with the moisture content range of 10…30 %. Raising the straw moisture content by 5 – 10 % leads to additional heat consumption to evaporate this moisture by 7-15 %. Using straw with the moisture content above 30 % lowers the specific dryer productivity by 25-30 %.
4. Using this dryer lowers the specific expenses on after harvesting post processing up to 30 %.

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